THE ATLAS OF MAJOR APPALACHIAN GAS PLAYS

Edited by
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U.S. Geological Survey (Ret.)
and
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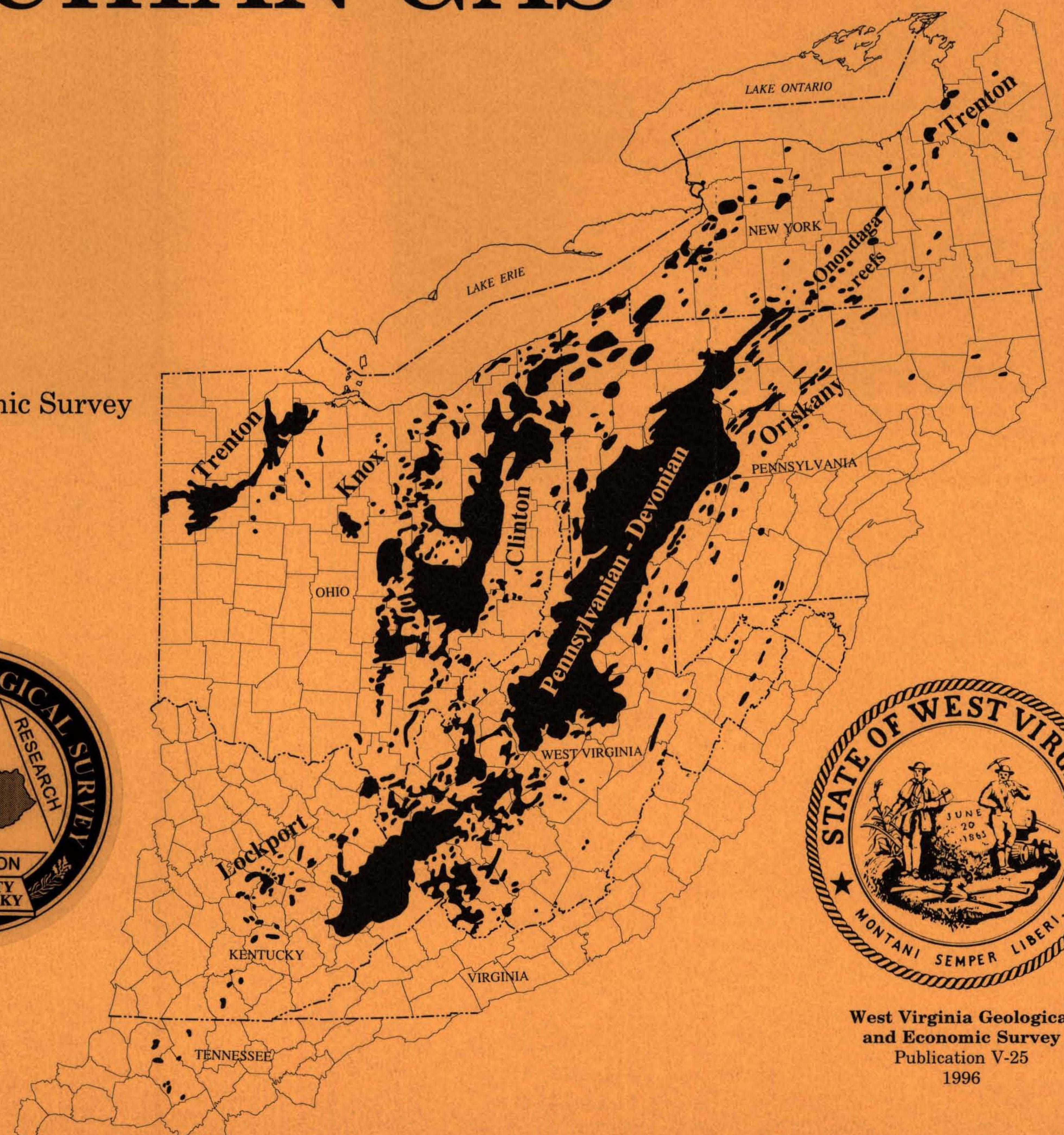

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Play Paf: Middle Pennsylvanian Allegheny Formation/Group Sandstone Play—Michael Edward Hohn

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Play Pps: Lower and Middle Pennsylvanian Pottsville, New River, and Lee Sandstone Play—Michael Edward Hohn

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Play Mgn: Upper Mississippian Greenbrier-Newman Limestones—Richard A. Smosna

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Play Mbi: Lower Mississippian Big Injun Sandstones—Ana G. Vargo and David L. Matchen

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Play Mws: Lower Mississippian Weir Sandstones—David L. Matchen and Ana G. Vargo

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Play Mfp: The Lower Mississippian Fort Payne Carbonate Mound Play—Robert C. Milici

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Play MDe: Lower Mississippian-Upper Devonian Berea and Equivalent Sandstones—Thomas E. Tomastik

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Play Dvs: Upper Devonian Venango Sandstones and Siltstones—Ray Boswell, L. Robert Heim, Gregory A. Wrightstone, and Alan Donaldson

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Play Dbs: Upper Devonian Bradford Sandstones and Siltstones—Ray Boswell, Bradley W. Thomas, R. Brandon Hussing, Timothy M. Murin, and Alan Donaldson

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Play Des: Upper Devonian Elk Sandstones and Siltstones—Alan Donaldson, Ray Boswell, Xiangdong Zou, Larry Cavallo, L. Robert Heim, and Michael Canich

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Play Dbg: Upper Devonian Fractured Black and Gray Shales and Siltstones Play—Robert C. Milici

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Play Dol: Middle Devonian Onondaga Limestone Reef Play—Arthur M. Van Tyne

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Play Dho: Fractured Middle Devonian Huntersville Chert and Lower Devonian Oriskany Sandstone—Kathy J. Flaherty

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Play Dos: Lower Devonian Oriskany Structural Play—John A. Harper and Douglas G. Patchen

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Play Doc: Lower Devonian Oriskany Sandstone Combination Traps Play—Douglas G. Patchen and John A. Harper

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Play Dop: Lower Devonian Oriskany Sandstone Updip Permeability Pinchout Play—Steven T. Opritza

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Play Sbi: Upper Silurian Bass Islands Trend—Arthur M. Van Tyne

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Play DSu: Lower Devonian-Upper Silurian Unconformity—Joseph F. Meglen and Martin C. Noger

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Play Sns: Upper Silurian Newburg Sandstone Play—Douglas G. Patchen

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Play Sld: Upper Silurian Lockport Dolomite-Keefer (Big Six) Sandstone—Martin C. Noger, Joseph F. Meglen, Matthew Humphreys, and Mark T. Baranoski

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Play Obe: Upper Ordovician Bald Eagle Formation Fractured Anticlinal Play—Christopher D. Laughrey and Robert M. Harper

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Play Obc: Upper Ordovician Bioclastic Carbonate ("Trenton") Play—Brandon C. Nuttall

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INTRODUCTION TO THE ATLAS OF MAJOR APPALACHIAN GAS PLAYS

by Douglas G. Patchen, Atlas Project Manager, West Virginia Geological and Economic Survey

Purpose

Commercial gas production began in the Appalachian basin more than 100 years ago. During this long period of exploration and development, production has been established in more than 100 stratigraphically discrete intervals in more than 1,000 named gas fields. Presently, the basin is considered to be mature and gas prone. Given the long history of production and the vast number of companies that have operated in this basin, it is not surprising that no attempt has been made at a basin-wide data compilation for historical and existing gas fields.

The U.S. Department of Energy (US DOE) contracted with the Appalachian Oil and Natural Gas Research Consortium (AONGRC) to prepare an atlas of major gas plays within the basin. US DOE had two main goals in entering into this contract: to write and illustrate play descriptions of all major gas plays in the basin; and to create a companion database containing geologic and engineering data on gas fields and reservoirs within each play.

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Atlas Organization

The various stratigraphic intervals that produce gas in the basin were organized into a series of gas plays for presentation in this atlas. A play is defined as a group of geologically similar drilling prospects having similar source, reservoir, and trap controls of gas migration, accumulation, and storage (modified from White, 1980; 1988). Thus, they share some common elements of risk with respect to the possible occurrence of natural gas.

Plays are commonly designated by their reservoir lithology, although play names can be modified by reference to trap type or other geologic similarities that control production within the play. Thus, plays can be classified according to depositional environments that produced the reservoir lithology, or the other geologic factors that control production within the play.

Play descriptions are presented in the atlas in stratigraphic order from youngest to oldest, or from top to bottom as penetrated by the drill bit. However, for those who are interested in a more geologic classification of plays, a second table of contents is included here which groups plays by geologic similarities.

Play descriptions follow a standard format that includes these major headings: Location, Production History, Stratigraphy, Structure, Reservoir, Description of Key Fields, Resources and Reserves, and Future Trends. Illustrations include the following: a pool/well location map on a standard basin base map with play outline; a regional map with all key fields identified; a stratigraphic column with both formal and drillers' terms; a correlation chart; an isopach map of the reservoir unit or structure map on the unit; a cross section (either stratigraphic or structural); a type log for key fields; and a pay or porosity map for key fields.

Each play description also includes a table of geologic and engineering data for key fields within the play. Data are organized into the categories of basic reservoir data; reservoir parameters; fluid and gas properties; and volumetric data.

In order to eliminate lengthy text passages in each play, the stratigraphic framework and the structural evolution of the basin are presented in brief introductory sections preceding the play descriptions.

Atlas Preparation

Once plays had been defined, authors were recruited to write and illustrate each play. Most of the illustrations in the atlas were originally drafted by the state geological surveys in Kentucky, Ohio, Pennsylvania, and West Virginia and provided to the West Virginia Geological and Economic Survey to meet uniform standards set by the production editor and approved by the Morgantown Energy Technology Center (METC). In a few instances, authors supplied illustrations that were printed as received. These illustrations, listed by figure number, were provided by the agencies indicated and printed as received:

Figures 4, 7, and 8, and Plates 1 and 2: West Virginia University;
Figures MDe-8, MDe-10, MDe-13, MDe-14, MDe-15, and MDe-24: Ohio Division of Oil and Gas;
Figures Dvs-3 and Dvs-12a-b: EG&G TSWV, Inc.;
Figures Dbs-3 and Dbs-23: EG&G TSWV, Inc.;
Figure Des-4: EG&G TSWV, Inc.;
Figures UDs-12, UDs-23, UDs-26, and UDs-33: EG&G TSWV, Inc.;
Figures Dho-7 and Dho-13: Pennsylvania Bureau of Topographic and Geologic Survey;
Figures Doc-5, Doc-6, and Doc-7: West Virginia Geological and Economic Survey;
Figures Dop-4, Dop-5, and Dop-9: Ohio Division of Oil and Gas;
Figure Sld-11: Ohio Division of Geological Survey;
Figures Scm-4, Scm-5, Scm-12, Scm-19, Scm-21, Scm-26, Scm-27, and Scm-30: Ohio Department of Natural Resources;
Figure Obe-8: Pennsylvania Bureau of Topographic and Geologic Survey;
Figure MOf-5: Ohio Division of Geological Survey;
Figures COk-14, COk-16, COk-17, and COk-21: Ohio Division of Geological Survey; and
Figures Cpk-8, Cpk-10, and Cpk-12: Ohio Division of Geological Survey.

Each author received support from the geological surveys in two important tasks: a search of the geologic and engineering literature, and data collection for every field and reservoir in each play. Play descriptions were subjected to sequential internal reviews by project team members, external reviews by industry geologists, review by geologists and engineers at METC, and initial and final reviews by the technical editor.

Database

The table of geologic and engineering data for each play description contains average values for key fields described or mentioned in the play description. A separate deliverable is a digitized database that contains the same parameters as well as additional parameters for all, or nearly all, of the fields in each play. Data entered into this database were gathered from the literature, from industry, and from the oil and gas files and databases at the various state geological surveys. In most cases, data were collected for a representative set of wells for each reservoir in each field and used to estimate average field values. These included original data from log and core analyses made specifically for this project. An attempt was made to gather all data elements for all fields listed in the tables. Where these data are not available, the data field has been left blank.

A more thorough discussion of the database is included in a separate section following this introduction.

Future

More than 40 tcfg have been produced from reservoirs in more than 1,000 named fields in New York, Pennsylvania, Ohio, West Virginia, Maryland, Kentucky, Virginia, and Tennessee. Proved reserves have been estimated to be 7.4 tcf (IPAA, 1994) and probable, possible, and speculative resources have been estimated to range from 25,464 bcf to 165,040 bcf (Potential Gas Committee, 1995), values which include estimates of coal bed methane potential.

Authors responsible for the play descriptions in this atlas have attempted to refine these reserve and resource estimates to the play level. The area of each play has been defined based on the extent of geologic controls that define the play. Various estimates have been made in regard to reserve and resource categories. Each author did not use the same technique in making these estimates. However, the technique used is described, or adequate references for estimates cited are given. In addition, enough information generally is given in the play descriptions, illustrations, and data tables to enable future workers to revise these resource estimates if they so desire.

Some of the older gas plays developed in stratigraphically shallower reservoirs have produced much of their expected resources. Although they are mainly of historical interest, detailed geologic studies and selective drilling may identify significant additional reserves to be recovered. Other gas plays, however, particularly those in stratigraphically deeper units or in structural plays along the eastern side of the basin, have been sparsely drilled and have good potential for future field discoveries.

TABLE OF CONTENTS BY PLAY CLASSIFICATION

INTRODUCTION TO THE DATABASE OF APPALACHIAN GAS FIELDS AND RESERVOIRS

Purpose

Although The Atlas of Major Appalachian Gas Plays is the most visible product of this project, its companion database product, The Database of Appalachian Gas Fields and Reservoirs, is equally as important to Appalachian basin gas producers. The main objective in creating a database of Appalachian gas fields was to collect information at the pool level, that is, by producing reservoirs within a gas field, that will provide basic field and reservoir data, parameters specific to the producing reservoir, fluid and gas properties, and volumetric data.

Data Sources

Sources for these data include publications in the geologic and engineering literature; geological survey files, both hard copy and electronic; and gas producers. Gas analyses data came from industry and from a database maintained by the U.S. Bureau of Mines. Ultimately, however, the state geological surveys in Kentucky, Ohio, Pennsylvania, and West Virginia are responsible for all data entered into the database, and should be contacted directly to determine a specific source for a given piece of information in any reservoir record.

Acknowledgements

Compilation of the database of Appalachian gas fields and pools was a cooperative project by the partners in the Appalachian Oil and Natural Gas Research Consortium. The state geological surveys in Kentucky, Ohio, Pennsylvania, and West Virginia were responsible for collecting and formatting data on all major gas reservoirs in their respective states. In addition, Arthur M. Van Tyne, Consultant, was charged with the responsibility of collecting data for New York, and Robert C. Milici, U.S. Geological Survey, collected data for Tennessee and Virginia. The state geological surveys in Maryland, Tennessee, and Virginia, and the Department of Environmental Conservation in New York provided additional data for this compilation.

Ronald R. McDowell, Senior Research Geologist for the West Virginia Geological and Economic Survey, served as Database Manager for this project. Brandon C. Nuttall, Senior Geologist at the Kentucky Geological Survey, prepared a topical report on "Data Collection and Compilation" that served as a set of guidelines for this effort.

Funds for the compilation of the database were provided by the U.S. Department of Energy (US DOE) as part of the gas atlas contract. Harold Shoemaker of US DOE's Morgantown Energy Technology Center (METC) was the project manager assigned to this project.

Data Elements and Definitions

Data elements chosen to be included in the database were those that were within the scope of the gas atlas project. The information collected became the basis for the geologic and engineering descriptions of each play in the atlas, as well as elements in the electronic database.

A "record" is a single line of data in the database. Each record in the database represents information for a single reservoir within a gas field, or, in some instances, a group of reservoirs assigned to the same play from which production is commingled. In the latter case, these reservoirs define the stratigraphic range of a play in a given gas field. Examples include the three Upper Devonian sandstone plays in Pennsylvania, and commingled production from several reservoirs within the same play in West Virginia. In West Virginia, these records for multiple reservoirs are included in the database in addition to records for individual reservoirs within the play. All records are a consistent length (nearly 700 characters), and all data values within a record are stored as ASCII characters. Each data value is space-delimited; that is, it is separated from its predecessors and successors by a single blank space.

Seventy data elements are included within each record. Included are basic reservoir data, such as field name, location, discovery date, number of wells, acreage, spacing, and geologic name of the producing reservoir; reservoir parameters, such as average pay and completion thickness, porosity, permeability, depth, and the initial and current pressure of the reservoir; fluid and gas properties, including gas gravity, Btu value, and gas and water saturations; and volumetric data, including cumulative production, years of production, original gas-in-place and reserves, remaining gas-in-place and reserves, initial and final open flows, and recovery factor.

The format of the database is shown in Table 1, which lists the variable, the number of characters provided for each variable, and the type of character. Data are listed as they occur within the record for a reservoir or group of reservoirs. Numerical codes for various data elements, including field status, depositional environment, trap, lithology, and gas type, are listed in Table 2. Definitions of each of the 70 data elements also are included in Table 1. Where variations in usage occurred between states, these are noted.

Database Preparation

The overall strategy developed to create the database was to expediently obtain as much data as possible from the best sources, and then move on to the secondary sources. This meant exhausting the best sources first, which were the state geological surveys and the larger gas producers.

The first step was to choose data elements to be collected, and to develop consistent definitions of those elements. Next, each state geological survey completed an inventory of data available in hard-copy files or digital files within its survey. These data were usually available by individual wells, and digital files

Table 1. Sequence of variables within a database record.

CHARACTERS Number	CHARACTERS Type	VARIABLES (Units)
3	I	State code—A three-digit number based on the American Association of Petroleum Geologists Committee on Statistics of Drilling codes.
6	A	EIA field number (-99999 = no number assigned)—A six-character field using codes assigned to producing reservoirs by the Energy Information Administration.
5	A	State field number—A four-digit numerical code assigned by the state surveys or by the Database Manager. In West Virginia, Ohio, and Kentucky, the numbers correspond to numbers on the state oil and gas fields maps; in Pennsylvania, the U.S. DOE field codes were used.
8	A	Age/Formation code—An eight-character text entry based on the American Association of Petroleum Geologists Committee on Statistics of Drilling age codes. The combined code refers to a specific reservoir name and the geologic age of that reservoir. Generic entries have been added for gas fields with commingled production from multiple reservoirs.
1	A	Commingled—If gas from the reservoir typically is produced with gas from other reservoirs in the field, "Yes" is recorded. For single reservoir fields, or for areas where reservoirs typically are produced separately, "No" is recorded.
35	A	Field name—A text field in which the name of the gas field within which the reservoir is located is given.
3	A	Gas Atlas play code—The name of the gas play within which the reservoir is located. Thirty options, corresponding to the 30 play descriptions in the atlas, are available.
1	I	Field status—The current status of the reservoir. Single options include abandoned, producing, or storage. Additional options are used for fields that currently have multiple status for one part of a field versus another: producing and storage, shut-in (non-producing), producing and abandoned and storage, enhanced or secondary recovery, or no information.
9.6	F	Latitude (decimal degrees)—The latitude location, in decimal degrees, of the geographic center of the reservoir in map view.
9.6	F	Longitude (decimal degrees)—The longitude location, in decimal degrees, of the geographic center of the reservoir in map view.
6	I	Average pay thickness (feet)—The average thickness of the gas-saturated zone as determined from density and porosity logs, or the unstimulated interval where gas enteres the well bore as noted on drillers' logs. It differs from the completion interval and the perforated interval commonly reported on drillers' logs.
6	I	Average thickness of completed interval (feet)—An average value for the thickness of the interval reported by drillers as the zone of completion.
2	A	Depositional environment code—The interpreted depositional environment for the reservoir rock. Twenty-three options, including unknown, are possible. Assignments were made on a per-play basis.
1	A	Trap type—The dominant type of trapping mechanism that created the reservoir. Five options are available: structural, stratigraphic, structural/stratigraphic, fractured, and no information.
2	A	Lithology—The primary lithology of lithologies of the reservoir. Choices include seven primary lithologies (sandstone, siltstone, shale, limestone, dolostone, chert, carbonate) and 26 combinations of primary/secondary lithologies.
4	I	Discovery date—The calendar year in which the first productive well that is now within the boundaries of the field or reservoir was drilled.
7	I	Initial open flow, discovery well (Mcf/day)—Initial open flow in thousands of cubic feet per day of the first well completed within each reservoir.
7	I	Average initial open flow, field (Mcf/day)—An average value for open flow, in thousands of cubic feet per day, prior to stimulation ("natural") of wells completed solely in the reservoir.
7	I	Average final open flow, field (Mcf/day)—An average value for open flow, in thousands of cubic feet per day, after stimulation of wells completed solely within the reservoir.
8	A	Oldest formation penetrated—The stratigraphically oldest formation penetrated by any well drilled within the gas field.
7	I	Number of producing wells—The number of wells thought to be currently producing; not necessarily the total number of wells that were drilled as producers. Derived by subtracting known abandoned wells from original producers.
7	I	Number of abandoned wells—The number of former producing wells that have been reported as plugged and abandoned; not wells that were drilled as dry holes.
1	A	Type of gas—Options include gas associated with oil production, nonassociated gas, or no information.
7	I	Productive area (acres)—The size of the reservoir, in acres, as seen in map view; not necessarily the size of the gas field which includes the reservoir.
6	I	Average well spacing (acres/well)—The average value of acres per well in the reservoir, not distance between wells. Usually derived by dividing total acres by the number of wells for mature reservoirs. For reservoirs that are not fully developed, the average acreage per well in the portion of the field that has been fully developed may have been used. In some states (Kentucky and Ohio), the legal spacing per well has been recorded, not the actual spacing.
1	A	Importance of heterogeneity due to structure—An estimation of how important geologic structure was in creating heterogeneity within the reservoir. Choices include dominant, locally important, minor, not important/not applicable, and no information.
1	A	Importance of heterogeneity due to fractures—An estimation of how important natural fractures within the reservoir were in creating heterogeneity within the reservoir. Choices are the same as above.
1	A	Importance of heterogeneity due to diagenesis—An estimation of how important diagenesis of the reservoir rock was in creating heterogeneity within the reservoir. Choices are the same as above.
1	A	Importance of heterogeneity due to deposition—An estimation of how important the depositional environment of the reservoir rock was in creating heterogeneity within the reservoir. Choices are the same as above.
1	A	Reservoir continuity—A subjective ranking of expected continuity of the reserovir with five options ranging from continuous (1) to discontinuous dominated by heterogeneity (5).
4	I	Initial reservoir temperature (°F)—The temperature in the reservoir in degrees Fahrenheit when the reservoir was discovered.
6	I	Initial reservoir pressure (psia)—The shut-in reservoir pressure in psi when the reservoir was first discovered.
6	I	Current reservoir pressure (psia)—The current, or latest, reservoir pressure, in psi, taken from production records or contributed by gas producers.
4	I	Date of current pressure measurement—The calendar year for which the current, or latest, reservoir pressure was measured.
12.4	F	Original gas-in-place (bcf)—Calculated original gas-in-place (OGIP) within the drainage area of the reservoir, in billions of cubic feet.
12.4	F	Original gas reserves (bcf)—Estimated original amount of gas that could be recovered from the reservoir; calculated from OGIP and the recovery factor.
4	I	Production history (starting date)—The earliest calendar year for which production data for the reservoir are available and used in the summation of cumulative (reported) production.
4	I	Production history (ending date or current)—The latest calendar year for which production data for the reservoir are available and used in the sumation of cumulative (reported) produciton; may be the current calendar year.
12.4	F	Actual reported production to date (bcf)—The summation of reported production from a set of representative wells in a reservoir or field over a period of years that can vary from well to well. For these reasons, the number of wells used to calculate the reported production and the number of years for which production was reported by well also are entered in the reservoir record. These data can be used to estimate total, but unreported, production from the reservoir.
5	I	Number of wells for reported production—The number of wells for which production values were available and summed as reported cumulative production.
6.2	F	Recovery factor—The percentage of OGIP estimated to be recoverable from the reservoir. A function of drive type, trap type, and reservoir lithology; not calculated from OGIP and production.
6.2	F	Average log porosity (%)—An average value of porosity calculated from log analysis of the pay zone. The number of wells (logs) contributing to the average also is recorded.
5	I	Number of wells contributing to average log porosity—The number of wells (logs) used in calculating average log porosity of the reservoir.
6.2	F	Minimum log porosity (%)—The lowest porosity calculated from log analysis within the pay zone.
6.2	F	Maximum log porosity (%)—The highest porosity calculated from log analysis within the pay zone.
6.2	F	Average core porosity (%)—An average value of porosity values within the pay zone reported from core analysis. The number of wells (cores) contributing to the average also is recorded.
5	I	Number of wells contributing to average core porosity—The number of wells (cores) used in calculating average core porosity of the reservoir.
6.2	F	Minimum core porosity (%)—The lowest porosity reported from core analysis within the pay zone.
6.2	F	Maximum core porosity (%)—The highest porosity reported from core analysis within the pay zone.
8.2	F	Average permeability (md)—An average value of all reported permeabilities from core analysis of cores taken in the reservoir with the direction not specified.
5	I	Number of wells contributing to average permeability—The number of wells (cores) used in calculating average permeability of the reservoir.
8.2	F	Minimum permeability (md)—The lowest permeability reported from core analysis within the pay zone with the direction not specified.
8.2	F	Maximum permeability (md)—The highest permeability reported from core analysis within the pay zone with the direction not specified.
8.2	F	Average horizontal permeability (md)—An average of all horizontal permeabilities reported from core analyses of cores taken in the reservoir. The number of wells (cores) contributing to the average also is entered.
8.2	F	Average vertical permeability (md)—An average of all vertical permeability values reported from core analayses of cores taken in the reservoir. The number of wells (cores) contributing to the average also is recorded.
6.2	F	Assumed matrix density—An assumed value for matrix density of the reservoir rock based on standard values that assume single lithologies; often taken from face sheets of well logs.
1	A	Earth pressure gradient—An estimation of whether the reservoir is currently underpressured, overpressured, or at normal earth pressure gradient. No information is a fourth option.
6	I	Average depth to producing interval (feet)—The average depth, in feet, to the top of the reservoir.
6.3	F	Average reservoir water resistivity (ohm-meters)—An average value for resistivity of formation water. Based on analyses of formation water samples in some cases, but in most cases standard value used by logging engineers (0.035 - 0.05) are reported.
6.2	F	Average reservoir water saturation (%)—An average value for water saturation determined by subtracting calculated gas saturation from 100 percent.
6.2	F	Average reservoir gas saturation (%)—An average value for gas saturation determined from log analysis of the pay zone, assuming oil saturation is zero.
6.3	F	Gas gravity—Gravity of gas produced from the reservoir, taken from gas analysis, in g/cc. Most data reported are from the U.S. Bureau of Mines; other data from companies.
5	I	Btu value—Heating value for gas in British thermal units derived from gas analyses. Most data reported were from the U.S. Bureau of Mines; other data from companies.
12.4	F	Remaining gas-in-place (bcf)—The difference between the OGIP and the estimated cumulative production (not reported production which in most cases is lower) from the reservoir.
4	I	Date for remaining gas-in-place—The calendar year for which estimates of remaining gas-in-place were made.
12.4	F	Remaining gas reserves (bcf)—The difference between original gas reserves and the estimated cumulative production (not reported production which in most cases is lower) from the reservoir.
4	I	Date for remaining gas reserves—The calendar year for which estimates of remaining gas reserves were made.
35	A	Description of typical log suite available—A lengthy text field in which typical logs run through the reservoir can be listed. Usually, only available log types were entered.
60	A	Description of typical completion practices—A lengthy text field in which the types of common well completions can be entered (natural, fractured, shot, etc.).
100	A	Comments—Spaces left at the end of a record for any additional comments; 100 characters long.

Notes: Character type A represents text; character type I represents an integer; and character type F represents a floating point (decimal). Missing or unknown values for numerical data (integers or floating decimals) are indicated by a "-" followed by the appropriate number of 9s, e.g., a missing value for an integer with four characters "-999."

had to be created by field and reservoir and manipulated to yield field and pool averages. Individual well locations, when sorted by play, resulted in the maps of production by play (see Figure 1 of each play description).

Even as each survey conducted this inventory of its data, the surveys also conducted a thorough literature search for information that could be used in writing play descriptions as well as to enter into a database of fields and pools. Survey publications; professional geologic and engineering journals; publications from the Gas Research Institute, US DOE, and the U.S. Bureau of Mines; and trade journals were searched for these data in a cooperative effort of the surveys and two departments at West Virginia University involved in the project. References collected were compiled using the Papyrus bibliographic software package. This separate data file is a third product of this overall gas atlas-database project.

Individual wells in each state were sorted by gas field to develop subsets of data to be used in mapping fields and pools and calculating field and pool averages of key data elements. Data were collected for every pool that produced in each gas field, and then decisions were made concerning which fields and pools to include in the final database. In fields with multiple reservoirs, only those reservoirs that contained most of the production were included, if most of the data elements could be found. Reservoirs with few producing wells, or reservoirs for which little data could be found, often were excluded.

After individual well data were combined into fields and pools, the pools were sorted by gas plays, and all entries in the final database are organized by gas plays. For single reservoir gas fields, this did not present a problem. But in gas fields that produce from numerous reservoirs, problems were encountered with commingled production. This problem was resolved to a certain degree by including data records for multiple reservoirs as well as for single reservoirs.

One space is provided in each reservoir record to specify whether production from the reservoir typically is commingled with other reservoirs, is produced alone, or if this is unknown. In most cases it is known if production is commingled, and "yes" was entered in the database for this element. Wells that produce from reservoirs within a given play were then separated into single completions versus commingled completions. Production data from single completions were entered into the database records for the appropriate reservoirs. Production data from commingled wells were added to the special record for the group of reservoirs that defines the stratigraphic extent of the play. In this way, most of the available production data could be entered into what is basically a reservoir-specific database.

Table 2. Numerical codes for different variables.

Field Status	0	NO INFORMATION
	1	Abandoned
	2	Producing
	3	Storage
	4	Producing and Storage
	5	Shut-in (non-producing)
	6	Producing and abandoned
	7	Abandoned and storage
	8	Enhanced or secondary recovery
Depositional Environment	0	UNKNOWN
	1	Non-marine
	2	Marine
	3	Bioherm
	4	Anoxic basin
	5	Supratidal
	6	Shelf
	7	Slope
	8	Shelf-slope
	9	Fluvial
	10	Braided fluvial
	11	Deltaic
	12	Fluvial-deltaic
	13	Shallow marine
	14	Coastal marine
	15	Marine shoreline
	16	Nearshore marine
	17	Shallow marine shelf sand
	18	Shallow marine carbonate
	19	Prodelta
	20	Slope turbidite
	21	Deeper shelf/slope
	22	Mixed fluvial-deltaic and carbonate shelf
Trap Type	0	NO INFORMATION
	1	Structural
	2	Stratigraphic
	3	Structural/Stratigraphic
	4	Fractured
Lithology	0	NO INFORMATION
	1	Sandstone
	2	Siltstone
	3	Shale
	4	Limestone
	5	Dolostone
	6	Sandstone/Siltstone
	7	Sandstone/Shale
	8	Sandstone/Limestone
	9	Sandstone/Dolostone
	10	Siltstone/Sandstone
	11	Siltstone/Shale
	12	Siltstone/Limestone
	13	Siltstone/Dolostone
	14	Shale/Sandstone
	15	Shale/Siltstone
	16	Shale/Limestone
	17	Shale/Dolostone
	18	Limestone/Sandstone
	19	Limestone/Siltstone
	20	Limestone/Shale
	21	Limestone/Dolostone
	22	Dolostone/Sandstone
	23	Dolostone/Siltstone
	24	Dolostone/Shale
	25	Dolostone/Limestone
	26	Chert
	27	Chert/Sandstone
	28	Chert/Siltstone
	29	Chert/Shale
	30	Chert/Limestone
	31	Chert/Dolostone
	32	Sandstone/Siltstone/Limestone
	33	Carbonate
Gas Type	0	NO INFORMATION
	1	Non-associated
	2	Associated
Commingled Production	0	NO INFORMATION
	1	Yes
	2	No
Influence of Different Types of Heterogeneity	0	NO INFORMATION
	1	Dominant
	2	Locally important
	3	Minor
	4	No important/Not applicable
Reservoir Continuity	0	NO INFORMATION
	1	Continuous to 5. Discontinuous
Earth Pressure Gradient	0	NO INFORMATION
	1	Underpressured
	2	Overpressured
	3	Normal

STRATIGRAPHIC HISTORY OF THE APPALACHIAN BASIN

by Robert C. Milici, U.S. Geological Survey

Introduction

The Appalachian basin is a long asymmetric synclinorium that extends southward from the shores of Lakes Erie and Ontario for more than 1,000 miles through New York, Pennsylvania, Ohio, West Virginia, eastern Kentucky, Virginia, and Tennessee, to northwestern Georgia and Alabama. This atlas encompasses the northern part of that basin, an area of approximately 175,000 square miles that extends from New York to northeastern Tennessee, and from the Blue Ridge Mountains westward to the Cincinnati arch. The thickness of the Paleozoic sedimentary fill in the Appalachian basin ranges from about 45,000 feet in the deepest part of the basin in central Pennsylvania to 2,000 or 3,000 feet in central Ohio, near the Cincinnati arch.

Geophysical evidence indicates that the eastern edge of the Appalachian basin lies east of the Blue Ridge structural front, where Lower Paleozoic rocks are buried beneath crystalline thrust sheets from New England southwestward to the southern Appalachian Piedmont (Pfeil and Read, 1980; Cook and Oliver, 1981; Harris and others, 1982; Read and Pfeil, 1983; Simpson and Sundberg, 1987).

Paleozoic Sequences

The Paleozoic rocks of the Appalachian basin may be divided into six major tectonically controlled stratigraphic sequences that are bounded, with minor exception, by unconformities of regional extent: the Iapetan rift and passive margin deposits; Taconic flysch deposits; post-Taconic molasse deposits; Acadian flysch deposits; Lower Carboniferous flysch, molasse, and stable shelf deposits; and syntectonic Alleghenian flysch deposits (de Witt and Milici, 1989, 1991). Tectonic terminology is preferred for use herein because it readily relates the gross subdivisions of Appalachian Paleozoic stratigraphy to the tectonic activities, within and marginal to the basin, that generated the sediments and led to their deposition and preservation within the basin.

Iapetan Rift and Passive Margin Sequence

Early synrift deposits: The oldest stratigraphic sequence in the Appalachian basin (Iapetan, Sauk) is bounded at the base by a major regional unconformity. The basal unconformity places rocks that range in age from Late Proterozoic on the eastern side of the Appalachian basin to latest Cambrian on the western side of the basin, near the Cincinnati arch, upon the 1.1 billion-year-old Grenvillian basement. A pre-Middle Ordovician, post-Knox unconformity serves as the upper boundary between the Iapetan (Sauk) sequence and the overlying Taconic (Tippecanoe) sequence. Deposition of this Iapetan group of rocks began in Late Proterozoic rift basins during the opening of the protoatlantic ocean Iapetus (Rankin, 1975, 1976; Rankin and others, 1989), and continued throughout the Cambrian into the Early Ordovician during the development of a passive continental margin. In general, the Cambrian and Lower Ordovician strata that were deposited on the eastern margin of the continent grade upward from sandstones and shales in the lower part of the section to limestones and dolomites in the middle and upper parts of the section. This general trend reflects the tectonic stability of the eastern margin of the North American craton as it moved away from the Iapetan spreading center, subsided, and was covered by shallow marginal seas under drift conditions (Read, 1989).

In general, on the eastern side of the Appalachian basin, the lower Iapetan sequence is composed of poorly sorted, immature siliciclastic sedimentary rocks (Ocoee Supergroup) (Figures 1a, 1b), which appear to have filled grabens in the Grenville basement that were active during Late Precambrian and Early Cambrian time (Wehr and Glover, 1985; Walker and others, 1994). These structures include the Mechums River graben in central Virginia (Gooch, 1958), and grabens in the Great Smoky Mountains in Tennessee and North Carolina and in the Grandfather Mountain window in western North Carolina (Wehr and Glover, 1985; Walker and others, 1994).

As the Iapetus widened, the margin of the continent cooled and subsided, so that the Paleozoic seas encroached upon the craton from east to west. Basal Cambrian deposits of the Chilhowee Group (Simpson and Sundberg, 1987) consist commonly of fluvial arkosic and feldspathic sandstones that were derived from the weathering and erosion of crystalline basement rocks (Schwab, 1971; Mack, 1980). The group averages about 4,000 feet thick, although in places in northeastern Tennessee, it may be as much as 7,500 feet thick (King and Ferguson, 1960). These relatively immature deposits in the lower part of the group are commonly overlain by shales and cleaner sandstones that reflect wave winnowing and redeposition of previously deposited sediment by transgressive seas. In Tennessee and southwestern Virginia, the Chilhowee Group consists of the Unicoi Formation at the base, overlain by the Hampton and Erwin formations. The Unicoi Formation contains basaltic volcanic rocks that are intercalated with fluvial siliciclastic strata and appears to have been deposited in a synrift tectonic environment (Bond and others, 1984). Overlying marine mudstones, siltstones, and sandstones of the Hampton Formation and marine-to-littoral *Scolithus*-bearing sandstones of the Erwin Formation apparently accumulated in a non-volcanic post-rift tectonic setting (Read, 1989). In western West Virginia, the Chilhowee Group is represented by 50 to 100 feet of sandstone, and is recognized as the basal sandstone unit by Ryder (1992). In general, the fluvial-to-marine transition recorded in the rock record by the Chilhowee Group reflects the change from an extensional tectonic environment to a passive continental margin setting along the eastern margin of the Appalachian basin (Simpson and Erickson, 1990; Walker and others, 1994).

Early passive margin carbonate strata: The Chilhowee Group is overlain by the Cambrian Shady Dolomite in Tennessee and southwestern Virginia and its equivalent, the Tomstown Dolomite in northwestern Virginia, adjacent Maryland, and nearby Pennsylvania. These carbonate units range generally from about 1,000 to 1,500 feet thick. The Tomstown consists generally of cyclic peritidal carbonate strata, whereas the correlative Shady Dolomite consists of deep-ramp pelletal limestone overlain initially by shallow water oolitic limestones, and then by littoral or peritidal cyclic carbonate strata (Read, 1989). In some places, the Shady Dolomite is characterized by archaeocyathid reefs (Butts, 1940) that apparently accumulated at or near the edge of the carbonate shelf (Rodgers, 1968; Pfeil and Read, 1980).

Late synrift deposits: Carbonate sedimentation, characteristic of the Shady and Tomstown dolomites, was much reduced or brought to an end along the continental margin during the Early Cambrian by siliciclastic deposition of the Rome Formation in Georgia, Tennessee, and southwestern Virginia, and the equivalent Waynesboro Formation in northern Virginia, Maryland, and Pennsylvania. This influx of siliciclastic sediments onto the continental margin appears to have been caused by renewed uplift, arching, and thinning of the crust within the interior of the continent, with subsequent rifting and formation of a regionally extensive intracratonic aulacogen, the Rome trough (McGuire and Howell, 1963; Harris, 1978; Webb, 1980; Sutton, 1981). The Rome trough appears to have been tectonically active for an extended period of time during the Paleozoic; it contains overthickened strata that range in age from Early Cambrian to at least as young as Devonian (Harris, 1978). Most of this activity occurred during the Cambrian, as is indicated by excessive thickness of the Rome Formation and Conasauga Group in western West Virginia, which is up to 6,200 feet thick (Donaldson and others, 1988; Ryder and others, 1995a, 1995b). Trilobite fossils were recovered from well samples about 2,000 feet below the top of the Rome Formation in the Rome trough in western West Virginia (Donaldson and others, 1988) and they indicate that most of the Rome in the trough is Middle Cambrian. The Conasauga Group also is overthickened within the trough and exhibits abrupt facies changes across buried fault blocks. Core samples described by Donaldson and others (1988), however, indicate that sedimentation kept pace with subsidence and that shallow marine and peritidal environments persisted during deposition of the Conasauga within the Rome trough.

The Rome Formation, which was restricted to Lower Cambrian rocks in the Valley and Ridge of Tennessee by Rodgers and Kent (1948), is almost everywhere truncated at its base by decollement in the Appalachian Valley and Ridge, so that its true thickness and the character of its lowermost strata are not well known. In some places, however, the exposed part of the formation ranges up to 2,000 feet thick. In general, the Rome Formation consists of a littoral red-bed sequence characterized by gray, greenish-gray, and grayish-red shales, siltstones, fine-grained sandstones, and minor amounts of limestone and dolomite (Rodgers, 1953; Samman, 1975). Some of the sandstones are interlaminated flaser-bedded with the finer-grained siliclastic rock. Evidence of shallow water deposition and intermittent subareal exposure, such as ripple marks, mud cracks, rain drop impressions, and halite casts, is abundant in these rocks. Burrows are common, and there are some tracks and remains of trilobites. The Waynesboro Formation is generally thinner and contains much more carbonate rock than the Rome. In western Virginia, the Waynesboro Formation is about 1,175 feet thick and up to 90 percent of the formation is composed of calcareous rocks (Haynes, 1991). The principal lithotypes of the Waynesboro include carbonate mudrocks, ribbon rocks, cryptalgal laminites, fenestral limestones, dolomite, and red and green mudstones. Haynes (1991) interpreted the Waynesboro to have been deposited in peritidal environments offshore of the dominantly siliciclastic red bed strata of the Rome Formation.

Regionally, the Rome Formation thins to the west, except in the area of the Rome trough, where it is as much as 3,000 feet thick in western West Virginia (Donaldson and others, 1988; Ryder and others, 1995a, 1995b). To the west of the Rome trough, in the subsurface of northern Kentucky, western West Virginia, and eastern Ohio, much of the rock called Rome may consist of younger

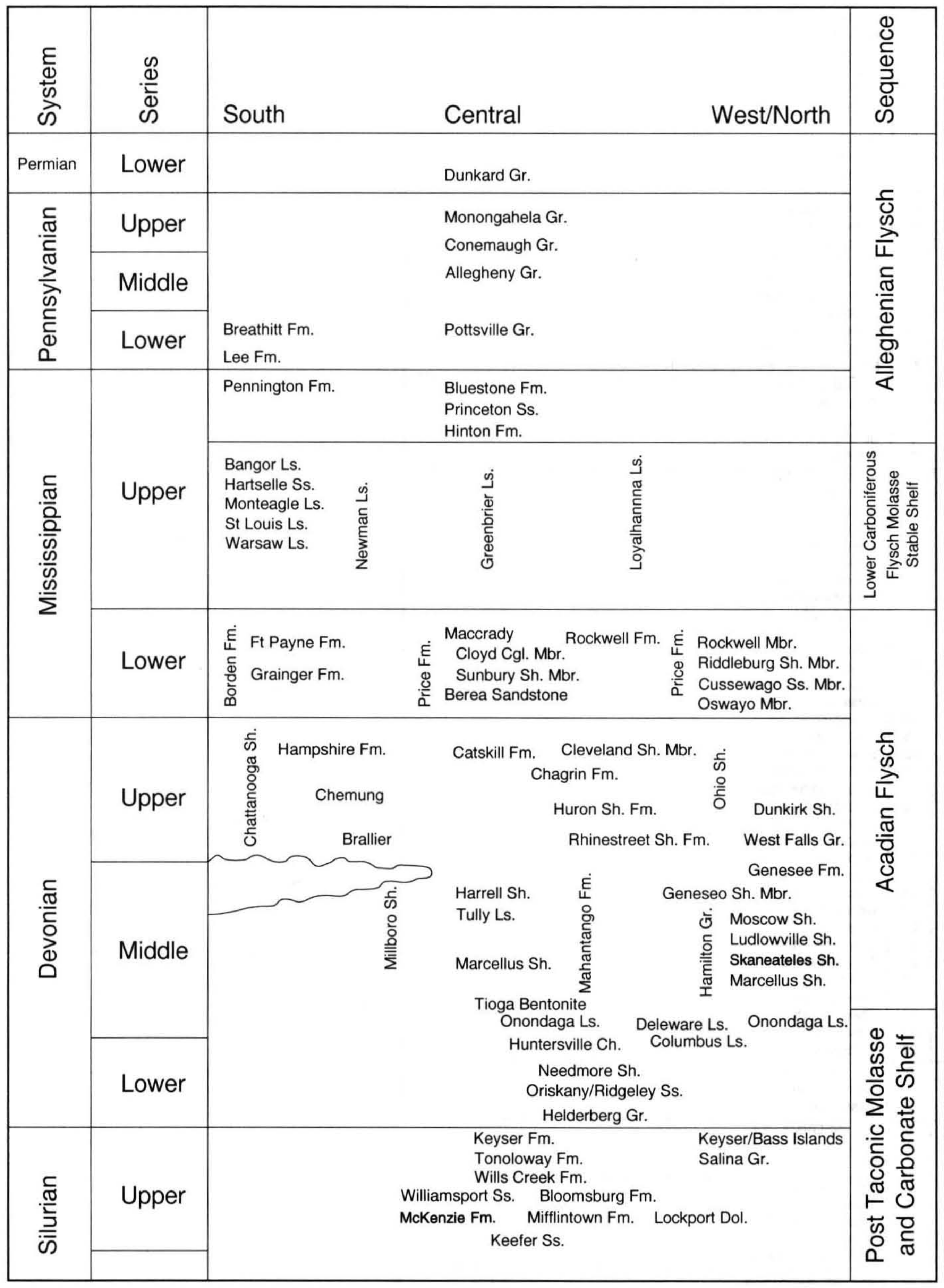

Figure 1a.

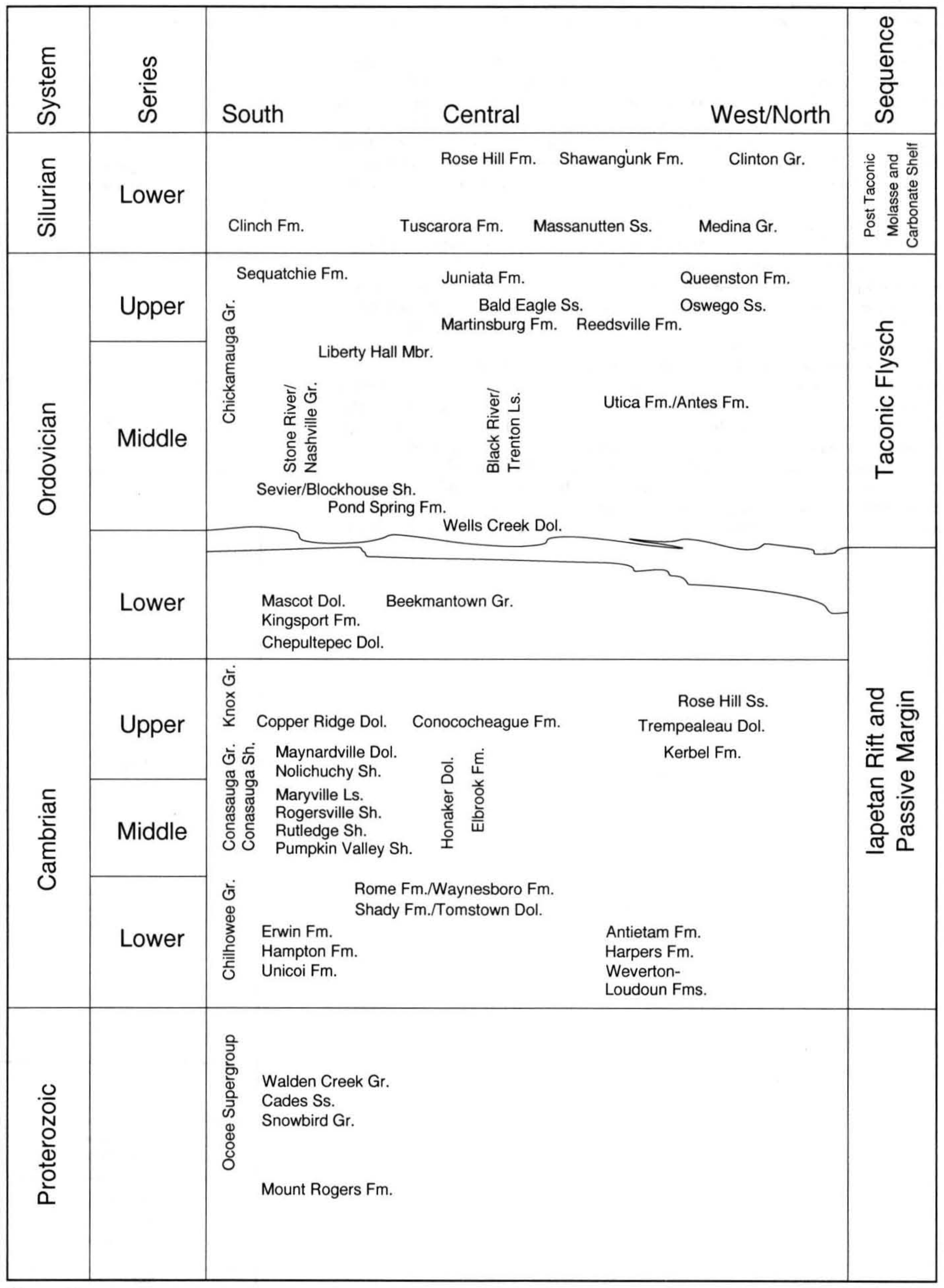

Figure 1b.

Figures 1a-b. Nomenclature for the 30-play study area in the Appalachian basin.

		KENTUCKY	OHIO	WEST VIRGINIA	SOUTHWESTERN PENNSYLVANIA	NORTHWESTERN PENNSYLVANIA	NEW YORK
PENNSYLVANIAN	UPPER		**MONONGAHELA GROUP** *Goose Run*	**MONONGAHELA GROUP** *Minshall* *Murphy* *Moundsville*	**MONONGAHELA GROUP**		
			CONEMAUGH GROUP *First Cow Run* *Macksburg 300-Foot*	**CONEMAUGH GROUP** *Cow Run* *Little Dunkard* *Big Dunkard*	**CONEMAUGH GROUP** *Little Dunkard* *Big Dunkard*		
	MIDDLE	**BREATHITT FORMATION OF ALLEGHENY GROUP**	**ALLEGHENY GROUP** *Second Cow Run* *Macksburg 500-Foot* Paf	**ALLEGHENY GROUP** *Burning Springs* *Gas* *Lower Gas* *Horseneck* Paf	**ALLEGHENY GROUP** *Gas* *Upper Gas* *Lower Gas* Paf	**ALLEGHENY GROUP**	
	LOWER	**LEE FORMATION OF POTTSVILLE GROUP** *Salt Sand* *First Salt* *Second Salt* *Horton* *Third Salt* *Williamsburg*	**POTTSVILLE SANDSTONE** *Macksburg 700-Foot* *Salt* *Sharon (Maxton)* Pps	**POTTSVILLE SANDSTONE** *First Salt* *Second Salt* *Third Salt* Pps	**POTTSVILLE SANDSTONE** *First Salt* *Second Salt* *Third Salt* Pps	**POTTSVILLE GROUP**	

Figure 2a. Stratigraphy of the Pennsylvanian system (Alleghenian flysch). Formal lithostratigraphic terminology shown in bold. Commonly used drillers' terminology shown in italics. Plays are represented by alpha designation.

		KENTUCKY	OHIO	WEST VIRGINIA	SOUTHWESTERN PENNSYLVANIA	NORTHWESTERN PENNSYLVANIA	NEW YORK
MISSISSIPPIAN	UPPER	**PENNINGTON FORMATION** *Ravencliff* **CARTER CAVES SANDSTONE** *Maxon* *Bradley* *Little Lime* Mmc		**MAUCH CHUNK GROUP** *Princeton* *Ravencliff* *Maxon* *Lower Maxon* *Blue Monday* Mmc	**MAUCH CHUNK FORMATION** *Maxton* Mmc		
		NEWMAN LIMESTONE *Big Lime* *Keener* Mgn	**MAXVILLE LIMESTONE** *Jingle Rock* Mgn	**GREENBRIER LIMESTONE** *Big Lime* *Keener* *Greenbrier Big Injun* Mgn	**GREENBRIER FORMATION AND LOYALHANNA FORMATION** *Keener* Mgn		
	LOWER	**FORT PAYNE FORMATION** Mfp					
		BORDEN FORMATION *Big Injun* *Keener* Mbi	**LOGAN FORMATION** *Keener* **CUYAHOGA FORMATION** *Injun* *Squaw* Mbi	**MACCRADY FORMATION** *Red Injun* **PRICE FORMATION** *Big Injun* *Squaw* Mbi	**BURGOON SANDSTONE** *Big Injun* Mbi		
		BORDEN FORMATION *First Weir* *Second Weir* Mws	**CUYAHOGA FORMATION** *Weir* Mws	**PRICE FORMATION** *Upper Weir* *Lower Weir* Mws	**SHENANGO FORMATION AND CUYAHOGA FORMATION** *Squaw* *Upper 30-Foot* Mws	**SHENANGO FORMATION AND CUYAHOGA FORMATION**	

Figure 2b. Stratigraphy of the Mississippian system (Lower Carboniferous flysch, molasse, and stable shelf sequence and Mississippian portion of Acadian flysch sequence). Formal lithostratigraphic terminology shown in bold. Commonly used drillers' terminology shown in italics. Plays are represented by alpha designation.

		KENTUCKY	OHIO	WEST VIRGINIA		SOUTHWESTERN PENNSYLVANIA	NORTHWESTERN PENNSYLVANIA	NEW YORK
DEVONIAN	UPPER	**SUNBURY SHALE** *Coffee Shale* **BEREA SANDSTONE** *Berea* MDe	**SUNBURY SHALE** *Coffee Shale* **BEREA SANDSTONE** *First Berea* **BEDFORD SHALE** *Second Berea* MDe	**SUNBURY SHALE RIDDLESBURG MEMBER OF PRICE FORMATION AND BEREA SANDSTONE** *Berea* **CLOYD MEMBER OF PRICE FORMATION** MDe		**BEREA SANDSTONE** *Berea -Murrysville* **BEDFORD SHALE CUSSEWAGO SANDSTONE** *Cussewago* MDe	**BEREA SANDSTONE AND CORRY SANDSTONE** *Berea-Corry* **BEDFORD SHALE CUSSEWAGO SANDSTONE** *Cussewago* MDe	
		CLEVELAND SHALE MEMBER OF OHIO SHALE UDs	**CLEVELAND SHALE MEMBER OF OHIO SHALE** *Gantz* UDs	**OSWAYO MEMBER OF PRICE FORMATION** Dbg	**OSWAYO MEMBER OF PRICE FORMATION** *Gantz*	**"VENANGO GROUP"** *Gantz*	**RICEVILLE FORMATION AND OSWAYO FORMATION** *First Venango*	**CONEWANGO GROUP**
		CHAGRIN SHALE MEMBER OF OHIO SHALE Dbg	**CHAGRIN SHALE MEMBER OF OHIO SHALE** *Gordon* *Fifth* Dbg	**VENANGO FORMATION AND GREENLAND GAP FORMATION** *Fifty-Foot* *Thirty-Foot* *Gordon Stray* *Gordon* *Fourth* *Fifth* *Bayard* *Elizabeth* *Warren* Dbg	**VENANGO FORMATION AND GREENLAND GAP FORMATION** *Fifty-Foot* *Thirty-Foot* *Gordon Stray* *Gordon* *Fourth* *Fifth* *Bayard* *Elizabeth* *Warren* Dvs	*Hundred-Foot* *Fifty-Foot* *Thirty-Foot* *Nineveh-Snee* *Gordon Stray-Gordon* *Fourth* *Fifth/McDonald* *Bayard* *Elizabeth* *Sweet Richard* **CHADAKOIN FORMATION** *First Warren* Dvs	**"VENANGO GROUP"** *Red Valley* *Second Venango* *Third Venango Stray* *Third Venango* **CHADAKOIN FORMATION** *First Warren* Dvs	**CONNEAUT GROUP**

Figure 2c. Stratigraphy of the upper half of the Upper Devonian series (part of the Acadian flysch). Formal lithostratigraphic terminology shown in bold. Commonly used drillers' terminology shown in italics. Plays are represented by alpha designation.

		KENTUCKY	OHIO	WEST VIRGINIA			SOUTHWESTERN PENNSYLVANIA	NORTHWESTERN PENNSYLVANIA	NEW YORK
DEVONIAN	UPPER	**OHIO SHALE**	**CHAGRIN SHALE** Dbg	**GREENLAND GAP FORMATION** Dbg		**GREENLAND GAP FORMATION** *Speechley* *Balltown* *Bradford* *Riley* Dbs	**"BRADFORD GROUP"** *Upper Warren* *Lower Warren* *Speechley Stray* *Speechley* *Tiona* *First Balltown* *Second Balltown* *Sheffield* *First Bradford* *Second Bradford* *Third Bradford* *Kane* Dbs	**"BRADFORD GROUP"** *Second Warren* *Third Warren* *First Bradford/Glade* *Clarendon Stray* *Clarendon* *Balltown* *Cherry Grove* *Speechley/Tiona* *Cooper Stray* *Second Bradford* *Harrisburg Run* *Sliverville* *Third Bradford* *Lewis Run* *Kane* Dbs	**CANADAWAY GROUP** *Glade* *First Bradford* *Chipmunk* *Second Bradford* *Harrisburg Run* *Richburg* *Third Bradford* *Waugh and Porter* Dbs
		Cinnamon	**HURON SHALE MEMBER OF OHIO SHALE** *Big Cinnamon* UDs						
			JAVA FORMATION Dbg	**BRALLIER FORMATION** *Benson* *Leopold* *Alexander* *Second Elk* *Third Elk* *Haverty* *Fox* *Sycamore* Dbg		**BRALLIER FORMATION** *First Elk* *Second Elk* *Third Elk* *Kane* Des	**"ELK GROUP"** *First Elk* *Second Elk* *Fourth Elk* **BRALLIER FORMATION** Des	**"ELK GROUP"** *Elk* *Sartwell/Haskill* *Humphrey* **JAVA FORMATION** Des	**WEST FALLS GROUP**
		UDs	**WEST FALLS FORMATION INCLUDING RHINESTREET SHALE MEMBER** **MARCELLUS SHALE** UDs	**TULLY LIMESTONE MAHANTANGO FORMATION MARCELLUS SHALE** UDs		**TULLY LIMESTONE MAHANTANGO FORMATION MARCELLUS SHALE** Dbg	**RHINESTREET SHALE MEMBER OF WEST FALLS FORMATION SONYEA FORMATION GENESEE FORMATION TULLY LIMESTONE HAMILTON GROUP INCLUDING MARCELLUS SHALE** Dbg	**RHINESTREET SHALE MEMBER OF WEST FALLS FORMATION SONYEA FORMATION GENESEE FORMATION TULLY LIMESTONE HAMILTON GROUP INCLUDING MARCELLUS SHALE** Dbg	**RHINESTREET SHALE MEMBER OF WEST FALLS FORMATION SONYEA FORMATION GENESEE FORMATION HAMILTON GROUP INCLUDING MARCELLUS SHALE**

Figure 2d. Stratigraphy of the lower half of the Upper Devonian series (part of the Acadian flysch). Formal lithostratigraphic terminology shown in bold. Commonly used drillers' terminology shown in italics. Plays are represented by alpha designation.

		KENTUCKY	OHIO	WEST VIRGINIA	SOUTHWESTERN PENNSYLVANIA	NORTHWESTERN PENNSYLVANIA	NEW YORK
DEVONIAN	MIDDLE	**ONONDAGA LIMESTONE** *Corniferous* DSu	**ONONDAGA LIMESTONE** *Big Lime*	**ONONDAGA LIMESTONE**	**ONONDAGA FORMATION**	**ONONDAGA FORMATION** Dol	**ONONDAGA LIMESTONE** Dol
	LOWER	Dsu	**BOIS BLANC FORMATION**	**HUNTERSVILLE CHERT** Dho	**HUNTERSVILLE CHERT** Dho	**BOIS BLANC FORMATION** *"Oriskany Sandstone"*	
		ORISKANY SANDSTONE DSu	**ORISKANY SANDSTONE** Dop, Doc	**ORISKANY SANDSTONE** Dos	**RIDGELEY SANDSTONE SHRIVER FORMATION** Dos, Doc	Dop, Dos	**ORISKANY SANDSTONE** Doc, Dos
SILURIAN	UPPER	**HELDERBERG FORMATION** DSu	**HELDERBERG FORMATION**	**HELDERBERG FORMATION**	**MANDATA SHALE CORRIGANVILLE LIMESTONE NEW CREEK LIMESTONE**		
		BASS ISLANDS FORMATION DSu	**BASS ISLANDS DOLOMITE**		**KEYSER FORMATION**	**BASS ISLANDS FORMATION** *Bass Islands zone* Sbi	**BASS ISLANDS FORMATION** *Bass Islands zone* Sbi
		SALINA FORMATION DSu	**SALINA FORMATION**	**SALINA FORMATION** *Newburg* Sns	**SALINA GROUP**	**SALINA FORMATION**	**SALINA FORMATION**
		LOCKPORT DOLOMITE Sld	**LOCKPORT FORMATION** Sld	**LOCKPORT DOLOMITE** Sld	**LOCKPORT DOLOMITE**	**LOCKPORT DOLOMITE** Sld	**LOCKPORT DOLOMITE**
	LOWER	**BIG SIX SANDSTONE** *Big Six* **ROSE HILL SHALE** Sld	**CLINTON GROUP** *Packer Shell*	**KEEFER FORMATION ROSE HILL FORMATION** Sld	**CLINTON GROUP**	**CLINTON GROUP**	**CLINTON GROUP**
		"Clinton sandstone" Scm	**CATARACT FORMATION** *Stray Clinton* *Red Clinton* *White Clinton* *Medina* Scm	**TUSCARORA SANDSTONE** Sts	**TUSCARORA SANDSTONE** Sts	**MEDINA GROUP INCLUDING GRIMSBY SANDSTONE CABOT HEAD SHALE WHIRLPOOL SANDSTONE** Scm	**MEDINA GROUP INCLUDING GRIMSBY SANDSTONE WHIRLPOOL SANDSTONE** Scm

Figure 2e. Stratigraphy of the Middle and Lower Devonian series and the Silurian system (post-Taconic molasse and carbonate shelf). Formal lithostratigraphic terminology shown in bold. Commonly used drillers' terminology shown in italics. Plays are represented by alpha designation.

		KENTUCKY	OHIO	WEST VIRGINIA	SOUTHWESTERN PENNSYLVANIA	NORTHWESTERN PENNSYLVANIA	NEW YORK
ORDOVICIAN	UPPER	**DRAKES FORMATION RICHMOND GROUP** *Queenston*	**QUEENSTON SHALE** *Red Medina*	**JUNIATA FORMATION**	**QUEENSTON SHALE/JUNIATA FORMATION**	**QUEENSTON SHALE/JUNIATA FORMATION**	**QUEENSTON SHALE**
		MAYSVILLE GROUP EDEN GROUP		**OSWEGO SANDSTONE MARTINSBURG FORMATION**	**BALD EAGLE SANDSTONE REEDSVILLE SHALE UTICA SHALE THROUGH HATTER FORMATION** Obe	**REEDSVILLE SHALE UTICA SHALE THROUGH HATTER FORMATION**	**OSWEGO SANDSTONE LORRAINE GROUP**
		TRENTON GROUP Obc	**TRENTON LIMESTONE** MOf	**TRENTON**	**LOYSBURG FORMATION**	**LOYSBURG FORMATION**	**TRENTON LIMESTONE**
	MIDDLE	**STONES RIVER-HIGH BRIDGE GROUP** *St. Peter Sandstone* Osp	**BLACK RIVER LIMESTONE GULL RIVER LIMESTONE WELLS CREEK FORMATION** MOf	**BLACK RIVER LIMESTONE WELLS CREEK FORMATION**	**BEEKMANTOWN GROUP**	**BEEKMANTOWN GROUP**	**BLACK RIVER GROUP**
	LOWER	**KNOX GROUP BEEKMANTOWN GROUP ROSE RUN SANDSTONE COPPER RIDGE DOLOMITE**	**KNOX GROUP** COk	**BEEKMANTOWN GROUP**			**TRIBES HILL FORMATION**
CAMBRIAN	UPPER	COk	**ROSE RUN TREMPEALEAU COPPER RIDGE DOLOMITE** *Krysik sandstone* COk	**ROSE RUN COPPER RIDGE DOLOMITE**	**GATESBURG FORMATION WARRIOR FORMATION**	**GATESBURG FORMATION WARRIOR FORMATION** COk	**LITTLE FALLS FORMATION THERESA FORMATION POTSDAM FORMATION**
	MIDDLE	**CONASAUGA FORMATION**	**CONASAUGA FORMATION**	**CONASAUGA FORMATION**	**POTSDAM SANDSTONE**	**POTSDAM SANDSTONE**	
		ROME FORMATION TOMSTOWN DOLOMITE Cpk	**ROME FORMATION**	**ROME FORMATION TOMSTOWN DOLOMITE**			
	LOWER	**ANTIETAM SANDSTONE** *Basal Sandstone* Cpk	**MT. SIMON SANDSTONE**	**MT. SIMON SANDSTONE** *Basal Sandstone*			

Figure 2f. Stratigraphy of the Ordovician and Cambrian systems (Taconic flysch and Iapetan rift and passive margin sequences). Formal lithostratigraphic terminology shown in bold. Commonly used drillers' terminology shown in italics. Plays are represented by alpha designation.

transgressive deposits of Middle Cambrian age or younger, that apparently are time equivalents to part of the Conasauga Group in the Appalachian Valley and Ridge (Harris, 1964; Ryder, 1992). In Ohio, the Middle-to-Late Cambrian interval is 500 to 800 feet thick and consists of carbonate rock, and some red and green shale, siltstone, and sandstone. A Late Cambrian deltaic system, represented by the Kerbel Formation, occurs in the subsurface of northern Ohio and apparently supplied siliciclastic sediments for equivalent rocks in the upper part of the Conasauga Group elsewhere in the basin (Janssens, 1973).

Later passive margin deposits: Following the deposition of the Rome Formation, carbonate sedimentation became dominant once again along the eastern margin of the continent, with the accumulation of the thick limestones and dolomites of the Elbrook Formation at and near the shelf edge. Koerschner and Read (1989, p. 25) concluded that the Elbrook and overlying Conococheague Formation constitute a "sequence of cyclic peritidal carbonates that formed on an aggraded, rimmed continental shelf." Toward the interior of the platform, where the Nolichucky Shale laps over the shelf-edge carbonate rocks, the carbonate unit is called the Honaker Dolomite. The Honaker and Nolichucky combined are equivalent to the Elbrook. A little farther to the west and south, more fine-grained siliciclastic sediments laterally equivalent to the lower parts of the Elbrook and Honaker were deposited in a Conasauga intrashelf basin in northwestern Georgia, eastern Tennessee, and adjacent parts of Kentucky and Virginia (Markello and Read, 1982; Hasson and Haase, 1988; Rankey and others, 1994). Within the intrashelf basin in eastern Tennessee, the Conasauga Group consists of several thick carbonate formations that are interbedded with shales. The Pumpkin Valley Shale at the base is overlain successively by the Rutledge Limestone, Rogersville Shale, Maryville Limestone (Srinivasan and Walker, 1993), Nolichucky Shale, and Maynardville Dolomite (Rodgers, 1953). These stratigraphic variations reflect changes in the relative amounts of fine-grained siliciclastics that entered into the basin, probably in response to variations in sea level. Farther to the west and south, in south-central Tennessee and northwestern Georgia where the formation is dominantly shale and is called Conasauga Shale, the carbonate formations of the Conasauga Group thin and persist only as remnants intercalated in the shale, many as thin beds of oolitic and intraclastic storm-driven washovers. Rankey and others (1994) concluded that the continental margin did not become completely tectonically stable until sometime in the Late Cambrian, when the shale-carbonate sequences in the Conasauga Group were superseded by the peritidal carbonates of the Knox Group.

Progressive inundation of the continent, coupled with continued tectonic stability of the continental margin during the Late Cambrian and Early Ordovician, resulted in the widespread accumulation of several thousand feet more of limestone and dolomite that constitute the Upper Cambrian and Lower Ordovician Knox Group in the southern Appalachians, and its lateral equivalents, the Cambrian Conococheague Formation and Ordovician Beekmantown Group in the central part of the Appalachian basin. These carbonate rocks, which constitute the uppermost stratigraphic units of the passive margin sequence, dominated the shelf margin and formed a thick, widespread platform deposit around the rim of the continent from southern New York to Oklahoma and Texas.

In general, the Cambrian part of the Knox Group, the Copper Ridge Dolomite, consists of 1,000 to 2,000 feet of gray, finely crystalline dolomite (Rodgers, 1953; Read, 1989). Peritidal stromatolites and ooids are common in some beds, and in some places where secondary porosity is enhanced by recrystallization of the carbonate rock, it contains traces of hydrocarbons. In many places, the Conococheague Formation, an eastern limestone facies of the Copper Ridge Dolomite, consists chiefly of peritidal carbonate cycles from 3 to 15 feet thick. Cycles, which consist of lime mudstones at the base, coarsen upward into pelletal oolitic grainstones, flat-pebble conglomerates, stromatolites or thrombolites, and are capped by laminites (Demicco, 1985; Read, 1989). In a few places, the Conococheague consists of shallow-shelf lagoonal facies composed of grainstones, thrombolites, ribbon carbonate rocks, and thin-bedded dolostones (Read, 1989).

The Ordovician part of the Knox Group and the equivalent Beekmantown Group range from about 300 feet thick along the western margin of the Appalachian basin to about 4,000 feet thick in the Pennsylvania depocenter (Read, 1989). These rock units represent environments that range from dominantly peritidal cyclic carbonate strata on the west to shallow subtidal, ramp, open marine, or biohermal shelf-edge deposits on the east (Read, 1989; Montanez and Read, 1992). In eastern and central Tennessee, the upper part of the Knox Group is renowned for the numerous occurrences and economic deposits of Mississippi Valley-type sphalerite mineralization that it contains. The economic mineralization commonly occurs in the Kingsport Formation, in solution-collapse breccias related to dilation caused by differential solution of underlying limestone beds. Montanez (1994) described the late diagenetic dolomitization of the Lower Ordovician part of the Knox Group and its relationship to the development of secondary porosity, mineralization, and hydrocarbon migration. She concluded that this secondary porosity allowed the diagenetic dolomites of the Knox to remain as "viable reservoirs during hydrocarbon migration in the Late Paleozoic" (Montanez, 1994, p. 1235).

The Post-Knox Unconformity

The onset of the Taconic orogeny (Rodgers, 1971) is marked almost everywhere in the Appalachian basin by an unconformity of regional extent described either as the "post-Knox" or "pre-Middle Ordovician" unconformity (Bridge, 1955; Milici, 1973; Harris and Repetski, 1983; Mussman and Read, 1986). Erosion of strata previously deposited on the carbonate platform was greatest in the southern and western parts of the Appalachian basin. In Alabama and Ohio, Middle Ordovician rocks lie upon Upper Cambrian strata; in New York, Middle Ordovician strata lie directly upon crystalline basement rocks along the southern shores of Lake Ontario. The unconformity is absent, or nearly so, from northern Virginia northeastward into the depocenter in Pennsylvania (Harris and Repetski, 1983: Mussman and Read, 1986).

Local relief upon the unconformity is as great as 100 or 200 feet (Rodgers and Kent, 1948; Milici and Smith, 1969; Mussman and Read, 1986) and in places deep sinkholes have been described that contain unusual fossils (Laurence, 1944; Caster and Brooks, 1956). Weathering and erosion apparently have produced a secondary porosity in sub-unconformity rocks so that in some places in Ohio, the Cambrian Trempeleau (Copper Ridge) Dolomite and the Cambrian (?) Rose Run Sandstone produce hydrocarbons (M. Baranoski and others, Cambrian-Ordovician Knox Group unconformity play, this atlas) (Figures 2a-2f) sourced from the Middle Ordovician Utica Shale(Riley and others, 1993; Ryder, 1994). The unconformity surface and related porosity and permeability are considered to be a migration pathway for hydrocarbons generated from nearby or distant source beds.

Taconic Flysch Sequence

Sedimentation of the Iapetan stratigraphic sequence apparently was terminated by an arc-continent collision that marked the first phases of the Taconic orogeny (Rodgers, 1971; Shanmugam and Lash, 1982; Wehr and Glover, 1985) and the closing of Iapetus during the latter part of the Ordovician Period. Drake and others (1989, p. 25), however, concluded that it is difficult "to quantify a realistic causative mechanism for Taconian deformation in the central and southern Appalachians." Nevertheless, an initial tectonic shock warped and raised up the margin of the continent so that the Lower Ordovician carbonate platform was eroded and a karst paleotopography of slight to moderate relief developed on the top of the Knox Group (post-Knox unconformity) everywhere except in the deepest part of the Appalachian basin (Mussman and Read, 1986). In general, environments of carbonate sedimentation changed from relatively restricted, perhaps hypersaline (Harris, 1973) in Early and Early Middle Ordovician time (Ryder, and others, 1992), to environments that were more normally marine in later Middle and Late Ordovician time, as is indicated by the greater abundance and diversity of fossil invertebrates contained in later Middle and Upper Ordovician rocks. In places, basal Middle Ordovician *terra rosa* deposits within formations such as the drillers' Wells Creek Dolomite, the Pond Spring Formation (Milici and Smith, 1969), and other correlative formations overlie the post-Knox unconformity. To the south and west in the Appalachian basin, these carbonate deposits are thick and form groups of rocks of remarkably similar lithology (Chickamauga Group or Supergroup, Stones River Group, Nashville Group, Black River Group, Trenton Limestone) that extend widely over the central and southern parts of the Appalachian basin (Wilson, 1949; Rodgers, 1953; Kay, 1956; Milici, 1969; Milici and Smith, 1969). Conspicuous ashfall beds within the Middle and Upper Ordovician sequence have been traced over much of the southern and central parts of the Appalachian basin by utilization of geochemical markers (Wilson, 1949; Huff and others, 1992).

Driven westward by collision of volcanic islands with the eastern margin of North America early in the Middle Ordovician, crystalline basement rocks of the Blue Ridge were thrust to the surface and, in places along the Blue Ridge front, shed coarse clastic conglomerates westward into subsiding early Taconic foreland basins from Virginia to Georgia (Rodgers, 1953; Kellberg and Grant, 1956; Kreisa, 1981; Shanmugham and Lash, 1982; Rader and Gathright, 1986; Cullather, 1992). Continued collision during the Ordovician lifted up the Taconic Highlands, an igneous and metamorphic terrane along the eastern margin of the Appalachian basin that was eroded and supplied vast quantities of siliciclastic sediment southward and westward onto the carbonate platform.

Turbiditic muds and silts (Sevier, Martinsburg, Reedsville, Utica, and Antes formations) progressively encroached upon and lapped over the Middle Ordovician carbonate ramp and platform deposits and become intermixed and interbedded with the carbonate sediments (Neuman, 1951; Walker and others, 1983). Where organically enriched and mature, these gray and black shales served both as source beds and seals for fractured limestone reservoirs. For example, in Ohio (Maslowski, 1986; Wickstrom and Gray, 1988) and New York (NYSDEC, 1987; Drazan, 1988) fractured Trenton Limestone reservoirs produce hydrocarbons that had their sources in associated fine-grained siliciclastic sedimentary rocks. In the Cumberland Saddle region of eastern Kentucky, where fractured Middle Ordovician limestones (L. Wickstrom, Middle Ordovician fractured carbonates, this atlas) (Figures 2a-2f) occur on the crest of the Cincinnati arch, some shallow wells in Ordovician carbonate formations initially produced up to 400 barrels of oil per hour (Hamilton-Smith and others, 1990).

In the Appalachian Valley and Ridge, carbonate buildups occur along the platform margin and ramp in Virginia and Tennessee (Read, 1980, 1982; Walker and others, 1983). Although known accumulations do not currently produce hydrocarbons, their proximity to potential basinal shale source beds (Liberty Hall, Sevier, and Blockhouse shales) suggests that in some places undiscovered buildups may be suitable targets for exploration.

The final phase of the Taconic orogeny is recorded by the sedimentary strata of the Queenston delta, the most widespread redbed complex in eastern North America (Dennison, 1976). The Queenston delta consists generally of non-calcareous red beds of the Juniata Formation in New York, Pennsylvania, West Virginia, Maryland, Virginia, and northeasternmost Tennessee (Thompson, 1970; Driese and Foreman, 1992), of calcareous red and green limestones and shales of the Sequatchie Formation (Milici and Wedow, 1977) in Kentucky, Tennessee, Alabama, and Georgia, and of grayish red shales and siltstones of the Queenston Formation and Bald Eagle (Oswego) Sandstone in Ontario, Canada, western New York, northwestern Pennsylvania, eastern Ohio, and eastern Kentucky (Dennison, 1976). The deltaic complex is thickest in central Pennsylvania, where it exceeds 1,600 feet (Dennison, 1976), and thins to a feather edge in central Ohio, eastern Kentucky, eastern Tennessee, and northern Georgia and Alabama. Dennison (1976, p. 25) argued that the great lateral extent of this subareal to very shallow water redbed deltaic deposit resulted from glacio-eustatic sea level lowering, ". . . rather than infilling of a basin by simple delta growth or building up of a fluvial plain." Therefore, the overall distribution of this Taconic clastic wedge appears to have resulted from a combination of the erosion of a late syntectonic source in the northeastern United States with glacio-eustatic lowering of sea level, which enhanced widespread lateral distribution of the redbeds within the confines of the Appalachian basin. The Queenston delta is not greatly productive of hydrocarbons. Natural gas, however, is produced from the Grugan field in central Pennsylvania, from reservoirs in the Bald Eagle Sandstone (Harper, 1984; Henderson and Timms, 1985; C. Laughrey and R. Harper, Upper Ordovician Bald Eagle Formation fractured anticlinal play, this atlas).

Post-Taconic Molasse and Carbonate Shelf Deposits

A period of tectonic quiescence followed the Taconic orogeny, and the Taconic highlands continued to shed molasse into the nearby Appalachian basin during the Silurian Period. Post-tectonic quartzose sandstones and conglomerates up to 2,000 feet thick, (Clinch Formation, Tuscarora Sandstone, Shawangunk Formation, Rose Hill Formation, Keefer Sandstone, Massanutten Sandstone, Mifflintown Formation), are overlain by red beds of the Bloomsburg Formation (Hoskins, 1961) over much of the central Appalachian basin. The Shawangunk is interpreted to be a fluvial deposit, whereas the Tuscarora and Clinch are chiefly littoral or beach-barrier deposits (Yeakel, 1962; Whisonant, 1977; Cotter, 1983). The Tuscarora and Clinch are overlain by the Rose Hill Formation and Keefer Sandstone in the Appalachian Valley from Virginia to Pennsylvania, and in turn by the Mifflintown Formation in the central Appalachian Valley and Ridge. Lateral equivalents of the Lower Silurian sandstones and conglomerates in New York are the Medina and Clinton groups, which consist of some 400 to 500 feet of marine and nonmarine sandstones and shales. In places, the Clinton is noted for the hematitic iron ore beds that it contains (Cotter and Link, 1993). In Ohio, western Pennsylvania, and western New York, the Clinton and Medina have been extensively drilled for natural gas (M. McCormac and others, Lower Silurian Cataract/Medina Group ["Clinton"] Sandstone play, this atlas) (Figures 2a-2f). Production is almost ubiquitous, so that gas fields, once widely separated, subsequently grew together into a large multi-state continuous accumulation as interfield areas were developed. In some areas, such as western New York, fields were converted to gas storage as production declined and the reservoir was depleted.

The Bloomsburg Formation is also up to 2,000 feet thick in eastern Pennsylvania (Hoskins, 1961), and consists of siliciclastic redbeds that accumulated as stream and perhaps high intertidal deposits (Epstein and Epstein, 1969). Partial equivalents to the Bloomsburg redbed sequence are marine sandstones, shales, and carbonate rock formations, such as the McKenzie Formation in Virginia, the Lockport Dolomite in Kentucky, Ohio, and New York, and the Williamsport and Wills Creek formations in West Virginia (Smosna and Patchen, 1978). The Williamsport Formation consists of delta front sandstone, about 50 feet thick, whereas the overlying Wills Creek Formation consists of about 400 feet of mudrock, limestone, and sandstone that were deposited in a variety of littoral environments.

Upper Silurian carbonate rock formations, represented by the Lockport Dolomite (Smosna and others, 1989; M. Noger and others, Upper Silurian Lockport Dolomite-Keefer [Big Six] Sandstone, this atlas), Tonoloway Formation, and the lower part of the Keyser Formation (A. Van Tyne, Upper Silurian Bass Islands trend, this atlas), formed as a series of reefs and banks in the western and southern parts of the central Appalachian basin. These deposits, coupled with the sediments of the Bloomsburg delta on the east, formed the perimeter of the Salina salt basin in which the 1,600-foot-thick Upper Silurian Salina Group accumulated. The group includes up to 1,300 feet of strata bearing salt and other evaporite minerals. The Salina is overlain by up to 150 feet of Upper Silurian limestone, shale, and dolomite in the central part of the Appalachian basin.

Carbonate shelf environments persisted from the Late Silurian into Early Devonian time in the Appalachian basin, where they are represented by the Helderberg Group. These carbonate shelf deposits range from about 250 feet thick in New York to about 400 feet thick in nearby Pennsylvania. Biohermal buildups of corals and crinoids or stromatoporoids and corals within the Helderberg have some potential as localized reservoirs for hydrocarbons. For example, Smosna and Warshauer (1979) described a very early Devonian stromatoporoid-coral buildup in western Virginia, possibly the oldest Devonian reef in North America, as about 40 feet thick and 325 feet across. The buildup is overlain by about 18 feet of fossiliferous, argillaceous micrite. Correlative units in southern West Virginia and in the central Appalachian Valley and Ridge exhibit a complexly interwoven fabric of lithofacies that have been summarized elsewhere by Milici and de Witt (1988). These shelf deposits are overlain by a widespread shallow marine sandstone deposit, the Oriskany (Ridgeley) Sandstone. The Oriskany, in general, extends as a blanket deposit within the Appalachian basin from New York to southwestern Virginia. In places, the formation is fossiliferous and calcareous. Where it is not well-cemented, the Oriskany has sufficient porosity to be an excellent reservoir for oil and natural gas (K. Flaherty, Fractured Middle Devonian Huntersville Chert and Lower Devonian Oriskany Sandstone, this atlas; J. Harper and D. Patchen, Lower Devonian Oriskany Sandstone structural play, this atlas; D. Patchen and J. Harper, The Lower Devonian Oriskany Sandstone combination traps play, this atlas; S. Opritza, Lower Devonian Oriskany Sandstone updip permeability pinchout, this atlas). The Oriskany is a major gas-producing unit in the Appalachian basin. Its intergranular porosity and permeability are enhanced locally by a well-developed fracture porosity, especially where the Oriskany is complexly folded and faulted within the splay-thrust anticlines that occur above regional decollement in the eastern part of the Appalachian Plateau (Gwinn, 1964). The giant Elk-Poca field, near Charleston, West Virginia, has produced more than 1 tcfg from a combination stratigraphic-structural trap within the Oriskany Sandstone.

The upper part of the shelf sequence in the eastern part of the Appalachian basin and in the adjacent Valley and Ridge consists of the dark gray Needmore Shale and its lateral equivalents: the Huntersville Chert in Virginia, West Virginia, and Pennsylvania; and the Onondaga, Delaware, and Columbus limestones in New York, Ohio, and eastern Kentucky (Oliver and others, 1971). Small reefs and pinnacle reefs occur in the Onondaga in south-central New York and adjacent Pennsylvania and are attractive targets for drilling (Oliver, 1963; Friedman, 1985). Friedman (1985) described seven gas-bearing Onondaga bioherms (A. Van Tyne, Middle Devonian Onondaga Limestone reef play, this atlas) (Figures 2a-2f), coral-crinoid mounds that occur as coral baffle stones in a matrix of coral and crinoid packstone. These buildups commonly cover 300 to 700 acres and range from 110 to 700 feet thick.

Acadian Flysch Deposits

Post-Taconic molasse and associated shelf sedimentation was terminated by the onset of the Acadian orogeny and the formation of the great Catskill delta during the remainder of the Middle and Late Devonian and the subsequent Price-Rockwell delta in the earliest Mississippian. Acadian tectonism apparently was caused by the collision of an ancient land mass, Armorica, with ancestral North America (Laurentia) and northern Europe (Baltica) (Perroud and others, 1984). A biotite-rich ash fall and several other closely related ash falls, called collectively the Tioga bentonite (Ebright and others, 1949), are perhaps associated with the onset of the orogeny. The Tioga is an important stratigraphic marker that occurs either on top of the Onondaga Limestone, within the upper part of the Columbus Limestone, or near the base of the Marcellus Shale. The biotite-rich ash bed apparently covered most, if not all, of the northeastern United States during the Middle Devonian, and is up to 2 feet thick in western Virginia (Dennison, 1963; Dennison and Textoris, 1970).

The Catskill delta marks a major change in the tectonic and depositional conditions that existed within the Appalachian basin. The relatively thin stable shelf deposits of limestone, dolomite, and clean, reworked sandstones that were deposited early in the Devonian gave away to the great thicknesses of siliciclastic sediments that mark the onset of the Acadian orogeny (Dennison, 1985; Woodrow and others, 1988). In general, the Catskill delta is a large-scale fill sequence, marked in its lower part by prodelta basinal black shales and in its upper part by nonmarine sandstones and shales. In detail, the internal stratigraphy of the delta is extremely complex (de Witt and Roen, 1985), as these strata accumulated in a variety of prodelta, littoral, and deltaic depositional environments that reflect complex interactions of changing subsidence rates, eustacy, tectonism, and climate. This complexity is illustrated by the detailed maps of sandstone distribution and illustrations of sandstone morphology that were obtained from a study of 700 well logs in West Virginia by Boswell and Jewell (1988). Boswell and Jewell (1988) related sandstone trends to fluvial-deltaic, shoreline, shallow marine, and deep marine depositional environments. Boswell and Donaldson (1988) described the fluvial-deltaic architecture of the upper part of the Catskill delta. They identified approximately five major sub-parallel deltaic systems, separated by lineaments, and concluded that their locations may have been controlled by basement structures. Boswell (1988) described variations in the stacking arrangements of littoral and marine sandstones and the abrupt thickening of certain stratigraphic units as additional evidence for deep-seated fault control in northern West Virginia. Hasson and Dennison (1988) summarized the stratigraphy of the Devonian shales on the eastern side of the Appalachian basin from Pennsylvania to Virginia. In general, they showed how the Millboro Shale section from the Tioga Middle Devonian ash bed at the base to the Brallier Formation at the top is broken on the east by a wedge of silty shale and siltstone called the Mahantango Formation. Where the Mahantango is present, the lower part of the shale sequence is called the Marcellus Shale, and the upper part includes the Harrell Shale and the Tully Limestone. Woodrow and others (1988) described the Middle and Upper Devonian of the Appalachian and part of the mid-continent region in detail. They showed how marine facies were displaced progressively to the west and southwest by the progressive development of the Catskill delta.

The petroleum geology of the Devonian and Mississippian black shale sequence in the Appalachian basin was summarized recently in Roen and Kepferle (1993). The stratigraphy of the delta consists of an intercalation of relatively thick black shale units, rich in organic matter and abnormally radioactive, with coarser grained deposits of gray and greenish-gray silty shales, siltstones, and fine-grained sandstones (de Witt and others, 1993). In general, the delta is a large fill sequence that becomes generally more nonmarine, both upward through the deposit and eastward toward the Pennsylvania depocenter. The oldest rocks of this Devonian gas shale sequence, the Hamilton Group, are preserved on the eastern side of the basin in central New York and in adjacent Pennsylvania and Ohio. The group consists of the Marcellus, Skaneateles, Ludlowville, and Moscow shales. The Hamilton Group is overlain by the Tully Limestone. The Tully is widely distributed from central New York to Pennsylvania and West Virginia. In the subsurface in Pennsylvania, the Tully is as much as 200 feet thick and serves as an important marker bed for drillers (de Witt and others, 1993).

To the west and south, the Middle Devonian part of the shale sequence is absent from the stratigraphic sequence and apparently was removed by erosion so that Upper Devonian beds unconformably overlie beds as old as Silurian in Kentucky and Middle Ordovician in central Tennessee (Wilson, 1949). The unconformity is significant because it explains the restriction of Hamilton Group and the lower beds of the Upper Devonian shale sequence to the northern and eastern side of the Appalachian basin (de Witt and others, 1993). On the northeastern side of the Appalachian basin in West Virginia, the Catskill delta consists of about 4,000 feet of shale, siltstone, and sandstone that are divided into the Brallier Shale at the base, the Chemung Formation, and the Hampshire Formation (Patchen and Hohn, 1993). Black shales rich in organic matter are more common in the lower part of the section. To the west, the deltaic sequence thins significantly to where it is less than 1,000 feet in western West Virginia. There, the section contains much more black shale and is more productive of autogenic gas (R. Boswell, Upper Devonian black shales, this atlas) (Figures 2a-2f). Similarly, from western New York to eastern Ohio, along the southern shore of Lake Erie, the Upper Devonian shales thin from east to west across the basin. On the east, where about 1,000 feet of section is preserved, black shale source beds, such as the Rhinestreet Shale Member of the West Falls Formation, occur at or near the base of the deposit. Overlying beds of the Chagrin Formation are dominated by gray shale and siltstone and contain relatively little organic matter (Broadhead, 1993). The section thins to 500 feet thick or less in a short distance to the west, where it is mostly submature black shale, rich in organic matter. Craft and Bridge (1987) studied the sedimentology of the West Falls Formation in south-central New York. They concluded that the bedforms and sedimentary structures observed indicated that the depositional environment was that of delta-lobe progradation and offshore bar development on a shallow marine shelf affected episodically by intense tropical storms.

The black shale beds (Marcellus Shale, Rhinestreet Shale Member of the West Falls Formation, Huron Member of the Ohio Shale, and Cleveland Member of the Ohio Shale) are principal source beds for hydrocarbons and are major self-sourced reservoirs for natural gas in the Appalachian basin. In general, the relatively large amounts of organic matter in these deposits reflect both the high rate of organic productivity and the slow sedimentation rates of the black muds that occurred in the nutrient-rich epeiric seas around the fringes of the Catskill delta. In addition, the relatively large amount of organic matter contained in these strata attests to the occurrence of anoxic conditions on the sea floor that would facilitate preservation of this organic matter as it accumulated upon the sea bottom prior to burial (Ettensohn, 1985). The thickness of the Acadian clastic wedge is greatest in the eastern Pennsylvania depocenter, where it attains 1,000 feet (Harris, 1978).

The preservation of this vast deltaic deposit, and the regional intertonguing of black and gray siliciclastic facies therein, reflects the overall subsidence of the Appalachian basin necessary to accommodate these sediments as well as subsidiary episodes of transgression and regression. In addition, onset of Devonian deltaic deposition and associated episodes of high organic productivity reflect a long-term climate change from the conditions favorable to the deposition of evaporites that existed in the Late Silurian to more humid conditions that apparently occurred in the Devonian, when the earliest known forest, the Gilboa Forest, developed on the upper reaches of the Catskill delta.

In general, the strata of the Catskill delta thin dramatically to the south and west across the Appalachian basin, and at its distal margin in southern Tennessee, the Devonian-Mississippian Chattanooga Shale is only about 8 feet thick at its type section (Glover, 1959; Conant and Swanson, 1961). The Mississippian part of the sequence, like the underlying Devonian, is thin and fine-grained around the periphery of the delta, and becomes thicker and coarser grained to the east and north. Sandy deposits, such as the Berea Sandstone, form more porous reservoirs within the Lower Mississippian part of the shale sequence and serve as major reservoirs for hydrocarbons (T. Tomastik, Lower Mississippian-Upper Devonian Berea and equivalent sandstones, this atlas) (Figures 2a-2f).

The stratigraphy of the upper part of the Catskill deltaic sequence, the Price-Rockwell delta complex in West Virginia, Virginia, and Tennessee, has been described by Kreisa and Bambach (1973), Bartlett (1974), Kammer and Bjerstedt (1986), and Bjerstedt and Kammer (1988). Bjerstedt (1988a, 1988b) showed how trace fossils could be used together with lithologic features to determine littoral and nearshore depositional environments of the Price Formation, from oxygen-deficient deep-water basin plain environments to platform and delta and alluvial plain environments. The relative effects of eustatic and tectonically induced sea-level changes on sedimentation were discussed by Dennison and Head (1975) and Johnson and others (1985). Johnson and others (1985) concluded that Devonian eustatic sea-level changes, represented by at least 14 transgressive-regressive cycles, were caused chiefly by mid-plate thermal uplift and submarine volcanism, and that continental glaciation played a minor role.

The Lower Mississippian Price Formation grades into the Grainger Formation from southwestern Virginia into Tennessee (Hasson, 1973). In Tennessee, the Grainger ranges in thickness from several hundred feet to more than 1,000 feet of siliciclastic sediments. The Price grades upward into evaporite-bearing red beds of the Maccrady Formation (the drillers' Red Injun sand), which in the southwestern Virginia Valley and Ridge are thick enough to produce gypsum commercially. The Maccrady extends into the subsurface of eastern Kentucky, where it is up to 100 feet thick and grades laterally into purplish-red shales of the Borden Formation in east-central Kentucky, which are only a few tens of feet thick (Kepferle, 1977). Farther to the north, along the structural grain of the mountain chain in southwestern Virginia, the Price bears coal. Kammer and Bjerstedt (1986) abandoned the use of the term Pocono Formation as a correlative of the Price in West Virginia. Instead, they extended the Price Formation for use throughout the state, except in the northeastern Panhandle where equivalent strata are almost entirely nonmarine and are called the Rockwell Formation. In southwestern Virginia and southern West Virginia, the Price Formation includes the Cloyd Conglomerate and the Sunbury Shale at its base. In northern West Virginia, the Price Formation of Kammer and Bjerstedt (1986) consists of the Oswayo Member and Cussewago Sandstone Member in its lower part which are unconformably overlain by the Riddlesburg Shale Member and the Rockwell Member in the upper part of the formation (Kammer and Bjerstedt, 1986).

Kammer and Bjerstedt (1986) and Bjerstedt and Kammer (1986) noted that deposition of the Price Formation and its lateral equivalent, the Rockwell Formation, occurred in two depositional basins separated by a positive area, which they called the West Virginia dome. North of the dome, the Price Formation and Rockwell Formation are generally more nonmarine and a little older than the Price Formation to the south of the dome.

Lower Carboniferous Flysch, Molasse, and Stable Shelf Deposits

Carbonate deposits, some siliceous, replace the Lower Mississippian siliciclastics to the south and west across the Appalachian basin. In the northern part of the Cumberland Plateau in Tennessee and adjacent Kentucky, Waulsortian-type buildups within the Fort Payne Formation (Kinderhookian) produce oil and gas (MacQuown and Perkins, 1982; R. Milici, The Lower Mississippian Fort Payne carbonate mound play, this atlas) (Figures 2a-2f). The Fort Payne Formation, 100 to 200 feet thick, is overlain by carbonate formations that were mapped into the central Appalachian region by Butts (1940) from the Mississippi Valley region, and bear the names Warsaw Limestone and St. Louis Limestone (Cooper and Lumsden, 1981). The St. Louis is overlain by oolitic and fossiliferous fragmental carbonate strata, equivalents of the Ste. Genevieve and Gasper formations of the Mississippi Valley region, but called the Monteagle Limestone, Hartselle Formation, and Bangor Limestone in the Plateau region of Tennessee (Stearns, 1963; Roberts and Lumsden, 1982; Lumsden and others, 1983); the Greenbrier Limestone or Newman Limestone in eastern Kentucky, eastern Tennessee, Virginia, and West Virginia; and the Greenbrier or Loyalhanna formations in Pennsylvania (Arkle and others, 1979; Edmunds and others, 1979; Englund, 1979; Milici and others, 1979; Rice and others, 1979). Both the Greenbrier and Monteagle-Hartselle-Bangor interval contain sufficient interoolitic porosity to serve as natural gas reservoirs (R. Smosna, Upper Mississippian Greenbrier/Newman limestones, this atlas) (Figures 2a-2f) throughout much of the southern part of the Appalachian basin. An eastern equivalent of the Mississippian limestone sequence, the Newman Limestone, occurs in eastern Kentucky and the Valley and Ridge of Tennessee and southwestern Virginia. In general, the Newman contains more shaly intervals than equivalent carbonate rocks on the Plateau (Sanders, 1952).

Alleghenian Flysch Deposits

The terminal phase of Appalachian deformation, called the Alleghenian orogeny by Rodgers (1949), began during the Late Mississippian and was caused by the final closing of Iapetus and the assemblage of the supercontinent, Pangea. The increasing effects of continental collision and tectonic uplift on the eastern margin of the Appalachian basin resulted in a major change in the types of sediment that were accumulating in the basin during the Carboniferous, from marine strata dominated by carbonate rock and shale to littoral or nonmarine, coal-bearing siliclastic strata. Donaldson and Shumaker (1981) summarized the tectonic events and paleogeographic history of the Appalachian region from the Upper Devonian to the Permian. They concluded that Upper Devonian to Lower Pennsylvanian clastic wedges prograded into the Appalachian basin generally from the northwest, and that a younger, Middle Pennsylvanian to Permian clastic wedge prograded into the Appalachian basin from the southeast, filling in first the Pocahontas basin in Virginia, eastern Kentucky, and southern West Virginia, and then the Dunkard basin in Pennsylvania, adjacent Maryland, northern West Virginia, and eastern Ohio. In the Anthracite district of eastern Pennsylvania, the initial stage of the Alleghenian orogeny is represented by 6,000 to 8,000 feet of terrestrial red beds known as the Mauch Chunk Formation (Edmunds and others, 1979). Red beds thin to the south and east across the Appalachian basin, and appear to grade laterally into Upper Mississippian limestone deposits in the basin interior and into the Lower Pennsylvanian formations of the Pottsville Group.

Throughout much of the Appalachian basin, these siliciclastic red-bed deposits overlie and are interbedded with the upper part of the Mississippian marine limestone shelf deposits in a melange of littoral to shallow marine depositional environments. Similarly, in places in eastern Tennessee and southwestern Virginia, the Pennington Formation and its equivalents, the Hinton Formation, Princeton Sandstone, and Bluestone Formation, appear to grade laterally into conglomeratic quartzose sandstones in the lower part of the Lee Formation (Englund, 1979; Milici and others, 1979). In these areas, lithologic units commonly classified as Mississippian grade laterally into lithologic units commonly classified as Pennsylvanian, so that marine and littoral limestones and mudrock are laterally equivalent to marine and nonmarine coal-bearing strata. To the west, in Ohio, eastern Kentucky, and western West Virginia, however, the boundary between the Mississippian red bed deposits and black and gray coal-bearing shales, siltstones, and sandstones of Pennsylvanian age appears to be erosional (Collins, 1979; Rice and others, 1979), although an alternative interpretation has been proposed (Horne and others, 1974).

In general, the lithologic changes across the Mississippian-Pennsylvanian boundary, regardless of the depositional relationships across the contact, appear to reflect a major change in the climatic conditions that existed in the Appalachian basin, from dominantly dry and warm to dominantly wet and warm (Cecil and others, 1994). As indicated by the abundance of red beds and the absence of black shales and coal deposits, prevailing climates during the Late Mississippian were generally dry; oxidizing conditions prevailed; and organic productivity and preservation were relatively low. As a result, source rock potential of these Upper Mississippian strata is poor. With the onset of warmer and wetter climates during the Pennsylvanian, however, organic productivity, primarily the amount of plant material available to the environment, increased significantly and depositional conditions changed from oxidizing to reducing in a relatively short time. As a result, the red and green colors of Upper Mississippian shales and mudstones were replaced vertically by coal-bearing, sulfidic, black and gray shales, siltstones, and sandstones of Pennsylvanian age throughout the Appalachian basin. Heckel (1995) showed how glacially induced eustatic changes in sea level in combination with paleogeography could control depositional cycles in Upper Middle to Upper Pennsylvanian coal-bearing units. Because of their relatively high content of terrigenous organic material, some Pennsylvanian strata and coal beds in the Appalachian basin have a considerable potential for generating natural gas or coal-bed methane.

The Pottsville Group consists of about 300 feet of fine- to coarse-grained coal-bearing siliciclastic sediments throughout much of the Appalachian basin. The Pottsville contains relatively large amounts of quartzose sandstones and is characterized by the high purity and coking nature of its coal beds. Overlying Allegheny, Conemaugh, and Monongahela groups of Pennsylvanian age are composed almost entirely of sandstones, siltstones, and shales with coal beds, some limestones, and a few marine zones. Although thicknesses of these groups range greatly over the basin, they rarely exceed 500 feet each. Depositional environments range from shallow shelf and estuarine to swamp, delta, and strand plain (Donaldson, 1974; Ferm, 1974; Milici, 1974). Greb and Archer (1995) described tidally formed cyclic rythmites within the Breathitt Formation in eastern Kentucky, which occur within a sandstone unit that was deposited in estuarine or shallow shelf and intertidal environments. The Pittsburgh coal bed, perhaps the single greatest mineral resource in North America, is at the base of the Monongahela Group.

Strata of the Permian Dunkard Group comprise the youngest deposits of Paleozoic age in the Appalachian basin. The Dunkard consists of coal-bearing siliciclastic strata up to about 600 feet thick. Red beds are common as are extensive shallow water lake and swamp deposits (Berryhill and others, 1971).

The Paleozoic Era and deposition within the Appalachian basin ended with the final episode of Alleghenian deformation, continental collision, the assemblage of Pangea, and the formation of the thrust-faulted and folded Appalachian Mountain chain. Subsequently, during the Early Mesozoic, extensional processes resumed along the eastern continental margin as Pangea broke apart and numerous rift basins collapsed into extended and thinned continental crust, and a new ocean basin, the modern Atlantic Ocean, began to form.

STRUCTURAL HISTORY OF THE APPALACHIAN BASIN

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Introduction

Location: The gas-producing part of the Appalachian foreland, outlined on many maps as the Appalachian basin (Riggs, 1960; Landes, 1970; St. John, 1980), encompasses a broad area between the structural Allegheny front on the east (Plate 1), the Cincinnati and other contiguous arches on the west, the Canadian shield on the north (Figure 1), and a less distinct boundary on the south where the basin narrows between the Nashville Dome and the Pine Mountain thrust in southern Kentucky and northern Tennessee (Plate 1). The more intensely deformed sedimentary rocks of the Valley and Ridge and Great Valley physiographic provinces, which lie between the Allegheny front and Precambrian rocks of the Blue Ridge, form the Appalachian thrust belt. Except for a small area in the Pennsylvania-West Virginia region, rocks of the thrust belt are largely unproductive (J. Harper and D. Patchen, Lower Devonian Oriskany Sandstone structural play, this atlas), and thus they are considered to be within a frontier area. The thrust belt extends the full length of the Appalachian orogen (Figure 1), whereas the broad Appalachian basin, as defined here, is found in the western part of the central Appalachian foreland. The transition between intense deformation in the thrust belt and the relatively undeformed and highly productive basin is abrupt at the emergent Pine Mountain thrust in the Kentucky and Tennessee, whereas it occurs over a wide area of folded rocks above buried, blind thrusts in West Virginia, Maryland, and Pennsylvania (Plate 1).

Sequential Structural History

Background: Recognition of the role that plate tectonics have played in creating foreland structure, the availability of geophysical surveys, and subsurface maps based on data from hundreds of thousands of shallow wells have helped geologists piece together a general history of deformation in the basin that has extended over the past billion years. Previous studies recognized three major tectonic events that created or affected structures in the basin, including the Grenville orogeny (~900 Ma), Iapetian rifting (~570 ma), and the Allegheny orogeny (~275 Ma). The first two of these deformations predated the formation of the Appalachian foreland. Reactivation of basement structures formed by the earlier two deformations influenced subsequent geologic events including the distribution of hydrocarbons in the basin; thus, both Grenville and Iapetian structure will be discussed briefly.

Precambrian: Metamorphic and igneous rocks that are the result of the Precambrian Grenville deformation (~900 Ma) form basement under practically all of the Appalachian foreland. These highly deformed rocks have been studied in detail where they come to the surface on the north flank of the basin at the Canadian shield and the Adirondack uplift (Figure 1).

Basement comes to the surface in the Blue Ridge several tens of miles east of the basin to form the eastern margin of the thrust belt (Figures 1, 2). Outcropping Precambrian Grenville basement rocks of the Blue Ridge (Plate 1) and metasedimentary and metavolcanic rocks along its eastern flank within the Piedmont Province have been thrust westward over sedimentary and low-grade metasedimentary rocks of the adjacent foreland. The structural history of basement rocks in the Blue Ridge is complex, because it not only has undergone Grenville deformation, but it has been deformed by Paleozoic orogenic events associated with the formation of the Appalachian orogen.

Autochthonous basement rises westward from under the Blue Ridge thrust sheet toward the arches along the western margin of the basin. The Grenville front (Plate 2), the line that separates Grenville basement from older basement of the granite-rhyolite and Keweenawan basement (Drahovzal and others, 1992) to the west, follows the Cincinnati and contiguous arches (Plate 1) just east of their crests. The fact that the Grenville front roughly follows the western margin of the basin suggests that the location of that margin was at least in part determined by earlier basement structure.

Little is known about the internal structure of Grenville rocks under the Paleozoic sedimentary rocks of the basin. That which is known is inferred from a few deep-reflection seismic surveys (Beardsley and Cable, 1983; Culotta and others, 1990; Riley and others, 1993), extrapolation of outcrop studies southward from the Canadian shield, and from regional magnetic and gravity investigations (Ammerman and Keller, 1976; Kulander and Dean, 1978). For example, several regional faults that follow linear magnetic and/or gravity anomalies (King and Zeitz, 1978; Black, 1986) have been interpreted to be Grenville structures.

Steeply dipping coherent reflections on deep seismic records also have been interpreted to be faults or compositional banding in Grenville basement rocks that show intra-basement structure. Perhaps the most notable of the latter are the east-dipping events at the Grenville front in Ohio (Pratt and others, 1989), which are interpreted to be Grenville basement thrust over older basement to the west. This interpretation, and similar east-dipping reflections seen on a seismic profile obtained along strike near the Grenville front under Lake Huron, are compatible with surface mapping on the Canadian shield (Wynn-Edwards, 1972). West-dipping reflections from the basement in east-central Ohio have been called the Coshocton zone. These have been correlated with similar west-dipping reflections in Tennessee and west-dipping shear zones in the Adirondacks and Canada (Culotta and others, 1990).

The surface of Grenville basement commonly can be identified as a strong reflection on seismic profiles in areas where basement is shallow and uncomplicated by fault offsets. It was a low-relief surface when late Precambrian and Early Cambrian seas transgressed westward, first at the continental margins and then along and away from grabens of the Eastern Interior Graben System (Figure 3) into the continental interior. Seismic reflections from the top of basement can be difficult or impossible to distinguish from those of overlying sandstones and the base of the Cambro-Ordovician carbonate section in the Rome trough area (Figures 3, 4). It commonly is impossible to identify the top of the basement with any degree of certainty under the complexly deformed allochthon in the eastern foreland. Thus, the precise depth to basement and the location of basement structures along the eastern margin of the basin and under the thrust belt of the Valley and Ridge Province are speculative (Figure 1, Plate 2).

Early and Middle Cambrian: Offset of the basement surface along faults of the Eastern Interior Graben System (Figure 3) and, specifically, faults of the Rome trough (Figure 4) in the Appalachian basin occurred in association with the formation of the Iapetus Ocean during the Late Precambrian and Early Cambrian subsidence (Allen, 1988; Goodmann, 1992). Fault-reactivation diagrams (Wilson and others, 1994) of basement faults within the rift and overlying basin rocks indicate that nearly all of the structural relief, whether across reactivated Grenville or along newly formed faults, was caused by this Early and Middle Cambrian extensional deformation.

Subsequent orogenic deformation at the plate margin has obscured structural relationships between failed rifts of the Eastern Interior Graben System and their successful counterparts at the plate margin (Figure 3). However, radiometric dates (Bartholomew and others, 1991) from Catoctin volcanic rocks of the successful rift sequence deposited on Grenville basement (Plate 1) at the plate margin (Figure 3) provide an Eocambrian (~570 my) date. Assuming the failed rifts of the Eastern Interior Graben System are structurally related to the rifts at the plate margin, then the Rome trough is the same age or slightly younger (Read, 1989) than sea-floor spreading at the plate margin.

Upper Cambrian to Middle Ordovician: The time interval between Iapetian rifting and the onset of Middle Ordovician subduction associated with the Taconic orogeny was one of relative crustal stability and formation of a broad carbonate shelf (Read, 1989) across much of the eastern and southern North American (Laurentian) plate. The crustal response after rifting may have been similar to that of other cratonic basins of North America that evolved from rifts into much broader, shallow, sag basins (Shumaker, 1986b). If this were the case, then a broad and shallow sag basin (Wagner, 1976; Ryder and others, 1991; Shumaker and Wilson, 1995) developed above the Rome trough during the Late Cambrian through Early Ordovician time approximately along the axis of the Appalachian basin.

Middle Ordovician to Permian: Most of what is known about orogenic deformation during this time interval comes from the study of highly deformed and metamorphosed rocks that originally were deposited at or near the plate margin and which are now exposed in the Blue Ridge and Piedmont provinces (Hatcher, 1989; Bartholomew and others, 1991). The Taconic orogeny, the oldest of three defined Appalachian orogenic events, is generally ascribed to the onset of deformation and accretion of a micro-continent at the North American plate margin during the Middle Ordovician. The Appalachian foreland began to assume its present shape during the Middle Ordovician as subduction and deformation

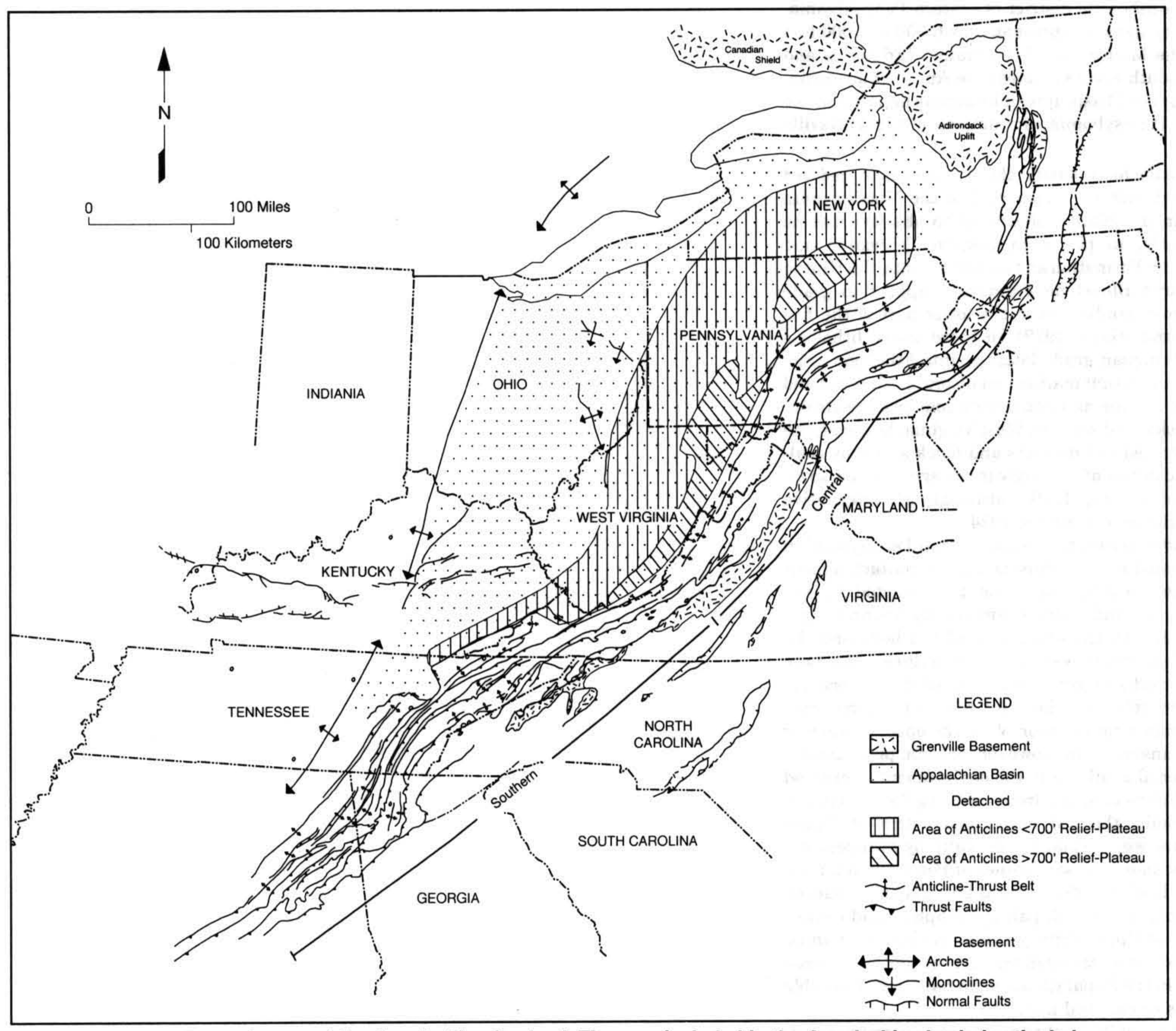


Figure 1. Tectonic map of the Appalachian foreland. The area included in the Appalachian basin is stippled.

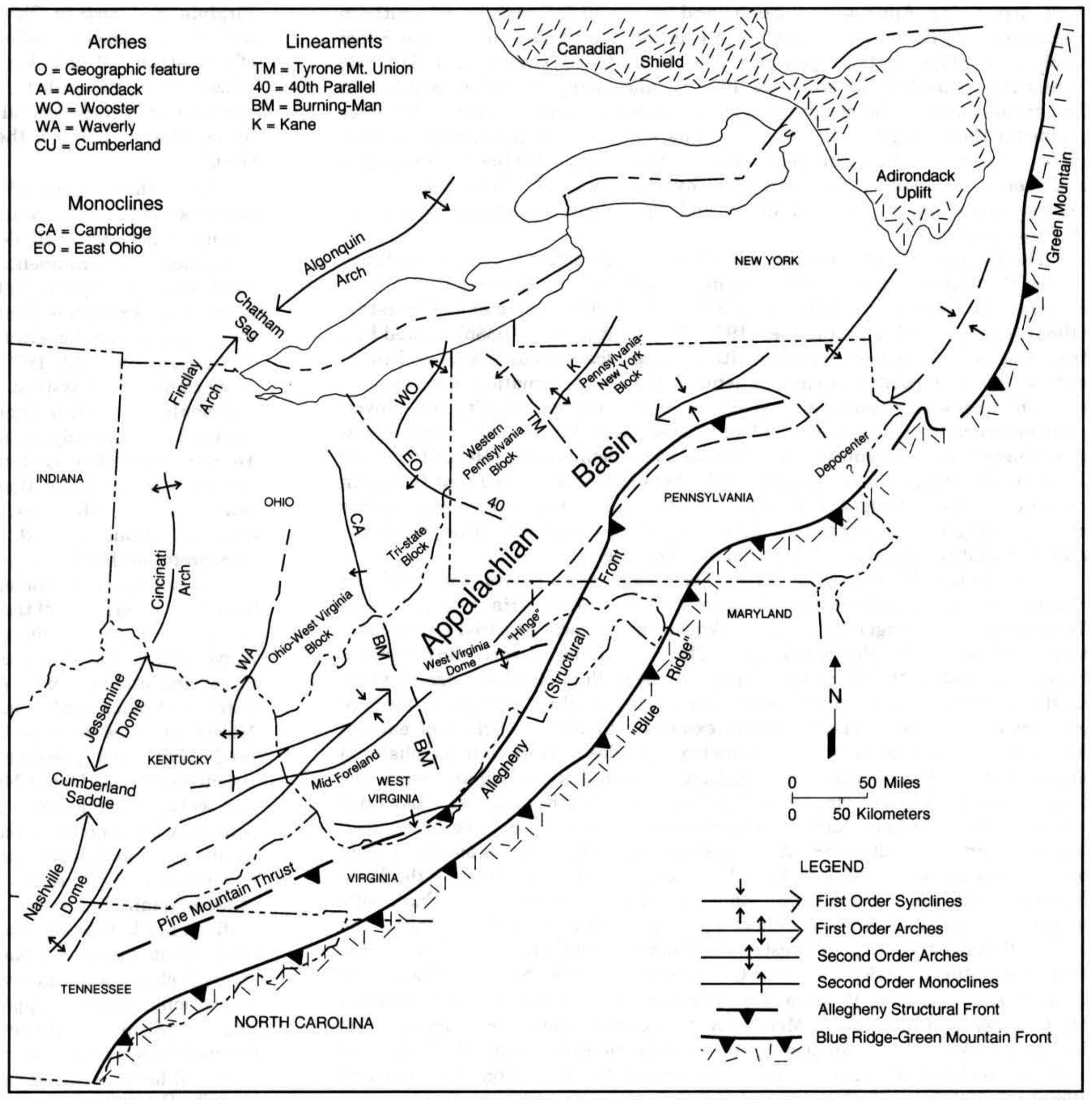


Figure 2. Middle and Upper Paleozoic structural elements of the Appalachian basin. The Allegheny front and the Blue Ridge are shown for reference only. Both formed during the late Paleozoic Allegheny orogeny.

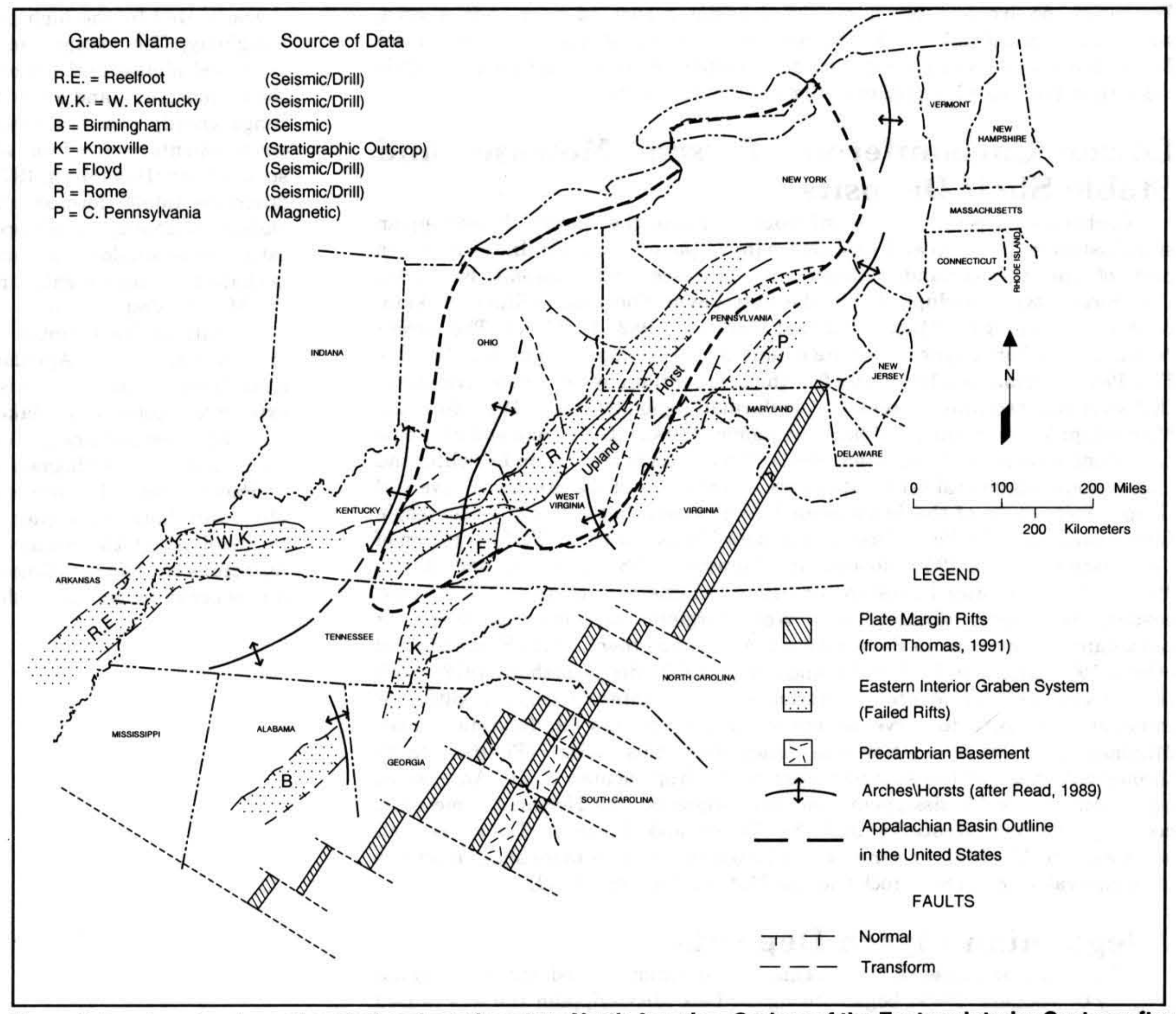


Figure 3. Iapetan structure of central and southeastern North America. Graben of the Eastern Interior System after Shumaker (1986b). Rifts and transform faults at the plate margin from Thomas (1991). Position of arches from Read (1989a).

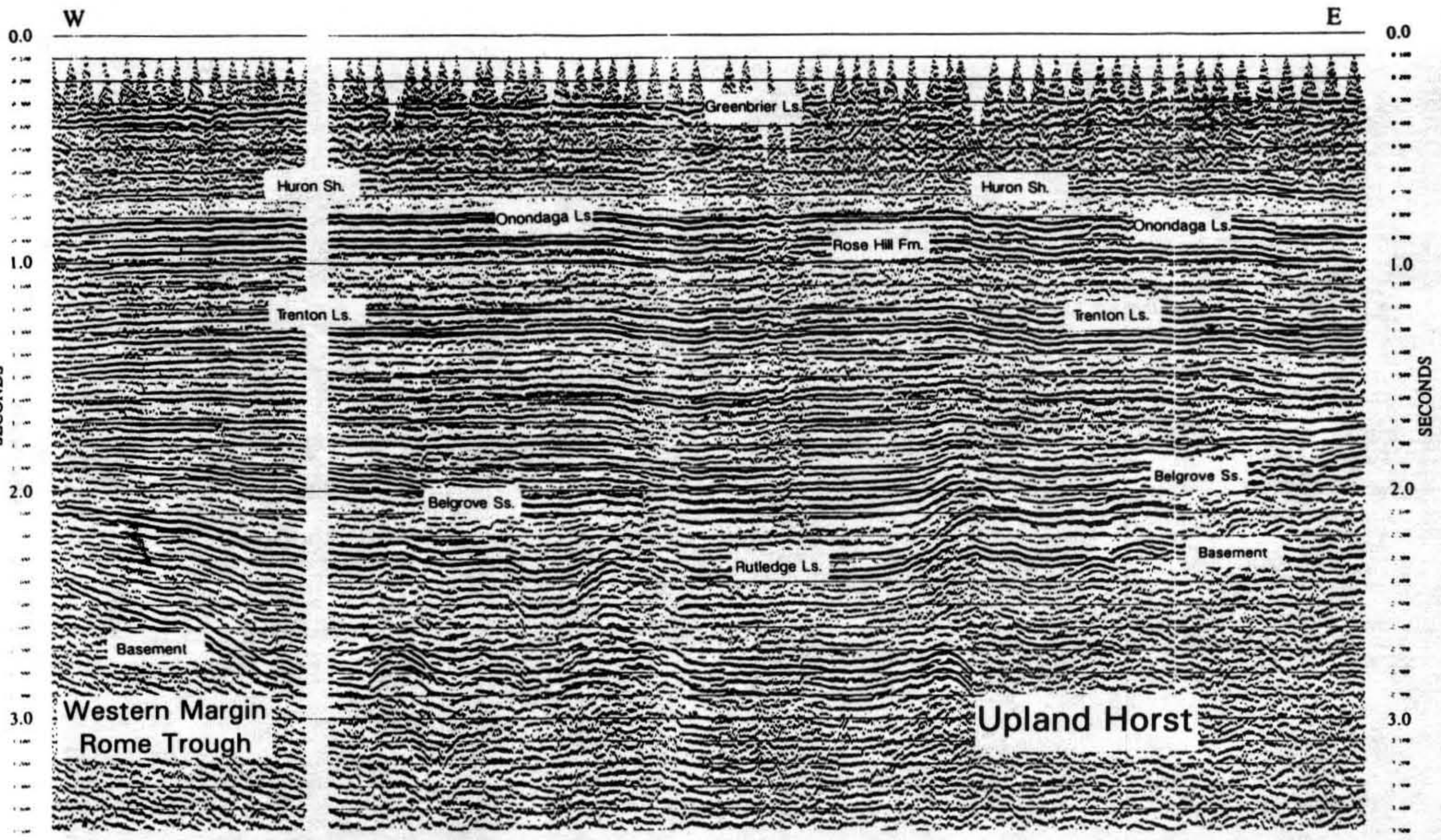


Figure 4. Seismic profile, which crosses the Rome trough, is located at the letter 'R' of Figure 3. Rocks of the rift sequence extend approximately from the reflection correlated with basement to the reflection correlated with the Rutledge Limestone (D. Harris and M. Baranoski, Cambrian pre-Knox Group play, this atlas, Figure Cpk-3). Carbonate shelf rocks, perhaps deposited in a sag basin, occur approximately between reflections correlated with the Rutledge and Trenton units, whereas foreland rocks extend from the Trenton reflection to the surface. The seismic interpretation is by T.H. Wilson (Shumaker and Wilson, 1995). The Ohio-West Virginia hinge zone of Harris and Baranoski (this atlas, Figure Cpk-4; Ryder and others, 1991) lies just beyond the west end of this line. Figure courtesy of GTS Corp.

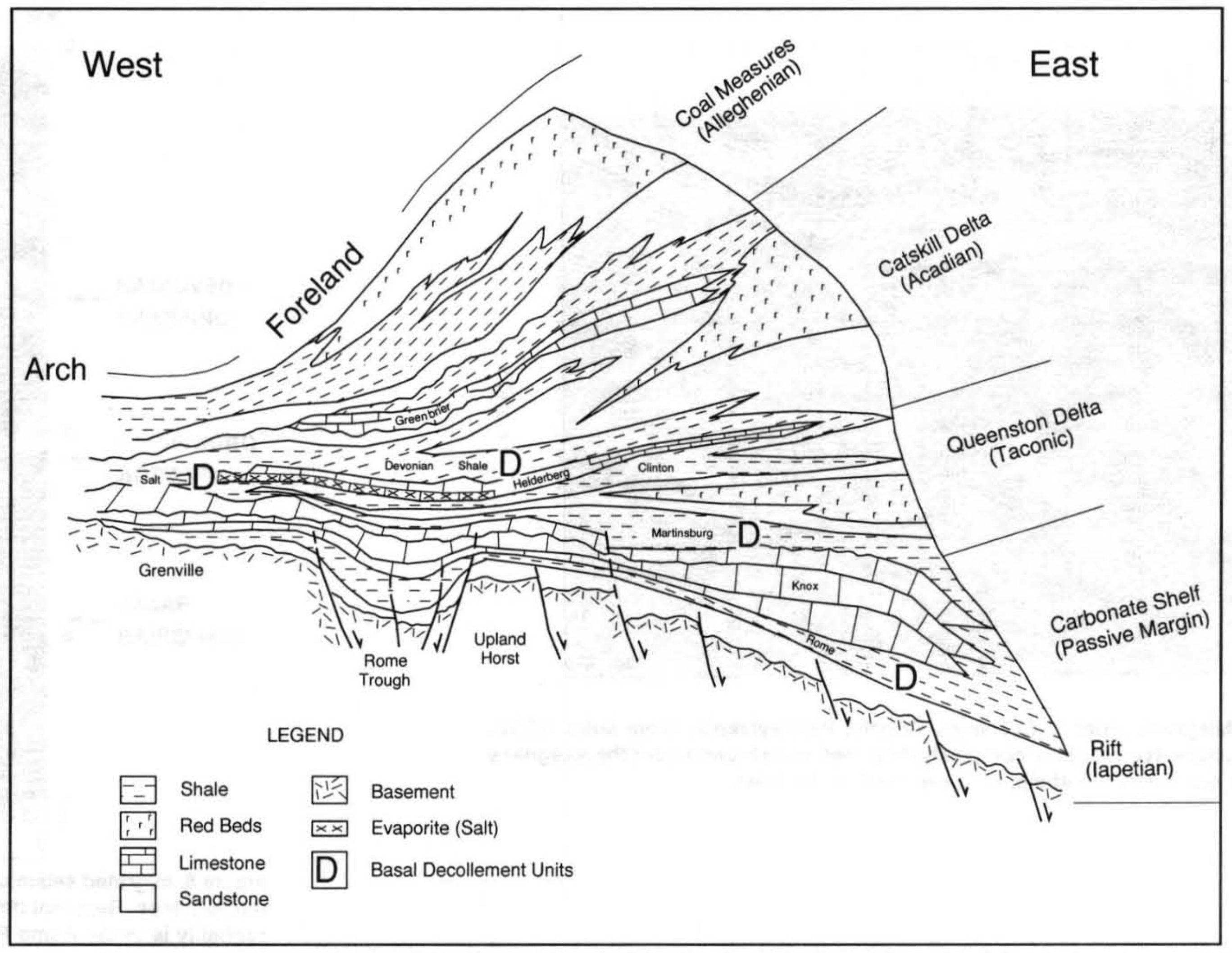


Figure 5. Diagrammatic representation of the Central Appalachian foreland stratigraphic wedge (after A. Donaldson, oral commun., 1995). The thick shales and salt form prominent decollement zones.

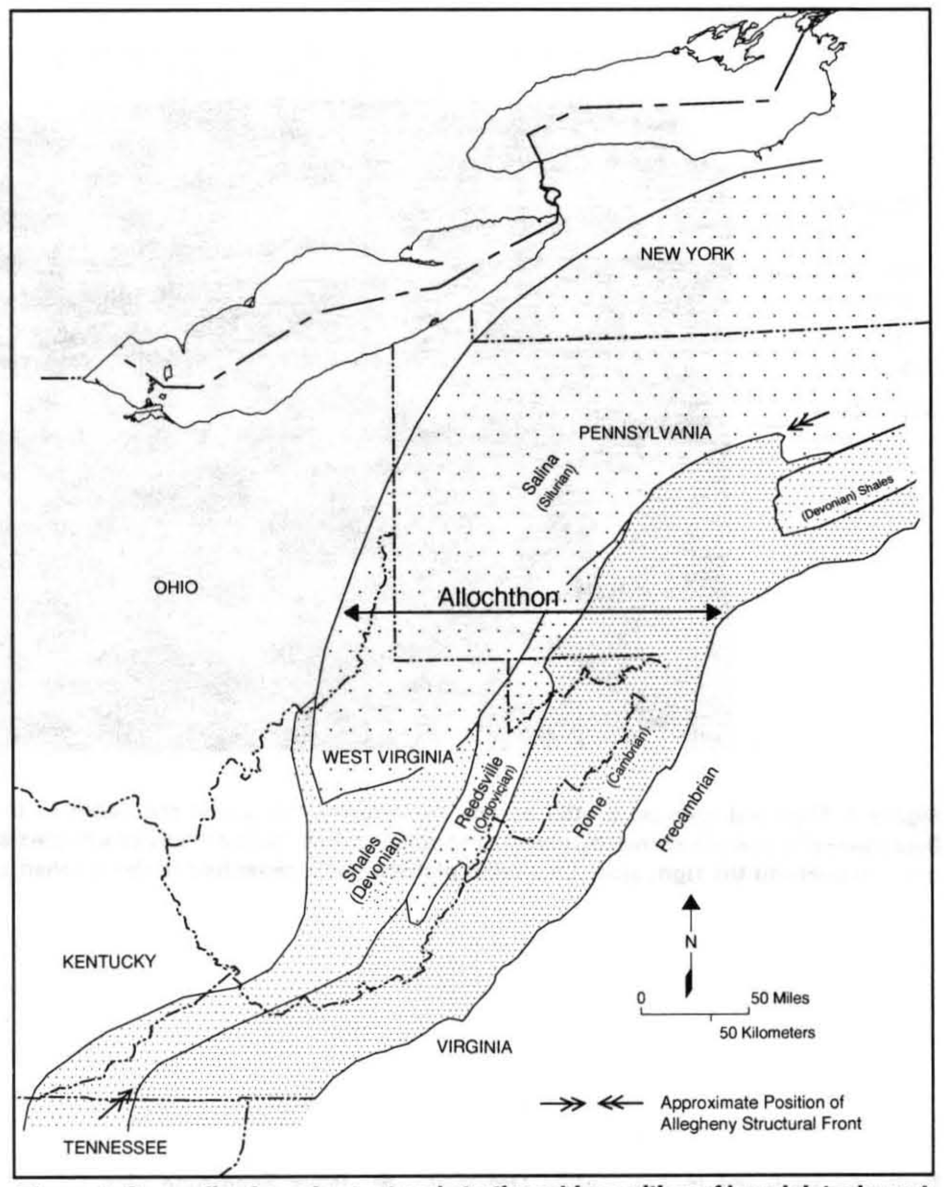


Figure 6. Generalized areal extent and stratigraphic position of basal detachment zones of the allochthon in the Central Appalachian foreland. Rome Formation detachment is largely found in the thrust belt, in the Valley and Ridge physiographic province.

started at the plate margin. The other major orogenic events in the Central Appalachians, the Acadian and Allegheny orogenies, are correlated with the collision of the North American plate with other continental plates that eventually led to the formation of Pangea at the end of the Paleozoic.

In the Appalachian basin, the Taconic and Acadian orogenies were largely reflected by changes in subsidence rates, by the influx of sediments from the hinterland, and by the assimilation of Cambrian grabens and any successor sag basins into a developing and deepening foreland (Figure 4; also see cross sections of Plate 1). The assimilation of the Rome trough probably helped create a broader central Appalachian foreland as compared with the Appalachian foreland to the north or south (Figures 1, 3).

Regional stratigraphic studies in the Appalachian foreland have viewed the three orogenies as reflected by the westward-prograding Queenston, Catskill-Pocono, and clastic wedges or deltas that are classically associated with the Taconic, Acadian, and Allegheny orogenies (Figure 5). Cyclicity is evident in each wedge. In the older two wedges, it is seen by the deposition of deeper water mud and turbidites, which were followed by westward-prograding sands and red beds, regressive shallow-water carbonates, and by terminating regional unconformities (Figure 5).

Several studies of the foreland (Tankard, 1986; Beaumont and others, 1988) have focused on basin models that predict the response of the crust to variations in tectonic and sedimentary loading and unloading at the plate margin, whereas other studies have mapped subtle stratigraphic variations that have outlined growth structures (Harper, 1989; Riley and others, 1993) and basement blocks (Figure 2) within the basin (Lavin and others, 1982; Shumaker and Wilson, 1995). Detailed work also has attempted to differentiate base-level variations caused by eustatic, climatic, and tectonic changes (Dennison, 1989; Ettensohn, 1992b).

Model studies (Beaumont and others, 1988) have challenged the long-held view of a relatively stable basin architecture by predicting the presence of migrating crustal arches, called peripheral bulges, that move across the foreland in response to tectonic and sedimentary loading at the plate margin. Several structural elements, such as the Cincinnati, Cambridge, and Waverly arches (Figure 2), have been interpreted to be peripheral bulges (Tankard, 1986; Beaumont and others, 1988; Ettensohn, 1992a; Diecchio, 1993) at various times during the Paleozoic. On the other hand, stratigraphic and preliminary seismic studies have linked many structures such as the Cambridge arch and Mid-foreland hinge with faults at the margin of basement blocks (Figure 2) that have a history of recurrent movement during foreland subsidence (Harper, 1989; Wilson and others, 1993). For example, the Mid-foreland hinge (Figure 2), which affected the deposition of mid and upper Paleozoic sediments (Shumaker and Wilson, 1995), lies along the West Virginia segment of the east-margin fault of the Rome trough (Figures 3, 4).

These and other studies suggest that foreland subsidence took several different forms as the Appalachian foreland developed. Well established is the broad "geosynclinal" subsidence of the Appalachian foreland toward the hinterland and plate margin. It appears, however, that additional subsidence occurred in the grabens that were incorporated into the foreland, particularly where such grabens (failed rifts) of the Eastern Interior Graben System connected with successful rifts at the plate margin. Dewey and Burke (1974) suggested that such intersections formed structural lows and depocenters in the foreland. The depocenter in eastern Pennsylvania (Figure 2) may correspond with such a graben system that connected with successful rifts at the plate margin.

Crustal subsidence in the foreland not only was influenced by preexisting crustal structure and crustal composition, but it apparently subsided as smaller, semi-independent crustal blocks that at least in part are bounded by faults. These blocks subsided at varied rates. Some tilted while adjacent blocks were comparatively stable, so that apparent offsets along faults changed amounts and direction with time (Wilson and others, 1993). Such variations in the rate of subsidence caused drape folds above some horst blocks, whereas in others, a change in the direction of relative movement of basement blocks created inversion structures such as anticlines above basement depressions. Note, for example, the reversal of structural relief above the east-margin fault of the Rome trough (Figure 4) at and above the reflection correlated with the Ordovician Trenton Limestone. It is likely that basement blocks like those seen in Figure 2 extend to the east, but they are undiscernible within and under the structurally complex parts of the allochthon.

Specific times or episodes of accelerated subsidence (Ettensohn, 1992a) and apparent structural reversals (Wilson and others, 1993) may be related to orogenic events in the core of the Appalachian belt. Subsidence diagrams suggest that changes in rates of subsidence may have occurred during the onset of the Middle Ordovician Taconic and Middle Devonian Acadian orogenies (Goodmann, 1992). Presumably, episodes of increased subsidence, such as during the Middle Devonian, also created relatively deeper water and the potential for preservation of source beds for westward-prograding sandstone reservoirs that resulted from orogenies, sea-level changes and, possibly, climatic changes in the hinterland.

Permian: Nearly all of the faults and folds seen at the surface within the Appalachian foreland were caused by detached deformation associated with the Allegheny orogeny (Plate 1; Figure 1). There is evidence for two phases of deformation in the foreland: an Early Pennsylvanian phase that did not greatly affect the rocks of the basin; and a Late Pennsylvanian-Early Permian stage (Geiser and Engelder, 1983) that created the folds and thrusts of the basin. These structures formed above sole faults that rise through the stratigraphic section away from the Blue Ridge area toward the continental interior.

In general, three thick shale units and one evaporite unit (Figure 5) contain the major decollement faults in the foreland. Shales of Cambrian age such as those of the Rome Formation are the principal basal-detachment horizons in the thrust belt east of the Allegheny front (Figure 6). To the west, regional basal detachments include the Ordovician Reedsville Shale (Martinsburg Formation), the Upper and Middle Devonian black shales, and the Silurian evaporites of the Salina Formation (Figures 6, 7).

In the northwestern and west-central parts of the basin, the Silurian salts form important detachment horizons (Figures 5, 6), whereas the Devonian shales carry the basal detachment zones in the southern part of the basin. Thus, the basal detachment horizon rises along a blind thrust sheet from the Rome Formation east of the Allegheny front to the Salina on the west in the northern part of the basin (Figure 6), whereas the step of the thrust sheet in the southern part of the basin is from the Rome to the Devonian shales (Figure 6). The Reedsville Shale (Martinsburg Formation) serves as the basal detachment horizon directly west of the Allegheny front in southern Pennsylvania and central West Virginia (Figures 6, 7, 8) in an area of higher amplitude folds. The basal thrust is found in the salt west of these high folds. Any number of additional overlying, incompetent units can serve as zones of detachment (Dennison, 1989). Units below the regional basal detachment can form the basal detachment locally under a specific fold, under deeply buried small folds, or within small areas of the basin. For example, the basal detachment shown in Figure 8 is in the Rome Formation in an area where major surface folds are most commonly detached in the Reedsville Shale (Figure 6).

Tectonic transport of sedimentary rocks within the allochthon is presumed to be at right angles to fold axes (Plate 1). Changes in fold style occur across the foreland and along strike where there is a lateral rise and termination of basal detachment thrusts and where there was differential movement within the allochthon caused by changes in the deforming stress, preexisting basement structure, and/or the thinning of incompetent units that are decollement horizons. The cross-strike linear terminations of folds, called cross-strike structural discontinuities (Wheeler, 1980), are ascribed to such differences in rates, amounts, and/or directions of movement of adjacent allochthonous thrust sheets (Rodgers, 1963; Gwinn, 1964). Differential movement is demonstrable from regional study of slickenline orientations (Evans, 1994), by comparing differences in shortening across the foreland, and by measuring and restoring unique geologic lines, such as isopach lines, that predate the deformation that created the offset.

Certain detached structures near the outer margin of the allochthon were influenced by basement faults. For example, basement faults like those under the East Ohio monocline (Figure 2) can be traced into detached structures (Wagner and Lytle, 1976; Lavin and others, 1982; Root, 1992) that form cross-strike structural discontinuities. Likewise, several specific basement faults seen on seismic profiles lie below detached folds (Beardsley and Cable, 1983; Shumaker, 1986a).

Most studies of basement faults in the basin lack sufficient data to determine slip directions or amounts; thus, faults are generally classified by apparent offsets of geological features or possibly by the geometric relationships among various structural features such as the orientation of fault arrays. Data from exposed fault zones on the Cincinnati (Black, 1986) and Findlay (Onasch and Kahle, 1991) arches in Ordovician and Silurian rocks suggest that several episodes of minor amounts of strike-slip and dip-slip movement have occurred there. In addition, limited seismic coverage in the Rome trough shows reflection geometries in Cambro-Ordovician rocks that are typical of tilted-block normal faults and flower-shaped, strike-slip faults. Likewise geophysical and lineament studies (Ammerman and Keller 1976; King and Zietz, 1978; Lavin and others, 1982; Harper, 1989) have suggested strike-slip movement along buried and inferred faults such as those at the margins of basement blocks (Figure 3). It is likely that basement faults not only have a complex history of recurrent movement, but also a complex history in relation to slip direction.

On the other hand, there is a sufficient number of wells in many parts of the basin to determine if lateral movement occurred along basement faults during the latter part of the Paleozoic. For example, wells drilled into producing sandstones of the Lower Silurian Cataract/Medina Group ("Clinton") Sandstone play (McCormac and others, this atlas) along the western side of the basin provide sufficient data to develop rather detailed, regional lithofacies and isopach maps that fail to show large offset or deviation of stratigraphic lines across basement structures such as the Cambridge arch and the East Ohio fault system. These data limit the amount of strike-slip movement that could have occurred along any fault on the western side of the basin (Plate 1) to a few miles since the Lower Silurian. The same statement can be made regarding post-Middle Devonian movement for basement faults in the central part of the basin above the Rome trough. Strike-slip offsets of a few hundred feet to a few miles may be present, but even small amounts of strike-slip movement remain to be documented by lateral offset of unique lines that predate Allegheny deformation.

Post-Permian: Because many of the regional faults in eastern Kentucky offset Pennsylvanian sedimentary rocks in a normal sense, it has been presumed that the latest basement movements in the basin related to relaxation of Alleghenian stress. However, the report of faulted Quaternary terrace deposits (Van Arsdale, 1986) casts doubt as to the age of latest, albeit small offsets along basement faults found at the surface.

Recent fluid inclusion studies (Evans, 1994) from mineralized fractures and the occurrence of both Mesozoic and Cenozoic dikes at several localities in the basin suggest that fractures were open for the passage of fluids during both the Mesozoic and Cenozoic (Dennison, 1989).

Structural Influence on Accumulation of Hydrocarbons

Geologic structure plays a critical role in several plays discussed in this atlas. Those plays that are defined by structural closure and fault seals largely relate to detached deformation found in the eastern and northern parts of the basin. They include plays in the Tuscarora (K. Avary, The Lower Silurian Tuscarora Sandstone fractured anticlinal play, this atlas), Bald Eagle (C. Laughrey and R. Harper, Upper Ordovician Bald Eagle Formation fractured anticlinal play, this atlas), Bass Islands (A. Van Tyne, Lower Silurian Bass Islands trend, this atlas) and Oriskany (J. Harper and D. Patchen, Lower Devonian Oriskany Sandstone structural play, this atlas) plays. Also associated with detached deformation are the Oriskany Sandstone (J. Harper and D. Patchen, Lower Devonian Oriskany Sandstone structural play, this atlas), Huntersville Chert (K. Flaherty, Fractured Middle Devonian Huntersville Chert and Lower Devonian Oriskany Sandstone, this atlas) and the Devonian shales (R. Boswell, Upper Devonian black shales, this atlas) fracture plays. The other fracture play, the Middle Ordovician fractured carbonates (L. Wickstrom, this atlas) is commonly associated with reactivated basement faults that are found along the western side of the basin.

Basement Structure: Perhaps the most significant effect that basement structure has had on hydrocarbon production has been its influence on the deposition of sediments within the basin. Physical relief associated with minor reactivation of Grenville and Iapetian structures affected the character, distribution, and thickness of sediments being deposited in the basin (Donaldson and Shumaker, 1981; Shumaker and Wilson, 1995). Block boundaries and basement arches, such as those outlined in Figure 2, appear to have been important at various times in localizing the extent of lithofacies of many Silurian, Devonian, and Mississippian rock units (Shumaker and Wilson, 1995), and in this way, they and other basement structures affected the distribution of reservoirs, source beds, and sealing units in the basin (Harper, 1989; Riley and others, 1993).

The broad arches of the basin and the drape folds that formed above basement horsts (Figure 2) probably were important in determining the direction of primary migration and the location of early-entrapped hydrocarbons. Less well appreciated for their importance to hydrocarbon entrapment in the Appalachian basin are structural highs in the sedimentary section above basement lows. For example, the hanging wall of the East-Margin fault (Figure 3) moved relatively upward during the Devonian (Gao and Shumaker, 1995) and Mississippian (C. Yang, oral commun., 1995), creating the ancestral Warfield anticline as an inversion structure in southwestern West Virginia (Plate 1). Such early-formed closures probably trapped hydrocarbons during the Middle and Late Paleozoic when hydrocarbons first were being generated from source beds such as the Ordovician and Devonian shales. Some regional closures, such as the Cincinnati arch and the inverted Warfield anticline (Plate 1), continued to develop through time to influence the direction of hydrocarbon migration and very likely were the locus for large hydrocarbon accumulations. However, changes or loss of closure above other early-formed basement structures may have caused the remigration of hydrocarbons. For example, deformation during the Permian Allegheny orogeny likely caused remigration of hydrocarbons within the area of the allochthon into some of the developing detached folds. Source beds, such as the Devonian shales, have continued to generate hydrocarbons that migrated into traps even after the end of the Paleozoic.

There are very few examples of fault-trap fields in the Appalachian basin because large offsets along basement faults generally predated deposition of the most highly productive reservoirs. However, an example of a sealing basement

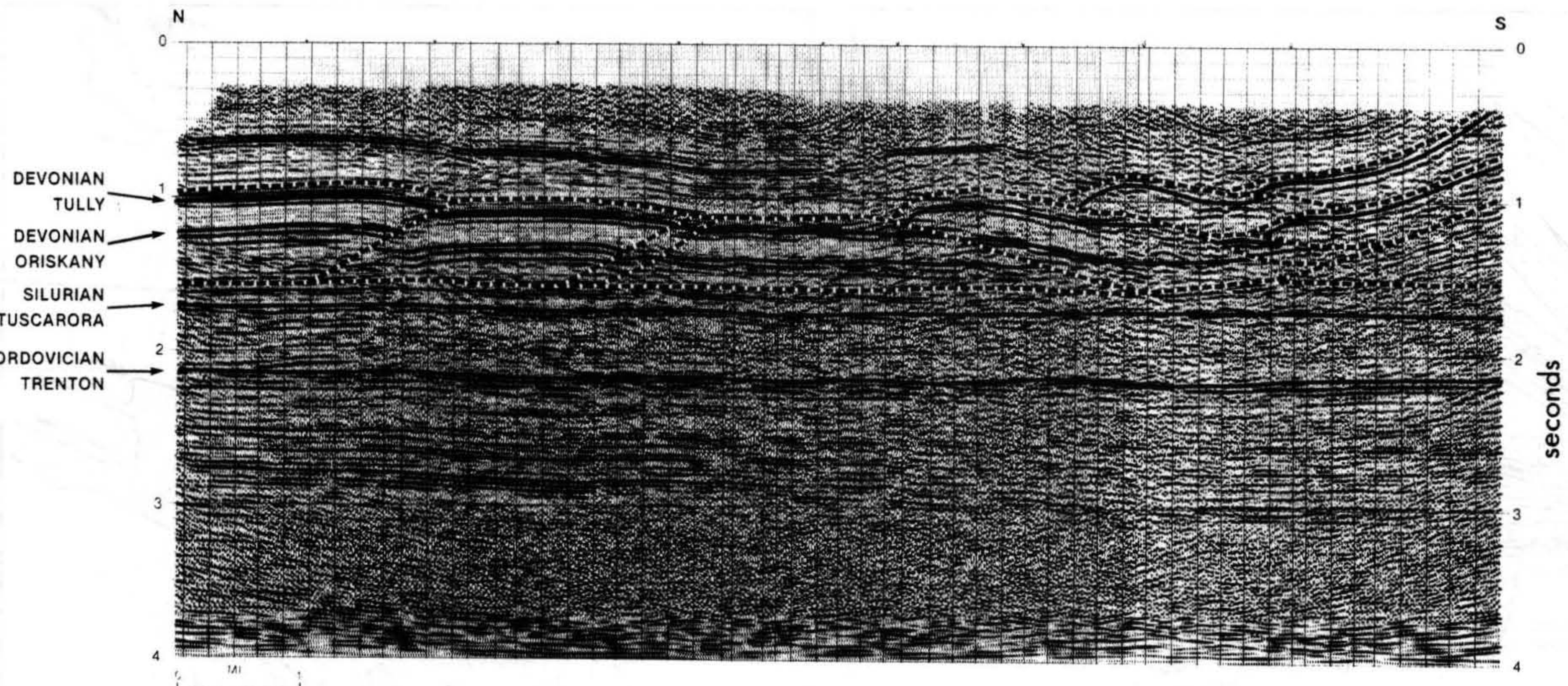


Figure 7. Migrated seismic profile across the eastern margin of the basin to the Allegheny front in Lycoming County, Pennsylvania. From Mitra (1986). Detachment zones are shown by heavy dashed lines. Imbricated slices of a duplex structure, typical of the complexly deformed zone found under the Allegheny front, is seen on the right side. Low-relief plateau folds, detached in the Silurian salt and Devonian shale, are seen west of the front.

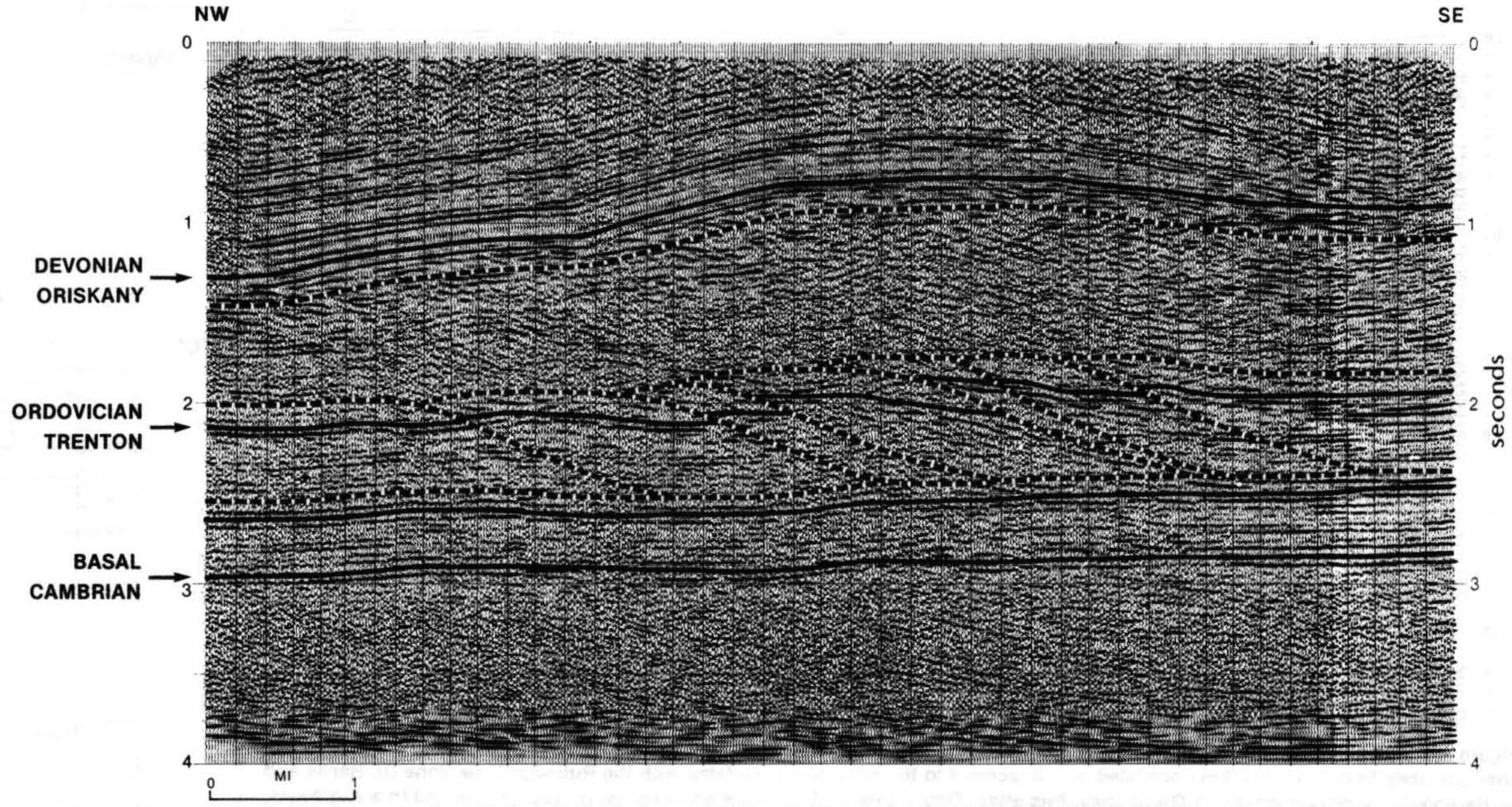


Figure 8. Migrated seismic profile across the Deer Park anticline in Somerset County, Pennsylvania. From Mitra (1986). Detachment zones are shown by heavy dashed lines. Regional detachment occurs within the Reedsville Shale (Martinsburg Formation) directly above the Trenton Limestone. The basal detachment probably is in the Rome Formation.

fault can be found in the Middle Ordovician St. Peter Sandstone play (M. Humphreys and A. Watson, this atlas, Figure Osp-9). Traps associated with basement faults may become very important in the future if exploration continues in rocks of the Rome Formation or Conasauga Group of the Cambrian rift sequence (D. Harris and M. Baranoski, Cambrian pre-Knox Group play, this atlas).

Basement structure also can play an indirect role in developing traps near the western margin of the basin. There, relief on the basement surface (Beardsley and Cable, 1983) can form paleogeomorphic traps in onlapping and overlying sedimentary rocks (D. Harris and M. Baranoski, Cambrian pre-Knox Group play, this atlas; M. Baranoski and others, Cambrian-Ordovician Knox Group unconformity play, this atlas, Figures COk-11, COk-12, COk-16, COk-17). Porous rocks, primarily dolomitic rocks, in erosional outliers also form traps (M. Baranoski and others, Cambrian-Ordovician Knox Group unconformity play, this atlas, Figures COk-20, COk-21, COk-22). The position and trends of porosity in carbonate rocks of several plays (D. Harris and M. Baranoski, Cambrian pre-Knox Group play, this atlas; M. Baranoski and others, Cambrian-Ordovician Knox Group unconformity play, this atlas; L. Wickstrom, Middle Ordovician fractured carbonates, this atlas) commonly relate to dissolution and dolomitization by fluids migrating along basement faults.

Detached Structure: Natural gas is produced in very limited amounts from rocks in the thrust belt east of the Allegheny front (Figure 1; J. Harper and D. Patchen, Lower Devonian Oriskany Sandstone structural play, this atlas, Figure Dos-2). Production largely has been from folds in the Oriskany Sandstone (Jacobeen and Kanes, 1975; J. Harper and D. Patchen, Lower Devonian Oriskany Sandstone structural play, this atlas, Figure Dos-7). Exploration for Oriskany production in that area is limited by structural complexity, small closures, and extensive areas where the reservoir has been eroded.

Several unsuccessful deep wells have been drilled into the fault-bend folds of the Cambro-Ordovician (Knox) carbonates (Figure 5; cross sections of Plate 1) of the thrust belt.

The eastern and central parts of the Appalachian basin west of the Allegheny front include detached structures that produce hydrocarbons in abundance (Plate 1). From east to west, and most complex to least complex, they include: a narrow zone of complexly deformed thrust blocks in a duplex structure a few miles wide along the Allegheny front (Figure 7); a zone of high-amplitude plateau folds (Figures 1, 8; K. Avary, The Lower Silurian Tuscarora Sandstone fractured anticlinal play, this atlas, Figures Sts-2, Sts-10) along the eastern side of the basin; and a zone of low-amplitude plateau folds extending westward to undeformed rocks in northwestern New York, eastern Ohio, and eastern Kentucky (Figure 1).

Fold and thrust-fault traps are found in the highly deformed Oriskany-Tuscarora section in a complexly deformed zone along the Allegheny front at the eastern margin of the basin in central Pennsylvania (J. Harper and D. Patchen, Lower Devonian Oriskany Sandstone structural play, this atlas, Figures Dos-12, Dos-13, Dos-14, Dos-15) and West Virginia (Figure 7; K. Avary, The Lower Silurian Tuscarora Sandstone fractured anticlinal play, this atlas, Figure Sts-19). The complex structure of this zone developed in the foreland sequence above the Reedsville Shale (Martinsburg Formation) in front of blind thrusts that have duplicated rocks of the passive margin sequence in the adjacent thrust belt (cross sections of Plate 1).

The high-amplitude, regularly spaced plateau folds along the eastern side of the basin in north-central Pennsylvania, such as the Wellsboro and Marshlands anticlines (Plate 1; J. Harper and D. Patchen, Lower Devonian Oriskany Sandstone structural play, this atlas, Figures Dos-17, Dos-18, Dos-19, Dos-20, Dos-21, Dos-22), are separated from a similar area of linear, closed folds, such as the Chestnut Ridge (J. Harper and D. Patchen, Lower Devonian Oriskany Sandstone structural play, this atlas, Figure Dos-8) and Laurel Hill anticlines (Plate 1) in northern West Virginia and southwestern Pennsylvania by a complexly faulted area and an area of low-relief folds of more irregular trend (Plate 1). The aforementioned West Virginia-Pennsylvania area also includes a number of folds detached in the Reedsville Shale (Martinsburg Formation) and detached locally in shales of the Cambrian Rome Formation west of the Allegheny front, such as in the Deer Park and Blackwater anticlines (Plate 1; Figure 8; K. Avary, The Lower Silurian Tuscarora Sandstone fractured anticlinal play, this atlas, Figure Sts-10). Some of these folds in southeastern West Virginia, such as Brown's Mountain anticline (Plate 1), approach the tight symmetry and high amplitude of those in the adjacent thrust belt.

The Oriskany (J. Harper and D. Patchen, Lower Devonian Oriskany Sandstone structural play, this atlas) and Tuscarora sandstones (K. Avary, The Lower Silurian Tuscarora Sandstone fractured anticlinal play, this atlas) produce gas from tight folds and thrust blocks (Gwinn, 1964) that fill the cores of open folds in the overlying rocks (K. Flaherty, Fractured Middle Devonian Huntersville Chert and Lower Devonian Oriskany Sandstone, this atlas, Figures Dho-8a, Dho-8b). Oriskany production is widespread, scattered in structural culminations along the folds across most of the area where the Salina salt and Reedsville Shale (Martinsburg Formation) detachments are present (K. Flaherty, Fractured Middle Devonian Huntersville Chert and Lower Devonian Oriskany Sandstone, this atlas, Figure Dho-7). Trapping conditions for production from the Tuscarora Sandstone are similar to those of the Oriskany except that detached folds (K. Avary, The Lower Silurian Tuscarora Sandstone fractured anticlinal play, this atlas, Figures Sts-2, Sts-10, Sts-11) occur only where the basal decollement is in the underlying Reedsville Shale or deeper units, for example, at the Leadmine and Cucumber fields (K. Avary, The Lower Silurian Tuscarora Sandstone fractured anticlinal play, this atlas, Figures Sts-10, Sts-11) in the West Virginia section of the high-amplitude plateau folds (Plate 1).

The presence of an incompetent unit, such as salt of the Salina Formation, permits low folds and, thus, potential traps to extend far to the west and north across the basin (Plate 1) (Van Tyne and others, 1980). The Upper Silurian Bass Islands trend of western New York is one such play where production comes from fault slices above the Salina decollement (A. Van Tyne, this atlas, Figure Sbi-6) in the distal part of the basin over 200 miles northwest of the Blue Ridge and Piedmont core area (Plate 1).

Bald Eagle production is found only in the Grugan field in north-central Pennsylvania. Production is from a fractured reservoir in a low-relief, detached fold located above a basement fault of Cambrian age (C. Laughrey and R. Harper, Upper Ordovician Bald Eagle Formation fractured anticlinal play, this atlas, Figures Obe-6, Obe-7). The superposition of a detached fold above a basement fault and the importance of fracture porosity in this field emphasize a relationship among pre-orogenic basement structure, foreland deformation (Shumaker, 1986a), and the development of fracture porosity seen in several plays.

Low-amplitude plateau anticlines west of the high-amplitude plateau folds (Figure 1; Plate 1) influenced the distribution of hydrocarbons throughout the post-salt section such that gas is found in one or more shallow sandstones on the crests of almost every anticlinal closure (M. Hohn, Lower and Middle Pennsylvanian Pottsville, New River, and Lee Sandstone play, this atlas, Figure Pps-8). These fields are usually classified as combination or stratigraphic traps, because the structures are broad, of very low relief, and because stratigraphic and diagenetic factors in the reservoir have a controlling influence on the entrapment of gas.

In the southern part of the basin, folds above the Devonian shale basal decollement commonly have a smaller amplitude and wavelength, and they do not extend as far into the basin as their salt-cored counterparts to the north. Shale-cored folds on a regional, west-dipping homocline, directly west of the high-amplitude plateau folds of central West Virginia, commonly lack closure. Their importance to production generally comes not from structural closure, but from fractures which can enhance production from stratigraphic traps in Devonian siltstone and shales of that area (R. Milici, Upper Devonian fractured black and gray shales and siltstones, this atlas).

Fractured Reservoirs: There are several reservoirs in the basin that commonly depend on fracture porosity for their commercial production. The Middle Ordovician fractured carbonates (L. Wickstrom, this atlas) are largely found in the nearly flat-lying rocks along the western margin of the basin. Fracture porosity in this reservoir commonly is associated with faults of small offset (L. Wickstrom, this atlas, Figures MOf-8, MOf-9, MOf-10), but such porosity may occur in apparently undeformed rocks that lie above large faults in the basement.

The Devonian shale (R. Milici, Upper Devonian fractured black and gray shales and siltstones, this atlas; R. Boswell, Upper Devonian black shales, this atlas) and the Huntersville Chert (K. Flaherty, Fractured Middle Devonian Huntersville Chert and Lower Devonian Oriskany Sandstone, this atlas) are fractured-reservoir plays that are generally associated with structural deformation found in the central and eastern parts the basin.

The Devonian shale (R. Boswell, Upper Devonian black shales, this atlas) is most productive in areas that lie at and just beyond what traditionally is considered to be the margin of the allochthon (Figure 6). Commercially viable wells in eastern Kentucky and West Virginia generally have horizontal slickensides or a low-angle, shear system or systems of slickensided fractures (R. Boswell, Upper Devonian black shales, this atlas) that indicate differential movement in the shale in response to Alleghenian (Evans, 1994) and perhaps to other more local stresses. Zones of abnormally abundant, open fractures can occur throughout the shale section, but open fractures are commonly more numerous in the highly organic shales, thus creating what has been called a porous fracture facies (Shumaker, 1980) in what probably were Alleghenian detachment (high pressure) horizons. Vertical, extensional fractures, and partially mineralized, open fractures within or adjacent to the detachment horizons are the most productive. Small faults and low-relief flexures above large basement faults were important in concentrating Alleghenian stresses and forming trends of highly productive, open fractures.

The change in facies from Devonian shales to siltstone in central West Virginia (R. Milici, Upper Devonian fractured black and gray shales and siltstones, this atlas) is also a zone of transition of production from fractured shale to siltstone reservoirs, a zone where it usually is difficult to differentiate the percent of gas produced out of fractured shale from that produced from intergranular and/or fracture porosity in the siltstones. A further complication in determining the nature of production from these interbedded lithologies is the occurrence of many small folds and thrust faults that undoubtedly influence production in this part of the allochthon.

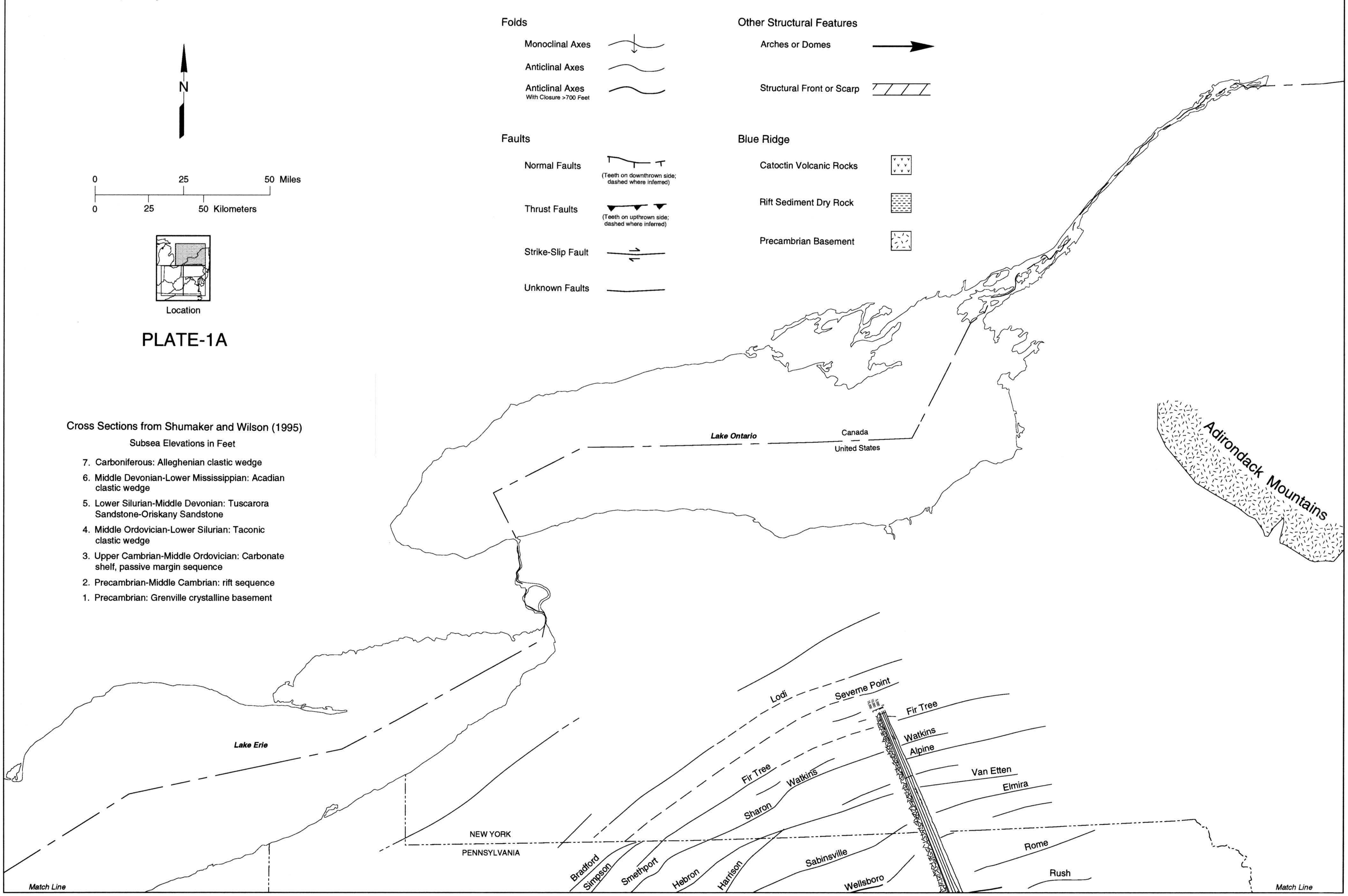
Fractured cherts of the Huntersville form commercial porosity in the complexly deformed cores of the high-amplitude plateau folds (K. Flaherty, Fractured Middle Devonian Huntersville Chert and Lower Devonian Oriskany Sandstone, this atlas, Figures Dho-8a, Dho-8b, Dho-11, Dho-13, Dho-14, Dho-16, Dho-18). Faults generally have thrust the fractured chert along with the Oriskany into overlying, and generally tight, black-shale source beds.

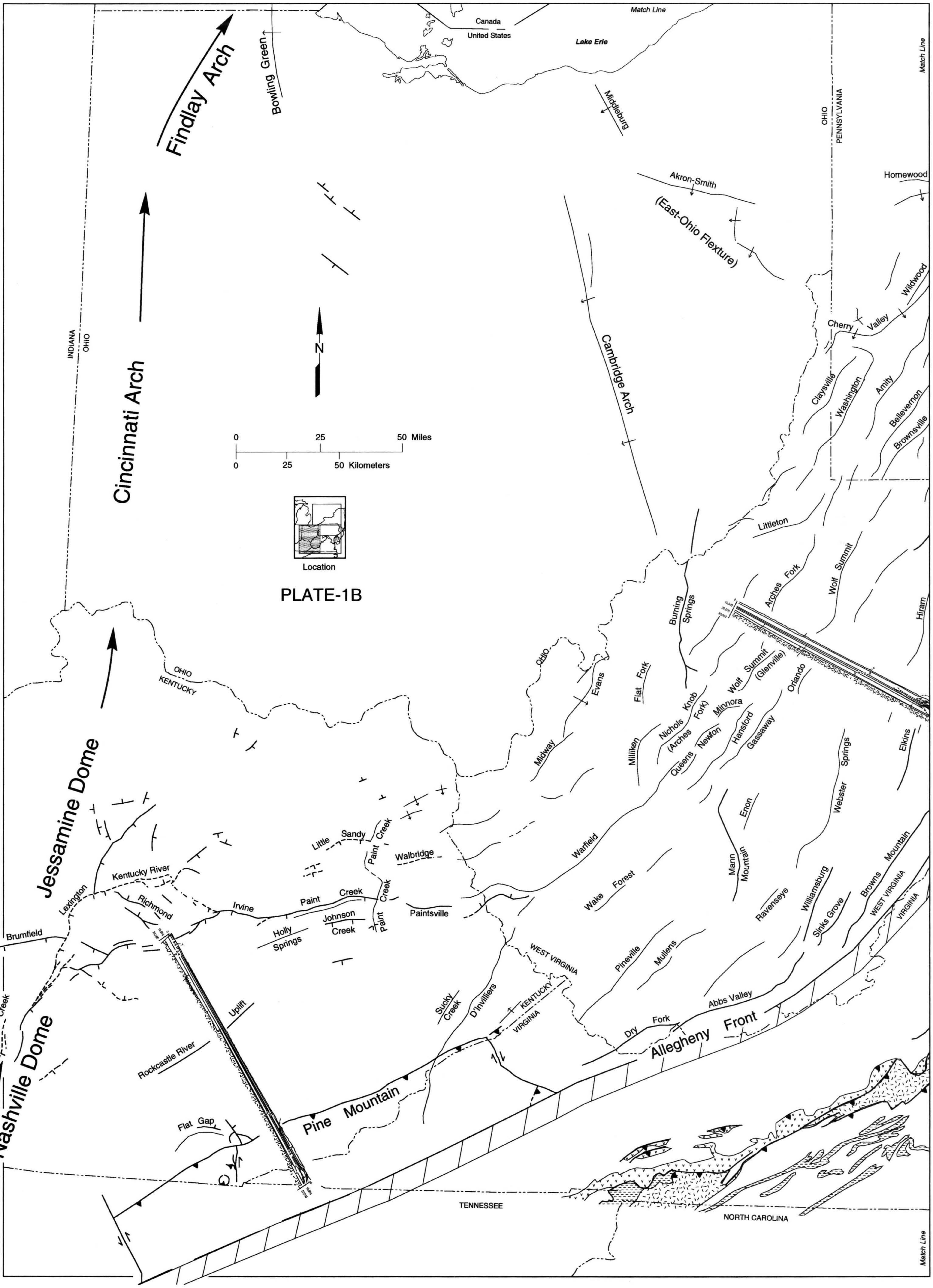
Fractures have enhanced permeability in many reservoirs other than those previously mentioned, particularly in those brittle rocks that are within and at the margins of the allochthon (Figure 6). As drilling continues to test older reservoirs in the basin and as geophysical methods improve, it is anticipated that fractures associated both with basement and detached structures will play an increasingly important role in the search for subtle hydrocarbon traps.

PLATE 1

Tectonic Map of the Appalachian Basin

Compiled by Robert C. Shumaker




Match Line
Canada
United States
Lake Erie
Bowling Green
Findlay Arch
Middleburg
OHIO
PENNSYLVANIA
Akron-Smith
(East-Ohio Flexture)
Homewood
Cincinnati Arch
INDIANA
OHIO
N
Cambridge Arch
Cherry
Valley
Wildwood
Claysville
Washington
Amity
Bellevernon
Brownsville
0 25 50 Miles
0 25 50 Kilometers
Location
PLATE-1B
Littleton
Arches Fork
Wolf Summit
Burning Springs
Hiram
OHIO
KENTUCKY
Flat Fork
Evans
Wolf Summit (Glenville)
Orlando
Nichols Knob (Arches Fork)
Minnora
Milliken
Queens
Newton
Hansford
Gassaway
Midway
Elkins
Webster Springs
Jessamine Dome
Enon
Little Sandy Creek
Walbridge
Paint Creek
Warfield
Mann Mountain
Kentucky River
Lexington
Richmond
Irvine
Paint Creek
Paintsville
Johnson Creek
Paint Creek
Wake Forest
Ravenseye
Williamsburg
Sinks Grove
Browns Mountain
WEST VIRGINIA
VIRGINIA
Brumfield
Holly Springs
WEST VIRGINIA
KENTUCKY
Pineville
Mullens
Goose Creek
Uplift
Sucky Creek
D'Invilliers
VIRGINIA
Abbs Valley
Dry Fork
Allegheny Front
Nashville Dome
Rockcastle River
Pine Mountain
Flat Gap
TENNESSEE
NORTH CAROLINA
Match Line

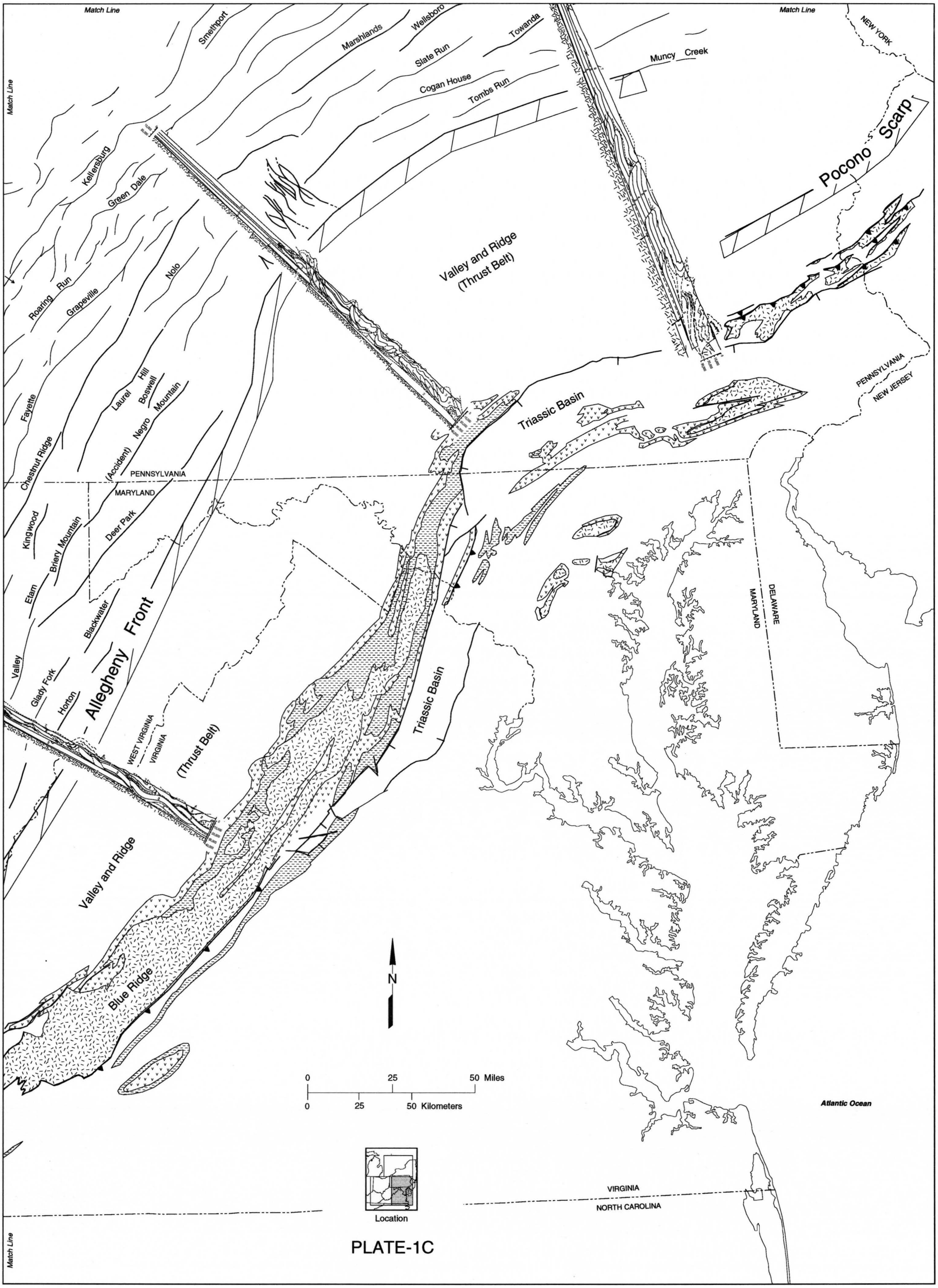

Match Line
Match Line
Match Line
Match Line
Smethport
Marshlands
Wellsboro
Towanda
Slate Run
Cogan House
Tombs Run
Muncy Creek
NEW YORK
Pocono Scarp
Kellersburg
Green Dale
Valley and Ridge
(Thrust Belt)
Roaring Run
Grapeville
Nolo
Laurel Hill
Boswell
Negro Mountain
Fayette
Chestnut Ridge
(Accident)
PENNSYLVANIA
MARYLAND
Triassic Basin
PENNSYLVANIA
NEW JERSEY
Kingwood
Briery Mountain
Deer Park
Etam
Blackwater
Allegheny Front
DELAWARE
MARYLAND
Valley
Glady Fork
Horton
WEST VIRGINIA
VIRGINIA
(Thrust Belt)
Triassic Basin
Valley and Ridge
Blue Ridge
N
0
25
50 Miles
0
25
50 Kilometers
Atlantic Ocean
Location
VIRGINIA
NORTH CAROLINA

PLATE-1C

PLATE 2

Structure Contours on Top of Precambrian (Grenville) Basement in the Appalachian Basin

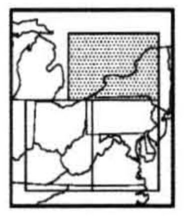
Compiled by Robert C. Shumaker

N

0 25 50 Miles

0 25 50 Kilometers

Contour Interval = 1000 Feet



Location

PLATE-2A

LEGEND

Thrust Faults
(Teeth on upthrown side; dashed where inferred)

Unclassified Faults (Known)
(Teeth on downthrown side; dashed where inferred)

Rift Sediment Dry Rocks
(Eocambrian)

Catoctin Volcanic Rocks
(Eocambrian)

Precambrian Basement

Wells Penetrating Basement

Primary sources of data by state:

New York: Rickard (1973)

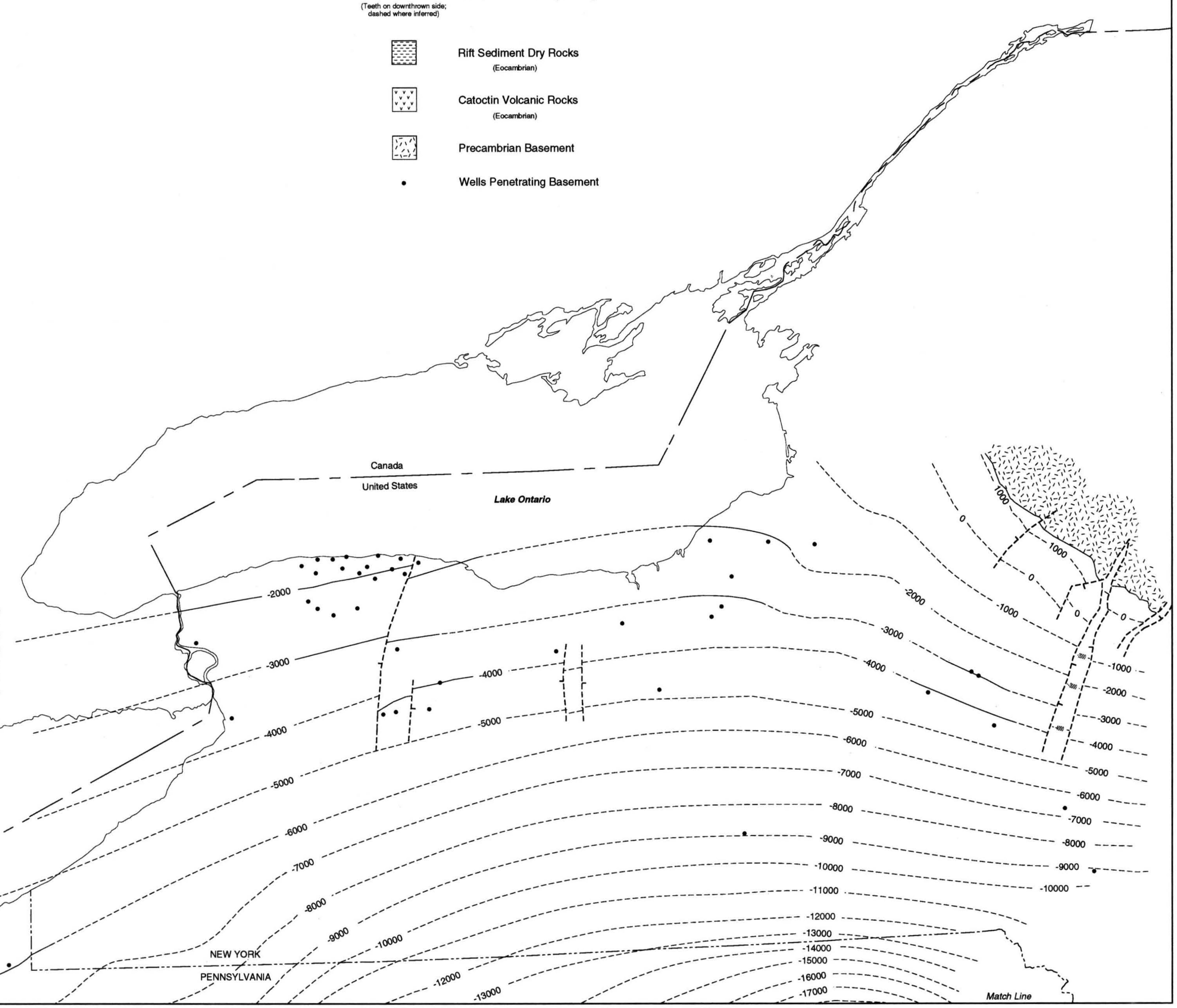
Pennsylvania: Faill (1996)

Ohio: Ohio Division of Geological Survey (unpublished data)
M. Baranoski (oral/written commun., 1994),
Drahovzal and others, (1992).

West Virginia: R. Beardsley (unpubublished data),
J. Dominic, D. Gao, K. Donaldson (unpublished data)
R. Shumaker, T. Wilson, and L. Zheng (unpublished data)

Kentucky: Wilson and Sutton (1973),
Drahovzal and Noger (1995), Shumaker (unpublished data)

The compiler used the sources of data listed above but has modified individual state maps to present an interpretation which he feels is consistent with deformation by crustal extension. Modification of the referenced maps was also required to smoothly join contours on the basement surface at state boundaries. Early and Middle Cambrian extension, that created the Eastern Interior Graben System, formed most of the basement faults shown on the map. The compiler assumes full responsibility for the interpretation shown, as it differs from several of the maps supplied by the authors referenced above.



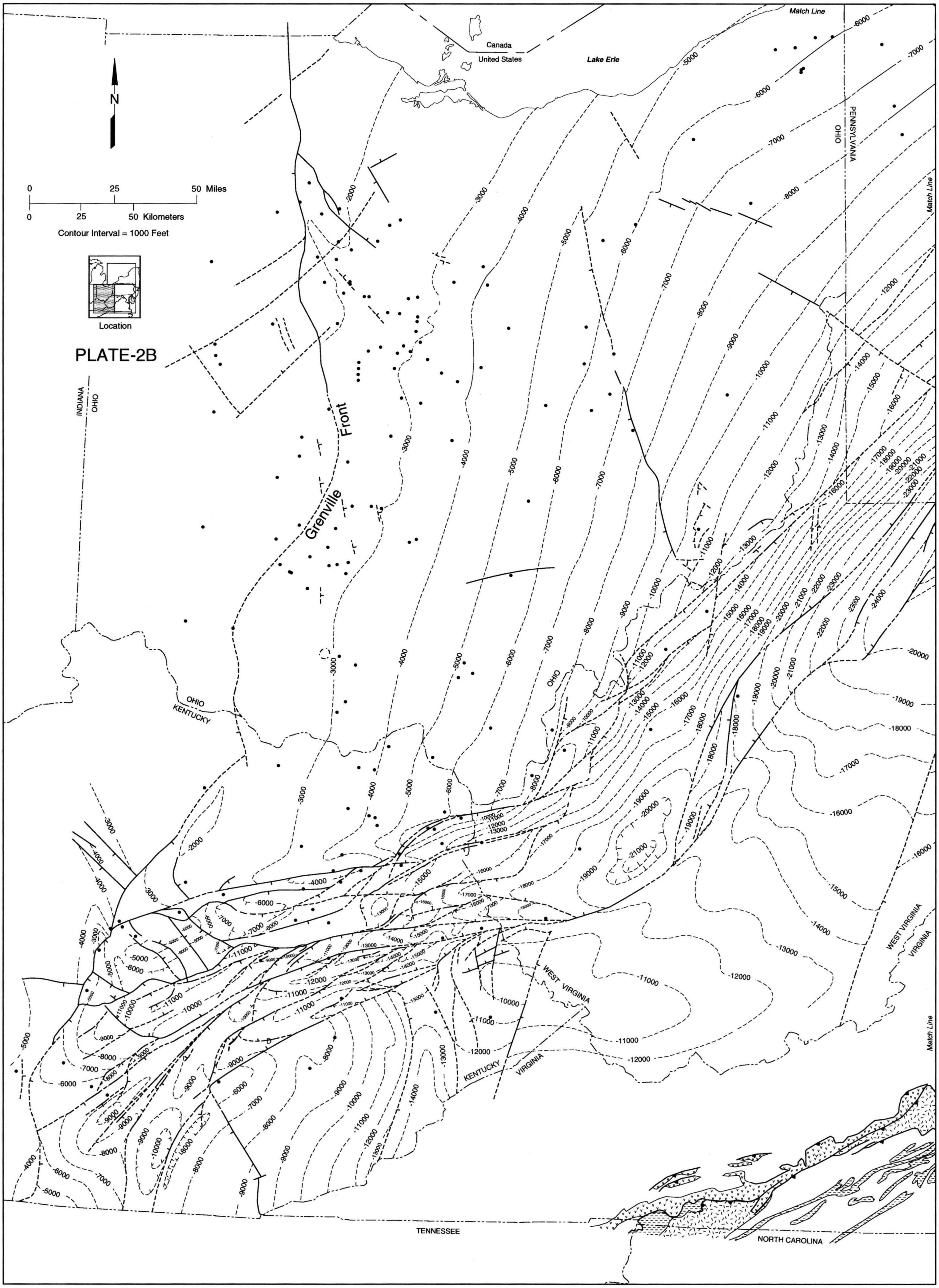
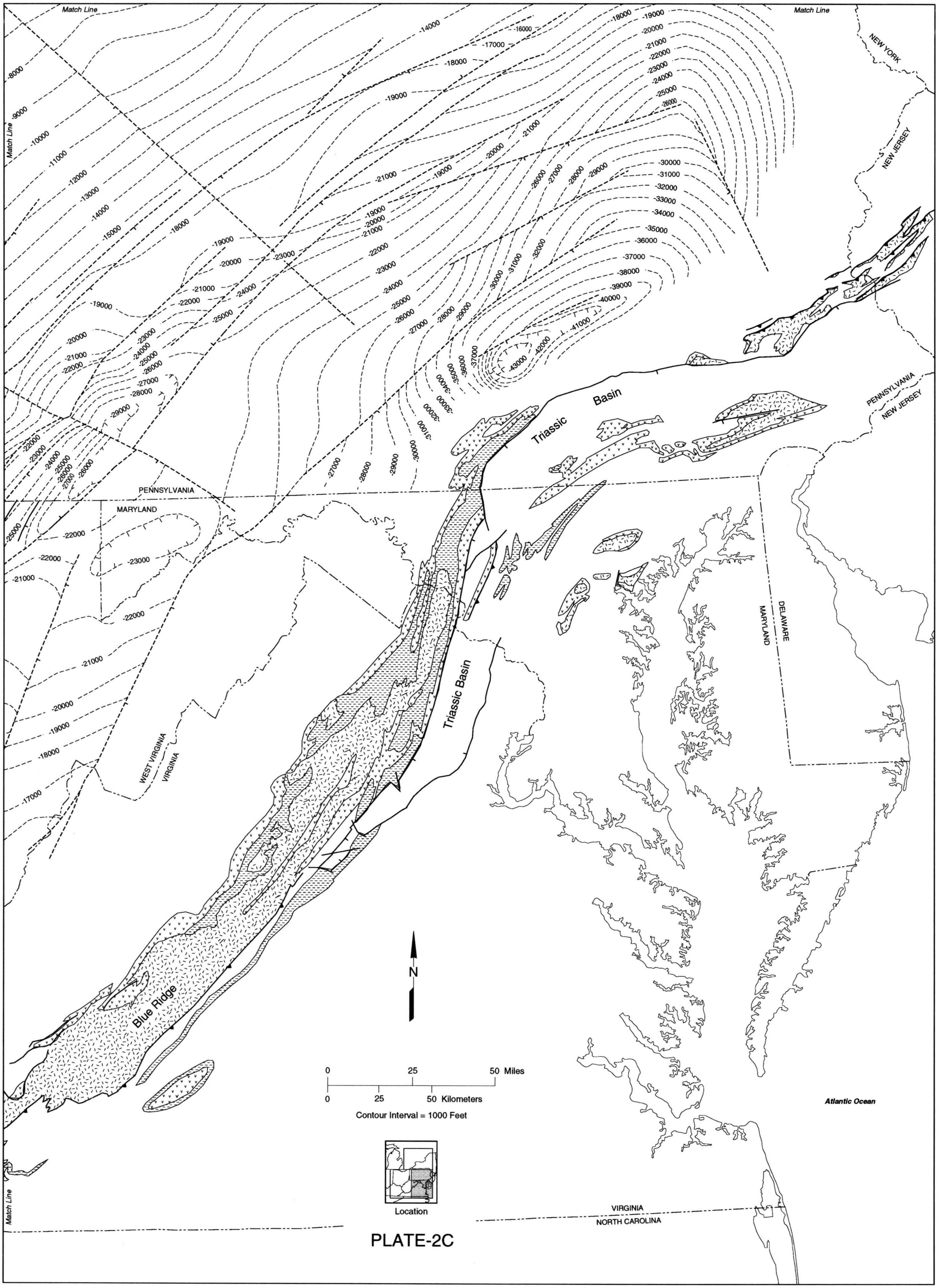


PLATE-2B
N
0 25 50 Miles
0 25 50 Kilometers
Contour Interval = 1000 Feet
Location
Canada
United States
Lake Erie
Match Line
PENNSYLVANIA
OHIO
INDIANA
OHIO
Grenville Front
OHIO
KENTUCKY
WEST VIRGINIA
KENTUCKY
VIRGINIA
WEST VIRGINIA
VIRGINIA
TENNESSEE
NORTH CAROLINA



Match Line
NEW YORK
NEW JERSEY
PENNSYLVANIA
NEW JERSEY
PENNSYLVANIA
MARYLAND
Triassic Basin
Triassic Basin
Blue Ridge
WEST VIRGINIA
VIRGINIA
DELAWARE
MARYLAND
Atlantic Ocean
VIRGINIA
NORTH CAROLINA
0 25 50 Miles
0 25 50 Kilometers
Contour Interval = 1000 Feet
Location

PLATE-2C

PLAY Paf: MIDDLE PENNSYLVANIAN ALLEGHENY FORMATION/GROUP SANDSTONE PLAY

by Michael Edward Hohn, West Virginia Geological and Economic Survey

Location

The Middle Pennsylvanian Allegheny Formation/Group play is characterized by shallow sandstone stratigraphic or structural traps, which are located in fluvial to fluvial-deltaic deposits in southwestern Pennsylvania, northwestern West Virginia, and eastern Ohio (Figures Paf-1, Paf-2).

Production History

The first well drilled specifically for petroleum in West Virginia was completed in 1860, and produced oil from the drillers' Burning Springs sand, correlated by Hennen (1911) with the Upper Freeport Sandstone of the Allegheny Formation (Figure Paf-3). The Allegheny Formation was probably first drilled for gas during the latter part of the nineteenth century. Since then, isolated wells and some small groups of wells have produced gas from several intervals within the Allegheny Formation. In many wells, gas was found in the course of drilling for deeper targets and production is sometimes commingled. Using the average cumulative production of 200 MMcfg for wells producing from fluvial-deltaic rocks of Pennsylvanian age, the estimated total production of gas from the 903 known completions in the Allegheny Formation/Group is 180.6 bcfg.

Stratigraphy

The Allegheny Formation/Group consists of interbedded sandstones, siltstones, shales, limestones, and coal beds lying between the top of the Upper Freeport coal bed, and the Homewood Sandstone/Formation of the underlying Pottsville Group (Figure Paf-3). In West Virginia, the Allegheny rocks are assigned the rank of formation, whereas in Ohio and Pennsylvania the Allegheny rocks have group status (Figure Paf-3). For general use here, the term Allegheny without rank designation is applied. Producing sandstones are the Upper Freeport Sandstone, Lower Freeport Sandstone, Kittanning Sandstone, and the Clarion Sandstone. The Allegheny is Middle Pennsylvanian in age.

Drillers have called producing units within the Allegheny the Burning Springs, the Gas sands, the Horseneck, the Macksburg 300- and 500-foot, and the Second Cow Run or Peeker. Within West Virginia, the Burning Springs was correlated by Hennen (1911) with the Upper Freeport Sandstone, which is just below the Upper Freeport coal. The Gas sands correlate with the Lower Freeport Sandstone (Hennen, 1911; Filer, 1985). The Horseneck, near the base of the Allegheny in West Virginia, apparently correlates with the Clarion Sandstone (Filer, 1985). In Pennsylvania, McGlade (1967) correlated an Upper Gas sandstone with the Freeport Sandstone, and Gas or First Gas sandstone with the Kittanning Sandstone, whereas Harper and Laughrey (1987) called the Freeport Sandstone, Kittanning Sandstone, and the Clarion Sandstone the First, Second, and Third Gas sands, respectively (Figure Paf-3). Alkire (1951) correlated the Second Cow Run or Peeker in Ohio with the Lower Freeport Sandstone, and the Macksburg 500-foot sand with the Clarion Sandstone. In some localities, the Upper Freeport Sandstone is called the Macksburg 300-foot, although this drillers' name most often is applied to the Mahoning Sandstone of the overlying Conemaugh Group (Alkire, 1951).

Freeport and Kittanning sandstones are massive, hard, and range from very fine- to fine-grained in Pennsylvania (McGlade, 1967), medium-coarse in Ohio (Alkire, 1951), to coarse-grained on outcrop in West Virginia (Hennen and Reger, 1913). The Clarion Sandstone is fine-grained and massive (Alkire, 1951).

Sandstones of the Allegheny were deposited in fluvial channels on an alluvial plain, upper delta plain, or lower delta plain (Ferm and Cavaroc, 1968; Flores and Arndt, 1979; Donaldson and Shumaker, 1981; Staub and Richards, 1993). Consisting of lenticular bodies, coalescing locally (Figure Paf-4), with sharp lower contacts and multiple internal scour surfaces, individual Allegheny sandstones show wide variation in thickness, between 0 and 75 feet in southwestern Pennsylvania (McGlade, 1967), and between 15 and 100 feet in West Virginia (Hennen and Reger, 1913). Facies changes from very fine-grained sandstone to thin-bedded sandstones, siltstones, and shales to silty shale occur over short lateral distances (McGlade, 1967). In parts of West Virginia, the Upper Freeport Sandstone merges with the overlying Mahoning Sandstone of the Conemaugh Group (Hennen, 1911). The high degree of discontinuity probably accounts for production coming from scattered wells rather than large, well-defined fields, despite the widespread prevalence of gas shows from Allegheny sandstones.

Structure

The Allegheny Formation/Group sandstone play is located in the central part of the Appalachian Plateau, in the foreland fold province in which Paleozoic rocks have been deformed into long, open folds, trending northeast to southwest. The amplitude of the folds in the eastern part of the play area is as much as 1,000 feet. Westward, to western West Virginia and eastern Ohio, the relief of the folds in the play area decreases to 100 feet or less. An exception to this is the Burning Springs anticline in Wood, Wirt, and Ritchie counties, West Virginia (Figure Paf-2). The anticline has an amplitude of about 1,600 feet and an approximate strike of north-south that is noticeably askew to the regional trend of the folds.

Reservoir

Early discoveries of gas in the Allegheny tended to occur on anticlines in Pennsylvania and West Virginia. More recent discovery of gas within synclines shows that production is influenced very little by structure in the shallow reservoirs of Pennsylvania (Harper and Laughrey, 1987). The lenticular nature of individual sandstones within the Allegheny suggests that the gas has accumulated in stratigraphic or combination traps. Probable sources of gas are the thick sequence of Devonian shales, ranging from mature to supermature, and

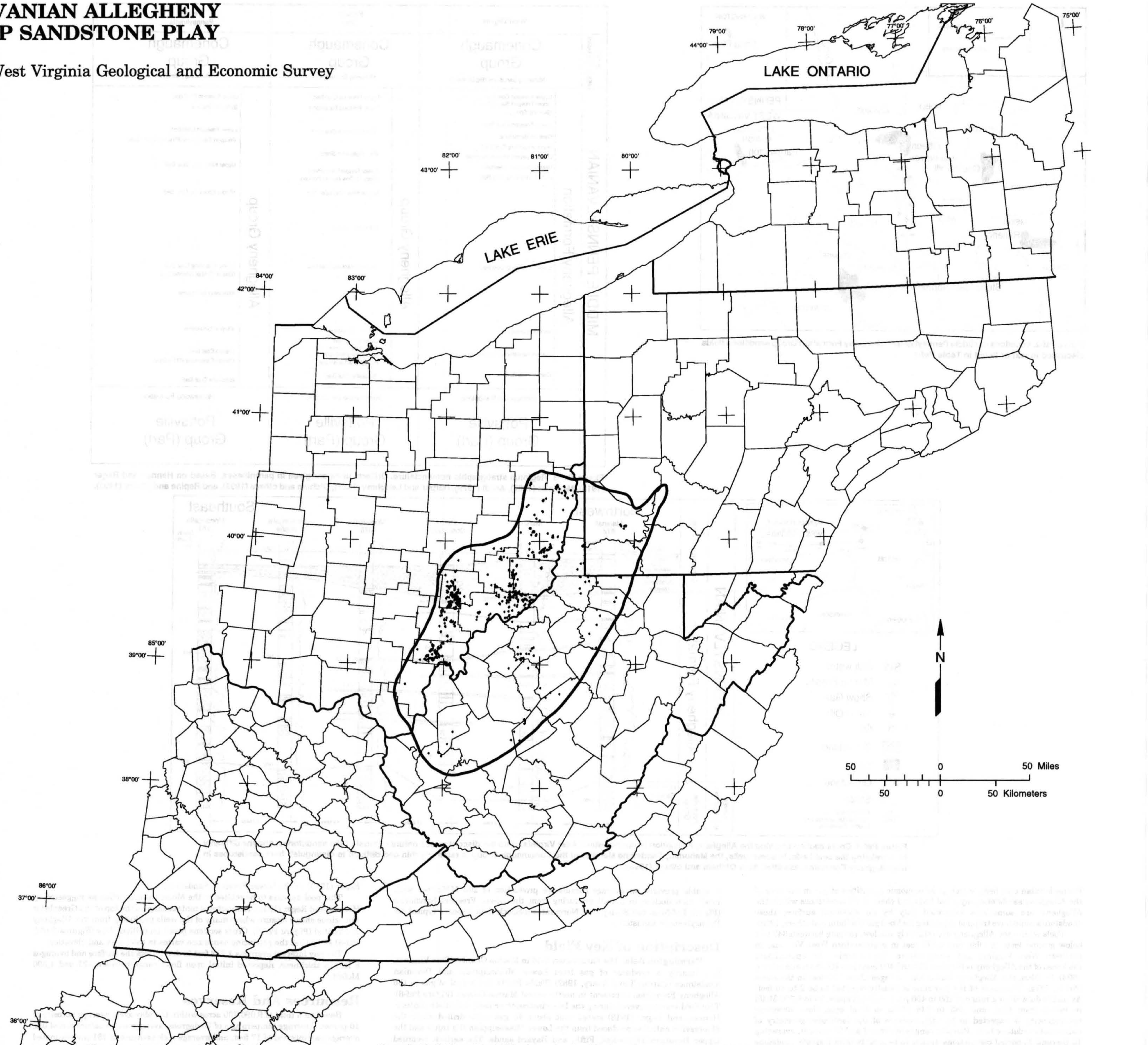


Figure Paf-1. Outline of the Middle Pennsylvanian Allegheny Formation/Group sandstone play within the Appalachian basin. Dots represent individual wells; areas where dots have merged represent fields.

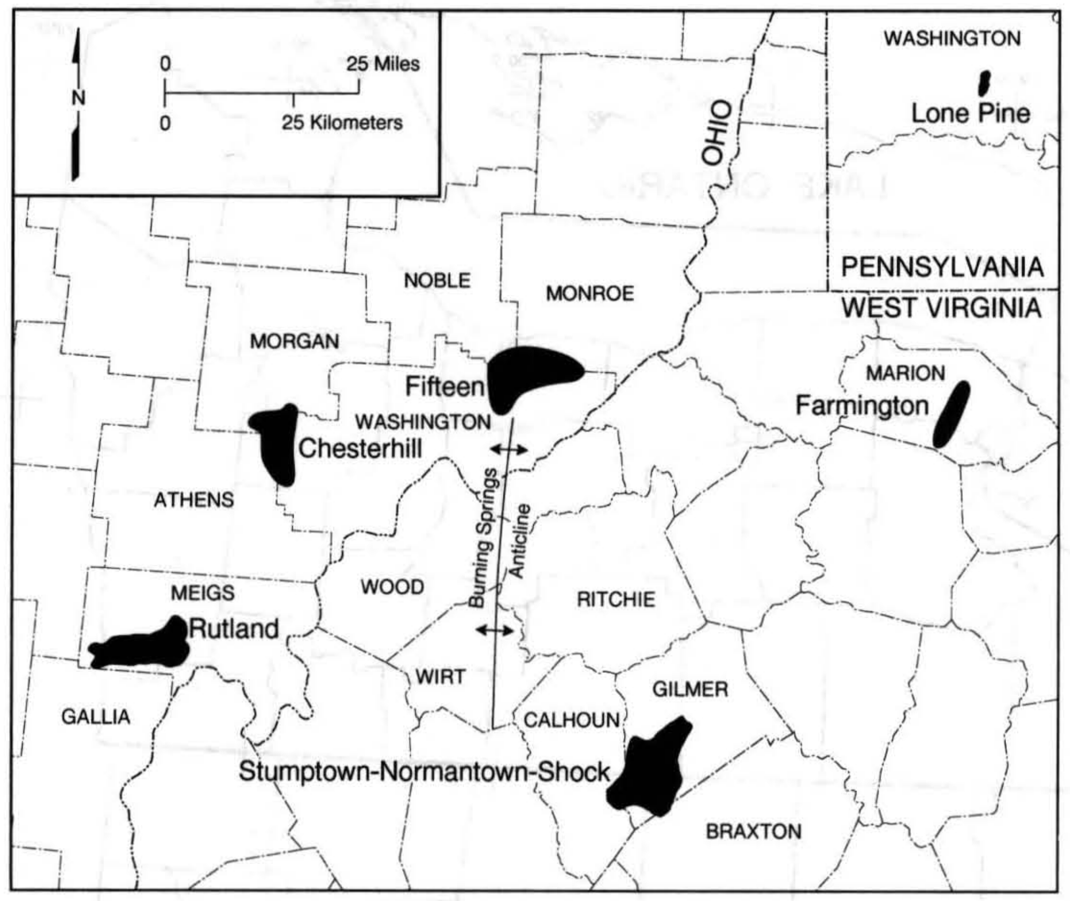


Figure Paf-2. Locations of Middle Pennsylvanian Allegheny Formation/Group sandstone fields discussed in text or listed in Table Paf-1.

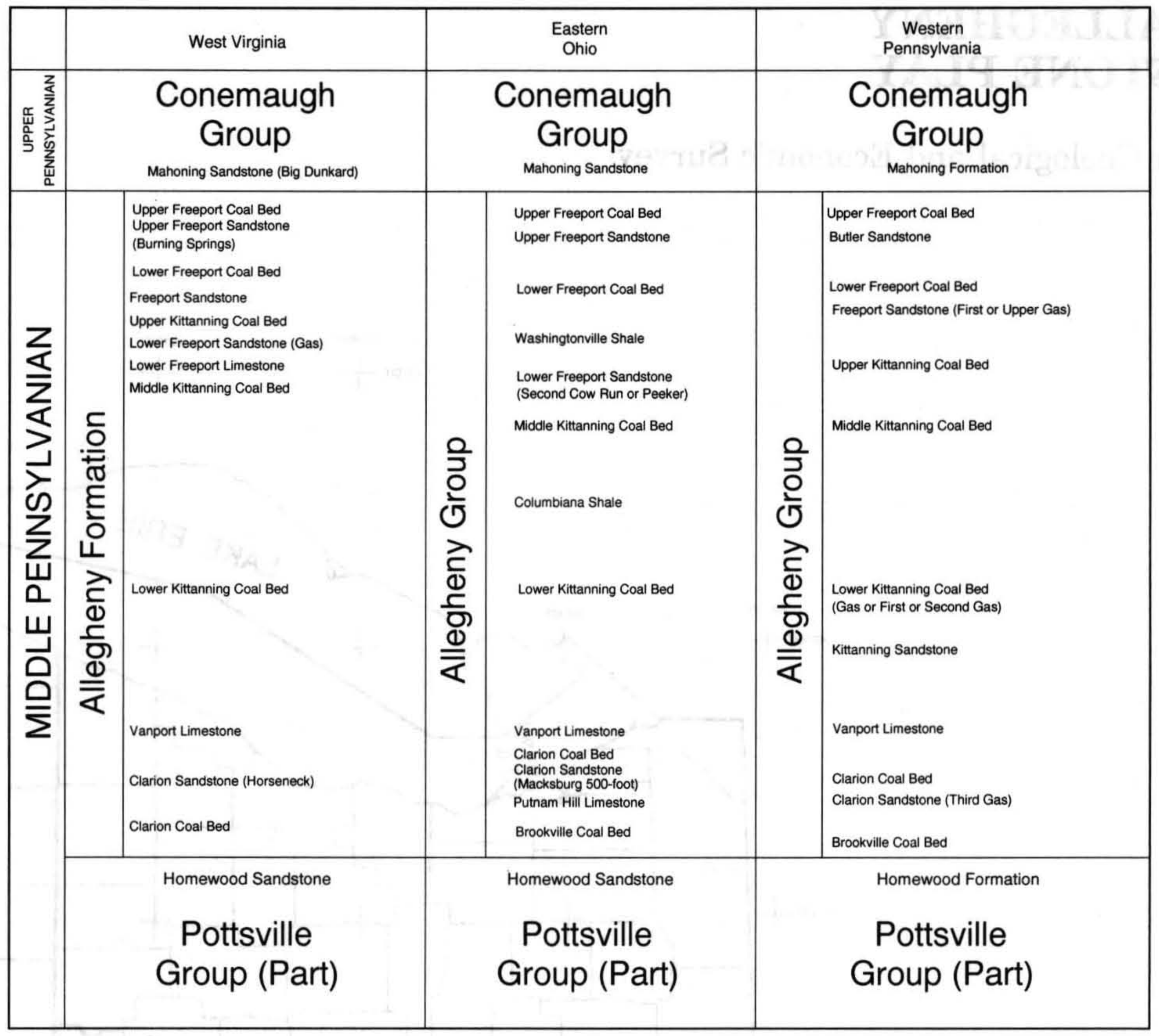


Figure Paf-3. Regional stratigraphic nomenclature. Drillers' units are given in parentheses. Based on Hennen and Reger (1913), McGlade (1967), Arndt (1979), Harper and Laughrey (1987), Oldham and others (1993), and Repine and others (1993).

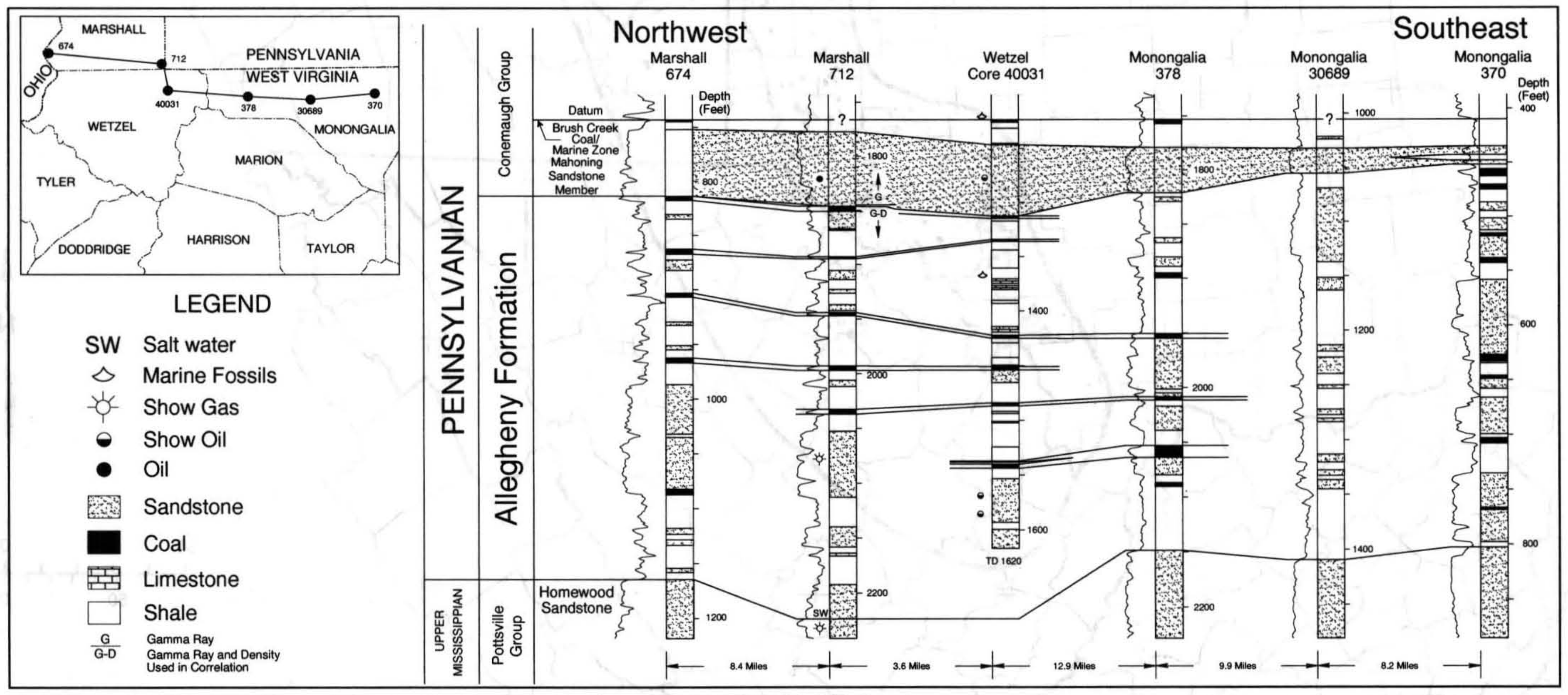


Figure Paf-4. Cross section showing the Allegheny Formation in northwestern West Virginia. Note the discontinuous nature of most of the sandstones, and the difficulty in correlating the coal beds. In some wells, the Mahoning Sandstone Member of the Conemaugh Group is relatively thin and difficult to distinguish from sandstones in the Allegheny Formation. Modified from Oldham and others (1993).

TABLE Paf-1		Rutland OH	Fifteen OH	Chesterhill OH	Lone Pine PA	Farmington WV
BASIC RESERVOIR DATA	POOL NUMBER	341050749	341670028	341150657	37904	47064
	DISCOVERED	1929	1905	1906		1906
	DEPTH TO TOP RESERVOIR	670	725	671		1,143
	AGE OF RESERVOIR	Middle Pennsylvanian	Middle Pennsylvanian	Middle Pennsylvanian	Middle Pennsylvanian	Middle Pennsylvanian
	FORMATION	Allegheny	Allegheny	Allegheny	Allegheny	Allegheny
	PRODUCING RESERVOIR	Allegheny	Allegheny	Allegheny	Gas Sand	Gas Sand
	LITHOLOGY	sandstone	sandstone	sandstone	sandstone	sandstone
	TRAP TYPE	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic
	DEPOSITIONAL ENVIRONMENT	fluvial-deltaic	fluvial-deltaic	fluvial-deltaic	fluvial-deltaic	fluvial-deltaic
	DISCOVERY WELL IP (Mcf)					
	DRIVE MECHANISM	gas cap	gas cap	gas cap	gas cap	water
	NO. PRODUCING WELLS	18	63	74		3
	NO. ABANDONED WELLS	48	3	64		20
	AREA (acreage)	50	294	129		27,554
	OLDEST FORMATION PENETRATED	Clinton	Pottsville	Pottsville	Upper Devonian	Upper Devonian
	EXPECTED HETEROGENEITY DUE TO:	deposition	deposition	deposition	deposition	deposition
RESERVOIR PARAMETERS	AVERAGE PAY THICKNESS (ft.)	27	17	25	39	9
	AVERAGE COMPLETION THICKNESS (ft.)					120
	AVERAGE POROSITY--LOG (%)					
	MINIMUM POROSITY--LOG (%)					
	MAXIMUM POROSITY--LOG (%)					
	NO. DATA POINTS					
	POROSITY FEET					
	RESERVOIR TEMPERATURE (°F)					
	INITIAL RESERVOIR PRESSURE (psi)	175		260	300	
	PRODUCING INTERVAL DEPTHS (ft.)	345-995	240-1,210	383-958		1,232-1,263
	PRESENT RESERVOIR PRESSURE (psi) / DATE					40/1986
FLUID & GAS PROPERTIES	Rw (Ωm)					0.5
	GAS GRAVITY (g/cc)					
	GAS SATURATION (%)					
	WATER SATURATION (%)					
	COMMINGLED	no	no	no		yes
	ASSOCIATED OR NONASSOCIATED	nonassociated		nonassociated		nonassociated
	Btu/scf					
VOLUMETRIC DATA	STATUS (producing, abandoned, storage)	producing	producing	producing	producing	producing
	ORIGINAL GAS IN PLACE (Mcf)					
	ORIGINAL GAS RESERVES (Mcf)					
	PRODUCTION YEARS	1930-1945		1930-1946		1979-1992
	REPORTED CUMULATIVE PRODUCTION (Mcf)	5,600,000	22,000	322,000		39,871
	NO. WELLS REPORTED	96	2	12		1
	ESTIMATED CUMULATIVE PRODUCTION (Mcf)	18,480,000	2,640,000	5,520,000		
	REMAINING GAS IN PLACE (Mcf)/DATE					
	REMAINING GAS RESERVES (Mcf)/DATE					
	RECOVERY FACTOR (%)	80	80	80		
	INITIAL OPEN FLOW (Mcf/d)	350	100	500	321	866
	FINAL OPEN FLOW (Mcf/d)					

Pennsylvanian coal beds, which yield economic quantities of gas in the area of the Allegheny sandstone play. Coal beds and channel-fill sandstones within the Allegheny are sometimes separated only by an erosional surface; these sandstones could have trapped migrating coal-bed gas (Oldham and others, 1993).

Pools within the Allegheny are relatively shallow, ranging between 347 feet below ground level in Ohio and 2,273 feet in northwestern West Virginia. In northern West Virginia and southwestern Pennsylvania, the approximate thickness of the Allegheny is between 200 and 400 feet thick (Oldham and others, 1993). In Ohio, the Allegheny Formation averages about 200 feet in thickness (Arkle, 1974). Thickness of the pay zone is usually reported to be 2 to 40 feet. Available data show a range of 260 to 400 psi in rock pressure, 70 to 8,500 Mcf/d in initial open flow, and 285 to 848 Mcf/d in final open flow. Reservoir heterogeneity is expected to be high because of the lenticular geometry of individual sandstone beds. Porosity ranges between 7 and 22 percent, averaging 10 percent. Reported completions appear to be mainly from a single sandstone interval within a given well. Most completions before the 1950s were open hole; most completions since have been nitrogen fractured. The little information available provides an average cumulative production of 200 MMcf per well. Production decline in a well producing from the Lower Freeport Sandstone (Figure Paf-5) in the Stumptown-Normantown-Shock field appears typical for Pennsylvanian sandstone.

Description of Key Field

Farmington field: The Farmington field in Marion County, West Virginia, is primarily a producer of gas from Lower Mississippian and Devonian sandstones (Cardwell and Avary, 1982) (Table Paf-1), but a pool of gas in the Allegheny Formation is present in north-central Marion County (Figure Paf-6). This field was discovered during the late nineteenth or early twentieth century. Hennen and Reger (1913) stated that about 40 gas wells drilled along the Mooresville anticline produced from the Lower Mississippian Big Injun and the Upper Devonian Thirty-foot, Fifth, and Bayard sands. The earliest recorded completion within the Allegheny Formation in this field was in 1906; since then, about 50 wells have been completed within an interval identified by Hennen and Reger (1913) as the Lower Freeport Sandstone.

This pool appears to be related to the Mooresville anticline as suggested by Hennen and Reger (1913). A structural contour map on the top of the Greenbrier Limestone shows closure where many of the wells producing from the Allegheny are located (Figure Paf-6). Cross sections based on drillers' logs (Figures Paf-7, Paf-8) show that the producing sandstone varies in thickness and elevation.

The pay interval averages 1,232 feet in depth from the surface and averages 8 feet in thickness. Reported initial open flows range between 431 and 1,300 Mcfg/d.

Resources And Reserves

Based on a total of 9,090,700 acres within the play area, average porosity of 10 percent, average temperature of 70 degrees, average water saturation of 0.5, average pay interval of 17 feet, and average rock pressure of 181 psi, estimated original gas in place equals 4.3 tcf. Subtracting known estimated production of .1806 tcf gives a remaining resource base of 4.1 tcf.

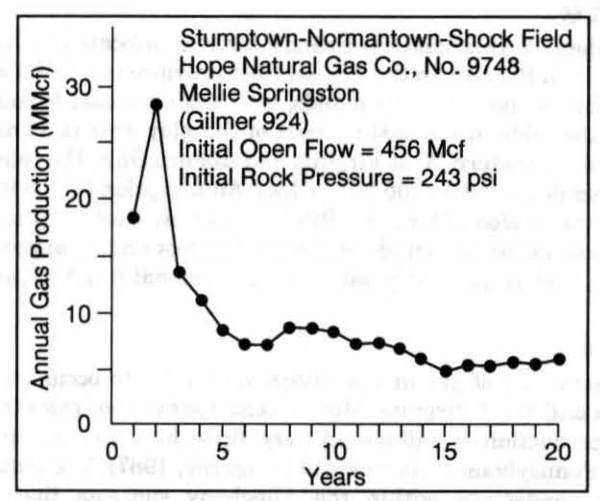


Figure Paf-5. Decline curve for a well completed in the Lower Freeport Sandstone in 1952.

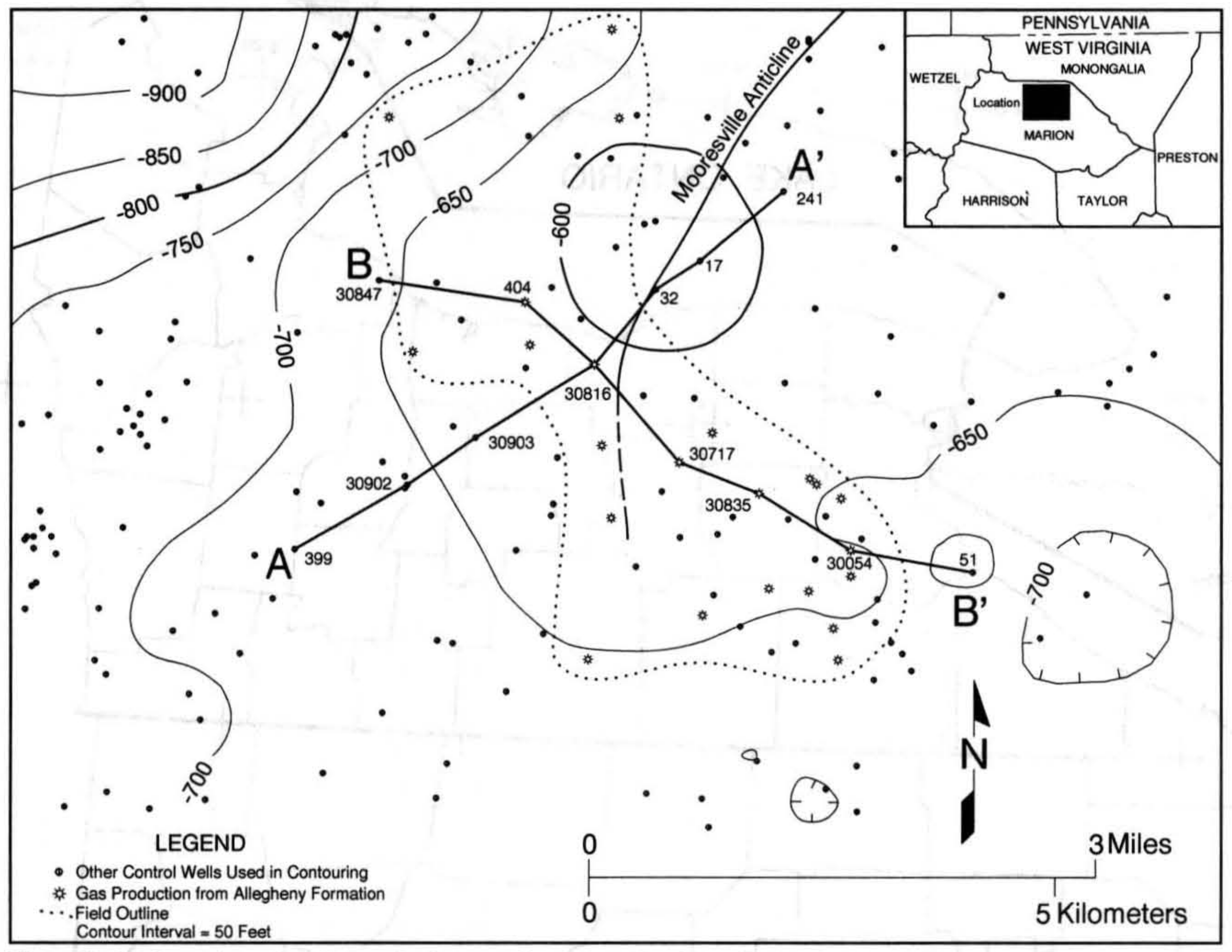


Figure Paf-6. Location of wells producing gas from the Allegheny Formation in the Farmington field of central Marion County, West Virginia. Also shown are wells penetrating the Allegheny Formation. Contours represent the base of the Greenbrier Limestone (Upper Mississippian) to show the relationship between Allegheny production and the Mooresville anticline. Lines of cross sections A-A' and B-B' (Figures Paf-7, Paf-8) are also shown.

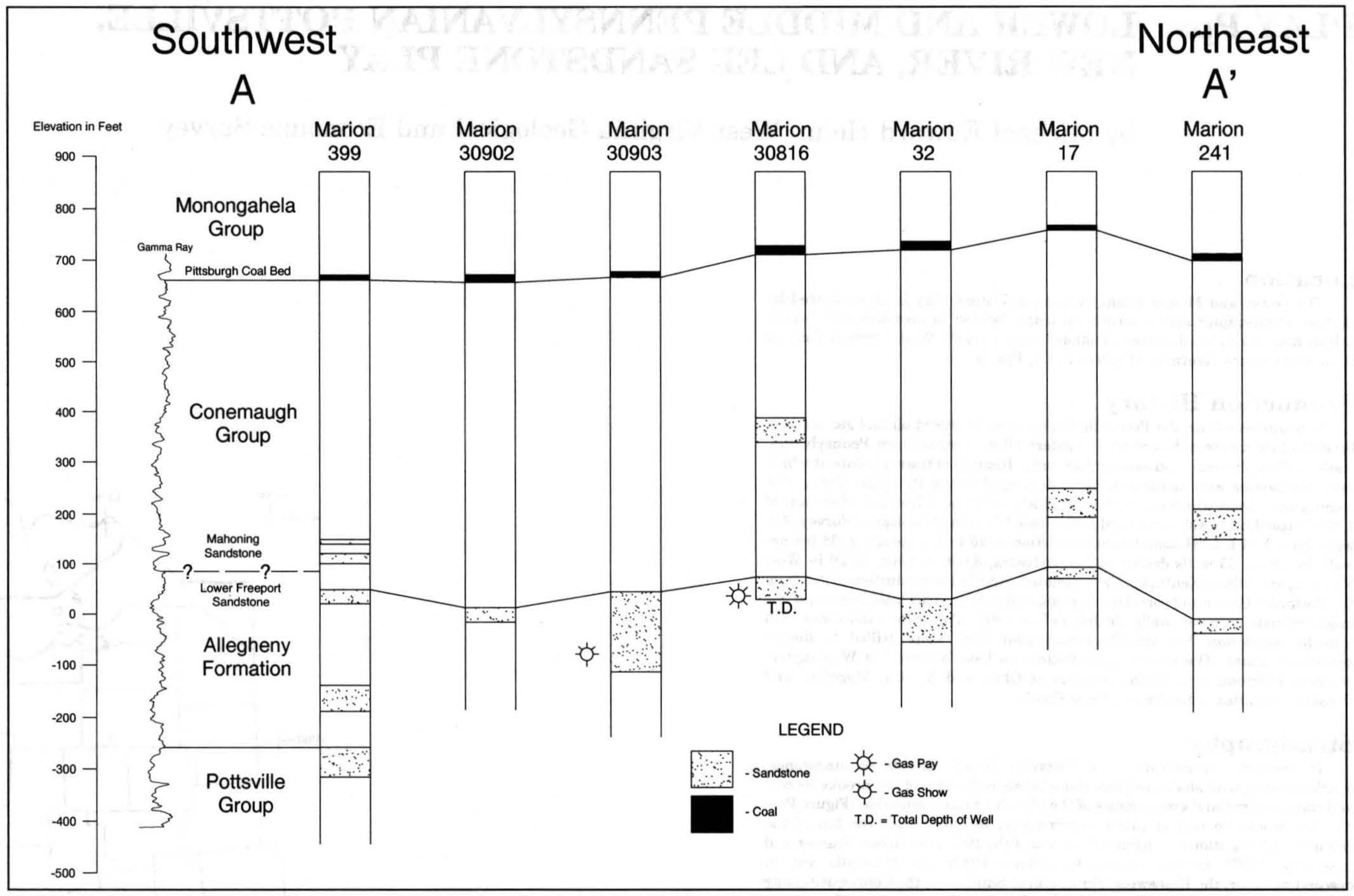


Figure Paf-7. Cross section A-A' of a gas pool producing from the Lower Freeport Sandstone of the Allegheny Formation in central Marion County, West Virginia. Location of cross section is shown in Figure Paf-6. Well designations are indicated by West Virginia county name and state permit number.

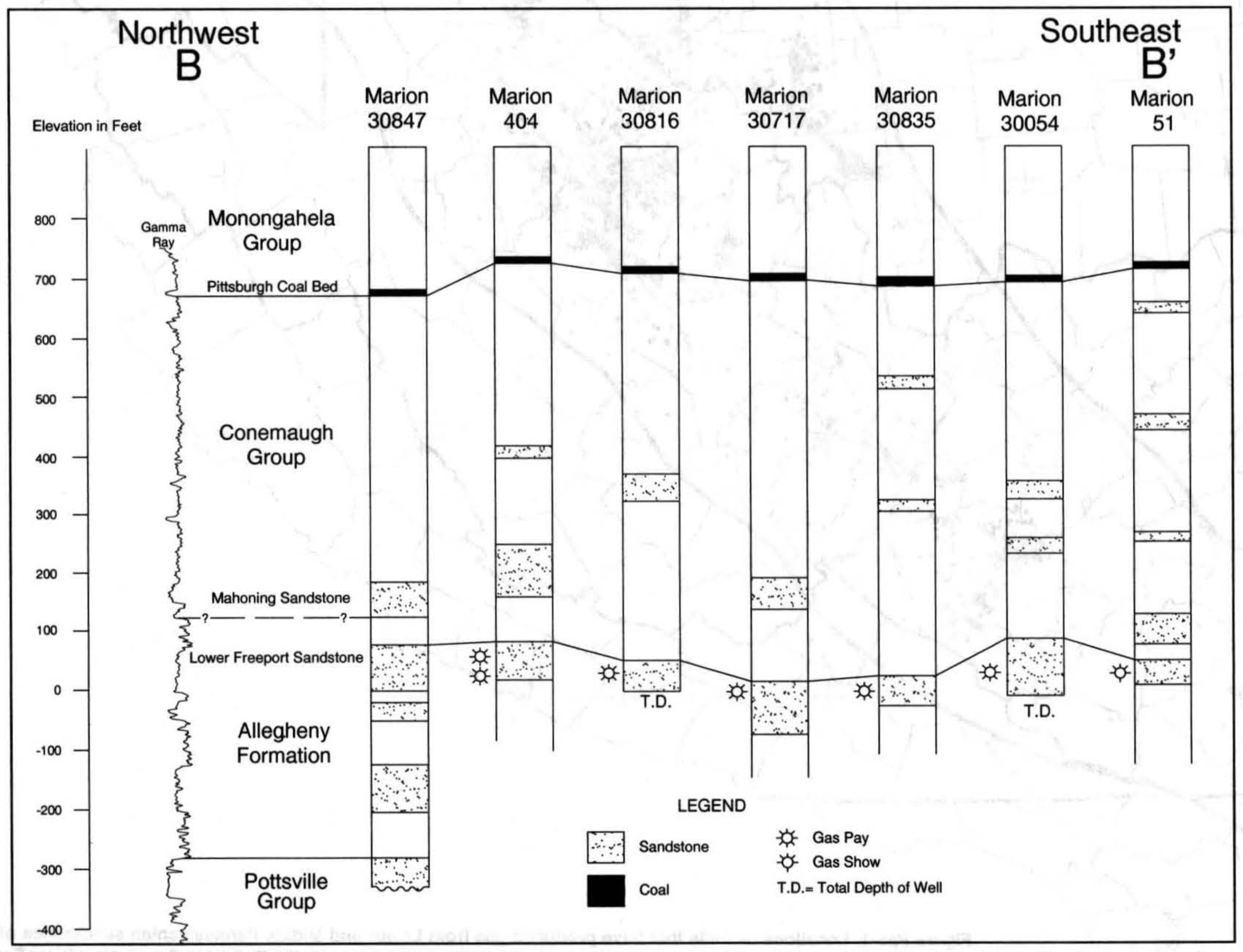


Figure Paf-8. Cross section B-B' of a gas pool producing from the Lower Freeport Sandstone of the Allegheny Formation in central Marion County, West Virginia. Location of cross section is shown in Figure Paf-6. Well designations are indicated by West Virginia county name and state permit number.

Future Trends

Small but economic reserves probably are still to be found in sandstones of the Allegheny Formation/Group. Several authors have cited the frequency of gas shows from Allegheny sandstones in Pennsylvania (McGlade, 1967), West Virginia (Hennen, 1911), and Ohio (Alkire, 1951). McGlade (1967) points out that limited gas production in southwestern Pennsylvania predates modern stimulation and completion methods. Observing that initial potentials from the Kittanning Sandstone average about 250 Mcf/d, Harper and Laughrey (1987) suggested that the Allegheny should be evaluated more closely as a shallow source of gas.

An important future trend could be the production of coal-bed methane from the Allegheny and younger formations. Production has been reported from the Lower Freeport, Kittanning, and Clarion coal beds in southwestern Pennsylvania (Oldham and others, 1993). Most coal-bed gas has been produced from the Pittsburgh coal bed of the Monongahela Group, but the Allegheny coals are thought to be a better prospect because of their higher rank and greater gas content (Kelafant and others, 1988). Gas contents average between 200 and 250 scf/T for coals in the Allegheny Formation, compared with 100 to 150 scf/T for the Pittsburgh coal (Markowski, 1995). Coal beds within the Allegheny Formation/Group, Conemaugh Group, and Monongahela Group contain an estimated total of 0.7 to 7.4 tcfg in southwestern Pennsylvania and northern West Virginia (Markowski, 1995). Kelafant and others (1988) estimated 50.5 tcf gas in place for Allegheny coal beds out of an estimated 61 tcf for all coals in the northern Appalachian coal basin, which includes parts of southwestern Pennsylvania, northwestern West Virginia, and eastern Ohio. In places, coal beds and channel-fill sandstones of the Allegheny are separated only by an erosional surface, suggesting that these sandstones could be traps for coal-bed gas (Oldham and others, 1993). Interest in coal-bed methane from the Allegheny Formation/Group has been limited somewhat by the laterally discontinuous nature of the coal beds.

PLAY Pps: LOWER AND MIDDLE PENNSYLVANIAN POTTSVILLE, NEW RIVER, AND LEE SANDSTONE PLAY

by Michael Edward Hohn, West Virginia Geological and Economic Survey

Location

The Lower and Middle Pennsylvanian sandstone play is characterized by shallow stratigraphic and/or structural traps, located in near-shore or fluvial-deltaic deposits in southwestern Pennsylvania, western West Virginia, eastern Ohio, and eastern Kentucky (Figures Pps-1, Pps-2).

Production History

Sandstones within the Pottsville Group have produced oil and gas since at least the late nineteenth century in eastern Ohio, southwestern Pennsylvania, western West Virginia, and eastern Kentucky. Because of the early date at which most discoveries were made and fields developed in the Pottsville Group, few records exist from which cumulative production can be calculated. However, of 1,136 Pottsville gas wells on record at the Ohio Division of Geological Survey, 250 wells have had a total cumulative production of 20 bcfg, averaging .08 bcf per well. Based on 33 wells drilled in Pennsylvania, 3,666 in Ohio, 2,029 in West Virginia, and 468 in Kentucky, the estimated cumulative production of gas from the Pottsville Group and correlatives is about 500 bcfg. This total leaves out the indeterminate number wells drilled before 1900. Pottsville sandstones still provide production, but usually commingled from wells drilled to deeper production zones. The newest pool discoveries have occurred in Washington, Monroe, Belmont, and Gallia counties of Ohio, and Martin, Magoffin, and Breathitt counties of Kentucky (Table Pps-1).

Stratigraphy

In western Pennsylvania, the Pottsville Group consists of sandstones, conglomerates, coal, shale, and limestone between the base of the Brookville coal and the top of red and green shales of the Mauch Chunk Formation (Figure Pps-3). The Brookville coal is rarely recognizable, in which case the top of the Homewood Formation is considered the top of the Pottsville Group (Harper and Laughrey, 1987). In this region, formations within the Pottsville are, in descending order, the Homewood Formation or Sandstone, the Connoquenessing Formation, and the Sharon Formation. Sandstones in the upper two formations can range from coarse-grained sandstones or conglomerates at the base to fine-grained siltstone and shale at the top (Meckel, 1967). The Connoquenessing Formation consists of two sandstones, the Upper and Lower Connoquenessing. The Sharon Formation includes the Sharon Conglomerate, restricted to northwestern Pennsylvania. In Ohio, the Massillon and Sharon sandstones are quartz arenites that correlate with the Connoquenessing and Sharon formations of Pennsylvania (Alkire, 1951). The Pottsville Group in northern West Virginia is generally undifferentiated (Patchen and others, 1985a), although names such as the Homewood Sandstone and Connoquenessing are used. In addition to sandstones, the Pottsville Group in northern West Virginia includes coals and shales. Further south and west, correlatives of the Pottsville are the Kanawha, New River, and Pocahontas formations in West Virginia, and the Breathitt (in part) and Lee formations in Kentucky (Figure Pps-3). The stratigraphic relationship showing the thickness variations and nature of the sandstones of Lower and Middle Pennsylvanian age is illustrated in a regional cross section through the producing areas of eastern and central West Virginia (Figure Pps-4). The Kanawha Formation is a sequence of sandstones, siltstones, shales, mudstones, and coals, with siderite, limestone, and flint clay (Blake, 1992). Arndt (1979) placed the upper boundary at the top of the Kanawha Black Flint and the lower boundary at the base of the Lower Douglas coal bed. The proportion of sandstone to shale increases upward within the Kanawha Formation. The lowest informal member (Figure Pps-5) thins and disappears from south to north in West Virginia (Blake, 1992). The Lee and equivalent New River are dominated by massive quartz arenites, and lithic arenites in southeastern West Virginia. Minor constituents include siltstones, shales, mudstones, and coals. This interval is thickest in southeastern West Virginia, thins to the north and west, and is absent in northern West Virginia. At the base of the Pottsville Group, the New River Formation, and the Lee Formation is an important Mississippian-Pennsylvanian disconformity in the Appalachian basin that is key in published debates over the origin of the basal quartz arenites of the Pennsylvanian (Englund, 1979). The Pocahontas Formation underlies the New River Formation in southeastern West Virginia, but is very thin or absent in the areas of gas production.

Drillers have used a number of names for producing units in the Lower and Middle Pennsylvanian sandstone play. In Pennsylvania, sandstones of the Pottsville Group are generally called the First, Second, and Third Salt, the first correlating with the Homewood Sandstone, and the second and third with sandstones of the Connoquenessing Formation (McGlade, 1967). These sandstones, the drillers' Salt sands, were named for their brine content. In Ohio, these sandstones occur in uppermost Lower and in Middle Pennsylvanian rocks. The Salt or First Salt refers to the Massillon Sandstone. The drillers' Maxton sandstone in Ohio is the basal Sharon Conglomerate. The Macksburg 700-foot has limited geographic extent and uncertain stratigraphic position in the upper part of the Pottsville Group, and has been given a number of additional names by drillers in Ohio, such as Macksburg stray, First Germantown, Macksburg 800-foot, Second Germantown, First Salt, Brill, and Schramm (Alkire, 1951). Drillers in West Virginia often apply the name Second Cow Run to both the Homewood and sandstones within the overlying Allegheny Formation (Hennen, 1911; Filer, 1985). In northern West Virginia, Early Pennsylvanian-age rocks are thin or absent, and the drillers' Salt is largely or entirely Middle Pennsylvanian in age. Up to three of these sandstones may be recognized by drillers: the First Salt, correlating with the Homewood; the Second Salt, correlating with the Upper

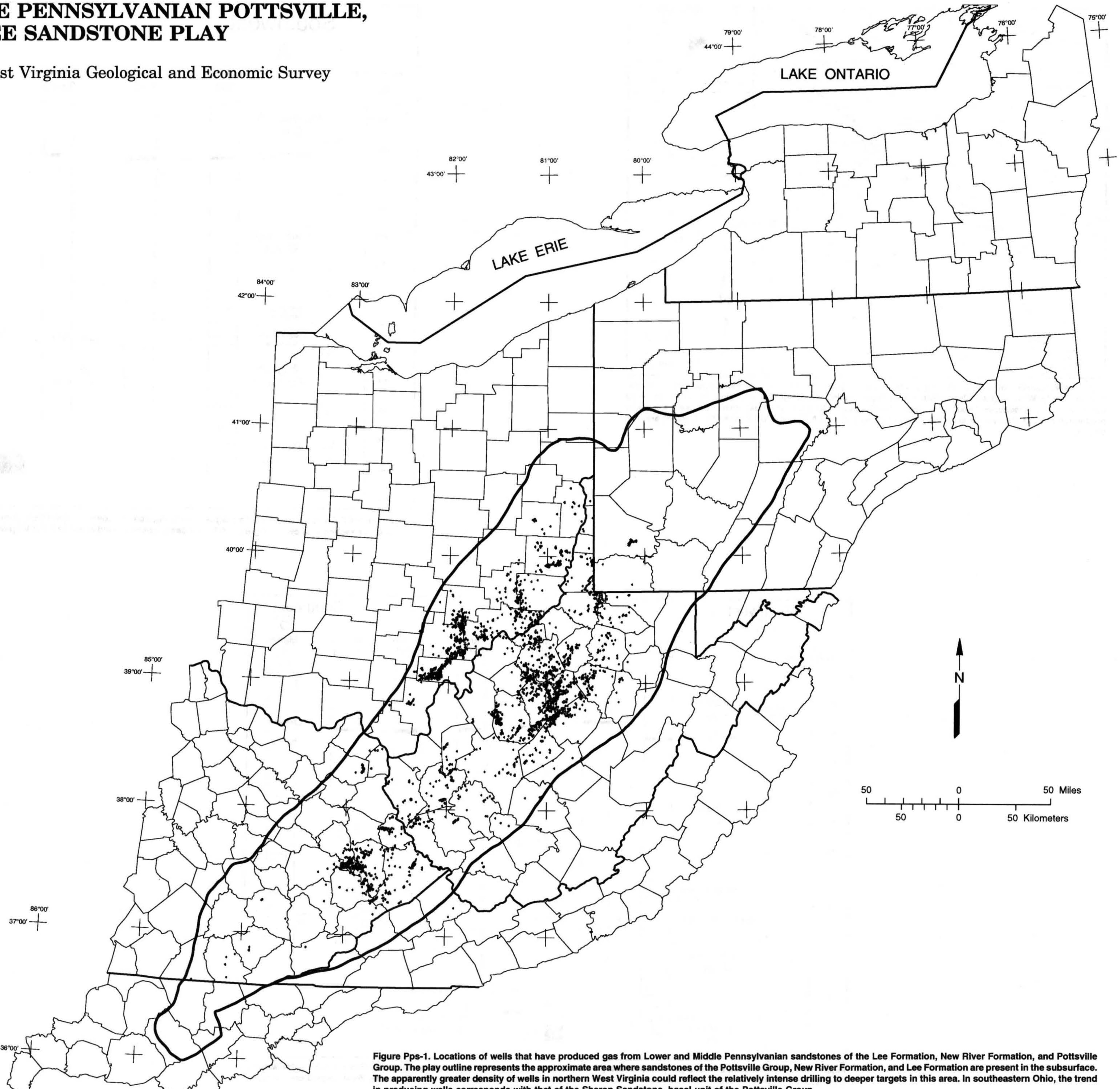


Figure Pps-1. Locations of wells that have produced gas from Lower and Middle Pennsylvanian sandstones of the Lee Formation, New River Formation, and Pottsville Group. The play outline represents the approximate area where sandstones of the Pottsville Group, New River Formation, and Lee Formation are present in the subsurface. The apparently greater density of wells in northern West Virginia could reflect the relatively intense drilling to deeper targets in this area. In southeastern Ohio, the trend in producing wells corresponds with that of the Sharon Sandstone, basal unit of the Pottsville Group.

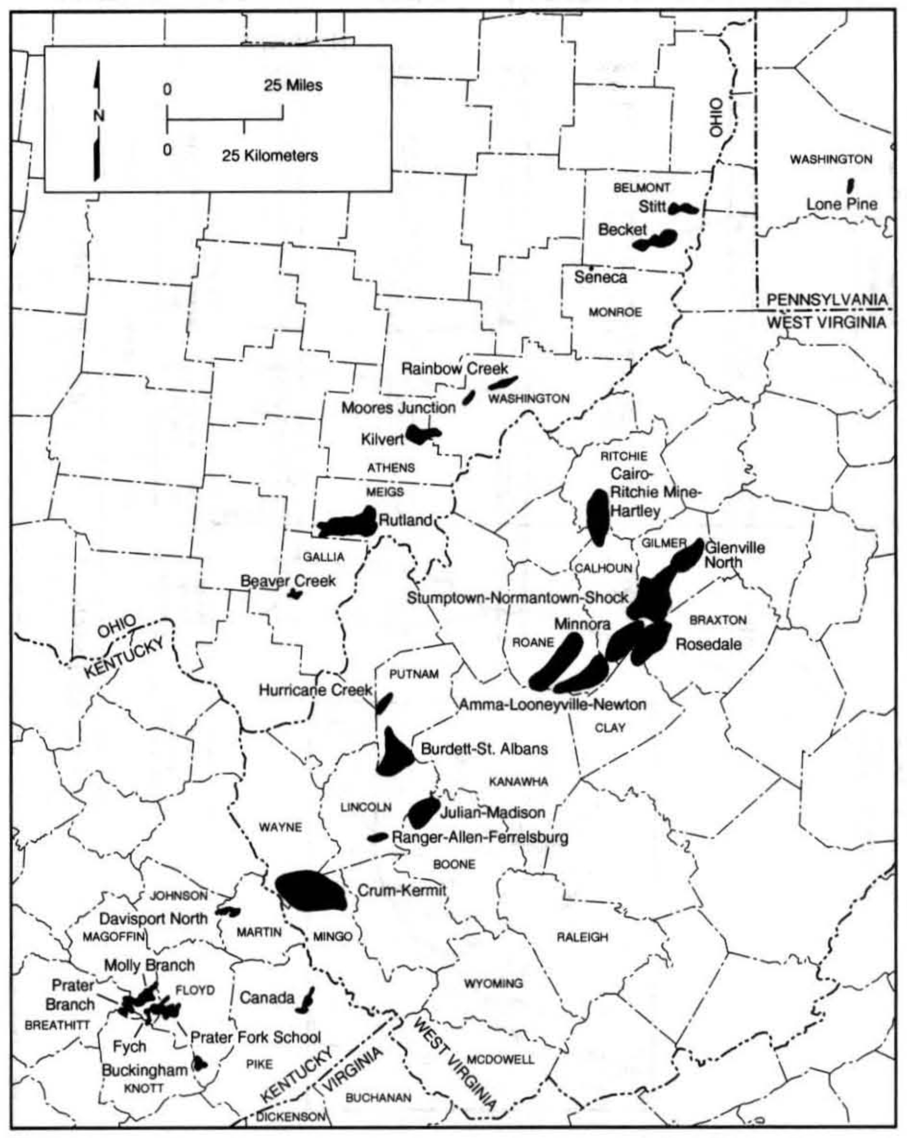


Figure Pps-2. Locations of Lower and Middle Pennsylvanian fields discussed in text or listed in Table Pps-1. Other productive areas illustrated in Figure Pps-1 are not shown.

Connoquenessing Sandstone; and the Third Salt, correlating with the Lower Connoquenessing Sandstone. Unfortunately, the lenticular nature of these sandstones (Figure Pps-6) means that drillers' terms were probably inconsistently applied, and in some cases, refer to sandstones in the Allegheny Formation (Oldham and others, 1993). Units within the Lee Formation in Kentucky and the New River Formation in southern West Virginia have been referred to as Salt. Alternate names for the Salt in Kentucky are the Beaver, Horton, and Pike in Floyd and Knott counties, and the Wages, Jones, and Epperson in Knox County (McFarlan, 1943).

The contact of the Pottsville Group with the overlying Allegheny Formation is often difficult to determine from geophysical logs in northern West Virginia, southwestern Pennsylvania, and eastern Ohio because of the lenticular nature of sandstones in both formations. Within Ohio, paying sandstones can be identified as Pottsville only by determining their position relative to known coal beds and marine limestones that can be correlated over county-wide areas (Figure Pps-7). For instance, the only drillers' unit used in Ohio that can be reliably correlated with a unit within the Pottsville is the Maxton or the drillers' Lower Pennsylvanian sand. In Pennsylvania and much of West Virginia, the Pottsville Group overlies the Mauch Chunk Formation. In western West Virginia and southeastern Ohio, erosion associated with the disconformity results in the Pottsville Group lying directly on the Upper Mississippian Greenbrier Limestone, or the Lower Mississippian Price Formation. Basal sandstones of the Pottsville can be confused with Lower and Upper Mississippian sandstones. Drillers' units are difficult to correlate from well to well in Ohio, western Pennsylvania, and northern West Virginia, even within fields. Names such as First, Second, and Third Salt may have little more than local (within-field) significance.

Regardless of age or formation, the gas-producing sandstones of this play are hard, massive, gray to white in color and, in places, soft and friable. Producing sandstones consist of one or more massive quartz arenites separated by gray to black silty shales, siltstones, sandstones, or thin coals.

The depositional environment of the Lower and Middle Pennsylvanian sandstones is under debate. A fluvial model interprets the quartz arenites as deltaic and alluvial deposits (summarized by Rice, 1984; Chesnut, 1988; Rice and Schwietering, 1988; Beuthin, 1989) deposited by rivers flowing from north-northeast. The barrier-bar model views Mississippian and Pennsylvanian clastics as part of a continuum of facies in which quartz arenites represent barrier island complexes (Ferm, 1974; Ferm and Weisenfluh, 1989). Both models attempt to explain the widespread quartz arenites that contrast with lithic arenites comprising much of the Pennsylvanian sediments. The fluvial-deltaic model proposes a cratonic source for these clean sandstones, as opposed to an eastern source for the lithic arenites. The barrier-bar model describes the quartz arenites as the result of winnowing of fluvial-deltaic lithic arenites. Studies of individual sandstones within the Lower and Middle Pennsylvanian, recognition of a widespread Mississippian-Pennsylvanian disconformity, and biostratigraphy (Meckel, 1967; Houseknecht, 1980; Rice, 1984; Chesnut, 1988; Beuthin, 1989) tend to support the fluvial model. Sandstones deposited in both fluvial-deltaic and barrier-bar environments can display a high degree of reservoir heterogeneity, including discontinuities in the same reservoir between wells, and multiple, discrete pay zones (Galloway and Hobday, 1983).

TABLE Pps-1

		Stumptown-Normantown-Shock WV	Rosedale WV	Amma-Looneyville-Newton WV	Cairo-Ritchie Mine-Hartley WV	Crum-Kermit WV	Glenville North WV	Ranger-Allen-Ferrellsburg WV	Lone Pine PA	Canada Dist. Big Sandy KY
BASIC RESERVOIR DATA	POOL NUMBER	47180	47202	47198	47120	47243	47182	47275	37904	1600347
	DISCOVERED	1901	1901	1908	1890		1892			1931
	DEPTH TO TOP RESERVOIR (ft)	1,430	1,630	1,320	1,600	1,030	1,210	724	1,436	1,280
	AGE OF RESERVOIR	Pennsylvanian	Pennsylvanian	Pennsylvanian	Pennsylvanian	Pennsylvanian	Pennsylvanian	Pennsylvanian	Pennsylvanian	Pennsylvanian
	FORMATION	Pottsville	Pottsville	Pottsville	Pottsville	New River	Pottsville	New River	Pottsville	Lee
	PRODUCING RESERVOIR	Salt sands	Salt sands	Salt sands	Salt sands	Salt sands	Salt sands	Salt sands	Salt sands	Lee
	LITHOLOGY	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone
	TRAP TYPE	structural/ stratigraphic	structural/ stratigraphic	structural/ stratigraphic	structural/ stratigraphic	structural/ stratigraphic	structural/ stratigraphic	structural/ stratigraphic	structural	stratigraphic
	DEPOSITIONAL ENVIRONMENT	fluvial-deltaic	fluvial-deltaic	fluvial-deltaic	fluvial-deltaic	fluvial-deltaic	fluvial-deltaic	fluvial-deltaic	fluvial-deltaic	fluvial-deltaic
	DISCOVERY WELL IP (Mcf)			1,165						789
	DRIVE MECHANISM	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion
	NO. PRODUCING WELLS	62	52	31	21	30	21	12		22
	NO. ABANDONED WELLS	30	18	26	23	10	22	15		0
	AREA (acreage)									3,963
	OLDEST FORMATION PENETRATED	Devonian Shale	Devonian Shale	Upper Devonian	Upper Devonian	Devonian Shales	Alexander (Upper Devonian)	Onondaga Limestone	Upper Devonian	Ohio
	EXPECTED HETEROGENEITY DUE TO:	deposition	deposition	deposition	deposition	deposition	deposition	deposition	deposition	deposition
RESERVOIR PARAMETERS	AVERAGE PAY THICKNESS (ft.)	26	19	11	79	25	15	26	8	22
	AVERAGE COMPLETION THICKNESS (ft.)	26	19	11	79	25	15	26		46
	AVERAGE POROSITY–LOG (%)									11
	MINIMUM POROSITY–LOG (%)									6
	MAXIMUM POROSITY–LOG (%)									13
	NO. DATA POINTS									2
	POROSITY FEET									2.42
	RESERVOIR TEMPERATURE (°F)									72
	INITIAL RESERVOIR PRESSURE (psi)	405	560	410	450	300	360	440	222	700
	PRODUCING INTERVAL DEPTHS (ft.)	868-2,038	1,122-1,952	957-1,958	1,104-1,945	560-1,655	992-1,654	428-1,424		
	PRESENT RESERVOIR PRESSURE (psi) / DATE		65		160					180/1992
FLUID & GAS PROPERTIES	Rw (Ωm)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.06
	GAS GRAVITY (g/cc)									
	GAS SATURATION (%)									87
	WATER SATURATION (%)									13
	COMMINGLED	yes	yes	yes	yes	yes	yes	yes	yes	yes
	ASSOCIATED OR NONASSOCIATED	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated
	Btu/scf									
VOLUMETRIC DATA	STATUS (producing, abandoned, storage)	producing	producing	producing	producing	producing	producing	producing	producing	producing
	ORIGINAL GAS IN PLACE (Mcf)									
	ORIGINAL GAS RESERVES (Mcf)									
	PRODUCTION YEARS	1979-1992	1981-1992	1930-1993	1951-1993	1951-1992	1983	1948-1993		
	ACTUAL CUMULATIVE PRODUCTION (Mcf)	169,077	87,795	525,400	574,800	559,432	2,960	316,600		
	NO. DATA POINTS	5	5	17	18	13	6	9		
	ESTIMATED CUMULATIVE PRODUCTION (Mcf)									
	REMAINING GAS IN PLACE (Mcf)/YEAR									
	REMAINING GAS RESERVES (Mcf)/YEAR									
	RECOVERY FACTOR (%)									
	INITIAL OPEN FLOW (Mcf/d)	534	514	1,120	253	1,075	388	916	728	
	FINAL OPEN FLOW (Mcf/d)	422	437	416	214	479	543	1,451		784

		Fych Dist. Big Sandy KY	Molly Branch Sch. Dist. Big Sandy KY	Davisport North Dist. Big Sandy KY	Prater Fork Sch. Dist. Big Sandy KY	Buckingham Dist. Big Sandy KY	Prater Branch Dist. Big Sandy KY	Kilvert OH	Becket OH	Rutland OH	Rainbow Creek OH	Moores Junction OH	Seneca OH	Stitt OH
BASIC RESERVOIR DATA	POOL NUMBER	1600750	1601329	1600533	1601581	1600288	1601580	340090696	340130118	3401050749	341670012	341670691	341110083	340130147
	DISCOVERED	1925	1925	1912	1921	1925	1984	1909	1909	1927	1962	1962	1979	1924
	DEPTH TO TOP RESERVOIR (ft)	1,100	850	553	661	1,300	1,250	800	1,225	800	1,054	1,097	1,172	1,150
	AGE OF RESERVOIR	Pennsylvanian	Pennsylvanian	Pennsylvanian	Pennsylvanian	Pennsylvanian	Pennsylvanian	Pennsylvanian	Pennsylvanian	Pennsylvanian	Pennsylvanian	Pennsylvanian	Pennsylvanian	Pennsylvanian
	FORMATION	Pottsville	Pottsville	Lee	Lee	Pottsville	Lee	Pottsville	Pottsville	Pottsville	Pottsville	Pottsville	Pottsville	Pottsville
	PRODUCING RESERVOIR	Pottsville	Pottsville	Lee	Lee	Pottsville	Lee	Pottsville	Pottsville	Pottsville	Pottsville	Pottsville	Pottsville	Pottsville
	LITHOLOGY	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone
	TRAP TYPE	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	structural/ stratigraphic	stratigraphic	straigraphic	stratigraphic	stratigraphic
	DEPOSITIONAL ENVIRONMENT	fluvial-deltaic	fluvial-deltaic	fluvial-deltaic	fluvial-deltaic	fluvial-deltaic	fluvial-deltaic	fluvial-deltaic	fluvial-deltaic	fluvial-deltaic	fluvial-deltaic	fluvial-deltaic	fluvial-deltaic	fluvial-deltaic
	DISCOVERY WELL IP (Mcf)	440	100	133	213	313	464							
	DRIVE MECHANISM	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas cap	gas cap	gas cap	gas cap	gas cap	gas cap	gas cap
	NO. PRODUCING WELLS	47	51	36	26	22	14	33	21	101	4	3	7	16
	NO. ABANDONED WELLS	9	8	9	2	1	0	32	29	173	3	0	0	11
	AREA (acreage)	6,916	6,015	3,345	4,146	2,146	4,451	155	340	503	43	30	50	
	OLDEST FORMATION PENETRATED	Corniferous	Rose Hill	Lee	Corniferous	Lee	Rose Hill							
	EXPECTED HETEROGENEITY DUE TO:	deposition	deposition	deposition	deposition	deposition	deposition	deposition	deposition	deposition	deposition	deposition	deposition	deposition
RESERVOIR PARAMETERS	AVERAGE PAY THICKNESS (ft.)	9	20		23	22	27	30	24.8	23	19.8	43	20	22
	AVERAGE COMPLETION THICKNESS (ft.)	65	48	26	81	33	20							
	AVERAGE POROSITY–LOG (%)	13	12			15	13		7					9
	MINIMUM POROSITY–LOG (%)	6	6			6	6		0					2
	MAXIMUM POROSITY–LOG (%)	14	14			21	20		>14					20
	NO. DATA POINTS	1	1			1	13		1					1
	POROSITY FEET	1.17	2.4			3.3	3.51							1.98
	RESERVOIR TEMPERATURE (°F)	70		64		71	71							
	INITIAL RESERVOIR PRESSURE (psi)	303			265			310	243	241		433		
	PRODUCING INTERVAL DEPTHS (ft.)													
	PRESENT RESERVOIR PRESSURE (psi) / DATE	280/1990			130/1965	325/1991	180/1991							
FLUID & GAS PROPERTIES	Rw (Ωm)	0.1	0.1	0.19	0.08	0.05	0.06							0.06
	GAS GRAVITY (g/cc)													65
	GAS SATURATION (%)	46	60				72							
	WATER SATURATION (%)	54	40				28							35
	COMMINGLED	no	no	no	no	no	yes							yes
	ASSOCIATED OR NONASSOCIATED	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated							nonassociated
	Btu/scf													
VOLUMETRIC DATA	STATUS (producing, abandoned, storage)	producing	producing	producing	producing	producing	producing	producing	producing	producing	producing	producing	producing	producing
	ORIGINAL GAS IN PLACE (Mcf)													
	ORIGINAL GAS RESERVES (Mcf)													
	PRODUCTION YEARS	1990-1992					1984-1992							
	ACTUAL CUMULATIVE PRODUCTION (Mcf)	24,000					559,000							
	NO. DATA POINTS	1					12							
	ESTIMATED CUMULATIVE PRODUCTION (Mcf)													
	REMAINING GAS IN PLACE (Mcf)/YEAR													
	REMAINING GAS RESERVES (Mcf)/YEAR													
	RECOVERY FACTOR (%)													
	INITIAL OPEN FLOW (Mcf/d)													
	FINAL OPEN FLOW (Mcf/d)	687	393	455	392	720	1,484							

Structure

Fields producing from the Lower and Middle Pennsylvanian sandstones lie in areas of gentle folding. Locally, gas production appears to be confined to structural highs in some areas of southwestern Pennsylvania (Fettke, 1953), Kentucky (McFarlan, 1943), Ohio, and West Virginia, which suggests that structure was the sole trapping mechanism. However, in most cases structure, where involved, only enhances the predominant trapping mechanisms of stratigraphic and/or diagenetic porosity and permeability barriers.

Reservoir

McFarlan (1943) and Fettke (1953) consider the only requisite for commercial production from sandstones in this play to be sufficient porosity and permeability. In places, stratigraphic traps are enhanced by structure. In northern West Virginia, completions in Lower and Middle Pennsylvanian sandstones tend to be concentrated along anticlines (Figure Pps-8). Probable sources of gas in the Pottsville Group are Pennsylvanian coals and organic-rich shales found within the Pottsville Group and correlatives (Blake, 1992), and the thick sequence of Devonian shales, ranging from mature to supramature in areas with fields having Pottsville production. Depending on the source of gas, migration pathways may range from only a few feet to much longer.

Pools of Salt gas are among the shallowest in the basin, as little as 400 feet deep in Lincoln County, West Virginia. These sandstones rarely exceed 200 feet in thickness in Pennsylvania (Harper and Laughrey, 1987), and several hundred feet in northern West Virginia. The Salt of Ohio is 20 to 40 feet thick, and the Maxton 10 to 200 feet thick (Alkire, 1951). The New River Formation is more than 1,000 feet thick in southern West Virginia (Blake, 1992). The Lee generally ranges between 100 and 600 feet in thickness (McFarlan, 1943). Reported thickness of the pay zone within the Salt ranges between 5 and 200 feet, averaging 20 feet. Available data show a range of 68 to 700 psi in rock pressure, 70 to 3,700 Mcf/d in initial open flow, and 30 to 2,285 Mcf/d in final open flow. The lenticular geometry of individual sandstone reservoirs of this play indicate that they are highly discontinuous within all but the smaller fields. Porosities range between 2 and 20 percent within wells, averaging 12 percent. Most drillers in central and southern West Virginia report a single zone of gas production near the top of the quartz arenites. Haught (1964) noted that wells were seldom fractured during completion. More recently, wells have been completed by fracturing with nitrogen. In most places, these sandstones contain salt water, and many wells begin to produce water after only a few hours or days. Available data gave an average cumulative production of about 200 MMcf (based on 22 wells) in West Virginia; 80 MMcf (250 wells) in Ohio; and 30 MMcf (12 wells) in Kentucky. Individual wells can range between 1 to more than 800 MMcf cumulative production. McFarlan (1943) states that wells are relatively short lived, but gives no specific data. Some wells with available data in West Virginia produced for many decades. Figure Pps-9 shows production decline curves from three wells completed in West Virginia. Average well life is 29 years.

Description of Key Fields

Hurricane Creek and Burdett-St. Albans fields: The Hurricane Creek field in Putnam County and nearby Burdett-St. Albans field in Kanawha, Lincoln, and Putnam counties are examples of gas production from the New River Formation. Hurricane Creek field was discovered in 1899 (Cardwell and Avary, 1982). The discovery date of the Burdett-St. Albans field is unknown,

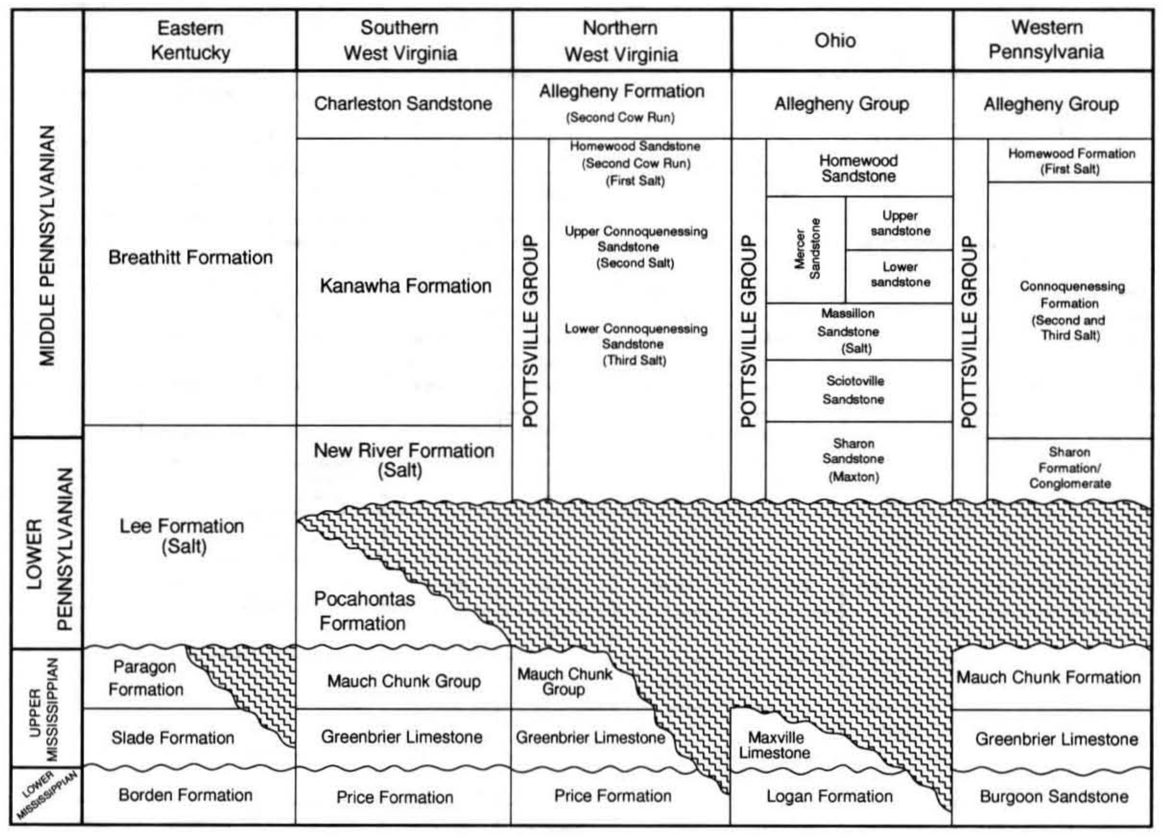


Figure Pps-3. Regional stratigraphic nomenclature. Based on Arndt (1979), Majchszak (1984), Patchen and others (1985a), Rice and others (1987), and Rice and Schwietering (1988).

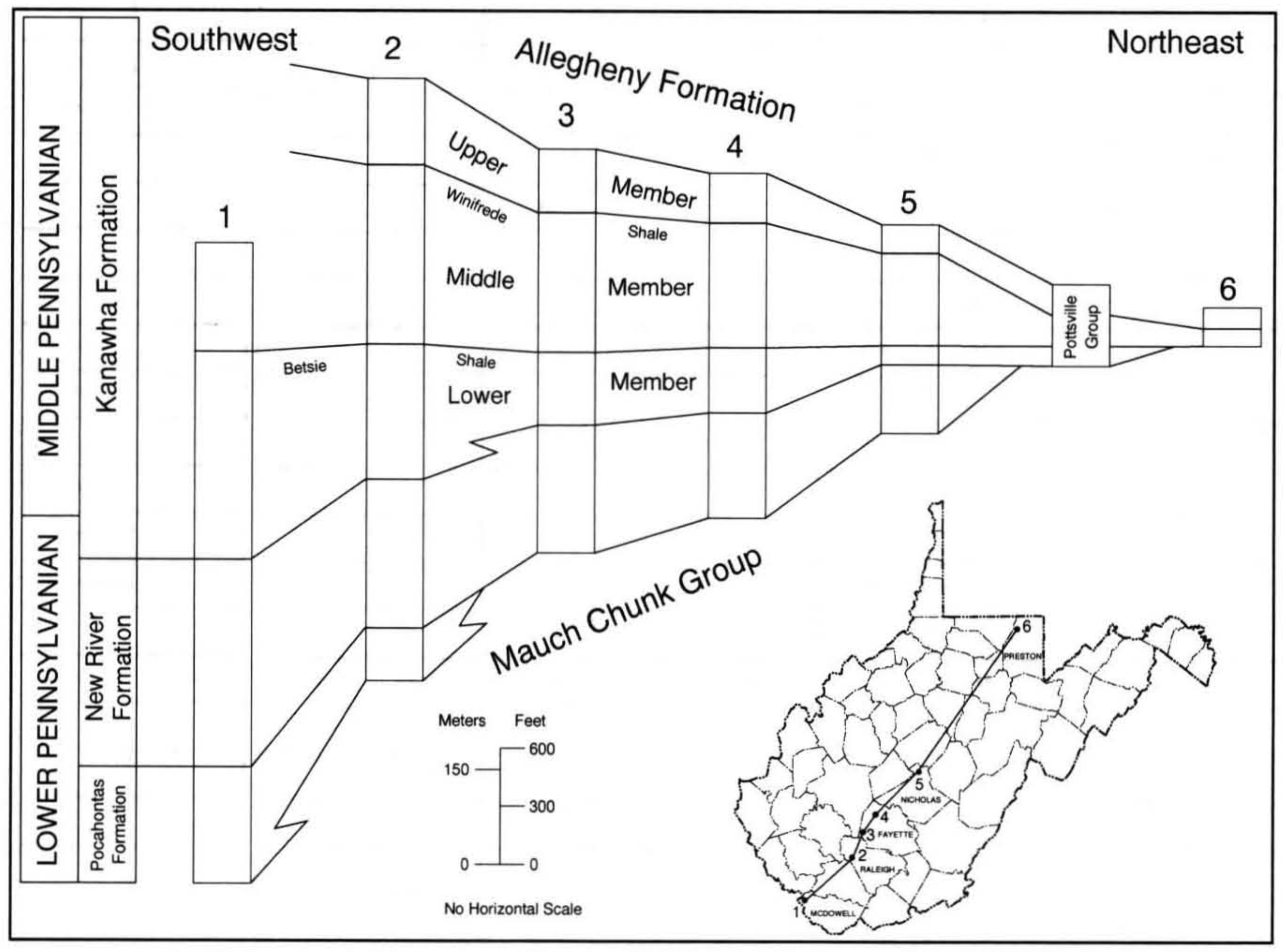


Figure Pps-5. Schematic cross section of the Kanawha and New River formations in West Virginia, showing the thinning and disappearance of New River Formation from south to north, as well as the thinning of the lower part of the Kanawha Formation in the same direction. Modified from U.S. Geological Survey (1992).

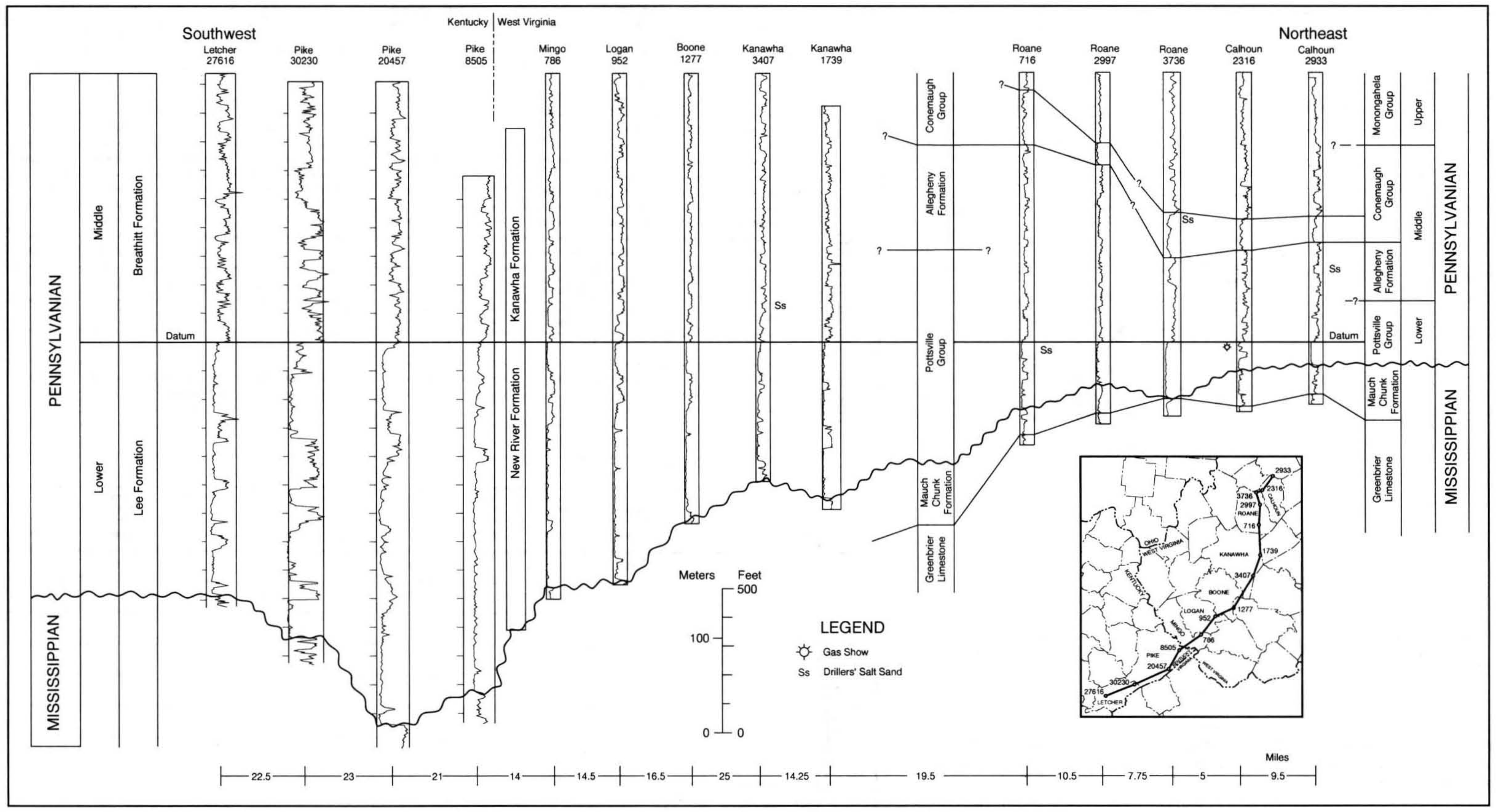


Figure Pps-4. Cross section constructed from gamma-ray logs of Lower and part of the Middle Pennsylvanian rocks in central West Virginia and eastern Kentucky, showing thinning of the quartz arenites of the Lee and New River formations from southwest to northeast, and erosional surface at the base of the Pennsylvanian. In Roane 3736, erosion has removed rocks of the Mauch Chunk Formation completely, and the resultant paleovalley was the site of a thickened section of massive sandstone in the New River Formation. Log picks for Kentucky and the first four wells in West Virginia are taken from Rice and others (1987). The well at the northeastern end of the cross section is located about 11 miles southwest of Ritchie 3218 in Figure Pps-6.

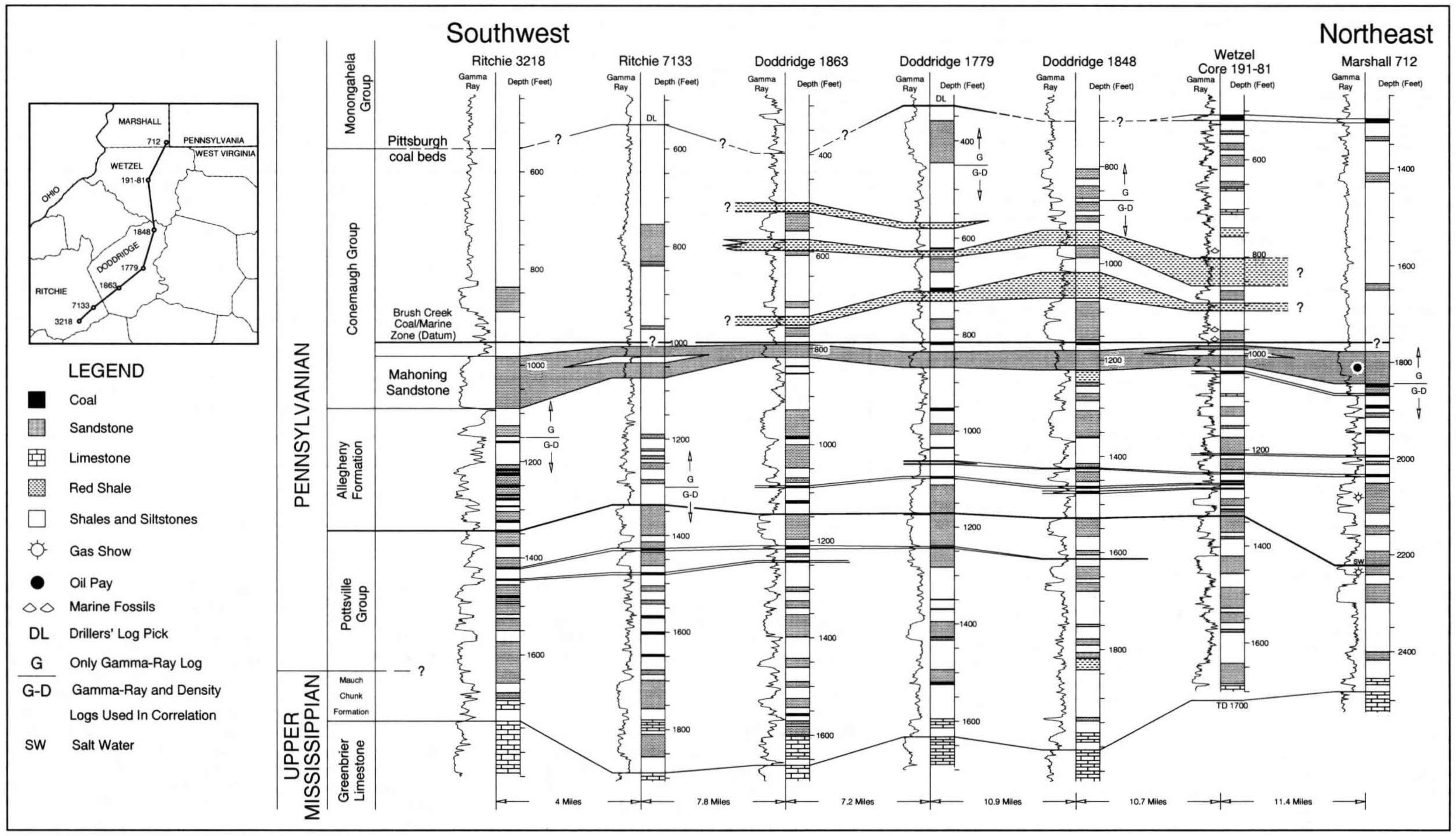
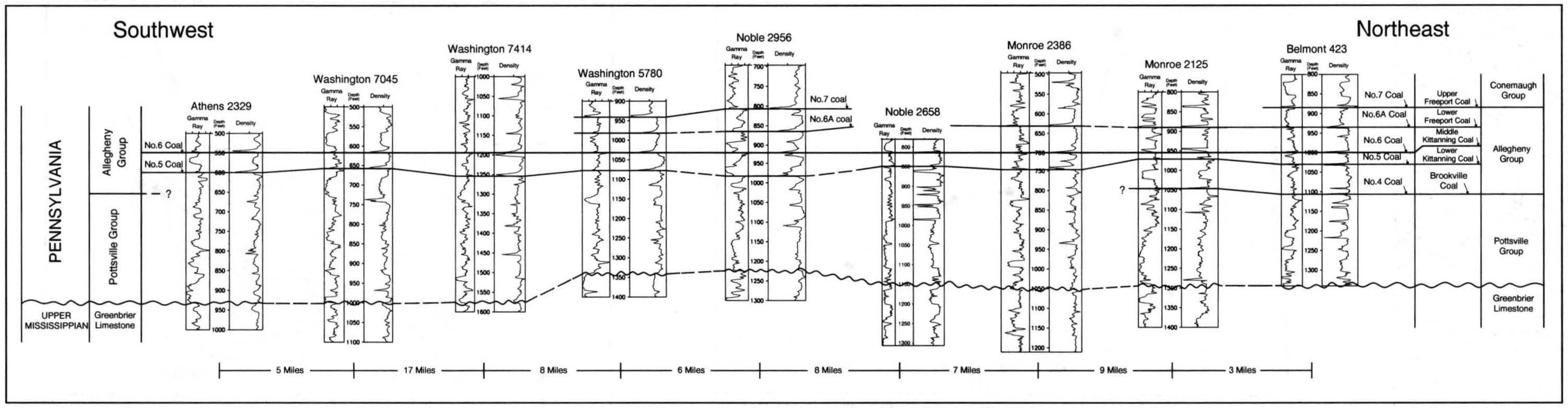


Figure Pps-6. Cross section showing Pottsville and overlying rocks in northern West Virginia. Redrawn and modified from Oldham and others (1993). Note the poor continuity of sandstone units between wells.

but probably was also in the 1890s. Early drilling centered largely on structural highs.

In southern West Virginia, massive sandstones at the top of the New River Formation are relatively easy to distinguish from shales at the base of the overlying Kanawha Formation, both by the drillers and on gamma-ray logs (Figure Pps-4). A cross section of lithologic logs within Hurricane Creek field (Figure Pps-10) shows that drillers observed as many as three units within the New River, and that thin zones of production occur near the top. These units are the First, Second, and Third Salt, depending on the number of units observed by the driller. Producing zones average 12 feet thick in Hurricane Creek and Burdett-St. Albans fields.

Representing fluvial deposition within a post-Mississippian paleovalley, sandstone bodies within the New River are probably lenticular and geographically limited. Gas is most likely trapped by permeability barriers between sandstone bodies or where a structural trap exists. These barriers might be laterally extensive shales within the New River Formation, or tight shaly zones associated with massive fluvial sandstones. The limited vertical extent of the pay interval relative to the thickness of the massive sandstones suggests the latter. Also, early gas migration into and entrapment within incipient pre-Allegheniian paleo-structural highs could have restricted diagenesis, therefore preserving porosity and permeability.



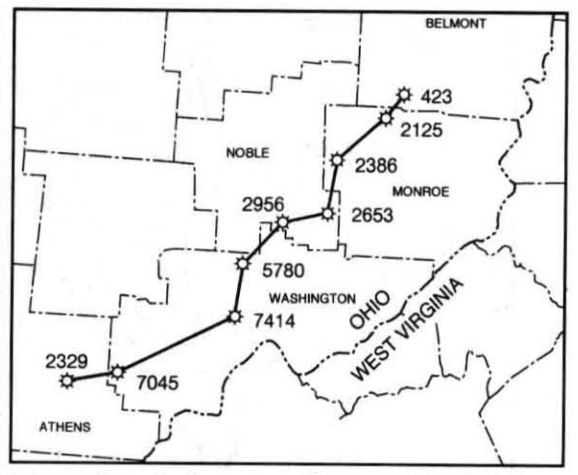


Figure Pps-7. Cross section constructed from gamma-ray logs of a Pottsville Group interval in Ohio, following the work of Lamborn (1951), Sturgeon (1958), Struble and others (1971), and Collins and Smith (1977). Cross section courtesy of Matt Warner, Ohio Division of Geological Survey. As in West Virginia, the continuity of massive sandstone units between wells is low. In the absence of key marker beds such as the Brookville coal bed, the top of the Pottsville Group cannot be determined with certainty from geophysical logs.

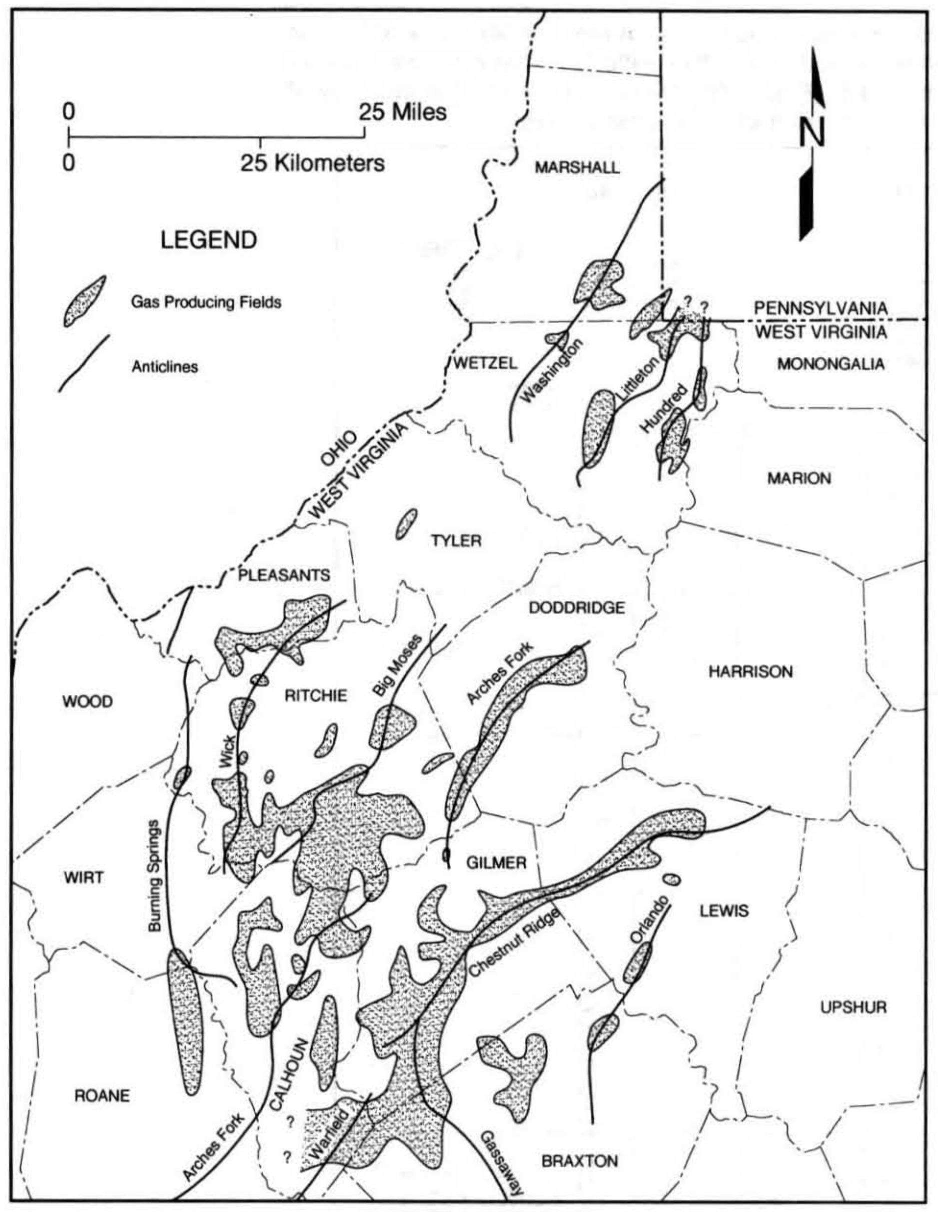


Figure Pps-8. Map comparing areas of high density of completions in the Salt with important anticlines. Axes of anticlines are based on the structure of the base of the Greenbrier Limestone. Modified from a map provided by Philip L. Martin of CNG Producing Company.

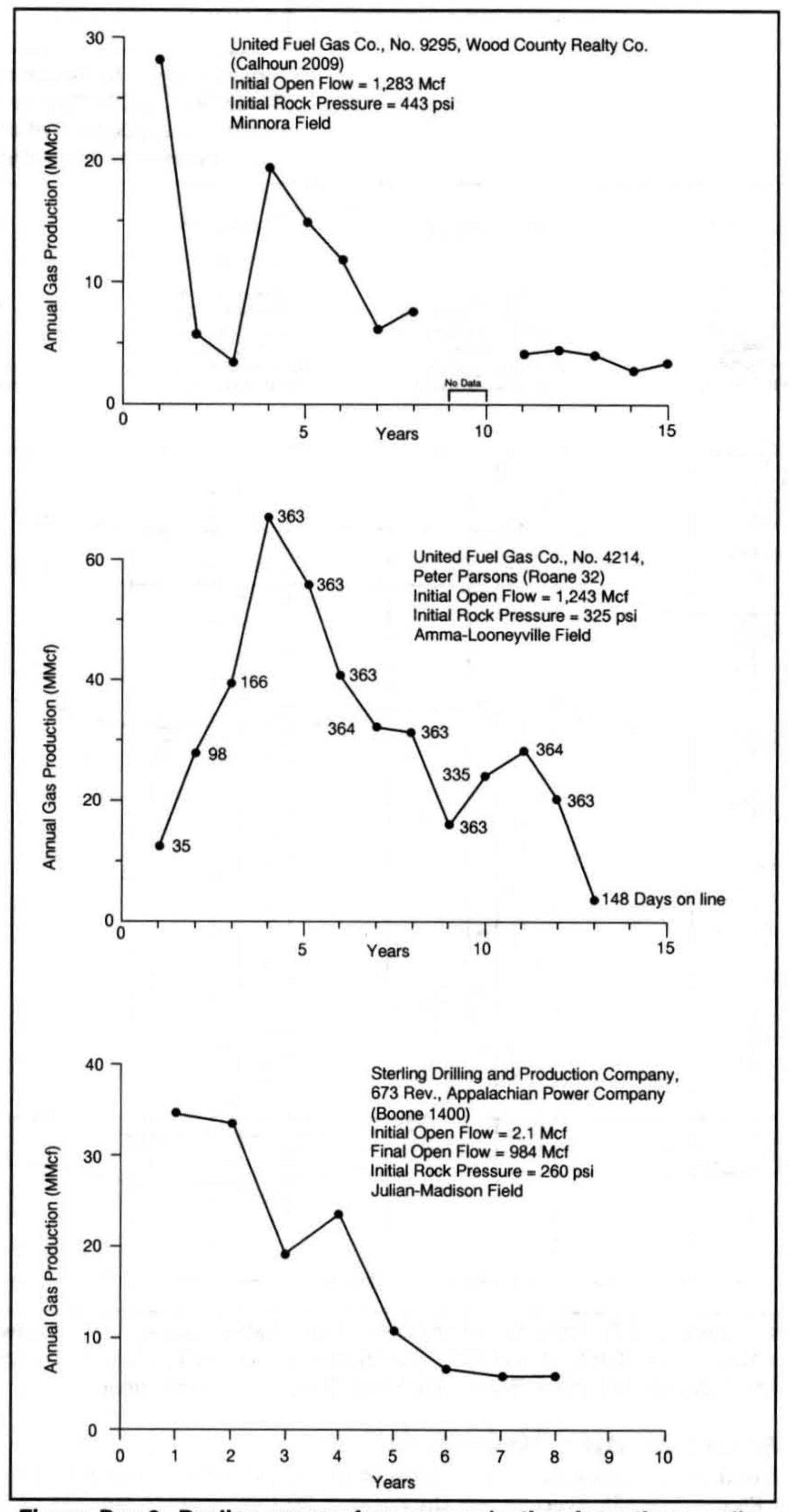


Figure Pps-9. Decline curves for gas production from three wells: Calhoun 2009, completed in 1963; Roane 32, completed in 1930; and Boone 1400, completed in 1982.

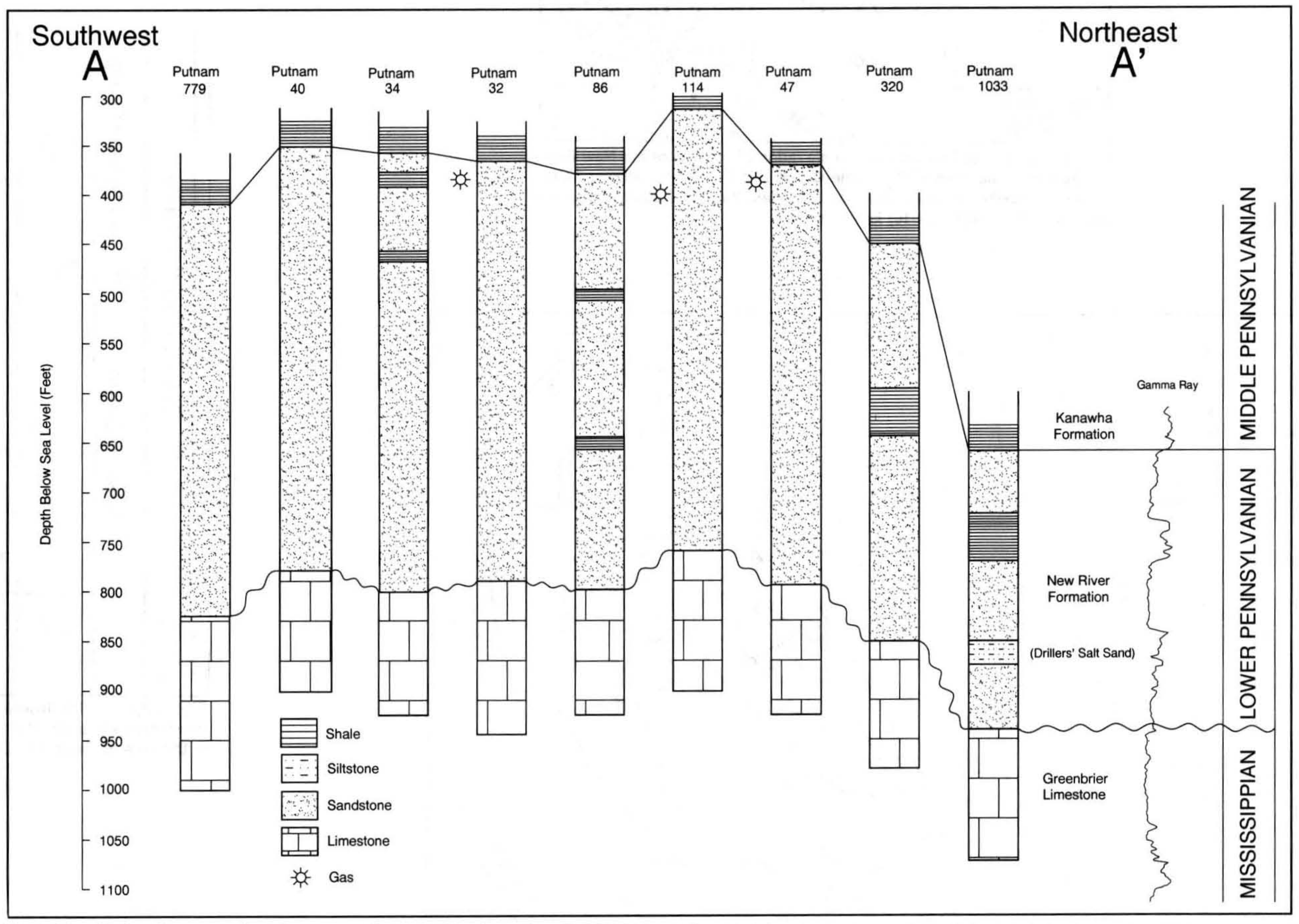


Figure Pps-10. Southwest-northeast cross section A-A', Hurricane Creek field, Putnam County, West Virginia, based on drillers' lithologic logs. Gamma-ray log from a well shown to the northeast shows the correspondence of drillers' Salt sands in this field with the New River Formation. Location of cross section A-A' is shown in Figure Pps-11.

In the case of the Hurricane Creek and Burdett-St. Albans fields, a structure contour map on the top of the Salt suggests closure in the areas of gas production (Figure Pps-11). Krebs (1911) reports initial open flows of 1,000 and 3,500 Mcfg/d from two early wells in the Burdett-St. Albans field. Average initial open flow in the Hurricane Creek field was about 500 Mcfg/d for wells drilled since 1929.

Beaver Creek field: Discovered in 1971, the Beaver Creek field of Gallia County, Ohio, represents a modern Pottsville gas field. The discovery well, Quaker State Oil Refining Corp., No. 1 G. Waugh, *et al.* (Ohio permit number Gallia 154), yielded an initial potential of 2,300 Mcfg/d, and an initial rock pressure of 300 psi from the Salt. Sixteen additional wells were drilled through 1986. Ten wells were plugged by 1989, and the remaining seven wells have not produced since 1988. Cumulative production for 15 wells was 900 MMcfg. Figure Pps-12 shows a decline curve for a well in this field.

Structural mapping of the Number 6 coal shows a small elongate dome over the main producing area (Figure Pps-13). A cross section (Figure Pps-14) shows subtle structural closure that appears to have minimal trapping influence and overlying shales that act as a seal. Core analyses of these shales recorded vertical permeability less than 0.1 md. Pressures have been highly variable throughout the productive history of the field, ranging between 20 and 400 psi (W. Haas, Jr., Valentine Oil Properties, written commun., 1993). This suggests that local faulting and stratigraphic heterogeneity might have created compartments that control gas production pressures, rates, and volumes. Geophysical logs and the work of Kettering (1984) show a major channel filled with Sharon Sandstone beneath the productive sandstone in this field. The Sharon Sandstone is porous (10 to 20 percent) and highly permeable in this area, and might be in partial communication with the overlying sandstone units. Log analyses also show presence of possible source rocks below the Salt: the Sharon coal and an organic-rich shale in the same stratigraphic position as this coal.

Core analyses of the producing sandstones of this play indicate average porosity of 13 percent and average horizontal permeability of 90 md.

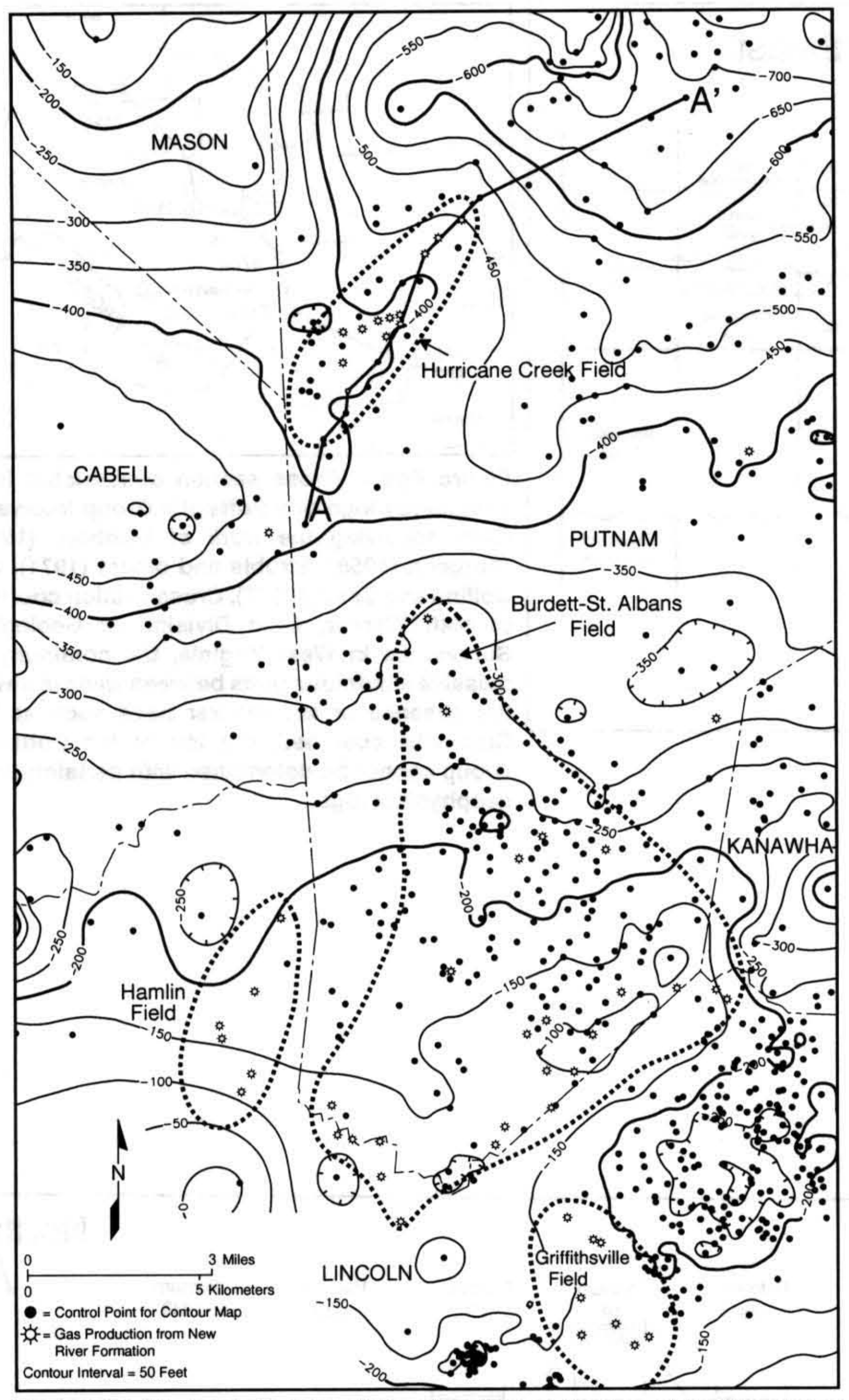


Figure Pps-11. Contour map of the elevation of the top of the New River Formation in the area of Hurricane Creek and Burdett-St. Albans fields, Putnam, Lincoln, and Kanawha counties, West Virginia. Location of cross section A-A' (Figure Pps-10) is also shown.

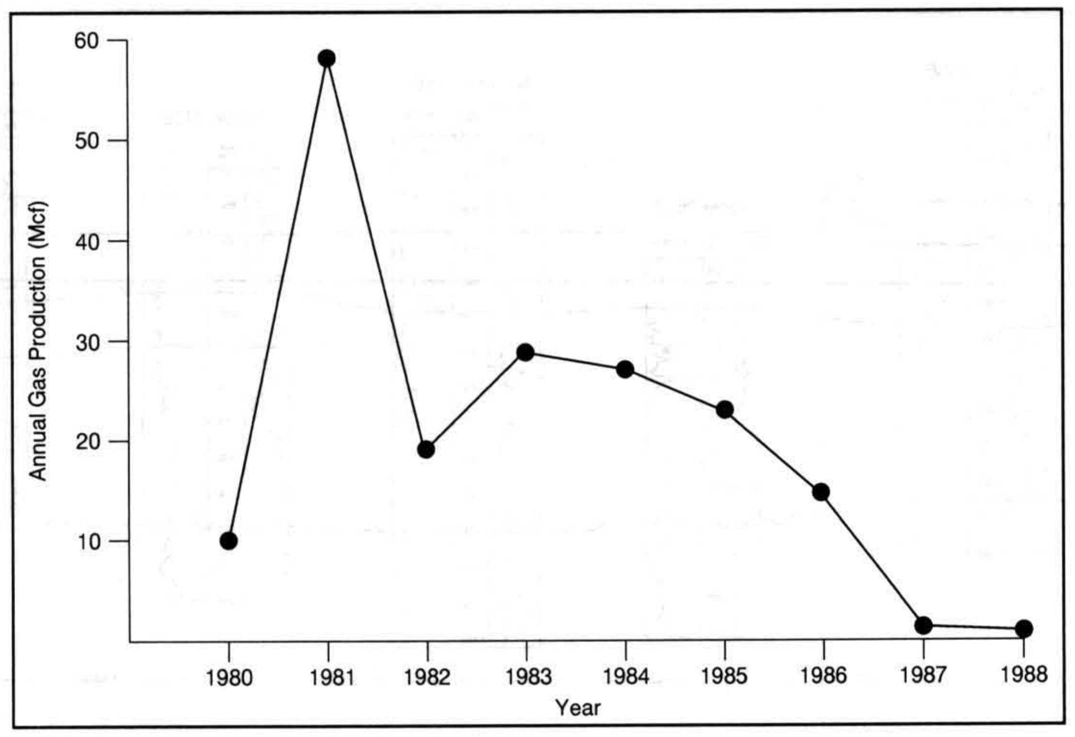


Figure Pps-12. Typical decline curve for a well completed in the Pottsville Group (Gallia 2161 in Figure Pps-14) in Beaver Creek field, Gallia County, Ohio.

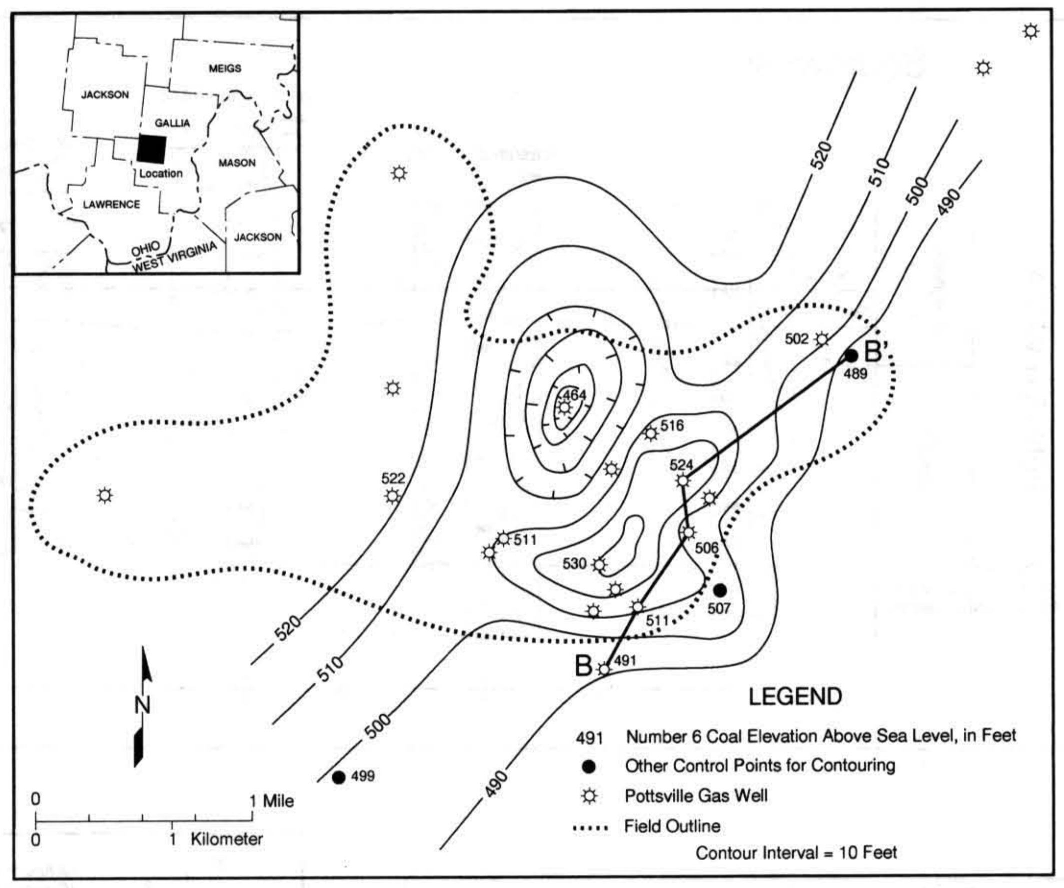


Figure Pps-13. Structure contour map representing the top of the Number 6 coal in Beaver Creek field, Gallia County, Ohio, showing that productive wells lie on the crest and flank of an anticline. Location of cross section B-B' (Figure Pps-14) is also shown. Map courtesy of Matt Warner and Mark Baranoski, Ohio Division of Geological Survey.

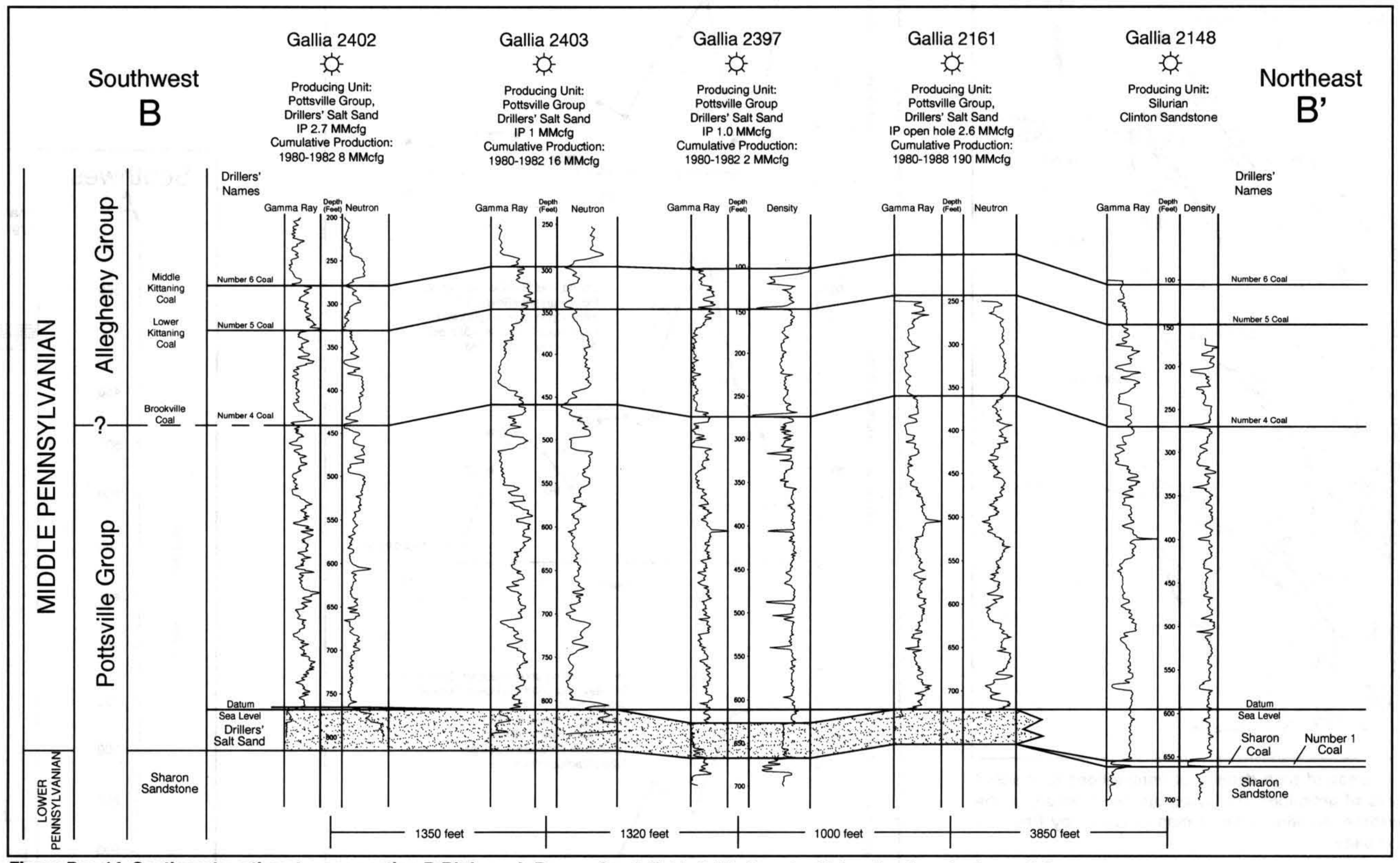


Figure Pps-14. Southwest-northeast cross section B-B' through Beaver Creek field, Gallia County, Ohio, showing pinchout of the productive sand to the northeast. Both depositional and structural factors are critical to existence of this field. Location of cross section B-B' is shown in Figure Pps-13. The Sciotoville Sandstone is not present in the area of these wells. Courtesy of Matt Warner and Mark Baranoski, Ohio Division of Geological Survey.

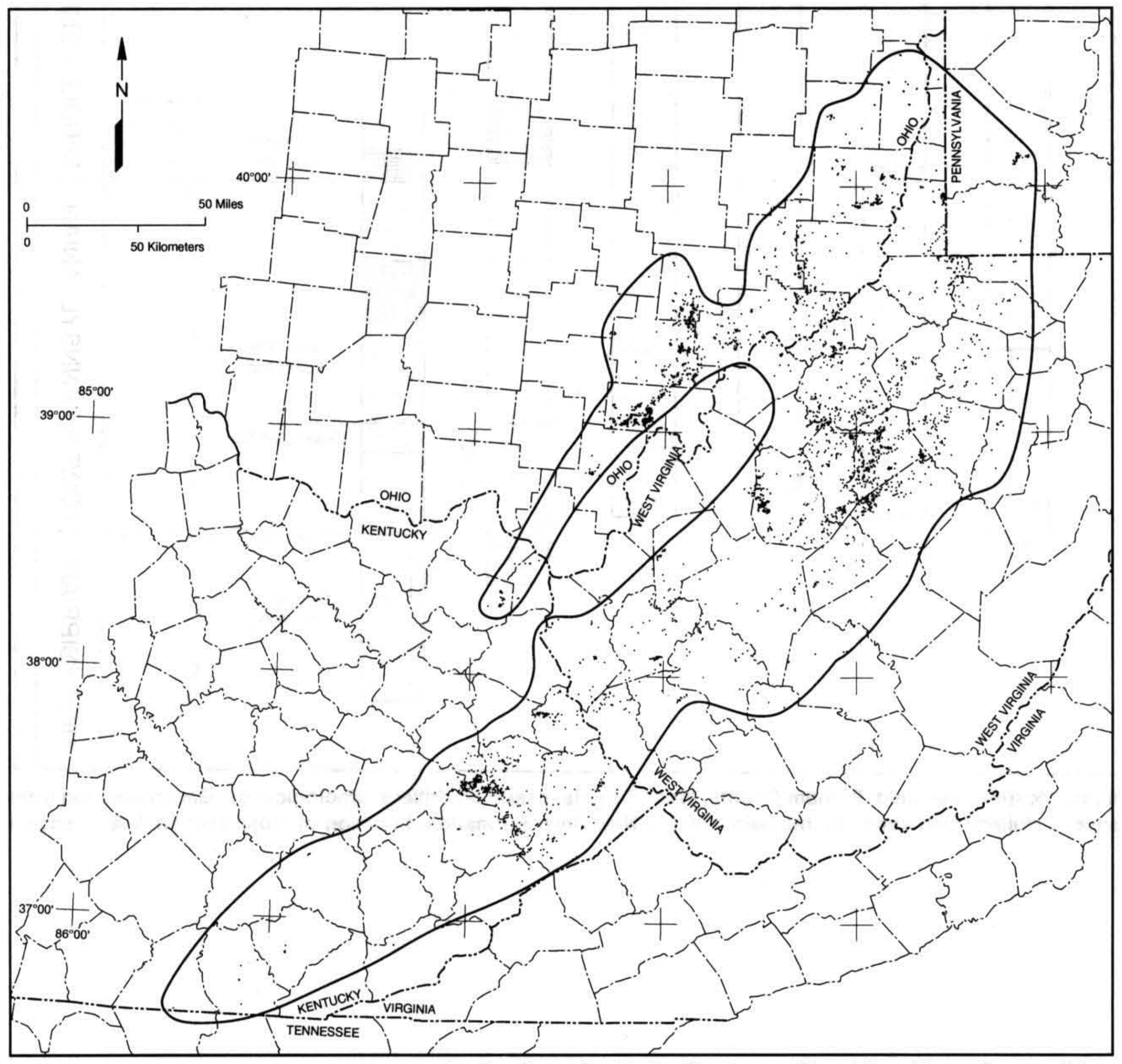


Figure Pps-15. Map showing the area productive from the Pottsville Group, New River Formation, and Lee Formation. The area enclosed by the outline was used to estimate original gas in place.

Resources and Reserves

Based on the following data—a total of 13,093,515 acres in the productive area (Figure Pps-15), average pay thickness of 20 feet, average porosity of 12 percent, average water saturation of 0.46, and average temperature of 70°F, average water saturation of 0.46, and average rock pressure of 316 psi—the estimated original gas in place is 16.23 tcf. Subtracting the .50 tcf of estimated production leaves 15.73 tcf in remaining gas in place. Assuming a recovery factor of 80 percent, reserves may total as much as 12.58 tcf.

Future Trends

Although discovery of large Pottsville gas fields is unlikely, new Salt pools continue to be found in Ohio, Kentucky, and West Virginia, in many cases in the course of drilling for deeper targets. From a total of 29,749 wells drilled in West Virginia since 1969, 243 were completed in Lower and Middle Pennsylvanian sandstones, a ratio of 0.82 Pennsylvanian completions per 100 wells drilled. Average cumulative production for 60 of these wells equalled 26,585 Mcfg. Therefore, one can expect cumulative production of about 22,000 Mcfg from Pennsylvanian sandstones for every 100 wells drilled in West Virginia. This assumes that Lower and Middle Pennsylvanian rocks do not become an important target for drilling in the future. In northern West Virginia, southwestern Pennsylvania, and southeastern Ohio, almost exclusive rotary drilling has targeted deeper reservoirs over the last 20 to 30 years. In many wells, intermediate casing has been set through the Salt with no logs being run or oil and gas shows noted or reported even if encountered. Therefore, a surprising amount of gas may have been overlooked in the Lower and Middle Pennsylvanian sandstones. Reserves per well probably will be small compared to deeper reservoirs, but a proportionately lower budget drilling and completion plan aimed at shallow depths and low pressures and volumes might find economic success in this interval (P. Martin, written commun., 1994).

Coal beds in the Pocahontas and New River formations have become targets for production of coal bed gas in an area that includes Raleigh, Wyoming, and McDowell counties, West Virgina, and Buchanan and Dickenson counties, Virginia (see Figure Pps-2 for location of these counties). Gas contents of 500 to 600 standard cubic feet per ton of coal are expected for depths of 1,500 to 2,500 feet. Total resources from the area are estimated to be 4.8 tcf (Kelafant and Boyer, 1988). In Pennsylvania, Ohio, and northern West Virginia, Pottsville coals are thin and exhibit lower gas content, offering little prospect of commercial development (Kelafant and others, 1988).

PLAY Mmc: UPPER MISSISSIPPIAN MAUCH CHUNK GROUP AND EQUIVALENT STRATA

by Charles A. Barlow, Consulting Geologist

Location

The Upper Mississippian Mauch Chunk Group play extends from southwesternmost Pennsylvania, south and southeastward across West Virginia and eastern Kentucky, and into southwest Virginia (Figures Mmc-1, Mmc-2). There is productive potential from Mauch Chunk rocks basically everywhere within the subcrop/outcrop limits (Figure Mmc-3) and perhaps outside the general outcrop band in some of the structures of the eastern fold belt. The Mauch Chunk group play produces gas from numerous lenticular fluvial sandstones in about 170 fields extending from southwestern Pennsylvania to southwestern Virginia (Figure Mmc-1).

There are two fields producing outside the generalized subcrop/outcrop limit of the Mauch Chunk Group (compare Figures Mmc-2 and Mmc-3, Mercer County). Athens and Bozoo fields are situated along the Abbs Valley anticline in Mercer County (Athens field), and Summers and Monroe counties (Bozoo field), West Virginia, southeast of the generalized outcrop line and produce from Maxon sandstone (Figure Mmc-4). Cumulative production data for these fields have not been made available and such production outside the general outcrop limit (Figure Mmc-3) is quite rare.

Production History

The earliest gas-only production from the Pennington Formation (Mauch Chunk equivalent) (Figure Mmc-4) in Kentucky appears to be from Martin County in 1899, although early recording of drilling data makes for some uncertainty. Gas production has occurred from at least 68 fields in 16 counties, according to the Kentucky Geological Survey computer database. Cumulative production data are not available.

The earliest gas-only production in West Virginia from the Mauch Chunk appears to be from Harrison County in 1901, although early recording of drilling data makes this uncertain. Gas production has occurred from at least 101 fields in 26 counties, according to the West Virginia Geological and Economic Survey computer database. Most activity in West Virginia before the 1970s occurred in the northwestern part of the state. In the 1970s and early 1980s, new fields were discovered in southeastern West Virginia as operators looked for relatively shallow production in Mississippian reservoirs.

In Pennsylvania, only in southwestern Greene County has the Mauch Chunk Formation been documented to have been gas productive. Production began prior to 1907 (Stone and Clapp, 1907) and according to Harper and Laughrey (1987), the producing unit was the Maxton Sandstone of drillers' terminology. As far as can be ascertained, there is no current production from the Mauch Chunk in this area. Cumulative production data for the area are not available.

The earliest Bluestone and Hinton Formation (Mauch Chunk equivalents) (Figure Mmc-4) gas production in Virginia is from Buchanan County in 1948, according to Virginia Division of Mineral Resources records. To date, production seems to be limited to Buchanan, Dickenson, and eastern Wise counties. The author was unable to obtain Virginia production data other than well locations shown in Figure Mmc-1.

A conservative minimum estimate for cumulative production from Mauch Chunk reservoirs is 336 bcf, based on 4,200 wells with an average of 80 MMcf produced from each well.

Stratigraphy

The Mauch Chunk derives its name from an exposure near the town of Jim Thorpe (formerly known as Mauch Chunk) in eastern Pennsylvania. In this area, the Mauch Chunk Formation is in excess of 2,400 feet in thickness and grades upwards transitionally into the Pottsville Group (Hoque, 1965). The Mauch Chunk of the type locality consists of red and gray shales and siltstones, dominantly red sandstones, and some thin limestones.

In southwestern Pennsylvania, the Mauch Chunk Formation overlies and intertongues with the Loyalhanna and Wymps Gap limestones, which merge to form the Greenbrier Formation of southwestern Pennsylvania (Edmunds and others, 1979) (Figure Mmc-4).

In West Virginia, the Mauch Chunk Group was described in great detail by Reger and Price (1926) from the area of the New River Gorge in Summers County, where it consists of red, green and gray to black shale, sandstone, and limestone. The uppermost formation is the Bluestone, followed in descending order by the Princeton Sandstone, Hinton Formation, and Bluefield Formation (Figure Mmc-4). The Mauch Chunk is present in the subsurface of most of the gas-productive areas of the state except for the northern panhandle and most counties along the Ohio River (Figure Mmc-3). Usage of various informal subsurface subdivisions of the formations of the Mauch Chunk in West Virginia (Figure Mmc-4) has been somewhat inconsistent dating back to the early days of drilling. Confusion over the position of the Pennsylvanian-Mississippian boundary (basal Pottsville) has led to some of the inconsistencies in terminology.

In eastern Kentucky, the Pennington Formation is the equivalent of much of the Mauch Chunk Group (Figure Mmc-4). The productive extent seems to reach from Boyd County southwestward to Whitley County and southeastward from this line to the state border (Figure Mmc-1); however, the actual area of production from the various subdivisions of the Pennington is uncertain, mainly because of confusion of the position the Pennsylvanian-Mississippian boundary. Some production attributed to Mississippian strata (Maxon) is actually from lower Pennsylvanian (Figure Mmc-4).

Figure Mmc-3 shows general trends of thickness of the Mauch Chunk Group/Pennington Formation, also known as the Paragon Formation (Ettensohn and others, 1984), for the play area. Work by Okolo (1977) in a part of Leslie County, Kentucky, shows Pennington thicknesses to range from 350 to 660 feet,

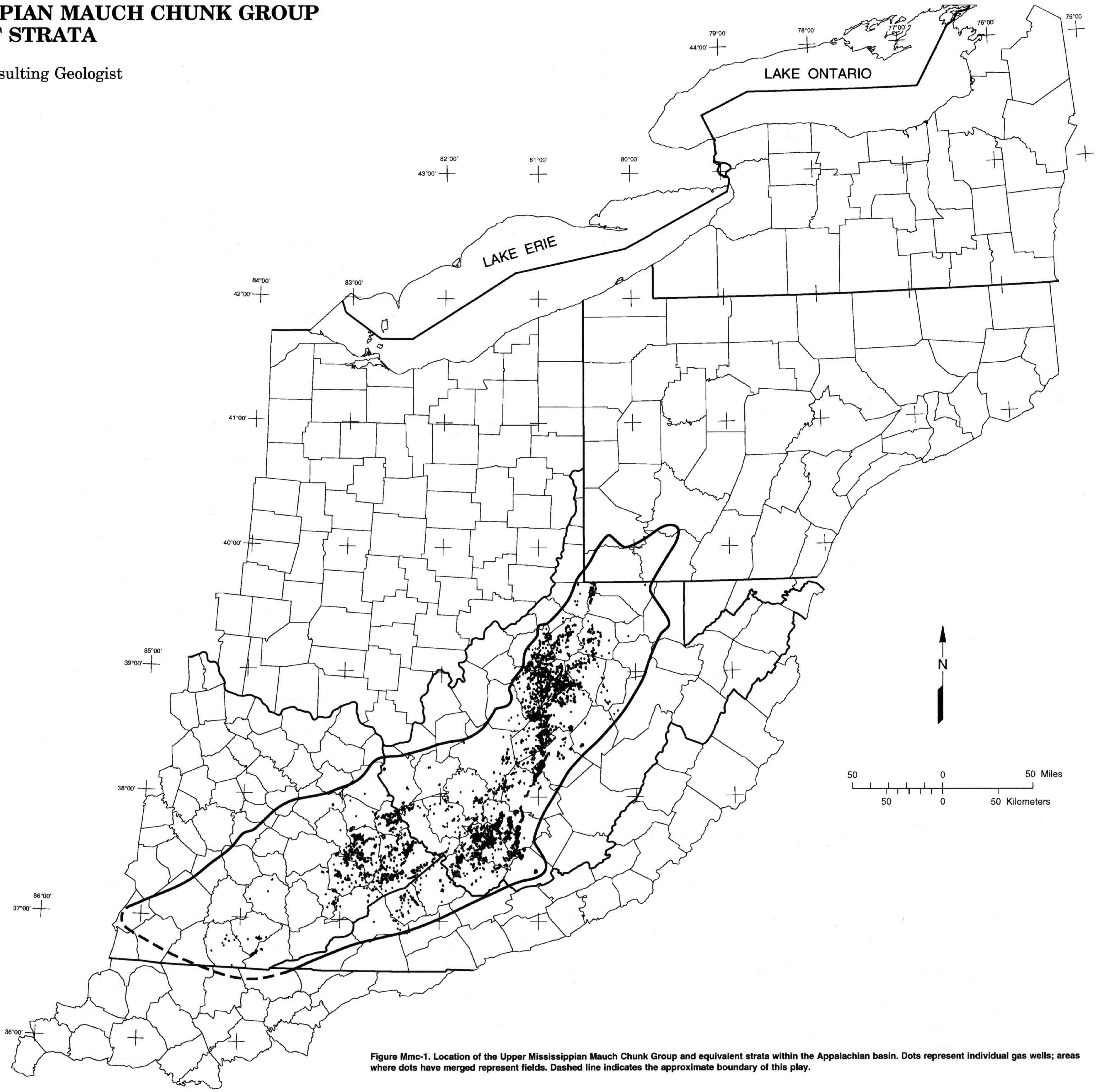


Figure Mmc-1. Location of the Upper Mississippian Mauch Chunk Group and equivalent strata within the Appalachian basin. Dots represent individual gas wells; areas where dots have merged represent fields. Dashed line indicates the approximate boundary of this play.

Figure Mmc-2. Locations of Upper Mississippian Mauch Chunk Group fields discussed in text or listed in Table Mmc-1. Other productive areas depicted in Figure Mmc-1 are not shown.

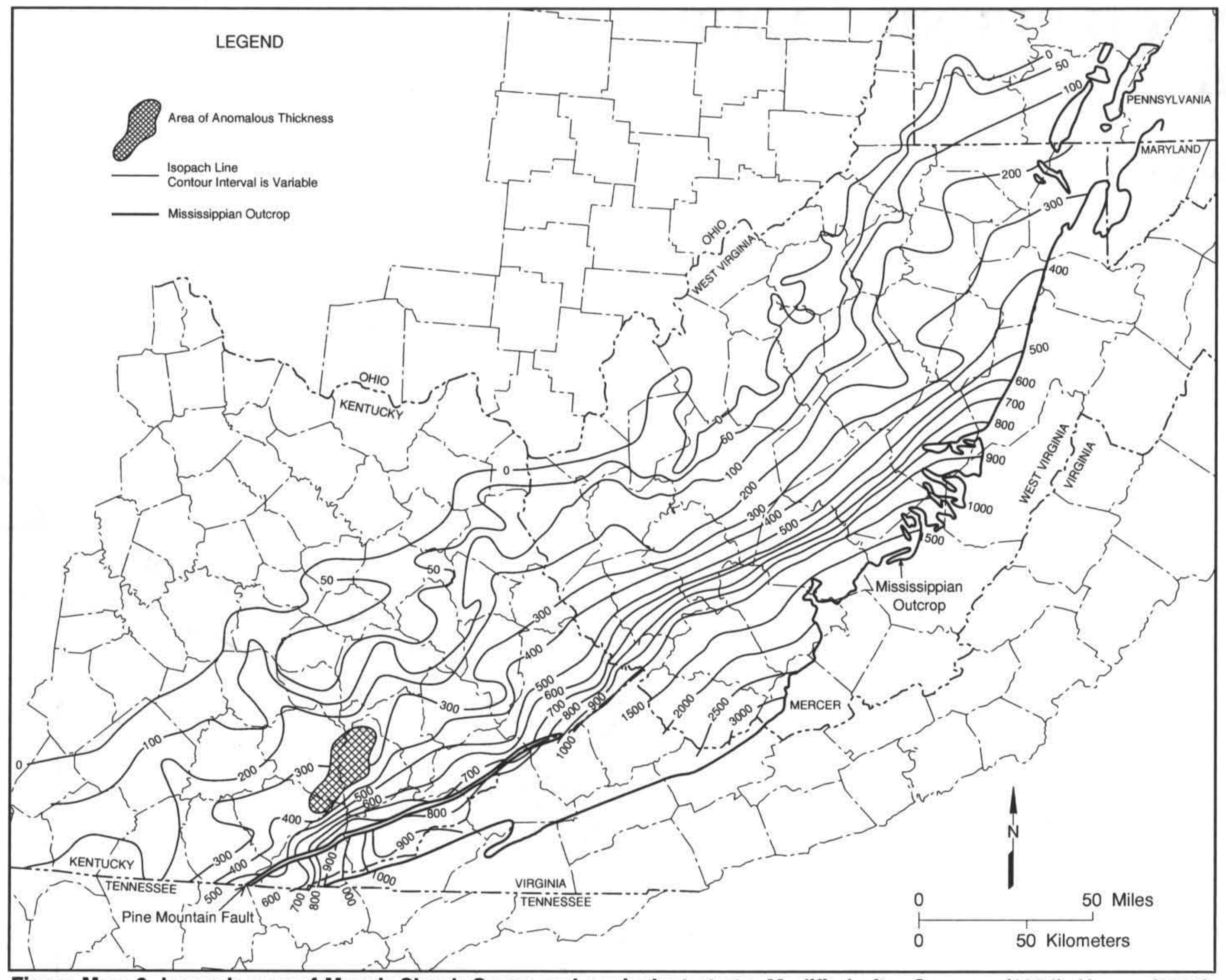


Figure Mmc-3. Isopach map of Mauch Chunk Group and equivalent strata. Modified after Sprouse (1954), Hoque (1968), Dennison and Wheeler (1975), Beuthin (1989), and Sable and Dever (1990).

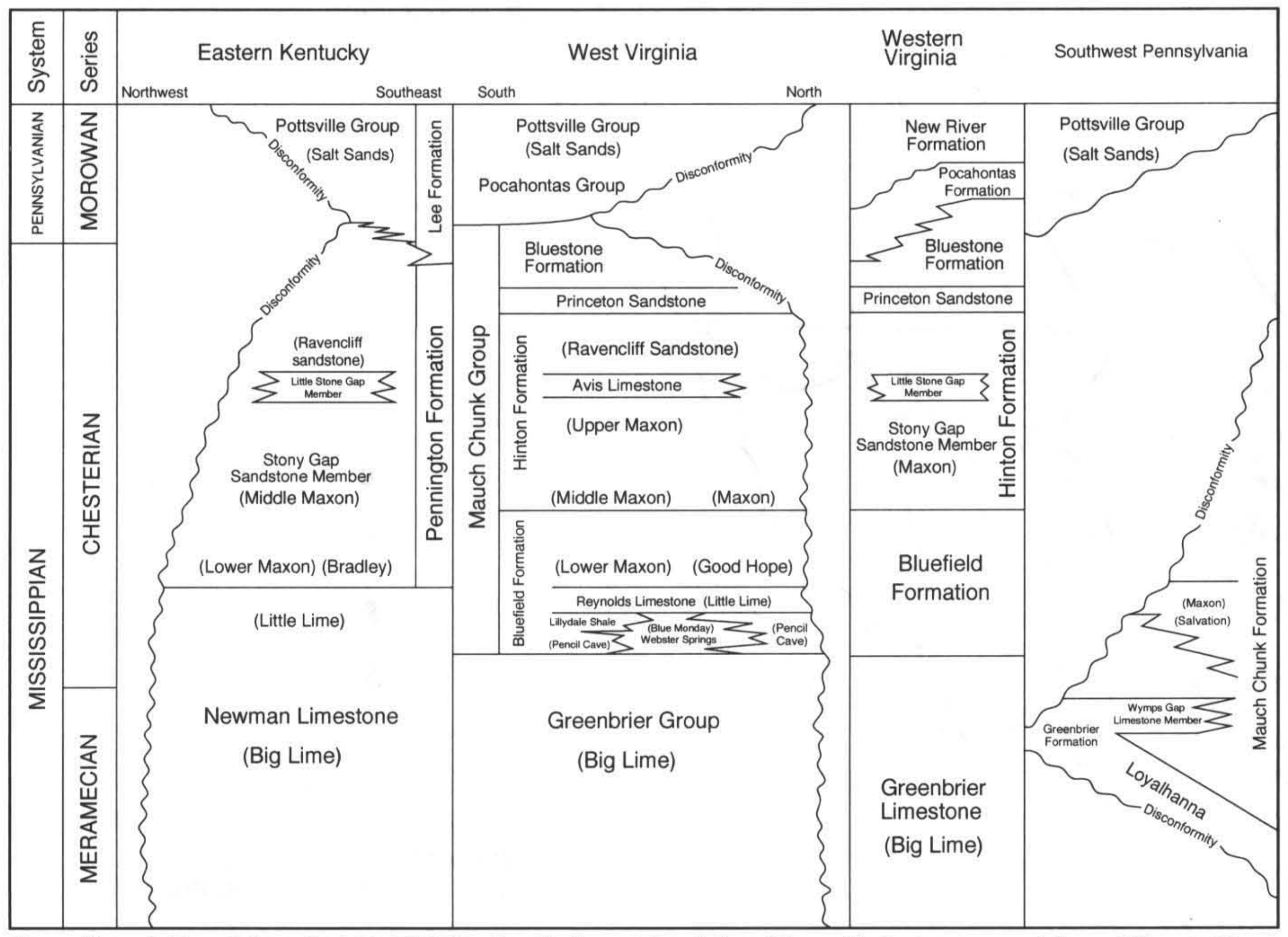


Figure Mmc-4. Correlation chart highlighting the stratigraphic relationship and industry nomenclature of Mauch Chunk Group and equivalent and bounding strata. Modified from Hamilton (1958), Presley (1977), Arkle and others (1979), Edmunds and others (1979), Rice and others (1979), and Sable and Dever (1990).

with much of the variation resulting from variable depth of scour prior to deposition of the overlying Pottsville (see cross-hatched area on Figure Mmc-3). Additional variations of the Mauch Chunk Group/Pennington Formation thickness result from inconsistent placement of the Mississippian-Pennsylvanian boundary.

The Mauch Chunk Group and the Pennington Formation consist of mixed, mostly clastic, lithologies (sandstones, siltstones, and shales) of both marine and non-marine origin. Thin coals of possible deltaic origin are present in the Mauch Chunk of southern West Virginia (Dennison and Wheeler, 1975). Fluvial deposits are present in northeastern West Virginia and Maryland, and southwestern Virginia, and dominantly marine deposits are preserved in Tennessee and Kentucky (Dennison and Wheeler, 1975). Away from the depocenter in southeastern West Virginia (Figure Mmc-3), the overall thickness decreases, as does the quantity of coarse-grained clastics. The reservoir-quality sandstones are locally developed within the sequence.

The uppermost productive unit within the Mauch Chunk is the Princeton Sandstone (Figure Mmc-4), named for exposures near Princeton, West Virginia. This name was applied to gas-productive sandstones in several fields in Wyoming County, West Virginia, in the early 1940s. Additional drilling through the years, growing availability of geophysical logs, and subsequent correlation has shown that most of the sandstones producing in the Wyoming County area were actually not the Princeton, but stratigraphically lower sandstones.

The Princeton is generally a quartz arenite to lithic arenite with grain size varying from very fine to conglomeratic. Cement is apparently largely quartz and subordinate carbonate. The percentage of clay, mica, and rock fragments can range from minuscule to significant.

The next lower productive interval consists of the drillers' Ravencliff sandstone(s) (Figure Mmc-4). The name probably originates from the town of Ravencliff in McGraws field in eastern Wyoming County, West Virginia. The industry usage of Ravencliff applies to one or more sandstone bodies that immediately overlie the Avis Limestone of Reger and Price (1926), or that have been deposited in channels or valleys cut into or through the Avis.

Miller (1964) suggested that the name Avis Limestone should be replaced by Little Stone Gap Member. However, Avis will be used here because it is more widely used in industry, and the New River locality of Reger and Price (1926) is more lithologically representative than the Little Stone Gap locality of Wilpolt and Marden (1959).

The next lower productive interval encompasses the various Maxon sandstones of the Hinton and Bluefield formations (Figure Mmc-4). The original form was Maxton, taken from the Maxton farm near Sistersville field (White, 1904) in Tyler County, West Virginia. The productive Maxton sandstone at Sistersville is a basal Pennsylvanian Pottsville sandstone (see Tyler 998, cross section B-B', Figure Mmc-6). The earliest reference found to Maxon sandstone is from Greene County, Pennsylvania (Ashley and Robinson, 1922). This probably refers to a thick upper Mississippian sandstone similar to that seen in Greene 22091 (cross section C-C', Figure Mmc-6).

Although Maxon production has been reported from Boyd and Lawrence counties, Kentucky, this production is likely from a basal Pottsville sandstone, similar to the situation in western Wetzel and Tyler counties, West Virginia. The Pottsville sandstone sits on about 30 feet of shale overlying the Newman Limestone (Big Lime) in southern Lawrence County. A short distance to the north, the basal Pottsville sandstone directly overlies the Newman.

In southwestern Pennsylvania and northern to central West Virginia, Maxon sandstones are generally undifferentiated. Southward, a thicker section is developed near northern Kanawha County, West Virginia, which allows differentiation into upper, middle, and lower Maxon sandstones.

The distribution of upper Maxon sandstones tends to be irregular, although in some areas such as Nicholas and Fayette counties, West Virginia, individual sandstone bodies are extensive (Figure Mmc-5). The sandstone bodies may occur anywhere from the base of the Avis to the top of the middle Maxon.

Middle Maxon sandstone is apparently equivalent to the Stony Gap Sandstone of the Hinton and Pennington formations (Figure Mmc-4) at outcrop in Virginia and Kentucky (Wilpolt and Marden, 1959). Middle Maxon sandstones are the most laterally persistent within the productive area including eastern Kentucky, although they by no means comprise a blanket deposit (Figures Mmc-7, Mmc-8). They are also the most consistent in stratigraphic position.

Lower Maxon sandstones are considered to be equivalent to various outcrop sandstones within the Bluefield Formation of Virginia and West Virginia (Figure Mmc-4). The equivalent sandstones have also been referred to as Bradley sandstone in eastern Kentucky (Figure Mmc-4). Lower Maxon sandstones tend to be somewhat irregularly distributed areally and may occur stratigraphically anywhere within the interval from the base of the middle Maxon to the top of the Little Lime (Figure Mmc-4). It is not uncommon to find these sands deposited in scours into the top of the Little Lime. Presley (1977) demonstrated this situation in the area of northeastern Lewis and southeastern Harrison counties, West Virginia.

From examination of geophysical log signatures (generally sharp bottom and fining-upward), and well cuttings (fair to good sorting, sub-rounded to rounded grains), the majority of Maxon sandstones were deposited in fluvial environments. Nicholas 445 (No. 1 D.E. Bell, Appalachian Exploration and Development), located within Twenty Mile Creek East field in Nicholas County, West Virginia, was cored in an upper Maxon sandstone interval. Cross bedding and mud clast inclusions in the sandstone core from this well are consistent with a fluvial origin for the sandstone (Kamm and Heald, 1983; Wrightstone, 1985).

The next lower productive unit is the drillers' Little Lime (Figure Mmc-4), which is the Reynolds Limestone Member of Reger and Price (1926). The Little Lime of eastern Kentucky is considered to be part of the upper Newman Limestone, although from examination of cross section D-D' (Figure Mmc-7) it is the same Little Lime as in West Virginia. The unit is widespread with a fairly consistent gamma-ray log character (see Figures Mmc-5, Mmc-6, Mmc-7, Mmc-8). In general, it is a brown to gray-brown argillaceous to silty limestone grading upwards into shale.

Production from the Little Lime is scattered and not of major importance. The earliest reference found to Little Lime production comes from Reger's (1916) description of a flowing oil well in Gilmer County, West Virginia. Only six possible Little Lime producers are listed for eastern Kentucky, and there are probably fewer than 100 in West Virginia. Production seems to be from the lower section of the Little Lime. No detailed description of the unit could be located with a corresponding geophysical log. In the few geophysical logs observed in wells with Little Lime production, the interval seems to be fairly clean. Carpenter (1976) describes an oolitic to skeletal grainstone lower section of Little Lime, in parts of Gilmer and Braxton counties, West Virginia. It is possible that porosity preservation or development in this sort of grainstone forms the typical productive interval of the Little Lime. Such grainstones probably were deposited in a shallow carbonate shelf environment.

The lowermost productive unit of the Mauch Chunk is the drillers' Blue Monday sandstone (Figure Mmc-4), which is equivalent (Flowers, 1956) to the Webster Springs sandstone of Reger (1920). The Blue Monday is one of the least studied important reservoirs in the central portion of the basin. It is not known to occur outside West Virginia.

Carpenter (1976) studied the Blue Monday in Gilmer and Braxton counties, West Virginia. He found the Blue Monday sitting directly on the Big Lime in some places and sitting on the Pencil Cave (Lillydale shale, Figure Mmc-4), overlying the Big Lime, in others. In his study area, thicker Blue Monday is somewhat entrenched into the top of the Big Lime. Carpenter concluded that the Blue Monday may be a product of tidal-dominated estuarine and sand flat deposition.

The position of the Mississippian-Pennsylvanian boundary in northern West Virginia and southwestern Pennsylvania makes it difficult to identify the stratigraphic position of producing strata in the area. Stratigraphic cross section B-B' (Figure Mmc-6a) extends from the Ohio River near Sistersville in Tyler County, West Virginia, eastward to just south of Mannington in Marion County, West Virginia. Cross section C-C' (Figure Mmc-6b) trends northwards from western Marion County into Greene County, Pennsylvania.

In Figures Mmc-6a and Mmc-6b, cross section C-C' intersects cross section B-B' at Marion 281/294 (a composite log of two wells in close proximity). At Wetzel 1174, the Maxon sandstone is entrenched into the top of the Big Lime, having cut out the Little Lime. The Maxon sandstone in this well is a reservoir for oil in Burton field. This same sandstone is present in Greene 22091, drilled in 1986 and completed in a lower zone. This well appears to be in the same field mentioned by Stone and Clapp (1907) that had gas production from the Maxon or Salvation sandstone, and it is assumed that this logged Mississippian sandstone in Greene 22091 is indeed the formerly productive interval.

The basal Pottsville unconformity has been cut progressively farther down into the Mississippian, going north along cross section C-C'. The position of the basal Pottsville (Mississippian-Pennsylvanian boundary) is also structurally lower north along the cross section.

Structure

Structure appears to be of relatively minor importance in determining the presence of Mauch Chunk fields and/or pools. The author is unaware of a single instance in the main portion of the play area where gas is trapped in a Mauch Chunk reservoir strictly by four-way anticlinal closure. Athens and Bozoo fields may be pure structural traps but are outside the main portion of the play.

Reservoir

The primary trap within the Mauch Chunk is porosity pinch-out in sandstone or sandstone pinch-out. Vertical sealing is by shale, siltstone, and occasionally limestone. Available data indicate that sandstone porosity is primary, as it has been preserved from cementation. The usual cement is quartz although carbonate is occasionally present. The reasons for porosity preservation at one locality and not at another remain obscure.

A much less common reservoir type found within the Mauch Chunk is porosity in limestone bounded laterally by non-porous limestone. Information on this type of reservoir is mostly limited to what can be garnered from geophysical logs.

There appears to be no published information on source rock for Mauch Chunk gas accumulations. Although most Mauch Chunk rocks are red to green at outcrop, there are fairly thick dark gray to black sections encountered in drilling that may contain sufficient organic carbon to have generated gas. The presence of occasional gassy coal beds within the section argues for sufficient thermal maturity. The average heating value for Mauch Chunk gas is around 1,050 Btu/cf. The presence of oil in Maxon sandstones in eastern Kentucky has not been researched, and Btu values of oil-associated gas are not included in this average.

In general, porosity within sandstone reservoirs of the Mauch Chunk is thought to be intergranular. Limited core data support this assumption. An upper Maxon sandstone interval was cored in Nicholas 445, Nicholas County, West Virginia, and has produced gas from part of the cored interval. Kamm and Heald (1983) discussed analysis of this core. The cored interval was previously assumed to be part of a Ravencliff sandstone. Petrographic work indicates that a pressure solution of silica, followed by redeposition as quartz overgrowth, has been largely responsible for reduction of porosity and permeability in the sandstone. Additionally, carbonate cementation in the lower portion of the sand body has further reduced porosity.

Cross-bedding with grading of grain size and collection of insolubles along stylolitic contacts affected permeability within the sandstone body. Core porosities ranged from 6 to 10 percent in perforated zones, while permeabilities ranged from 1 to 50 md. Porosity and permeability did not necessarily vary dependently.

Kamm and Heald (1983) mentioned another core, of either upper Maxon or actual Ravencliff sandstone, from the Raleigh 460 well in Pax field, Raleigh County, West Virginia. Kamm (1981) provided a table of various parameters from the core of Raleigh 460. Relative to the other core discussed, it appears to have more clay, less mono-crystalline quartz, less porosity (maximum of 7.3 percent), and poorer sorting.

The author's work with various reservoirs of the Ravencliff and Maxon intervals indicates that the general drive mechanism for production is gas-expansion. Areas in northern Kanawha and western Fayette counties, West Virginia, contain definite water-drive reservoirs in middle and lower Maxon sandstones. Dave Cox (oral commun., 1993) of Peake Operating stated that there is a water-drive Ravencliff sandstone reservoir in southeastern Fayette County, West Virginia.

Generally, most middle to lower Maxon sandstones have relatively low log porosity (less than 6 percent) and probably low permeability. Numerous samples

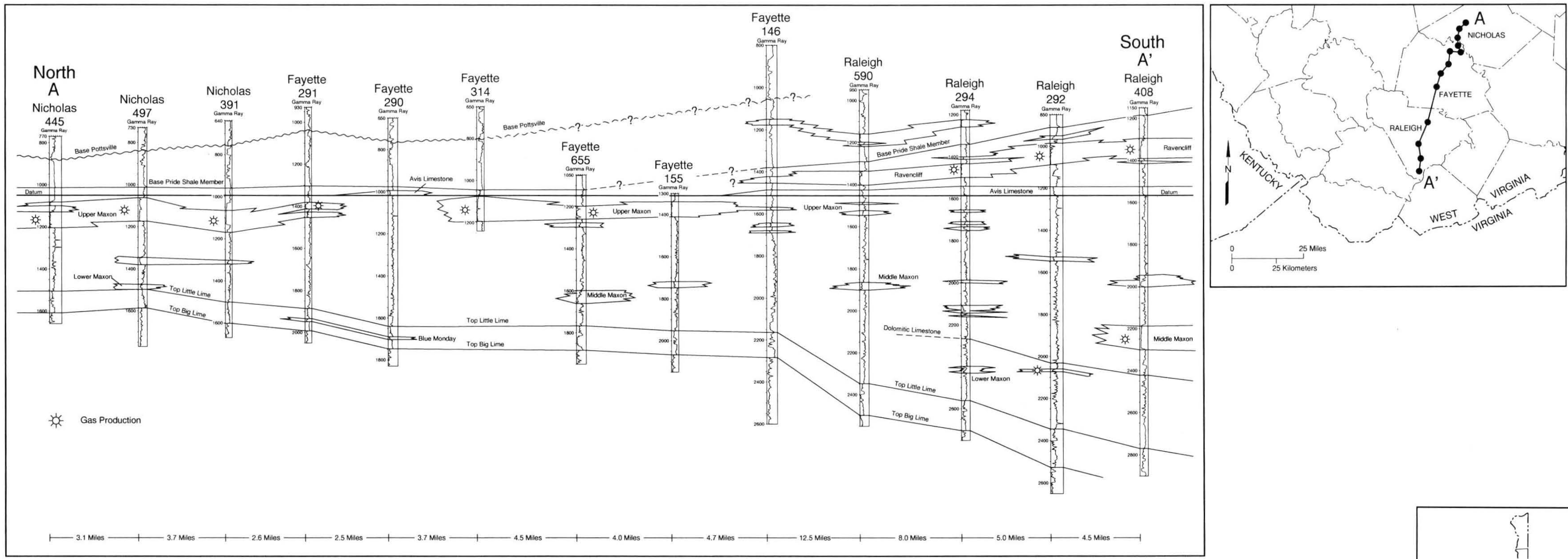


Figure Mmc-5. Stratigraphic cross section A-A' of Mauch Chunk Group and surrounding strata, Nicholas County to Raleigh County, West Virginia. Datum is the base of the Avis Limestone. This section is oriented roughly parallel to strike and crosses several of the fields with Mauch Chunk production. The lenticular nature of the Mauch Chunk Group sandstones is apparent as are the different productive zones in the fields. The section thickens from north to south. At the northern end of the cross section, the Upper Maxon is the producing interval in Twenty Mile Creek East field (Nicholas 445, Nicholas 497). This sand, previously identified as Ravencliff, occurs below the Avis Limestone. Ramsey field is just south of Twenty Mile Creek East field (Fayette 291, Fayette 314, Fayette 655). The Upper Maxon is productive in the northern part of the field; however, in the southern part of the field, the Middle Maxon is the producing interval. Fayette 290 is located about 2 miles southeast of Ramsey field. Note the absence of sandstone in the entire Mauch Chunk interval. Fayette 155 is located in a small unnamed area of production south of Ramsey field. The pay in this well is in the Big Lime. Other pays in the unnamed area are in the Ravencliff. Fayette 146 is similar to Fayette 290 in that it is southeast of the productive trend and lacks well-developed sandstones. In Mabscott field (Raleigh 590, Raleigh 294), the productive zone is the Ravencliff, above the Avis Limestone. At the southern end of the section, the Ravencliff and the Middle Maxon produces in Rhodell field (Raleigh 408). There is also Lower Maxon production in the eastern part of Rhodell field. There is a dolomitic limestone marker bed near the top of the Lower Maxon interval. This is visible on density logs at about 2,420 feet in Raleigh 408, and at about 2,260 feet in Raleigh 294. This marker can also be traced westward across southern West Virginia on cross section D-D' (Figure Mmc-7). Raleigh 408 is a tie well with cross section D-D' (Figure Mmc-7).

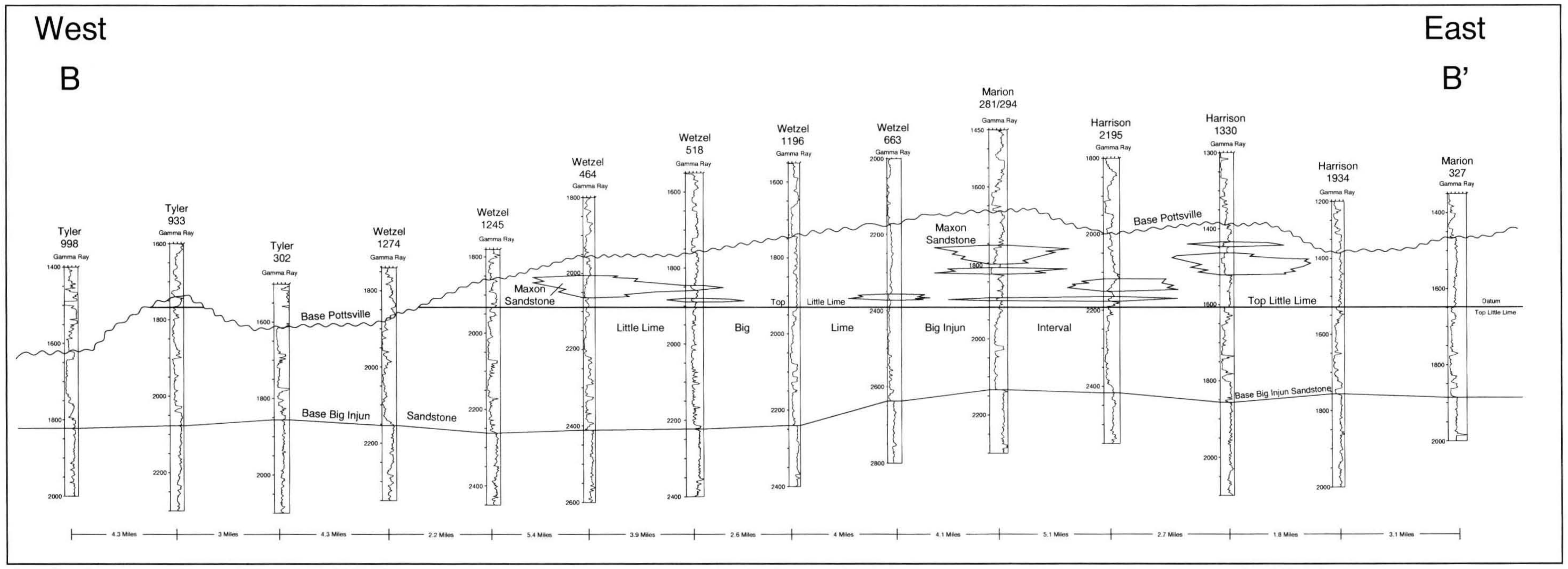


Figure Mmc-6a.

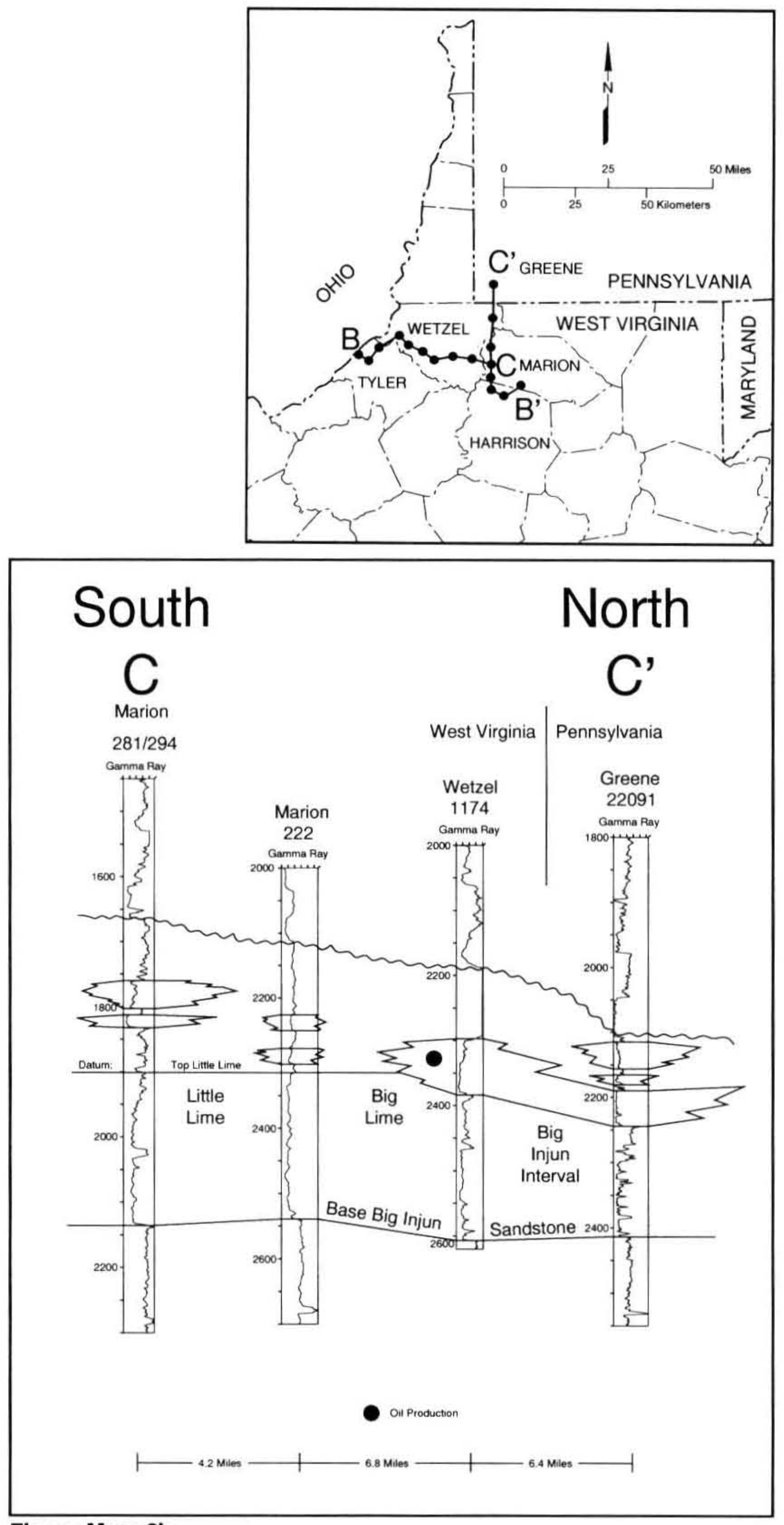
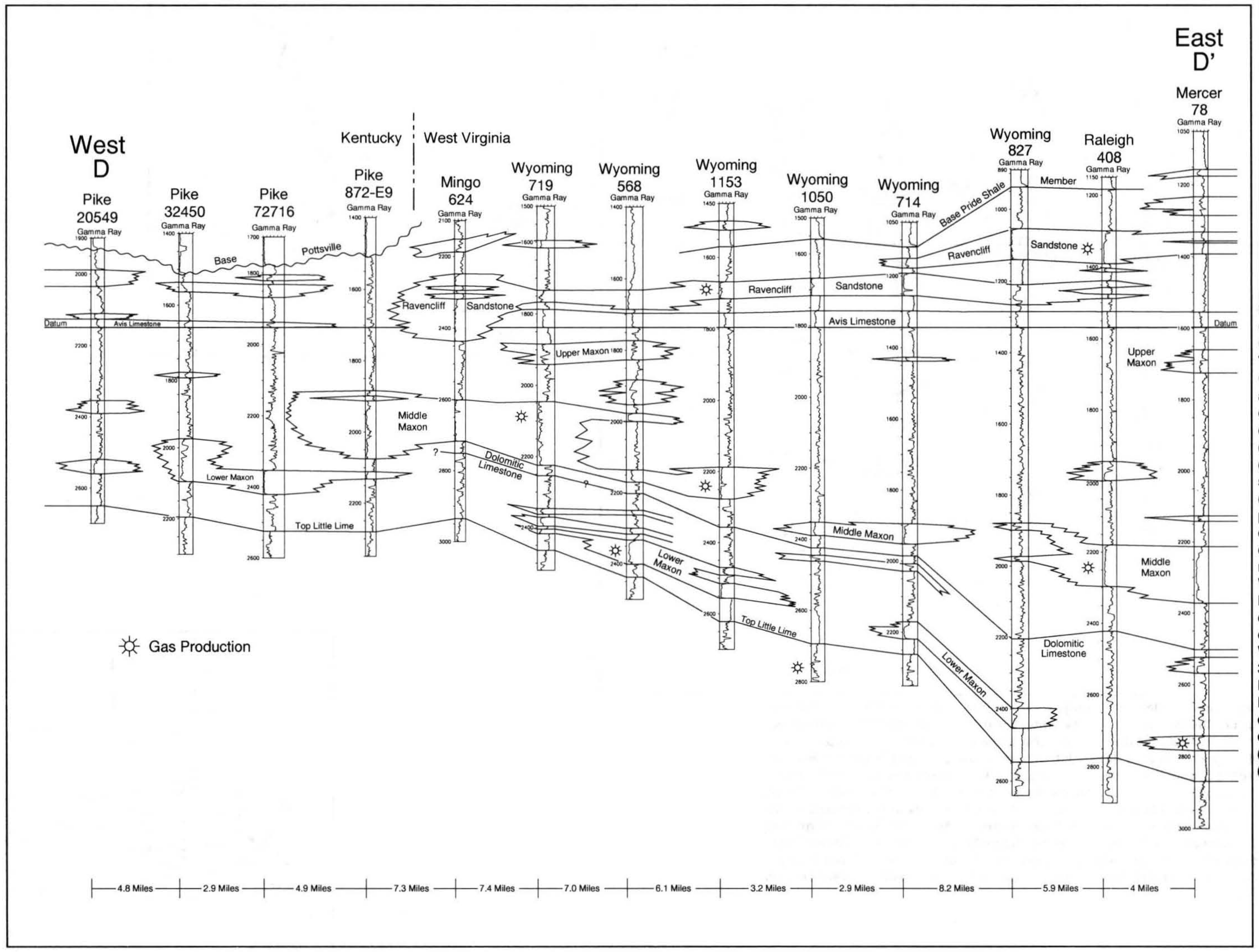


Figure Mmc-6b.

Figures Mmc-6a-b. Stratigraphic cross sections of Mauch Chunk Group and surrounding strata. Datum is the top of the Little Lime. Figure Mmc-6a. Cross section B-B', Tyler County to Marion County, West Virginia. Figure Mmc-6b. Cross section C-C', Marion County, West Virginia to Greene County, Pennsylvania. Wells are identified by county name and permit number. To avoid possible look-alike miscorrelations from use of only gamma-ray logs, all correlations have been verified by both gamma-ray and neutron and/or density logs where possible. Datum is the top of the Little Lime or its estimated position based on other markers. Various Maxon sandstones are visible along cross section B-B' from Marion 327 proceeding westward. The basal Pottsville unconformity cut progressively deeper into the Mauch Chunk west of Wetzel 464 and, except for a high spot at Wetzel 933, formed a continuously westward-sloping surface to the Ohio River. The Little Lime has been removed west of Wetzel 1245 except for the local erosional high at Tyler 933. The basal Pottsville sandstone is in contact with the Big Injun sandstone of early to middle Mississippian age in Tyler 998 on the west end of cross section B-B'.



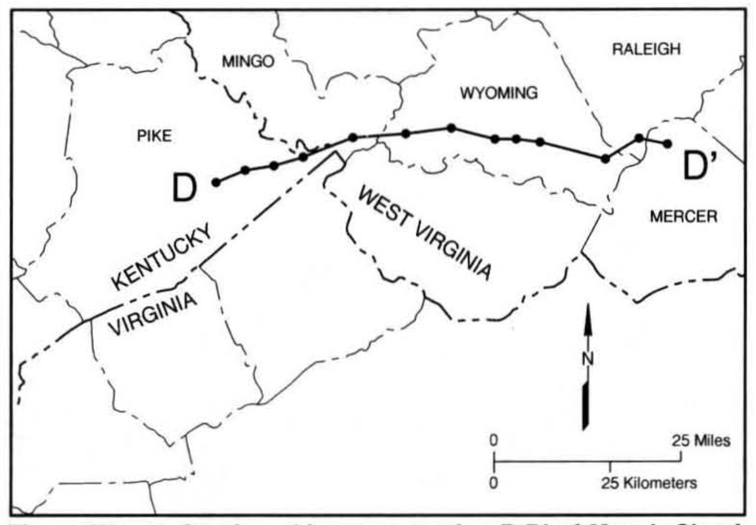
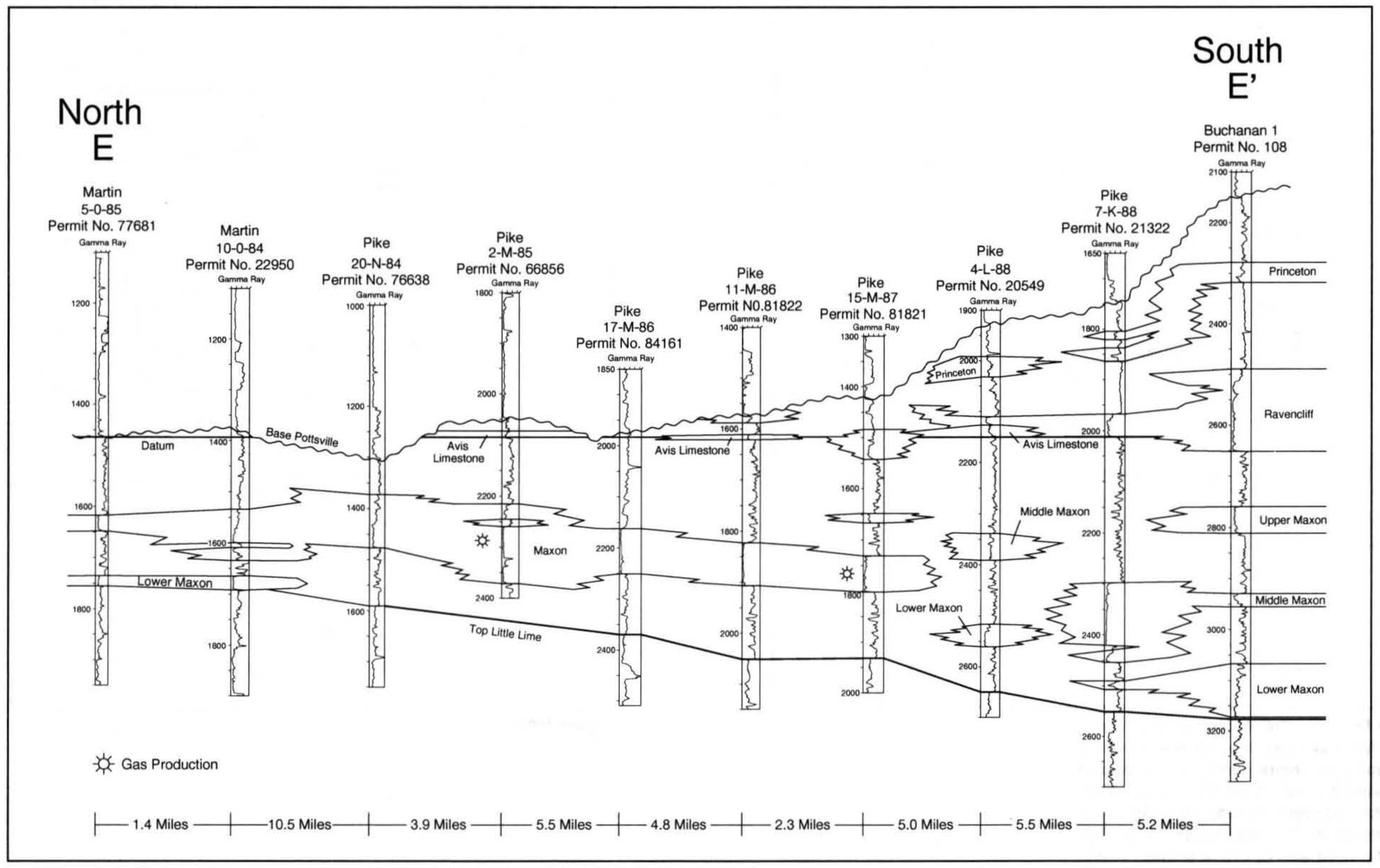


Figure Mmc-7. Stratigraphic cross section D-D' of Mauch Chunk Group and surrounding strata, Pike County, Kentucky, to Mercer County, West Virginia. Datum is the base of the Avis Limestone. This section is oriented perpendicular to strike. The entire Mauch Chunk interval thins from east to west. A channel in the Ravencliff appears to be preserved in western Wyoming and eastern Mingo counties, West Virginia (Mingo 624), where the Avis was completely removed by scouring in the Ravencliff channel. Schalla (1984) showed this as a "Maxon" sand; however, Wrightstone (1985) interpreted this as a Ravencliff sand body. Upper Maxon sandstones are not shown on this cross section, except locally (Wyoming 719). Lenticular Upper Maxon sand bodies may be present, but most of the interval is shaley. A middle Maxon channel sand is present in Rhodell field (Raleigh 408) at the eastern end of the cross section. Another larger, probably deltaic middle Maxon package extends from western Wyoming County, West Virginia, to eastern Pike County, Kentucky (Wyoming 719, Mingo 624, Pike 872-E9). Three lower Maxon fluvial channels are evident in the central and western parts of the cross section (the easternmost one is shown in Wyoming 1153, Wyoming 568, and Wyoming 719; the central one in Pike 872-E9, Pike 72716, and Pike 32450; the westernmost channel is shown in Pike 20549). The Little Lime is productive in Wyoming 1050 in Pineville field. The Little Lime in other wells in the section has a similar appearance on gamma-ray logs; however, no porosity is apparent on the density logs. Raleigh 408 is a tie well with cross section A-A' (Figure Mmc 5). Pike 20549 is a tie well with cross section E-E' (Figure Mmc 8).



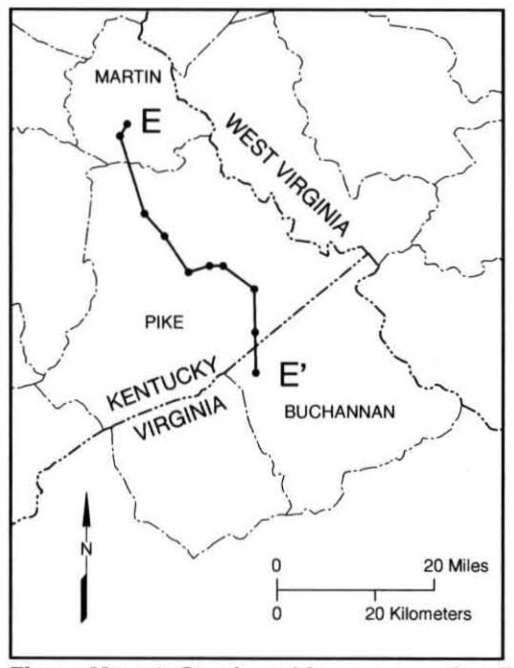


Figure Mmc-8. Stratigraphic cross section E-E' of Mauch Chunk Group and surrounding strata, Martin County, Kentucky, to Buchanan County, Virginia. Datum is the base of the Avis Limestone. The basal Pottsville sandstone was deposited in a progressively deeper scour into the Mississippian section from south to north except for a few local reversals. Similar Pottsville erosion in seen in northern West Virginia on cross section B-B' (Figure Mmc-6). The thick Ravencliff sandstone at the southern end of this cross section was deposited in a valley cut through the Avis (Buchanan 108). This is similar to the thick sandstone trend in western Wyoming and eastern Mingo counties, West Virginia (Figure Mmc-7). Identification of sandstones above the Ravencliff as Princeton in the area at the eastern end of the cross section is somewhat problematic. Relatively few upper Maxon sandstones are preserved in this part of Kentucky. The middle Maxon, by contrast, is a nearly continuous sandstone along the section. With the exception of Pike 66856 in Meta DBS field, no pays are shown within the Mauch Chunk in the wells used in this section. Logs through the interval were available for more recently drilled wells targeting deeper reservoirs. Many Maxon completions were made in older wells that were not logged. Lower Maxon sandstones are nearly as sparse as those in the Upper Maxon, although there has been limited production reported from them (Hamilton, 1958).

of well cuttings of these sandstones examined by the author show common quartz overgrowths. Repetitive fining-upward sequences also are commonly observed. In general, intervals with relatively high log porosities have better sorting and greater (at least medium) grain size within those same intervals. Almost all sandstones with more than 8 percent log porosity and greater than 60 ohm-meters deep resistivity in the middle and lower Maxon intervals in southern West Virginia will be gas productive.

Completion strategies have varied greatly over the history of development of this play. In earlier times, natural completion and shooting with nitroglycerin were the alternatives. In the 1950s, the introduction of hydraulic fracturing generally improved recovery from sandstones. While fracturing large intervals with water and/or gelled water carrying sand was the general technique in the 1960s and 1970s, the general practice currently is to perforate intervals with better log porosities and frac with gas assist, usually nitrogen. Foam fracs of 75 to 90 quality (10 to 25 percent liquid) with varying sand load have been common for the last 10 to 15 years. Although dependent on character of the section encountered, most perforated intervals now range from 10 to 40 feet.

The majority of Maxon wells experience steep initial decline, perhaps 75 percent over the initial three to five years of production, and then decline flattens markedly. A sizable minority of Maxon wells experience decline in the 5- to-10-percent range throughout their productive life.

Description of Key Fields

Rhodell field: Rhodell field, located in Raleigh, Wyoming, and Mercer counties, West Virginia (Figure Mmc-9), is a good example of a Ravencliff productive area in that it is areally extensive and probably has good cumulative production (see Figure Mmc-5). Mauch Chunk production was established in the field by a Maxon completion in 1944, and the first Ravencliff completion was made in 1965 (Table Mmc-1). The total extent of Ravencliff production has covered about 18,900 acres within the field, representing 82 wells, either commingled or Ravencliff-only.

Cumulative production for this field is not available. Partial cumulative data have been obtained by the author that indicate reasonably good production for Ravencliff-only wells. Two wells put on line in 1973, for which 1976 and 1977 data were missing, produced an average of 170,244 Mcf through 1979. Six wells put on line in 1975, for which 1976 and 1977 data were missing, produced an average of 42,520 Mcf through 1979. Five wells put on line in 1978 produced from 7,659 to 96,683 Mcf through 1979, and averaged 30,956 Mcf for the period. The low producing well of this group has been plugged. These wells were hydraulically fractured. Open flow measurements for the group ranged from 33 to 782 Mcf/d with shut-in casing pressure ranging from 135 to 160 psi. Most wells producing from Ravencliff in this field are Ravencliff-only completions.

The Raleigh 408 well (No. 17 McCreey Coal Land (20482) Columbia Gas Transmission) has been selected as an example of a typical completion of a Ravencliff sandstone interval. Figure Mmc-9 shows a geophysical log section of this well in the Ravencliff interval including gamma-ray and density curves. Log porosity within the productive portion of the sandstone varies from 6 to 11 percent. The initial gas flow check on the Ravencliff was 47 Mcf/d shortly after drilling through this interval. The well was perforated (4.5-inch casing) from 1,336 to 1,348 feet with seven holes and from 1,366 to 1,378 feet with seven holes. Treatment was hydraulic fracture with 7,500 pounds of 80/100 sand and 37,500 pounds of 20/40 sand in 687 barrels of fluid. This well was also perforated and fractured in a Maxon interval. Commingled open flow after treatment was 1,108 Mcf/d, measured after being open one hour.

Figure Mmc-9 reveals that structure, in general, plays little part in localizing production from the Ravencliff in Rhodell field. Trapping is essentially stratigraphic.

Twenty Mile Creek East field: Twenty Mile Creek East field, located in Nicholas County, West Virginia (Figure Mmc-10), is a good example of upper Maxon sandstone production, although the main pay in this field has previously been identified as Ravencliff. Production from this trend continues to the south; the field boundary at the county line is arbitrary. The field probably has good cumulative production and is areally extensive; it is located along the northern portion of cross section A-A' (Figure Mmc-5). Mauch Chunk play production was established in the field by a Blue Monday completion in 1949 and a middle to lower Maxon completion in 1953, while the first upper Maxon completion was made in 1976 (see Table Mmc-1). Upper Maxon production covers about 9,000 acres within the field. A total of 80 wells have been completed in upper Maxon zones in the field, the large majority of which are upper Maxon only.

Cumulative production for this field has not been made available. Partial cumulative data have been obtained by the author that indicate reasonably good production for upper Maxon-only wells. Six wells were put on line in 1978 and produced an average of 80,690 Mcf through 1979. Five wells were put on line in 1979 and produced an average of 47,355 Mcf for the year. All but one of the wells mentioned here were hydraulically fractured. Open flows from the fractured wells ranged from 492 Mcf/d to 5,083 Mcf/d. Open flow from the unstimulated completion was 2,310 Mcf/d. Shut-in casing pressure ranged from 174 to 200 psi. If this group of wells represents average performance for the field, the upper Maxon was a very productive zone.

The Nicholas 445 well has been selected as an example of a typical completion of an upper Maxon interval. Figure Mmc-10 shows a geophysical log section of the upper Maxon interval including gamma-ray and density curves. Log porosity within the productive portion of the sandstone varies from 6 to 12 percent. As discussed previously, this well was cored through part of the Ravencliff interval. It was perforated (4.5-inch casing) from 1,135 feet to 1,141 feet with six holes, from 1,154 feet to 1,158 feet with four holes, and from 1,162 feet to 1,170 feet with eight holes. Treatment was hydraulic fracture with 1,500 gallons of 15 percent HCl, 15,000 pounds of 80/100 sand, and 75,000 pounds of 20/40 sand in 615 barrels of fluid. Open flow was 492 Mcf/d measured after being open four hours. Shut-in casing pressure was 180 psi after an undisclosed interval of time. Cumulative production from 1979 through 1992 for Nicholas 445 is more than 250 MMcf.

The field well location and structure map (Figure Mmc-10) reveals that structure has little to do with localization of production from the upper Maxon reservoir in Twenty Mile Creek East field. Trapping is essentially stratigraphic.

Rock House West DBS field: Rock House West DBS field, located in Pike County, Kentucky (Figure Mmc-2), has been chosen as an example of middle to lower Maxon sandstone production. Hamilton (1958) documented high volume

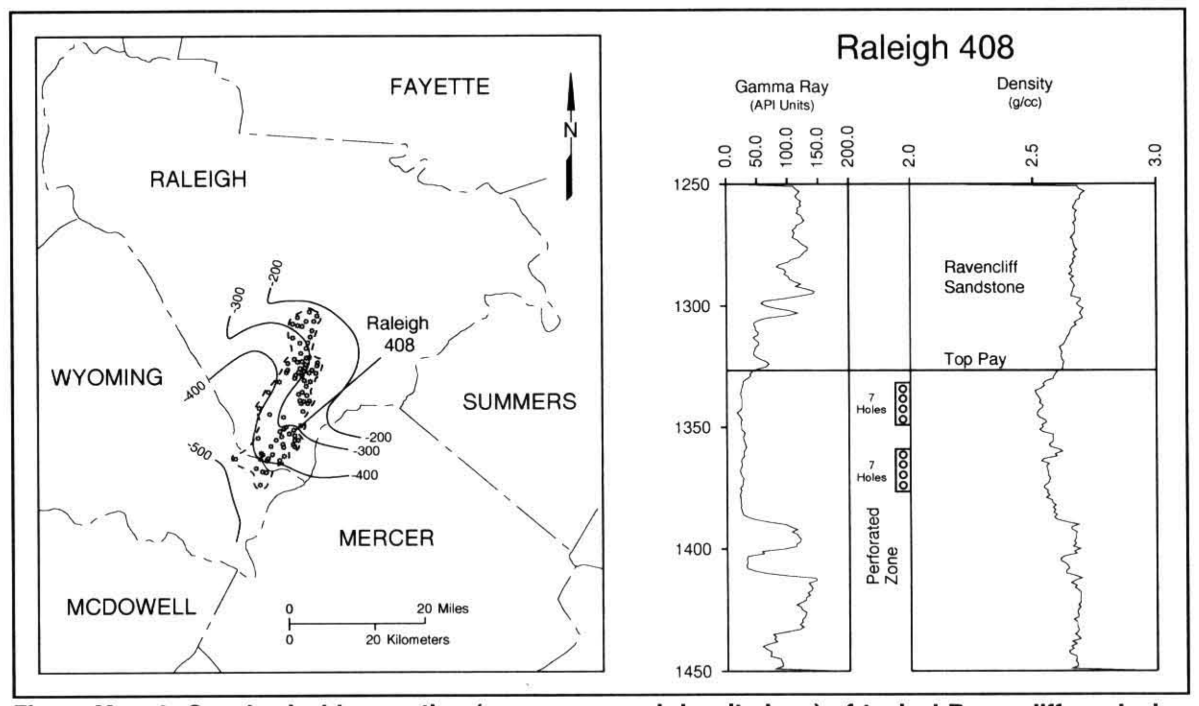


Figure Mmc-9. Geophysical log section (gamma-ray and density logs) of typical Ravencliff producing interval in Rhodell field, Raleigh County, West Virginia. Location map shows Ravencliff producing wells in Rhodell field. Structural contours on top of Big Lime. Contour interval = 100 feet. Modified after Haught (1968).

Maxon production from wells in this field. Pennington (Mauch Chunk equivalent) production was established by a Maxon completion in 1944 (Table Mmc-1). There appear to be at least 12 wells currently producing from Maxon within the field, probably as commingled multiple completions. No logs were obtained from Rock House West DBS field; however, logs from Meta DBS and Johns Creek DBS fields (Figure Mmc-11) are probably typical.

Hamilton (1958) presented a tabulation of numerous wells in the areas of what are now Rock House West DBS and Virgie Consolidated fields. Of 18 probable middle to lower Maxon wells, not commingled with deeper zones, the average yearly production was 61,198 Mcf with a range from 2,300 Mcf to 381,150 Mcf. The average length of production at the time of Hamilton's study was 5.5 years with a range from 2 to 11 years. Partial production information on four more recent commingled wells in the field has been provided. These wells are thought to be more than 10 years old and have an averaged yearly production of around 12,000 Mcf for the most recent three years.

Information on a few Maxon-only wells for three other Kentucky fields, Pigeon West, Canada, and Drift West, indicates an average cumulative production of 2,200,000 Mcf over an average life of 56 years. These wells are most likely exceptional and a true average of Maxon cumulative production is significantly less.

Meta DBS and Johns Creek DBS fields: Maxon production was established in Meta DBS field in 1945 and unstimulated open flows have averaged 2,244 Mcf/d. Pike 66856 was drilled in 1985 as a deeper formation test within Meta DBS field in 2-M-85 (Carter coordinates) and the log suite through the middle Maxon includes gamma-ray and density curves. Log porosity through the main sand body ranges from 5 to 20 percent. The Maxon sandstone shown in Pike 66856 was found to be pressure depleted.

The Pike 74004 well was drilled in 1987 within Johns Creek DBS field, just west of Meta DBS, in 6-M-85 (Carter coordinates) and the log suite through the middle Maxon sandstone includes gamma-ray and density curves (Figure Mmc-11). Maxon production was established in Johns Creek DBS field in 1948. In Pike 74004, log porosities range from 13.6 to 18 percent within the perforated interval. Natural flow from the Maxon interval before running pipe was 1,685 Mcf/d. The well was perforated from 1,610 to 1,626 feet, apparently through both 8-5/8-inch and 5-1/2- inch casing. Treatment was hydraulic fracture with 1,000 gallons of acid, 12,500 pounds of sand, 110 barrels of fluid, and 252,000 standard cubic feet of nitrogen. The well produced 150 Mcf/d into line against 160 psi back-pressure after treatment.

Figure Mmc-11 reveals that structure appears to play little part in localizing productive Mauch Chunk (Pennington) fields/pools in the illustrated area of eastern Kentucky. The presence of porous sandstone is thought to be the major controlling factor. There are areas with downdip water in porous sandstone, indicating apparent water-drive in some reservoirs.

Pineville field: Pineville field, located in Wyoming County, West Virginia (Figure Mmc-12), has been chosen as an example of production from the Little Lime. It is located along cross-section D-D' (Figure Mmc-7). Mauch Chunk play production was established in the field in 1942 by a Little Lime completion (see Table Mmc-1). Most completions of Mauch Chunk intervals since that time have not been Little Lime. There are only five wells producing from Little Lime within the field, according to the West Virginia Geological and Economic Survey computer database, all of which are commingled multiple completions.

TABLE Mmc-1

	Twenty Mile Creek East WV	Twenty Mile Creek East WV	McGraws WV	McGraws WV	Pineville WV	Pineville WV	Pineville WV
BASIC RESERVOIR DATA							
POOL NUMBER	47317323	47317335	47248319	47248325	47250319	47250325	47250331
DISCOVERED	1948	1949	1921	1937	1943	1943	1942
DEPTH TO TOP RESERVOIR	1,271	1,675	1,707	2,229	1,477	1,966	2,368
AGE OF RESERVOIR	Upper Mississippian	Upper Mississippian	Upper Mississippian	Upper Mississippian	Upper Mississippian	Upper Mississippian	Upper Mississippian
FORMATION	Hinton/ Bluefield	Bluefield	Hinton	Hinton/ Bluefield	Hinton	Hinton/ Bluefield	Bluefield
PRODUCING RESERVOIR	Maxon	Blue Monday	Ravencliff	Maxon	Ravencliff	Maxon	Little Lime
LITHOLOGY	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	limestone
TRAP TYPE	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic
DEPOSITIONAL ENVIRONMENT	fluvial-deltaic	estuarine/ shallow shelf	fluvial-deltaic	fluvial-deltaic	fluvial-deltaic	fluvial-deltaic	shallow shelf
DISCOVERY WELL IP (Mcf)	1,302	105	341		1,043	411	445
DRIVE MECHANISM	gas expansion	gas expansion	gas expansion	gas expansion/ water drive	gas expansion	gas expansion/ water drive	gas expansion
NO. PRODUCING WELLS	90	6	141	82	27	8	5
NO. ABANDONED WELLS	9	2	30	27	8	0	1
AREA (acreage)	11,880	960	46,000	29,321	7,665	1,752	1,314
OLDEST FORMATION PENETRATED	Devonian Onondaga	Devonian Onondaga	Silurian	McKenzie	Devonian Onondaga	Devonian Onondaga	Devonian Onondaga
EXPECTED HETEROGENEITY DUE TO:	sand/porosity pinchout	sand/porosity pinchout	sand/porosity pinchout	sand/porosity pinchout	sand/porosity pinchout	sand/porosity pinchout	porosity pinchout
RESERVOIR PARAMETERS							
AVERAGE PAY THICKNESS (ft.)							
AVERAGE COMPLETION THICKNESS (ft.)	26	9	25	55	33	37	16
AVERAGE POROSITY-LOG (%)							
MINIMUM POROSITY-LOG (%)	6						
MAXIMUM POROSITY-LOG (%)	12						13
NO. DATA POINTS	1						1
POROSITY FEET							
RESERVOIR TEMPERATURE (°F)			72				
INITIAL RESERVOIR PRESSURE (psi)	200	545	415	595	375	780	
PRODUCING INTERVAL DEPTHS (ft.)	872-2,274	1,408-2,308	734-3,043	1,521-3,483	1,164-1,925	1,342-2,389	2,090-2,761
PRESENT RESERVOIR PRESSURE (psi) / DATE			45/1985	118/1987			
FLUID & GAS PROPERTIES							
Rw (Ωm)	0.05	0.05	0.05	0.05	0.5	0.5	0.5
GAS GRAVITY (g/cc)	0.611			0.567			
GAS SATURATION (%)							
WATER SATURATION (%)							
COMMINGLED	no	no	no	yes	yes	yes	yes
ASSOCIATED OR NONASSOCIATED	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated
Btu/scf	1,091			1,026			
VOLUMETRIC DATA							
STATUS (producing, abandoned, storage)	producing	producing/ abandoned	producing	producing	producing	producing	producing
ORIGINAL GAS IN PLACE (Mcf)							
ORIGINAL GAS RESERVES (Mcf)							
PRODUCTION YEARS	1981-1993	1881-1993	1947-1993	1946-1993	1958-1993	1981-1993	
REPORTED CUMULATIVE PRODUCTION (Mcf)	37,800	6,400	6,321,000	2,764,700	1,230,400	80,700	
NO. WELLS REPORTED	6	1	66	16	7	1	
ESTIMATED CUMULATIVE PRODUCTION (Mcf)							
REMAINING GAS IN PLACE (Mcf)/YEAR							
REMAINING GAS RESERVES (Mcf)/YEAR							
RECOVERY FACTOR (%)							
INITIAL OPEN FLOW (Mcf/d)	2,046	792	558	1,195	456	1,925	127
FINAL OPEN FLOW (Mcf/d)	1,650		740	702	435	103	

	Rhodell WV	Rhodell WV	Smithton-Flint-Sedalia WV	Smithton-Flint-Sedalia WV	Stumptown-Normantown-Shock WV	Stumptown-Normantown-Shock WV	Stumptown-Normantown-Shock WV	Rosedale WV	Rosedale WV
BASIC RESERVOIR DATA									
POOL NUMBER	47268319	47268325	47099325	47099335	47180325	47180331	47180335	47202325	47202335
DISCOVERED	1972	1944	1905	1924	1920	1923	1924	1926	1926
DEPTH TO TOP RESERVOIR	1,280	2,320	1,712	1,725	1,582	1,823	1,728	1,800	1,995
AGE OF RESERVOIR	Upper Mississippian	Upper Mississippian	Upper Mississippian	Upper Mississippian	Upper Mississippian	Upper Mississippian	Upper Mississippian	Upper Mississippian	Upper Mississippian
FORMATION	Hinton	Hinton/ Bluefield	Hinton/ Bluefield	Bluefield	Hinton/ Bluefield	Bluefield	Bluefield	Hinton/ Bluefield	Bluefield
PRODUCING RESERVOIR	Ravencliff	Maxon	Maxon	Blue Monday	Maxon	Little Lime	Blue Monday	Maxon	Blue Monday
LITHOLOGY	sandstone	sandstone	sandstone	sandstone	sandstone	limestone	sandstone	sandstone	sandstone
TRAP TYPE	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic
DEPOSITIONAL ENVIRONMENT	fluvial-deltaic	fluvial-deltaic	fluvial-deltaic	estuarine/ shallow shelf	fluvial	shallow shelf	estuarine/ shallow shelf	fluvial	estuarine/ shallow shelf
DISCOVERY WELL IP (Mcf)								1,580	
DRIVE MECHANISM	gas expansion	gas expansion/ water drive	gas expansion/ water drive	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion/ water drive	gas expansion
NO. PRODUCING WELLS	82	75	26	9	59	5	20	12	83
NO. ABANDONED WELLS	2	3	19	1	36	1	3	5	62
AREA (acreage)	15,792	14,664	11,385	2,530	22,325	1,410	5,405	2,278	19,430
OLDEST FORMATION PENETRATED	Devonian Hampshire	Devonian Hampshire	Silurian Salina	Silurian Salina	Devonian Helderberg	Devonian Helderberg	Devonian Helderberg	Silurian McKenzie	Silurian McKenzie
EXPECTED HETEROGENEITY DUE TO:	sand/porosity pinchout	sand/porosity pinchout	sand/porosity pinchout water leg	sand/porosity pinchout	sand/porosity pinchout	porosity pinchout	sand/porosity pinchout	sand/porosity pinchout	sand/porosity pinchout
RESERVOIR PARAMETERS									
AVERAGE PAY THICKNESS (ft.)									
AVERAGE COMPLETION THICKNESS (ft.)	25	28	13	10	14	6	14	11	16
AVERAGE POROSITY-LOG (%)									
MINIMUM POROSITY-LOG (%)	6								
MAXIMUM POROSITY-LOG (%)	11								
NO. DATA POINTS	1								
POROSITY FEET									
RESERVOIR TEMPERATURE (°F)	67	80							
INITIAL RESERVOIR PRESSURE (psi)	135	420	630		450		650	495	605
PRODUCING INTERVAL DEPTHS (ft.)	778-2,102	1,800-2,900	1,455-2,040	1,520-1,939	1,200-2,815	1,550-2,320	1,426-2,045	1,145-2,212	1,655-2,360
PRESENT RESERVOIR PRESSURE (psi) / DATE			76/1983		98/1986		150/1986		
FLUID & GAS PROPERTIES									
Rw (Ωm)	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
GAS GRAVITY (g/cc)		0.563							
GAS SATURATION (%)									
WATER SATURATION (%)									
COMMINGLED	yes	no	yes	yes	yes	yes	yes	yes	yes
ASSOCIATED OR NONASSOCIATED	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	associated
Btu/scf		1,017							
VOLUMETRIC DATA									
STATUS (producing, abandoned, storage)	producing	producing	producing/ abandoned	producing	producing/ abandoned	producing	producing	producing/ abandoned	producing/ abandoned
ORIGINAL GAS IN PLACE (Mcf)									
ORIGINAL GAS RESERVES (Mcf)									
PRODUCTION YEARS	1973-1993	1964-1993	1979-1993	1981-1993	1922-1993		1979-1993	1981-1993	1981-1993
REPORTED CUMULATIVE PRODUCTION (Mcf)	8,618,000	1,126,800	226,600	44,700	2,629,500		210,000	337,000	687,000
NO. WELLS REPORTED	68	5	5	2	10		2	3	3
ESTIMATED CUMULATIVE PRODUCTION (Mcf)									
REMAINING GAS IN PLACE (Mcf)/YEAR									
REMAINING GAS RESERVES (Mcf)/YEAR									
RECOVERY FACTOR (%)									
INITIAL OPEN FLOW (Mcf/d)		309	1,633		1,448			1,976	95
FINAL OPEN FLOW (Mcf/d)	324	927	646		224		163	255	587

	Swandale-Widen WV	Warfield DBS KY	Rock House West DBS KY	Kayjay Consolidated KY
BASIC RESERVOIR DATA				
POOL NUMBER	47264335	1602071	1601674	1601090
DISCOVERED	1941	1899	1944	1979
DEPTH TO TOP RESERVOIR	1,880	1,173	2,082	2,333
AGE OF RESERVOIR	Upper Mississippian	Upper Mississippian	Upper Mississippian	Upper Mississippian
FORMATION	Bluefield	Pennington	Pennington	Pennington
PRODUCING RESERVOIR	Blue Monday	Maxon	Ravencliff/ Maxon	Maxon
LITHOLOGY	sandstone	sandstone	sandstone	sandstone
TRAP TYPE	stratigraphic	stratigraphic	stratigraphic	stratigraphic
DEPOSITIONAL ENVIRONMENT	estuarine/ shallow shelf	fluvial	fluvial	fluvial-deltaic
DISCOVERY WELL IP (Mcf)			94	4,579
DRIVE MECHANISM	gas expansion/ water drive	gas expansion	gas expansion	gas expansion
NO. PRODUCING WELLS	104	30	37	20
NO. ABANDONED WELLS	26	2	3	0
AREA (acreage)	29,770			
OLDEST FORMATION PENETRATED	Silurian McKenzie	Devonian Ohio	Middle Devonian	Mississippian Borden
EXPECTED HETEROGENEITY DUE TO:	sand/porosity pinchout	sand/porosity pinchout	sand/porosity pinchout	sand/porosity pinchout
RESERVOIR PARAMETERS				
AVERAGE PAY THICKNESS (ft.)		12	18	17
AVERAGE COMPLETION THICKNESS (ft.)	12			
AVERAGE POROSITY-LOG (%)			12	13
MINIMUM POROSITY-LOG (%)	9			
MAXIMUM POROSITY-LOG (%)	12.5			
NO. DATA POINTS	1		2	7
POROSITY FEET				
RESERVOIR TEMPERATURE (°F)	75	72	77	74
INITIAL RESERVOIR PRESSURE (psi)	743		620	
PRODUCING INTERVAL DEPTHS (ft.)	1,470-2,234			
PRESENT RESERVOIR PRESSURE (psi) / DATE				
FLUID & GAS PROPERTIES				
Rw (Ωm)	0.05	0.06	0.06	0.06
GAS GRAVITY (g/cc)		0.681	0.665	0.674
GAS SATURATION (%)			84	58
WATER SATURATION (%)			16	42
COMMINGLED	yes			
ASSOCIATED OR NONASSOCIATED	nonassociated	nonassociated	nonassociated	associated
Btu/scf		1,169	1,133	1,107
VOLUMETRIC DATA				
STATUS (producing, abandoned, storage)	producing			
ORIGINAL GAS IN PLACE (Mcf)				
ORIGINAL GAS RESERVES (Mcf)				
PRODUCTION YEARS	1941-1993			
REPORTED CUMULATIVE PRODUCTION (Mcf)	6,096,200			
NO. WELLS REPORTED	43			
ESTIMATED CUMULATIVE PRODUCTION (Mcf)				
REMAINING GAS IN PLACE (Mcf)/YEAR				
REMAINING GAS RESERVES (Mcf)/YEAR				
RECOVERY FACTOR (%)				
INITIAL OPEN FLOW (Mcf/d)	871			
FINAL OPEN FLOW (Mcf/d)	598	853	1,998	1,884

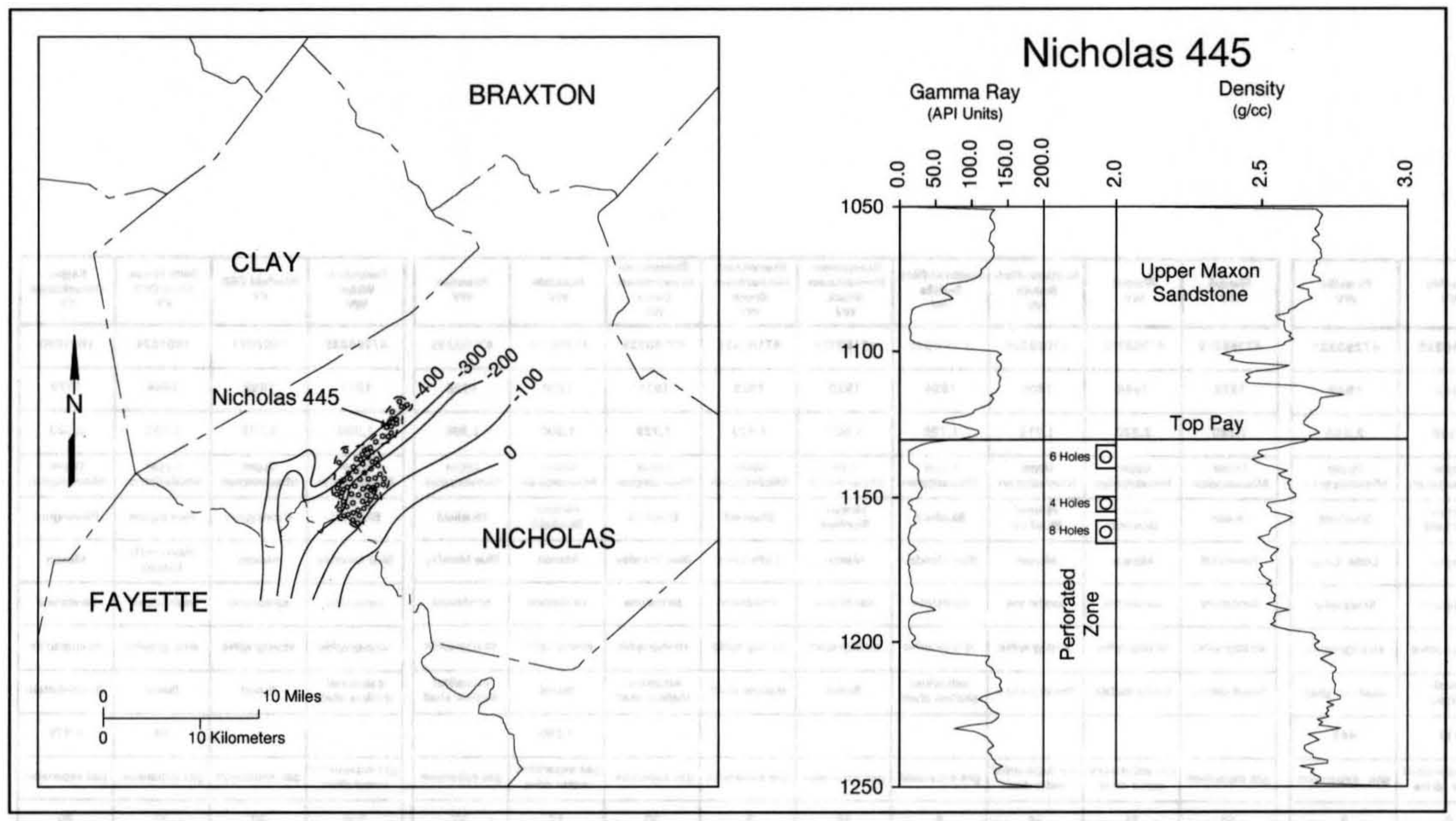


Figure Mmc-10. Geophysical log section of typical Upper Maxon producing interval in Twenty Mile Creek East field, Nicholas County, West Virginia. Location map shows Upper Maxon producing wells in Twenty Mile Creek East field. Structural contours on top of the Big Lime. Contour interval = 100 feet. Modified after Haught (1968).

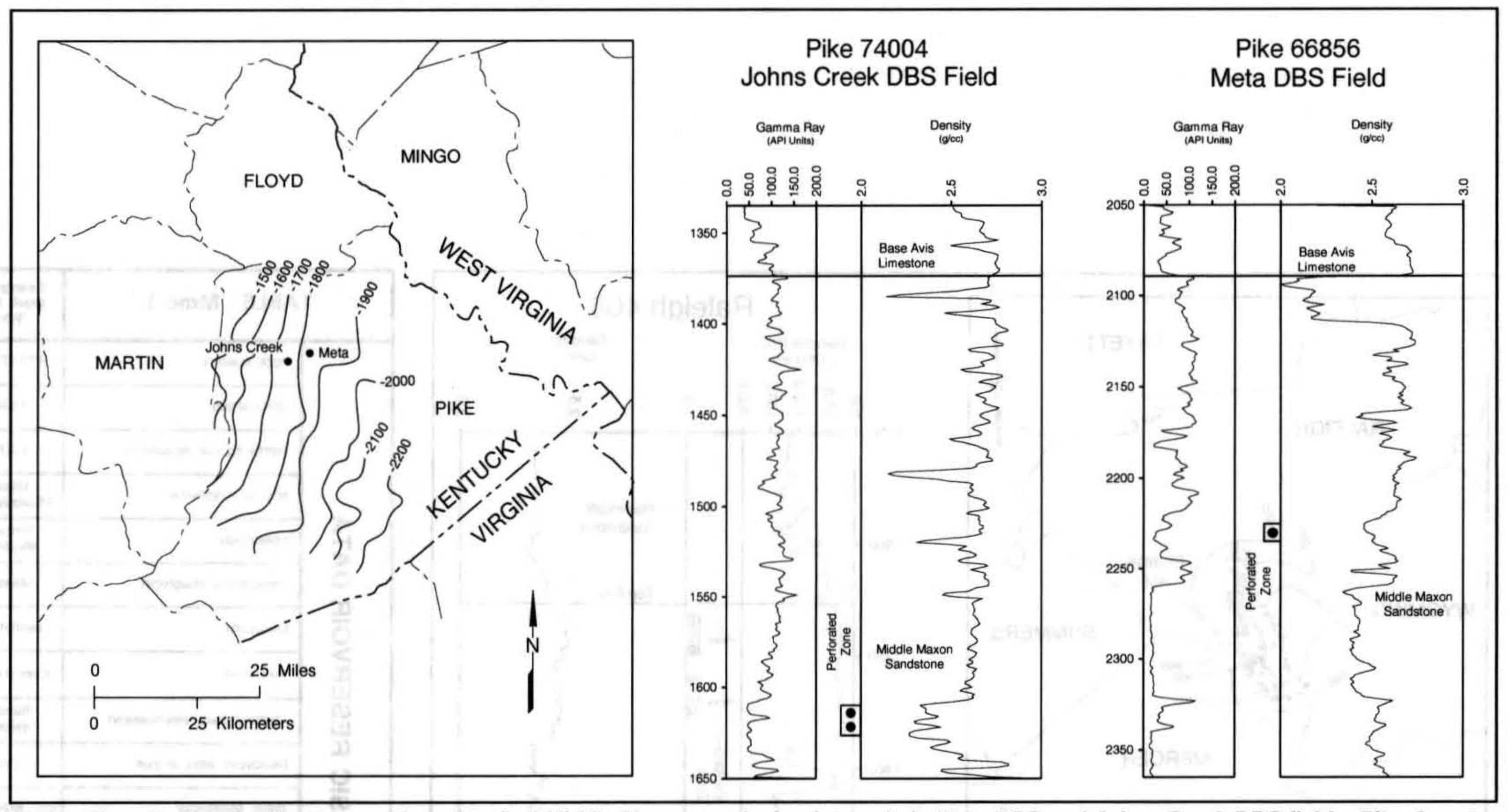


Figure Mmc-11. Geophysical log section of typical Middle Maxon producing intervals in Meta DBS and Johns Creek DBS fields, Pike County, Kentucky. Location map shows Mauch Chunk (Pennington) producing wells in Meta DBS and Johns Creek DBS fields. Structural contours on top of Ohio Shale. Contour interval = 100 feet. Modified after Moody and others (1987).

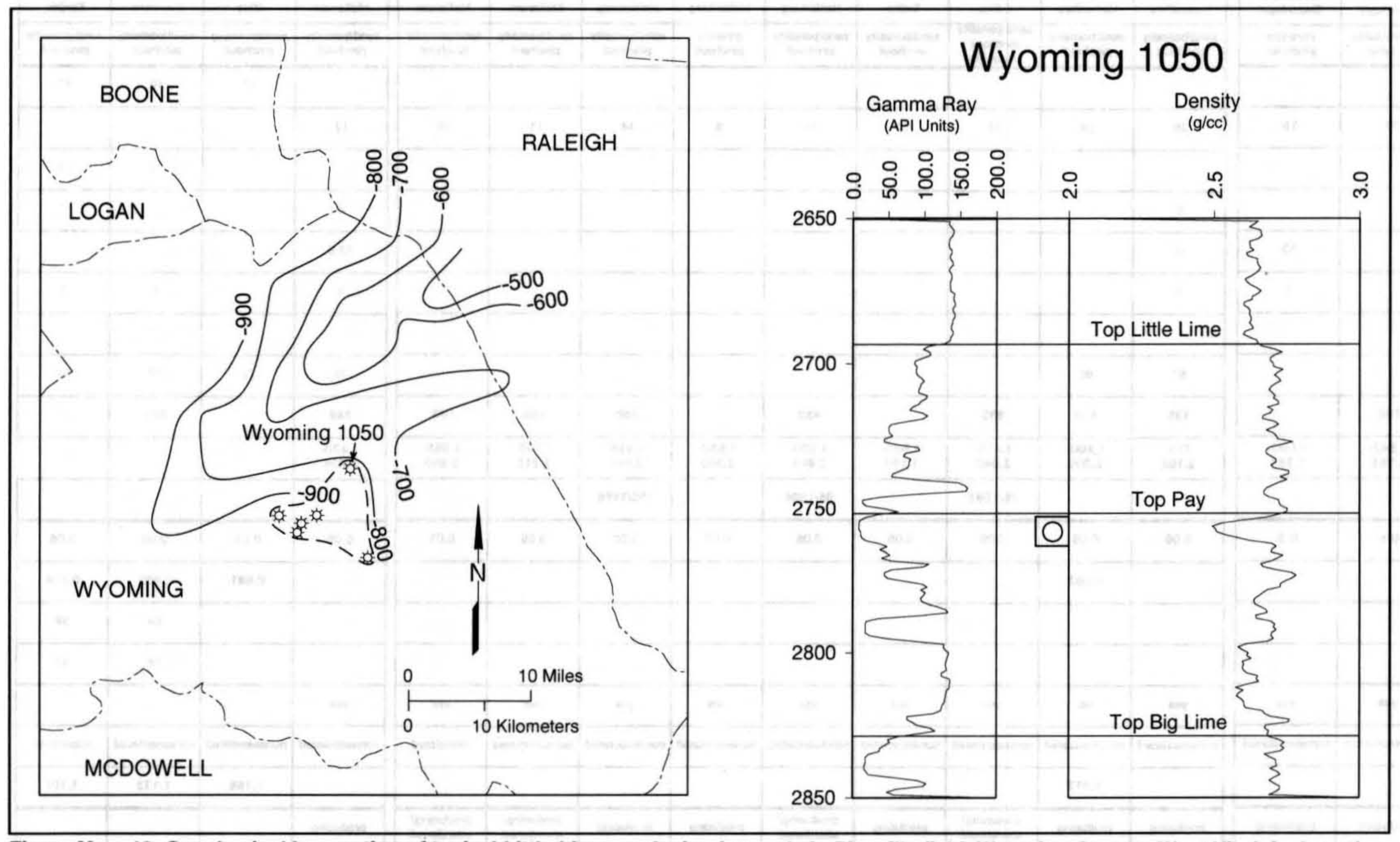


Figure Mmc-12. Geophysical log section of typical Little Lime producing intervals in Pineville field, Wyoming County, West Virginia. Location map shows Little Lime producing wells in Pineville field. Structural contours on top of Big Lime. Contour interval = 100 feet. Modified after Haught (1968).

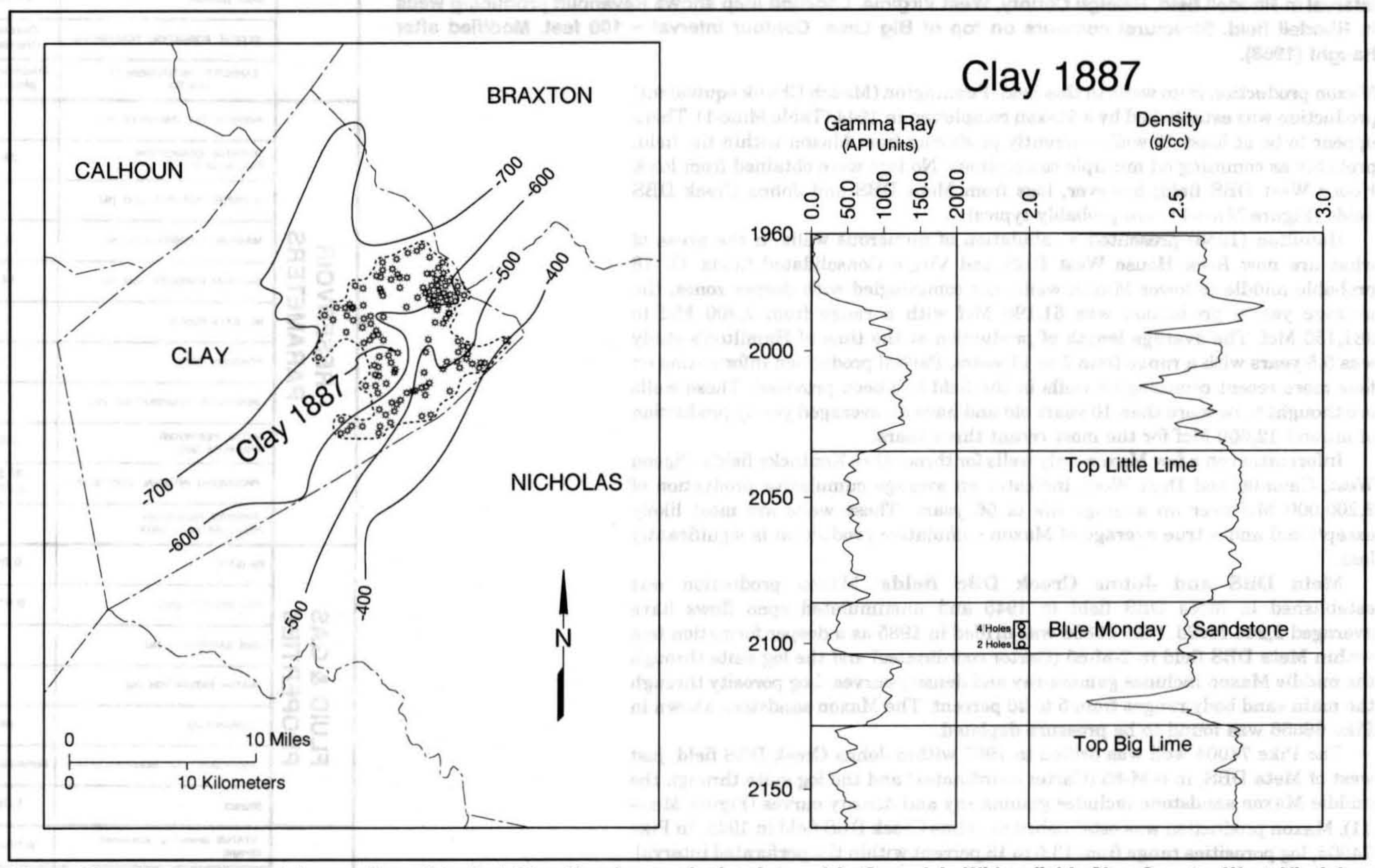


Figure Mmc-13. Geophysical log section of typical Blue Monday producing interval in Swandale-Widen field, Clay County, West Virginia. Location map shows Blue Monday producing wells in Swandale-Widen field. Structural contours on top of Big Lime. Contour interval = 100 feet. Modified after Haught (1968).

Cumulative production for the Wyoming 1050 well (Cabot Oil and Gas, No. B-15 Pocahontas Land Company) is 101,860 Mcf for the period of 1990 through 1992.

The Wyoming 1050 well has been selected as an typical example of a Little Lime completion. Figure Mmc-12 shows a section of a geophysical log through this interval and includes gamma-ray and density curves. Log porosity is at a maximum of about 13 percent within the completed zone. The well was perforated (4.5-inch casing) from 2,754 feet to 2,761 feet. Treatment was hydraulic fracture with 155 barrels of 15 percent HCl and 143 barrels of gelled water. The Big Lime and Gordon were also completed in this well. Open flow of this multiple-completion was 1,008 Mcf/d after being open four hours.

So little is known about Little Lime production that it is uncertain if structure is generally important, as it usually is with Big Lime production. The field well location and structure map (Figure Mmc-12) reveals that Little Lime wells in Pineville field are nearly all close to, but off, the axis of the Pineville anticline. Porosity development is rare in the Little Lime, and it is not known if the development is linked to structural position. Insufficient information is available to ascertain whether porosity development in the play area as a whole is always the major factor in production or if there are areas of porous, wet Little Lime.

Swandale-Widen field: Swandale-Widen field, located in Clay County, West Virginia (Figure Mmc-13), has been chosen as an example of Blue Monday sandstone production because it is areally extensive, is thought to have good production, and geophysical logs were available for examination. Mauch Chunk play production in the field was established by a Blue Monday completion in 1941 (Table Mmc-1). The total area within the field, outlined by Blue Monday production, encompasses 39,000 acres, although not all wells within this area are Blue Monday producers, nor is the entire area drilled up. A total of 126 wells have been completed in Blue Monday sandstone in the field. The majority of wells are commingled completions with either Big Lime and/or Big Injun.

Cumulative production for this and other fields has not been made available. Partial cumulative data have been obtained by the author that indicate reasonably good production for Blue Monday-only wells. Four wells put on-line between 1941 and 1943 had average cumulative production of 414,480 Mcf through 1975. Five wells put on line between 1946 and 1950 had an average cumulative production of 549,792 Mcf through 1975. The wells mentioned above were all unstimulated completions with open flows ranging from 214 Mcf/d to 3,535 Mcf/d and shut-in casing pressure ranging from 535 psi to 743 psi. One hydraulically fractured well that went on-line in 1971 had cumulative production of 26,539 Mcf for the period of 1978 through 1979. One well drilled in 1979 was 1,000 Mcf/d with shut-in casing pressure of 500 psi. This latter well was reported to have shut-in casing pressure of 192 psi at the end of 1979.

The Clay 1887 well (John Neal, No. 1 W.E. King (405) Sterling Drilling) has been selected as a typical example of a recent Blue Monday completion. Figure Mmc-13 shows a section of a geophysical log of the interval and includes gamma-ray and density curves. Log porosity for the completed zone ranges from 9 to 12.5 percent. The well was perforated (4.5-inch casing) from 2,094 feet to 2,102 feet. Treatment was hydraulic fracture with 500 gallons of 15 percent HCl, 15,000 pounds of 80/100 sand, 30,000 pounds of 20/40 sand, and 505 barrels of fluid. The Big Injun was also completed in this well. Open flow of this dual-completion was 980 Mcf/d after being open 40 hours. Cumulative production for Clay 1887 from 1981 through 1992 is more than 150 MMcf.

The field well location and structure map (Figure Mmc-13) shows that structure has little to do with localizing production from Blue Monday in the field. Trapping is essentially stratigraphic. Well records indicate that there are areas within the field where the Blue Monday is probably non-porous, and other areas where it is reported to be wet. Wet wells are also not necessarily structurally lowest, suggesting additional heterogeneity within this field.

Resources and Reserves

Much of the drilling and production from fields/pools of this play occurred prior to permitting requirements and any requirements for reporting of production. Thus, cumulative production data for older areas are generally unobtainable. Additionally, reporting of production is not required by law everywhere within the play area. Even where production reporting is required, compliance has been and continues to be variable.

For areas of newer production—mostly post-war drilling—there can be difficulty in obtaining public domain production data. Well-documented Mauch Chunk completions exist in 4,200 wells. The author estimates an average recoverable figure of 80,000 Mcf per well for completions for the history of the play. This results mostly from wells in which Mauch Chunk intervals were not the primary target and discoveries were fortuitous.

Original gas in place is estimated at a minimum of 1.424 tcf. A rough statistical comparison of present completions versus total wells drilled combined with an estimate of missed opportunities leads the author to estimate that there are about 4,700 Mauch Chunk completions yet to be made in Kentucky, Virginia, and West Virginia. Careful work should ultimately recover an additional 376 bcfg.

Future Trends

Although much of the Upper Mississippian Mauch Chunk play area has been explored for Mauch Chunk and deeper zones, it is still possible to obtain new production in relatively heavily drilled areas. Pike 74004 (Figure Mmc-11) is an example of such infill production. Careful study of previous geophysical logs and well records for missed opportunities is how such discoveries will be made. There is still room for expansion of discoveries between existing fields and the general outcrop/subcrop limits (compare Figures Mmc-1 and Mmc-3). In general, the southern two-thirds of the play area has more exploration potential than the northern third because of lesser well density. Redevelopment potential probably exists throughout the play except in old, very densely drilled areas where casing/plugging is inadequate.

A potential target that has been ignored is the Maxon sandstones where they have been truncated by the basal Pennsylvanian unconformity, with the overlying strata possibly forming a seal. This could open up the entire northwestern extent of the play area to renewed scrutiny.

PLAY Mgn: UPPER MISSISSIPPIAN GREENBRIER/NEWMAN LIMESTONES

by Richard Smosna, West Virginia University

Location

Upper Mississippian carbonate rocks are prolific producers of natural gas in the Appalachian basin (Figures Mgn-1, Mgn-2). Approximately 3,400 wells produce from the Newman Limestone in 257 fields of eastern Kentucky; 6,000 wells from the Greenbrier Limestone in 183 fields of West Virginia; 300 wells in seven fields of Virginia; 54 wells from the equivalent Maxville Limestone in three fields of eastern Ohio; and an undetermined number of wells from the Monteagle Limestone in 35 fields of north-central Tennessee. Because the major gas production comes from the Greenbrier Limestone in West Virginia and the Newman Limestone in Kentucky, these two stratigraphic units are emphasized here. Pools in the Greenbrier/Newman Big Lime (drillers' name) occur throughout southwestern West Virginia and southeastern Kentucky, whereas Greenbrier Big Injun and Keener pools extend across the north-central part of West Virginia (Figure Mgn-3).

Production History

Of 63 large Greenbrier/Newman fields found in West Virginia, Kentucky, and Virginia since 1920, all but eight were discovered during three intervals of active exploration. Large fields are loosely defined as those with 20 or more wells and covering an area greater than 5,000 acres. Eleven fields were discovered from 1920 to 1931, 27 from 1941 to 1958, and 17 from 1970 to 1989. Presumably, these periods of exploration were related to post-war economic expansions and recent energy crises. The three small Ohio fields were discovered between 1903 and 1911. Of 35 Monteagle fields found in Tennessee, 31 were discovered in the period between 1979 and 1989 (Table Mgn-1). Cumulative production from the almost 10,000 wells in four states (West Virginia, Kentucky, Virginia, and Ohio) may have been as high as 2.9 tcf. Basic reservoir data, reservoir parameters, fluid and gas properties, volumetric data, and original gas reserves for 14 representative fields with sufficient information are presented in Table Mgn-1.

Stratigraphy

A basin-wide stratigraphic framework is lacking for Upper Mississippian limestones and dolomites. From Pennsylvania to Tennessee, these rocks are considered stratigraphically equivalent, but they have not been correlated in detail. A major problem is that geologists assign different names to equivalent strata across state boundaries: the Greenbrier Limestone (or Group) in West Virginia, Maryland, and Virginia; the Newman Limestone or Slade Formation in Kentucky; the Newman, Monteagle, and Bangor limestones in Tennessee; the Maxville Limestone in Ohio; and the Loyalhanna and Trough Creek limestones and the Deer Valley and Wymps Gap members of the Mauch Chunk Formation in Pennsylvania. In contrast, drillers in four states have long recognized the likeness of these rocks, which they generally call Big Lime. Here, a geological framework is presented that combines formal stratigraphic nomenclature of outcrop exposures and the drillers' names of subsurface units (Figure Mgn-4).

The Greenbrier Limestone, in parts of West Virginia, unconformably overlies a clastic sequence that has been called the Pocono Formation. Recently, it has been suggested that the term Pocono be replaced by the name Price. Here, however, this sequence will be referred to as the Pocono Formation.

In West Virginia, three distinct stratigraphic zones of the Greenbrier Limestone produce gas: the basal Big Injun, the middle Keener, and various oolite zones in the upper section. The basal unit consists of dolomitic sandstone, sandy dolomite, oolitic dolomite, dolomitic ooid grainstone, or sandy ooid grainstone (Martens and Hoskins, 1948). Drillers call this unit the Greenbrier Big Injun and often confuse it with the underlying Pocono or Price Formation (Ruley, 1970). Furthermore, the dolomitic section is highly irregular in distribution, which precludes mapping. This Greenbrier Big Injun correlates with the Loyalhanna Limestone of Pennsylvania (Overbey, 1967) and was deposited as submarine dunes of mixed quartz-carbonate sand in a nearshore-marine environment (Adams, 1970; Carney and Smosna, 1989). Dolomite is mostly secondary, having replaced ooids, fossils, and calcite cement (Smosna, 1989).

The Keener sandstone, a fine-grained, well sorted, calcite- or dolomite-cemented sandstone, occurs near the middle of the Greenbrier, but recognition and correlation are haphazard. Its distribution, therefore, appears to be neither continuous nor well defined. In northern West Virginia, the Keener sandstone may be an extension of the Savage Dam Member of the Mauch Chunk Formation from Pennsylvania (Frohne, 1967) (Figure Mgn-4). The Savage Dam represents barrier-island and offshore-shelf sands (Brezinski, 1989). Often, however, the Keener may be just a misidentification of the Greenbrier Big Injun, especially in areas where drillers also apply the name Big Injun to a sandstone of the upper Pocono Formation (Haught, 1959). Also, some oolitic dolomites in southern West Virginia are quartz-rich (Martens and Hoskins, 1948) and may be misidentified as a sandstone. Finally, vertical changes in dolomite and quartz content as well as in porosity and permeability exist within the Big Injun, and drillers may use these differences to distinguish between a Keener above and a Big Injun below (McCord and Eckard, 1963).

Ooid grainstones in the upper Greenbrier also serve as gas reservoirs. Development of these oolites commonly is thought to have had some important relationship to the underlying unconformity (Youse, 1964). They may have been deposited as shoreline sands associated with a Greenbrier transgression over the unconformity, lagoon-margin sands around topographic lows on the underlying Maccrady and Pocono formations, haloes surrounding topographic highs, and shoals atop submerged highs of the unconformity. In contrast, oolites in Wyoming County, West Virginia, accumulated as tidal bars oriented perpendicular to a structural hinge line (Kelleher and Smosna, 1993). Productive ooid-sand bodies elsewhere in southern West Virginia have a narrow, elongate shape with a

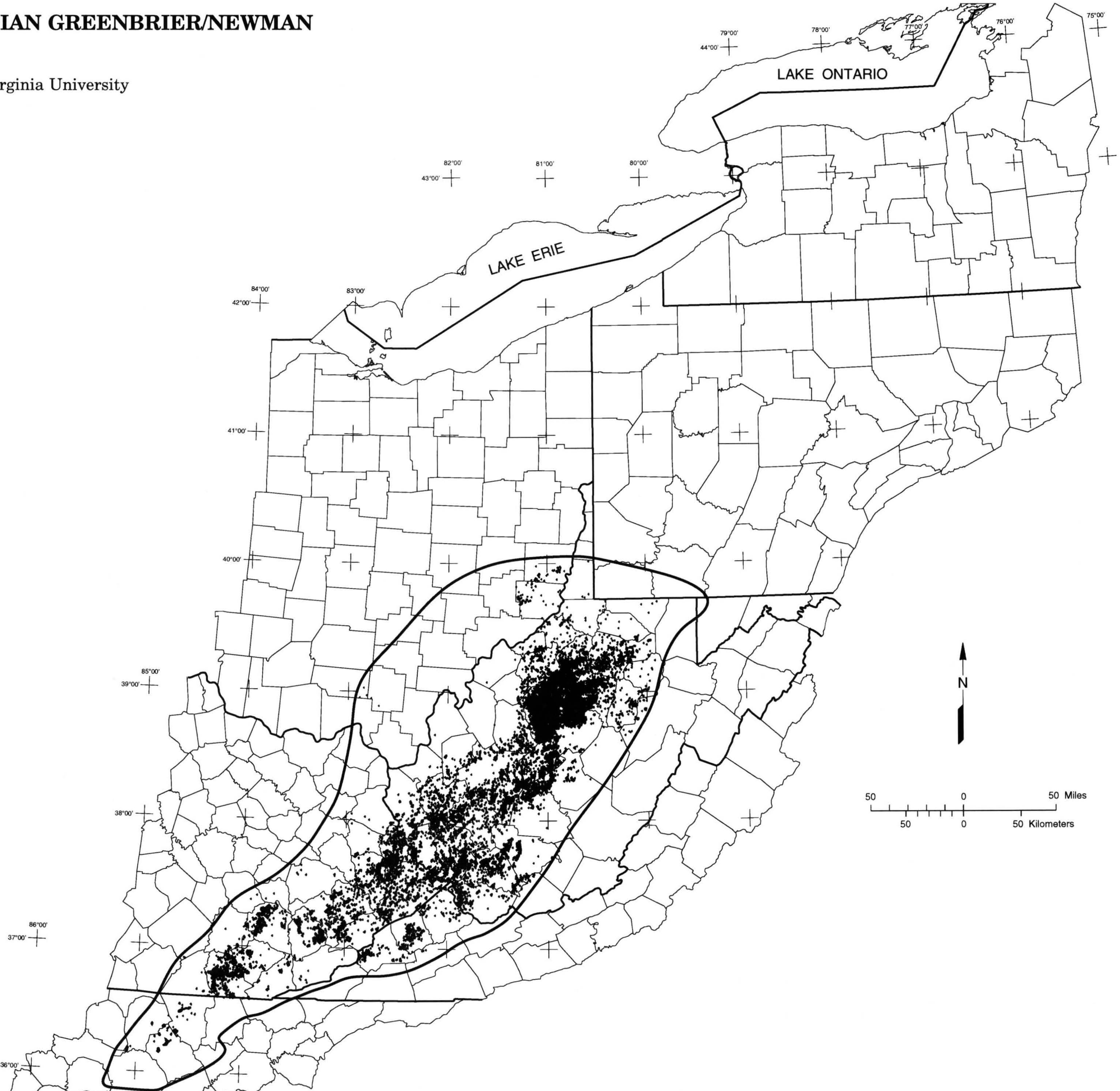


Figure Mgn-1. Outline of the Upper Mississippian Greenbrier/Newman Limestone play in the Appalachian basin. Most production to date comes from the central region, whereas the basin periphery has not been as fully explored. Dots represent individual gas wells; areas where dots have merged represent fields.

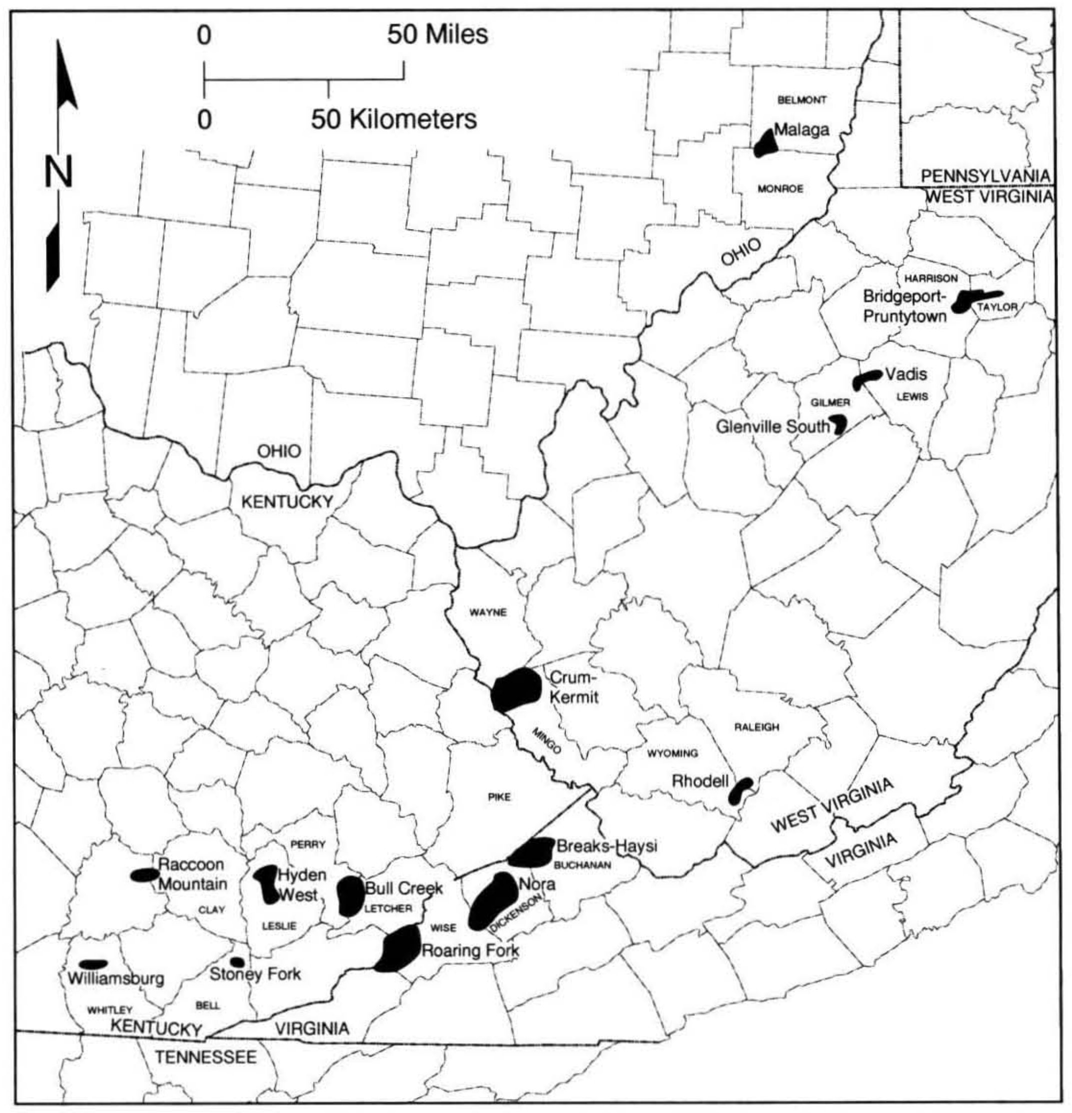


Figure Mgn-2. Location of Greenbrier and Newman Limestone fields discussed in text or listed in Table Mgn-1. Other productive areas depicted in Figure Mgn-1 are not shown.

	TABLE Mgn-1	Williamsburg KY	Bull Creek KY	Hyden West KY	Raccoon Mountain KY	Stoney Fork KY	Rhodell WV	Crum-Kermit WV	Vadis WV	Glenville South WV	Bridgeport-Pruntytown WV	Breaks-Haysi VA	Nora VA	Roaring Fork VA	Malaga OH
BASIC RESERVOIR DATA	POOL NUMBER	1602130332	1600302332	1600497332	1601600332	16019000332	47268315	47243345	47292365	47301365	47110355 47110365				100
	DISCOVERED	1920	1958	1955	1923	1953	1965	1899	1910	1922	1909	1955	1949	1954	1905
	DEPTH TO TOP RESERVOIR	1,350	2,750	2,226	1,020	2,992	3,128	1,756	1,834	2,073	1,426	3,361	4,050	4,157	1,182
	AGE OF RESERVOIR	Upper Mississippian	Upper Mississippian	Upper Mississippian	Upper Mississippian	Upper Mississippian	Upper Mississippian	Upper Mississippian	Upper Mississippian	Upper Mississippian	Upper Mississippian	Upper Mississippian	Upper Mississippian	Upper Mississippian	Upper Mississippian
	FORMATION	Newman	Newman	Newman	Newman	Newman	Greenbrier	Greenbrier	Greenbrier	Greenbrier	Greenbrier	Greenbrier	Greenbrier	Greenbrier	Maxville
	PRODUCING RESERVOIR	Big Lime	Big Lime	Big Lime	Big Lime	Big Lime	Big Lime	Big Lime	Big Injun	Big Injun	Keener-Big Injun	Big Lime	Big Lime	Big Lime	Big Lime
	LITHOLOGY	limestone/ dolomite	calcareous dolomite	calcareous dolomite	limestone	limestone	oolitic limestone	limestone	dolomite	calcareous sandstone	calcareous sandstone	oolitic limestone	oolitic limestone	oolitic limestone	limestone
	TRAP TYPE	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic
	DEPOSITIONAL ENVIRONMENT	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine
	DISCOVERY WELL IP (Mcf)	4,000	220	1,245	250	783	550					678	250		10,000
	DRIVE MECHANISM	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion
	NO. PRODUCING WELLS	262	141	91	25	11	69	139	249	434	107	29	138	73	18
	NO. ABANDONED WELLS	1	5	1	1	1	0	19	53	48	43				2
	AREA (acreage)	48,735	28,461	22,196	5,748	5,105						10,840	39,000	26,000	210
	OLDEST FORMATION PENETRATED	Clinton	Lockport	Clinton	Knox	Corniferous	Price	Corniferous	Upper Devonian	Upper Devonian	Brallier	Devonian Shale	Devonian Shale	Wildcat Valley Sandstone	Ohio
	EXPECTED HETEROGENEITY DUE TO:	deposition diagenesis	desposition diagenesis	deposition diagenesis	deposition diagenesis	deposition diagenesis	deposition diagenesis	deposition diagenesis	deposition diagenesis	deposition diagenesis	deposition diagenesis	deposition diagenesis	deposition diagenesis	deposition diagenesis	deposition diagenesis
RESERVOIR PARAMETERS	AVERAGE PAY THICKNESS (ft.)	11	24	23	15	16	40		15						20
	AVERAGE COMPLETION THICKNESS (ft.)						40	90	16	39	31	47	98	110	
	AVERAGE POROSITY--LOG (%)	10	14	15	12	13	10		13			2	2	2	18
	MINIMUM POROSITY--LOG (%)	2	4	4	4	4	6		10			<1	<1	<1	15
	MAXIMUM POROSITY--LOG (%)	21	25	26	19	21	15		20			18	25	20	27
	NO. DATA POINTS	50	19	21	12	3						8	15	7	1
	POROSITY FEET														
	RESERVOIR TEMPERATURE (°F)	72	86		62	85									
	INITIAL RESERVOIR PRESSURE (PSI)	240	549	460	185	530			600		450		500-1,000		380
	PRODUCING INTERVAL DEPTHS (ft.)	875-1,876	2,290-3,598	1,786-2,828	756-1,282	2,505-3,768	2,496-3,970	1,117-2,682	1,218-2,182	1,643-2,538	1,114-1,930	2,810-3,755	3,280-5,240	3,500-5,480	1,182-1,485
	PRESENT RESERVOIR PRESSURE (psi) / DATE	130/1992		475/1992	140/1989										
FLUID & GAS PROPERTIES	Rw (Ωm)	0.1	0.1	0.1	0.1	0.1						0.05	0.05	0.05	
	GAS GRAVITY (g/cc)		0.7	0.677											
	GAS SATURATION (%)	83	85	84	58	65									
	WATER SATURATION (%)	17	15	16	42	35									
	COMMINGLED	yes	no	yes	yes	yes	yes					yes	yes	yes	yes
	ASSOCIATED OR NONASSOCIATED	nonassociated	associated	nonassociated	nonassociated	associated	nonassociated	nonassociated	nonassociated	nonassociated		nonassociated	nonassociated	associated	
	Btu/scf		1,217	1,165											
VOLUMETRIC DATA	STATUS (producing, abandoned, storage)	producing	producing	producing	producing	producing	producing	producing	producing	producing	producing	producing	producing	producing	
	ORIGINAL GAS IN PLACE (Mcf)														
	ORIGINAL GAS RESERVES (Mcf)	21,200,000	77,300,000												
	PRODUCTION YEARS	1964-1993	1958-1993	1988-1992	1923-1993	1965-1992	1965-1993	1899-1993	1910-1993	1922-1993	1909-1993	1955-present	1949-present	1954-present	
	REPORTED CUMULATIVE PRODUCTION(Mcf)	5,032,474		52,499		1,896,619									
	NO. WELLS REPORTED	59		1		4									
	ESTIMATED CUMULATIVE PRODUCTION (MCF)		42,300,000		7,500,000		20,700,000	41,700,000	74,700,000	130,200,000	32,100,000				
	REMAINING GAS IN PLACE (Mcf)/DATE														
	REMAINING GAS RESERVES (Mcf)/DATE														
	RECOVERY FACTOR (%)														
	INITIAL OPEN FLOW (Mcf/d)						311	1,561	1,875	255	881				1,000
	FINAL OPEN FLOW (Mcf/d)	1,236	1,238	1,164	299	632	3,249	1,332	1,357	1,387	554	1,082	130	130	

similar north or northwestern trend, and these also may have formed as tidal bars oriented perpendicular to a hinge line.

In Kentucky, the Newman Limestone produces natural gas from two zones. An unnamed basal unit contains medium- to thick-bedded, cherty, skeletal, dolomitic limestone and finely crystalline dolomite. Locally, dolomite can account for up to 40 percent of the stratigraphic section (Nicholson, 1983), and production occurs where the dolomite is anomalously thick. Pay zones are confined to long and narrow tidal, fluvial, or estuarine channels that cut into the underlying Borden Formation. Scattered ooid grainstones that are locally dolomitized and occur throughout the Newman constitute another important reservoir. Horne and others (1974) interpreted the oolites as barrier-island facies that supposedly interfinger landward with tidal-flat red and green shales of the Pennington Formation and seaward with offshore red and green shales of the Borden Formation. This interpretation has been refuted by Ettensohn (1980), who posited that the oolites formed as submarine sand belts on a carbonate shelf, younger in age than the Borden and older than the Pennington. Nevertheless, distribution of oolites at the base of the Newman, like those of West Virginia, are thought to be related to the underlying unconformity.

Structure

Production trends rarely show a relation to structure, but several fields (for example, Vadis field in West Virginia) lie along anticlinal noses and may be structurally controlled in part (Ruley, 1970; Watts and others, 1982). Furthermore, major structural elements influenced the development of reservoir rocks in two ways, as follows.

A structural hinge line may be placed near the 200-foot or 300-foot isopach contour where the Greenbrier Limestone thins dramatically northwestward across West Virginia (Donaldson, 1974). Placement of this line is arbitrary, and a more reasonable position would parallel the 600-foot contour (Flowers, 1956). Additionally, Kelleher and Smosna (1993) identified a hinge line along the 900-foot contour. Perhaps differential subsidence throughout the region was accommodated along several hinge lines. More importantly, these hinge lines (Figure Mgn-5) could have controlled the depositional pattern of oolitic reservoirs; belts of tidal bars may trend along a hinge line.

In Kentucky, rejuvenation of basement structures during Mississippian time may have locally controlled the distribution of Newman fields. Pay zones in the basal dolomite of the Big Lime are concentrated along long, narrow trends generally interpreted as erosional channels on the pre-Newman unconformity. These channels tended to develop over paleotopographic highs, such as the Perry and Pike County uplifts (MacQuown and Pear, 1983) and the Hyden West and Hyden East highs of Leslie County (Okolo, 1977).

Moore (1987) and Moore and Moshier (1987) suggested that fractures identified by low-altitude remote sensing enhance gas production in the basal dolomite of the Newman in southern and eastern Kentucky. Although there is no anticlinal control, production is associated with prominent fractures and with fracture intersections. Production increases where the dolomite thickens, which may be along fracture systems (in contrast to the interpretation of pre-depositional channels). Fractures likely would have served as a conduit for dolomitizing fluids migrating into the Big Lime. Perhaps, too, fracturing weakened the underlying Borden shales and siltstones, allowing channels of the pre-Newman unconformity to form preferentially along the linear fracture traces.

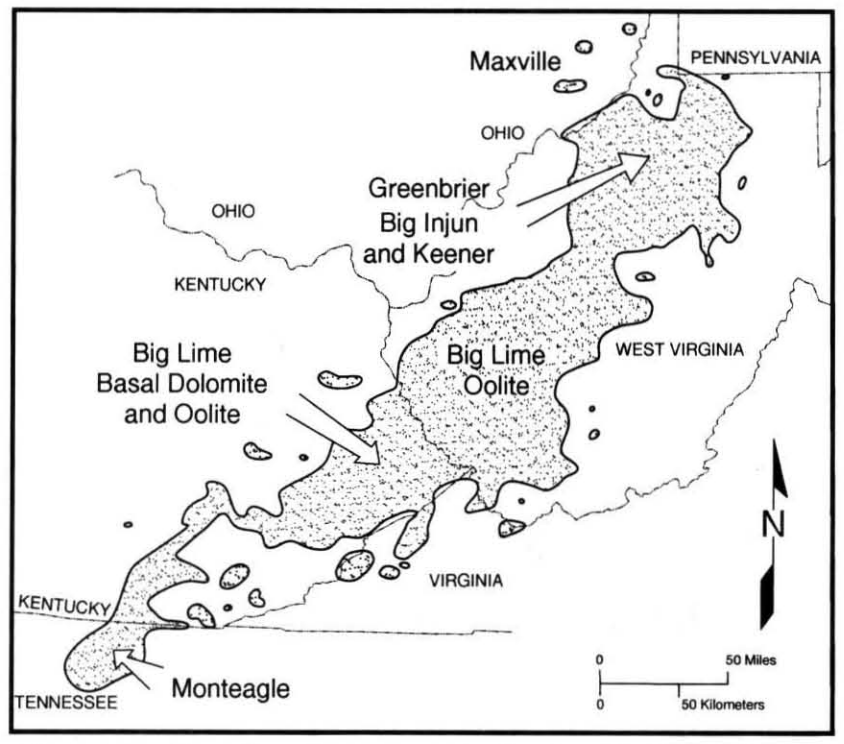


Figure Mgn-3. Location of present production from the Greenbrier and Newman limestones, illustrating the approximate area of major reservoirs (designated by drillers' names) in Kentucky, Ohio, Tennessee, Virginia, and West Virginia.

Reservoir

Most of the data concerning Upper Mississippian carbonate reservoirs are taken from the files of the West Virginia Geological and Economic Survey and the Kentucky Geological Survey.

Big Lime gas fields in West Virginia are stratigraphic traps: porous oolites grade laterally into nonporous, nonoolitic limestones. Pay zones, representing oolitic sand bodies, vary in thickness from 15 feet to as much as 97 feet, although exceptional reported thicknesses are probably vertically stacked oolites. The depth to the top of the reservoir in 23 large fields ranges between 1,000 and 5,000 feet, but depths of 1,600 to 2,900 feet are most common. Average initial open flows in these 23 fields were 19 to 8,330 Mcfg/d, but maximum reported open flows were large, as much as 25 MMcfg/d. Many different completion techniques are used on Big Lime wells: natural completion, acidize, acidize and fracture, fracture, and shoot. After treatment, final open flows varied between 21 and 12,228 Mcfg/d, averaging 1,230 Mcfg/d. The lowest reported rock pressure is 50 psi and the highest is 820 psi; 500 psi is a typical value. Most reservoirs are underpressured, a condition generally attributed to tectonic uplift of isolated pools accompanied by erosion of overlying units. Porosity is both interparticle (primary) and intraparticle (secondary oomoldic) and ranges between 3 and 28 percent, averaging 11 percent. Permeability is usually much less than 1 md but may be as high as 5 to 15 md.

Greenbrier Big Injun fields are stratigraphic and related to lateral permeability changes. The reservoir lithology may be sandy, oolitic, and/or dolomitic, whereas the seals consist of impermeable limestone. Pay-zone thickness can be as great as 70 feet, but it is typically 15 to 30 feet. Pay zones are shallow, that is, between 1,200 and 2,500 feet. Average initial open flows for 12 large fields are reported to be 46 to 4,500 Mcfg/d, and final open flows are 10 to 14,230 Mcfg/d with an average of 1,006 Mcfg/d. Almost all wells are treated by either acidizing or fracturing and acidizing. Rock pressures range from 115 psi to 840 psi, averaging 500 psi. Porosity (intercrystalline-dolomite, vuggy, moldic, and interparticle) averages 13 percent with a maximum near 20 percent (McCord and Eckard, 1963; Overbey and others, 1963; Frohne, 1967; Watts and others, 1982). Permeability, however, is low, averaging 1 md (reported values ranged between 0.1 and 99 md). In southwestern Pennsylvania, rocks of the Big Injun/Loyalhanna are porous, but they produce only salt water (Harper and Laughrey, 1987).

Very little data are available on reservoir characteristics of Keener fields. Fields usually have fewer than 30 producing wells. Drilling depths range from 1,200 to 3,000 feet with an average near 1,900 feet, and the reservoir thickness

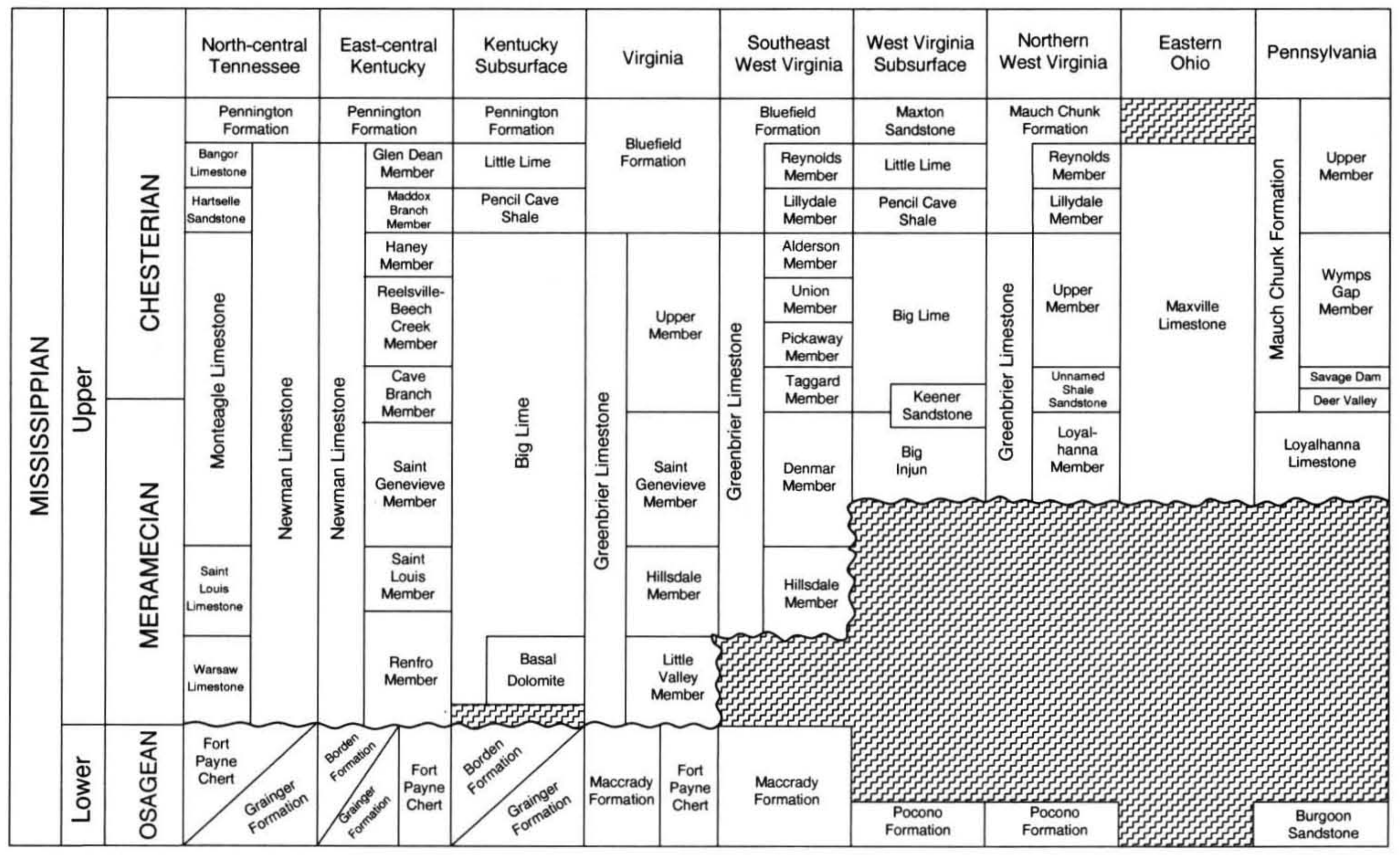


Figure Mgn-4. Correlation chart for Upper Mississippian limestones of the Appalachian basin. From Carney and Smosna (1989).

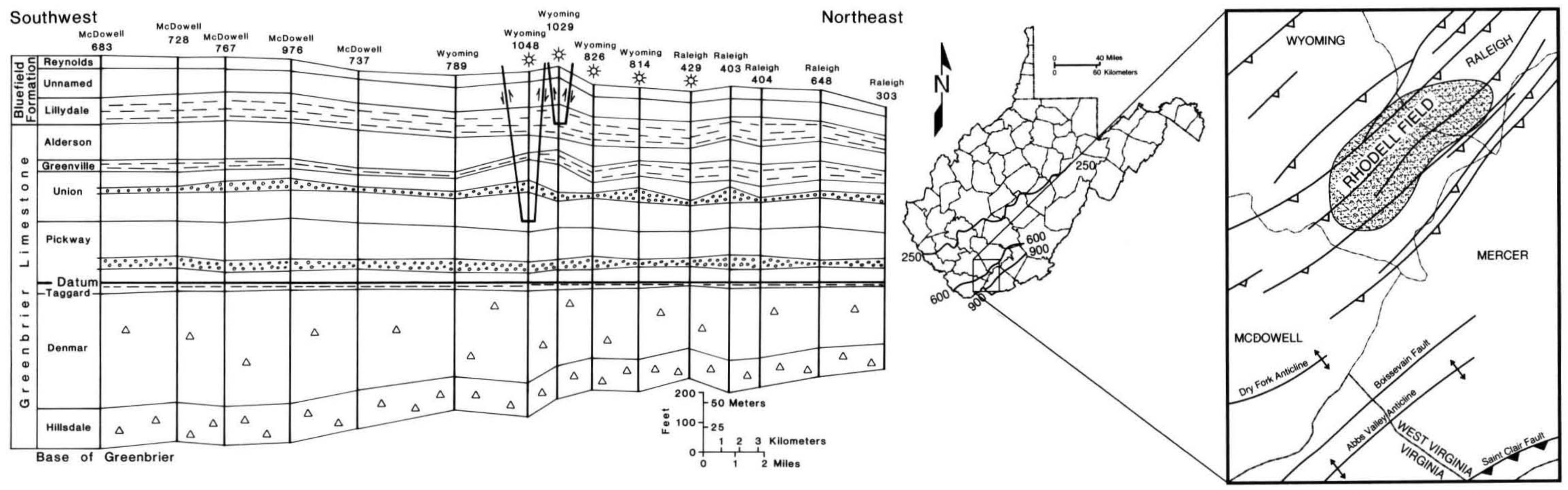


Figure Mgn-5. Southwest-northeast stratigraphic cross section through the Rhodell field in southern West Virginia. See Figure Mgn-8 for location of cross section; see inset map for location of the Rhodell field. Oolitic zones of the Union and Pickaway members are indicated by a pattern of circles. Two wells are cut by thrust faults that trend approximately parallel to the line of the section (inset map), and five producing wells lie within the Rhodell field. Also shown on location map are the 250-foot, 600-foot, and 900-foot isopach contours of the Greenbrier that likely follow structural hinge lines. From Kelleher and Smosna (1993).

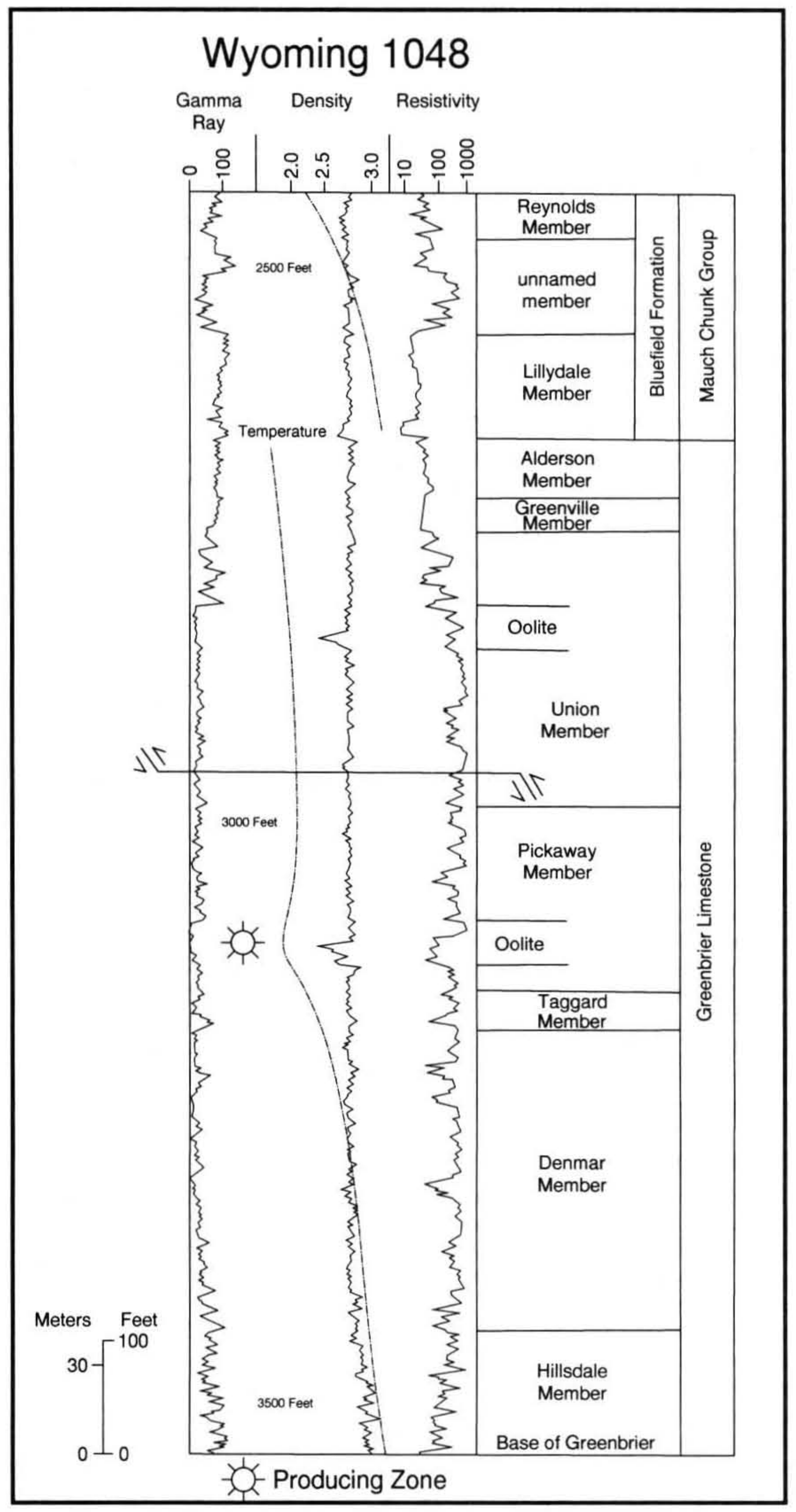


Figure Mgn-6. Geophysical logs for a representative well (West Virginia County permit number Wyoming 1048) of the Rhodell field includes gamma-ray, bulk density, resistivity, and temperature logs. Production in this well comes mainly from an oolite of the Pickaway Member, as indicated by the temperature curve (no scale). Most wells in the field, however, produce from an oolite in the Union Member. From Kelleher and Smosna (1993).

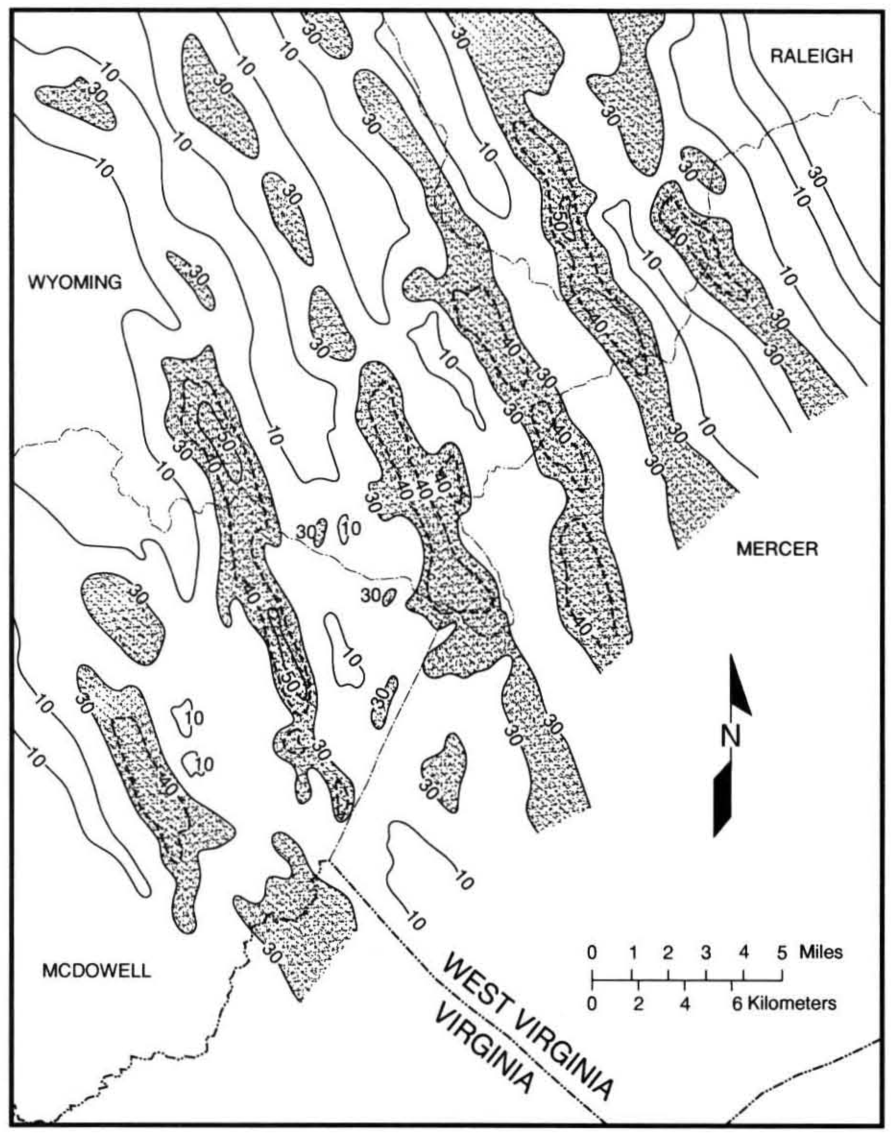


Figure Mgn-7. Isopach map of the oolitic Union Member in the vicinity of Rhodell field (see inset of Figure Mgn-5 for location). Thick oolite-bearing limestones (shaded) are interpreted as northwest-trending tidal bars, and the intervening thins are interpreted as channels. Contour interval = 20 feet (10 feet where line is dashed). From Kelleher and Smosna (1993).

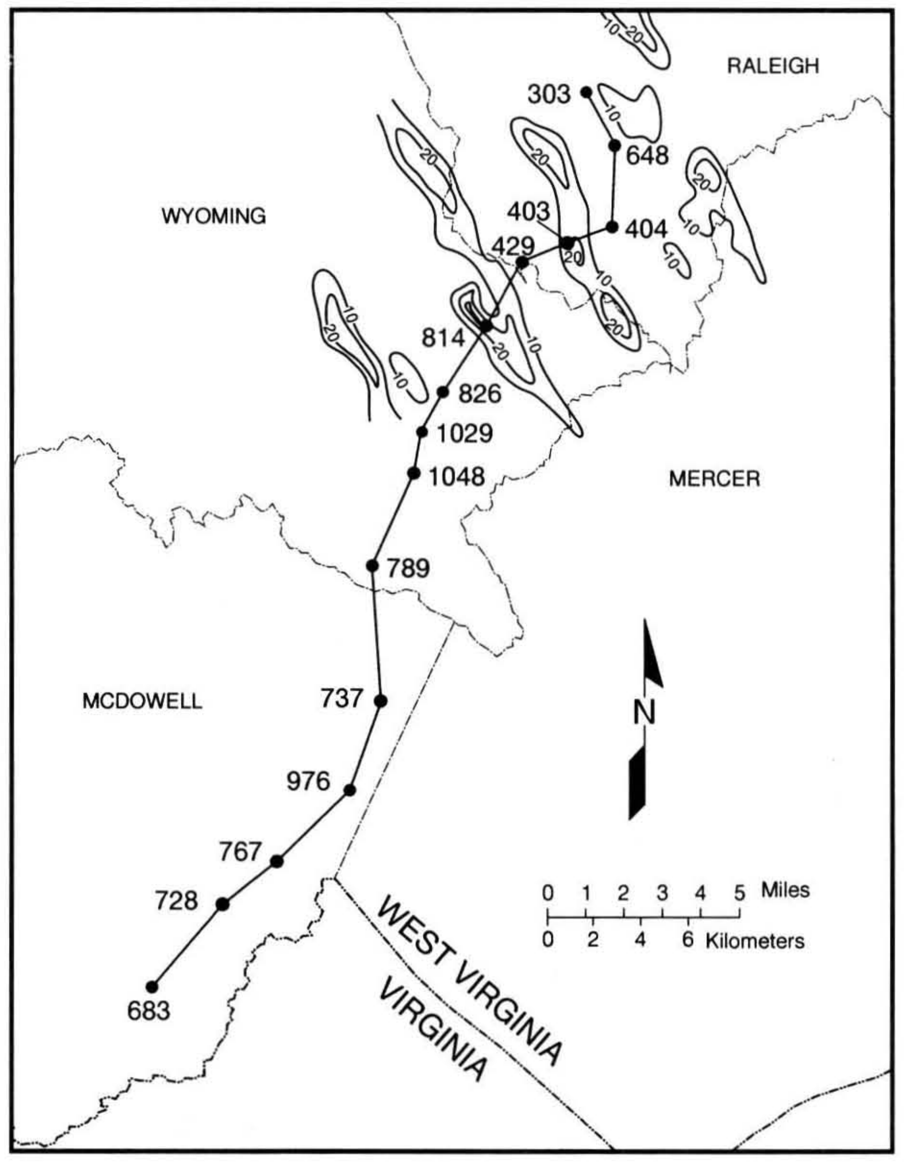


Figure Mgn-8. Isopach map of net pay in the oolitic Union Member, calculated as the stratigraphic interval with a bulk density equal to or less than 2.6 g/cc (equivalent to a porosity of 6 percent or more). Pay zones in the Rhodell field follow the crests of oolitic tidal bars. Contour interval = 10 feet. Line of cross section in Figure Mgn-5 is also indicated. From Kelleher and Smosna (1993).

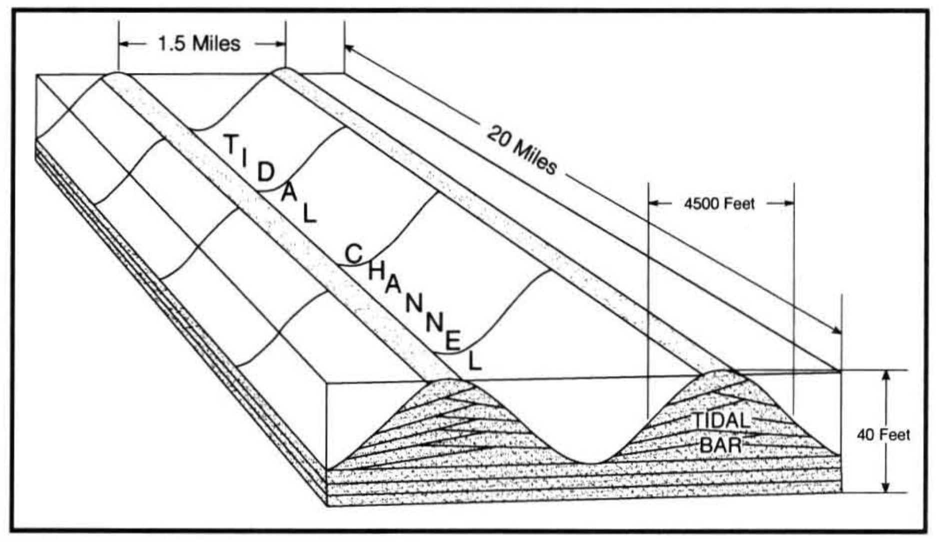


Figure Mgn-9. Block diagram illustrating the depositional geometry of oolitic tidal bars and intervening channels (Union Member of the Greenbrier Limestone) in the Rhodell field.

is 2 to 34 feet, averaging 12 feet. Mean initial open flows of 60 to 1,700 Mcfg/d have been reported in 12 small fields of northern West Virginia. Completion methods for 197 wells in the same 12 small fields are as follows: acidize and fracture (78 wells), fracture (61 wells), natural completion (33 wells), shot (23 wells), and acidize (2 wells). Final open flows vary between 26 and 3,894 Mcfg/d, averaging 600 Mcfg/d. Rock pressure is below 500 psi (reported values of 80 to 450 psi). Porosity (primary interparticle and/or dissolution of calcite cement) ranges from 3 to 21 percent and averages 10 percent; permeability ranges from 0.1 to 20 md.

Fields in the basal dolomite of Kentucky primarily occur along narrow, elongate, generally north-south trends. Drilling depth to the porous dolomite ranges from 900 to 3,800 feet, averaging 2,300 feet, and the pay zone is 10 to 25 feet thick, averaging 17 feet. Initial rock pressure varied from 225 to 700 psi. Initial open flows of the discovery wells in 11 large fields ranged between 63 to 4,000 Mcfg/d, averaging 1,600 Mcfg/d. However, some initial open flows as high as 30 MMcfg/d have been reported. Gas from Big Lime wells typically is commingled with oil (completed as combination oil and gas wells) and commingled with that from the deeper Ohio Shale and Berea Sandstone. Final open flows for all producing wells in the same 11 fields ranged from 442 to 4,581 Mcfg/d, averaging 1,400 Mcfg/d. Porosity, which is intercrystalline (pinpoint), vuggy, and interparticle, ranges between 4 and 26 percent; porosity averages 13 percent (as measured by geophysical logs) and ranges from 10 to 20 percent (as measured in cores). Permeabilities measured for two cores in the Bull Creek field of Letcher and Perry counties are as follows: minimum 0.18 md, average 19.4 md, and maximum 300 md. The drive mechanism is gas expansion. The customary stimulation strategy is to acidize and then fracture with water and sand, but some wells are fractured with acid or nitrogen.

Oolitic Big Lime fields of Kentucky are stratigraphic facies pinch-outs, as they are in West Virginia; however, fractures may connect the pay zones, especially in areas adjacent to the Pine Mountain overthrust. Depth to the pay zone varies between 760 and 4,600 feet, averaging 2,300 feet, and the thickness is 6 to 17 feet, averaging 12 feet. Initial rock pressures characteristically were low, ranging between 105 and 540 psi; perhaps fields had been depleted through Devonian fractures to the producing shale below. Initial open flows in the discovery wells of 20 large fields ranged from 84 to 11,300 Mcfg/d, averaging 1,300 Mcfg/d. Final open flows in all producing wells of these 20 fields were reported to be 119 to 23,283 Mcfg/d, averaging 2,200 Mcfg/d. Porosity is interparticle and moldic, and values calculated from geophysical logs range from 4 to 21 percent with typical porosities of 10 to 17 percent. The drive mechanism is gas expansion. Stimulation strategies include acidizing the open or perforated hole (most common); natural completion; or acidizing followed by fracturing with water or nitrogen (least common).

Greenbrier oolites in Virginia constitute a minor reservoir. Depth to the top of the pay zone ranges from 2,500 to 5,400 feet, whereas pay-zone thickness ranges from 17 to 194 feet (very thick sections consist of interbedded oolitic and non-oolitic limestones). Initial open flows ranged up to 678 Mcfg/d, and final open flows ranged from 42 to 900 Mcfg/d. Initial rock pressures vary between 500 and 1,000 psi, and the drive mechanism is gas expansion.

Likewise, the Maxville Limestone in Ohio is a minor reservoir. The depth range of the producing interval is 1,055 to 1,650 feet, and the pay zone varies between 20 and 30 feet in thickness. Initial open flows (field averages) ranged from 300 to 1,000 Mcfg/d, but after stimulation attempts of either fracturing or acidizing, final open flows dropped to 50 Mcfg/d on average. Most wells, therefore, are not treated. Gas is frequently associated with oil and commingled with gas production from other reservoirs. Only three fields have been discovered; each covers 190 to 480 acres and the well spacing is 10 acres. Log porosity ranges between 1 and 27 percent, averaging 12 percent. Initial rock pressures vary from 120 to 380 psi, and the drive mechanism is gas expansion.

The fossiliferous, oolitic Monteagle Limestone in Tennessee produces associated and nonassociated gas, but very little data are available. The following information is based on 15 or fewer wells. The producing interval lies at depths between 882 and 1,160 feet; average pay thickness is 29 feet. The perforated interval varies from 13 to 29 feet thick. Log porosity ranged from 11 to 30 percent. Initial open flows range from 2 to 1,579 Mcfg/d, but values between 30 and 70 Mcfg/d are typical. One final open flow is reported to be 488 Mcfg/d. Initial rock pressures range from 40 to 400 psi, with typical values of 100 to 200 psi. Well spacing is about 1,000 feet.

Description of Key Fields

Rhodell field: The Rhodell field of Raleigh and Wyoming counties, West Virginia, exemplifies those Greenbrier/Big Lime fields producing from oolite reservoirs (Figures Mgn-5, Mgn-6, Mgn-7, Mgn-8, Mgn-9) (Table Mgn-1). Kelleher and Smosna (1993) identified a series of oolite bars trending northwest-southeast

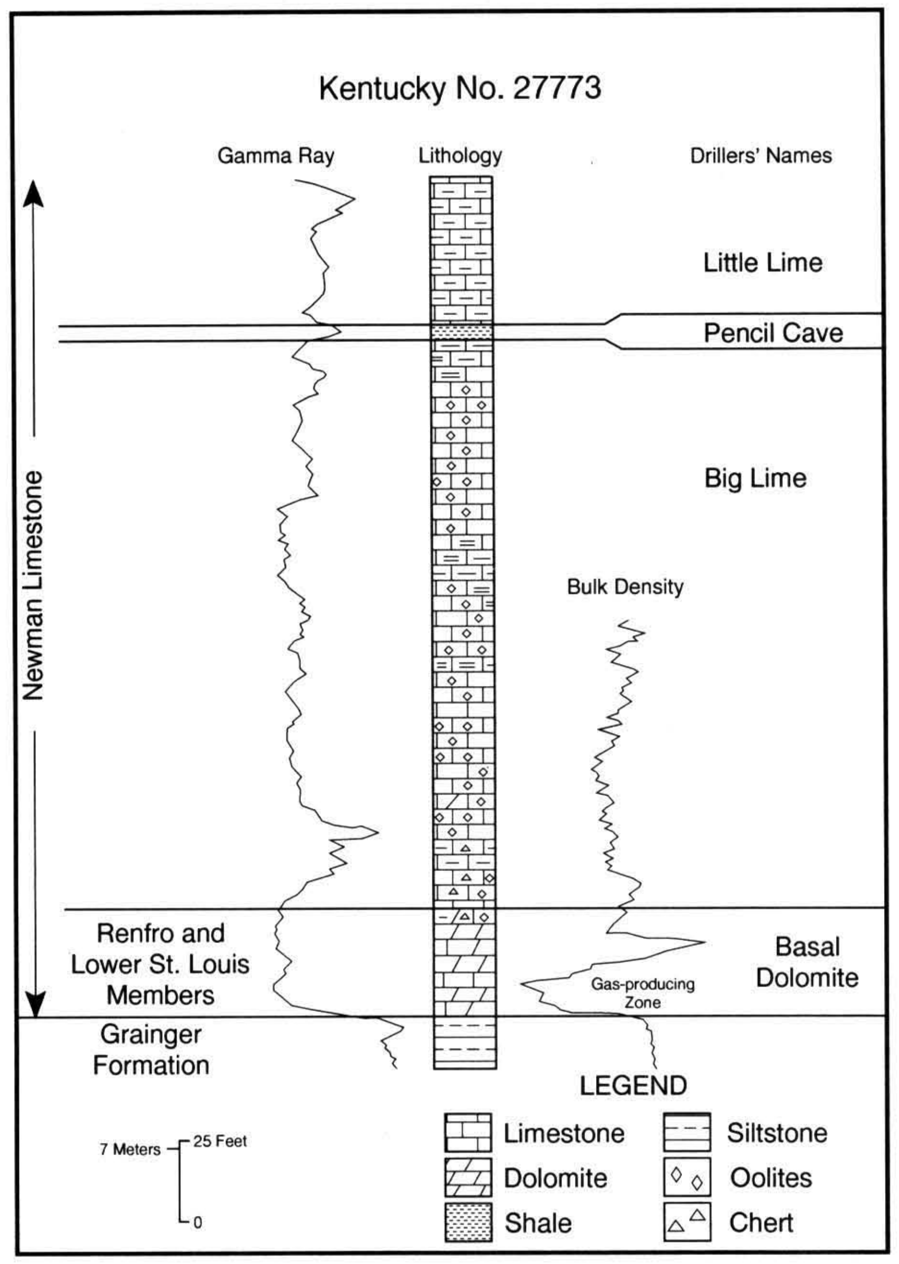


Figure Mgn-10. Plot of geophysical logs and lithologies for a representative well of the Hyden West field, Leslie County, Kentucky, includes gamma-ray and bulk density. Production in this well comes from the basal dolomitic unit of the Big Lime, equivalent to the Renfro and lower St. Louis members of the Newman Limestone. Location of the field is shown in Figure Mgn-11. From Birch (1983).

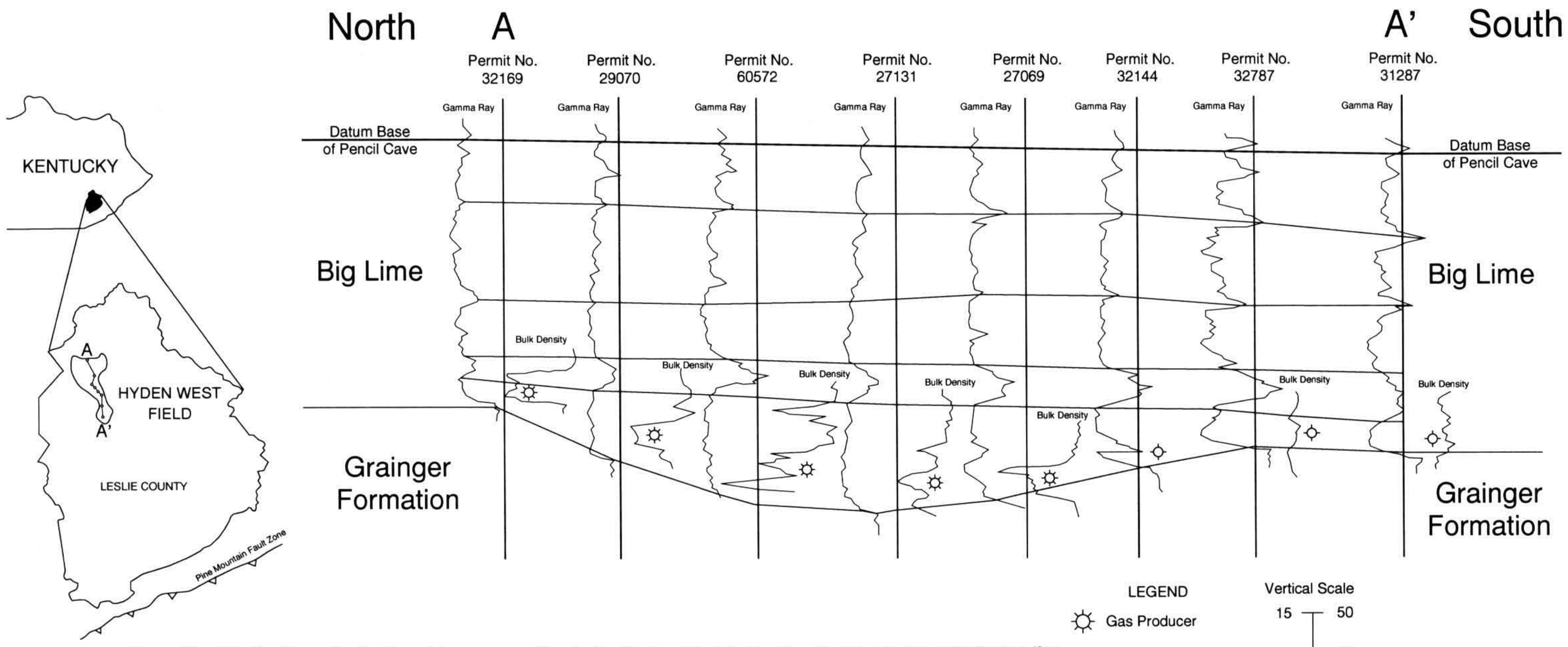


Figure Mgn-11. North-south stratigraphic cross section in the Hyden West field of Leslie County (inset indicates line of cross section) showing production from the basal dolomite channel. Correlation lines trace informal subsurface units of the Newman/Big Lime. Horizontal distances are not to scale. From Birch (1983).

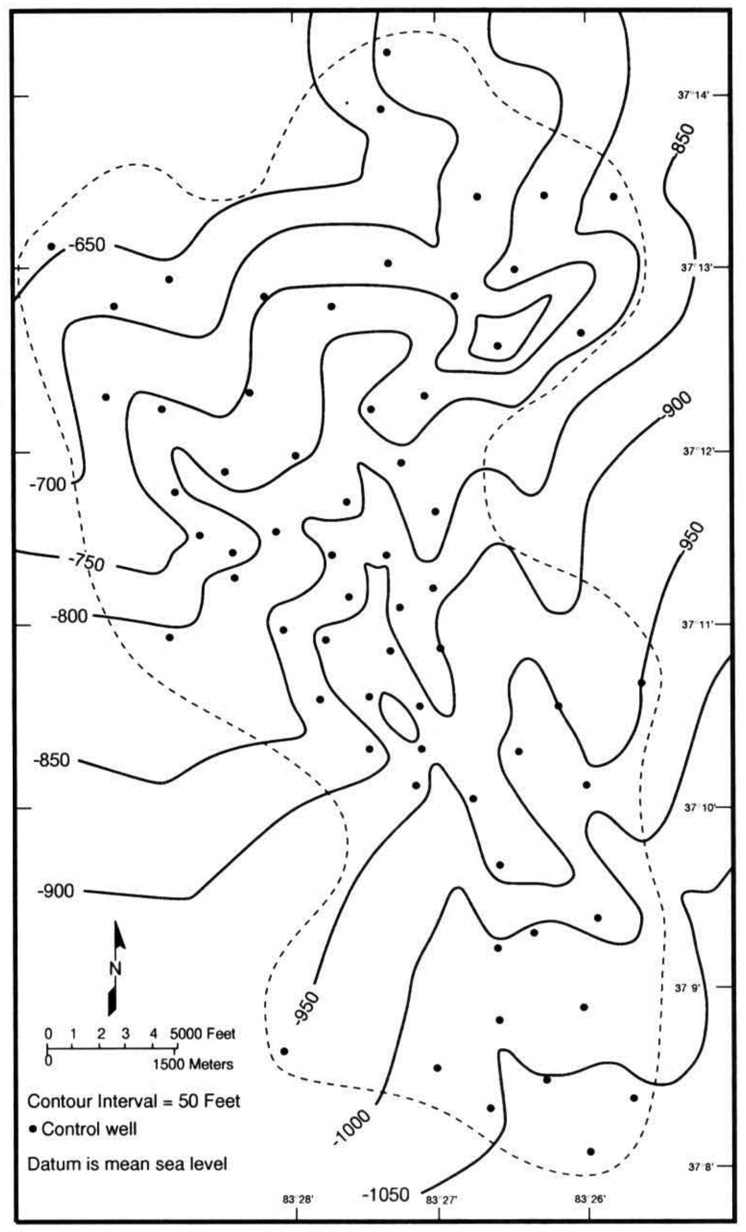


Figure Mgn-12. Structure map constructed for the base of the Newman Limestone (Big Lime) in the Hyden West field illustrates the presence of branching channels eroded into the top of the underlying Grainger Formation. See Figure Mgn-11 for location. Contour interval = 50 feet. From Birch (1983).

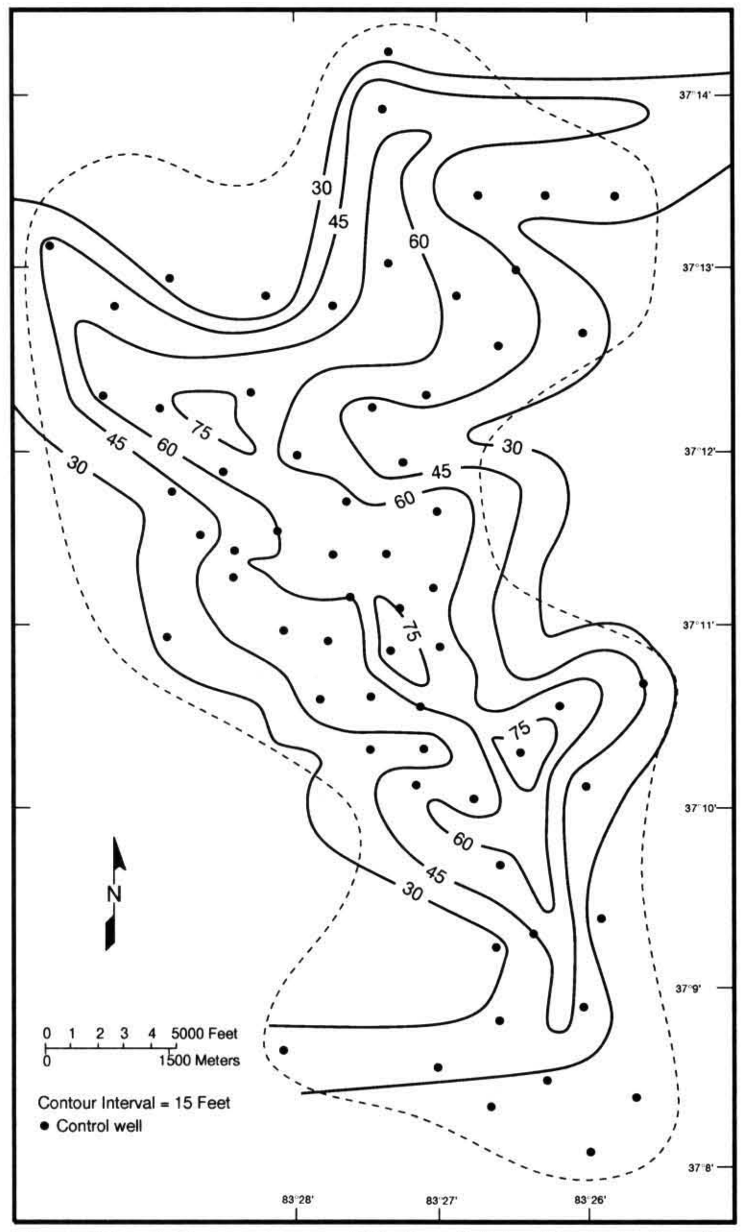


Figure Mgn-13. Isopach map of the basal dolomite, including the pay zone, in the Hyden West field. The greatest thickness correlates well to the interpreted channels on the underlying unconformity. See Figure Mgn-11 for location. Contour interval = 15 feet. From Birch (1983).

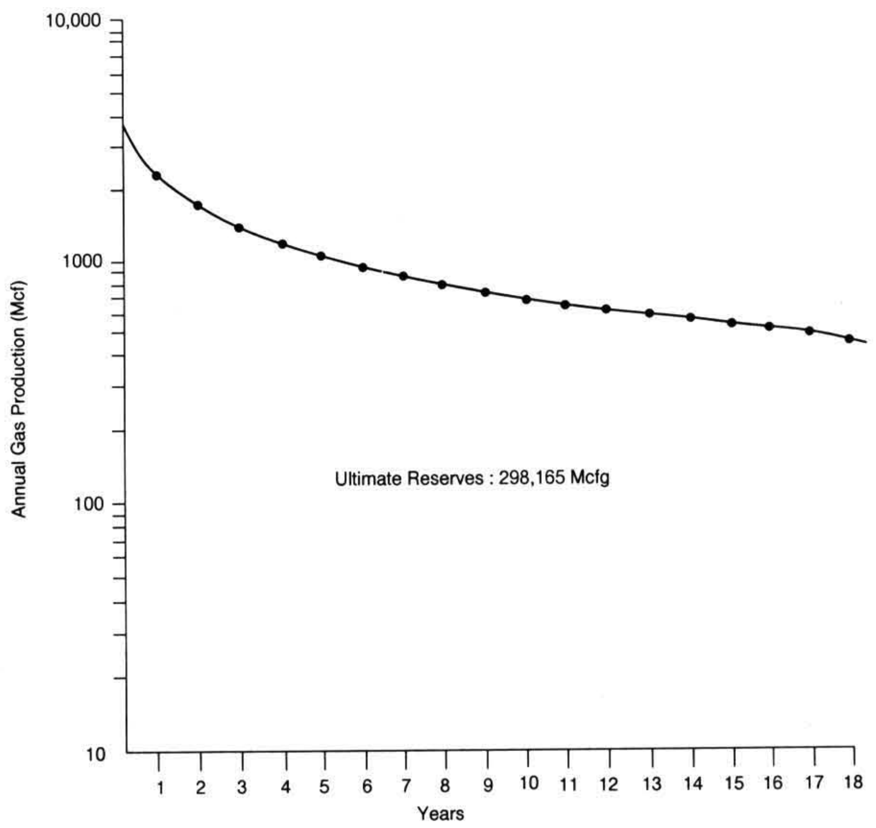


Figure Mgn-14. Composite decline curve generated for 48 Big Lime wells in southern West Virginia (gas not commingled with that from other formations). Mean ultimate reserve is calculated to be 298 MMcfg per well.

and parallel to regional dip. These bars average 40 feet thick, 4,500 feet wide, and 20 miles long, and they are spaced approximately 1.5 miles apart. Porosity is best developed (greater than 6 percent and average of 10 percent) on the crest of the bars, which is along the thickest part of each oolite trend. Partial leaching of individual ooids created the intraparticle-solution porosity. Permeability does not exceed 0.15 md, and the limestone is a low-porosity, low-permeability reservoir. The field was discovered in 1965 and has 69 wells. Reserves are difficult to determine because gas typically is commingled with gas from other formations, but recent drilling suggests that highside cumulative productions may exceed 1 bcfg per well. Initial open flows are frequently above 2 MMcfg/d. The Wyoming 1048 well in Rhodell field had an initial open flow of 4.2 MMcfg/d and produced 126.5 MMcfg in the first six months with no decline. Total production for this well is expected to be 2 bcf. Only dry gas is produced in the Rhodell field; formation water is not encountered regardless of structural position.

Hyden West field: Birch (1983) presented a detailed study of the Hyden West field in Leslie County, Kentucky, which illustrates a typical field in the basal Newman/Big Lime dolomite (Figures Mgn-10, Mgn-11, Mgn-12, Mgn-13). The unit consists of medium- to thick-bedded, fossiliferous, dolomitic limestone; fossiliferous limestone; and sucrosic dolomite with minor silt and chert. A structure map drawn on the underlying unconformity together with an isopach map of the basal unit depict a southeast-flowing channel that eroded into the underlying Borden or Grainger Formation. The meandering channel with branching tributaries is approximately 3 miles wide, 8 miles long, and perhaps 60 feet deep. It deepens to the south and has been filled by the basal Big Lime unit, ranging from 18 to 87 feet in thickness. Birch (1983) interpreted the channel to be either tidal or fluvial in origin. Maximum thickness of the dolomitic pay zone is 70 feet, and both the pay zone and basal unit as a whole thin toward the margins of the channel. The Hyden West field, discovered in 1955, covers more than 22,000 acres and contains 91 gas wells producing from the Big Lime. Typical gas saturations are 84 percent. This gas has a gas gravity of 0.677 and a Btu content of 1,165.

Resources and Reserves

The Kentucky Geological Survey keeps production data on 49 Newman fields in that state, although Newman/Big Lime gas is often commingled with gas from the Ohio Shale, Berea Sandstone, Corniferous Dolomite, Knox Dolomite, or other reservoir. These fields each contain up to 59 wells (mean of 7), have produced gas for as long as 77 years (mean of 25 years), and report a maximum cumulative production of 9,009 MMcfg (mean of 1,359 MMcfg). Cumulative production per well ranges between 2 and 1,917 MMcfg, with an average of approximately 300 MMcfg. Extrapolating the average per well value to all 3,400 Newman wells in the state, one can estimate cumulative production for the 257 discovered fields to be approximately 1 tcf as of 1993. If the recovery factor for gas is 80 percent, the original gas in place may have been 1.3 tcf, with 300 bcfg remaining in place.

Production data in West Virginia are sparse. Exceptional wells have a cumulative production of 1 to 2 bcfg and occasionally as high as 9 bcfg, although gas is generally commingled with that from other formations. Applying the same per well average as for Kentucky (300 MMcfg) to the 6,000 wells in West Virginia, cumulative production from the Greenbrier Limestone (Big Lime, Big Injun, and Keener) for 183 discovered fields is calculated to have been 1.8 tcf. However, a lower estimate of average production, 100 MMcfg per well, considered to be a minimum value, yields are more modest cumulative production of 600 bcfg for the 183 fields. Based on a recovery factor of 80 percent, the original gas in place may have been as much as 2.3 tcf, with 500 bcfg remaining in place. Figure Mgn-14 illustrates a composite decline curve generated for 48 Big Lime wells in southern West Virginia (gas not commingled). The mean ultimate reserve is calculated to be 298 MMcfg per well, but gas production varies widely depending on pay thickness, porosity, and permeability.

Future Trends

Despite a century of exploration efforts, little is known of the geology of the Newman and Greenbrier limestones in the subsurface. The nature of oolite shoals, the origin of channels on the basal unconformity, the depositional setting of sandy carbonate units, and the processes of dolomitization are poorly understood. Current knowledge of these reservoir lithologies is insufficient to predict accurately the occurrence, trend, size, and reserves of undiscovered fields. Future trends for exploration will depend on geological research aimed at unraveling the areal facies relations and diagenetic problems that remain unanswered.

Nevertheless, recent economic analyses by CNG Producing Company indicate that the Greenbrier Limestone may have the best rate of return for any shallow petroleum reservoir in West Virginia, and the same may be true for the Newman Limestone of Kentucky. The best approach for future exploration programs would be to search for the following: additional erosional channels at the base of the Newman especially over and around basement structures that might have been active in Mississippian time; and additional oolite tidal bars in the upper Greenbrier, especially along the 250-, 600-, and 900-foot isopach contours. Moreover, large areas of the basin periphery remain only lightly explored, as do several small areas within the central region (Figure Mgn-1).

PLAY Mbi: LOWER MISSISSIPPIAN BIG INJUN SANDSTONES

by Ana G. Vargo and David L. Matchen, West Virginia Geological and Economic Survey

Location

Big Injun sandstones (drillers' terminology) are widespread and prolific producers of oil and gas throughout the Appalachian basin. Producing Big Injun sandstones or equivalents are found from southwestern Pennsylvania to eastern Kentucky. Thousands of wells penetrate the fluvial-deltaic Big Injun sandstone reservoirs that were formed by structural and stratigraphic trapping mechanisms. The remnants of the fluvial-deltaic system essentially define the geographic distribution of the play (Figure Mbi-1).

Production History

The Big Injun, the most productive Lower Mississippian sandstone in the Appalachian basin, was first discovered in 1886 near Mount Morris, Pennsylvania (Figure Mbi-2), where a substantial oil field was discovered in a thick sandstone immediately beneath the Big Lime (Carll, 1890; Overbey and others, 1963). From discovery to the 1910s, the Big Injun was developed in southwestern Pennsylvania, northern West Virginia, and southeastern Ohio along structural trends. By the early 1900s, Big Injun production had been discovered in the Warfield District of the Big Sandy (Martin County, Kentucky) near the Kentucky-West Virginia border (Jillson, 1919a; Miller, 1919) (Figure Mbi-2), extending the productive area from southwestern Pennsylvania to eastern Kentucky. Development of the Big Injun in southern West Virginia and eastern Kentucky resulted in small, discrete fields, whereas the northern fields were larger, less easily defined, and often coalesced into county-sized fields (Figure Mbi-1). In Ohio, the earliest recorded discovery date for a Big Injun gas pool is 1897 for the Elk Run field in Washington and Monroe counties (Ohio Division of Geological Survey, written commun., 1994). Big Injun sandstone production was recorded in several other counties in southeastern Ohio, but was most prolific in these two counties (Bownocker, 1903a). Recent development (post-1930s) of Big Injun oil and gas production usually is confined to infill drilling in pre-existing fields, small structures, and extensions of known trends.

Determination of cumulative production for the Big Injun is complicated by several factors. Most fields are old and lack production data; gas frequently was flared from wells intended to produce oil; production typically is commingled from several zones; and the definition of the Big Injun is widely variable. These factors make determination of cumulative production for the Big Injun difficult. However, available production values for the Big Injun play (including Pocono Big Injun, undifferentiated Big Injun, Squaw, and commingled zones) in West Virginia total 658.5 bcf from 5,482 wells based on production data at the West Virginia Geological and Economic Survey. Production values from wells that produce exclusively from the play (excluding wells commingled with other zones) total 418.5 bcf from 3,589 wells.

In the absence of complete or even representative decline curves for the Big Injun fields, a crude estimate of cumulative production was determined by estimating what portion of the actual production was represented by the reported production for that field. Using the formula:

$$\% \text{ production} = \frac{\text{(number of wells reporting production)}}{\text{(total number of producing wells)}} \times \frac{\text{(average number of years reported)}}{\text{(number of years field is producing)}},$$

the percentage of production reported for each field (excluding wells with commingled production) was calculated. Dividing the reported production data for each field by this value field yielded an estimated cumulative production for each field. However, this estimate will be low for three reasons. First, the actual slope of the Big Injun decline curve is unknown; it is most certainly not linear (as assumed by the proportioning procedure used). Second, most wells have data available only after 1979 (when production was required to be reported to the State of West Virginia); these data represent the tail end of declining Big Injun production with an average of 15 percent of the decline curve represented in all Big Injun fields. Third, the number of producing wells estimated may be low because reports often were not filed for wells completed before 1929. Cumulative production estimates for fields in West Virginia (3,574 wells reporting production; 8,747 producing wells) were summed, giving a cumulative production of 3.965 tcfg.

Stratigraphy

Stratigraphic terminology in this play is highly variable and often confusing. The term Big Injun was first used when drillers encountered a thick sandstone beneath the Big Lime (Greenbrier Limestone) near Mount Morris, Pennsylvania. As the play evolved, the term was used for any productive interval near the base of the Big Lime or the top of the Lower Mississippian clastic section.

Many names have been applied to the Lower Mississippian section along the outcrop belts of the Appalachian basin. In the eastern outcrop belt, the terms Pocono, Price, and Rockwell are used to define this interval. In the western outcrop belt, Cuyahoga and Borden are used (Figure Mbi-3). In West Virginia, some early descriptions of the Lower Mississippian used the name Pocono Series (Hennen and Reger, 1913; Dally, 1956; Edmunds and others, 1979), as it occupies a similar position in the stratigraphic column and is similar in age to the Pocono Formation of northeastern Pennsylvania. Recent outcrop studies (Bjerstedt, 1986; Kammer and Bjerstedt, 1986; Bjerstedt and Kammer, 1988; Carter and Kammer, 1990) have abandoned the term Pocono in West Virginia in favor of the Price Formation of Virginia and have erected a new stratigraphic framework for Lower Mississippian rocks in West Virginia (Figure Mbi-3).

Although the Big Injun has not been defined in outcrop, there are equivalents throughout the outcrop belts. In southwestern Pennsylvania, the Lower Mississippian is divided into the Burgoon Formation (equivalent to the Big Injun), the Shenango Formation, and the Cuyahoga Group (Harper and Laughrey, 1987). In Ohio, the Lower Mississippian is divided into the Cuyahoga

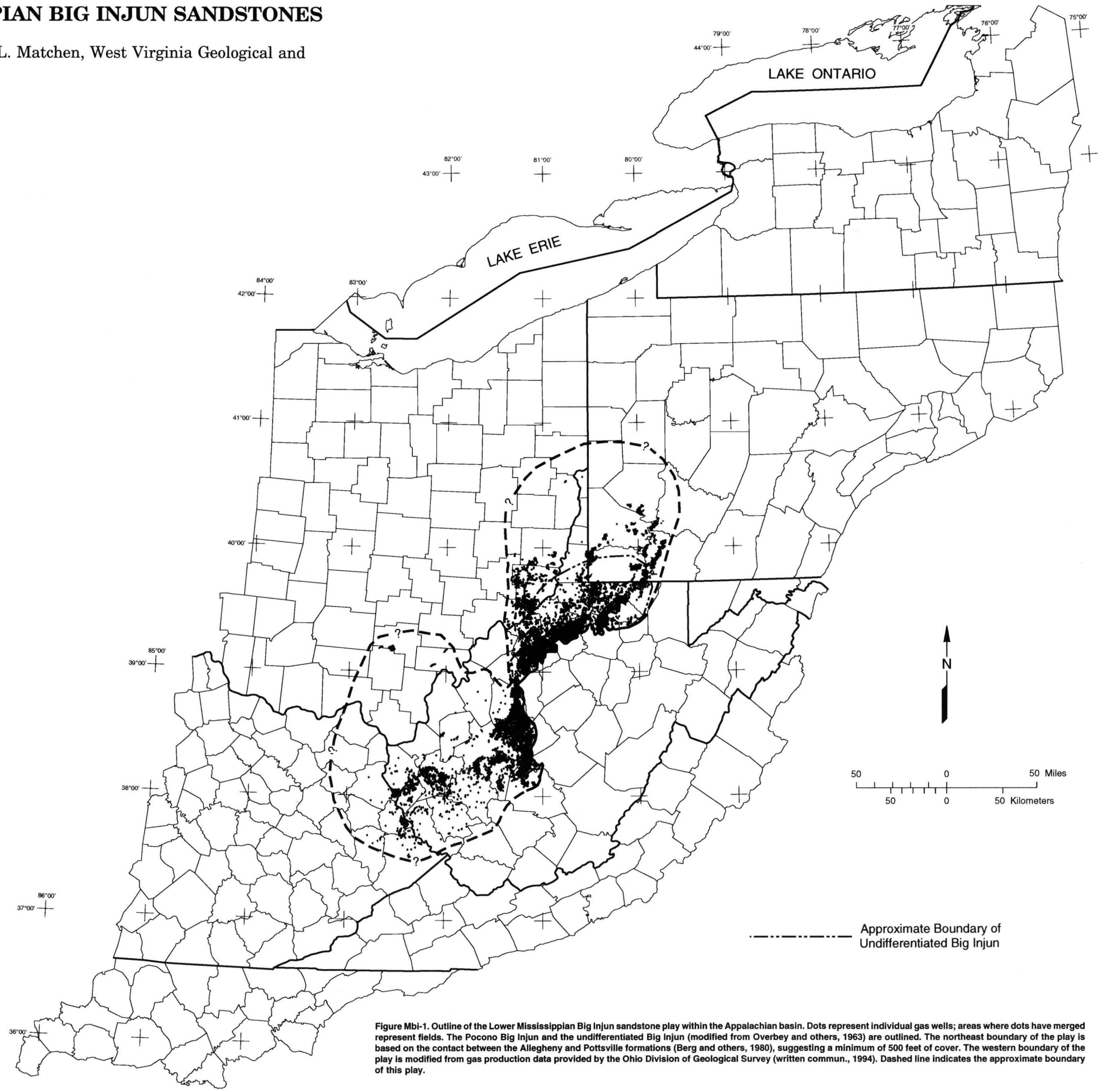


Figure Mbi-1. Outline of the Lower Mississippian Big Injun sandstone play within the Appalachian basin. Dots represent individual gas wells; areas where dots have merged represent fields. The Pocono Big Injun and the undifferentiated Big Injun (modified from Overbey and others, 1963) are outlined. The northeast boundary of the play is based on the contact between the Allegheny and Pottsville formations (Berg and others, 1980), suggesting a minimum of 500 feet of cover. The western boundary of the play is modified from gas production data provided by the Ohio Division of Geological Survey (written commun., 1994). Dashed line indicates the approximate boundary of this play.

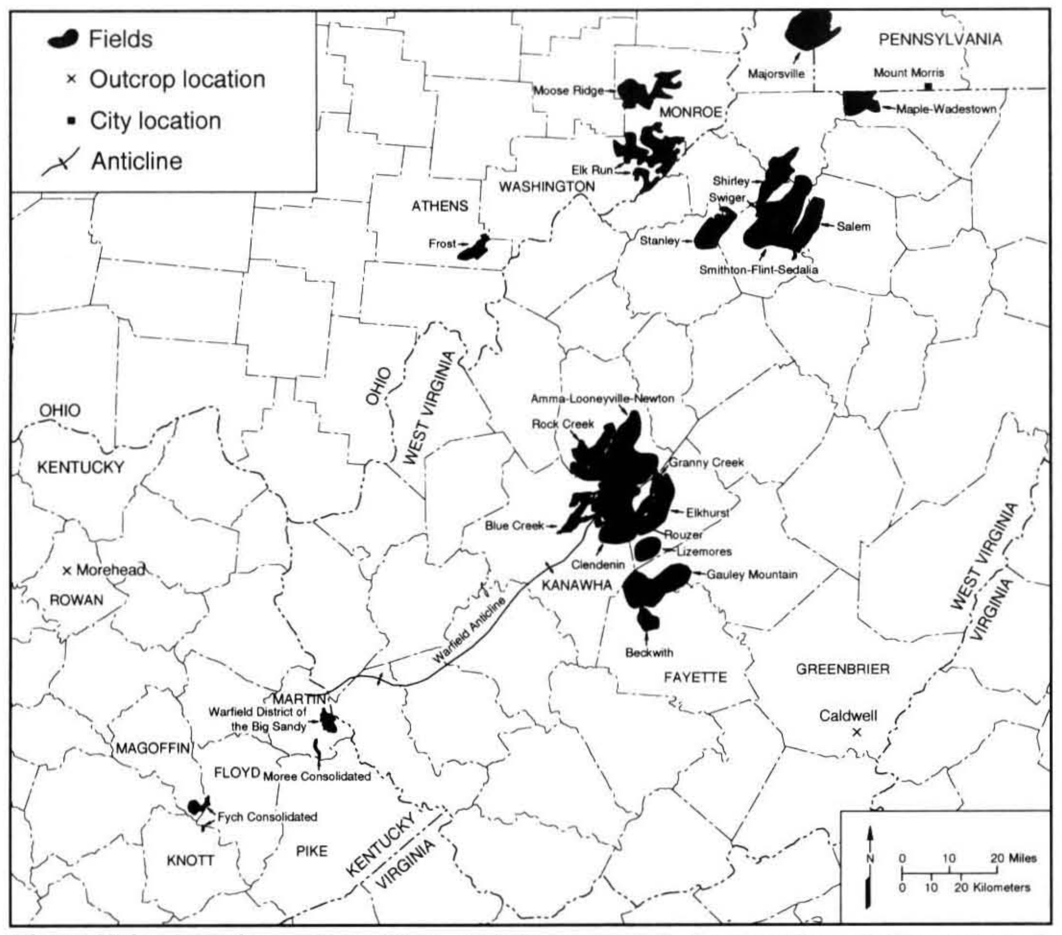


Figure Mbi-2. Location map for fields, anticlines, and outcrop localities mentioned in text and Table Mbi-1.

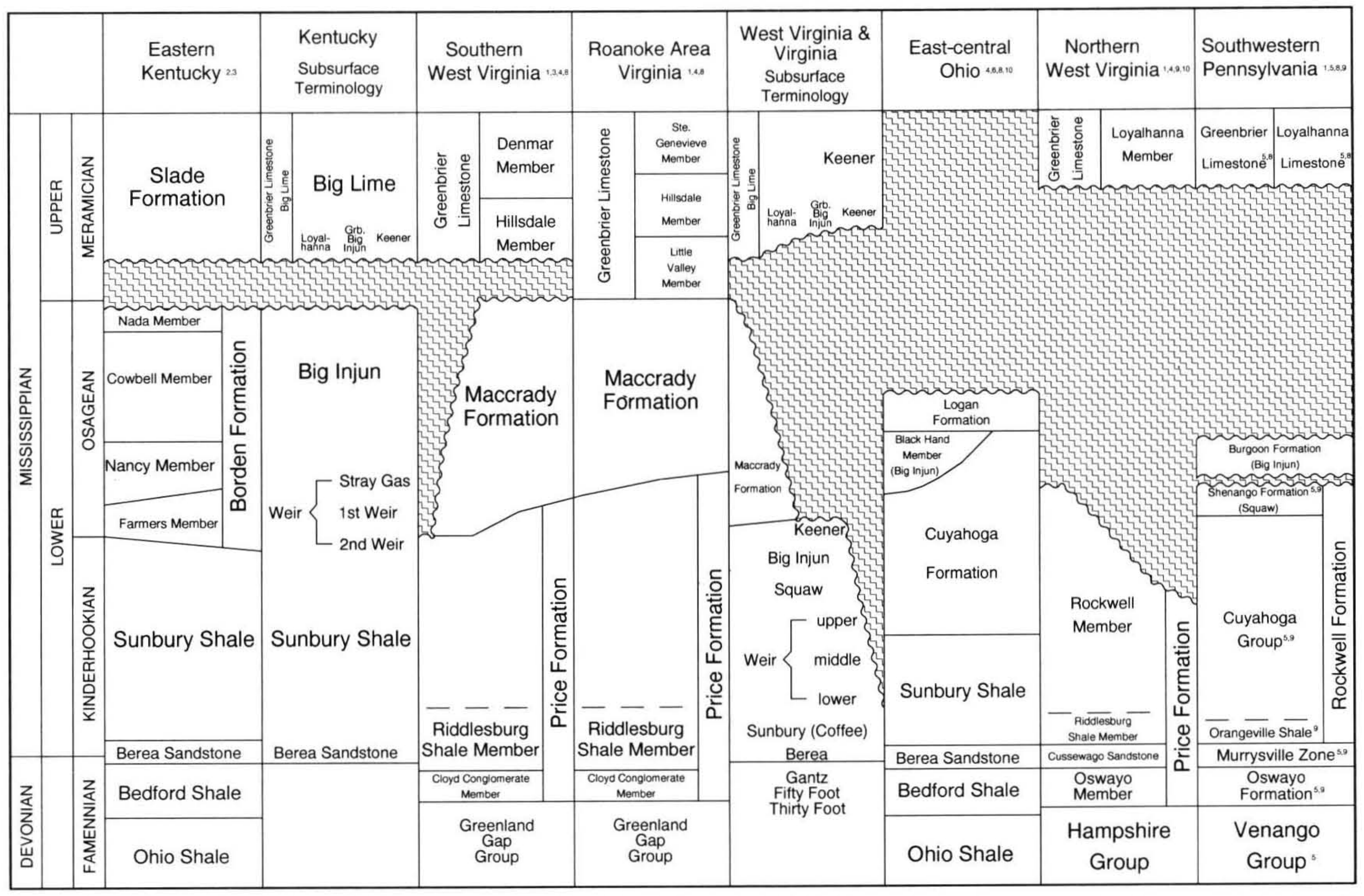


Figure Mbi-3. Chronostratigraphic chart showing nomenclature for the Lower Mississippian used in outcrop and subsurface areas. Numbers at top of columns refer to the following references: 1, Bjerstedt and Kammer (1988); 2, Chaplin (1980); 3, Matchen and Kammer (1994); 4, R. Smosna, Upper Mississippian Greenbrier-Newman Limestones, this atlas; 5, Harper and Laughrey (1987); 6, Bird (1988); 7, Carter and Kammer (1990); 8, Patchen and others (1985a); 9, T. Kammer (written commun., 1994); 10, Boswell and others (1987). For a complete listing of drillers' terminology for southwestern Pennsylvania, see Harper and Laughrey (1987). The vertical scale does not imply stratigraphic thickness of units.

and Logan formations (Patchen and others, 1985a). The Big Injun correlates with the Black Hand Member of the Cuyahoga Formation (Collins and Smith, 1977; Majchszak, 1984). In Kentucky, the name Borden Formation is used for the Lower Mississippian clastic interval (Chaplin, 1980; Patchen and others, 1985b), and the Big Injun is equivalent to the upper portion of the Cowbell Member of the Borden Formation. In West Virginia, Big Injun equivalents occur in the upper part of the Price Formation (Jewell, 1988; Hohn and others, 1993a).

In the subsurface, Price Formation (Matchen and Kammer, 1994), Cuyahoga Formation (Boswell and others, 1987), and Borden Formation (Sharpe, 1983; Matchen and Kammer, 1994) are used to identify this section of Lower Mississippian rocks. These units occupy a similar stratigraphic position—above the Sunbury Shale and its equivalents and below the Greenbrier Limestone and its equivalents or below the Maccrady Formation in southern West Virginia and Virginia. However, these units are time transgressive. In the eastern part of the Appalachian basin, the Price Formation is primarily Kinderhookian in age (Carter and Kammer, 1990; Matchen and Kammer, 1994). To the west, the Borden and Cuyahoga formations are primarily Osagean in age (Chaplin, 1980) (Figure Mbi-3).

Many subsurface terms have been applied to the Big Injun and its subdivisions. Early explorationists noted that, in the northern part of the basin, the upper part of the Big Injun was separated from the main sandstone by a thin bed of shale (Bownocker, 1903a; Hennen, 1909; Hennen and Reger, 1913). These explorationists called this upper sandstone the Keener (Figure Mbi-3). A similar situation occurs at the bottom of the Big Injun where a sandstone separated from the base of the Big Injun by 20 to 40 feet of shale was called the Squaw sandstone (Hennen, 1909). Later geologists (Haught, 1959; Ondrick, 1965; R. Smosna, Upper Mississippian Greenbrier-Newman Limestones, this atlas) redefined the Keener sandstone and placed it in the Greenbrier Limestone, which is generally accepted today. In spite of this, Keener is still applied in some cases to productive zones in the upper Price (Bell and others, 1993) and to other zones throughout the productive interval (Figure Mbi-3). Squaw is still used to name a sandstone beneath the Big Injun. In some situations, Squaw is used interchangeably with upper Weir (Swales, 1988; Zou, 1994).

Additional scrutiny of Big Injun well data revealed that, in some cases, the Big Injun is actually a sandy carbonate near the base of the Greenbrier Limestone (Overbey and others, 1963). To distinguish between the two units, the terms Pocono Big Injun and Greenbrier Big Injun were coined (Overbey and others, 1963; Ruley, 1970). The Greenbrier Big Injun may be the subsurface equivalent of the Loyalhanna Limestone of Pennsylvania (Ruley, 1970).

Introducing the above names to the subsurface terminology has added to the confusion. Drillers' records often identify the Greenbrier Big Injun as the Loyalhanna Limestone or Keener sandstone. In some areas, both the Keener and Greenbrier Big Injun terms are used for the same or different sandstones. Additionally, the Pocono Big Injun also has been called the Keener sandstone (Bell and others, 1993). This confusion and the drillers' habit of reporting the Loyalhanna and the Pocono Big Injun as a single unit called Big Injun (McGlade, 1967) make the use of drillers' records in analysis of the Big Injun play difficult.

Here, the Big Injun has been classified in the following manner: Greenbrier Big Injun, undifferentiated Big Injun, and Pocono Big Injun. Big Injun will refer to the Pocono Big Injun; the term Pocono is retained because most operators are familiar with this term. The Greenbrier (R. Smosna, Upper Mississippian Greenbrier-Newman Limestones, this atlas) and Pocono Big Injun units retain their accepted usage, but are differentiated only when there is reasonable certainty that production is from only one of these units. When commingled production occurs or the producing zone can not be determined, the term undifferentiated is used. Figure Mbi-1 shows the distribution of the Pocono Big Injun and the undifferentiated Big Injun.

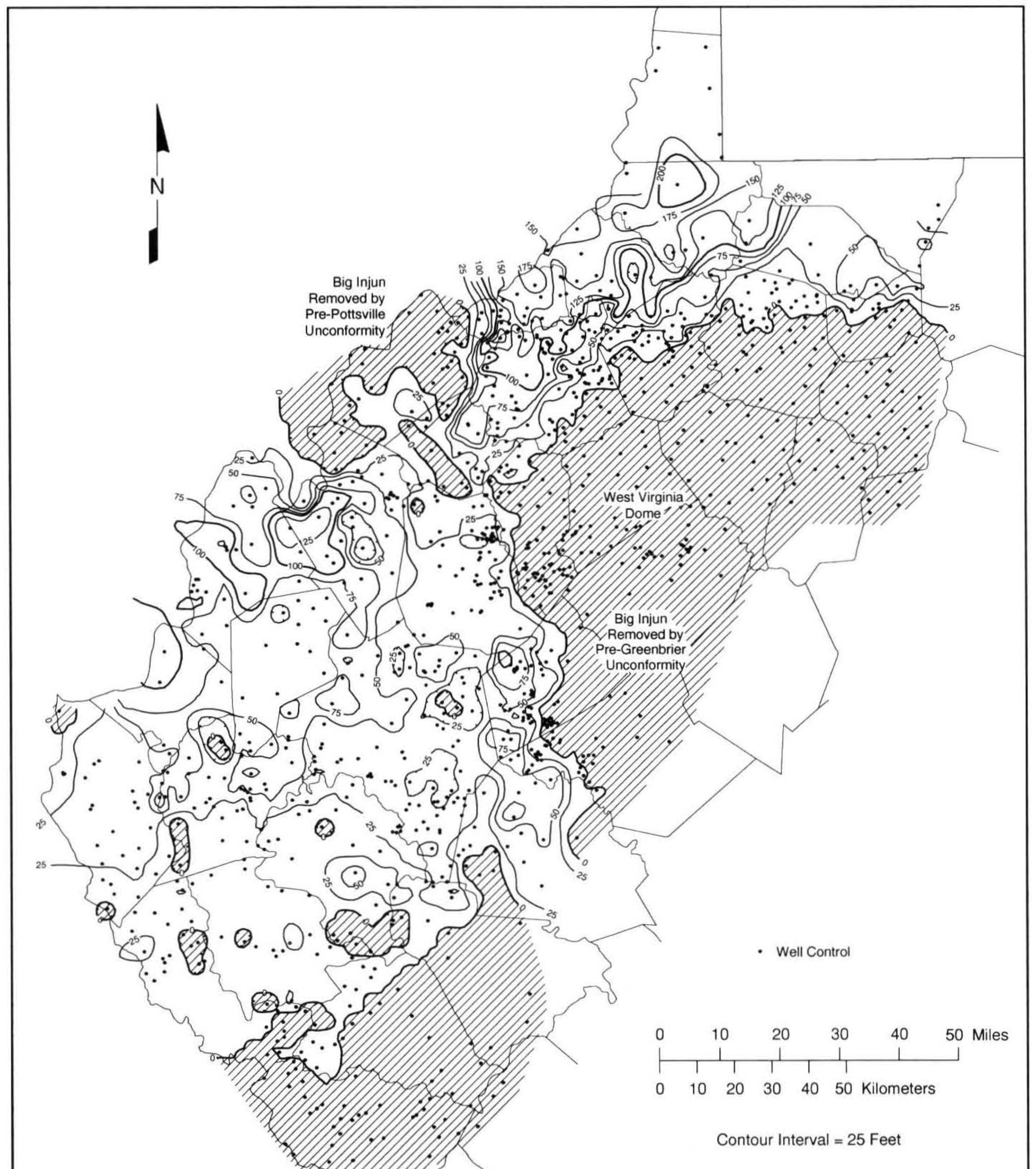


Figure Mbi-4. Isopach map of the Big Injun sandstone in West Virginia. The effect of the pre-Greenbrier unconformity on the Big Injun sandstone is evident, particularly around the West Virginia Dome. This map was compiled by the authors using wireline logs represented by the control points.

Distribution of the Pocono and undifferentiated Big Injun is restricted by two unconformities that truncate the Big Injun and represent the eastern, northern, and western stratigraphic limits of the play. The Big Injun (Burgoon) can be traced into northern Pennsylvania (Edmunds and others, 1979; Patchen and others, 1985a), although there is no reported production outside of southwestern Pennsylvania (Harper and Laughrey, 1987). In southern West Virginia, facies changes limit the productive areas of the Big Injun to localized sandstone accumulations.

The pre-Greenbrier unconformity truncates the Big Injun over most of northern and central West Virginia. The Lower Mississippian rocks have been completely removed by erosion over a semicircular area of central West Virginia (Dally, 1956; Yielding and Dennison, 1986) (Figure Mbi-4). This area has been called the West Virginia Dome (Bjerstedt and Kammer, 1988; Boswell and Jewell, 1988).

There is little information on the origins of the dome; however, its effects are evident in sandstone distribution patterns. The greatest erosion occurs over the central part of the dome in parts of Upshur and Randolph counties, West Virginia, where the Upper Devonian Gantz sandstone has been removed. The younger sandstones of the Lower Mississippian are absent over wider areas of central West Virginia (Boswell and Jewell, 1988), with the youngest (Big Injun) being absent over the widest area. The greatest thicknesses of Big Injun have been preserved in northwestern West Virginia (Figure Mbi-4), where the thickness of the Big Injun exceeds 200 feet locally. Figure Mbi-5 shows the severity of the truncation of the Big Injun.

The western and northern limits of the play are controlled by the pre-Pottsville unconformity that removed the Cuyahoga and/or Price formations and the overlying Greenbrier Limestone in western West Virginia, eastern Ohio, and northern Pennsylvania (Figures Mbi-1, Mbi-4). In these areas, Lower and Middle Pennsylvanian sandstones are in contact with the Cuyahoga and/or Price formations. In some cases, this resulted in the confusion of Big Injun with Lower and Middle Pennsylvanian sandstones in Ohio and West Virginia that drillers called Salt sands (Bownocker, 1903a) or the Maxton sandstone (Majchszak, 1984). This situation is illustrated in Figure Mbi-6, which shows the Pottsville Group sandstones directly overlying the Price Formation.

Lower Mississippian sediments represent the final phase of deposition in response to the Acadian Orogeny (Ettensohn, 1987). In general, the basin was filled from the east to west, although during early Mississippian time different rates of subsidence resulted in slower progradation in the southern part of the basin than the north. This allowed the shoreline to move farther westward in the north, producing a northwest-southeast trend (Kepferle, 1977; Lewis, 1983; Bjerstedt and Kammer, 1988). Therefore, the character of the Lower Mississippian sedimentation changes from north to south, resulting in the Big Injun sediments being deposited in a wide variety of depositional environments.

In the northern part of the basin, Big Injun sediments from outcrops in Pennsylvania are generally characterized as fine- to medium-grained, light gray sandstones, with sedimentary structures characteristic of a fluvial or fluvially dominated environment (McGlade, 1967; Harper and Laughrey, 1987). Core data from the subsurface of northern West Virginia suggests a similar environment.

In southern West Virginia, the Big Injun is thinner (Figure Mbi-7), which is the result of a facies change from shallow water deposition in the north to deep water deposition in the south. In outcrops of the Price Formation near Caldwell, Greenbrier County, West Virginia (Figure Mbi-2), rocks that are correlative with the Big Injun (Jewell, 1988) are medium- and fine-grained sandstones representative of distributary channel and distributary mouth-bar facies (Bjerstedt and Kammer, 1988). The Big Injun has a similar appearance in the subsurface. Core descriptions suggest that the Big Injun was deposited in a mouth bar environment (Smosna and Bruner, 1991; Hohn and others, 1993a; 1993b). In western Clay County, the Big Injun contains an upper coarse-grained member that is interpreted to be fluvial in origin (Swales, 1988; Smosna and Bruner, 1991; Hohn and others, 1993b; Zou, 1994).

The Big Injun in eastern Kentucky can be correlated to the Cowbell Member of the Borden Formation exposed in outcrops near Morehead, Kentucky (Figure Mbi-2). Lithologies within the Cowbell range from shales to very fine-grained sandstones (Chaplin, 1980; Lowry-Chaplin, 1987). The Cowbell is regarded as the distal equivalent of the Big Injun (Matchen, 1992). Sedimentary structures suggest that depositional environments for the Cowbell range from delta front to interdistributary bay (Chaplin, 1980; Lowry-Chaplin, 1987).

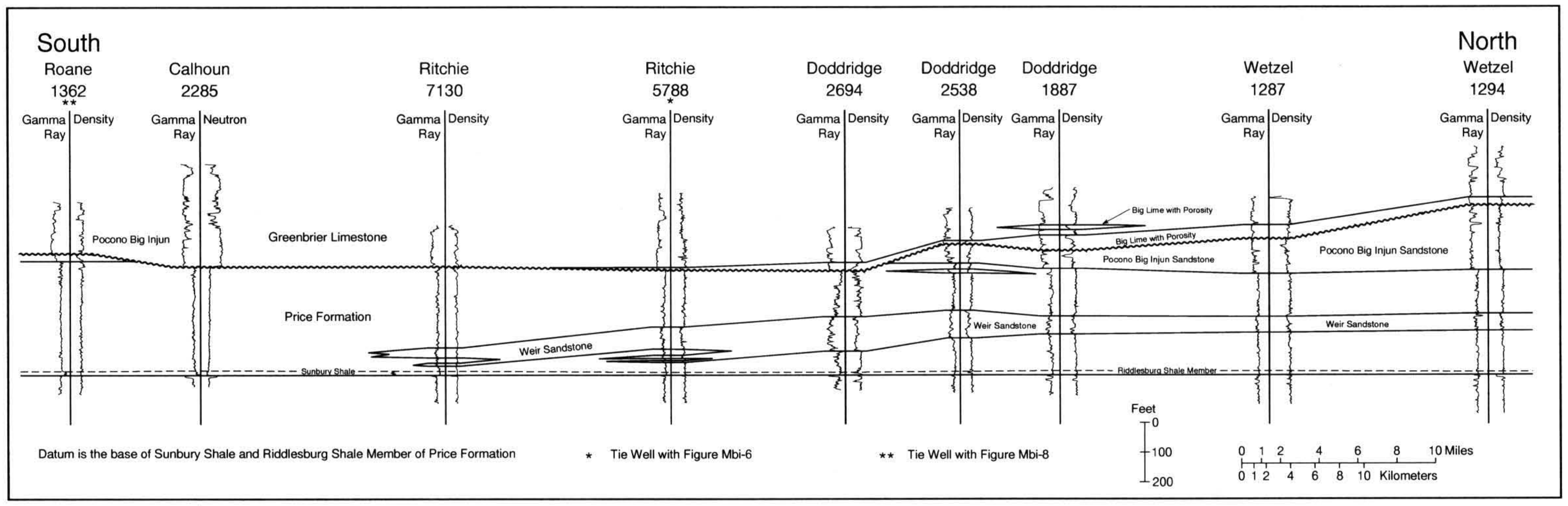
The identification of the Big Injun in the subsurface can be difficult in areas where the Big Injun has a gamma-ray log signature similar to the overlying Big Lime. Log signatures shown in Figure Mbi-8 illustrate the use of density logs to help differentiate the two units. However, in the northern and central parts of West Virginia, presence of porosity in the lower Greenbrier makes the determination of the pre-Greenbrier unconformity difficult.

In areas where the Big Injun is clearly identifiable, it displays a wide variety of wireline log signatures. Gamma-ray signatures show either cylindrical, bell-shaped, funnel-shaped, symmetrical, or irregular curves (Cant, 1984). The Greene 21495 well (Figure Mbi-8a) shows the difficulty in separating the Big Injun and Big Lime. The gamma-ray log suggests a clean sandstone through both intervals. In contrast, Pleasants 737 (Figure Mbi-8b) is serrated and fines upward at the top. Doddridge 3088 (Figure Mbi-8c) is thinner with an irregular curve shape, making the Big Injun signature easy to distinguish from the clean, blocky signature of the Big Lime.

South of the West Virginia Dome (Figures Mbi-8d, Mbi-8e), the Big Injun can be differentiated from the Big Lime using density logs. The gamma-ray signature has a step-down pattern that reflects the transition from limestone to sandstone. In Figure Mbi-8d, this pattern is actually composed of two steps that correspond to the coarse- and fine-grained subdivisions of the Big Injun identified in core (Hohn and others, 1993b). Figure Mbi-8e is lacking the coarse-grained component and has only the fine-grained portion of the Big Injun, also identified in core (Hohn and others, 1993a). In Kentucky, log signatures for the Big Injun (Figure Mbi-8f) are irregular, making it difficult to distinguish the Big Injun from the shales and siltstones common to the Borden Formation.

Structure

The central Appalachian Plateau is dominated by gently folded structures. The most productive portions of the Big Injun are associated with these structures, allowing early explorationists to demonstrate a relationship between anticlines and hydrocarbon accumulation (White, 1904). Natural gas accumulated



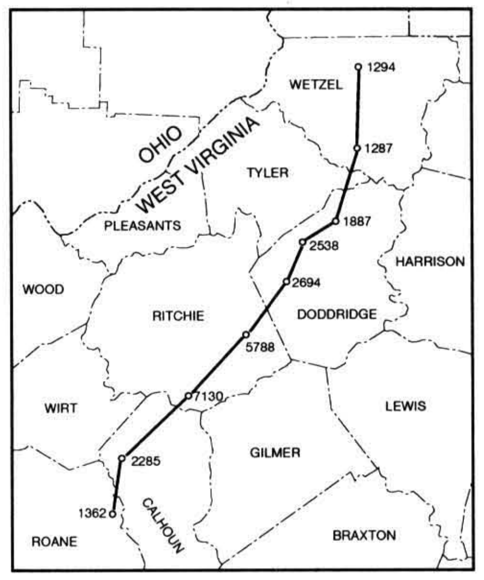


Figure Mbi-5. Regional north-south stratigraphic cross section of the interval from the top of the Devonian through the Lower Mississippian (including the bottom of the Greenbrier Limestone) in northern West Virginia. The truncation of the Pocono Big Injun by the pre-Greenbrier unconformity is shown. Wells (Wetzel 1287 and Doddridge 1887) that include porosity in both the Big Lime and Pocono Big Injun are examples of undifferentiated Big Injun. Identification of the pre-Greenbrier unconformity is based on regional correlation of gamma-ray and density logs without the aid of core information. Without lithologic evidence, many interpretations for this pick are possible. Well numbers correspond to the West Virginia county permit numbers used by the West Virginia Geological and Economic Survey.

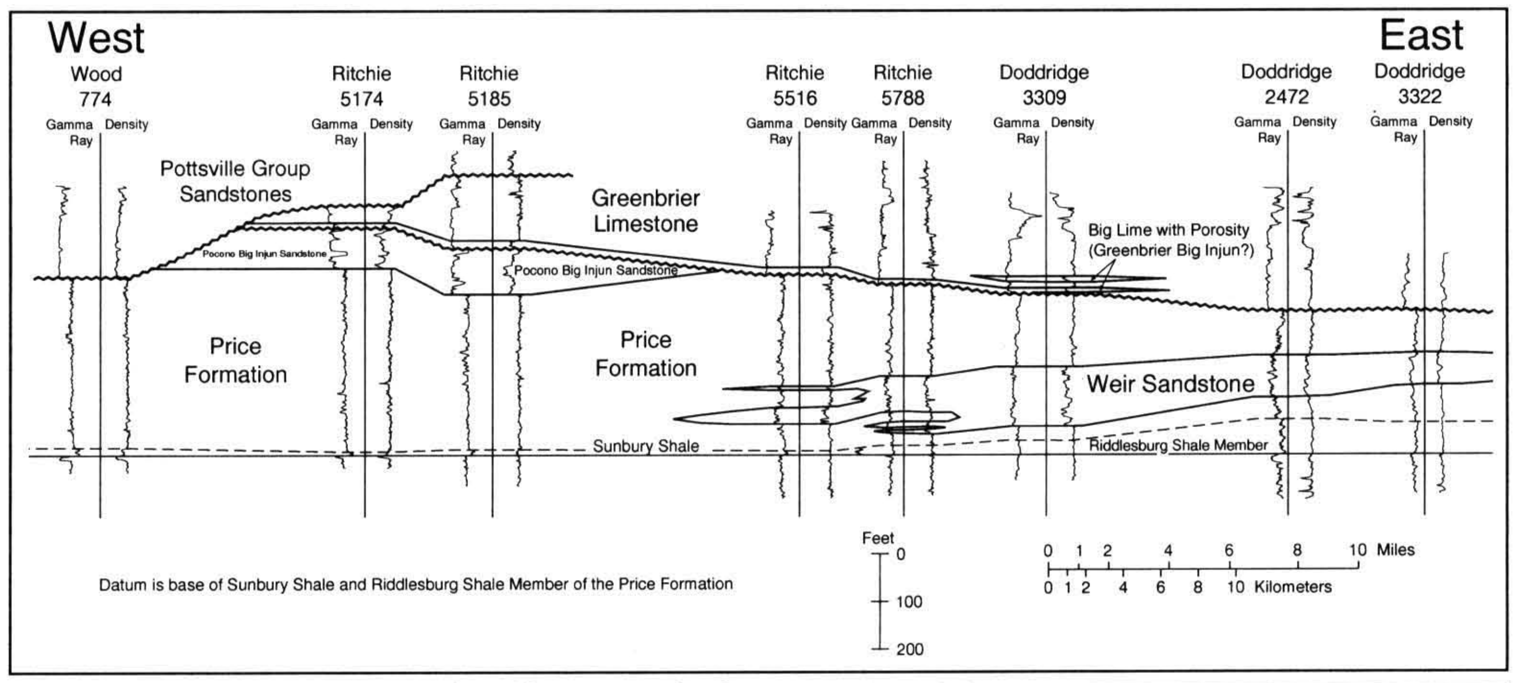
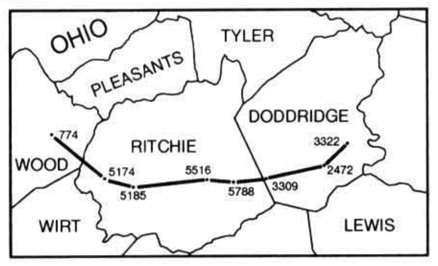


Figure Mbi-6. Regional east-west stratigraphic cross section in northern West Virginia. The distribution of Pocono Big Injun production is restricted by post-depositional erosion. Well numbers correspond to the West Virginia county permit numbers used by the West Virginia Geological and Economic Survey.



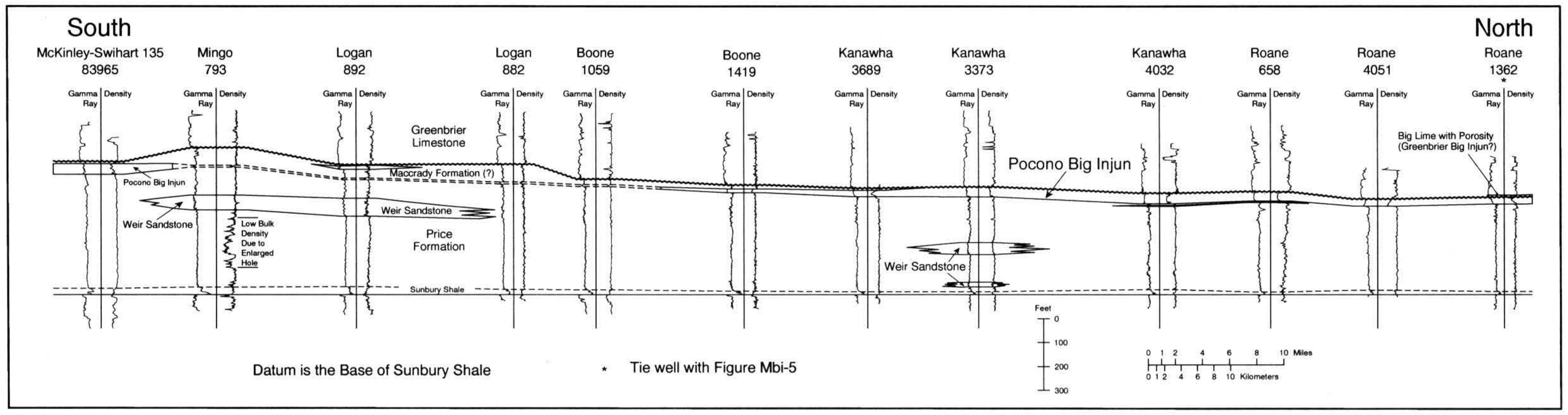
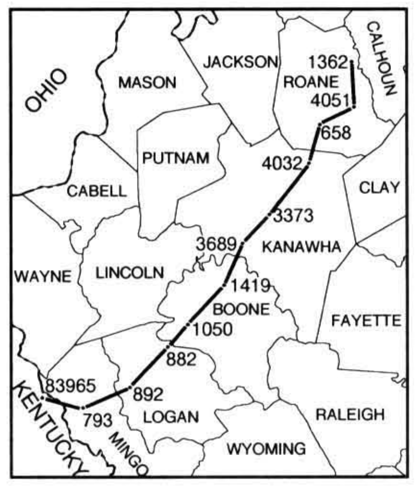
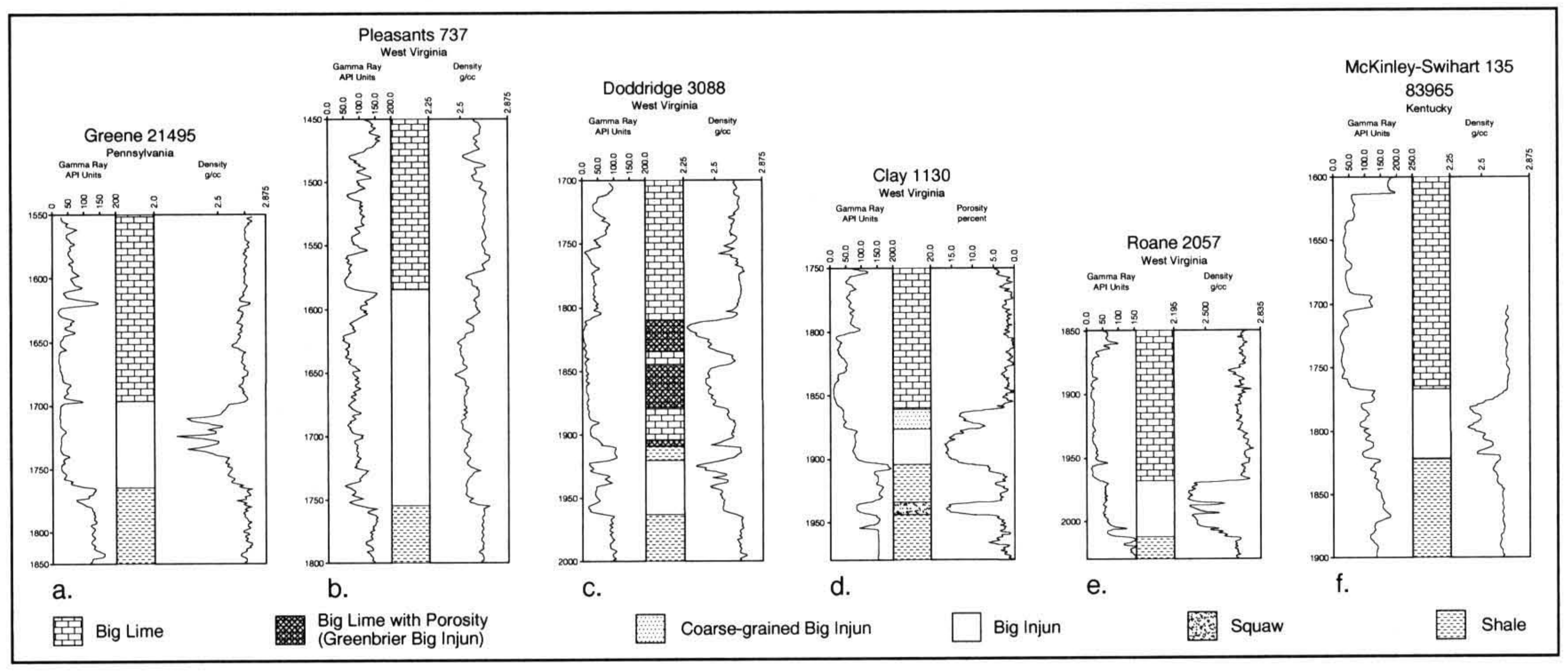


Figure Mbi-7. Regional north-south stratigraphic cross section in southern West Virginia illustrating the thinning of the Big Injun in southern West Virginia and the relationship between the Big Injun and the pre-Greenbrier unconformity. Well numbers correspond to the West Virginia county permit numbers used by the West Virginia Geological and Economic Survey and the well name and state permit numbers used by the Kentucky Geological Survey.





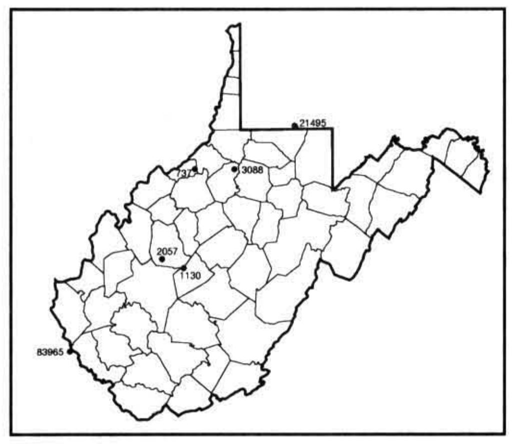


Figure Mbi-8. Type logs (gamma-ray and density) demonstrating the variety of Big Injun log signatures. Mbi-8a. Burgoon-equivalent of the Big Injun. Mbi-8b. Thick Pocono Big Injun. Mbi-8c. Undifferentiated Big Injun. Mbi-8d. Big Injun and Squaw in Granny Creek field. Mbi-8e. Big Injun in Rock Creek field. Mbi-8f. Cowbell Member equivalent of the Big Injun. Well numbers correspond to the West Virginia county permit numbers used by the West Virginia Geological and Economic Survey and the well name and state permit numbers used by the Kentucky Geological Survey.

along the crests of anticlines, forcing oil and water into the synclines. Structure maps (Cardwell, 1980; Cardwell, 1982a; Filer, 1985; Sweeney, 1986; Harper and Laughrey, 1987; Caramanica, 1988; Schwietering and Roberts, 1988) show this relationship. These structures are most prominent in the northern part of the productive area, where structures such as the Big Moses anticline, Arches Fork anticline (Cardwell and Avary, 1982), Amity anticline, and Fayette anticline (Harper and Laughrey, 1987) in northern West Virginia and Pennsylvania were identified and exploited (White, 1904). In Kentucky, the Warfield gas field in Martin County is associated with the southwest terminus of the Warfield anticline (Jillson, 1937) (Figure Mbi-2).

Reservoir

Most fields within the play were developed in the early 1900s. As a result, much of the reservoir information from early development is poor or incomplete. Two recent studies of oil reservoirs in Roane and Clay counties, West Virginia (Hohn and others, 1993a; 1993b), describe the Big Injun for that region. Reservoir characteristics in these fields are most likely similar to those found in the surrounding Big Injun gas reservoirs (Elkhurst, Amma-Looneyville-Newton, and Clendenin fields) (Figure Mbi-2). Reservoir parameters for selected fields that produce from the Big Injun are listed in Table Mbi-1.

Trap types range from stratigraphic to structural, with most classified as combination. Field locations in northern West Virginia were structurally controlled, and the Big Injun produced oil, gas, or water depending on the position of wells relative to folding (White, 1904). In central West Virginia, the combination of structure and stratigraphic pinchout of the Big Injun results in a series of oil and gas fields (for example, Granny Creek, Rouzer, and Elkhurst) (Figure Mbi-2). In the south, the Big Injun is generally a siltstone with minor sandstone intercalations; where these sandy accumulations coincide with an anticline, production may occur as in the Warfield District, Martin County, Kentucky.

The most obvious seal for Big Injun traps is the overlying Greenbrier Limestone. In areas where the Big Injun is overlain by shales and mudstones of the Maccrady or the Price Formation, these shales may serve as a seal. Locally in the southern region, an upper, coarse-grained sandstone is present (Elkhurst, Clendenin, and Granny Creek fields) (Figure Mbi-2). This unit is generally non-productive and in some cases exhibits zones of low porosity and permeability that may also serve as a seal (Hohn and others, 1993b; Zou, 1994).

The source of hydrocarbons for Lower Mississippian reservoirs in Cabell and Wayne counties is probably the Sunbury Shale, Ohio Shale, and the Rhinestreet Shale Member of the West Falls Formation (Schwietering and Roberts, 1988). Most likely, hydrocarbons for the Big Injun in the Appalachian basin originated in the Lower Mississippian and Upper Devonian black shales, and migrated upsection into the Big Injun and related reservoirs (Gautier and Varnes, 1993). In southwestern Pennsylvania, Harper and Laughrey (1987) showed that only the Marcellus and Genesee formations contain enough organic carbon to serve as source rocks for the Mississippian reservoirs. These formations are mature and may still have some dry-gas generative capacity remaining.

The Big Injun is a shallow reservoir where productive in the Appalachian basin, lying between 500 and 1,500 feet below sea level. Only in southern West Virginia is the Big Injun deeper than 1,500 feet below sea level.

Throughout the Appalachian basin, the Big Injun varies considerably in thickness. In the northernmost parts of the productive area, the Big Injun exceeds 200 feet in thickness. Production within this interval occurs from as many as four pay zones (Hennen, 1909). In this case, the pay may be limited to 40 or 50 feet of the total interval. In southwestern Pennsylvania, the pay zones usually occur in the upper portion of the unit (McGlade, 1967). South of the West Virginia Dome to eastern Kentucky, the Big Injun rarely exceeds 60 feet in thickness, and is commonly 25 to 40 feet thick. In this region, the pay zone is fine-grained (Hohn and others, 1993a) and typically includes the entire Big Injun.

Initial rock pressures within Big Injun traps have been consistently recorded in the 500 to 600 psi range, with some wells above and below this range (White,

TABLE Mbi-1		Warfield KY	Fych Consolidated KY	Moree Consolidated KY	Elk Run OH	Moose Ridge OH	Frost OH	Smithton-Flint-Sedalia WV	Beckwith WV	Amma-Looneyville Newton WV	Maple-Wadestown WV	Stanley WV	Elkhurst WV	Majorsville WV	Majorsville PA	Lizemores WV	Gauley Mountain WV
BASIC RESERVOIR DATA	POOL NUMBER	1602071337	1602240337	1600436337	341670022	341110068	341670700	47099371	47354375	47198375	47051371	47090371	47223375	47022371	37971	47355375	47263375
	DISCOVERED	1905	1922	1987	1897	1903	1922	1892	1913	1901	1905	1899	1913	1904	1905?	1949	1927
	DEPTH TO TOP RESERVOIR	1,785	1,632	2,086	1,500	1,400	1,200	1,990	2,194	1,821	2,297	1,937	1,908	1,632	1,714	2,285	2,175
	AGE OF RESERVOIR	Early Mississippian	Early Mississippian	Early Mississippian	Early Mississippian	Early Mississippian	Early Mississippian	Early and Middle Mississippian	Early Mississippian	Early Mississippian	Early and Middle Mississippian	Early and Middle Mississippian	Early Mississippian	Early Mississippian	Early Mississippian	Early Mississippian	Early Mississippian
	FORMATION	Borden	Borden	Borden	Cuyahoga	Cuyahoga	Cuyahoga	Price	Price	Price	Price	Price	Price	Price	Burgoon	Price	Price
	PRODUCING RESERVOIR	Big Injun	Big Injun	Big Injun	Big Injun/ Keener	Big Injun	Big Injun/ Keener	undifferentiated Big Injun	Big Injun	Big Injun	undifferentiated Big Injun	undifferentiated Big Injun	Big Injun	Big Injun	Big Injun	Big Injun	Big Injun
	LITHOLOGY	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	limestone/ sandstone	sandstone	sandstone	limestone/ sandstone	limestone/ sandstone	sandstone	sandstone	sandstone	sandstone	sandstone
	TRAP TYPE	combination	stratigraphic	stratigraphic	stratigraphic	structural	stratigraphic	combination	combination	combination	combination	combination	combination	combination	combination	combination	stratigraphic
	DEPOSITIONAL ENVIRONMENT	deltaic	deltaic	deltaic	fluvial/deltaic	fluvial/deltaic	fluvial/deltaic	fluvial/deltaic carbonate shelf	fluvial/deltaic	fluvial/deltaic	fluvial/deltaic carbonate shelf	fluvial/deltaic carbonate shelf	fluvial/deltaic	fluvial/deltaic	fluvial/deltaic	fluvial/deltaic	fluvial/deltaic
	DISCOVERY WELL IP (Mcf)	6,000	2,000	345	479	50	711			4,553						253	
	DRIVE MECHANISM	gas expansion	gas expansion	gas expansion	gas cap	gas cap	gas cap	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion
	NO. PRODUCING WELLS	44	24	4	293	147	136	474	35	442	12	11	144	38?	55	100	53
	NO. ABANDONED WELLS	2	3	0	56	56	115	216	3	179	22	29	27	11		1	7
	AREA (acreage)	5,520	3,240	480	3,804	1,970	1,309	46,850	3,810	70,302	4,634	11,616	14,710	3,434	2,301	11,463	23,790
	OLDEST FORMATION PENETRATED	Corniferous	Corniferous	Ohio		Ohio		Devonian?	Onondaga	Onondaga	Chemung	Devonian Shale	Angola	Upper Devonian	Upper Devonian	Upper Devonian	Upper Devonian
	EXPECTED HETEROGENEITY DUE TO:	depositional structure	depositional	depositional	depositional	depositional	depositional	diagenetic structure	diagenetic stratigraphic	diagenetic depositional	diagenetic deposition	diagenetic deposition	diagenetic deposition	deposition	deposition	diagenetic deposition	diagenetic deposition
RESERVOIR PARAMETERS	AVERAGE PAY THICKNESS (ft.)	19		9	30	30	20	47		32	90	42	26	28		26	33
	AVERAGE COMPLETION THICKNESS (ft.)	26	39	10				19	13	52	42	20	30			15	23
	AVERAGE POROSITY–LOG (%)	14		12				10	10.1	15.1	10.8	10.3	15			15	10
	MINIMUM POROSITY–LOG (%)	8		8				4	6	6	7.5	7	5.4			4	4
	MAXIMUM POROSITY–LOG (%)	19		15				19	23	25.6	17.8	25	23			22	23
	NO. DATA POINTS	12		3				13	10	4	1	14	7			14	19
	POROSITY FEET																
	RESERVOIR TEMPERATURE (°F)	75	72	76				73		76		76					78
	INITIAL RESERVOIR PRESSURE (psi)	255	495	420	231	285	715	302		331		486	422	440	379	428	398
	PRODUCING INTERVAL DEPTHS (ft.)	1,291-2,309	1,306-1,814	1,979-2,244	1,000-2,000	1,100-1,800	1,000-1,300	1,584-2,922	1,553-2,870	1,432-2,276	2,045-2,580	1,661-2,154	1,394-2,413	1,367-2,212	1,394-1,912	1,875-2,697	1,584-3,042
	PRESENT RESERVOIR PRESSURE (psi) / DATE	190/1989	196/1961	340/1989											605/1989		
FLUID & GAS PROPERTIES	Rw (Ωm)	0.05		0.05					0.05	0.05	0.05	0.05	0.05			0.05	0.05
	GAS GRAVITY (g/cc)	0.71	.698 (est.)	0.71				0.752	0.584		0.66						0.60
	GAS SATURATION (%)	84		74					66	50.8	60.8	59.9	55.7			73.6	59
	WATER SATURATION (%)	16		26					34	49.2	39.2	40.1	44.3			26.4	41
	COMMINGLED	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	no	yes
	ASSOCIATED OR NONASSOCIATED	nonassociated	nonassociated	nonassociated	associated	associated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	associated	nonassociated	nonassociated		nonassociated	nonassociated
	Btu/scf	1,193	1,147	1,193				1,232	1,053								1,082
VOLUMETRIC DATA	STATUS (producing, abandoned, storage)	producing	producing	producing	producing	producing	producing	producing	producing	producing	producing	producing	producing	storage	storage	producing	producing
	ORIGINAL GAS IN PLACE (Mcf)																
	ORIGINAL GAS RESERVES (Mcf)																
	PRODUCTION YEARS		1937-1992	1987-1992			1925-1968	1980-	1979-present	1979-present	1980-present	1899-present	1980-present	1980-present			1980-present
	REPORTED CUMULATIVE PRODUCTION (Mcf)		896,594	134,129			8,082,000	9,148,782	9,052,846	68,069,407	70,595	525,474	28,101,236	18,813		9,371,356	17,079,500
	NO. WELLS REPORTED						37	268	38	354	1	22	123			67	69
	ESTIMATED CUMULATIVE PRODUCTION (Mcf)							248,253,748		524,832,892	14,119,000	10,947,375	108,773,490			46,785,365	174,280,612
	REMAINING GAS IN PLACE (Mcf)/DATE																
	REMAINING GAS RESERVES (Mcf)/DATE																
	RECOVERY FACTOR (%)																
	INITIAL OPEN FLOW (Mcf/d)				208		789	806	100	1,848	623	1,402	123	2,619	477		175
	FINAL OPEN FLOW (Mcf/d)	845	959	222	223			977	617	501	153	455	747	667	3,345		749

1904). Some pressure differences have been recorded after additional zones were completed, which changed the final well pressure.

Initial open flow within the Big Injun play has been measured as high as 50 to 100 MMcf/d, and as low as 1 to 12 Mcf/d. Most wells fall between 0.5 to 1.0 MMcf/d. Many wells in the northern part of the productive area did not require stimulation to produce good results. The highest flow rates were often associated with structural highs. After stimulation, wells on the low end of that range (1 to 12 Mcf/d) often experienced final open flow rates in the 0.5 to 1.0 MMcf range.

One of the most productive gas wells drilled in West Virginia was the No. 1 Moses Spencer in Tyler County. In the fall of 1894, this well struck gas in the Big Injun at 1,750 feet. The well produced 50 to 100 MMcfg/d (Whiteshot, 1905; Hennen, 1909; Overbey and others, 1963), and was still billed as the world's largest volume gas well as late as 1929. Open pressure was estimated at 575 psi, and on August 27, 1895, the pressure was 450 psi (Whiteshot, 1905).

Recent studies of heterogeneity in Big Injun oil fields, Roane and Clay counties, West Virginia (Swales, 1988; Britton, 1993; Hohn and others, 1993a; 1993b; Hohn and others, 1994; Zou, 1994) provide the best and perhaps the only available information that can describe the heterogeneity of Big Injun gas reservoirs. In this area, heterogeneity seems to occur in two forms: stratigraphic and diagenetic. Stratigraphic heterogeneities consist of interbedded shales or argillaceous sandstones (Hohn and others, 1993a; 1993b; Zou, 1994), and can be identified using gamma-ray and density logs. Diagenetic heterogeneities can be identified by a high-density deflection without a similar reaction from the gamma-ray curve (Hohn and others, 1993a; 1993b) (see Figures Mbi-8d, Mbi-8e).

Core and thin-section analyses reveal several types of diagenetic heterogeneity within the Big Injun. In intervals where sand grains have chlorite coats, porosity is good and the sandstone is productive (Britton, 1993; Hohn and others, 1994). Where chlorite is not present, quartz overgrowths often fill the pores. In some intervals, carbonate (calcite, dolomite, and siderite) cementation (Swales, 1988; Britton, 1993) fills most of the available pore space regardless of chlorite coatings on grains. These diagenetic zones may be horizontal, inclined, or irregular in shape and may compartmentalize the reservoir (Hohn and others, 1993a; 1993b).

Big Injun sandstone porosity appears to be both primary and secondary. Secondary porosity may vary in some areas based upon diagenetic processes as discussed earlier. In diagenetically altered zones, porosity ranges from 0 to 10 percent; in good pay zones, porosity ranges from 15 to 25 percent (Nabors and others, 1960; McCord and Eckard, 1963; Hohn and others, 1993a; 1993b). Average porosity values for specific field pay zones are listed in Table Mbi-1.

The permeability for Big Injun reservoirs from the few published values suggest that it is fair to moderately good. Permeability in Rock Creek oil field ranges from 0 to 230 md in the few wells analyzed (Nabors and others, 1960). Permeability exceeded 100 md in only one well. These high permeability zones are restricted to thin, erratic, pebbly layers in the upper portion of the pay and do not seem to be continuous throughout the field. When secondary recovery projects were designed, the lower permeability zones (>50 md) were considered to be depleted by earlier oil development (Nabors and others, 1960).

It is widely accepted that most Big Injun reservoirs are driven by fluid expansion, but few data are available to support this. Some Big Injun oil and gas reservoirs have a weak water drive (G. Morrison, written commun., 1994). In the northern part of the basin, White (1904) noted the stratification of gas, oil, and water. Similar stratification can be observed in the Rock Creek oil field (Hohn and others, 1993a).

Gas gravity for the Big Injun ranges from 0.6201 to 0.7524, with an average of 0.6837 from 21 analyses in West Virginia (U.S. Bureau of Mines, 1993). Btu values for the Big Injun gas ranges from 1,071 to 1,281 Btu, with an average of 1,164 Btu from 26 analyses (U.S. Bureau of Mines, 1993).

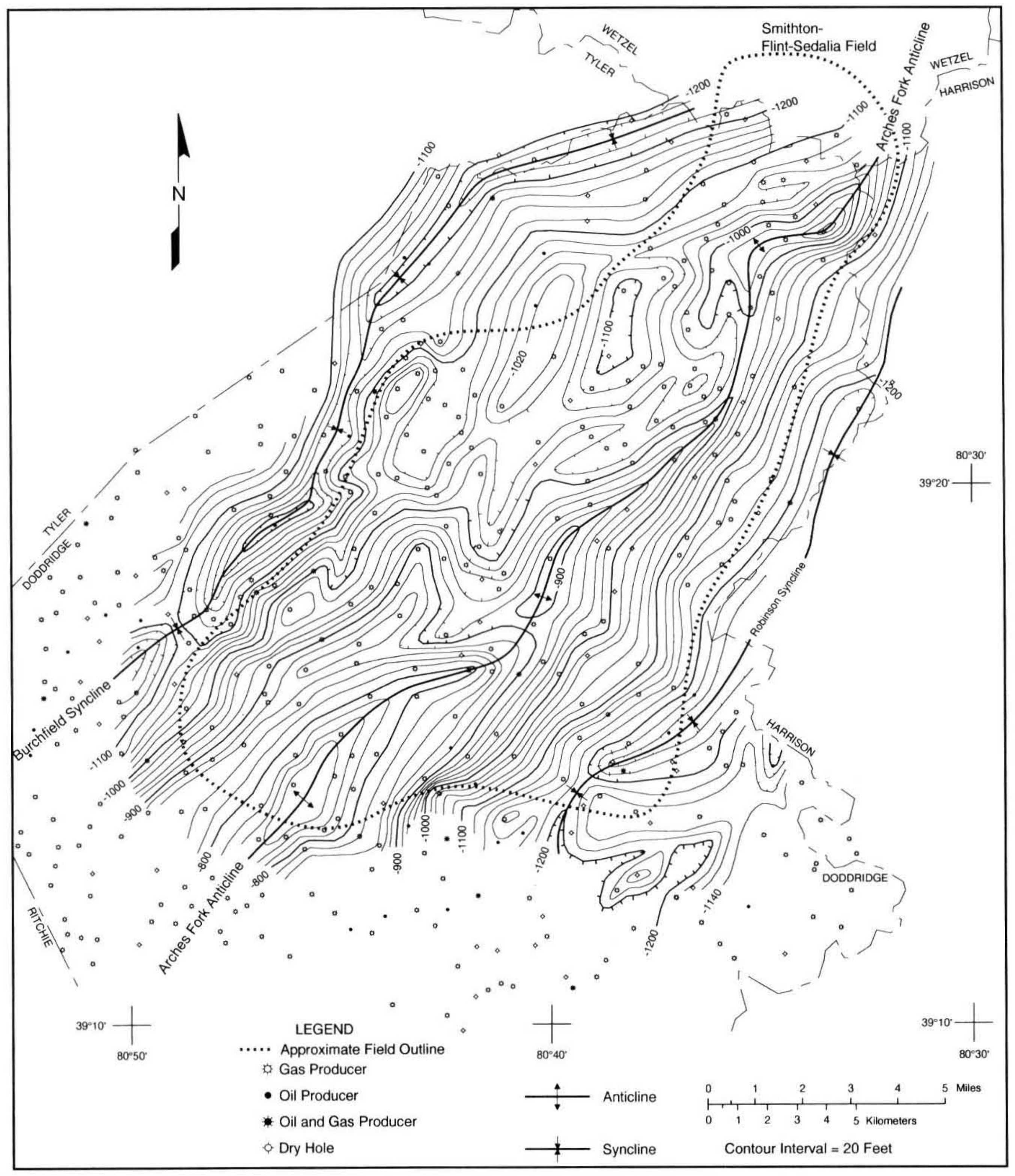


Figure Mbi-9. Structure map of the Smithton-Flint-Sedalia field taken from Cardwell (1982a). Contours are on the base of the Greenbrier Limestone.

Many early Big Injun wells produced prolifically without any stimulation, especially in northern West Virginia. Wells with low initial open flows usually were shot with nitroglycerine (White, 1904). Later, wells were hydraulically fractured with sand and water and treated with acid. In the Amma-Looneyville-Newton field (Figure Mbi-2) area, a number of wells were shot or fractured.

Description of Key Fields

Smithton-Flint-Sedalia field: The Smithton-Flint-Sedalia field in Doddridge County, West Virginia (Figure Mbi-2), lies within the historical hydrocarbon production region of northern West Virginia. This area already had been explored heavily and exploited for oil and gas when the earliest summaries of West Virginia oil and gas were written (White, 1904; Hennen, 1912).

The gas field lies along the crest of the Arches Fork anticline (Figure Mbi-9) and is paralleled by oil fields (Salem, Shirley, and Swiger) that lie in the Robinson and Burchfield synclines (Cardwell and Avary, 1982). Typical of fields in this region, production occurred from several zones, including the Big Injun.

In 1898, the Sedalia pool of the field was discovered by the Carter Oil Company's No. 1 Camden Heirs well with primary production in the Devonian Gordon Stray sandstone (Hennen, 1912). Development of the Big Injun gas pool soon followed. More than 650 of the field's 1,200 wells produce from the Big Injun. Many of these wells have been plugged and abandoned. The field has a history of high gas production from the Big Injun. An initial pressure of 765 psi was reported for the No. 1 Powell and Williams well, completed March 19, 1911, by the Pennsylvania Oil and Gas Company. Final open flow for the well was reported as 15 to 18 MMcf/d with a rock pressure of 720 psi (Hennen, 1912). Additional reports from wells on the crest of the anticline have flow volumes ranging from 0.5 to 16.75 MMcf (Figure Mbi-10). Regardless of the pay zone, this field clearly demonstrates the correspondence of high gas volumes to structure.

Of the 180 Big Injun wells drilled before 1930, 140 were left natural, and only 40 were shot. Later wells required stimulation by fracturing or fracturing and acid treatment. Annual production totals are available for 1980 to the present, when most exploration targeted deeper zones in the Upper Devonian. Production totals are presented in Table Mbi-1.

In the field, the Big Injun is undifferentiated (Figure Mbi-11). Most drillers record the entire porous zone as Big Injun. It would seem, however, that much

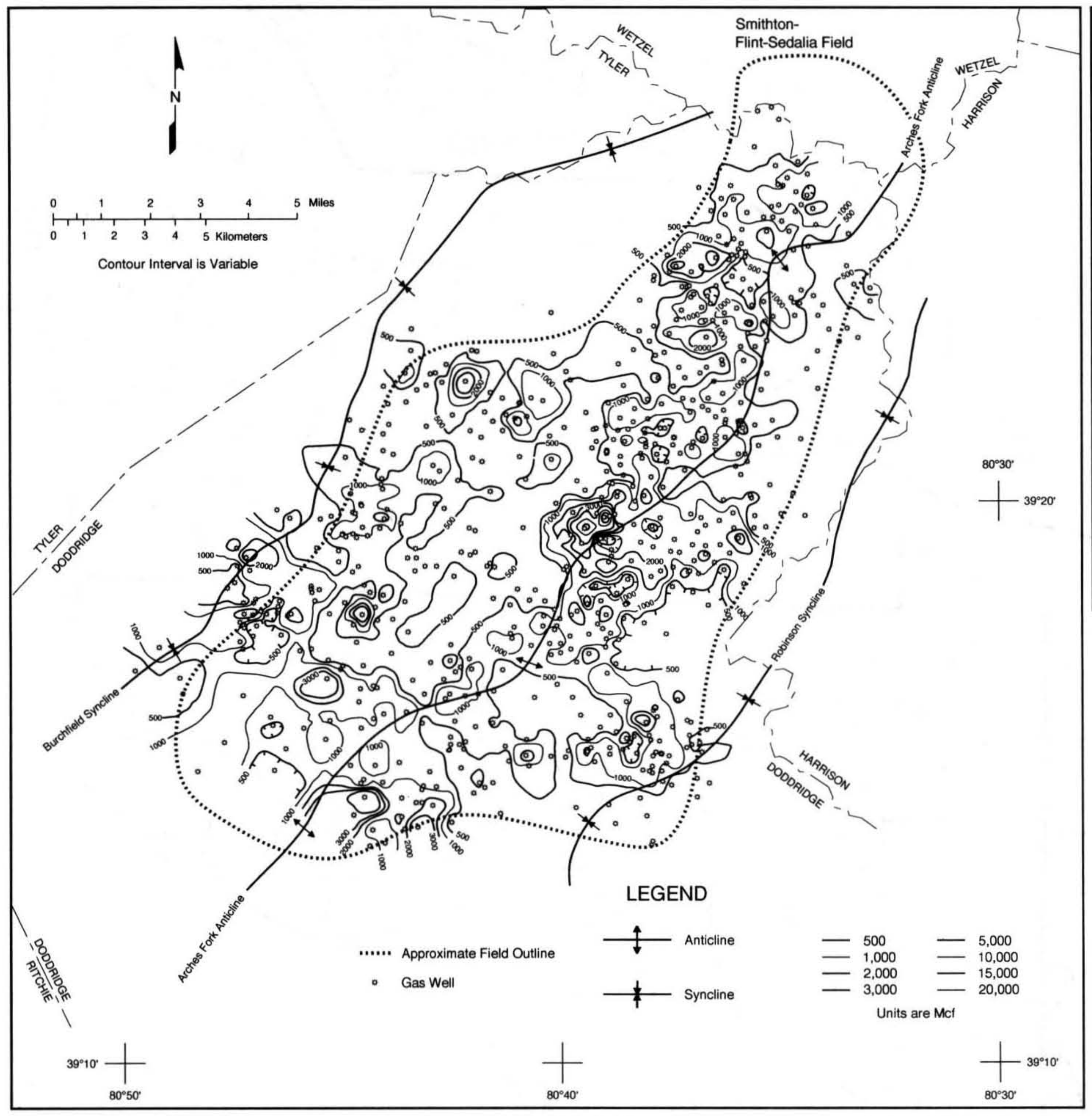
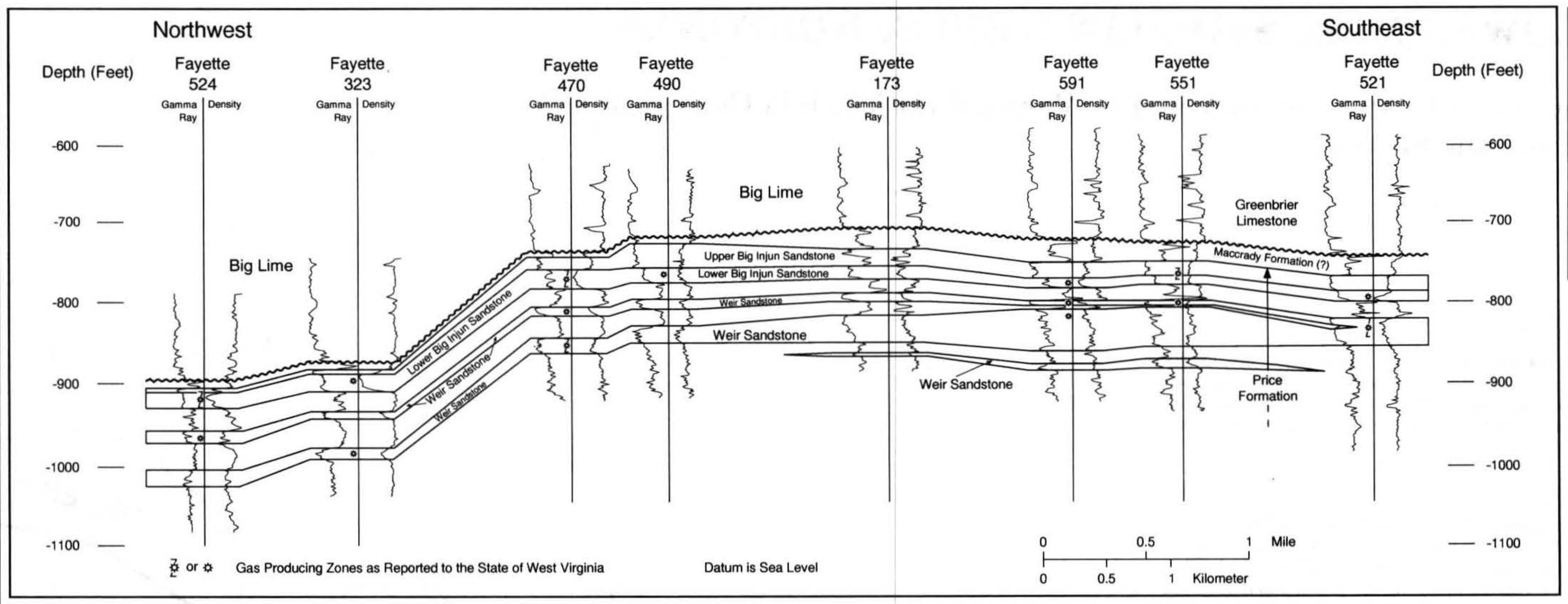


Figure Mbi-10. Initial open flow map of the Smithton-Flint-Sedalia field, as reported to the State of West Virginia (from the West Virginia Geological and Economic Survey Oil and Gas database), illustrating the relationship between anticlines and high initial open flow rates. Initial open flows may be commingled.



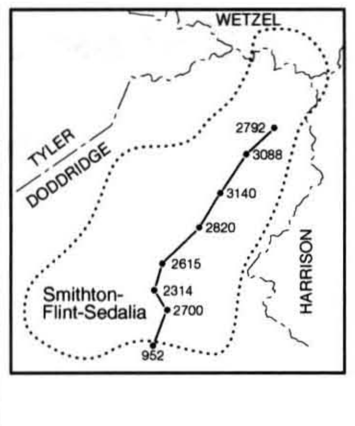


Figure Mbi-11. Northwest-southeast cross section through the Smithton-Flint-Sedalia field. The position of the pre-Greenbrier unconformity has been determined by regional correlation of gamma-ray and density logs. Most well records report the entire productive zone as Big Injun. Although they are separated on this figure, these productive zones are recognized as undifferentiated Big Injun for this report. Well numbers correspond to the West Virginia county permit numbers used by the West Virginia Geological and Economic Survey.

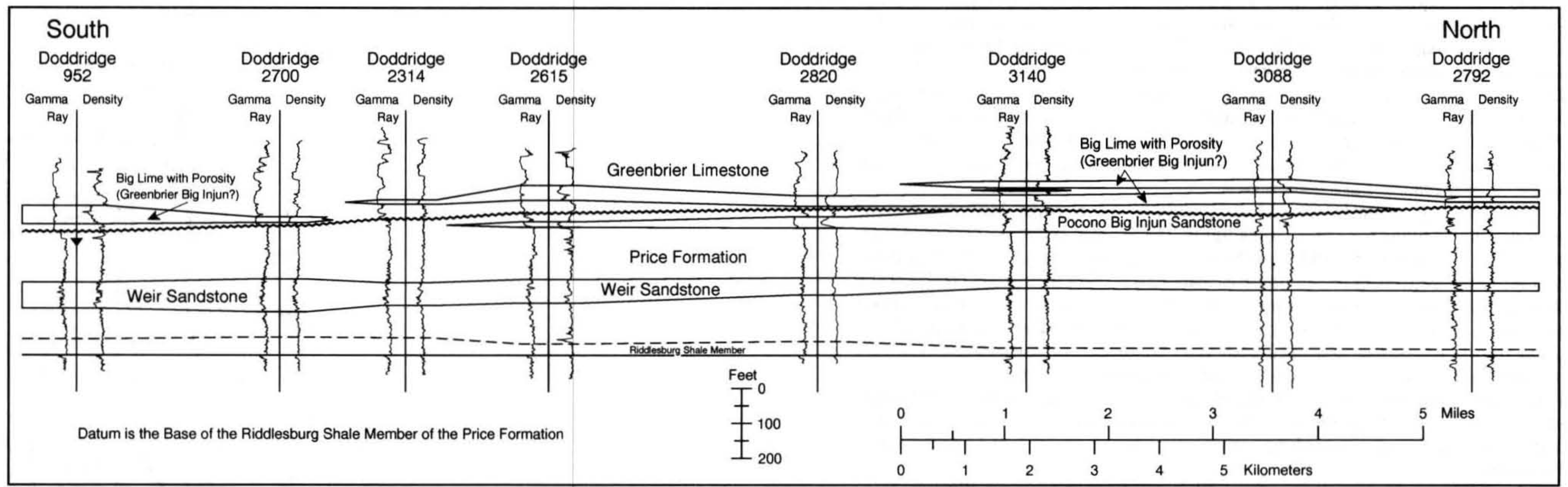


Figure Mbi-12. Structural cross section through the Beckwith field illustrating the anticlinal trap within Beckwith field and the location of the Big Injun pay zones within the lower part of the sandstone. Well numbers correspond to the West Virginia county permit numbers used by the West Virginia Geological and Economic Survey. See Figure Mbi-13 for line of cross section.

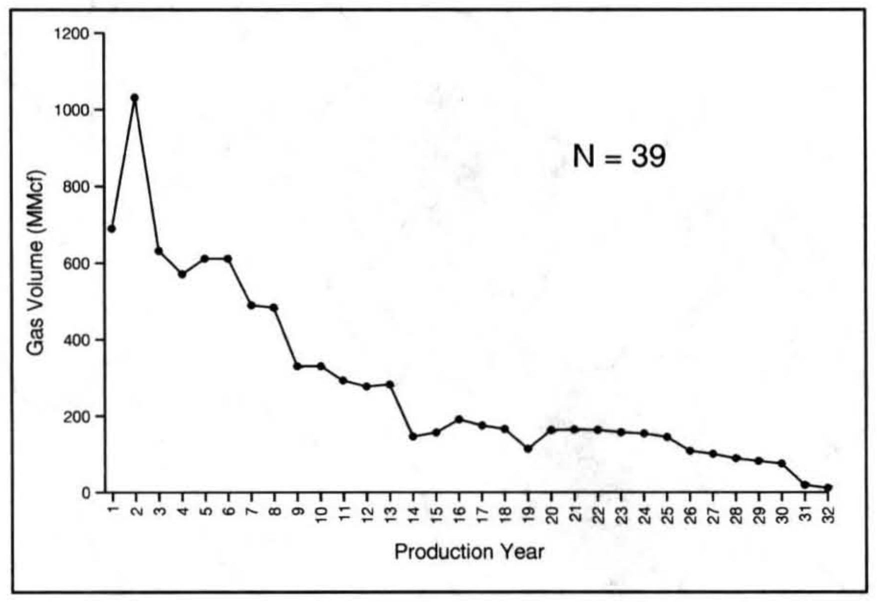


Figure Mbi-14. Composite decline curve for the Beckwith field.

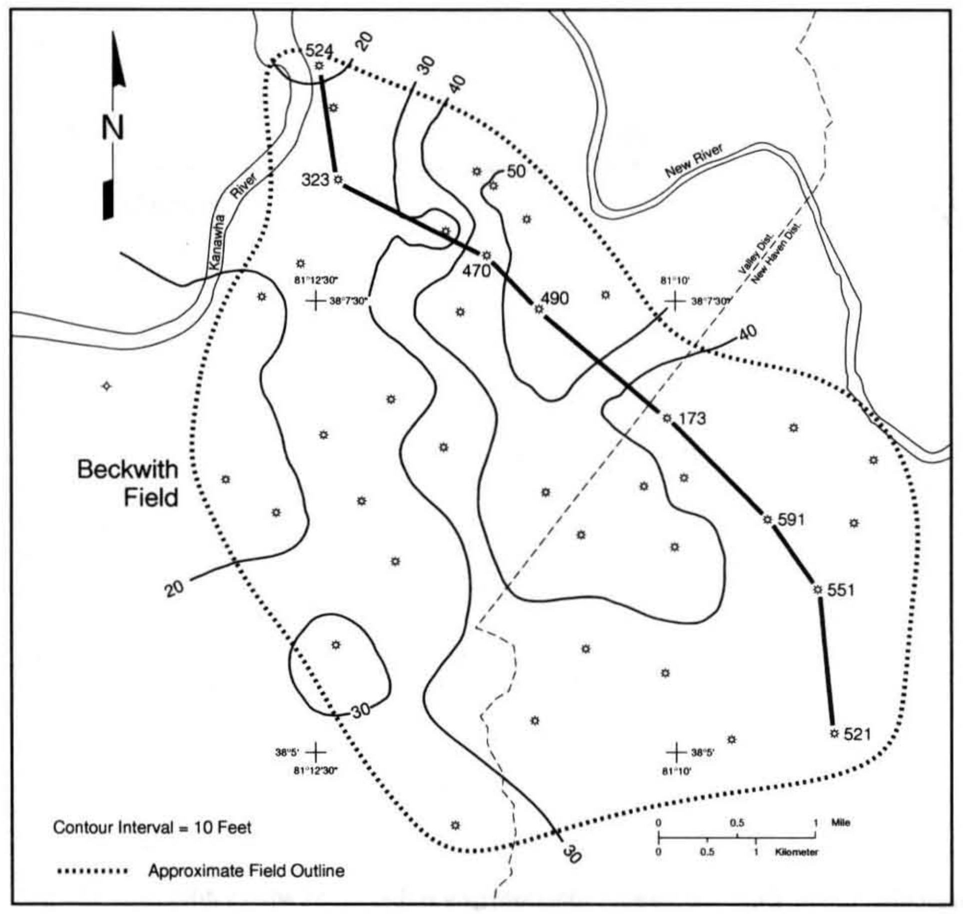


Figure Mbi-13. Isopach map of the Big Injun sandstone in Beckwith field.

of the best porosity is located in the Greenbrier Limestone. These two lithostratigraphic units create a multi-layered reservoir with several porous zones in the Greenbrier and a single zone in the Price Formation. The Pocono Big Injun ranges in thickness from 0 feet in the southern portion of the field to approximately 70 feet in the north.

Beckwith field: The Beckwith field in Fayette County, West Virginia (Figure Mbi-2), represents an example of a more recently developed Big Injun field. The field was discovered on February 8, 1961, and produces from both the Big Injun and Weir intervals. Of 41 producing wells, 38 produce from the Big Injun, with 32 being commingled with the Weir. The field lies on a small anticlinal structure that has a steep western flank that may be fault related (Figure Mbi-12), although there has been nothing published to support this conclusion. The field generally lies on the eastern flank of a plunging syncline that has been mapped on the Onondaga Limestone (Cardwell, 1982b).

All of these wells required some degree of stimulation primarily by hydraulic fracturing and acid wash. Average porosities for the Big Injun range from 7.7 to 11.4 percent based on nine log analyses. No core data are available to confirm these values. Gas saturations for these wells average about 67 percent. Thickness of the Big Injun ranges from less than 20 feet to more than 50 feet (Figure Mbi-13). The Big Injun is divided into an upper sandstone and a lower sandstone (Figure Mbi-12). These sandstones may be analogous to the coarse and fine sandstones identified in the Granny Creek field to the north (Hohn and others, 1993b), although core data are not available for complete confirmation. The Big Injun pay is primarily limited to the lower sandstone with its higher porosity. The lower Big Injun thickness is consistently between 15 and 20 feet.

Initial open flow in Beckwith field ranged from 28 to 2,144 Mcf/d. Initial rock pressures for the field were reported to range from 555 psi to 640 psi; in July 1980, the rock pressure for the field dropped to between 240 to 395 psi (CNG Transmission, written commun., 1993). Figure Mbi-14 presents a composite decline curve showing Big Injun and Weir gas production. Total production (all pay zones) from 38 wells in this field from 1962 to 1992 is 9.053 bcf. The gas gravity is reported to be between 0.578 and 0.588 g/cc (CNG Transmission, written commun., 1993).

Resources and Reserves

Most Big Injun discoveries have been exploited for more than 100 years, meaning that a large number of Big Injun wells have been depleted, plugged, and abandoned. Very old fields, incomplete or unavailable data, a widely variable definition of Big Injun, and commingling of production from several pay zones make resource and reserve calculations imprecise.

Many different numbers exist for the Big Injun reservoir. The authors estimated a cumulative production for the Big Injun in West Virginia to be 3.965 tcfg. Zammerilli (US Department of Energy/Morgantown Energy Technical Center, written commun., 1994) provided values for resources using the U.S. Department of Energy's simulator and a pressure of 409 psi and a temperature of 73.5°F. These figures utilized data collected by Boswell and others (1993) to calculate that 14.65 tcfg was originally in place, an estimated 3.07 tcfg have been produced to date, and an estimated 8.78 tcfg remain in place, of which an estimated 3.09 tcfg remain as recoverable gas for the Big Injun/Squaw reservoirs. Boswell and others (1993) reported a value of 30.8 tcfg originally in place for the Big Injun/Squaw reservoirs. This range of values for original gas in place (14.65 to 30.8 tcf) suggests that the actual value probably falls somewhere in the middle. Using a 75 percent recovery factor on the low value for original gas in place (14.65) leaves 10.988 tcfg recoverable resources. Using a lower recovery factor of 50 percent on the high value (30.8 tcfg) leaves 15.4 tcfg recoverable resources.

Additionally, proven reserves per well can be used to calculate total resources for the Big Injun/Squaw. Bagnall (Columbia Gas Transmission Corporation, written commun., 1972) calculated an average proven reserve per well of 609,994 Mcf from 748 wells. Multiplying the average proven reserve by 14,666 (the number of Big Injun wells in Kentucky, Ohio, and West Virginia), and an original proven reserve of 8.95 tcfg is obtained. Subtracting the estimated production of 3.965 tcfg from the original proven reserves leaves 4.985 tcfg as remaining proven reserve. This suggests that of the 10.988 tcfg recoverable resources, 3.965 tcfg have been produced, 4.985 tcfg remain as proven reserve, and 2.088 tcfg remain as possible and probable resources. However, by subtracting the original proven reserve (8.95 tcfg) from the high recoverable resource value (15.4 tcfg) a possible and probable resource figure of 6.45 tcfg is obtained.

Future Trends

The Big Injun has been a major play throughout the history of natural gas production in the Appalachian basin. Thousands of wells have been completed in the Big Injun, and many more have been drilled through the sandstone, generally defining the productive and stratigraphic extents of the interval. Although the extent of the play is well defined, development continues to occur within the play as Big Injun completions account for approximately 10 percent of total completions in West Virginia. Most likely, industry will rely on treatment of old wells, infill drilling, plugging back of deeper wells, and completion of the Big Injun interval (commingling) in wells that are targeted for deeper zones. Small fields (10 to 20 wells) may be discovered over local structures and in local stratigraphic traps, most likely in the southern part of West Virginia. Some potential also remains in Pennsylvania and Ohio, where little Big Injun exploration has occurred in recent years. Harper and Laughrey (1987) suggested that production potential still exists in Pennsylvania around historically productive areas. This is likely to be the case for Ohio as well.

PLAY Mws: LOWER MISSISSIPPIAN WEIR SANDSTONES

by David L. Matchen and Ana G. Vargo, West Virginia Geological and Economic Survey

Location

Lower Mississippian Weir sandstones (drillers' terminology) are locally significant producers of oil and gas throughout parts of West Virginia, eastern Kentucky, and southwestern Virginia (Figure Mws-1). Weir production occurs from several north-south-oriented trends that correspond to the location of deltaic system sandstone accumulations.

Production History

The Weir sandstone was first identified in 1911 near Weir, Kanawha County, West Virginia, in the No. 1 Falling Rock Cannel Coal well. This well was 2,340 feet deep and produced gas (1,605 to 1,640 feet) from a 95-foot-thick Weir sandstone (Krebs and Teets, 1914). This discovery was developed into Blue Creek (Hackberry Branch) oil field (Figure Mws-2). In Kentucky, Weir sandstones were first recognized in 1917, with the discovery of two important oil and gas pools along the Paint Creek uplift in Magoffin, Johnson, Elliott, and Lawrence counties (Jillson, 1919b; Jillson, 1922) (Figure Mws-2). These discoveries (Redbush and Win fields) made the Weir sandstone the most important hydrocarbon reservoir in Kentucky at the time (Jillson, 1922).

After the discovery of the Blue Creek (Hackberry Branch) field, the Weir was extensively developed in several fields (Clendenin, Campbell Creek, Slaughter Creek) in Kanawha County, West Virginia (Caramanica, 1988) (Figure Mws-2). Development of Weir fields throughout southern West Virginia continued at a slow pace throughout the middle part of the century (1940 to 1970) with some development occurring in southwestern Virginia (Roaring Fork field). By the 1970s, new production was developed in southern West Virginia (Ashland-Clark Gap-Eckman field) (Figure Mws-2). Since the 1950s, some operators in northern West Virginia have been completing Weir intervals that previously had been bypassed in wells drilled to Upper Devonian sandstones. This activity has been sporadic, and results have been mixed.

In Kentucky, several major oil and gas fields (Oil Springs, Isonville, Ivyton) were developed along the Paint Creek uplift. These fields generally produced both oil and gas from the Weir sandstone. Some development of Weir sandstones along this structure continues to the present, although no new sandstone trends other than Paint Creek have been identified (Kentucky Geological Survey, written commun., 1994). However, new production was discovered off the Paint Creek trend that is sometimes confused with Weir sandstone production. Most of this production occurs from naturally fractured siltstones and shales of the Borden Formation (sometimes called Waverly shale). This production occurs on the same stratigraphic interval as the Weir sandstone and is included in this play. This fractured production occurs along major anticlines in eastern and southeastern Kentucky.

Available production values from Weir sandstones in West Virginia total 310.9 bcf (including wells that are commingled) from 2,354 wells as determined from production data available at the West Virginia Geological and Economic Survey. Production values from wells that produce exclusively from the play (excludes commingled wells) total 131.4 bcf from 882 wells.

In the absence of complete or even representative decline curves for the Weir fields, a crude estimate of cumulative production was determined by estimating what portion of the actual production was represented by the reported production for that field. Using the formula:

$$\%\ \text{production} = \frac{\text{(number of wells reporting production)}}{\text{(total number of producing wells)}} \times \frac{\text{(average number of years reported)}}{\text{(number of years field is producing)}},$$

the percentage of production reported for each field (excluding wells with commingled production) was calculated. Dividing the reported production data for each field by this value yielded an estimated cumulative production for the field. However, this estimate will be low for five reasons. First, the actual slope of the Weir decline curve is unknown; it is most certainly not linear (as assumed by the proportioning procedure used). Second, most wells have data available only after 1979 (when production was required to be reported to the state); these data represent the end of declining Weir production with an average of 28 percent of the decline curve represented in all Weir fields. Third, the number of producing wells estimated may be low because reports were often not filed for wells completed before 1929. Fourth, this value does not include production that is commingled with several zones. Finally, Weir reservoirs may be misidentified in some parts of the basin. Cumulative production estimates for all fields in West Virginia (871 wells reporting production; 2,737 producing wells) were summed, giving a cumulative production of 1.753 tcfg.

Stratigraphy

In the subsurface, the Weir sandstones occur within the Price Formation in West Virginia and Virginia; Borden Formation in Kentucky; and Cuyahoga Group and Shenango Formation in Pennsylvania (Figure Mws-3). A summary of recent Lower Mississippian stratigraphic work is provided in the Big Injun play description (A. Vargo and D. Matchen, Lower Mississippian Big Injun Sandstones, this atlas). Weir sandstones occur at several positions between the base of the Big Injun-Squaw interval and the top of the Sunbury Shale and its equivalents.

Because of the variety, number, and position of Weir sandstones within the Lower Mississippian section, drillers have developed an informal terminology to identify the productive sandstones (Figure Mws-3). In West Virginia, Weir sandstones that are located 350 feet or more above the Sunbury Shale are called

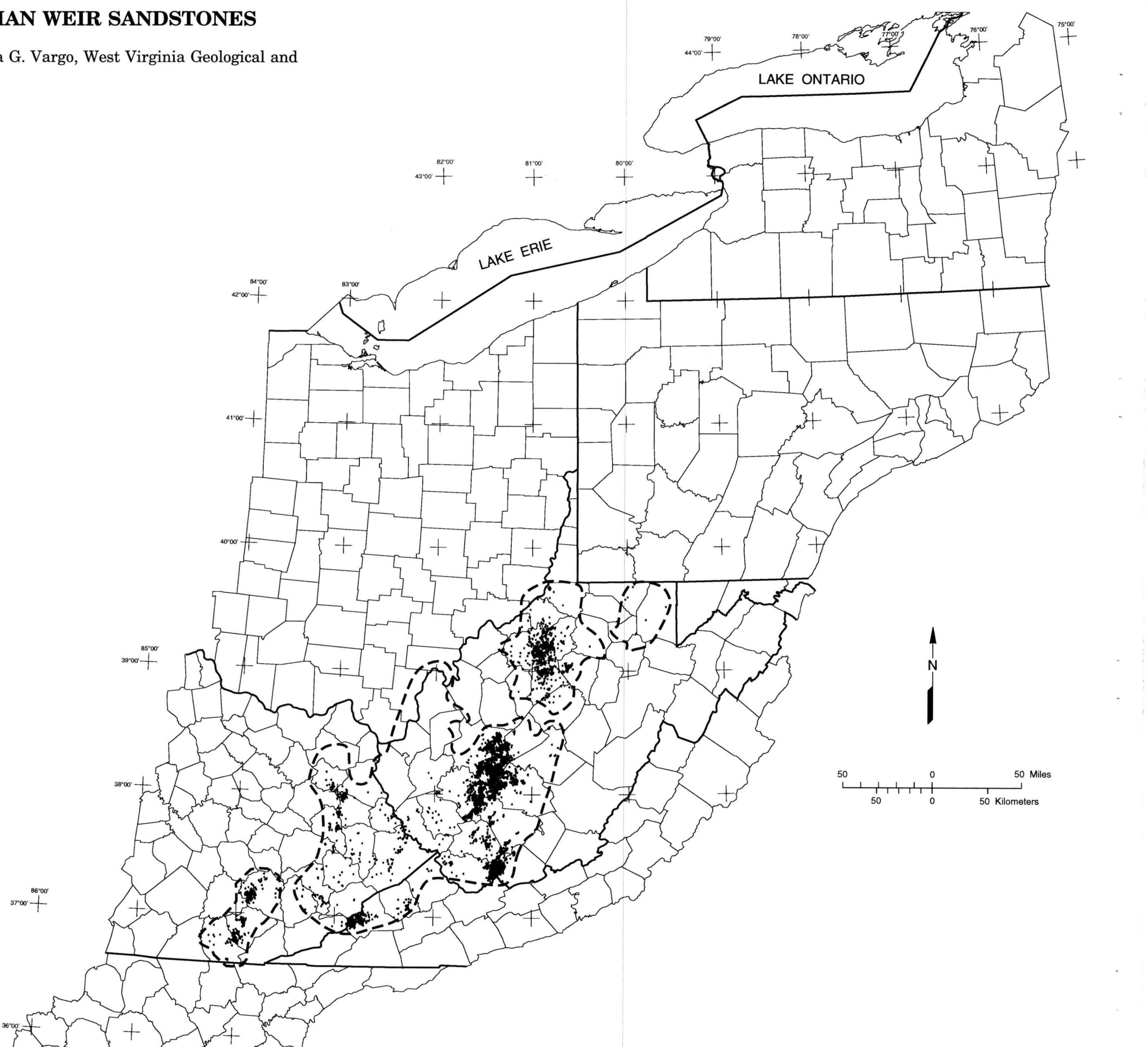


Figure Mws-1. Outline of the Lower Mississippian Weir sandstone play within the Appalachian basin. Dots represent individual gas wells; areas where dots have merged in most cases represent fields. Dashed line indicates the approximate boundary of this play.

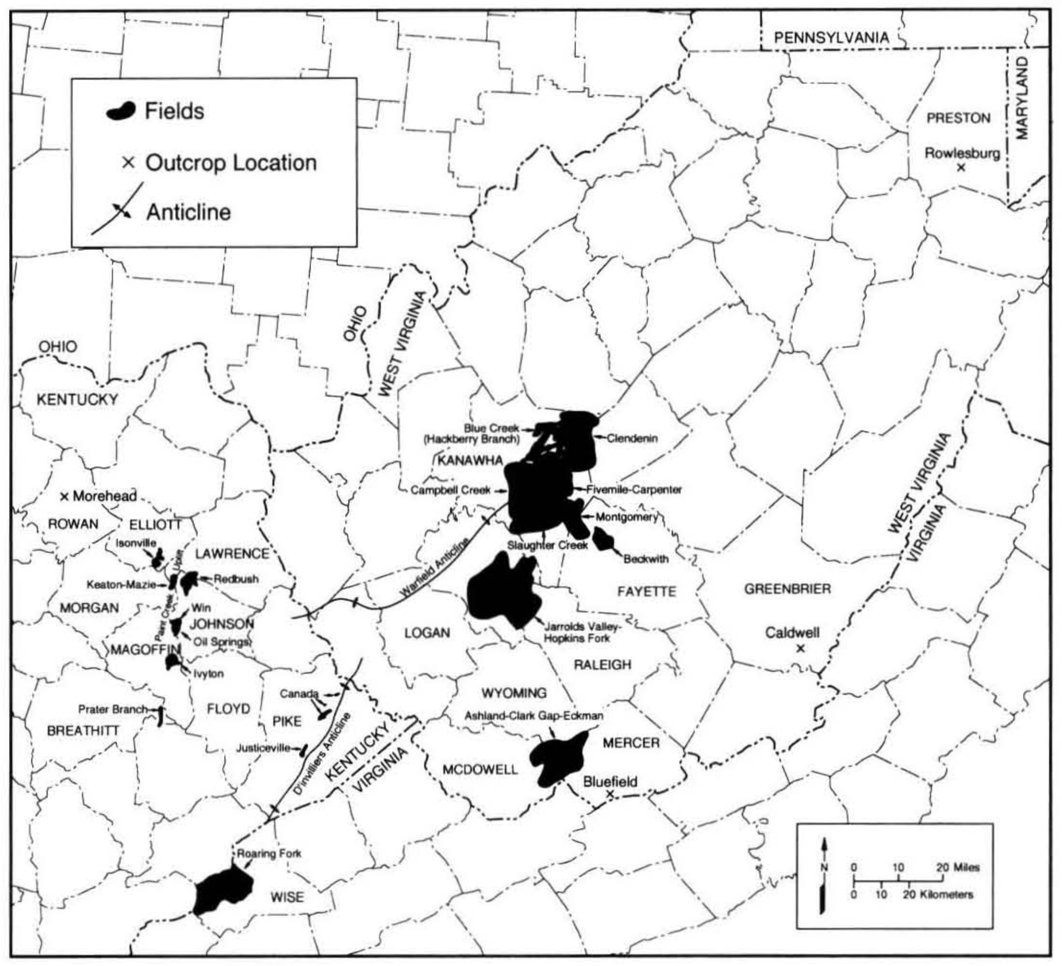


Figure Mws-2. Location map for fields, anticlines, and outcrop localities mentioned in the text and in Table Mws-1.

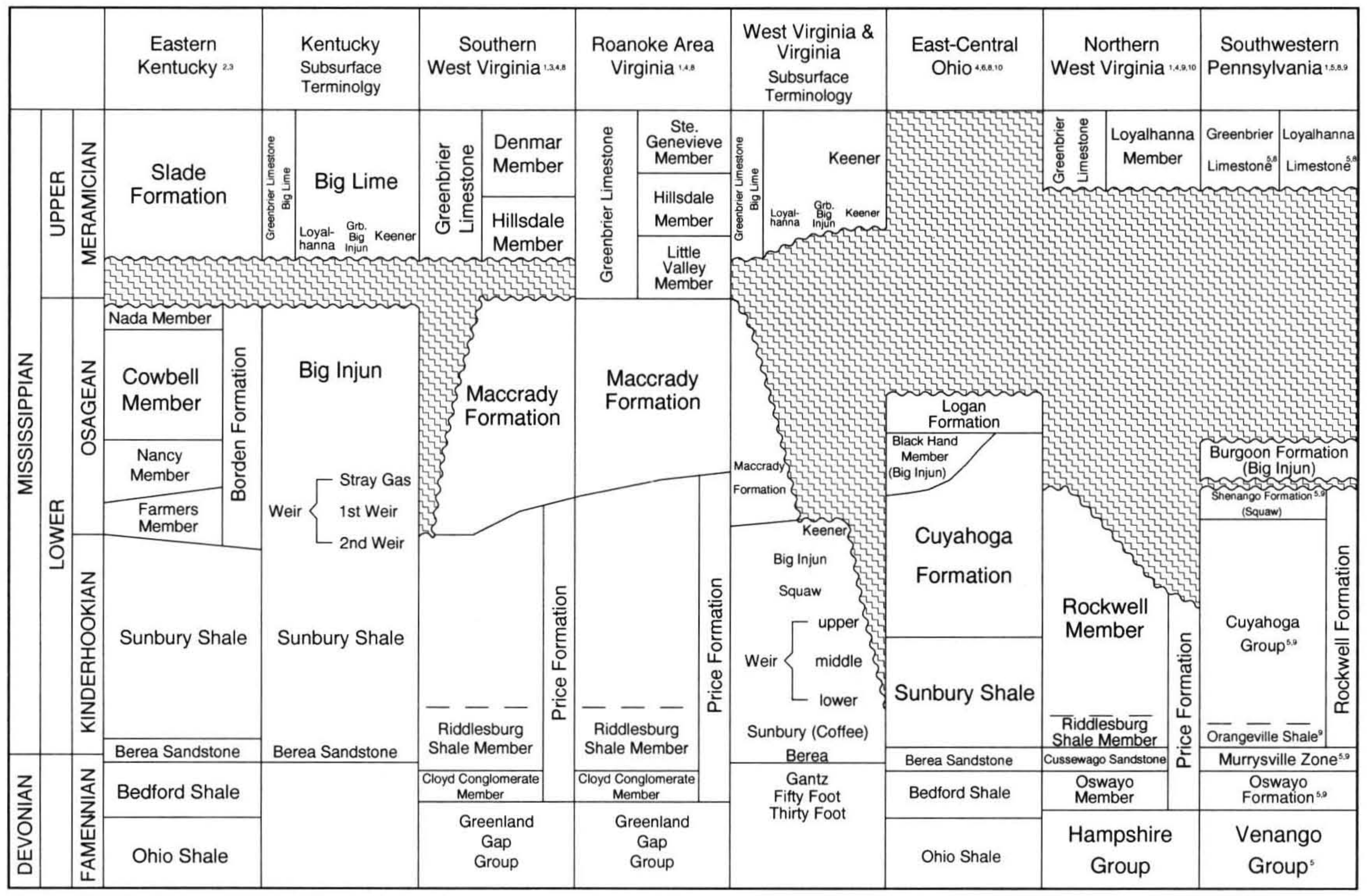
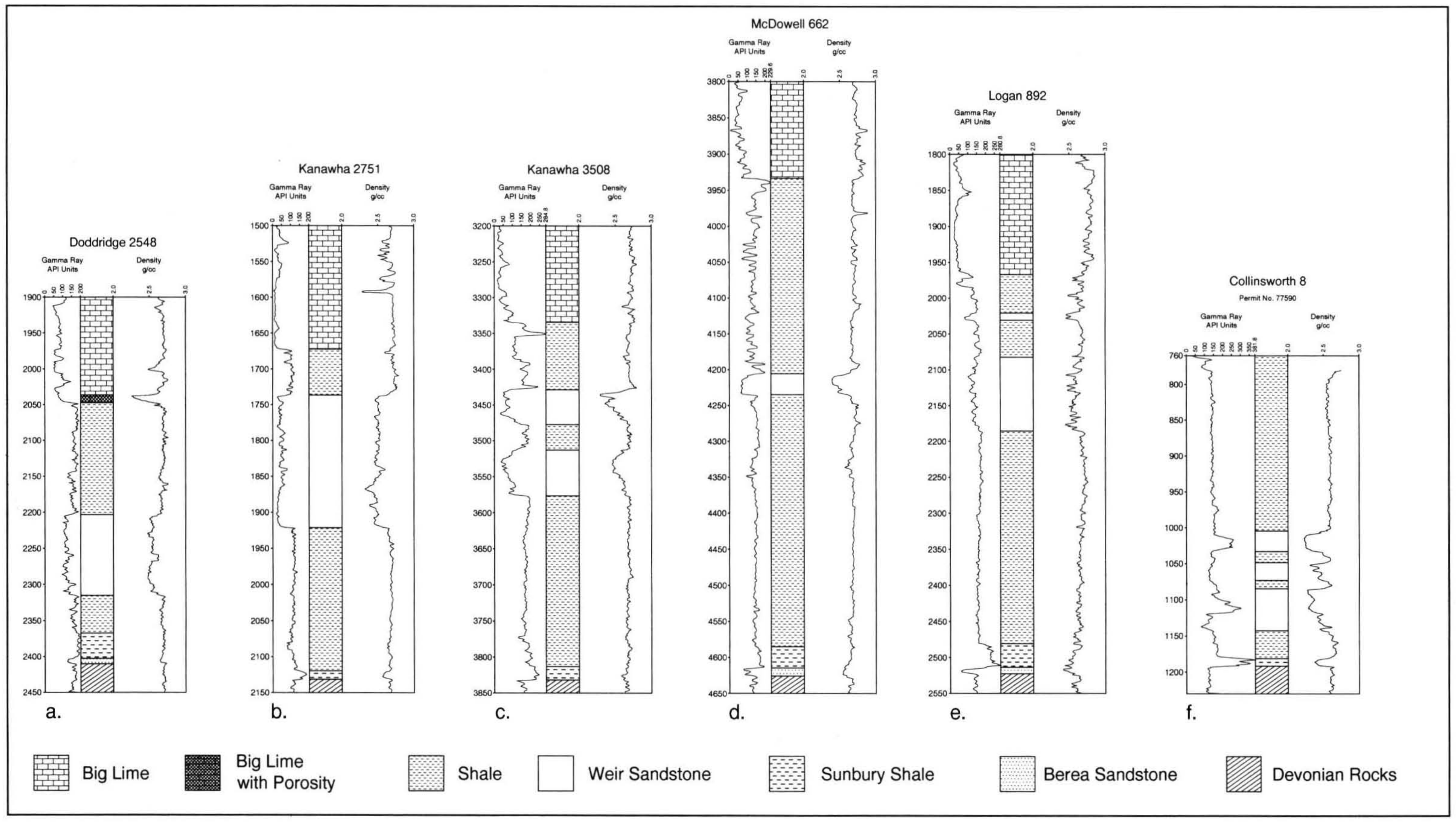


Figure Mws-3. Chronostratigraphic chart showing nomenclature for the Lower Mississippian used in outcrop and subsurface areas. Numbers at top of columns refer to the following references: 1, Bjerstedt and Kammer (1988); 2, Chaplin (1980); 3, Matchen and Kammer (1994); 4, R. Smosna, Upper Mississippian Greenbrier-Newman Limestones, this volume; 5, Harper and Laughrey (1987); 6, Bird (1988); 7, Carter and Kammer (1990); 8, Patchen and others (1985a); 9, T. Kammer (written commun., 1994); 10, Boswell and others (1987). The vertical scale does not imply stratigraphic thickness of units.



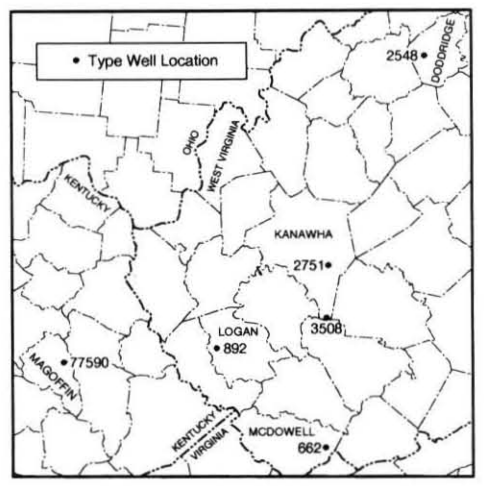


Figure Mws-4f. Type logs (gamma-ray and density) demonstrating the variety of Weir signatures. Mws-4a. Northern West Virginia Weir. Mws-4b. Thick Kanawha County Weir. Mws-4c. Upper and middle Weir of Kanawha County. Mws-4d. Southern West Virginia Weir. Mws-4e. Southwestern West Virginia Weir. Mws-4f. Weir from Kentucky showing a high gamma-ray response for the sandstone. Well numbers correspond to the West Virginia county permit numbers used by the West Virginia Geological and Economic Survey and the well name and state permit numbers used by the Kentucky Geological Survey.

upper Weir. Middle Weir sandstones commonly occur between 150 to 350 feet above the Sunbury Shale, and lower Weir sandstones occur within 100 feet of the Sunbury Shale or its equivalents. The Weir sandstone in northern West Virginia as defined by Peace (1985) is correlative to the Squaw sandstone of southwestern Pennsylvania as defined by Harper and Laughrey (1987).

In Kentucky, drillers have separated the Weir in descending order into the Stray Gas sandstone, 1st Weir, and 2nd Weir (Sharpe, 1983). These sandstones occupy the same stratigraphic position as the lower Weir of West Virginia but are time equivalents of the Big Injun sandstones of West Virginia. Additionally, these terms seem to be fairly consistent throughout the productive regions of Kentucky. In some cases, production occurs from thin sandstones or siltstones, but often this production is fracture related.

Of the drillers' terms used in West Virginia, the lower Weir is the easiest to define. This term is commonly applied to sandstones that overlie the Sunbury and Riddlesburg shales and their equivalents (Boswell, 1988b; Jewell, 1988; Matchen, 1992; Zou, 1994). Problems occur when drillers' terms are used in a regional context. Identification of specific middle and upper Weir sandstones of West Virginia is made difficult by the lack of regional marker beds within Lower Mississippian rocks. Several studies (Lewis, 1983; Boswell, 1985; Peace, 1985; Boswell, 1988b; Jewell, 1988; Zou, 1994) have correlated individual Weir sandstones. In some cases, the authors used different definitions for the individual sandstones, resulting in inconsistent use of the terms middle and upper Weir. Additionally, upper Weir is often used interchangeably with Squaw (Swales, 1988; Zou, 1994).

Log signatures for the Weir vary considerably in appearance (Figure Mws-4). Gamma-ray signatures are either cylindrical, funnel-shaped, symmetrical, or irregular (Cant, 1984), with some displaying a combination of types. In northern West Virginia, the Weir is low in the Lower Mississippian section (less than 100 feet above the Sunbury Shale), is about 100 feet thick, has a sharp top and base, and has a serrated gamma-ray curve shape (Figure Mws-4a). Figure Mws-4b is representative of the Weir in northeastern Kanawha County, where it was originally named. The Weir, situated approximately 200 feet above the Sunbury Shale, is 200 feet thick and has an abrupt top and bottom with a serrated gamma-ray signature. In other parts of Kanawha County, the log response indicates the Weir sandstone splits into two 50-foot-thick sandstones (Figure Mws-4c). To the south in McDowell County, West Virginia, the Weir occurs approximately 400 feet above the Sunbury Shale, is rarely thicker than 50 feet, and has a cylindrical log signature (Figure Mws-4d). To the west, in Logan County, West Virginia (Figure Mws-4e), Weir log signatures are symmetrical and serrated in shape and are assumed to represent siltier deposits (this Weir sandstone is rarely completed by drillers). Weir sandstones in the Paint Creek uplift area of Kentucky lie between 10 and 150 feet above the Sunbury Shale. The sandstones of this area are unusual as they can be recognized by a highly radioactive gamma-ray log response and an irregularly shaped signature (Figure Mws-4f). Sharpe (1983, p. 41) suggests this high gamma-ray response "is the result of a secondary process in which uranium flowing in the fluids deposits a uranium-salt mineral."

Weir sandstones were deposited in a variety of depositional environments ranging from prodeltaic to fluvial. In northern West Virginia, two general classifications can be made for Weir environments. To the northwest, the Weir is described as thinly interbedded siltstones, sandstones, and shales (McCord and Eckard, 1963). Boswell and Jewell (1988) correlated these Weir sandstones to an outcrop at Caldwell, in southern West Virginia. Bjerstedt and Kammer (1988) described the depositional environment for these sandstones at Caldwell as fan-slope. To the northeast, Boswell (1988b) correlated the Weir to an outcrop at Rowlesburg, West Virginia, which is interpreted as delta front sediments.

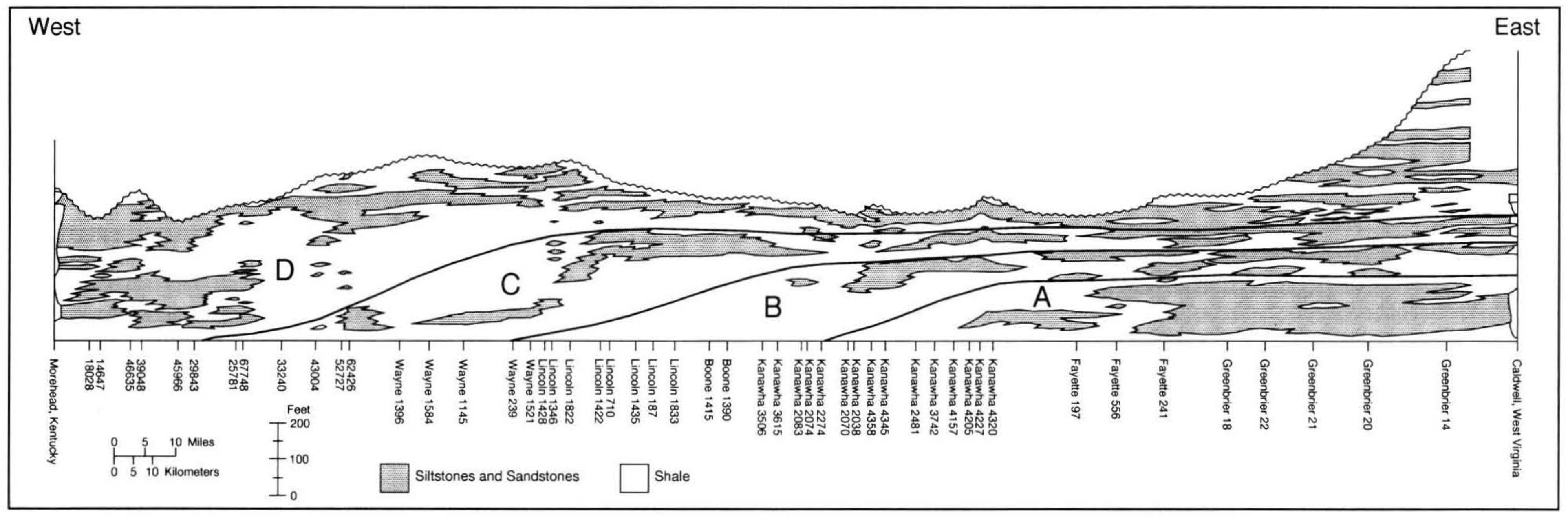
In central and southern West Virginia, Weir sandstones are fine- to medium-grained sandstones. Sedimentary structures identified in core (Privette, 1983; S. Rodeheaver, written commun., 1994; Zou, 1994) indicate that the basal portions of this thick sandstone succession were deposited in a fluvial-dominant deltaic environment. The middle and upper portions of this succession include sedimentary structures typical of tidal environments (Zou, 1994).

In Kentucky, Weir sandstones are parallel-bedded, very fine-grained to fine-grained and moderately well-sorted (Chaplin, 1980). These sandstones have been interpreted as turbidites (Moore and Clarke, 1970; Kepferle, 1977) and are time-equivalent basinal deposits of the fluvial-deltaic Big Injun sandstones that were deposited in West Virginia. These turbidites were formed when unconsolidated material of the delta was remobilized by minor disturbances like storms or seismic shocks (Kepferle, 1977), creating many small fans at the toe of the slope.

Subsurface correlations from outcrops at Caldwell, West Virginia, to the Morehead, Kentucky, outcrop show that the Lower Mississippian can be subdivided into four progradational units using sequence-stratigraphic methodology (Figure Mws-5). The progradational units become successively younger to the west, with each unit containing a complete suite of facies from basinal to delta plain (Matchen and Kammer, 1994).

An isopach map of total sandstone within the Weir interval reveals five trends oriented north-south that are labelled V, W, X, Y, and Z (Figure Mws-6). The trends correspond to portions of the progradational units identified in Figure Mws-5. In some cases, the trends (W and Z) occur in prodeltaic fan-slope deposits and are turbidite sandstones. In other cases, the trends (X and Y) are probably representative of delta front, nearshore marine deposits, with some fluvial influence likely in trend X. Trend V is composed of delta front and fluvial sandstones, as identified by Boswell (1988b). Trend V is not represented on Figure Mws-5 as it has been removed by erosion in southern West Virginia.

The X trend on Figure Mws-6 is associated with units B, C, and D of Matchen and Kammer (1994) (Figure Mws-5). The sandstones in the lower part of this trend correspond to the delta front of unit B, while the upper portions of this trend represent reworked transgressive and regressive delta plain deposits of units C and D. Trend Y in Figure Mws-6 corresponds to turbidite and delta front deposits of unit C. Trend Z is correlative with the turbidite deposits of unit D in Figure Mws-5. The rest of unit D is time-equivalent to the Big Injun sandstones deposited in West Virginia (see A. Vargo and D. Matchen, Lower Mississippian Big Injun Sandstones, this volume). Similar progradation patterns can be observed in the Weir in other parts of the basin. Figure Mws-7 shows the correlation of Weir sandstones in the northern part of West Virginia. The sandstones in the eastern part of this section are equivalent to the eastern lower Weir of Boswell (1988b), which he interpreted to be delta front deposits. The sandstones in the western part of this section are equivalent to the western lower



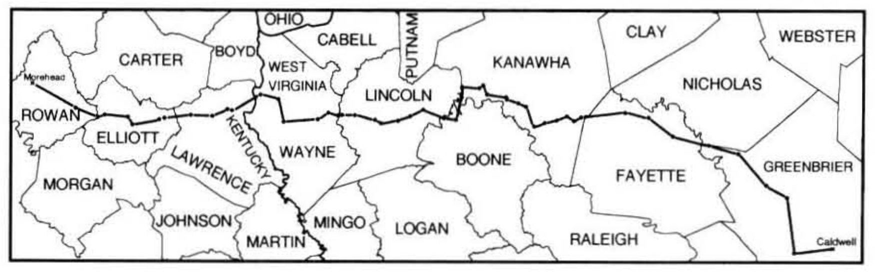
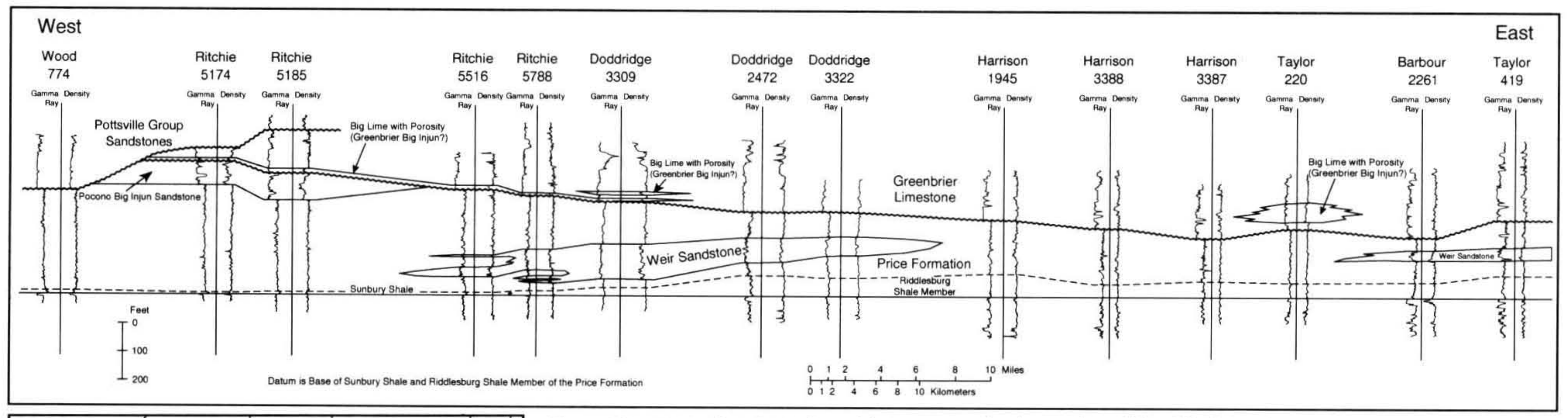


Figure Mws-5. Regional stratigraphic cross section of the Lower Mississippian interval. The base of the interval is the Sunbury Shale; the top of the interval is truncated by the pre-Greenbrier unconformity. The cross section connects the outcrop at Caldwell, West Virginia, as described by Bjerstedt and Kammer (1988) to the outcrop at Morehead, Kentucky, as described by Chaplin (1980). Datum is the Sunbury Shale. Well numbers correspond to the state permit numbers used by the West Virginia Geological and Economic Survey and the West Virginia county permit numbers used by the Kentucky Geological Survey. The solid lines represent boundaries between progradational units (Matchen, 1992). Each unit contains a full suite of facies from delta plain to turbidite deposition located in sequence from east to west. Figure modified from Matchen (1992).



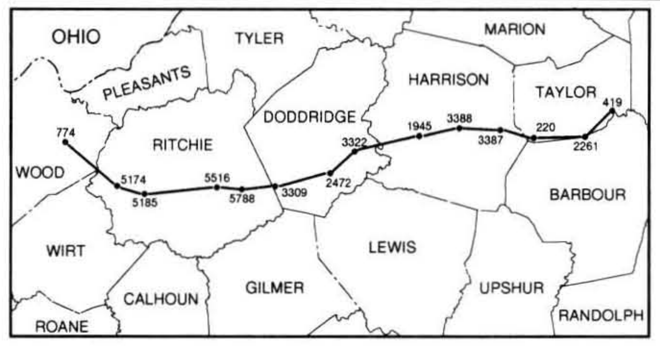


Figure Mws-7. Regional stratigraphic cross section in northern West Virginia. Well numbers correspond to the West Virginia county permit numbers used by the West Virginia Geological and Economic Survey.

Weir of Boswell (1988b), which he interpreted to be fan-slope deposits. All of the Weir sandstones in Figure Mws-7 are associated with unit A of Matchen and Kammer (1994) (Figure Mws-5).

Structure

The central Appalachian Plateau is dominated by gently folded structures. Most of the Weir fields are associated with these structures. The type area for the Weir is on the Warfield anticline in northeastern Kanawha County, West Virginia. In West Virginia, however, structure does not control the extent of gas production within the Weir sandstone, but it may enhance open flow rates. In the Beckwith field, Fayette County, West Virginia, the Weir produces from an area that shows some evidence of faulting and folding on a local scale.

In Kentucky, the relationship between production and structure has been clear since the fields of the Paint Creek uplift were first discovered. The Paint Creek uplift is a narrow, north-south trending anticlinal feature (Dohm, 1963; Sharpe, 1983) (Figures Mws-2, Mws-8), associated with the Paint Creek-Irvine and Kentucky River fault systems (Fulton, 1979). Most of the fields shown on Figure Mws-8 are also oil fields.

In some cases, Weir reservoirs are naturally fractured siltstones and shales of the Borden Formation whose production is enhanced by nitrogen fracturing. These reservoirs can be recognized on wireline logs by a decrease on the temperature curve, and a shale-like response on gamma-ray and density logs (Figure Mws-9). Local fracturing of the Borden is probably related to development of the Warfield and D'Invillier anticlines in southern West Virginia and eastern Kentucky (Figure Mws-2). Production from these fractured reservoirs occurs along the flanks of these anticlines (Ashland Exploration, written commun., 1994). A similar situation occurs in southeastern Kentucky, where gas shows in the Borden Formation are enhanced by nitrogen fracturing.

Reservoir

Weir reservoirs can be arranged into four general groups: delta front-delta slope siltstone and sandstone reservoirs, fluvial-deltaic sandstone reservoirs, prodeltaic turbidite sandstone reservoirs, and fractured prodeltaic siltstones and shales (fractured Borden). All of these reservoir groups are shown in Figure Mws-10. Trap types range from stratigraphic to structural, with most classified as a combination of both. Reservoir parameters for selected fields that produce from the Weir and fractured Borden are listed in Table Mws-1.

Throughout much of West Virginia and Kentucky, production from Weir sandstones can be related directly to the presence or absence of the sandstones. However, in the northern portion of the Y trend (Figure Mws-6), this pattern breaks down. In this area, Weir sandstones exceed 200 feet in thickness, and have reservoir quality porosity (15 to 20 percent) determined from wireline logs. However, few reports even mention the Weir in this area, and those that do indicate that the Weir and the overlying Big Injun contain only water.

Little has been written about the source of hydrocarbons for Lower Mississippian reservoirs. Most likely, hydrocarbons in the Weir reservoirs originated in the Upper Devonian black shales, and migrated upsection into the Weir and related reservoirs (Gautier and Varnes, 1993). Schwietering and Roberts (1988) suggest a similar source rock for western West Virginia, possibly the Sunbury, Ohio, and Rhinestreet shales. In northern West Virginia, the Marcellus and Genesee may be the source rock as suggested by Harper and Laughrey (1987) for southwestern Pennsylvania.

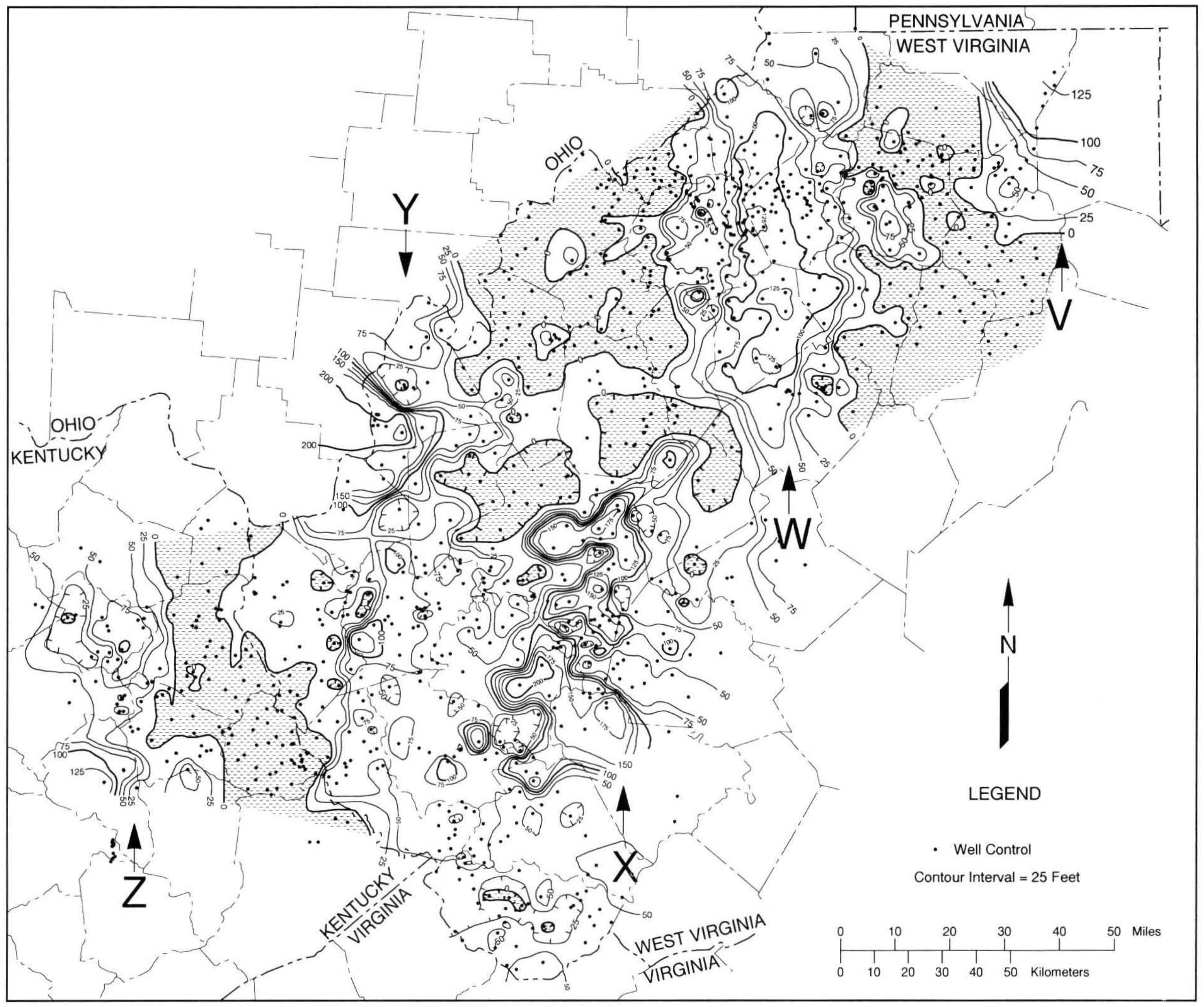


Figure Mws-6. Regional isopach map of the Weir sandstone combining all the Weir sandstones between the bottom of the Big Injun/Squaw interval and the top of the Sunbury Shale. The five north-south-oriented trends are labelled V, W, X, Y, and Z.

Unless otherwise noted, the following data is from the oil and gas database of the West Virginia Geological and Economic Survey. The average depths to the top of the Weir reservoirs range from 618 feet in the Isonville field of Kentucky to 5,140 feet in the Ashland-Clark Gap-Eckman field of West Virginia. Throughout the Appalachian basin, pay thickness of the Weir also varies considerably. The delta front-delta slope reservoirs average approximately 50 feet thick. The fluvial-deltaic reservoirs range between 20 and 150 feet in thickness. The prodeltaic reservoirs (both fractured and unfractured) range between 10 and 40 feet thick, averaging around 25 feet.

Pressures within Weir reservoirs vary with the depth of the reservoir. In the prodeltaic turbidite reservoirs of Kentucky, pressures are reported to be between 210 and 560 psi, averaging approximately 340 psi (Kentucky Geological Survey, written commun., 1993). In the fractured prodeltaic reservoirs, pressures range from 200 to 700 psi. In the fluvial-deltaic reservoirs, pressures range from 120 to 885 psi, averaging approximately 600 psi. In the delta front-delta slope reservoirs, gas production is commonly commingled with production from Maxton, Big Injun, and Upper Devonian sandstones. Reservoir pressure from wells with commingled gas production varies from 150 to 1,600 psi. The few recorded reservoir pressures from wells producing only from the Weir range from 500 and 800 psi.

All available initial open flow measurements reported from Weir reservoirs range between 2 and 30,000 Mcf. The few initial open flow values that are available for the prodeltaic reservoirs (fractured and unfractured) range from 40 to 3,888 Mcf. The fluvial-deltaic reservoirs have initial open flow measurements ranging from 2 to 30,000 Mcf, averaging around 1,000 Mcf. From delta front-delta slope reservoirs with commingled initial open flow values, a range of 5 to 5,000 Mcf is obtained. No initial open flow values for wells producing from only these reservoirs are available.

Final open flow volumes range from 1 to 40,700 Mcf and average approximately 900 Mcf. The final open flow for the prodeltaic turbidites ranges from 10 to 5,720 Mcf, whereas the final open flow for the fractured prodeltaic reservoirs ranges from 2 to 5,116 Mcf (Kentucky Geological Survey, written commun., 1993). In central and southern West Virginia, final open flow ranges from 1 to 40,700 Mcf, averaging approximately 900 Mcf. Final open flow values for commingled production from the delta front-delta slope reservoirs ranges from 25 to 5,000 Mcf.

Porosity in the prodeltaic turbidites ranges from 15 to 20 percent (Ashland Exploration, written commun., 1994). The fractured prodeltaic reservoirs have porosity values between 2 and 24 percent, averaging around 15 percent (Kentucky Geological Survey, written commun., 1993). The fluvial-deltaic reservoirs have porosity values between 10 and 17 percent, averaging around 12 percent (S. Rodeheaver, written commun., 1994). Porosity in the delta front-delta slope reservoirs generally falls between 5 and 10 percent, averaging around 7 percent.

Variations in porosity throughout the Weir reservoirs are the result of diagenesis. Most porosity is primary and intergranular, with some intragranular porosity resulting from the dissolution of feldspars (Privette, 1983; Ashland Exploration, written commun., 1994; S. Rodeheaver, written commun., 1994). In core descriptions, porosity is shown to be reduced by compaction and filling by quartz overgrowths (Privette, 1983; Ashland Exploration, written commun., 1994; S. Rodeheaver, written commun., 1994). Compaction is a minor problem in the Kentucky turbidites (Ashland Exploration, written commun., 1994), because of shallow burial depths. Privette (1983) calculates that compaction has reduced the initial porosity of the Weir by 25 percent in the Ashland-Clark Gap-Eckman field of West Virginia. Quartz overgrowths also reduce porosity in all of these areas. In some cases, porosity is preserved by chlorite coats that inhibit the formation of quartz overgrowths (S. Rodeheaver, written commun., 1994). However, the presence of chlorite coats in pore throats reduces permeability in the fluvial-deltaic reservoirs of West Virginia. This problem is minor in the turbidite reservoirs of Kentucky.

Permeability in the turbidites ranges between 5 and 10 md (Ashland Exploration, written commun., 1994). No values are available for the fractured Borden reservoir. Permeability of the Weir throughout West Virginia rarely exceeds 10 md, and averages close to 1 md (Cabot Oil and Gas, written commun., 1994; S. Rodeheaver, written commun., 1994) and in many cases is less than 1 md.

Little information is available on heterogeneity of Weir sandstones. However, petrographic analysis (Privette, 1983) shows that authigenic minerals (illite, calcite, and siderite) reduce porosity. The reduction of porosity in zones may be similar to the type of diagenetic heterogeneity described for the Big Injun sandstone in Granny Creek and Rock Creek fields (Hohn and others, 1993a; 1993b). The low permeability of Weir reservoirs (less than 10 md) suggests that drainage areas of individual wells may be small. The Weir turbidites of Kentucky have slightly higher permeabilities, but the sandstones are less continuous, suggesting that these reservoirs also have a small drainage area.

In northern and central West Virginia, Weir reservoirs are composed of stacked sandstones, from which one or two zones produce. In southern West Virginia, the Weir consists of a single pay zone averaging 30 feet in thickness. In Kentucky, the turbidites are composed of several thin, discontinuous pay zones.

The drive mechanism for Weir reservoirs is undocumented. Information from the Kentucky Geological Survey (written commun., 1994) suggests that gas expansion is the mechanism for the turbidite fields. There seems to be little water production associated with West Virginia Weir reservoirs, which suggests

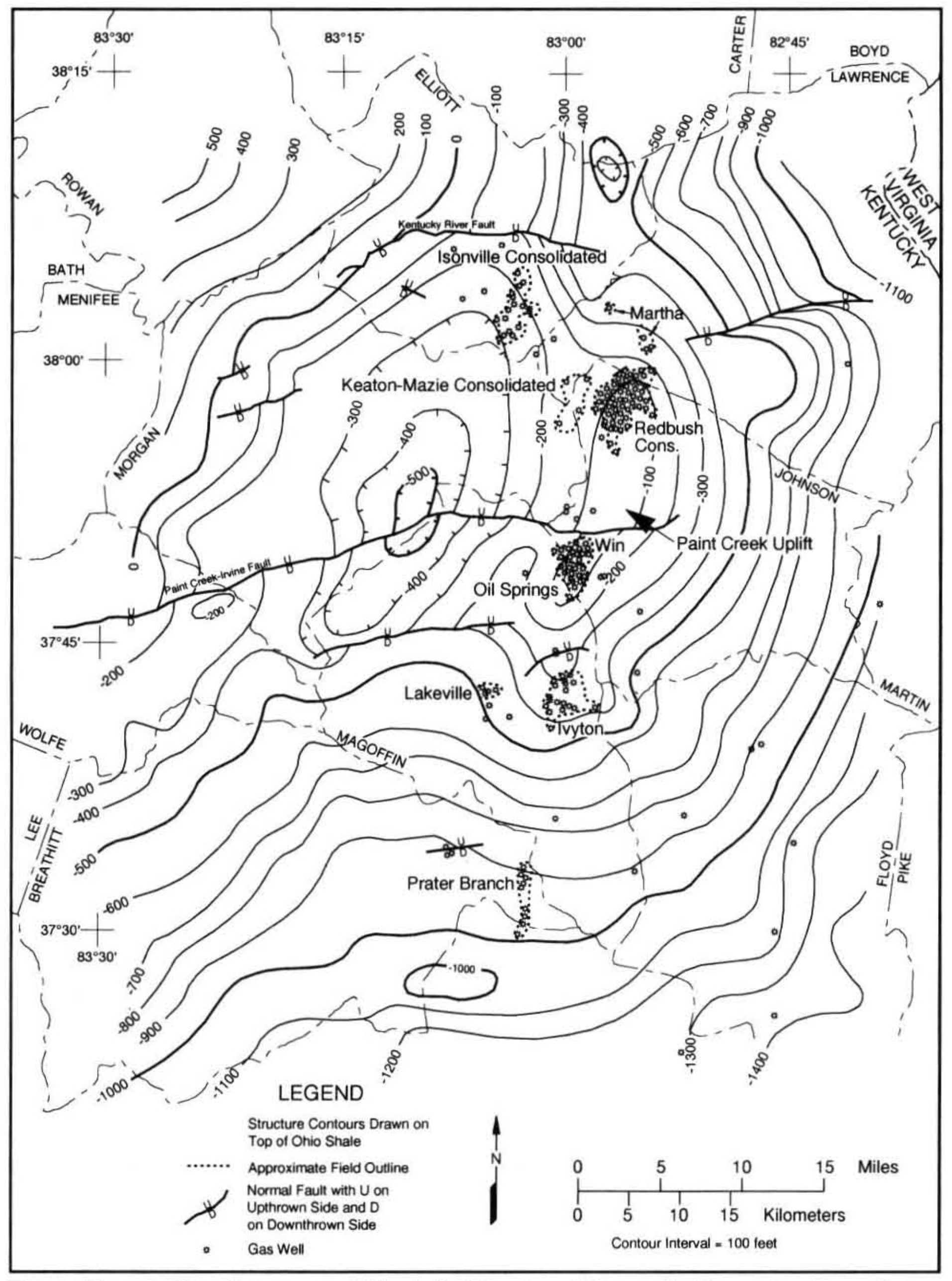


Figure Mws-8. Structure map of the Paint Creek uplift area in Kentucky. Most fields presented are combined oil and gas fields; only gas wells are shown. Modified from Fulton (1979).

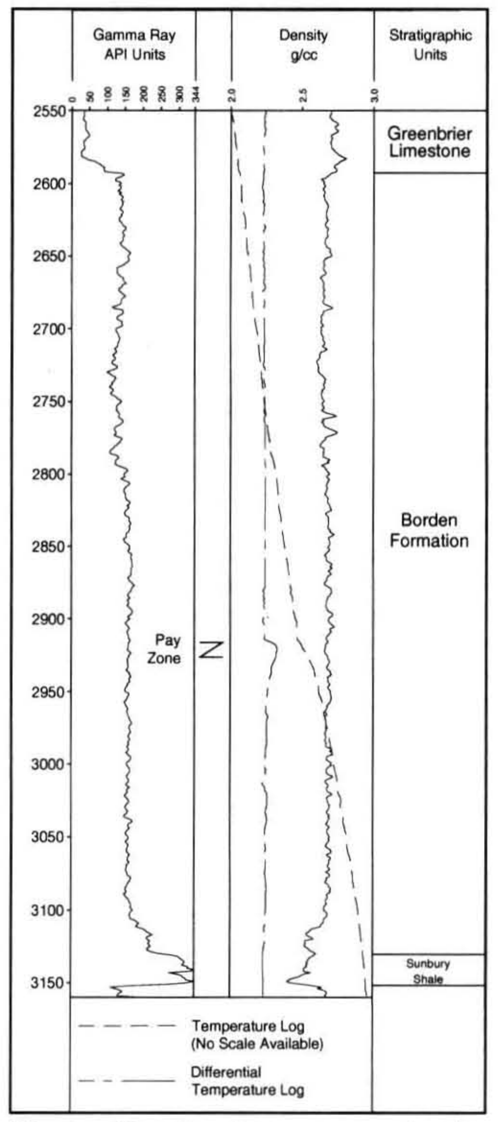


Figure Mws-9. Gamma-ray, density, temperature, and differential temperature logs from naturally fractured siltstones and shales of the Borden Formation from the No. 84 Will M. Smith Heirs well, Canada District of Big Sandy field, Pike County, Kentucky State Permit Number 81617.

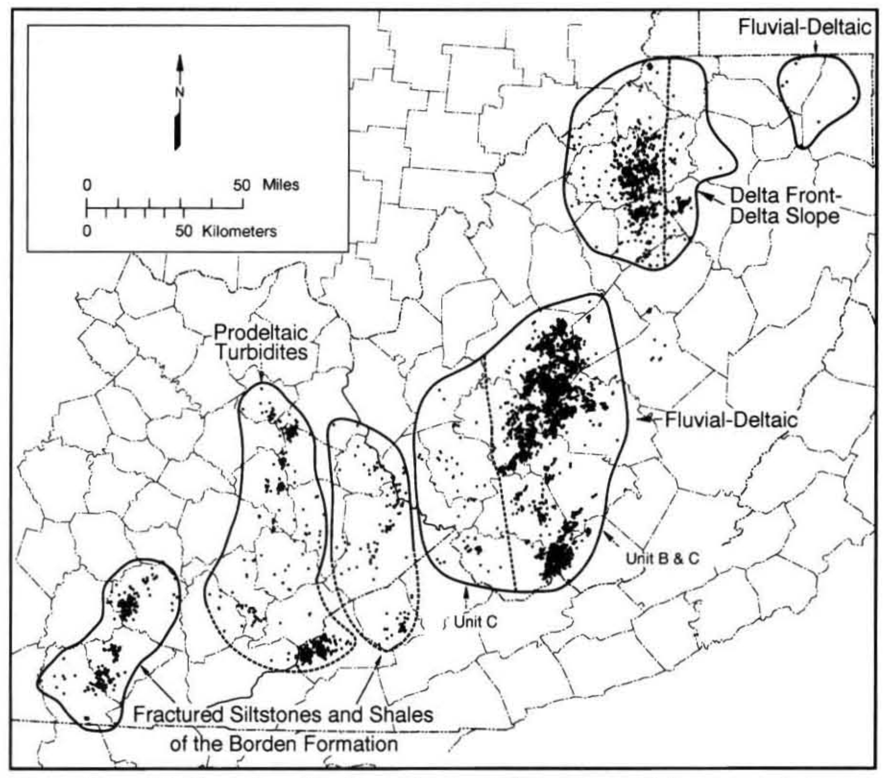


Figure Mws-10. Map showing the extents of the various Weir reservoir trends. In northern West Virginia, the boundary between fluvial-deltaic reservoirs and turbiditic reservoirs is based on the regional cross sections presented earlier. In southern West Virginia the fluvial-deltaic reservoirs are separated into those that produce from stacked sandstones that have been correlated to progradational units B and C, and those that produce only from unit C (see Figure Mws-5).

	TABLE Mws-1	Isonville KY	Ivyton KY	Keaton-Mazie KY	Oil Springs KY	Prater Branch KY	Redbush KY	Win KY	Justiceville KY	Roaring Fork VA	Campbell Creek WV	Fivemile-Carpenter WV	Blue Creek (Hackberry Br.) WV	Clendenin WV	Slaughter Creek WV	Montgomery WV	Beckwith WV	Jarrolds Valley-Hopkins Fork WV	Ashland-Clark Gap-Eckman WV
BASIC RESERVOIR DATA	POOL NUMBER	1601035337	1601037337	1601092337	1601439337	1601580337	1601630337	1602137337	1601087337		47214387	47216387	47218387	47220387	47241387	47242387	47354387	47247387	47378387
	DISCOVERED	1919	1920	1922	1920	1985	1917	1917	1939	1,955	1918	1929	1912	1911	1912	1916	1961	1919	1948
	DEPTH TO TOP RESERVOIR	912	1,139	788	887	2,090	732	843	2,326	3,867-6,168	1,875	1,784	1,888	1,927	2,157	2,257	2,122	2,943	4,194
	AGE OF RESERVOIR	Early Mississippian	Early Mississippian	Early Mississippian	Early Mississippian	Early Mississippian	Early Mississippian	Early Mississippian	Early Mississippian	Early Mississippian	Early Mississippian	Early Mississippian	Early Mississippian	Early Mississippian	Early Mississippian	Early Mississippian	Early Mississippian	Early Mississippian	Early Mississippian
	FORMATION	Borden	Borden	Borden	Borden	Borden	Borden	Borden	Borden	Price	Price	Price	Price	Price	Price	Price	Price	Price	Price
	PRODUCING RESERVOIR	Weir	Weir	Weir	Weir	Weir	Weir	Weir	Borden	Weir	Weir	Weir	Weir	Weir	Weir	Weir	Weir	Weir	Weir
	LITHOLOGY	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	siltstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone
	TRAP TYPE	combination	combination	combination	combination	combination	combination	combination	structural	stratigraphic	combination	combination	combination	combination	combination	combination	combination	combination	combination
	DEPOSITIONAL ENVIRONMENT	turbidites	turbidites	turbidites	turbidites	turbidites	turbidites	turbidites	marine/delta front		fluvial/deltaic	fluvial/deltaic	fluvial/deltaic	fluvial/deltaic	fluvial/deltaic	fluvial/deltaic	fluvial/deltaic	fluvial/deltaic	fluvial/deltaic
	DISCOVERY WELL IP (Mcf)		1,900	500	200	3,888	300	1,000	2,595		1,965		10,000	7,194					
	DRIVE MECHANISM	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion
	NO. PRODUCING WELLS	35	27	5	14	10	58	36	4	146	77	73	40	142	236	119	38	264	279
	NO. ABANDONED WELLS	0	10	9	0	0	30	0	1		20	8	15	24	36	21	3	52	4
	AREA (acreage)	2,338	3,489	989	1,116	1,337	5,399	1,315	950		13,477	13,719	4,073	19,841	32,240	19,687	8,056	72,072	49,582
	OLDEST FORMATION PENETRATED	Clinton	Clinton	Ohio	Rose Hill	Corniferous	Bedford	Rose Hill	Ohio	Hancock Dolomite	Upper Devonian	Sonyea Group	Upper Devonian	Upper Devonian	Onondaga	Helderberg	Onondaga	McKenzie	Berea
	EXPECTED HETEROGENEITY DUE TO:	structure/ deposition	structure/ deposition	structure/ deposition	structure/ deposition	structure/ deposition	structure/ deposition	structure/ deposition	fractures	deposition/ structural/fracture diagenesis	deposition	deposition	deposition	deposition	deposition	deposition	deposition	deposition	deposition
RESERVOIR PARAMETERS	AVERAGE PAY THICKNESS (ft.)	19	15	19	20	18	43	40	29	109	33	37	31	32	58	32	32	152	26
	AVERAGE COMPLETION THICKNESS (ft.)	57	17	87	33	18	43	43	35										
	AVERAGE POROSITY–LOG (%)	16	14	15	20	18					6.9	10.1	9.3	9.3	12.5	13.6	8.4	7.7	11
	MINIMUM POROSITY–LOG (%)	10	6	10	6	10					3.6	8.5	7.7	8.7	8	10.4	6.9	10.8	6
	MAXIMUM POROSITY–LOG (%)	20	16	18	23	23					10.2	11.6	16.6	10.2	18	18.8	14	4	15
	NO. DATA POINTS	3	1	2	3	5					8	9	1	4	2	8	8	12	48
	POROSITY FEET																		
	RESERVOIR TEMPERATURE (°F)	63	73	66	70	77	67	67				73		76		87	76	89	100
	INITIAL RESERVOIR PRESSURE (psi)	340	400	210		560		285	589	900-1,650	264-380	185-458		375-530	200-470	217-435		160-830	
	PRODUCING INTERVAL DEPTHS (ft.)	618-1,115	966-1,261	690-963	700-1,053	1,770-2,310	413-865	700-1,016	2,239-2,485	3,867-6,268	1,214-2,423	1,263-2,394	1,505-2,030	320-2,324	1,416-3,032	1,312-3,254	1,115-2,653	741-4,075	1,356-5,137
	PRESENT RESERVOIR PRESSURE (psi) / DATE	320/1986				470/1992	200/1924	46/1985											
FLUID & GAS PROPERTIES	Rw (Ωm)	0.07	0.03	0.06	0.03		0.06	0.06		0.05	0.05	0.05				0.05	0.05		
	GAS GRAVITY (g/cc)								0.628					0.771			0.589	0.596	0.567
	GAS SATURATION (%)	45	25	49		46					62.3	75.7			46	77.3	69.4	50	63
	WATER SATURATION (%)	55	75	51		54					37.7	24.3			54	22.7	30.6	50	37
	COMMINGLED	yes	no	no	no	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	no
	ASSOCIATED OR NONASSOCIATED	associated	associated	associated	associated	nonassociated	nonassociated	associated	nonassociated	nonassociated	nonassociated	nonassociated	associated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated
	Btu/scf								1,119					1,316			1,056	1,066	1,016
VOLUMETRIC DATA	STATUS (producing, abandoned, storage)	producing	producing	producing	producing	producing	producing	producing	producing	producing	producing	producing	producing	producing	producing	producing	producing	producing	producing
	ORIGINAL GAS IN PLACE (Mcf)																		
	ORIGINAL GAS RESERVES (Mcf)																		
	PRODUCTION YEARS					1985-1992			1939-1992		1918-1992	1929-1992	1912-1992	1911-1992	1912-1992	1916-1992	1961-1992	1919-1992	1948-1992
	REPORTED CUMULATIVE PRODUCTION (Mcf)					364,000			1,917,000		1,288,877	6,408,503	2,727,573	9,936,891	4,612,127	3,514,144	9,052,846	28,951,350	23,301,500
	NO. WELLS REPORTED										25	37	7	51	91	34	38	100	279
	ESTIMATED CUMULATIVE PRODUCTION (Mcf)										24,786,096	71,205,589	37,882,958	160,272,435	100,263,630	83,670,095		361,891,875	116,515,750
	REMAINING GAS IN PLACE (Mcf)/DATE																		
	REMAINING GAS RESERVES (Mcf)/DATE																		
	RECOVERY FACTOR (%)																		
	INITIAL OPEN FLOW (Mcf/d)										678	1,242	1,925	1,080	843	669		471	84
	FINAL OPEN FLOW (Mcf/d)	206	779	363	75	1,987	493	583	2,914	100-6,343	564	873	388	445	795	754	520	1,677	1,025

that fluid expansion drives these reservoirs as well.

Gas gravity for the Weir ranges from 0.5915 to 0.7000 g/cc, with an average of 0.6451 g/cc from four analyses from the fluvial-deltaic reservoirs. Btu values for Weir gas ranges from 1,036 to 1,193 Btu, with an average of 1,125 Btu from five analyses (U.S. Bureau of Mines, 1993).

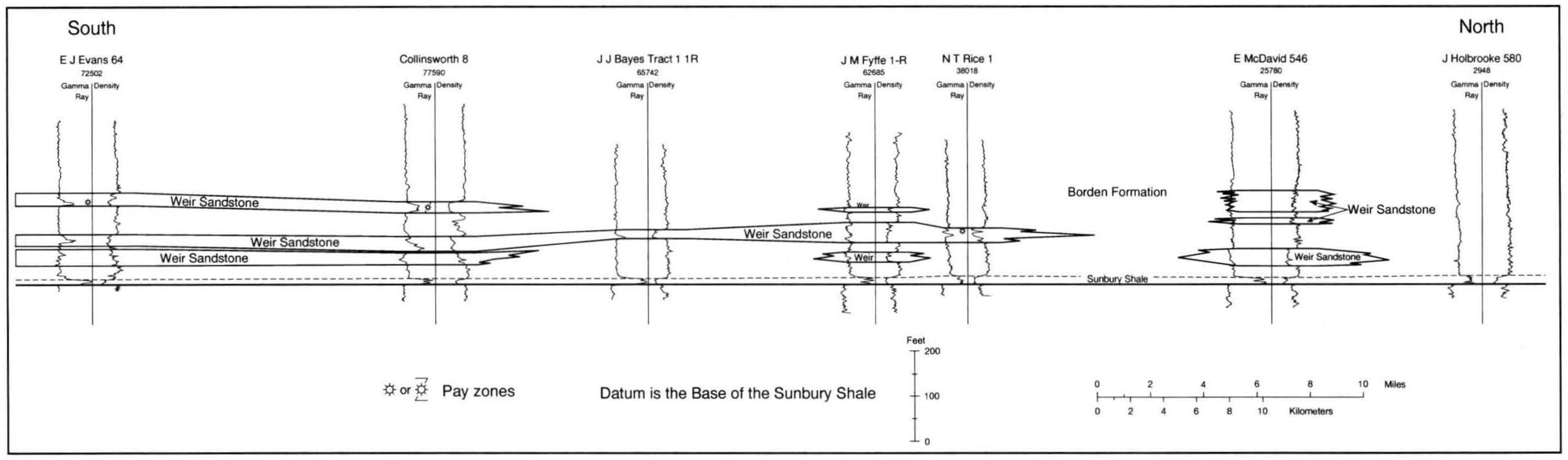
Due to very low permeability, most Weir wells require stimulation to produce economic quantities of gas. Early wells were shot with nitroglycerine; later wells were completed by hydrofracturing and propping with sand, followed by an acid wash.

Description of Key Fields

The fields of the Paint Creek uplift (Figure Mws-8) all produce from the Weir turbidites of eastern Kentucky. Sharpe (1983) provided a description of part of the Oil Springs field on the uplift; otherwise, little information has been published recently about these fields. The trend was discovered in 1917 (Redbush and Win fields) (Jillson, 1937) with most of the important fields (Ivyton, Isonville, Oil Springs, Keaton-Mazie) developed between 1918 and 1930. A few fields (Martha, Lakeville, and Prater Branch) (Figure Mws-8) were discovered more recently. Most of these fields produce both oil and gas, but only the Redbush and Prater Branch fields are exclusively gas producers (Kentucky Geological Survey, written commun., 1993).

The turbiditic sandstones of this trend are composed of parallel-bedded, fine-grained, moderately well-sorted sandstones that are texturally submature to mature. Moore and Clarke (1970) and Kepferle (1977) interpreted these sandstones as turbidites. Over 200 feet of turbiditic deposits have been locally observed on outcrop (Chaplin, 1980). Out of that thickness of sandstone, three sandstone zones can be identified in the subsurface, of which the upper two are often exploited across the Paint Creek uplift trend (Figure Mws-11).

The fields align along a trend perpendicular to the Kentucky River and Paint Creek-Irvine fault systems (Figure Mws-8). The traps are either fault-bounded or up-dip pinchouts that were developed along these fault trends. These faults mark the northern edge of the Rome trough in Kentucky (Ettensohn, 1980) and step down to the south. The displacement to the south makes the northernmost reservoir (Isonville) the shallowest (618 to 1,115 feet in depth) and the southernmost reservoir (Prater Branch) the deepest (1,770 to 2,310 feet in depth). Production information for these fields is generally unavailable; however, the Kentucky Geological Survey has data available for the Prater Branch field in Breathitt County, Kentucky. Seven wells in this field have produced a total of



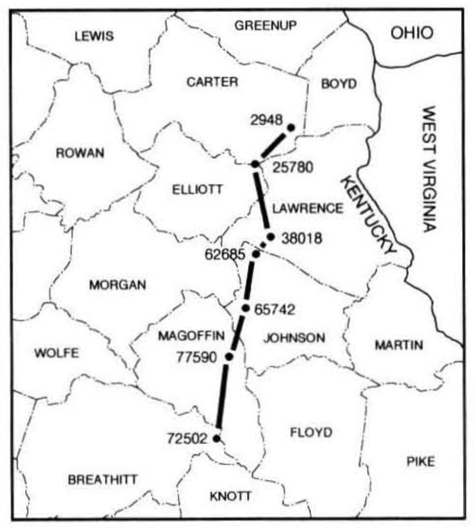


Figure Mws-11. Cross section through the Paint Creek uplift area of Kentucky. Wells are identified by farm name, well numbers, and Kentucky state permit numbers.

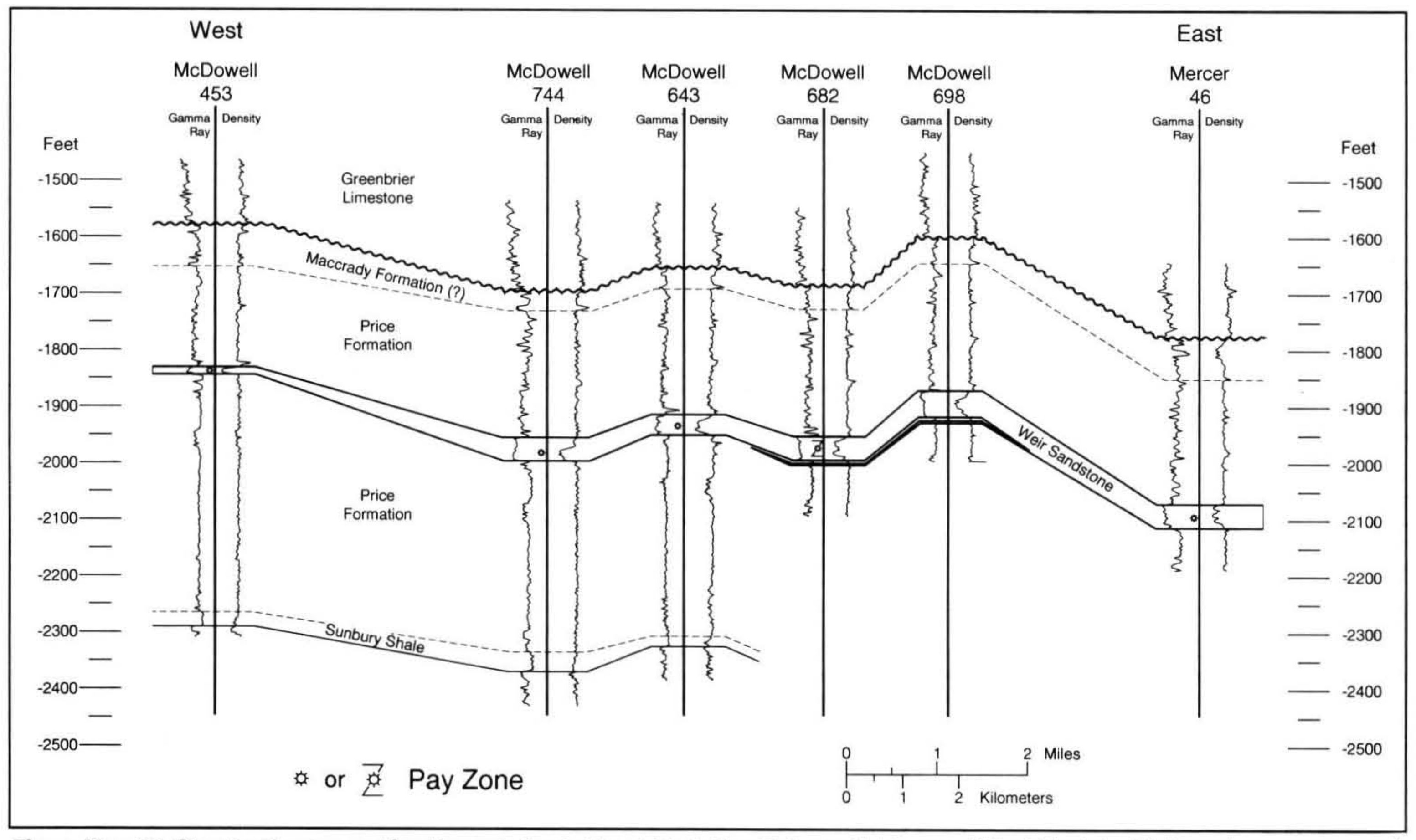


Figure Mws-12. Structural cross section through the Ashland-Clark Gap-Eckman field area of West Virginia. Well numbers correspond to the West Virginia county permit numbers used by the West Virginia Geological and Economic Survey. See Figure Mws-13 for line of cross section.

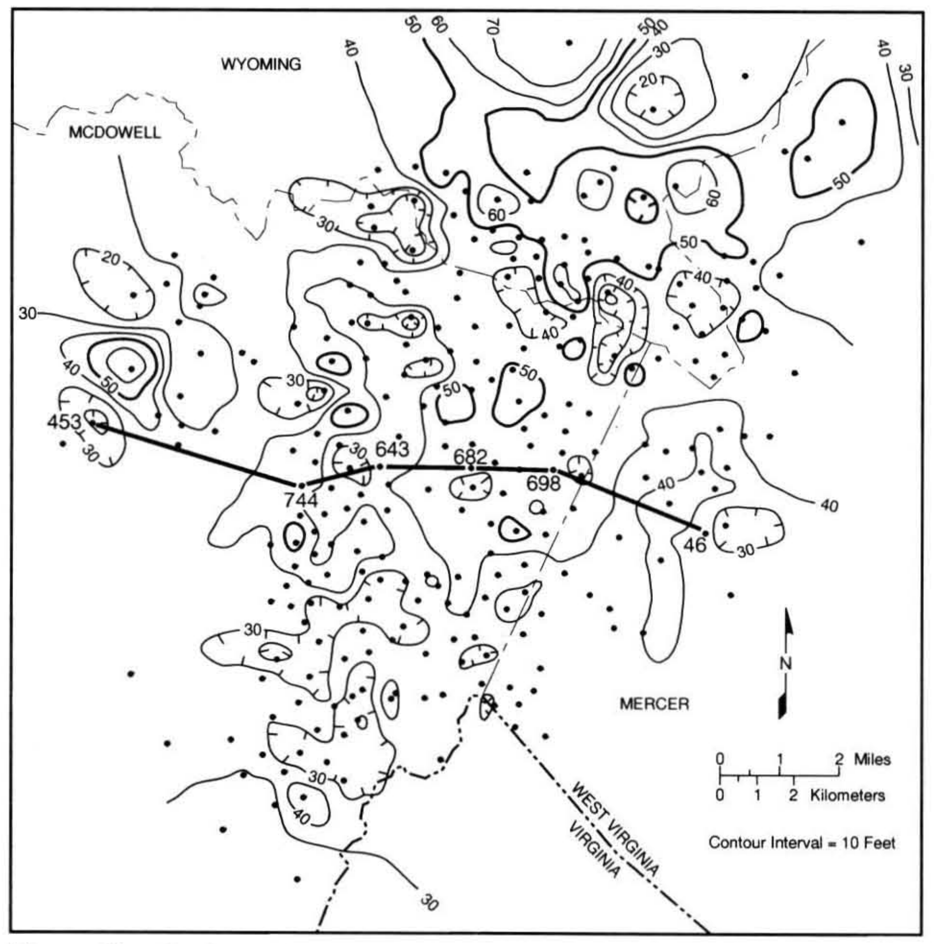


Figure Mws-13. Isopach map of the Weir sandstone in the Ashland-Clark Gap-Eckman field area. Line of cross section (Figure Mws-12) is also shown.

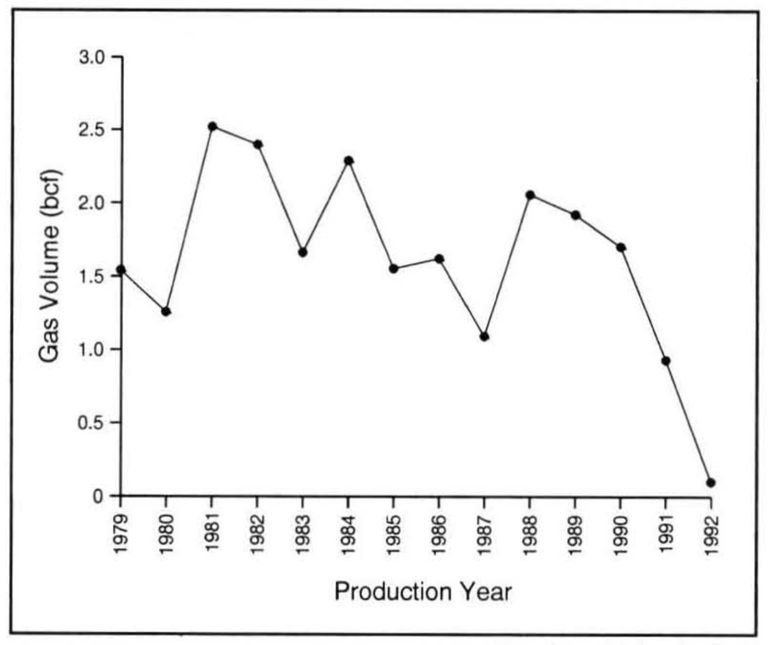


Figure Mws-14. Production since 1979 for the Ashland-Clark Gap-Eckman field as reported to the State of West Virginia from the West Virginia Geological and Economic Survey oil and gas production database.

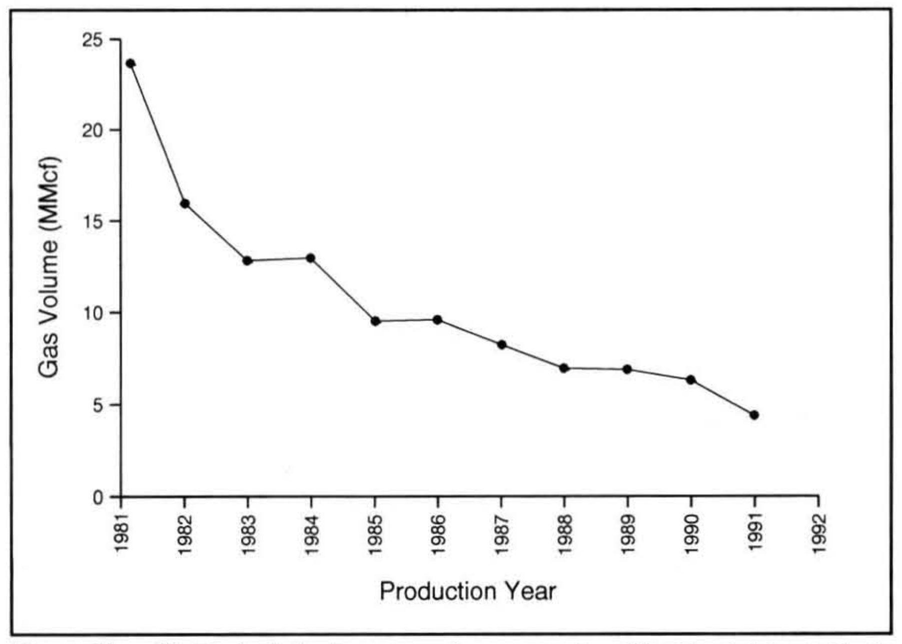


Figure Mws-15. Typical decline curve for a recent well in the Ashland-Clark Gap-Eckman field as reported to the State of West Virginia from the West Virginia Geological and Economic Survey oil and gas production database. Cumulative production from 1981 to 1991 for this well is 119 MMcfg.

364,000 Mcf since 1985, for an average of 60,667 Mcf per well.

Ashland-Clark Gap-Eckman field: The Ashland-Clark Gap-Eckman field is located in eastern McDowell, southeastern Wyoming, and western Mercer counties of southern West Virginia (Cardwell and Avary, 1982) (Figure Mws-2). Discovered in 1948 (probably in a search for Berea gas), only four wells were drilled until the 1970s, after which 275 wells were completed in the field. The field currently consists of 279 wells with Weir production. Only two of these wells were unstimulated; the rest were hydrofractured and washed with acid.

The trap was created by an updip pinchout of the Weir (Figure Mws-12) with several local folds that may have contributed to the trap. The top of the Weir pay lies between -1,800 and -2,150 feet in depth, with the pay averaging 26 feet thick. An isopach of the Weir sandstone in the field (Figure Mws-13) shows a lobate pattern in eastern McDowell County with the sandstone thinning to the south and west; this pattern suggests a deltaic depositional environment for the Weir.

West Virginia Geological and Economic Survey production data for the field begin in 1979 (Figure Mws-14). Total reported production for this field since 1979 has been 23.3 bcfg, from 279 wells. A typical decline curve for a single well is shown in Figure Mws-15. Initial open flows for the field range from 2 to 1,309 Mcf, averaging 84 Mcf. Final open flows are between 26 and 5,180 Mcf, averaging 1,025 Mcf. Rock pressures have been reported between 170 and 875 psi, averaging 543 psi. Porosity in the field is between 10 and 15 percent and averages around 12.5 percent (Privette, 1983; Cabot Oil and Gas, written commun., 1994).

Privette (1983) concludes that production in Ashland-Clark Gap-Eckman field is primarily controlled by the thickness of the sandstone. He notes that production is limited to the 30-foot or greater pay zones with only a few wells producing from thinner pays. Maximum thickness of the sandstone is 75 feet.

Resources and Reserves

Due to incomplete or unavailable data, and commingling of production from multiple pay zones, resource and reserve numbers are imprecise. Many different numbers exist for the Weir reservoir. The authors estimated a cumulative production for the Weir in West Virginia to be 1.8 tcfg. Zammerilli (USDOE/METC, written commun., 1994) provided values for resources using the Department of Energy's simulator and a pressure of 433.8 psi and a temperature of 75.2° F. These values utilized data collected by Boswell and others (1993) to calculate that 9.89 tcfg was originally in place, an estimated 7.94 tcfg remain in place, an estimated 3.91 tcfg remain as recoverable gas, and an estimated 1.1 tcfg has been produced from the Weir reservoirs. Boswell and others (1993) in Appendix 1 reported a value of 26.59 tcfg originally in place for the Weir reservoirs. This range of values for original gas in place (9.89 to 26.59 tcf) suggests that the actual value probably falls somewhere in the middle. Using a 50 percent recovery factor on the low value leaves 4.945 tcfg as recoverable resources, and on the high value leaves 13.295 tcfg as recoverable resources.

Additionally, proven reserves per well can be used to calculate total resources for the Weir. Bagnall (Columbia Gas Transmission Corporation, written commun., 1972) calculated an average proven reserve per well of 858,859 Mcf from 189 wells. Multiplying 858,859 Mcf by 3,302 (the number of Weir wells in Kentucky Geological Survey and West Virginia Geological and Economic Survey databases) yields an original proven reserve of 2.8 tcfg. Subtracting the estimated production of 1.8 tcfg from the original proven reserve leaves 1 tcfg as remaining proven reserve. This suggests that of the 4.945 tcfg original recoverable resource, 1.8 tcfg have been produced, 1.0 tcfg remain as proven reserve, and 2.145 tcfg remain as probable and possible resources. However, by subtracting the original proven reserve (2.8 tcfg) from the high recoverable resource (13.295), a possible and probable resource of 10.495 tcfg is obtained.

Future Trends

The Weir interval has been penetrated by thousands of wells, generally defining the extent of production and stratigraphic trends. Although the trends are well defined, development continues to occur within these trends as Weir completions account for approximately 10 percent of total completions in West Virginia. Industry will continue to rely on re-treatment of old wells, infill drilling, step outs, plugging back of wells that produced from deeper zones, and completion of the Weir interval (commingling) in wells targeted for deeper zones. Possibilities in the fluvial-deltaic trend in central and southern West Virginia exist over local structures and in small sandstone lenses around the primary trend. Discovery and development of new fracture trends may continue. The location of some of these trends is, in part, dependent on obvious surface and subsurface features such as fault zones and folds; others will be less obvious and their locations are difficult to predict. Small combination traps may be identified along the Paint Creek uplift in Kentucky away from the major fields that have already been defined. McGlade (1967) and Harper and Laughrey (1987) were cautious about the potential in the Squaw sandstone of Pennsylvania, and neither reported significant production. Although McGlade (1967) suggested that modern treatment techniques might result in production from the Squaw, Harper and Laughrey (1987) did not report any significant production from this sandstone.

PLAY Mfp: THE LOWER MISSISSIPPIAN FORT PAYNE CARBONATE MOUND PLAY

by Robert C. Milici, U. S. Geological Survey

Location

At present, most of the successful wells drilled into the carbonate mound play in the Lower Mississippian Fort Payne Formation are within Scott, Morgan, and Fentress Counties, Tennessee, although many other successful Fort Payne wells have been completed in adjacent counties in Tennessee and, to a lesser extent, in nearby Kentucky. The approximate extent of the play is shown in Figure Mfp-1.

Production History

The first production of oil and associated gas from the Fort Payne Formation in the Appalachian basin was established in the Cumberland Saddle area in Wayne and McCreary counties, Kentucky, in the period between 1895 and 1910 (Wilson, 1971). Porous zones in the Fort Payne Formation, called the Beaver sands (near the base) and the Corder Stray (near the top) by drillers, consist of vugs in very fossiliferous, crinoidal, clean limestones that are intercalated with shaley or silty beds. In Wayne County, Kentucky, the Beaver is about 25 to 50 feet above the base of the formation, and the Corder Stray is about 200 feet above the Beaver.

Bryozoan-rich, vugular, Waulsortian-type carbonate mounds (Wilson, 1975) in the Fort Payne Formation were explored and developed as a significant oil and gas play in mainly Fentress, Morgan, and Scott counties, Tennessee, in the 1970s to the early to mid-1980s (MacQuown, 1982; MacQuown and Perkins, 1982) (Figure Mfp-2). The carbonate mound play is essentially an oil play that has yielded a significant amount of associated natural gas. Only a few fields are dominated by gas-producing wells, and even in these the gas is very likely a cap over oil accumulations in nearby fields. Figure Mfp-2 illustrates the principal fields that have produced oil and/or natural gas from the Fort Payne in Tennessee, including those with commingled production from other formations, especially from the Monteagle and Bangor limestones.

As of 1991, the Fort Payne Formation had produced approximately 7 million barrels of oil in Tennessee. If commingled Fort Payne and Monteagle oil is included, total oil production from the principal Fort Payne fields is approximately 12 million barrels, including about 3 million barrels estimated to have been produced before 1970. During the post-1970 days of exploration, natural gas wells situated higher on local structures were shut in or the gas was vented into the atmosphere in attempts to produce oil. For example, approximately 1.3 bcfg were vented into the atmosphere during the three-year period from 1974 to 1976 from the Indian Creek, Oneida West, Burrville, Gum Branch, and Lick Branch fields in the northern Tennessee part of the Cumberland Plateau. With the construction of pipelines and gathering line systems, however, the natural gas resources of the region were developed and produced commercially along with the oil, beginning generally in the mid-1970s. At present, Fort Payne gas is produced and marketed in significant but declining quantities. Maximum annual gas production from the Fort Payne in Tennessee occurred in 1984, when about 2.26 bcfg was produced. Production in 1991, the last year of record, was about 0.57 bcf. Oil production from the Fort Payne reached a maximum in 1982, when a little less than 661,000 barrels were produced. As of 1991, annual Fort Payne oil production in Tennessee (1991) had declined to about 169,000 barrels (data from the Tennessee Division of Geology).

The first oil produced from the Fort Payne Formation in Tennessee was from the Boone Camp field in Morgan County in 1924. The current phase of oil and gas development in the Fort Payne fields of Tennessee began in 1943, however, when the Oneida West field (Figure Mfp-2) was discovered by the No. 1 H.F. Cooper well, which tested about 1 MMcfg/d from the Fort Payne (Perkins, 1970). That gas, and more from another well that was completed nearby in the Monteagle Limestone, was used locally in the city of Oneida, the only market available at that time. Subsequently, oil was discovered in a porous zone in the Fort Payne by the Vawter No. 1 Thompson heirs, which successfully produced about 150 barrels of oil per day natural from a depth of about 1,450 feet in 1969 (Statler, n.d.; 1971). Since then, oil and gas have been produced from 24 moderate-sized fields in Tennessee and from several additional small fields and wells in Tennessee and Kentucky. Of the larger fields, Fort Payne production in seven fields was generally commingled with gas that was produced from younger Mississippian reservoirs.

The most prolific gas-producing fields in the Fort Payne carbonate mound play of the northern Tennessee part of the Cumberland Plateau are the Hurricane Ridge West (2.2 bcf cumulative production as of 1991) and Stockton Southwest (1.4 bcf) fields in Fentress County, the Burrville (3.0 bcf) field in Morgan County, the Gum Branch field (1.7 bcf) in Scott and Morgan counties, and the Low Gap-Reuben Hollow (1.4 bcf) and Stanley Junction (1.1 bcf) fields in Scott County (Table Mfp-1). Production from the latter three fields is commingled, chiefly with gas produced from the Monteagle Limestone. Four fields in Tennessee have produced more than 1 million barrels of oil from the Fort Payne as of 1991. These include the Indian Creek field (1.86 million barrels), the Gum Branch field (1.1 million barrels), the Lick Branch field (1.2 million barrels), and the Oneida West field (1.4 million barrels). As with gas, Fort Payne oil produced from the Gum Branch field is commingled with that from the Monteagle Limestone. Cumulative gas production from the Fort Payne, including commingled gas produced from the Monteagle and Bangor limestones, was approximately 14 bcf as of 1991.

Stratigraphy

The basic stratigraphic framework and nomenclature (Figure Mfp-3) of the Mississippian strata in the Cumberland Plateau of Tennessee were developed during the past several decades by the Tennessee Division of Geology (Wilson,

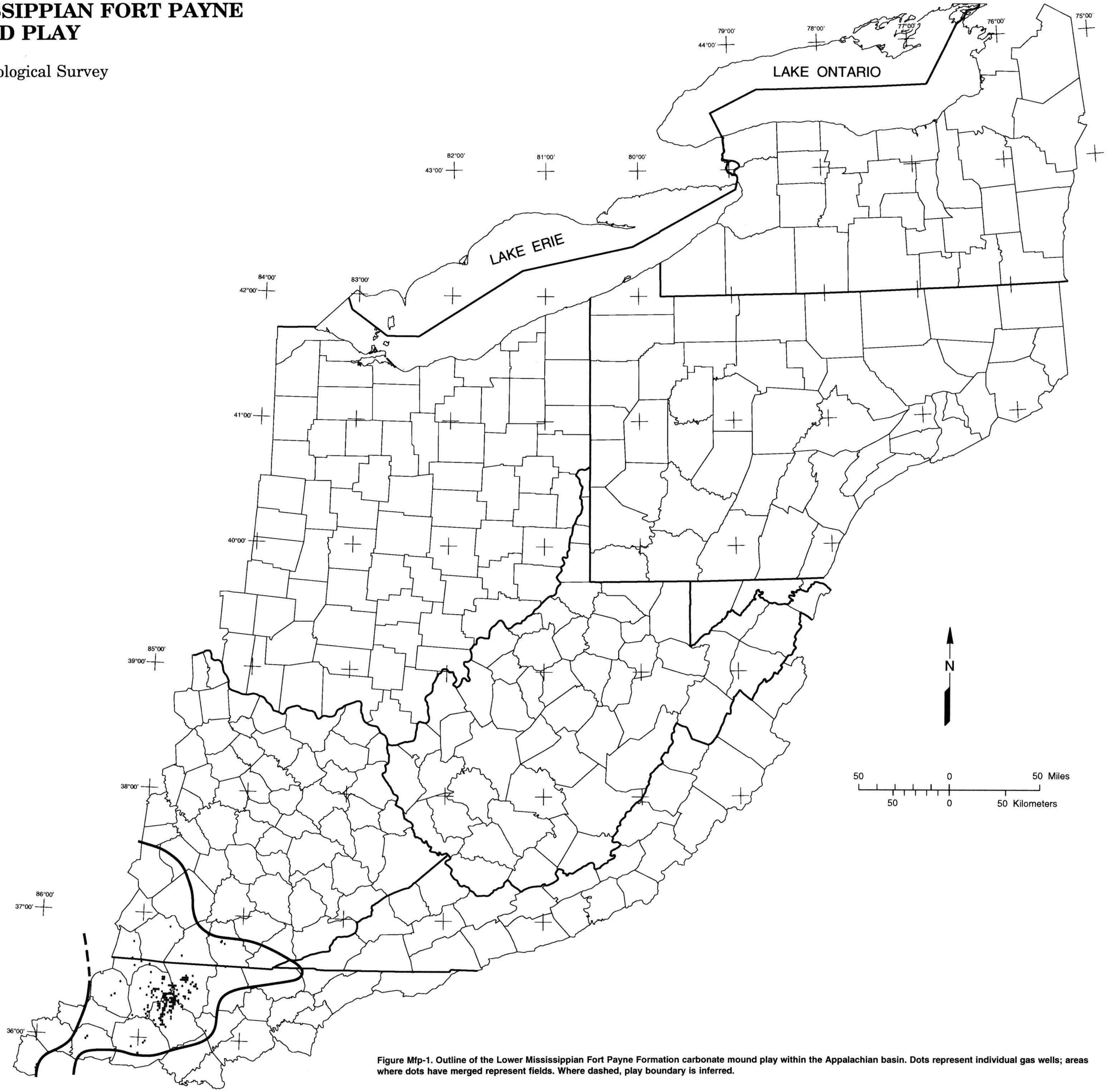


Figure Mfp-1. Outline of the Lower Mississippian Fort Payne Formation carbonate mound play within the Appalachian basin. Dots represent individual gas wells; areas where dots have merged represent fields. Where dashed, play boundary is inferred.

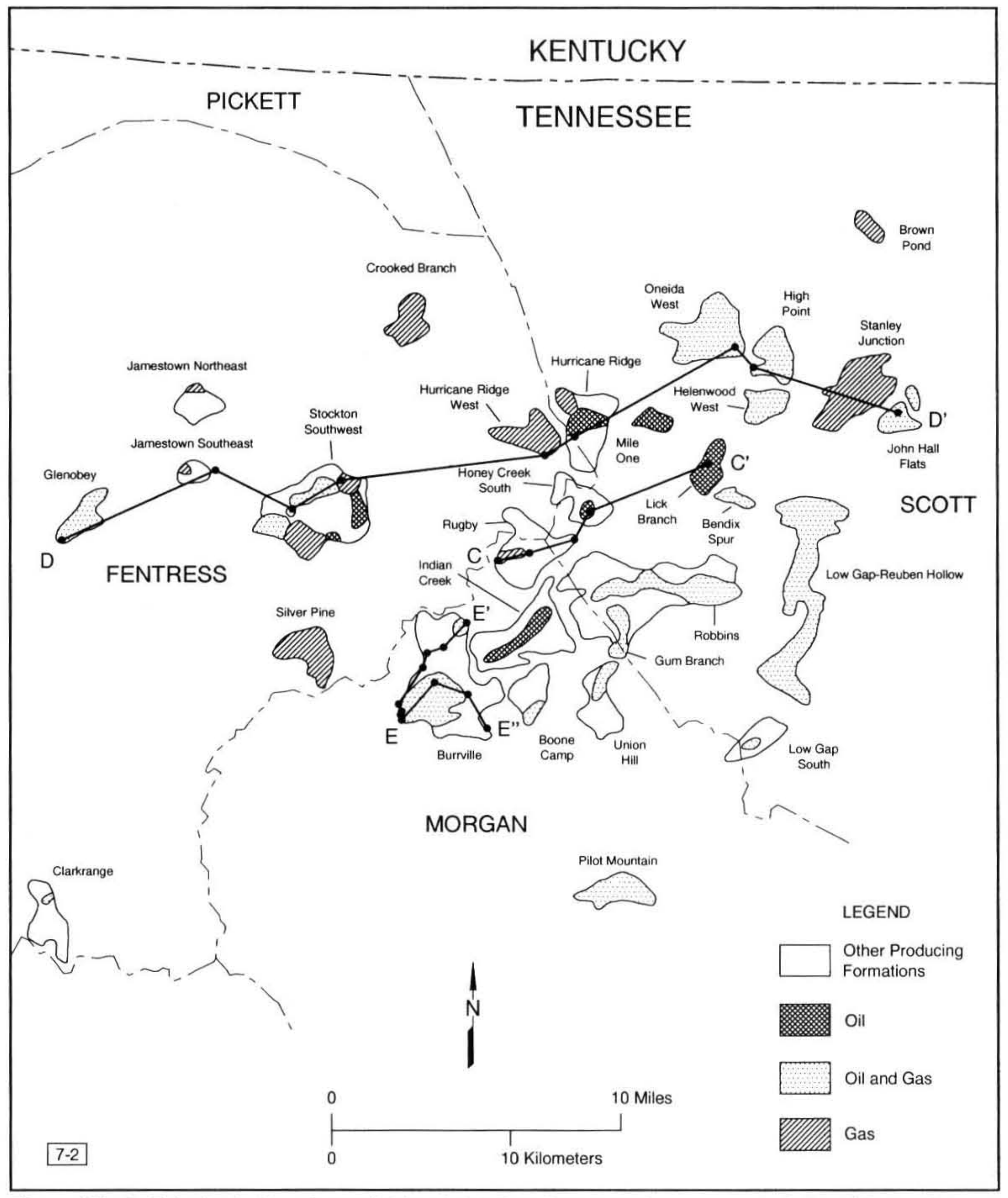


Figure Mfp-2. Principal oil and gas fields of the Fort Payne carbonate mound play. Lines of cross sections C-C' (Figure Mfp-10), D-D' (Figure Mfp-11), E-E' (Figure Mfp-12), and E-E" (Figure Mfp-13) also are shown.

1956; Wilson and others, 1956; Wilson and Stearns, 1960; Stearns, 1963).

At the base of the Mississippian sequence, the Chattanooga Shale occupies the distal part of the great Catskill delta that was deposited in the Appalachian basin largely in response to the Acadian orogeny (Milici and de Witt, 1988). This deltaic sequence contains some of the premier source beds for hydrocarbons in the basin.

In the northern part of the Cumberland Plateau of Tennessee (Figure Mfp-4), the post-Acadian Mississippian section is approximately 900 feet thick and has been described by Milici and others (1979). The Fort Payne Formation and the subadjacent very thin greenish-gray Maury Shale comprise a massive, silica-rich carbonate rock sequence that occupies the stratigraphic interval between the impure carbonate strata of the Warsaw Limestone above, and the gray and black shales and siltstones of the Chattanooga Shale below (Figure Mfp-3). The Warsaw Limestone, in turn, is overlain by the relatively pure limestones of the Mississippian carbonate platform sequence, including the St. Louis Limestone, the Monteagle Limestone, the Hartselle Sandstone, and the Bangor Limestone; then by red and green shales, siltstones, sandstones, and carbonate rocks of the Pennington Formation of Late Mississippian age; and then by Pennsylvanian coal-bearing siliciclastic rocks.

The Fort Payne Formation, of Kinderhookian and Osagean (?) age (Conkin and Conkin, 1975), is a lithologically heterogeneous carbonate-dominated unit that occurs between Devonian and Lower Mississippian siliciclastic rocks of the Catskill delta and the limestones of the Upper Mississippian platform. In Tennessee, the Fort Payne extends from the Highland Rim in the central part of the state eastward beneath the Cumberland Plateau to the western part of the Valley and Ridge province (Figure Mfp-4). To the east and north, it interfingers with the siliciclastic rocks of the Grainger, Price, and Maccrady formations in Tennessee and southwestern Virginia, and with the red and green shales and gray deltaic shales and siltstones of the Borden Formation in Kentucky. To the south and east in northern Alabama and northwestern Georgia, the peritidal carbonates of the Fort Payne Formation (Figure Mfp-5) thin to 150 feet or less and are overridden by the gray and green prodelta shales of the Floyd Shale.

The regional stratigraphy of the Fort Payne in Tennessee was summarized by Milici and others (1979). In general, the formation ranges from a little less than 100 feet to about 300 feet thick. The most common lithology is a siliceous carbonate rock, called silicastone or porcelanite, that in many places is interbedded with calcareous shales and siltstones. In some places, bryozoan-rich limestones occur within or at the top of the formation, and these more porous zones are the principal reservoirs in the oil- and gas-producing areas of the northern plateau region in Tennessee.

The base of the Fort Payne is marked almost everywhere by a 3-foot-thick bed of the Maury Shale, a distinctive greenish-gray, phosphatic, glauconitic shale (Figure Mfp-3). The Maury is too thin to be mapped as a separate unit and is commonly included within the Fort Payne, rather than with the underlying Chattanooga Shale. The Maury is lithologically similar to thin green shale beds within the Fort Payne, and its upper contact with the Fort Payne Formation appears to be gradational.

Chowns and Elkins (1974) described the origin of quartz-filled geodes in the Fort Payne as pseudomorphs after early diagenetic anhydrite nodules similar to

PLAY Mfp-1		Hurricane Ridge West TN	Stockton Southwest TN	Burrville TN	Gum Branch TN	Low Gap/ Reuben Hollow TN	Oneida West TN	Stanley Junction TN
BASIC RESERVOIR DATA	POOL NUMBER							
	DISCOVERED	1977	1979	1975	1973	1976	1977	1973
	DEPTH TO TOP RESERVOIR							
	AGE OF RESERVOIR	Mississippian	Mississippian	Mississippian	Mississippian	Mississippian	Mississippian	Mississippian
	FORMATION	Fort Payne	Fort Payne	Fort Payne	Fort Payne	Fort Payne	Fort Payne	Fort Payne
	PRODUCING RESERVOIR	Fort Payne	Fort Payne	Fort Payne	Fort Payne	Fort Payne	Fort Payne	Fort Payne
	LITHOLOGY	bryozoan packstone/ wackestone	bryozoan packstone/ wackestone	bryozoan packstone/ wackestone	bryozoan packstone/ wackestone	bryozoan packstone/ wackestone	bryozoan packstone/ wackestone	bryozoan packstone/ wackestone
	TRAP TYPE	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic
	DEPOSITIONAL ENVIRONMENT	bryozoan bioherm	bryozoan bioherm	bryozoan bioherm	bryozoan bioherm	bryozoan bioherm	bryozoan bioherm	bryozoan bioherm
	DISCOVERY WELL IP (Mcf)							
	DRIVE MECHANISM	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion
	NO. PRODUCING WELLS	10	16	12	28	32	3	23
	NO. ABANDONED WELLS	3						
	AREA (acreage)			700			1,155	
	OLDEST FORMATION PENETRATED	Chattanooga	Ordovician	Nashville	Trenton	Nashville	Copper Ridge	Nashville
	EXPECTED HETEROGENEITY DUE TO:	deposition fractures diagenesis	deposition fractures diagenesis	deposition fractures diagenesis	deposition fractures diagenesis	deposition fractures diagenesis	deposition fractures diagenesis	deposition fractures diagenesis
RESERVOIR PARAMETERS	AVERAGE PAY THICKNESS (ft.)	36	14	13.9	16	28	21	13.6
	AVERAGE COMPLETION THICKNESS (ft.)							
	AVERAGE POROSITY–LOG (%)	11	9.7	9	7	6.8	12.7	9.2
	MINIMUM POROSITY–LOG (%)	5	4					
	MAXIMUM POROSITY–LOG (%)	16	13	19	12	13	22	16
	NO. DATA POINTS	19	24	11	5	6	14	13
	POROSITY FEET	3.96	1.36	0.78	1.12	1.9	2.67	1.25
	RESERVOIR TEMPERATURE (°F)						90	
	INITIAL RESERVOIR PRESSURE (psi)	300	265	600	750	1,000	770	850
	PRODUCING INTERVAL DEPTHS (ft.)						1,350-1,700	
	PRESENT RESERVOIR PRESSURE (psi) / DATE	245						
FLUID & GAS PROPERTIES	Rw (Ωm)							
	GAS GRAVITY (g/cc)							
	GAS SATURATION (%)			85				
	WATER SATURATION (%)			15			10	
	COMMINGLED	yes	yes					
	ASSOCIATED OR NONASSOCIATED	nonassociated	associated	associated	associated	associated	associated	associated
	Btu/scf							
VOLUMETRIC DATA	STATUS (producing, abandoned, storage)	producing	producing	producing	producing	producing	producing	producing
	ORIGINAL GAS IN PLACE (Mcf)						2,166,500	
	ORIGINAL GAS RESERVES (Mcf)							
	PRODUCTION YEARS	1985-1991	1980-1993	1975-1991	1983-1991	1978-1991	1977-1991	1981-1991
	REPORTED CUMULATIVE PRODUCTION (Mcf)	2,201,845	1,420,847	2,979,822	1,509,580	1,375,563	456,900	1,127,166
	NO. WELLS REPORTED							
	ESTIMATED CUMULATIVE PRODUCTION (Mcf)							
	REMAINING GAS IN PLACE (Mcf)/DATE							
	REMAINING GAS RESERVES (Mcf)/DATE							
	RECOVERY FACTOR (%)							
	INITIAL OPEN FLOW (Mcf/d)							
	FINAL OPEN FLOW (Mcf/d)							

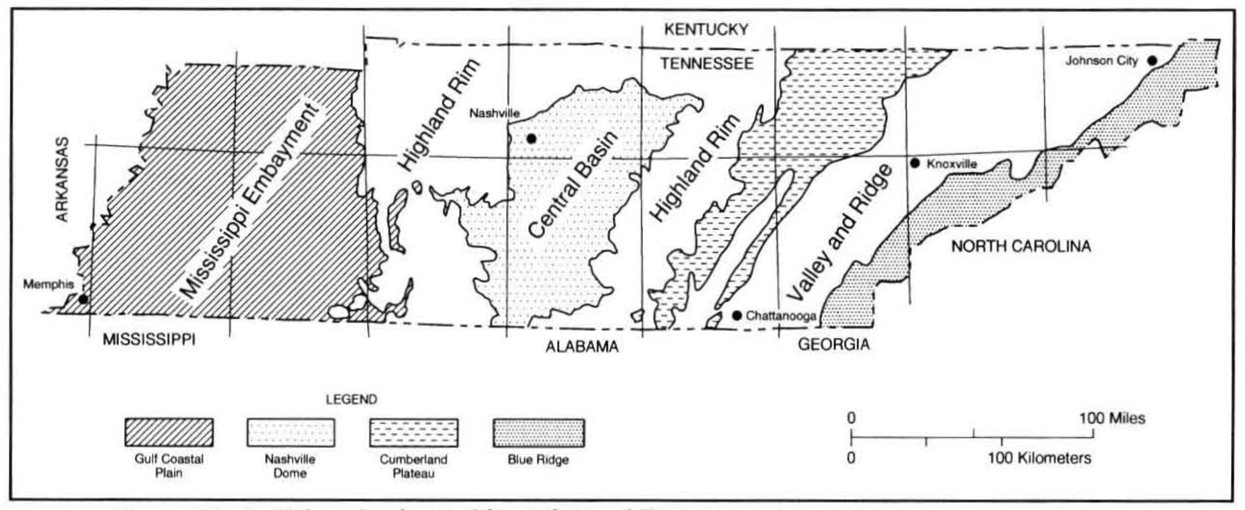


Figure Mfp-4. Major physiographic regions of Tennessee. From Milici and others (1979).

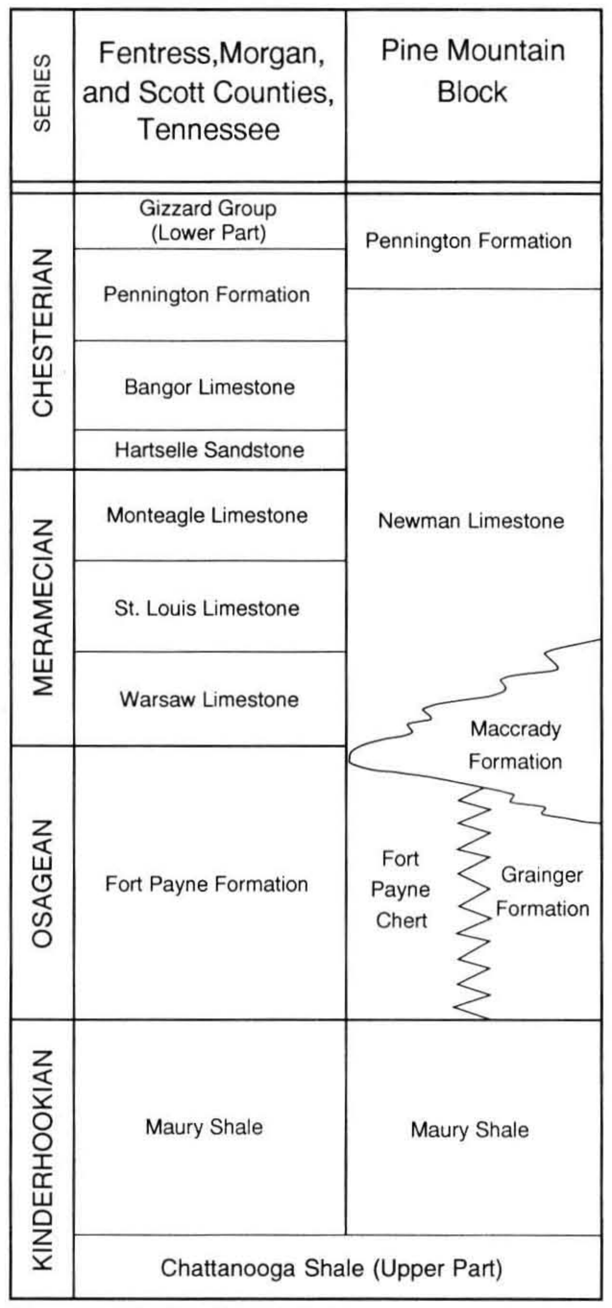


Figure Mfp-3. Stratigraphic nomenclature of Mississippian formations in the Cumberland Plateau region of Tennessee. Modified from Englund (1964, 1968) and Milici and others (1979).

those that are associated with modern arid tidal flat and lagoonal deposits. They identified occurrences of spiculite and siliceous sponge spicules within both the Fort Payne Formation and the Warsaw Limestone, and suggested that these siliceous fossils may have been the source of the abundant silica in much of the formation.

Marcher (1963) described an area of extensive bioherm development (Figure Mfp-6) at or near the base of the Fort Payne Formation in north-central Tennessee. These bioherms occur in a north-south-trending area approximately 30 miles long and 10 miles wide. In general, the bioherms range from a few tens to hundreds of feet across and in places are up to almost 100 feet thick. The enclosing beds of the Fort Payne consist of well-bedded calcareous and siliceous siltstone that appears to arch over the biohermal mounds. Marcher (1963) recognized three general lithologic units within the individual bioherms: a core, inner flanking beds, and outer flanking beds (Figure Mfp-6). Cores consist of argillaceous limestone and calcareous shale that contain abundant crinoidal and algal debris. Inner flanking beds are generally thin and irregular, and consist chiefly of algal material in an argillaceous and dolomitic matrix. Outer flanking beds are massive and lenticular and consist of relatively sparse crinoidal and algal debris in a matrix of medium- to coarse-grained dolomitic limestone. A rubble of argillaceous limestone occurs within the dolomitic limestone in some places in the outer beds. These rubble beds commonly contain irregular vugs and in some places are a very porous and permeable dolomite.

MacQuown (1982) and MacQuown and Perkins (1982) described similar biogenic structures in the subsurface of the Cumberland Plateau of Tennessee as Waulsortian-type carbonate mounds. They divided the lower part of the Fort Payne Formation into two units: a lower submound unit, and an upper mound unit. In effect, the submound unit becomes thicker and occupies the entire carbonate portion of the Fort Payne Formation in intermound areas. This unit consists of several microfacies, defined by MacQuown and Perkins (1982) as cherty, limey, dolomitic, evaporitic, and silty microfacies. The mound unit, where present, consists of a mud-supported microfacies of mudstone and wackestone and a grain-supported microfacies of packstone and grainstone. The grainstone is the principal reservoir rock. It commonly consists of large bryozoan fragments that are associated with intergranular to vuggy porosity. Unlike the buildups described by Marcher (1963), these Waulsortian-type mounds do not appear to contain significant amounts of algae. Recognition of mound/submound/intermound environments, and the likelihood of production, depends on the presence of bryozoan wackestones and packstones at the top or in the upper part of the Fort Payne carbonate section instead of fine-grained cherty carbonate rock. MacQuown and Perkins (1982) defined the upper part of the Fort Payne Formation as consisting of a siliciclastic or detrital facies of shale, siltstone, and minor limestone. These beds are lithologically transitional with the overlying Warsaw Limestone, which is siltier and sandier and contains less limestone. The transitional interval is several tens of feet thick and, in general, serves as an effective seal for the hydrocarbon-bearing Waulsortian-type mounds. MacQuown and Perkins (1982) pointed out that the carbonate mound facies in the Fort Payne has many characteristics in common with Waulsortian-type mounds described elsewhere in Europe and western North America.

Lumsden (1988) studied the petrology of the Fort Payne Formation at four widely separated localities in Tennessee, from the western Highland Rim to the northeastern Cumberland Plateau. He concluded that the Fort Payne is dominantly a dolomitic porcelanite with lesser amounts of fossiliferous carbonate rock and cherty dolomite. According to Lumsden (1988), the Fort Payne appears to have been deposited generally under dysoxic to anoxic bottom conditions on a broad, tectonically stable marine ramp and at water depths of 30 to 300 feet. In support of MacQuown and Perkins (1982), Lumsden (1982) concluded that the Waulsortian-type mounds that occur within the Fort Payne and produce most of the hydrocarbons were developed on local submarine topographic highs where the sea waters were relatively enriched in oxygen.

The overlying Warsaw Limestone consists of about 115 to 200 feet of impure limestone and calcareous and dolomitic siliciclastic rock. The thickness of the Warsaw interval appears to range over several tens of feet in Tennessee; because contacts with underlying and overlying formations are gradational, the boundaries of the Warsaw with the Fort Payne Formation and St. Louis Limestone commonly are placed differently by different workers. The Warsaw is sufficiently shaley and dense to form an effective seal over Fort Payne reservoirs.

Structure

In general, the elevation of the top of the Chattanooga Shale descends from about 200 feet above sea level in central Fentress County, Tennessee, to about 500 feet or more below sea level in Scott and Morgan counties (MacQuown and Perkins, 1982). This structural trend reflects the regional dip of the flank of the Cincinnati arch to the east. MacQuown (1982) and MacQuown and Perkins (1982) observed that there is a significant relationship between relatively small-scale anticlinal structures superimposed on this regional surface and the locations of the Fort Payne fields. In essence, they showed that the locations of the mounds coincide approximately with gentle anticlinal trends in the underlying Chattanooga Shale, which they in turn related to draping and differential compaction of the Chattanooga over underlying topographic highs on the pre-Chattanooga unconformity. MacQuown and Perkins (1982) concluded that biogenic debris was generated and accumulated preferentially on these slightly elevated areas on the sea floor, perhaps in environments slightly more oxic than those in adjacent depressions. The locations of the Rugby, Indian Creek, Boone Camp, Burrville, Union Hill, Gum Branch, and Honey Creek South fields coincide with structural highs on the top of the Chattanooga Shale (MacQuown and Perkins, 1982) (Figures Mfp-7, Mfp-8).

Reservoir

The geologic and engineering data and characteristics of the principal Fort Payne gas-producing fields are summarized in Table Mfp-2. Much, if not all, of the gas produced from the Fort Payne is associated with oil. Hurricane Ridge West and Stanley Junction fields, in which production is restricted almost entirely to gas, appear to be gas segregations from adjacent oil fields (Figure Mfp-9). In general, Table Mfp-2 summarizes data from fields that have produced 1.0 bcfg or more. The Oneida West field is included, however, because of its relative importance as a major oil producing field in the Fort Payne carbonate mound play. A more detailed reservoir engineering study of the Indian Creek oil field

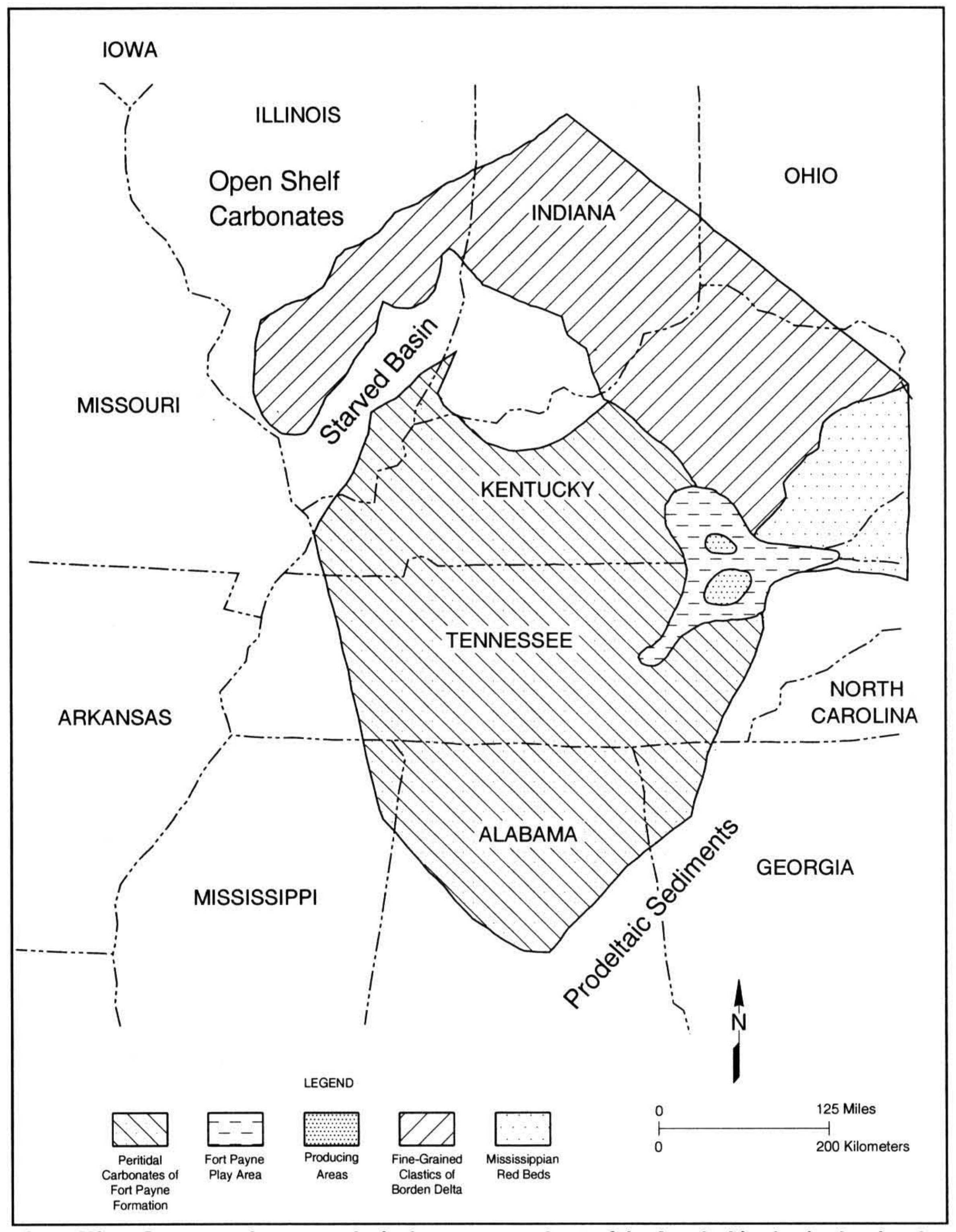


Figure Mfp-5. Osagean paleogeography in the west-central part of the Appalachian basin showing the main productive area in Tennessee, the historically productive area in Kentucky, and the approximate play boundary. Modified from Chowns and Elkins (1974).

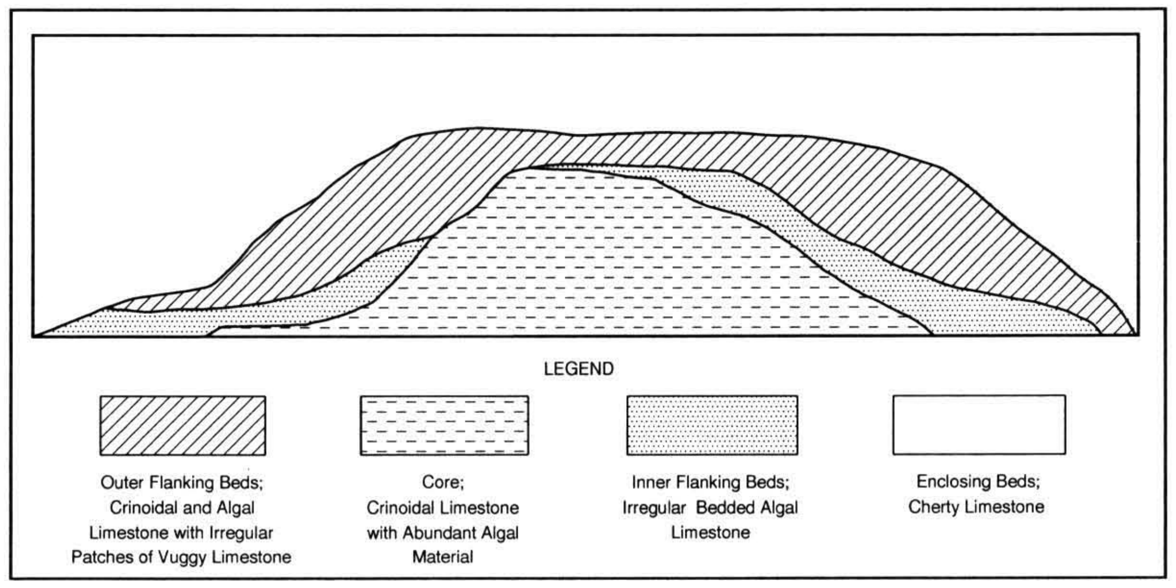


Figure Mfp-6. Schematic cross section of bioherms in the Fort Payne Formation in north-central Tennessee. From Marcher (1963).

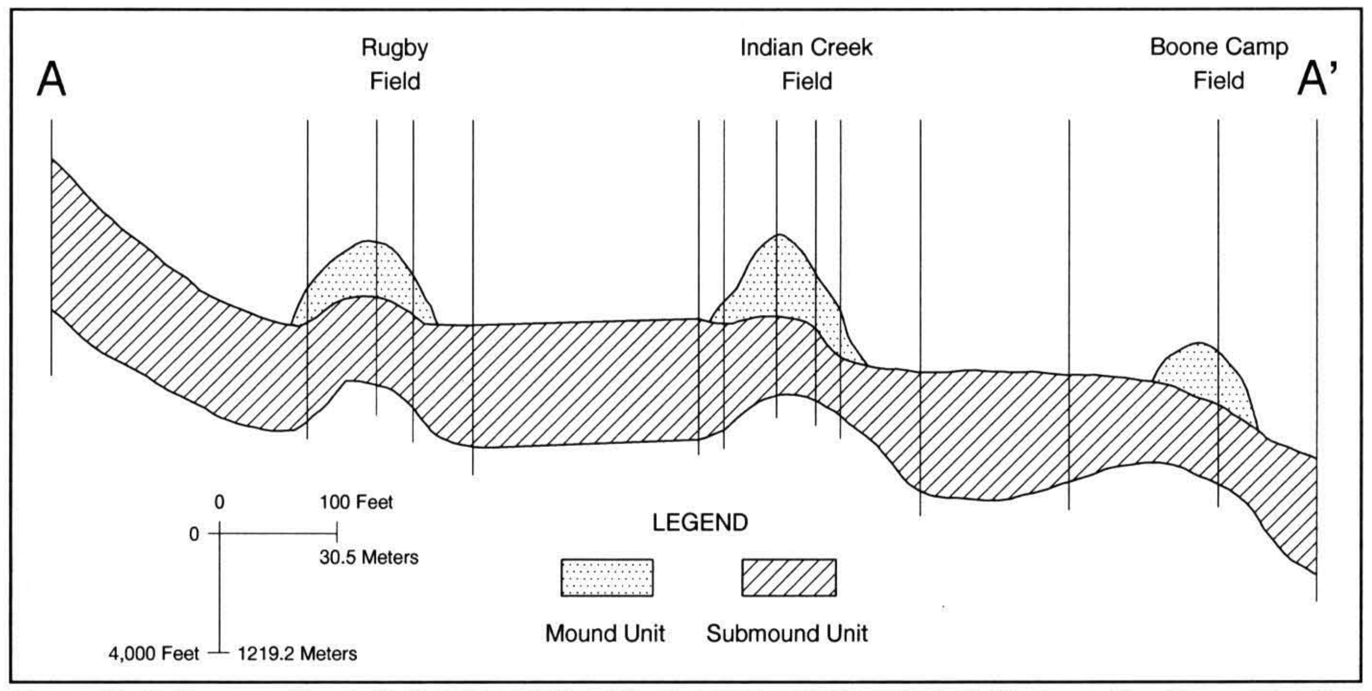


Figure Mfp-8. Cross section A-A' showing relationship of mound units to anticlinal structures. See Figure Mfp-7 for location. Modified from MacQuown and Perkins (1982).

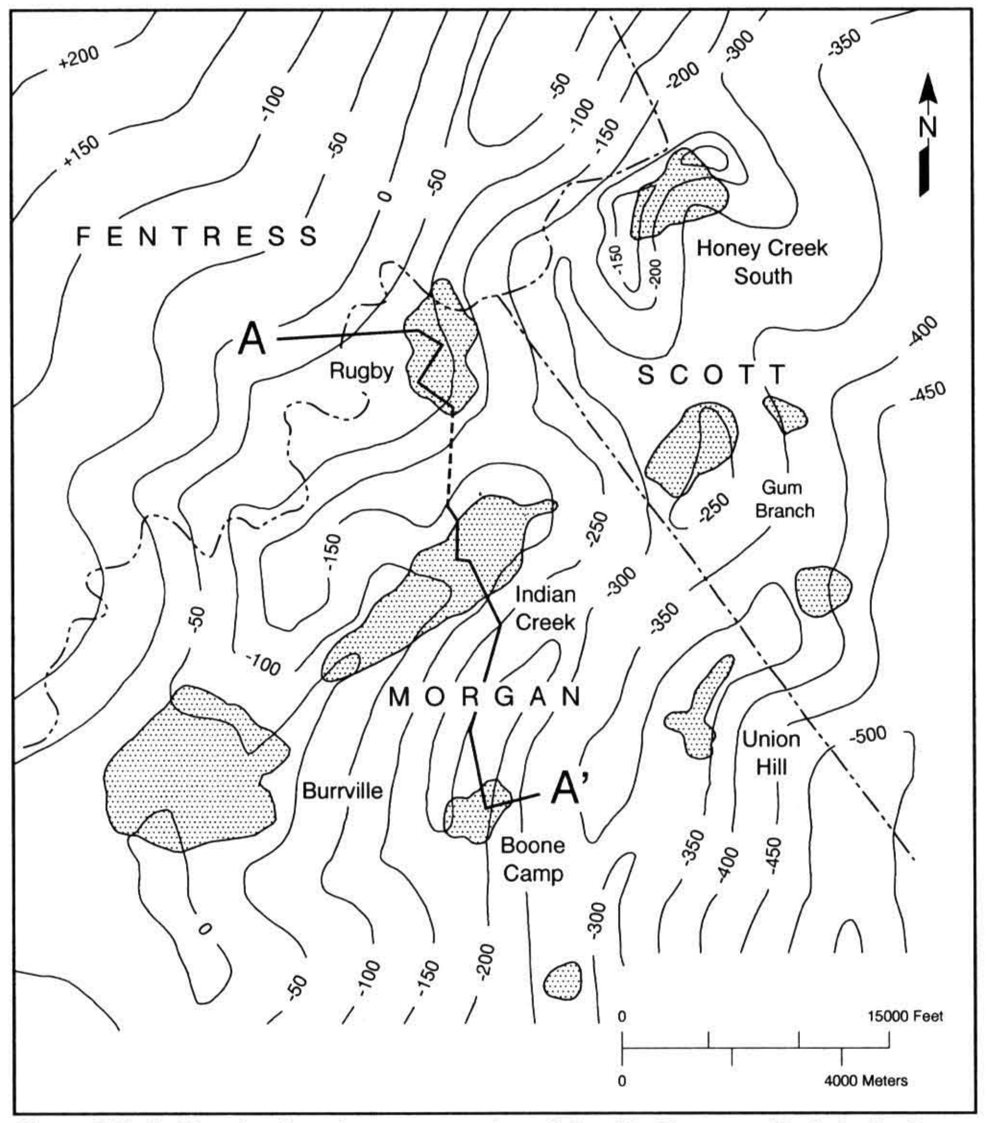


Figure Mfp-7. Structural contour map on top of the Chattanooga Shale in Fentress, Morgan, and Scott counties, Tennessee, showing the relationship of anticlinal structures to locations of fields producing from mound units. Contour interval = 50 feet. Line of cross section A-A' (Figure Mfp-8) is shown. From MacQuown and Perkins (1982). See Figure Mfp-2 for location.

Table Mfp-2. Annual gas production (in Mcf) from Fort Payne fields in Fentress, Morgan, and Scott counties, Tennessee. Data are from the files of the Tennessee Division of Geology.

County	Field	Dis. Date	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	Subtotal	No. of Wells	Prod/Well
Fentress	Clarkrange	1977							0	0	0		7,623	0	0	0	0	0	0	0	0	7,623	1	7,623
	Crooked Branch	1975															37	370	0	0	0	407	3	136
	Glenobey	1979							0	0	0			0	20,602	23,883	15,187	15,359	0	0	0	75,031	8	9,379
	Honey Creek South	1972												8,979	5,029	6,635	11,220	10,556	6,771	1,046	875	51,111	3	17,037
	Hurricane Ridge West	1977											6,539	414,634	497,697	369,965	290,979	209,205	157,826	140,746	114,254	2,201,845	12	183,487
	Rugby	1973											138,189	2,655	96,308	65,789	24,207	13,575	8,403	7,719	7,915	364,760	20	18,238
	Silver Pine	1983											15,405	0	0	0	0	0	0	0	0	15,405	3	5,135
	Stockton Southwest	1978											629,690	299,473	140,626	98,436	94,826	68,196	63,668	21,978	3,954	1,420,847	51	27,860
Morgan	Boone Camp	1924	1,757	1,286	0	0		0			0	2,240	7,292	42,766	45,463	34,721	21,698	31,327	27,667	25,225	20,062	261,504	5	52,301
	Burrville	1974		0	6,467	4,803	8,461	6,960	5,616	66,051	297,331	256,336	606,371	549,377	336,070	208,954	209,217	149,812	119,090	112,887	126,019	2,979,822	49	60,813
	Gum Branch	1973											20,552	55,684	36,054	29,286	22,674	8,150	5,706	13,493	8,506	200,105	8	25,013
	Pilot Mountain	1981									0	0		0	0	0	12,422	5,614	8,981	12,311	8,814	48,142	2	24,071
	Rugby	1973			0	0	0		0	0	298	65,496		7	8,407	5,023	1,751	2,056	58	0	0	83,096	4	20,774
	Union Hill	1975							20,853	3,915	39,778	27,632	31,142	152,862	127,086	37,032	33,186	31,599	38,699	30,371	19,699	593,854	17	34,933
Scott	Bendix Spur	1978							0	0	0	0	7,803	12,275	9,624	11,579	6,959	3,424	4,911	5,165	6,861	68,601	6	11,434
	Brown Pond	1970																7,296	12,664	13,827	15,086	48,873	3	16,291
	Gum Branch	1971	0						0	0	78,270	108,499	170,846	218,269	296,943	219,258	129,001	85,168	79,168	66,512	57,646	1,509,580	52	29,030
	Helenwood West	1973	0		0	0	0	23,436	23,386	11,839	3,550	3,451	3,691	3,615	2,782	1,689	762	2,193	0	0	0	80,394	4	20,099
	Honey Creek South	1972	0	0	0	0			0	0	0	0	0	11,945	14,196	3,247	7,633	2,926	252	583	524	41,306	2	20,653
	Hurricane Ridge	1977							0	0	0	0	18,163	259,884	123,192	91,795	76,712	59,743	46,476	40,577	33,337	749,879	9	83,320
	John Hall Flats	1980								0	0	0	1,475	7,476	253	2,374	4,692	13,839	5,143	11,612	5,465	52,329	3	17,443
	Low Gap-Reuben Hollow	1976						27,571	212,920	115,196	110,435	60,635	77,716	101,468	168,492	156,783	111,688	71,160	57,535	53,302	50,662	1,375,563	51	26,972
	Low Gap South	1977													2,947	9,066	3,570	6,061	5,948	7,912	5,008	40,512	5	8,102
	Mile One	1977					0	0	0	0		0	0	0	0	0	0	0	0	0	482	482	10	48
	Oneida West	1969	0	0			60,081	52,844	54,009	73,211	55,754	67,097	46,631	23,707	4,718	8,358	4,949	2,120	2,488	93	840	456,900	20	22,845
	Robbins	1980								10,995	6,557		40,882	8,740	3,790	2,495	2,600	1,919	1,511	1,544	2,188	83,221	6	13,870
	Rugby	1973														2,256	4,366	2,387	9,484	11,913	4,881	35,287	2	17,644
	Stanley Junction	1980									63,425	112,948	114,463	174,734	129,702	109,414	95,142	84,618	84,296	86,363	72,061	1,127,166	30	37,572
TOTALS			1,757	1,286	6,467	4,803	68,542	110,811	316,784	281,207	655,398	704,334	1,944,473	2,258,550	2,069,981	1,498,038	1,185,478	888,673	746,745	665,179	565,139	13,973,645	389	35,922

was published by MacQuown and Perkins (1982) as representative of the reservoir characteristics of the Fort Payne mound reservoir. The basic data for the Oneida West and Indian Creek fields are reported in Table Mfp-3.

The traps appear to be biohermal buildups that consist largely of bryozoans with admixed fossil fragments of crinoids and other invertebrates. Enclosing lithologies of silicastone or shaley limestone are impervious enough to serve as excellent seals. The most likely source rock is the Chattanooga Shale, with perhaps some contribution from indigenous shales and mudstones in the upper part of the Fort Payne Formation or overlying Warsaw Limestone. Although there is little information concerning thermal maturation and kerogen content of the Chattanooga in Fentress, Morgan, and Scott counties, Tennessee, data provided by Schmoker (1993) for eastern Kentucky and southwestern Virginia suggest that a zone of thicker, relatively mature Chattanooga Shale source rocks extends southward into Tennessee to the east of the Cumberland Plateau. The hydrocarbons in the Cumberland Plateau in Tennessee, therefore, may have migrated from the fold-and-thrust belt up the regional dip toward the crest of the Cincinnati arch, so that some were trapped in porosity zones in the Fort Payne. The coincidence of thermal maturation trends with thickness trends of the Acadian clastic wedge indicates that initial hydrocarbon generation and migration may have occurred during the early depositional phases of the Acadian orogeny, when synorogenic Devonian black shales were buried deeply by the great wedge of the prograding Catskill delta (Milici, 1993). Hydrocarbons generated were ultimately driven to the west by additional sediment loading during the early phases of the Alleghanian orogeny and, lastly, by thrust loading during the main phase of Alleghanian deformation.

The biohermal buildups within the Fort Payne Formation, which in different places may occur at slightly different stratigraphic positions, are interspersed within several other carbonate lithologies. Interconnections and migration pathways between porous buildups apparently are along fractures. MacQuown and Perkins (1982) recognized several different types of porosity in these buildups, including hairline fractures, breccia, stromatactis cavities, primary intergranular porosity, and moldic, vugular, and intercrystalline secondary porosity. MacQuown and Perkins (1982) observed that primary intergranular to vuggy porosity most commonly occurred in bryozoan grainstones and suggested that secondary porosity occurred where diagenetic solutions increased pore sizes in some of the reservoir zones, perhaps as the result of relative uplift and subareal exposure of the carbonate mound facies. The relationships of stratigraphy, porosity, bryozoan bioherms, and hydrocarbon production are shown in Figures Mfp-10, Mfp-11, Mfp-12, and Mfp-13.

Drilling depths to the pay range from about 980 feet to 1,970 feet, and average about 1,475 feet. Pay thicknesses range from 10 to 40 feet, and porosities in productive wells range locally from 12 to 22 percent. Rock pressure, commonly reported as shut-in casing pressure, ranges from 265 to 1,000 psi. In general, these pressures are measured and reported by drillers after treatment. Treatment of choice is 1,000 to 4,000 gallons of 15 to 25 percent hydrochloric acid through perforations. In some wells, treatment was in the open hole, and in a few wells nitrogen was used to assist the acidization process.

Average daily gas production per well for the Hurricane Ridge, Burrville, and Stockton Southwest fields is shown in Figure Mfp-14. Average maximum daily production of gas ranged from about 34 Mcf/d in the Stockton Southwest field to 126 Mcf/d in the Hurricane Ridge West field in the early to mid-1980s, computed on an annual basis. As of 1991, average annualized production per well has declined to 10 Mcf/d or less for the Burrville and Stockton Southwest fields, and to about 31 Mcf/d for the Hurricane Ridge West field.

Description of Key Fields

Oneida West field: Production from Oneida West field, in Scott County, Tennessee (Figure Mfp-2; Table Mfp-1), is from multiple porosity zones in the Fort Payne at drilling depths that range from about 1,350 to 1,700 feet. Perkins (1970) recognized that production in the Fort Payne was chiefly from porosity zones in bryozoan-rich, crinoidal carbonate buildups or mounds that occurred locally within more siliceous and cherty Fort Payne carbonate rock.

As of July 1974, calculated remaining gas-in-place in the Oneida West field was 1,166.5 MMcf. Since then, at least 457 MMcfg has been produced, and there may be a reserve of about 710 MMcf in the field. The amount of recoverable oil estimated in 1974 was 1,350,000 barrels, which has proved to be low. Current production of oil from the Fort Payne in the Oneida West field is 1,416,649 barrels (1991 data).

Burrville field: The Burrville field in Morgan County, Tennessee (Figure Mfp-2; Table Mfp-1), was discovered in 1975 when the No. 1 Starr-Davidson-State well was drilled to a depth of 1,475 feet by Petroleum Development Corporation and Dixie Oil Company. A porosity zone 16 feet thick was encountered in the Fort Payne, together with an excellent show of oil. By 1977, there were 32 producing oil wells and eight shut-in gas wells in the field, with hydrocarbon production from both the Monteagle and Fort Payne. The Fort Payne, however, was the principal oil reservoir. White (n.d. a; n.d. b) estimated that original oil in place was 3,077,763 stock tank barrels of oil. Of this amount, the Burrville field had produced 800,787 barrels by 1991, somewhat more than the 564,000 barrels of oil estimated by White as the probable economic cutoff. White (written commun., 1977, files, Tennessee Division of Geology) estimated conservatively that Fort Payne gas reserves in wells having high gas/oil ratios are about 1.4 bcf, considerably less than the gas subsequently produced from the field.

Log cross sections in the Burrville field (Figures Mfp-12, Mfp-13) illustrate the relationship of hydrocarbon occurrence and production to relatively high porosity zones within the limestone unit of the Fort Payne Formation. Descriptions of samples filed with the Tennessee Division of Geology for some of these wells consistently indicate an association of bryozoan-rich crinoidal packstones and wackestones with these high porosity zones, the Waulsortian-like buildups first recognized by MacQuown (1982). In addition, Figure Mfp-13 illustrates a significant variation of the thickness of the limestone unit in the Fort Payne Formation, with a hydrocarbon show occurring within thin but noncherty limestone.

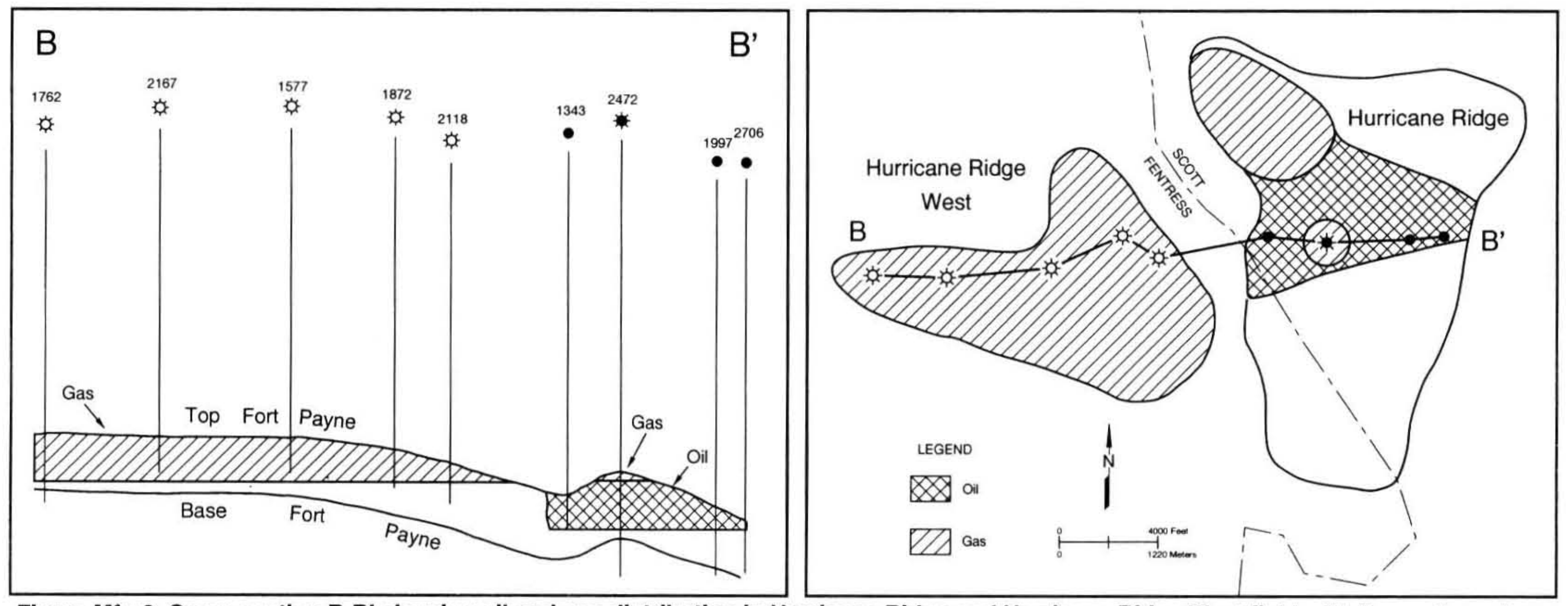


Figure Mfp-9. Cross section B-B' showing oil and gas distribution in Hurricane Ridge and Hurricane Ridge West fields. Well permit numbers are from the files of the Tennessee Division of Geology. See Figure Mfp-2 for exact location of fields.

Table Mfp-3. Reservoir data for oil- and gas-producing areas of the Oneida West and Indian Creek fields. Oneida West field data from White (n.d. b). Indian Creek field data from MacQuown and Perkins (1982).

	ONEIDA WEST FIELD		INDIAN CREEK FIELD	
	OIL	GAS	OIL	GAS
Reservoir	Fort Payne Formation		Fort Payne Formation	
Depth (feet)	1,700	1,700	1,400-1,500	1,400-1,500
Area (acres)	1,118	1,155		
Average Thickness (feet)	8.5	8.5	40+ gross porosity thickness	
Reservoir Volume (acre-feet)	9,458	9,565	15,297	4,945
Estimated Average Porosity (%)	10	10	8.03	6.87
Estimated Average Water Saturation (%)	10	10	30	30
Estimated Original Reservoir Pressure	770	770	948	948
Reservoir Temperature (°F)	90	550	72	72
Gravity of Gas (air - 1.000) (estimated)		0.6		
Super Compressability Factor, Z (estimated)		0.84		0.84
Calculated Gas Originally in Place (MMcf)		2,166.5		991
Cumulative Gas Production, July 1974 (MMcf)		1,000		
Calculated Remaining Gas in Place, July 1974 (MMcf)		1,166.5		
Gravity of Oil (°API)	39		36	
Estimated Solution Gas/Oil Ratio (scf/bbl)	250		406	
Estimated Formation Volume Factor (BSTO)	1.127			
Original Oil Volume (BSTO)	5,861,000		7,274,400	
Calculated Recoverable Oil (bbls)	1,350,000			
Calculated Oil Recovery, July 1974 (bbls)	1,034,036			
Remaining Recoverable Oil (bbls)	315,964			
Calculated Solution Gas in Place (MMcf)	1,465		2,954	
Estimated Cumulative Solution Gas Produced, July 1974 (MMcf)	1,000			
Estimated Solution Gas Remaining, July 1974 (MMcf)	465			
Absolute Permeability Oil Column (md)			55	
Residual Oil Saturation (%)			22	

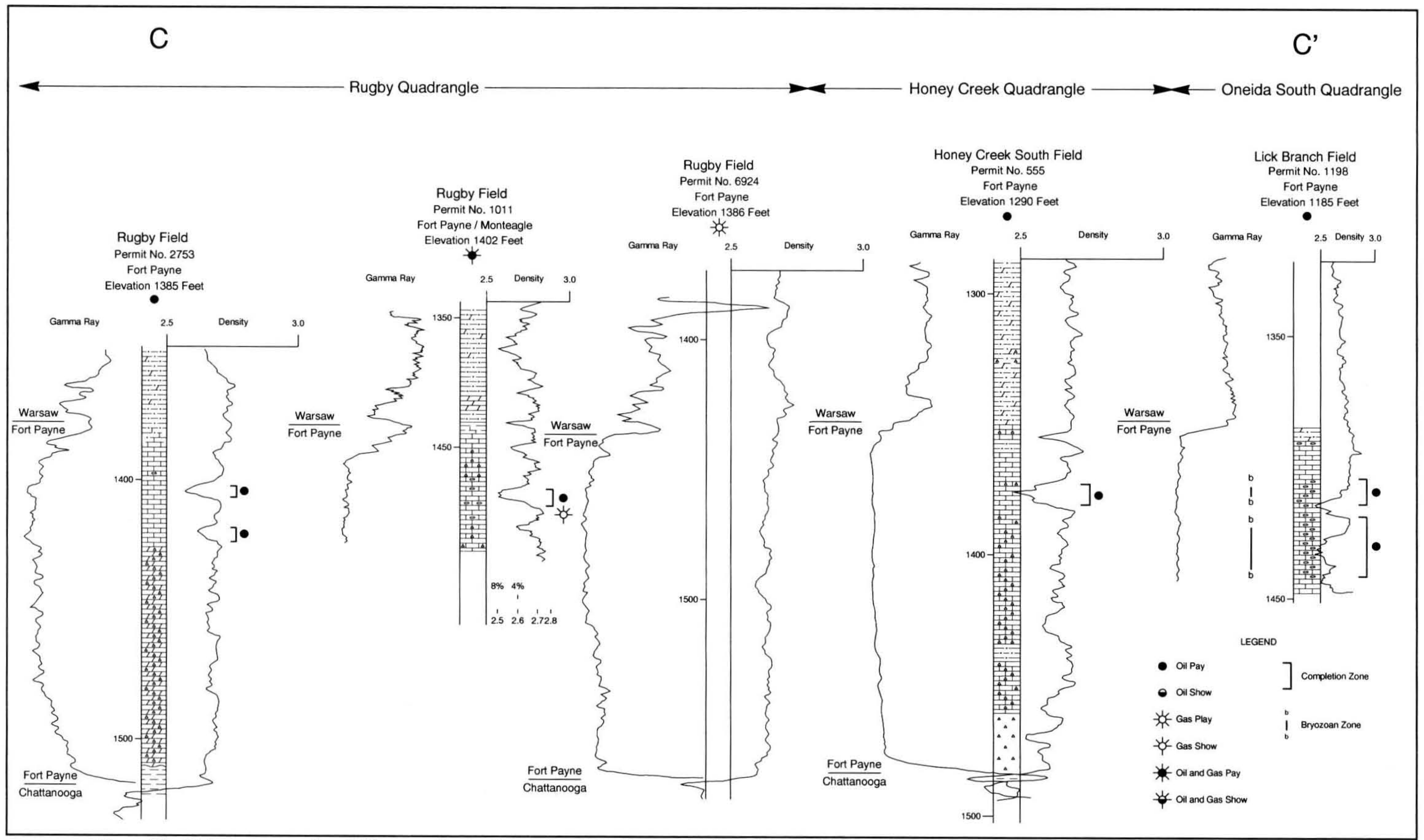


Figure Mfp-10. Log cross section C-C' across Rugby, Honey Creek South, and Lick Branch fields. Well permit numbers are from the files of the Tennessee Division of Geology. See Figure Mfp-2 for location of cross section. Well headings list producing formations, permit numbers, and elevations of wells. Well depths are in feet below surface.

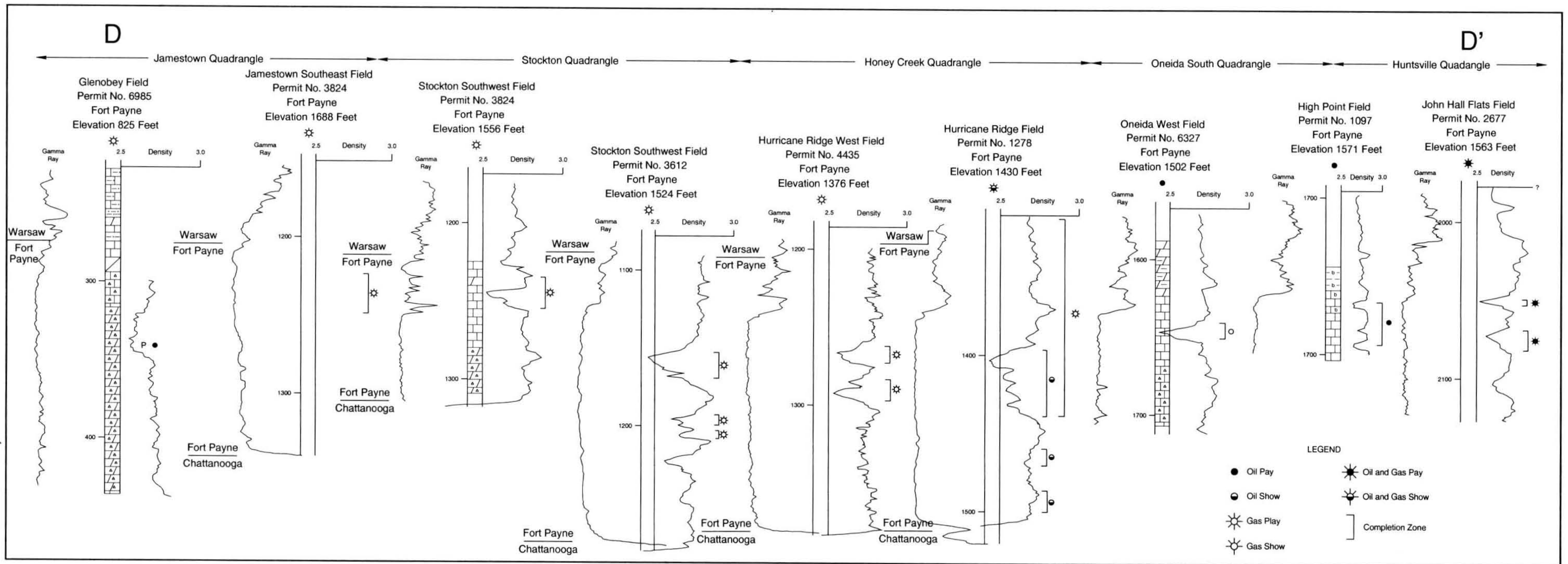


Figure Mfp-11. Log cross section D-D' from Glenobey to John Hall Flats fields. Well permit numbers are from the files of the Tennessee Division of Geology. See Figure Mfp-2 for location of cross section. Well headings list producing formations, permit numbers, and elevations of wells. Well depths are in feet below surface.

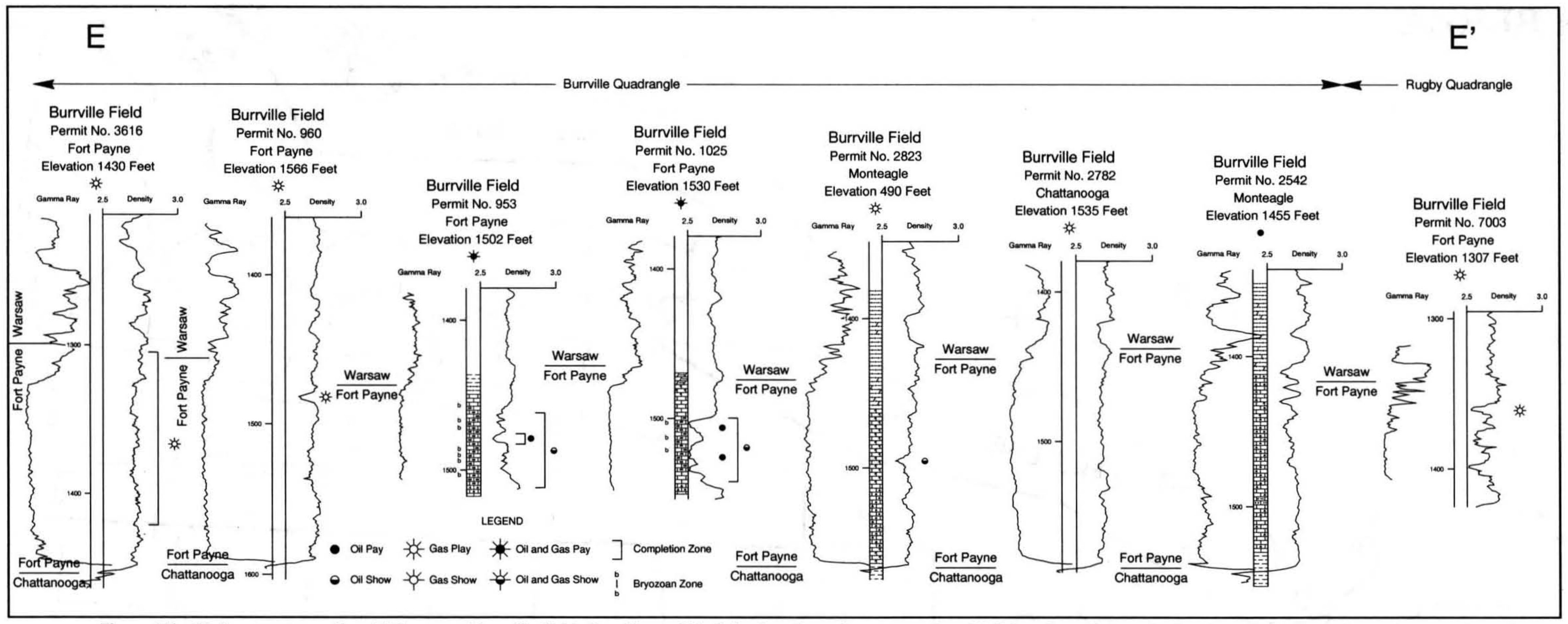


Figure Mfp-12. Log cross section E-E' across Burrville field. See Figure Mfp-2 for location of cross section. Well headings list producing formations, permit numbers, and elevations of wells. Well depths are in feet below surface.

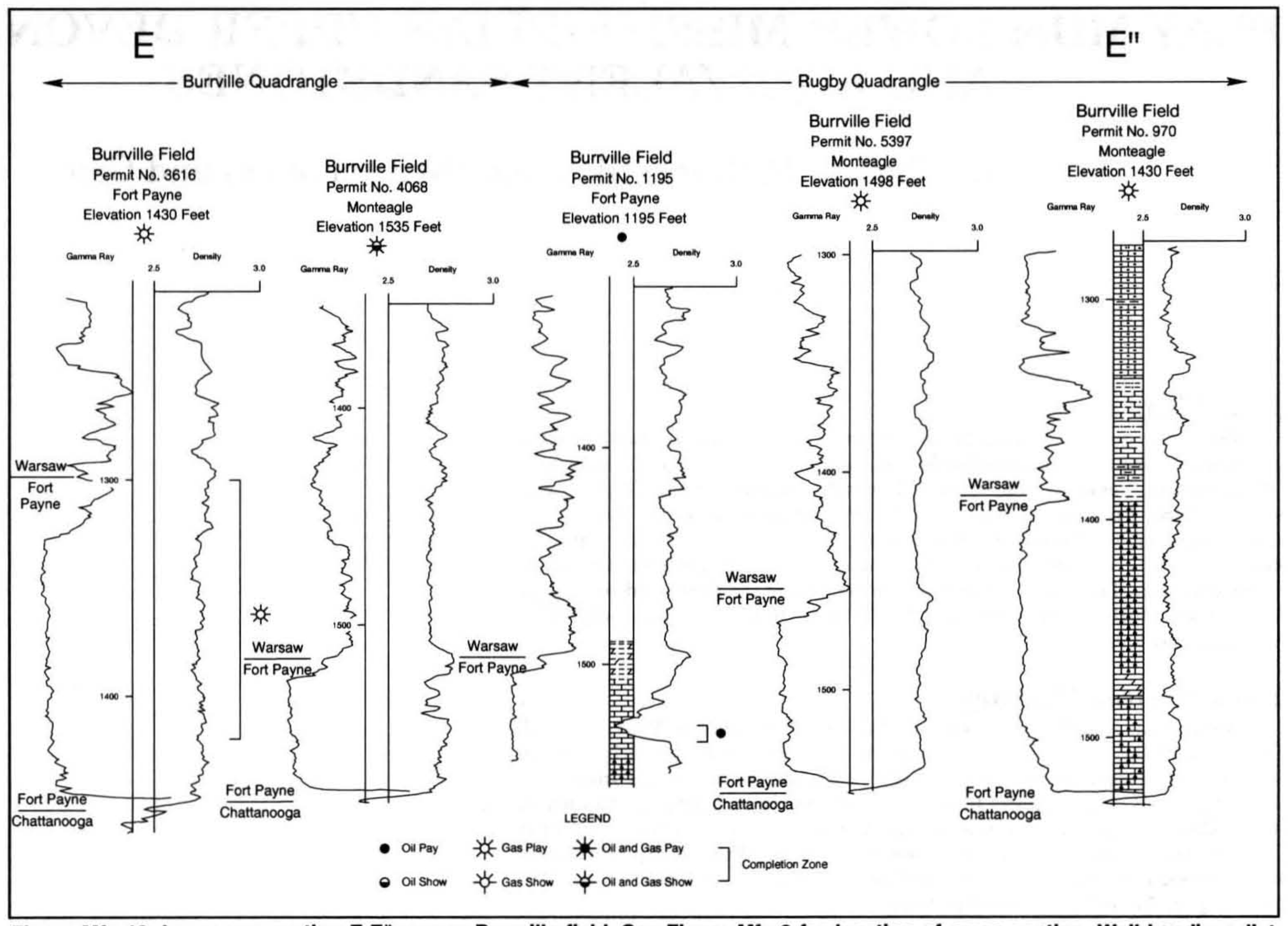


Figure Mfp-13. Log cross section E-E" across Burrville field. See Figure Mfp-2 for location of cross section. Well headings list producing formations, permit numbers, and elevations of wells. Well depths are in feet below surface.

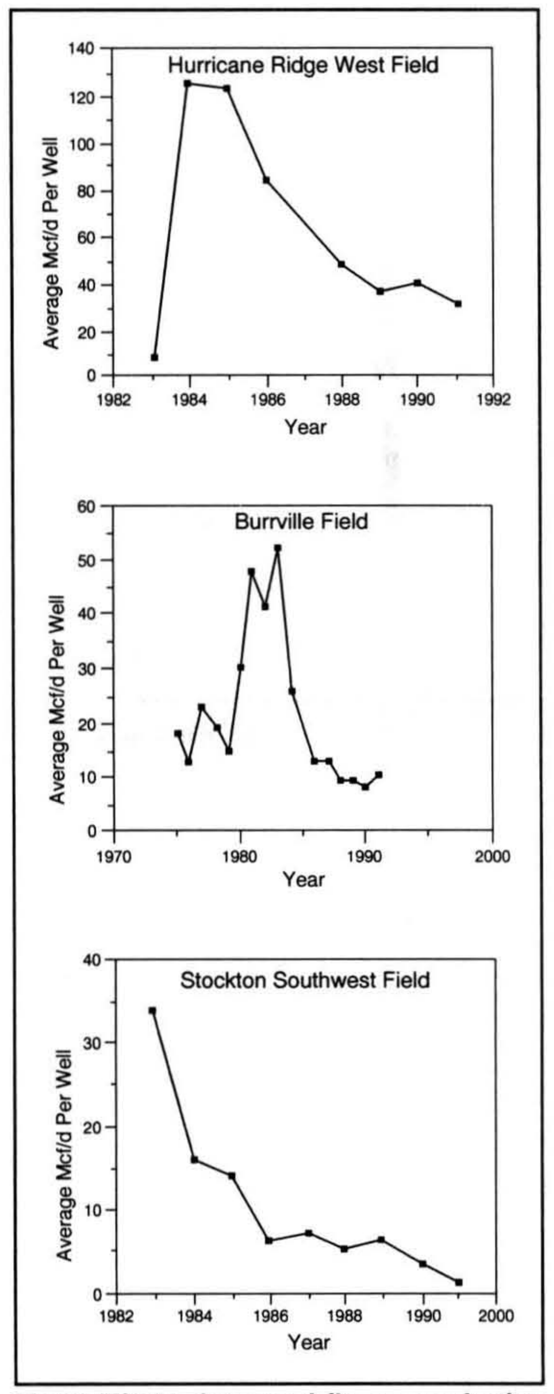


Figure Mfp-14. Average daily gas production per well for Hurricane Ridge West, Burrville, and Stockton Southwest fields.

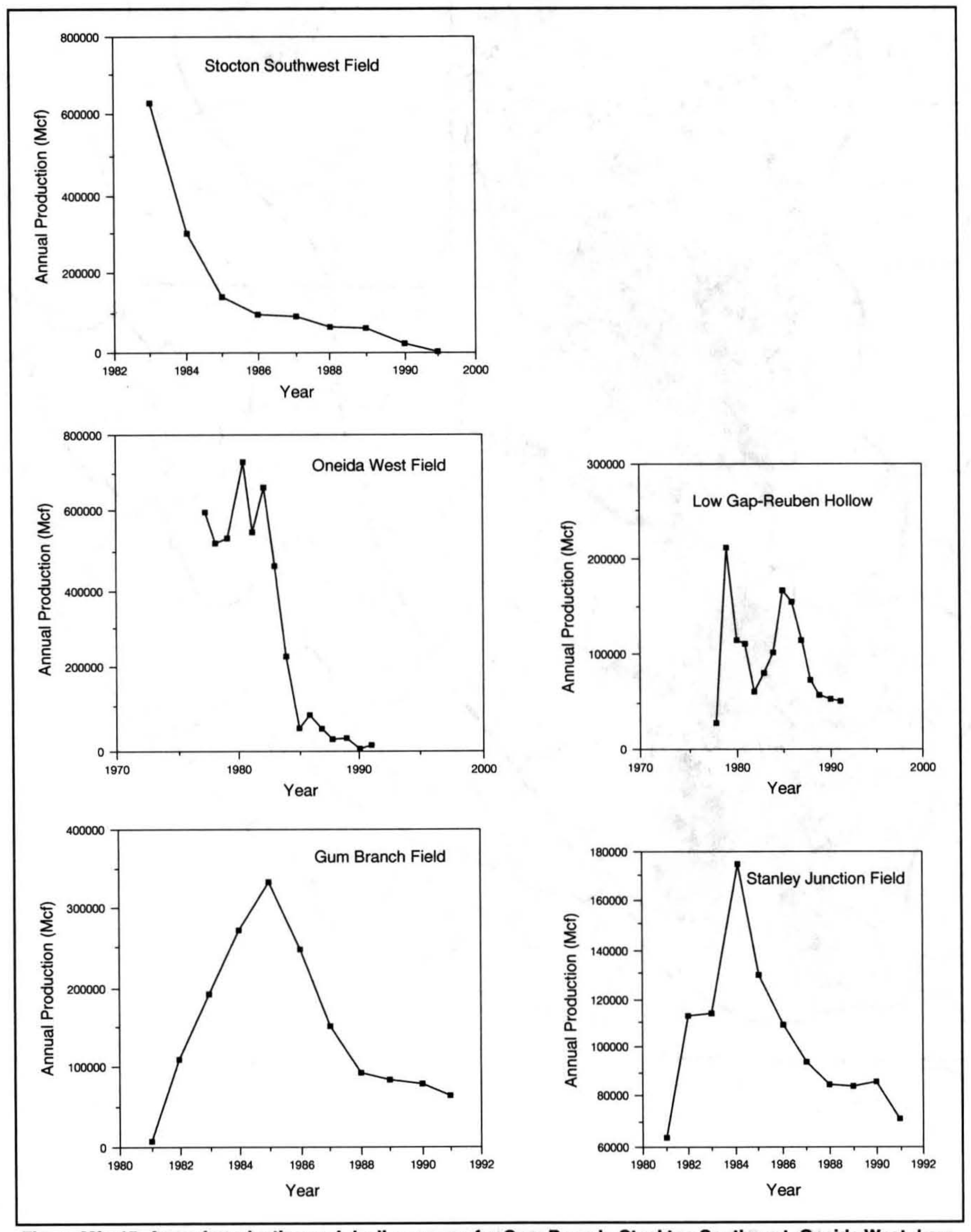


Figure Mfp-15. Annual production and decline curves for Gum Branch, Stockton Southwest, Oneida West, Low Gap-Reuben Hollow, and Stanley Junction fields.

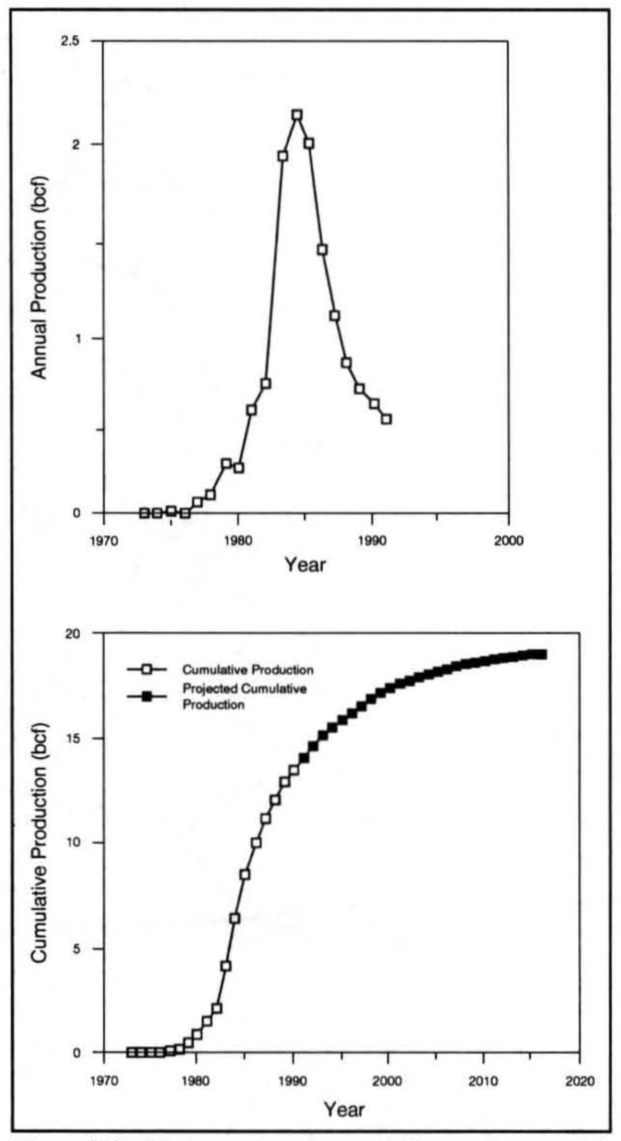


Figure Mfp-16. Annual, and cumulative and projected cumulative production curves for the Fort Payne carbonate mound play in Tennessee.

Resources and Reserves

The major fields producing gas from the Fort Payne exhibit similar decline curves, from the maximum production rates that occurred in the late 1970s to mid-1980s to the present-day low levels of production (Table Mfp-1; Figures Mfp-15, Mfp-16). As a result, the overall cumulative production curve for Fort Payne gas has started to flatten, and at current rates of decline, ultimate production from existing fields is projected to be about 19 to 20 bcf in about 25 years (Figure Mfp-16). This projection, if accurate, indicates that 6 bcfg remains to be produced in addition to the 14 bcf that has already been produced (Table Mfp-2).

Future Trends

The future of the Fort Payne carbonate mound play depends upon the use of existing and new technologies to locate the more porous zones in the Fort Payne at relatively shallow drilling depths of about 980 feet or less to 1,970 feet or more below the surface of the Cumberland Plateau, and in the Cumberland Saddle region of Tennessee and Kentucky, where the formation is less deeply buried. Similar reef-like structures have been found in Mississippian strata in the Williston Basin of North Dakota by reflection seismic surveying (Burke and Diehl, 1993). Because of their biogenic nature and need for nutrients, it is reasonable to expect Waulsortian-like buildups in the Appalachians to occur along and near the northern rim of the Fort Payne carbonate platform, especially along the Borden delta front in eastern Kentucky and along the sediment-starved basin escarpments in northwestern Kentucky and Illinois (Figure Mfp-5). It should be noted, however, that the buildups in Tennessee appear to be near, but not along, the northeastern rim of the restricted Fort Payne carbonate platform and, consequently, these known buildups do not appear to be representative of a shelf-edge play.

PLAY MDe: LOWER MISSISSIPPIAN-UPPER DEVONIAN BEREA AND EQUIVALENT SANDSTONES

by Thomas E. Tomastik, Ohio Division of Oil and Gas

Location

Productive gas pools and fields in the Lower Mississippian-Upper Devonian Berea Sandstone and equivalent rocks occur in broad linear trends from eastern Ohio, western Pennsylvania, eastern Kentucky, western West Virginia, and southwestern Virginia (Figure MDe-1). Producing trends are defined by depositional and structural influences and are further subdivided into the fluvial-deltaic, shallow marine, barrier island, and structural-fluvial-deltaic trends (Figure MDe-2). The limits of this play are defined by the Berea and equivalent rocks outcrop belt, which occurs in parts of Ohio, Pennsylvania, Kentucky, West Virginia, and Virginia.

Production History

Natural gas was first discovered in the Berea Sandstone in East Liverpool, Ohio, in 1859 or 1860 (Newberry, 1878; Orton, 1888). All of the early wells in East Liverpool were drilled for oil or salt water, but the flow of gas from some wells prompted special efforts to save gas for heating and lighting (Newberry, 1878). East Liverpool, in fact, was among the first Ohio towns to use natural gas for domestic and manufacturing purposes (Orton, 1888). Further exploration and development in this area led to the inclusion of this gas pool into the St. Clair field (Figure MDe-3), discovered in 1885.

Wildcatting was hectic and development was rapid during the boom period of 1860 to 1861 in Ohio and Pennsylvania (Owen, 1975). By the late 1860s, acceptance of the anticlinal theory led to significant discoveries in Berea and equivalent rocks. Exploration of existing surface structure trends led to the development of giant gas fields such as Murrysville (1878) and Oakford (1885) in western Pennsylvania (Figure MDe-3). By the late 1890s, Berea exploration began to develop along trends associated with depositional rather than structural settings.

Since the initial discovery of gas in East Liverpool, Ohio, 221 fields have been developed in this play in the Appalachian basin. Between 1871 and 1900, 33 gas fields were discovered in eastern and southeastern Ohio, western Pennsylvania, and central West Virginia, including Leechburg (1871), Murrysville (1878), Greenville (1880), Oakford (1885), Saxonburg (1886), and Nine Mile Run (1894) in Pennsylvania; St. Clair (1885), Gilmore (1889), Corning Consolidated (1891), McConnelsville Consolidated (1896), Barnesville Consolidated (1897), Chatham (1899), and Bolin Mills (1900) in Ohio; and Gay-Fink Consolidated (1894) in West Virginia (Figure MDe-3).

From 1901 to 1939, Berea exploration and development led to the discovery of 92 new fields in Ohio, Pennsylvania, Kentucky, and West Virginia. Some of the more significant discoveries included Cheshire Consolidated (1904), Cow Run Consolidated (1904), Bells Run Consolidated (1904), Peoli (1912), Perry-Ashland (1913), Derwent (1918), Mt. Zion Consolidated (1922), and Fourmile (1939) fields in Ohio; Valcourt (1911) field in Pennsylvania; Beech Farms Consolidated (1915) and Cordell Consolidated (1917) fields in Kentucky; and Burdett-St. Albans (1906) and Palermo-Mud River (1908) fields in West Virginia (Figure MDe-3; Tables MDe-1, MDe-2).

Between 1940 and 1970, most new field discoveries occurred in Kentucky, West Virginia, and Virginia. The Berea Sandstone became a major gas reservoir in Virginia during this time with the discovery of the High Knob field (Figure MDe-3) in southwestern Virginia in 1944 (Nolde and Milici, written commun., 1994). Additional important discoveries during this time included Canada (1942) and Nigh Consolidated (1945) fields in Kentucky; Nora (1948), Glick (1950), Breaks-Haysi (1955) and Berwind (1961) fields in Virginia; and Baileysville (1943), Mann-Oceana (1945), Gilbert (1947), Big Sandy (1950), and Huff Creek (1960) fields in West Virginia (Figure MDe-3).

From the 1970s to 1990s, most of the activity involved infill drilling that extended existing Berea fields and pools. However, several significant fields were discovered in Virginia and Kentucky. These fields included Roaring Fork (1984), Coeburn (1987) in Virginia; and Jobe Branch (1977), Big Laurel Schools (1988), and Road Fork (1990) in Kentucky (Figure MDe-3).

Reliable production data are very difficult to obtain in the Appalachian basin. Of the approximately 15,834 Berea and equivalent wells drilled in the basin, actual cumulative gas production data were obtained from 5,036 Berea, Second "Berea," Murrysville, and Cussewago wells representing 151 fields in Ohio, Virginia, West Virginia, and Kentucky. Total cumulative production for these wells through 1992 was 600 bcf, yielding an estimated total cumulative production for the Lower Mississippian-Upper Devonian Berea Sandstone and equivalent rocks of 1,886 bcf.

Stratigraphy

The Berea Sandstone and equivalent rocks occur throughout much of the Appalachian basin (Figure MDe-4). Figure MDe-5 illustrates the generalized nomenclature of the Upper Devonian to Lower Mississippian rocks across the Appalachian basin. Producing units of this play are the Berea Sandstone, Murrysville sandstone, Cussewago Sandstone, and Second "Berea" sandstone. Summaries of previous historical work on the stratigraphy of the Berea and equivalent rocks can be found in Newberry (1870), White (1881), Orton (1888), and Butts and Leverett (1904). More recent research in the Appalachian basin includes Pepper and others (1954), Larese (1974), Potter and others (1983), Kammer and Bjerstedt (1986), and Harper and Laughrey (1987; 1989).

Originally named the Berea grit by Newberry (1870) from exposures at Berea, Ohio, the Berea Sandstone is a medium- to fine-grained clay-bonded

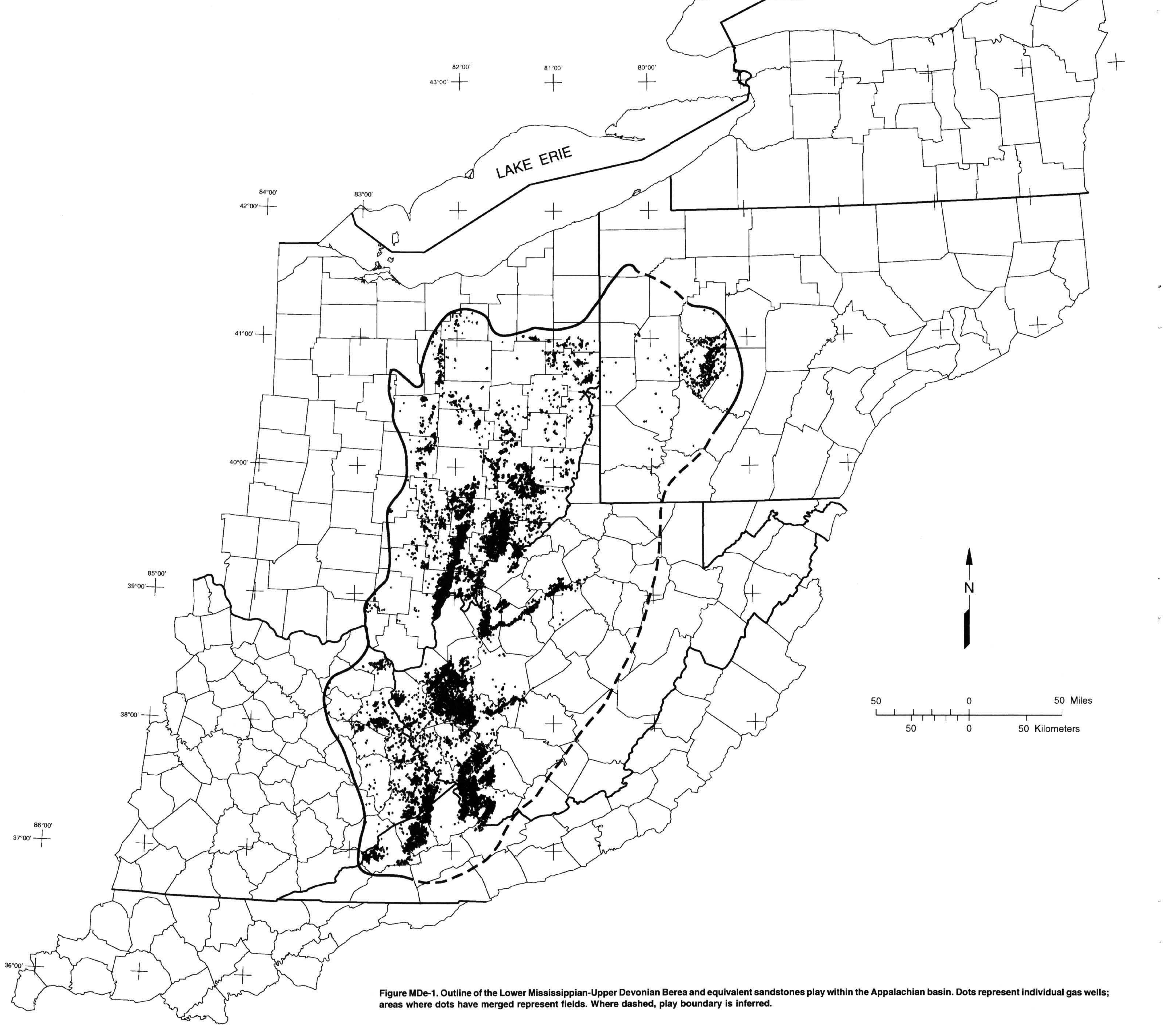


Figure MDe-1. Outline of the Lower Mississippian-Upper Devonian Berea and equivalent sandstones play within the Appalachian basin. Dots represent individual gas wells; areas where dots have merged represent fields. Where dashed, play boundary is inferred.

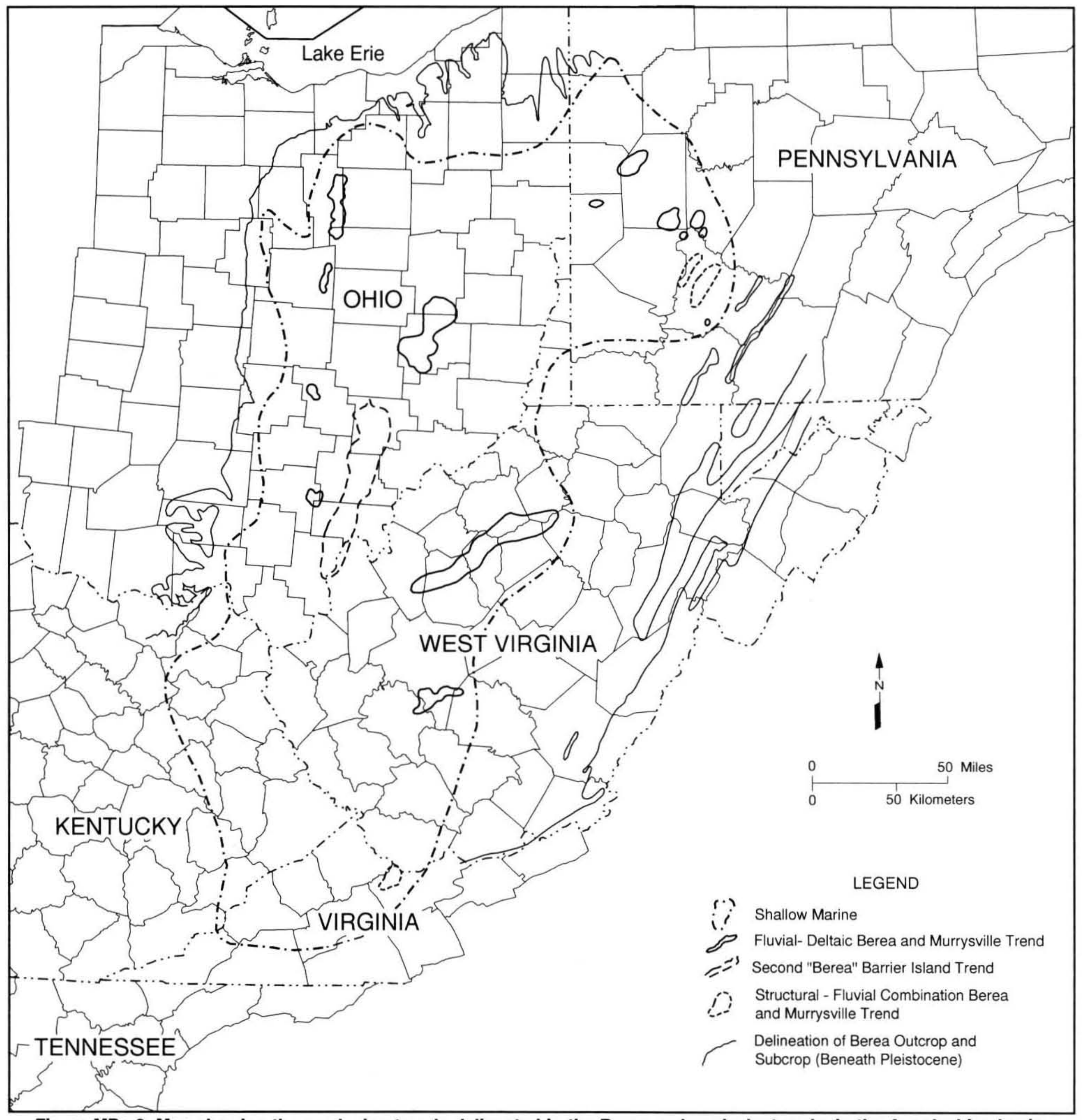


Figure MDe-2. Map showing the producing trends delineated in the Berea and equivalent rocks in the Appalachian basin.

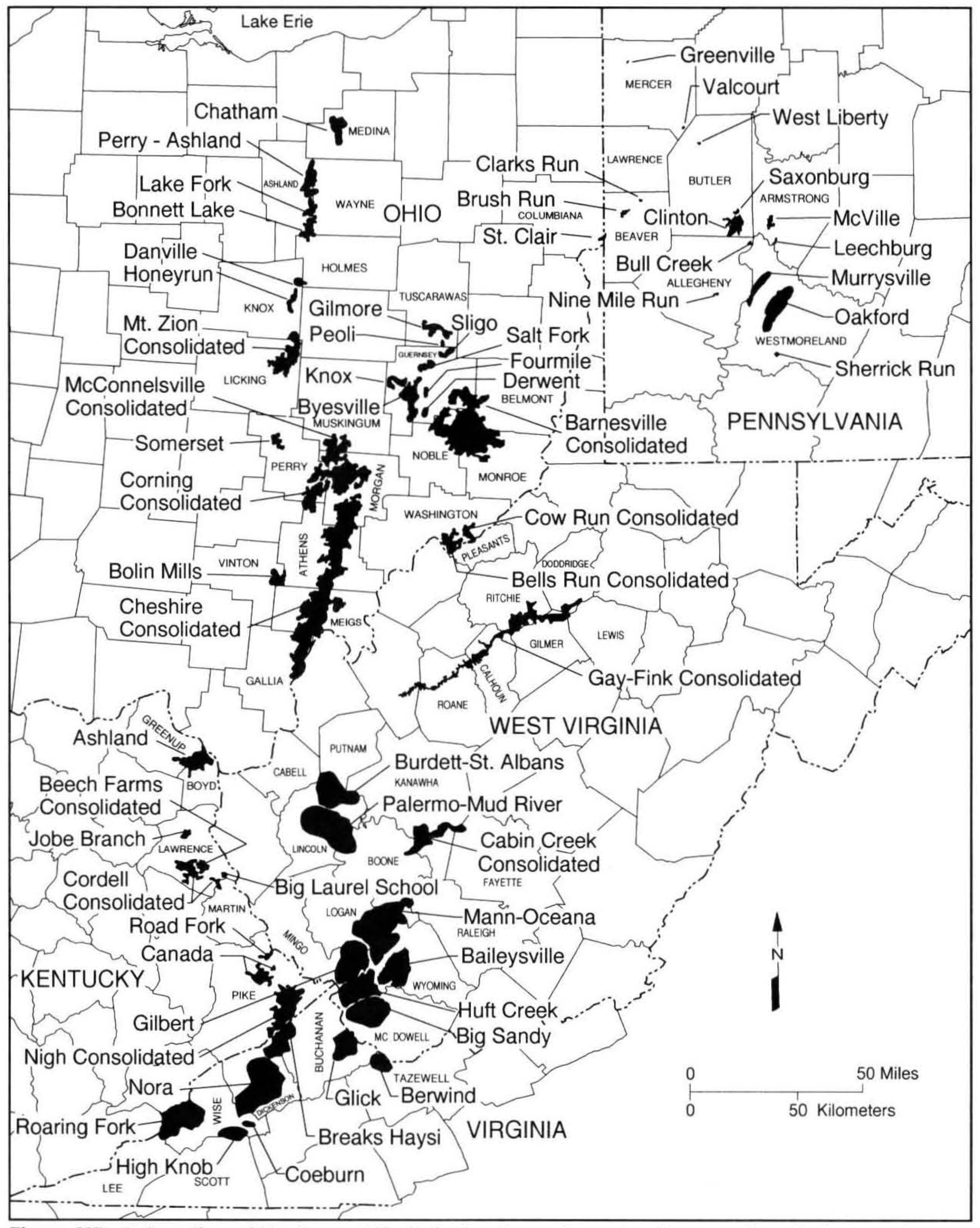


Figure MDe-3. Location of the Lower Mississippian-Upper Devonian Berea and equivalent sandstones productive gas pools and fields mentioned in text or listed in Table MDe-1. Other productive areas illustrated in Figure MDe-1 are not shown.

quartz sandstone that ranges in thickness from a few feet to more than 235 feet (Pepper and others, 1954). Figure MDe-6 represents the type gamma-ray geophysical logs used for the Berea Sandstone in this study. The first log (API No. 3400523569) represents an example of the fluvial-deltaic Berea facies found in north-central Ohio, whereas the second log (API No. 3416724157) is indicative of the shallow marine Berea facies that occurs in southeastern Ohio.

Butts and Leverett (1904) named the Murrysville sandstone for the prolific gas reservoir drilled near the town of Murrysville in Westmoreland County, Pennsylvania. Historically, this sandstone has been designated as Berea, First, Salt, Gas, or Butler Thirty-foot sand (Hughes, 1933). The Murrysville sandstone is an informal term having no formal counterparts (Harper and Laughrey, 1989). Pepper and others (1954) and Kammer and Bjerstedt (1986) preferred the name Cussewago Sandstone in place of Murrysville. Correlations by Harper and Laughrey (1987), however, indicate that the Cussewago Sandstone is equivalent only to the lower third to one-half of the thick Murrysville sandstone sequence of western Westmoreland County. East of the Monongahela and Allegheny rivers, the Murrysville is more or less a single, thick sandstone unit (Harper and Laughrey, 1989). West of these rivers, however, the Murrysville sandstone splits, in ascending order, into the Cussewago Sandstone, Bedford Shale, and Berea Sandstone, which become persistent throughout westernmost Pennsylvania, Ohio, and West Virginia (Harper and Laughrey, 1989). Harper and Laughrey (1989) identified the lower two-thirds of the thick Murrysville as the "Cussewago equivalent member" and the upper third interval the "Berea equivalent member."

The Murrysville is composed of poorly cemented, very fine-grained to coarse-grained, white, gray, or greenish-yellow sandstone that maintains an average thickness of approximately 60 feet near its type locality (Harper and Laughrey, 1987; 1989). In outcrop near Cramer, Indiana County, Pennsylvania, the Murrysville is 36 to 97 feet thick and is overlain by the Riddlesburg Shale (Harper and Laughrey, 1989). At this site, the Murrysville sandstone lies disconformably on the gray shales and thin limestones of the subjacent Venango Group (Harper and Laughrey, 1989).

The Cussewago Sandstone is part of the sequence of rocks named by White (1881) for exposures along the Cussewago Creek valley in western Crawford County, Pennsylvania. Because White's (1881) type locality of Cussewago rocks is somewhat indefinite, de Witt (1946) defined the Cussewago as the typical friable, greenish-yellow to greenish-brown quartz sandstone below the Bedford Shale.

The Second "Berea" sandstone was first encountered approximately 30 feet below the Berea in oil and gas wells drilled in the vicinity of McConnelsville in Morgan County, Ohio (Pepper and others, 1954). Originally, this sandstone was called a stray gas sand; later, drillers coined the term Second "Berea."

According to de Witt (1970), most of the Bedford Shale and all of the Berea Sandstone are of Early Mississippian age. However, paleontological evidence presented by Carter and Kammer (1990), Feldmann and others (1992), Roen (1993), and Harper (1993) suggests that the Berea Sandstone and equivalent rocks are Late Devonian in age. Because the issue of the age of units described above has not been resolved, here this play is considered to be Late Devonian to Early Mississippian in age.

Stratigraphic variations of the Berea Sandstone and equivalent rocks are well defined throughout most of the Appalachian basin. The unit was deposited in diverse depositional environments (Potter and others, 1983). Some of the major depositional features likely to be recognized in the Berea include meandering, anastomosing, and braided alluvial deposits; fluvial deposits; lower delta plain deposits; deltas; and coastal and shelf deposits (Potter and others, 1983).

The three major stratigraphic environmental trends identified in the Berea and equivalent rocks in the Appalachian basin are fluvial-deltaic facies, shallow marine facies, and the Second "Berea" barrier island facies.

Fluvial deposits in the Berea and equivalent rocks were identified in Ohio, West Virginia, and Pennsylvania. Figure MDe-7 illustrates gamma-ray log characteristics and thickness variations of the fluvial-deltaic rocks. One of the major fluvial-deltaic features in Ohio was the Ontario River, which deposited sediments that formed what was named the Red Bedford Delta by Pepper and others (1954). The presence of this river system is indicated by the apparent sand-filled channels cut into the Bedford Shale (Figure MDe-8). The sinuous channels are, for the most part, continuous for more than 40 miles in Ashland, Holmes, and Knox counties, Ohio (Pepper and others, 1954). Additional channel deposits occur in Medina, Tuscarawas, Guernsey, Athens, and Vinton counties, Ohio. Pepper and others (1954) interpreted the Gay-Fink and Cabin Creek producing trends in West Virginia as fluvial channel deposits. Larese (1974), in a more detailed study of the trends, also concluded that the Gay-Fink and Cabin Creek trends represented channel-fill deposits. Harper and Laughrey (1989) completed an extensive investigation of the Murrysville sandstone in southwestern Pennsylvania and postulated that a braided river flowed across a coastal plain or lower delta plain during Early Mississippian time and was responsible for deposition of the Murrysville sandstone. This interpretation is consistent with the conclusions of Pepper and others (1954) that the Murrysville originated as a distinctive prograding delta complex during Early Mississippian time.

Shallow marine facies of the Berea Sandstone and equivalent rocks in the Appalachian basin were deposited as extensive sheet sands that represent a wide range of nearshore and coastal environments (Pepper and others, 1954; Larese, 1974; Cox, 1992). Marine shelf sandstones form a major part of the Berea Sandstone in the Appalachian basin (Rothman, 1978; Potter and others, 1983; Pashin and Ettensohn, 1987). The shelf represents one of the most complex shallow depositional environments because of the interaction of ocean currents, storm-generated currents, and tidal currents (Walker and Cant, 1984). Shoreline sand bodies exhibit upward coarsening in grain size; the scale of sedimentary structures also increases in the upward direction (Larese, 1974). Since the marine facies represents a different type of reservoir when compared to the fluvial-deltaic deposits, it is separated into another trend.

The Second "Berea" sandstone represents a barrier island system extending 95 miles from Gallia County northward to Muskingum County, Ohio, (Figure MDe-9) (Pepper and others, 1954; Busch, 1974; Mele, 1981; Potter and others, 1983). The Second "Berea" is a localized trend within the marine facies. The sand body is 3 to 15 miles wide, is composed of reworked delta deposits, has a convex upper surface, and thins more abruptly eastward from the crest. On the seaward side, the barrier's eastern margins are relatively straight, whereas its western margins are irregular owing to the erratic deposition in the lagoon on the landward side of a barrier island system (Pepper and others, 1954; Busch, 1974). A bay is present in the Second "Berea" in the Morgan County area (Figure MDe-9). In this bay, the sand is exceptionally silty and very low in permeability (Busch, 1974). This bay serves as a barrier between the McConnelsville Consolidated field and the larger Cheshire Consolidated field to the south (Figure MDe-3). A tidal inlet is also conspicuous in the central part of the barrier island complex (Busch, 1974). Tidal inlets are a series of passes that connect the lagoonal area to the open ocean and are characterized by deep channels and lateral channel margin bars (Klein, 1982). On either side of the inlet, sand has been deposited farther back into the lagoon. A tidal delta seems to be the likely environment of this sand deposition (Busch, 1974).

Barrier island and strand plains are prominent depositional features of many modern coasts and are supplied and molded almost entirely by marine processes (McCubbin, 1982). The environments of sand deposition include: beach and shoreface environments on the seaward side of barriers and strand plains; inlet channels and tidal deltas, separating barriers laterally; and washover fans on the landward or lagoonward side of barriers (McCubbin, 1982). Figure MDe-10 illustrates some of the features typically associated with barrier island environments.

Structure

Figure MDe-11 illustrates the major structural features affecting Upper Devonian to Lower Mississippian Berea and equivalent rocks in the Appalachian basin. Structural features of major importance include the Cambridge arch; Pine Mountain fault; Dry Fork, Murrysville, Grapeville, Burning Springs, and Flat Fork anticlines; Evans monoclinal flexure; and the Akron-Suffield fault zone (Jefferies, 1952; Lytle, 1963; Perkey, 1981; Filer, 1985; Coogan and Wells, 1992; Nolde and Milici, 1993).

Hydrocarbon accumulation in the Berea and equivalent rocks appears to be primarily stratigraphic. Some fields, however, are combination traps because they have been affected by localized structural features (Larese, 1974; Coogan and Wells, 1992; Cox, 1992, Nolde and Milici, 1993). The Murrysville field, which is located on the Murrysville anticline and the Oakford field, situated on the Grapeville anticline, are the best examples of these combination traps. Figure MDe-12 shows the relationship structural influences have with the Berea Sandstone in southwestern Virginia. These structural influences appear to have little control over gas production except, perhaps, to enhance the fracture porosity within the fields (Nolde and Milici, 1993). In addition, no relation exists between the volume of gas produced from the Berea and the position of wells with respect to anticlinal and synclinal structures (Harris and Roen, 1984). Indeed, the data support the concept that the Berea is a fractured-blanket reservoir that will yield commercial production anywhere it is penetrated and properly treated (Harris and Roen, 1984).

Reservoir

The Berea Sandstone and equivalent rocks are separated into four main producing trends in this play (Figure MDe-2). Although these different trends vary in reservoir characteristics, they also have many characteristics in common.

The primary trapping mechanism in this play is stratigraphic (Larese, 1974; Warrner, 1978; Mele, 1981; Cox, 1992). Permeability barriers resulting from facies changes seem to be the most important trapping method in this play (Larese, 1974; Mele, 1981; Cardwell and Avary, 1982). This is particularly true in the case of the fluvial-deltaic and Second "Berea" barrier island deposits, which pass from productive sands into non-productive deltaic and marine shales. Generally, structure and diagenesis play only minor or local roles in the entrapment of hydrocarbons in the Berea. However, combination trends have been identified in the Berea and equivalent rock units, and production seems to be influenced by both structural and depositional features.

Hydrocarbon accumulations in the Berea Sandstone and equivalent units may have been derived from the organic-matter-rich Ohio Shale or Sunbury Shale. Cole and others (1987), on the basis of stratigraphic relationship and geochemical characteristics, concluded that the Sunbury Shale was the source of hydrocarbons in the Berea. Harris and Roen (1984) and Nolde and Milici (1993) believed gas produced in Virginia from the Berea was generated in the underlying Devonian shales and that gas from the Berea may in places be draining the underlying shales through fractures.

From analysis of conodont color alteration data, Epstein and others (1977) noted that levels of thermal maturation in the Appalachian basin were controlled mainly by depth of burial. Oil and associated gas occur in fields and pools in areas of relatively low-level thermal maturation in the western part of the basin, whereas only nonassociated dry gas occurs in the more mature rocks of the Valley and Ridge of Pennsylvania and adjacent states (deWitt, 1993).

Depths to gas-producing zones in pools and fields of the Berea Sandstone and equivalent rocks range from 178 feet in Medina County, Ohio, to 6,620 feet in Wise County, Virginia. Pay thicknesses range from 1 to 108 feet and average 19 feet. Reservoir pressure ranges from 92 to 1,100 psi with an average of 466 psi. Initial open flows range from a show of gas to 40,000 Mcf. Final open flows range from 5 to 5,276 Mcf/d. Variations in pay thickness, reservoir pressure, and open flows occur within the four different trends (Table MDe-3).

Estimated cumulative production per well for the entire play is 119 MMcf. Decline curves were constructed for yearly cumulative production from 39 fluvial-deltaic Berea wells in Ohio (Figure MDe-13) and from 111 Second "Berea" wells in southeastern Ohio (Figure MDe-14). Additionally, a pressure decline curve was constructed from the 111 Second "Berea" wells (Figure MDe-15). These data, along with average cumulative production per well, were used to extrapolate total cumulative production figures.

Well spacing tends to vary from state to state. The average acreage per well is 118 acres. Well longevity also varies across the basin, with some wells capable of producing for 55 to 60 years. For this study, average well longevity is estimated at 40 years.

Heterogeneity in the reservoir of this play results from a combination of depositional, structural, and diagenetic features. Depositional processes resulting in facies changes are the dominant factors affecting reservoir heterogeneity. Locally, subtle structures such as small paleotopographic highs and noses can play important roles in hydrocarbon segregation and production (Warrner, 1978; Coogan and Wells, 1992; Cox, 1992). Diagenetic influences such as cementation, compaction, and feldspar dissolution have caused the porosity and permeability variations in the unit (Larese, 1974). Porosities determined from cores and logs in the reservoir range from 2 to 26 percent and average about 12 percent. Most of the primary porosity is intergranular. Secondary porosity has developed with the dissolution of potash feldspar and replacement of framework minerals (Larese, 1974). Patchy dolomite, quartz, and minor amounts of siderite are the most common cements. Kaolinite, illite, and chlorite are the most abundant clays (Larese, 1974; Jackson, 1985). Permeability determined from core samples of the reservoir sandstones ranges from 0.01 to 480 md and averages about 3.84 md.

The dominant drive mechanism in the fields of this play is solution gas, whereas water has a local role as a partial drive mechanism. Historically, completion practices have included natural production, shooting the well with nitroglycerin, acidizing, or hydraulic fracturing. Historically, early Berea wells were either completed naturally or shot with varying amounts of nitroglycerin. Since the mid-1950s, however, most Berea wells have been completed by perforation and hydraulic fracture. In several areas of the basin, such as central and north-central Ohio, where the Berea reservoir is usually less than 1,000 feet deep, many of the wells still are stimulated by nitroglycerin or some other type of explosive.

Description of Key Fields

Key fields were selected for this play based on geographic distribution and stratigraphic and production trends. Five fields were chosen to represent the variations in reservoir characteristics of the Berea Sandstone and equivalent rocks in the Appalachian basin. Two fields were chosen to represent the shallow marine trend. One field was selected as an example of the fluvial-deltaic trend. One field was chosen as a representative of the Second "Berea" barrier island trend, and the remaining field was selected as an example of the structural-fluvial-deltaic trend.

TABLE MDe-1

Section	TABLE MDe-1	Cheshire Consolidated OH	Barnesville Consolidated OH	McConnelsville Consolidated OH	Derwent OH	Byesville OH	Gilmore OH	Chatham OH	Perry-Ashland OH	Murrysville PA
BASIC RESERVOIR DATA	POOL NUMBER	3401074339	3401065339	341075339	3400109339	3400131339	3400164339	3400396339	3400938339	3700913342
	DISCOVERED	1904	1897	1896	1918	1885	1889	1899	1913	1878
	DEPTH TO TOP RESERVOIR	1,081	836	1,073	1,148	1,021	980	178	505	910
	AGE OF RESERVOIR	Devonian/ Mississippian	Devonian/ Mississippian	Devonian/ Mississippian	Devonian/ Mississippian	Devonian/ Mississippian	Devonian/ Mississippian	Devonian/ Mississippian	Devonian/ Mississippian	Devonian/ Mississippian
	FORMATION	Berea	Berea	Berea	Berea	Berea	Berea	Berea	Berea	Murrysville
	PRODUCING RESERVOIR	Berea Second Berea	Berea	Berea Second Berea	Berea	Berea	Berea	Berea	Berea	Murrysville
	LITHOLOGY	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone
	TRAP TYPE	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	structural stratigraphic
	DEPOSITIONAL ENVIRONMENT	shallow marine	shallow marine	shallow marine	fluvial/ deltaic	fluvial/ deltaic	fluvial/ deltaic	fluvial/ deltaic	fluvial/ deltaic	fluvial/ deltaic
	DISCOVERY WELL IP (Mcf)									
	DRIVE MECHANISM	solution gas	solution gas	solution gas	combination	combination	combination	combination	combination	combination
	NO. PRODUCING WELLS	2,075	568	242	0	22	51	47	127	0
	NO. ABANDONED WELLS	622	164	49	27	119	35	17	0	200
	AREA (acreage)	26,970	9,080	2,910	270	1,390	670	12,000	153	28,405
	OLDEST FORMATION PENETRATED	Medina	Oriskany	Beekmantown	Clinton	Clinton	Clinton	Trempealeau	Kerbel	Kane
	EXPECTED HETEROGENEITY DUE TO:	deposition diagenesis	deposition diagenesis	deposition diagenesis	deposition diagenesis	deposition diagenesis	deposition diagenesis	deposition diagenesis	deposition diagenesis	deposition structure
RESERVOIR PARAMETERS	AVERAGE PAY THICKNESS (ft.)	12	10	16	6	12	7	51	18	18
	AVERAGE COMPLETION THICKNESS (ft.)							51		
	AVERAGE POROSITY--LOG (%)	12	10	11		13	11	16	14	
	MINIMUM POROSITY--LOG (%)	2.2	3.5	5		11	4	3	2	
	MAXIMUM POROSITY--LOG (%)	23	18	19		15	20	28	26	
	NO. DATA POINTS	469	32	11	0	1	4	6	25	0
	POROSITY FEET	1.44	1	1.76	1.02	1.56	0.77	5.1	2.88	
	RESERVOIR TEMPERATURE (°F)							65		
	INITIAL RESERVOIR PRESSURE (psi)	700	780	480	575	575	500	150	210	650
	PRODUCING INTERVAL DEPTHS (ft.)	1,081-1,910	836-2,126	1,073-1,710	1,148-1,370	1,021-1,326	980-1,347	178-670	505-900	910-2,286
	PRESENT RESERVOIR PRESSURE (psi) / DATE	285/1976	256/1972	148/1972	32/1934	72/1954	100/1963	60/1936	90/1948	
FLUID & GAS PROPERTIES	Rw (Ωm)	0.05	0.05	0.05	0.05	0.06	0.038	0.08	0.09	
	GAS GRAVITY (g/cc)	0.699		0.677						0.558
	GAS SATURATION (%)	27.4	41	24.3		64	30	23.4	58	
	WATER SATURATION (%)	49.7	44	21.2	42	32	45	37	39	
	COMMINGLED	no	yes	no	no	no	no	no	no	yes
	ASSOCIATED OR NONASSOCIATED	associated	associated	associated	nonassociated	associated	associated	associated	associated	nonassociated
	Btu/scf	1,156		1,130		1,121				
VOLUMETRIC DATA	STATUS (producing, abandoned, storage)	producing	producing	producing	abandoned	producing	producing	producing	producing	abandoned
	ORIGINAL GAS IN PLACE (Mcf)	296,000,000	98,094,000	60,177,000	1,107,000	12,241,000	4,428,000		8,713,000	
	ORIGINAL GAS RESERVES (Mcf)	192,000,000	63,761,000	39,115,000	720,000	8,000,000	2,878,000		5,663,000	
	PRODUCTION YEARS	1925-1992	1901-1972	1925-1992	1928-1934	1926-1954			1885-1888	
	REPORTED CUMULATIVE PRODUCTION (Mcf)	47,178,000	9,059,000	5,917,000	133,000	450,000	344,000		74,000	
	NO. WELLS REPORTED		104							
	ESTIMATED CUMULATIVE PRODUCTION (Mcf)	144,000,000	44,633,000	29,336,000	720,000	7,736,000	2,302,000		4,530,000	438,000,000
	REMAINING GAS IN PLACE (Mcf)/DATE	104,000,000/ 1994	34,333,000/ 1994	21,062,000/ 1994	387,000/ 1994	4,241,000/ 1994	1,550,000/ 1994		3,050,000/ 1994	
	REMAINING GAS RESERVES (Mcf)/DATE	48,000,000/ 1994	19,128,000/ 1994	9,779,000/ 1994	0/ 1994	264,000/ 1994	576,000/ 1994		1,133,000/ 1994	0/ 1994
	RECOVERY FACTOR (%)	65	65	65	65	65	65		65	65
	INITIAL OPEN FLOW (Mcf/d)	114	619	109	769	293	457	5-898	40	1,000-25,000
	FINAL OPEN FLOW (Mcf/d)	122		129		76	499		49	

Section	TABLE MDe-1	Oakford PA	Ashland KY	Beech Farms Consolidated KY	Canada DBS KY	Cordell Consolidated KY	Nigh Consolidated KY	Big Sandy WV	Huff Creek WV	Burdett-St. Albans WV	Cabin Creek Consolidated WV	Gay-Fink Consolidated WV	Berwind VA
BASIC RESERVOIR DATA	POOL NUMBER	3700927342	1600060339	1600142339	16000347339	1600478239	160141239	4700285339	4700303339	4700211339	4700240339	4700163339	4500000339
	DISCOVERED	1885	1912	1915	1942	1917	1945	1950	1960	1906	1919	1909	1963
	DEPTH TO TOP RESERVOIR	1,199	883	1,203	2,589	935	3,206	4,295	3,843	2,211	2,394	2,186	4,820
	AGE OF RESERVOIR	Devonian/ Mississippian	Devonian/ Mississippian	Devonian/ Mississippian	Devonian/ Mississippian	Devonian/ Mississippian	Devonian/ Mississippian	Devonian/ Mississippian	Devonian/ Mississippian	Devonian/ Mississippian	Devonian Mississippian	Devonian Mississippian	Devonian Mississippian
	FORMATION	Murrysville	Berea	Berea	Berea	Berea	Berea	Berea	Berea	Berea	Berea	Berea	Berea
	PRODUCING RESERVOIR	Murrysville	Berea	Berea	Berea	Berea	Berea	Berea	Berea	Berea	Berea	Berea	Berea
	LITHOLOGY	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone
	TRAP TYPE	structural stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic
	DEPOSITIONAL ENVIRONMENT	fluvial/ deltaic	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	fluvial/ deltaic	fluvial/ deltaic	fluvial/ deltaic
	DISCOVERY WELL IP (Mcf)			421	84	15	313	60	5,276	143			
	DRIVE MECHANISM	combination	solution gas	solution gas	solution gas	solution gas	solution gas	solution gas	solution gas	solution gas	solution gas	solution gas	solution gas
	NO. PRODUCING WELLS	600	64	59	114	125	171	241	174	218	65	64	25
	NO. ABANDONED WELLS	48	2	0	3	4	6	13	3	62	61	49	1
	AREA (acreage)	24,962	13,200	5,425	16,274	17,871	33,630	45,145	37,623	50,063	6,486	13,017	4,160
	OLDEST FORMATION PENETRATED	Kane	Clinton	Ohio	Corniferous	Clinton	Ohio	Gordon	Onondaga	Onondaga	Helderberg	Precambrian	Chattanooga
	EXPECTED HETEROGENEITY DUE TO:	deposition structure	deposition diagenesis	deposition diagenesis	deposition diagenesis	deposition diagenesis	deposition diagenesis	deposition diagenesis	deposition diagenesis	deposition diagenesis	deposition structure	deposition structure	deposition structure
RESERVOIR PARAMETERS	AVERAGE PAY THICKNESS (ft.)	51	15	13	15	17	20	18	18	21	20	8	9
	AVERAGE COMPLETION THICKNESS (ft.)		52	42	58	54	47						9
	AVERAGE POROSITY--LOG (%)	17	9	11	8	11	8		10				
	MINIMUM POROSITY--LOG (%)	2	5	4	7	3							
	MAXIMUM POROSITY--LOG (%)	26	12	14	14	14	12						
	NO. DATA POINTS	4	14	7	21	18	30	0	7	0			0
	POROSITY FEET	8.67	1.35	1.43	1.2	1.87	1.6	1.08	1.8	1.96			
	RESERVOIR TEMPERATURE (°F)	73	72	74	81	75	90						
	INITIAL RESERVOIR PRESSURE (psi)	550	245	400	605	500	350	753	617	352		543	355-925
	PRODUCING INTERVAL DEPTHS (ft.)	1,199-2,130	883-1,432	1,203-1,557	2,589-3,787	935-2,040	3,206-4,626	3,512-5,019	3,412-5,169	1,985-2,505	2,394-3,386	2,186-2,680	4,820-5,996
	PRESENT RESERVOIR PRESSURE (psi) / DATE	74/1952	600/1988	390/1962	430/1992	258/1992	600/1992						
FLUID & GAS PROPERTIES	Rw (Ωm)	0.05	0.07	0.06	0.07	0.06	0.1	0.05	0.05	0.05	0.05	0.05	0.05
	GAS GRAVITY (g/cc)		0.675	0.646	0.605	0.675							
	GAS SATURATION (%)		47	77	72	75	63		78				
	WATER SATURATION (%)		53	23	28	25	37						
	COMMINGLED	yes	yes	no	yes	yes	yes	yes	yes	yes	yes	yes	yes
	ASSOCIATED OR NONASSOCIATED	nonassociated	associated	nonassociated	nonassociated	associated	nonassociated				associated	nonassociated	nonassociated
	Btu/scf		1083	1070	1085	1083	1085						
VOLUMETRIC DATA	STATUS (producing, abandoned, storage)	storage	producing	producing	producing	producing	producing	producing	producing	producing	producing	producing	producing
	ORIGINAL GAS IN PLACE (Mcf)						100,210,000	98,825,000	87,677,000	110,440,000	4,267,000	153,833,000	72,361,000
	ORIGINAL GAS RESERVES (Mcf)						65,136,000	64,236,000	56,990,000	71,786,000	2,774,000	99,991,000	47,034,000
	PRODUCTION YEARS						1954-1992	1956-1993	1961-1992	1916-1992	1991-1992	1916-1992	1964-1994
	REPORTED CUMULATIVE PRODUCTION (Mcf)						8,095,518	30,145,634	18,628,850	8,565,941	35,224	28,316,251	11,288,277
	NO. WELLS REPORTED							147	80	180	2	40	6
	ESTIMATED CUMULATIVE PRODUCTION (Mcf)	88,000,000					52,109,000	51,389,000	45,592,000	57,429,000	2,219,000	79,993,000	37,627,590
	REMAINING GAS IN PLACE (Mcf)/DATE						35,074,000/ 1994	34,589,000/ 1994	30,687,000/ 1994	38,654,000/ 1994	1,493,000/ 1994	53,842,000/ 1994	25,327,000/ 1994
	REMAINING GAS RESERVES (Mcf)/DATE	0/ 1994					13,027,000/ 1994	12,847,000/ 1994	11,398,000/ 1994	14,357,000/ 1994	555,000/ 1994	19,998,000/ 1994	9,406,000/ 1994
	RECOVERY FACTOR (%)	65											
	INITIAL OPEN FLOW (Mcf/d)	10,000-40,000							447	87	45	3,503	show-3,846
	FINAL OPEN FLOW (Mcf/d)		71	145	319	234	807	2,082	1,093	215	59	2,659	200-12,840

Section	TABLE MDe-1	Glick VA	High Knob VA	Nora VA	Roaring Fork VA	Breaks-Haysi VA
BASIC RESERVOIR DATA	POOL NUMBER	4500000339	4500000339	450000339	450000339	450000339
	DISCOVERED	1950	1944	1948	1984	1955
	DEPTH TO TOP RESERVOIR	4,502	3,318	4,000	4,216	3,200
	AGE OF RESERVOIR	Devonian Mississippian	Devonian Mississippian	Devonian Mississippian	Devonian Mississippian	Devonian Mississippian
	FORMATION	Berea	Berea	Berea	Berea	Berea
	PRODUCING RESERVOIR	Berea	Berea	Berea	Berea	Berea
	LITHOLOGY	sandstone	siltstone	siltstone & sandstone	siltstone	sandstone
	TRAP TYPE	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic
	DEPOSITIONAL ENVIRONMENT	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine
	DISCOVERY WELL IP (Mcf)					
	DRIVE MECHANISM	solution gas	solution gas	solution gas	solution gas	solution gas
	NO. PRODUCING WELLS	56	29	332	126	76
	NO. ABANDONED WELLS	0	3	13	0	0
	AREA (acreage)	8,960	5,120	55,200	20,160	12,160
	OLDEST FORMATION PENETRATED	Chattanooga	Poteet	Onondaga	Hancock	Knox
	EXPECTED HETEROGENEITY DUE TO:	deposition structure	deposition structure	deposition structure	deposition structure	deposition structure
RESERVOIR PARAMETERS	AVERAGE PAY THICKNESS (ft.)	15	60	71	81	35
	AVERAGE COMPLETION THICKNESS (ft.)	15	60	71	81	35
	AVERAGE POROSITY--LOG (%)			5.68		
	MINIMUM POROSITY--LOG (%)					
	MAXIMUM POROSITY--LOG (%)					
	NO. DATA POINTS	0	0	12	0	
	POROSITY FEET			4.03		
	RESERVOIR TEMPERATURE (°F)					
	INITIAL RESERVOIR PRESSURE (psi)	320-1,100	440-730	500-850		495-510
	PRODUCING INTERVAL DEPTHS (ft.)	4,504-5,300	3,300-4,800	4,000-5,500	4,216-6,620	3,200-4,900
	PRESENT RESERVOIR PRESSURE (psi) / DATE					
FLUID & GAS PROPERTIES	Rw (Ωm)	0.05	0.05	0.05	0.05	0.05
	GAS GRAVITY (g/cc)			0.62		
	GAS SATURATION (%)			54.6		
	WATER SATURATION (%)			45.4		
	COMMINGLED	yes	yes	yes	yes	yes
	ASSOCIATED OR NONASSOCIATED	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated
	Btu/scf					
VOLUMETRIC DATA	STATUS (producing, abandoned, storage)	producing	producing	producing	producing	producing
	ORIGINAL GAS IN PLACE (Mcf)					63,958,000
	ORIGINAL GAS RESERVES (Mcf)					41,573,000
	PRODUCTION YEARS					1972-1994
	REPORTED CUMULATIVE PRODUCTION (Mcf)					31,725,891
	NO. WELLS REPORTED					58
	ESTIMATED CUMULATIVE PRODUCTION (Mcf)					33,258,000
	REMAINING GAS IN PLACE (Mcf)/DATE					22,385,000/ 1994
	REMAINING GAS RESERVES (Mcf)/DATE					8,315,000/ 1994
	RECOVERY FACTOR (%)					
	INITIAL OPEN FLOW (Mcf/d)	show-931	100-1,426			show-2,402
	FINAL OPEN FLOW (Mcf/d)	show-1,200	43-1,555	100-1,400	60	103-5,180

TABLE MDe-2	Cheshire Consolidated OH	Derwent OH	Chatham OH	Perry-Ashland OH	Beech Farms Consolidated KY	Cordell Consolidated KY	Big Sandy WV	Huff Creek WV	Burdett-St. Albans WV	Nora VA
AVERAGE POROSITY--CORE (%)	14.2	17	16	18	13.3	13.2	6.13	6.5	9.5	5
MINIMUM POROSITY--CORE (%)	2.1	6	3	4	11.2	11.6	5.27	5	5	
MAXIMUM POROSITY--CORE (%)	21.1	22	28	24	17.5	15.7	7.84	8	14	
NO. DATA POINTS	15	1	27	30	1	1	1	1	1	4
AVERAGE PERMEABILITY (md)	9.5	22	40.3	29	34	0.84	0.013	0.05	9	0.014

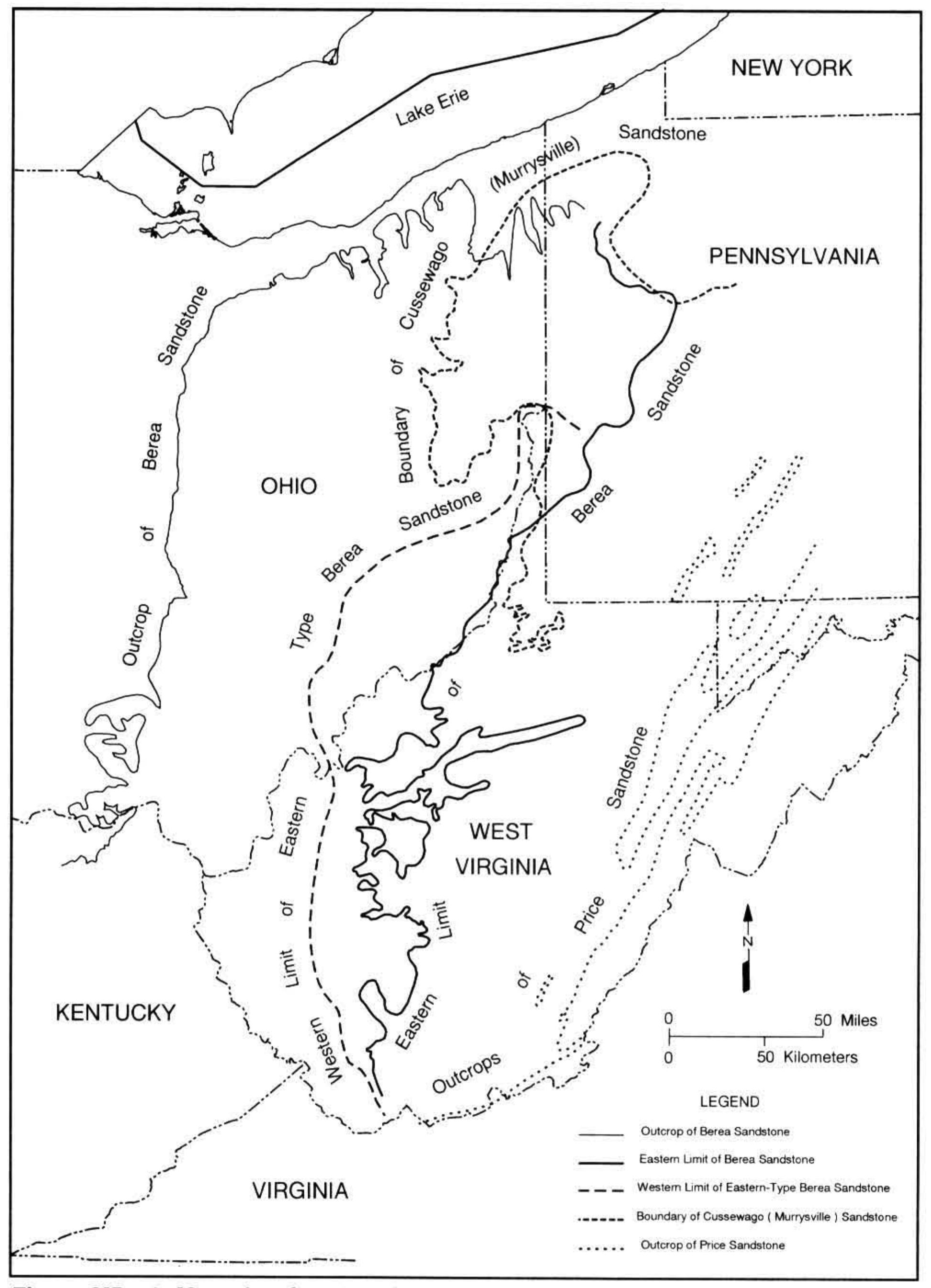


Figure MDe-4. Map showing the distribution of the different types of Berea and equivalent rocks in the Appalachian basin. Modified from Pepper and others (1954).

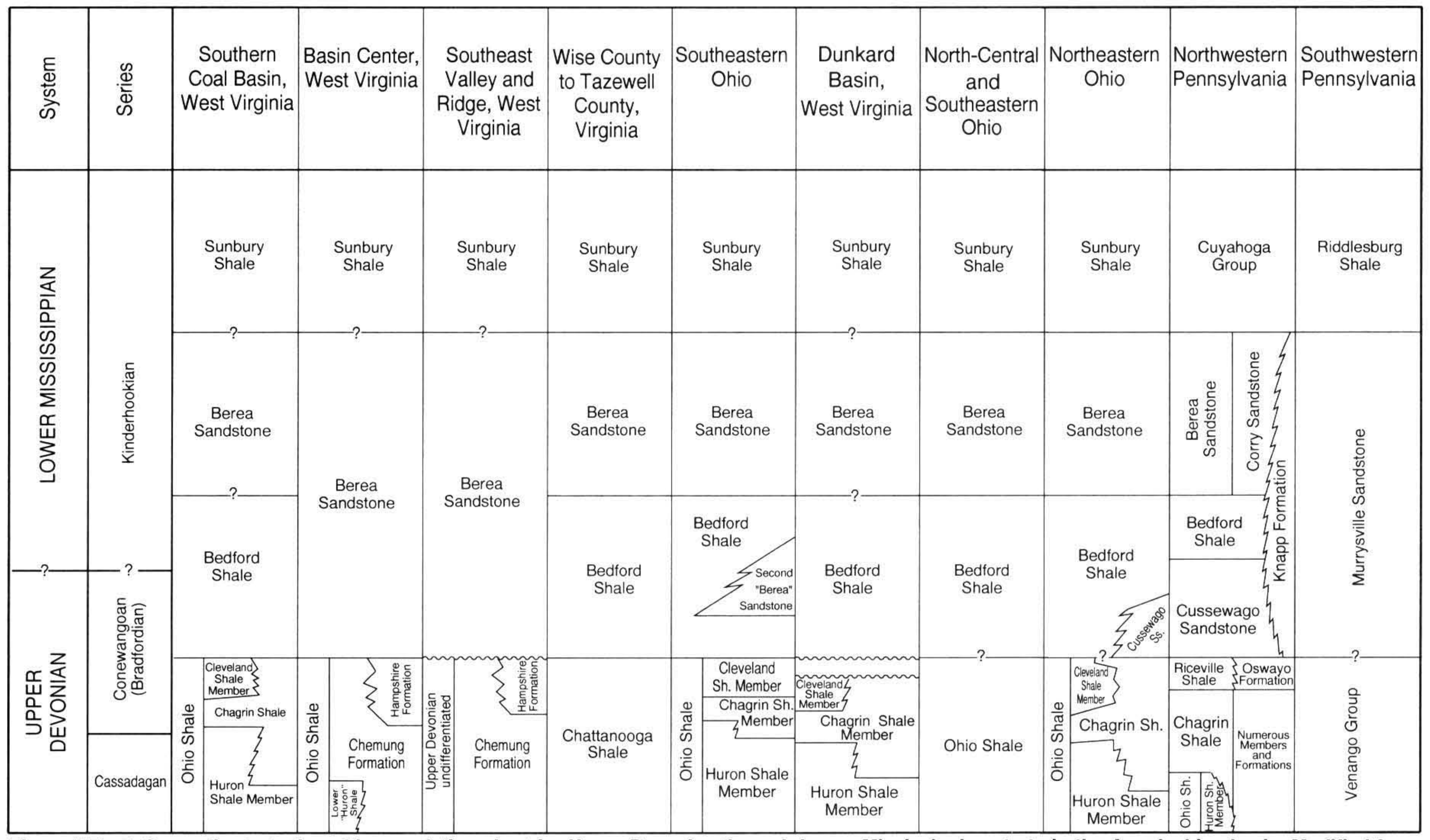


Figure MDe-5. Generalized stratigraphic correlation chart for Upper Devonian through Lower Mississippian strata in the Appalachian basin. Modified from Patchen and others (1985a) and Harper and Laughrey (1989).

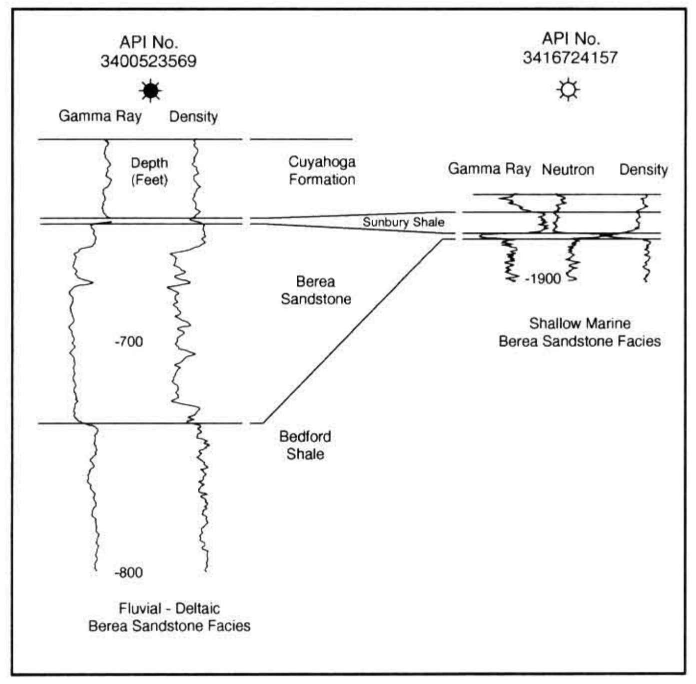


Figure MDe-6. Type geophysical logs for the Berea Sandstone in this study. The first log (API No. 3400523569) represents a typical channel fill deposit in the fluvial-deltaic Berea facies in north-central Ohio. The second log (API No. 3416724157) is indicative of the shallow marine Berea facies in southeastern Ohio.

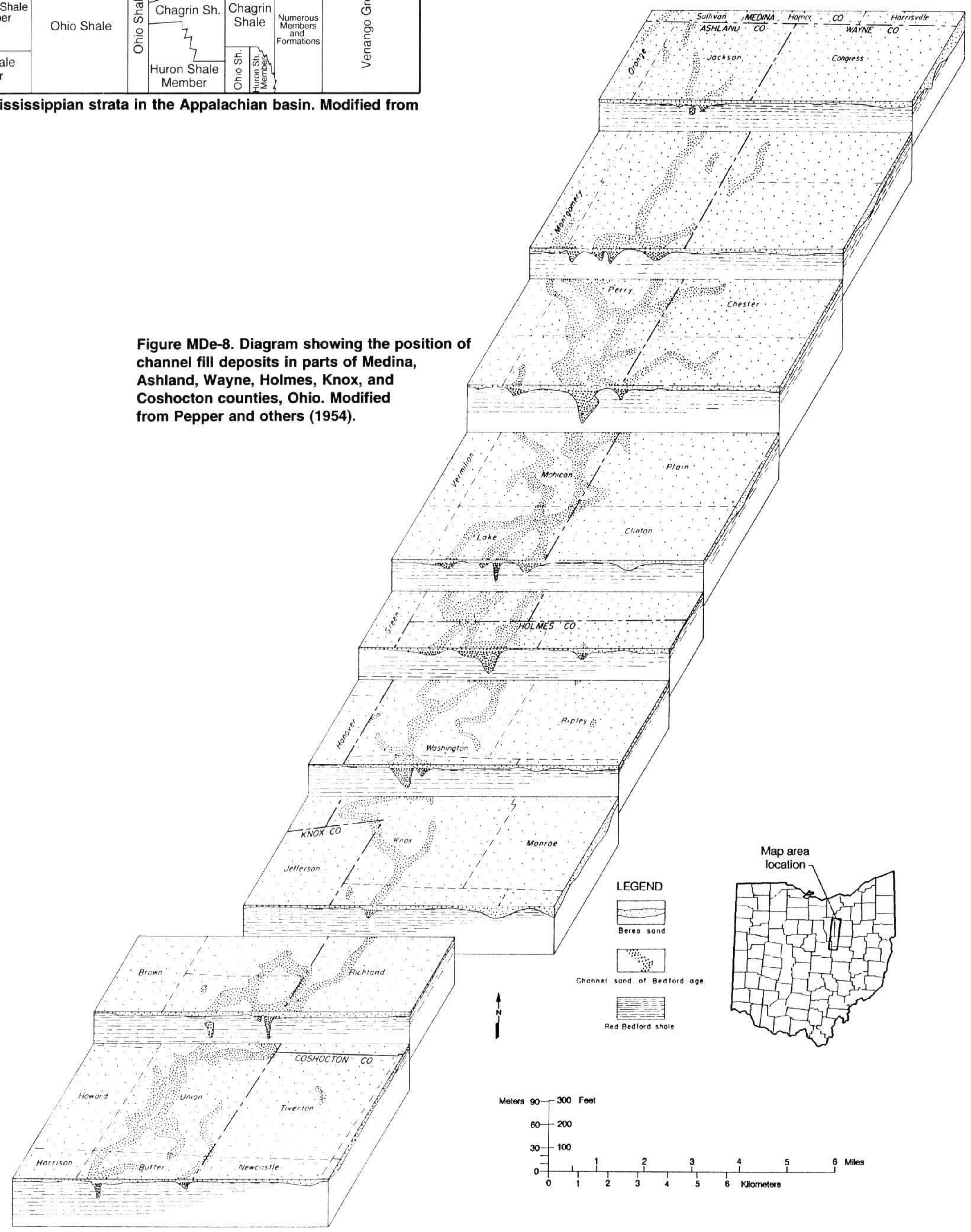


Figure MDe-8. Diagram showing the position of channel fill deposits in parts of Medina, Ashland, Wayne, Holmes, Knox, and Coshocton counties, Ohio. Modified from Pepper and others (1954).

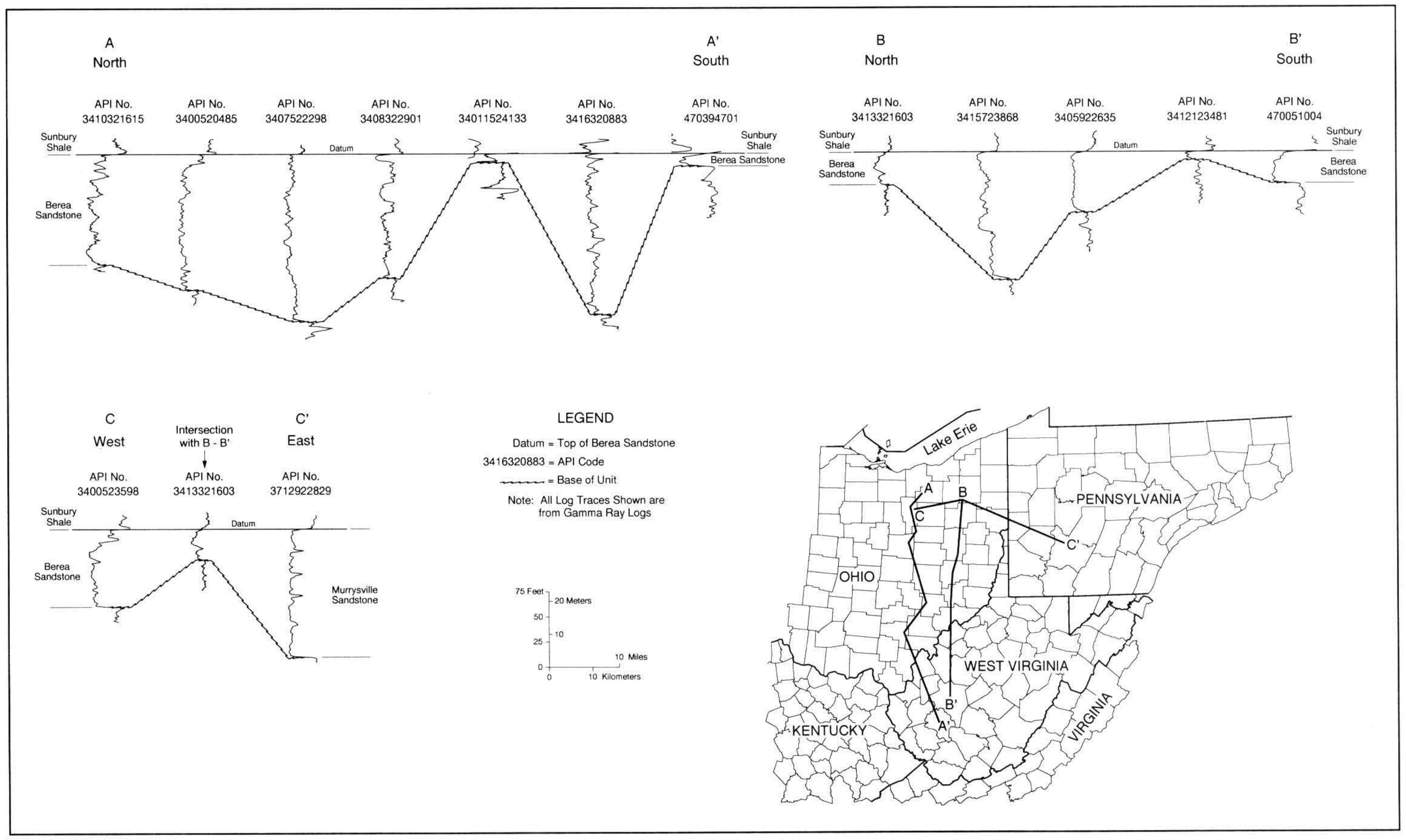


Figure MDe-7. Stratigraphic cross sections and gamma ray characteristics of the fluvial-deltaic Berea and equivalent rocks in the Appalachian basin.

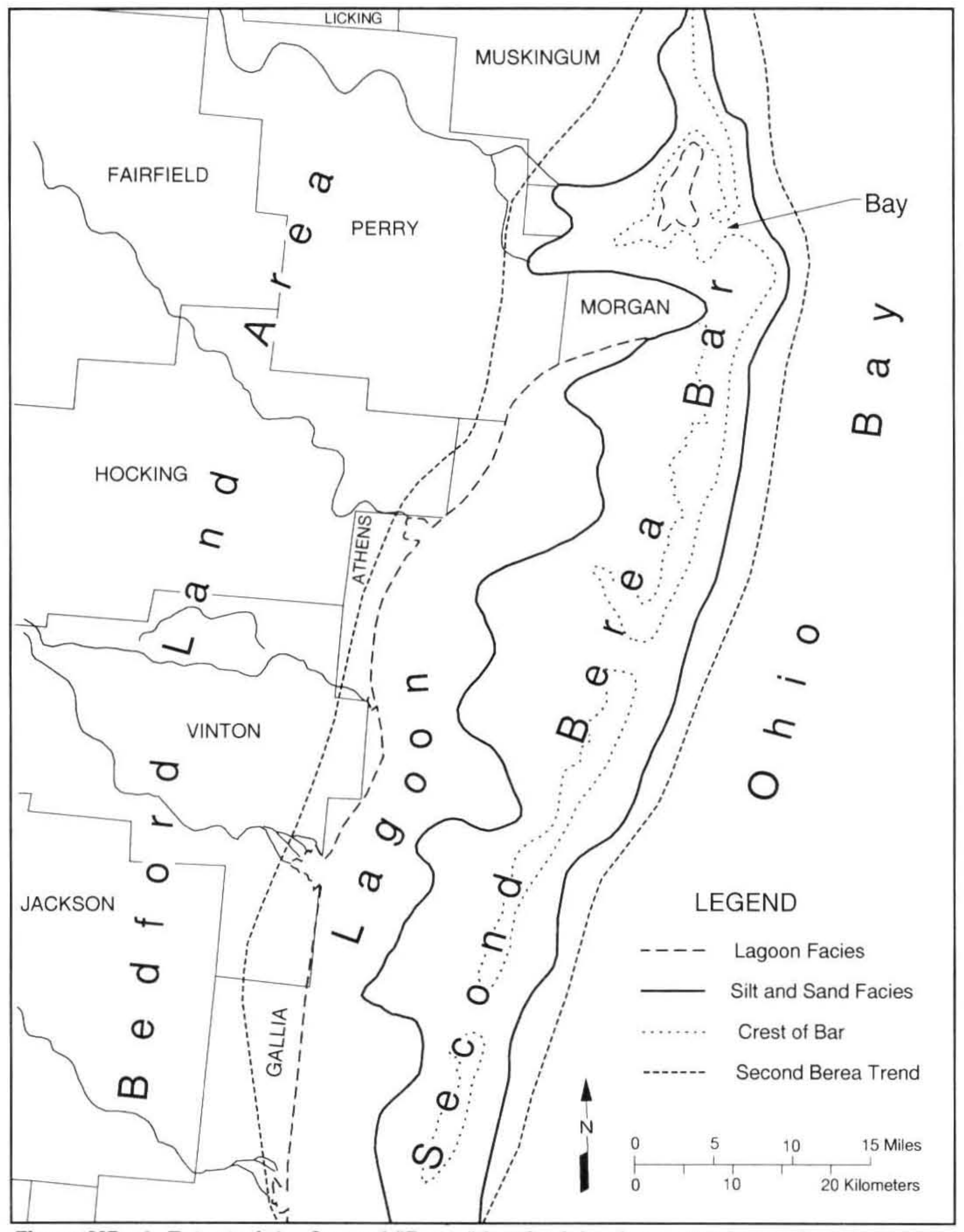


Figure MDe-9. Extent of the Second "Berea" barrier island complex in southeastern Ohio and the subenvironments associated with this trend. Modified from Pepper and others (1954).

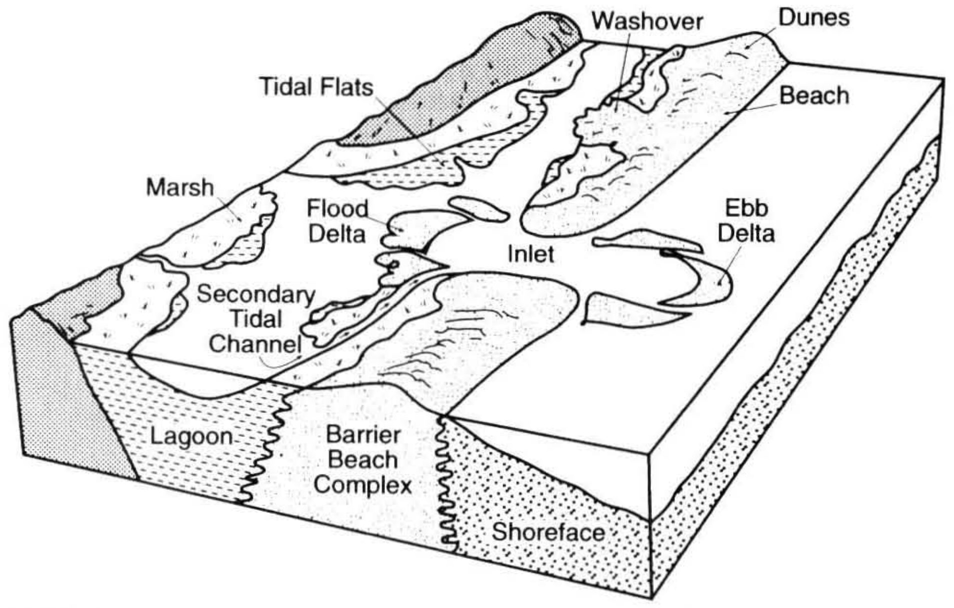


Figure MDe-10. Subdivision of a typical modern barrier island system and its environments. Modified from Reinson (1984).

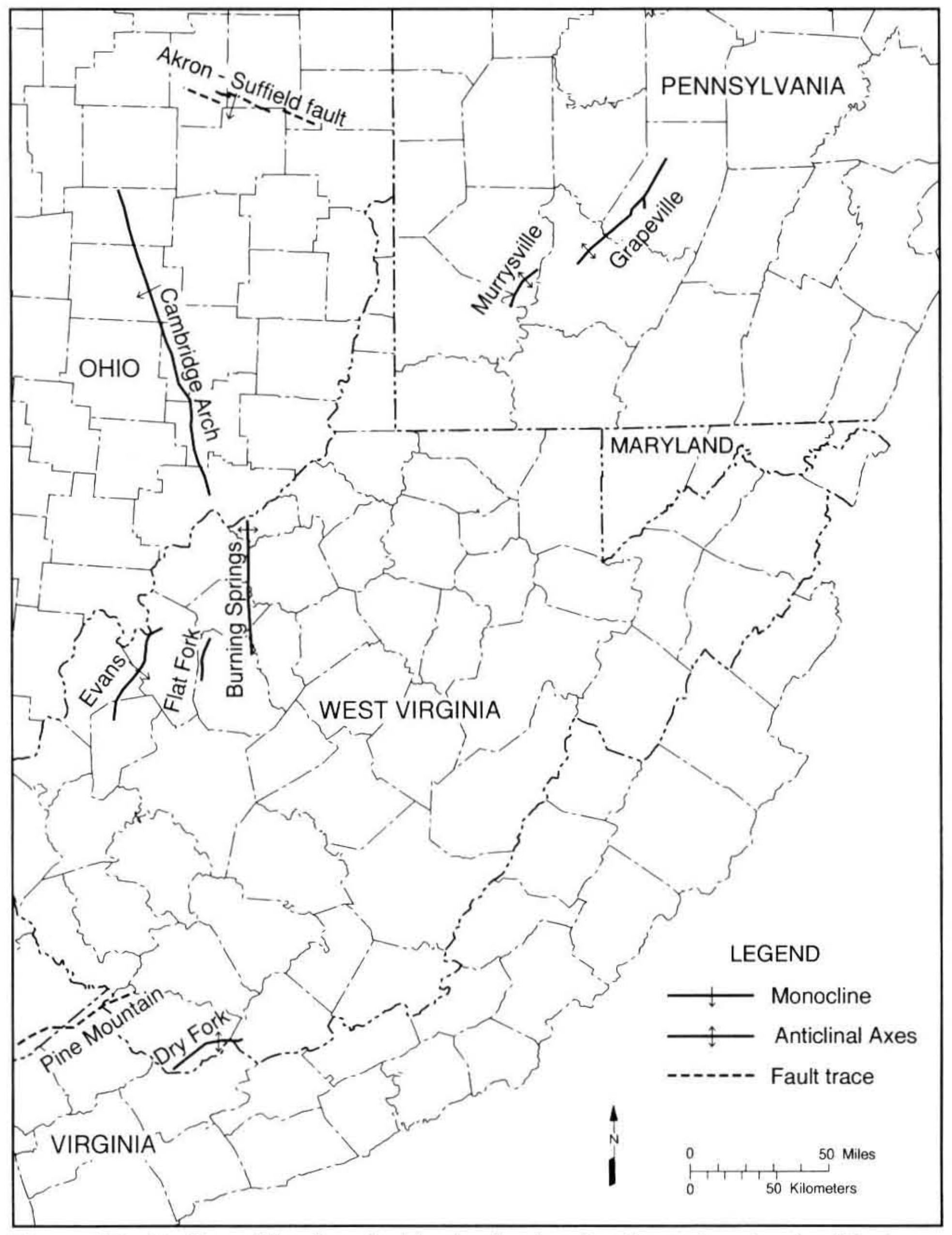


Figure MDe-11. Map of the Appalachian basin showing the major structural features associated with the Lower Mississippian-Upper Devonian Berea Sandstone and equivalent rocks.

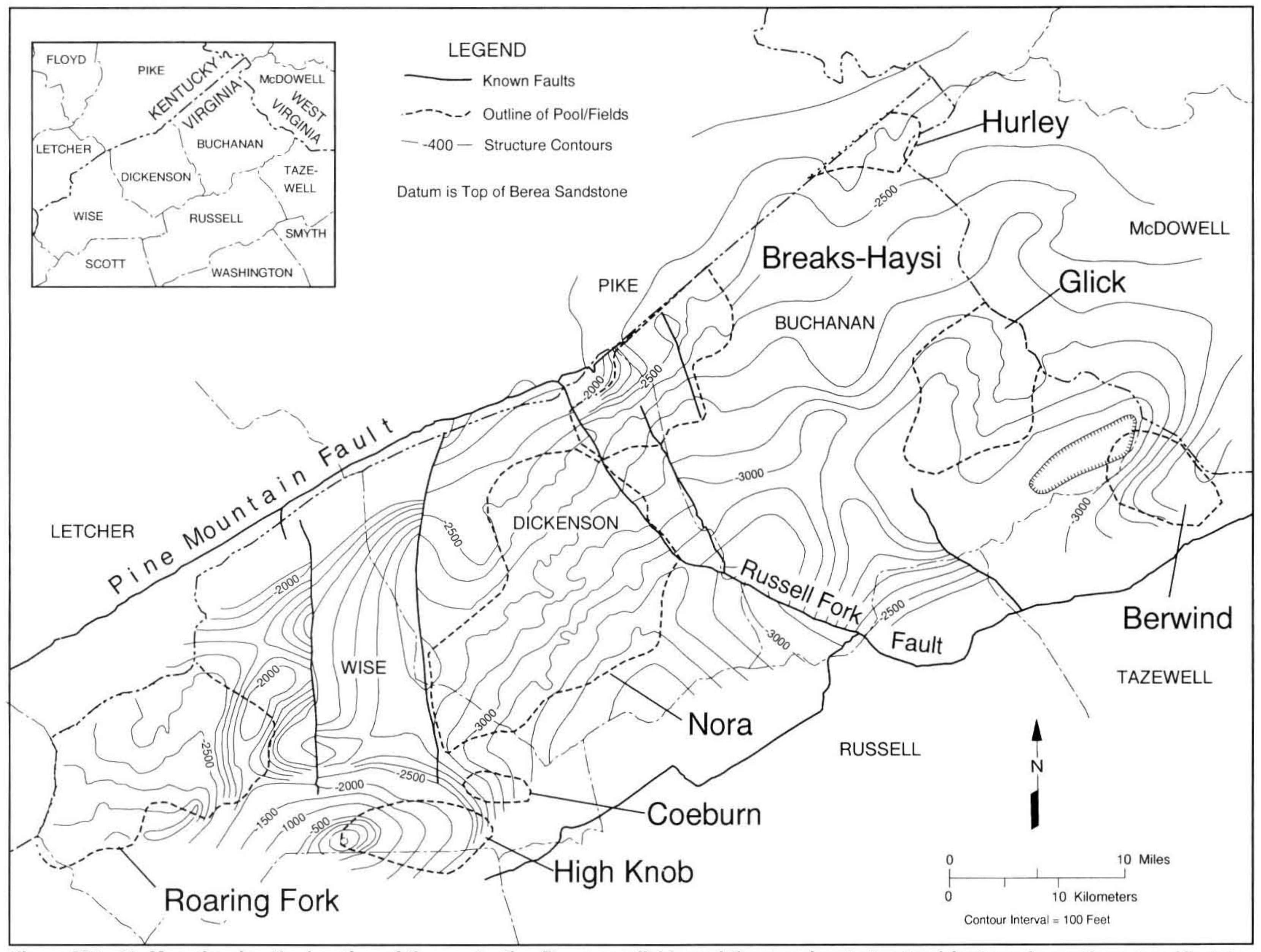


Figure MDe-12. Map showing the location of the productive Berea gas fields and the prominent structural features in southwestern Virginia. Modified from Nolde and Milici (written commun., 1994).

Table MDe-3. Reservoir characteristics of the different producing trends in the Berea and equivalent rocks in the Appalachian basin.

Trend Type	Pay Thickness (in feet)	Porosity (%)	Reservoir Pressure (psi)	Open Flow (Mcf)	Est. Cumulative Production Per Well (MMcf)
Second Berea	14	11.5	590	112	96
Shallow Marine	29	8.9	636	547	133*
Fluvial-deltaic	15	12.8	493	210	138
Combination	26	17	642	1,000-40,000	668*

*Some production commingled with other plays

Barnesville Consolidated field: Located in Guernsey, Noble, Belmont, and Monroe counties, Ohio, the Barnesville Consolidated field was discovered in 1897 (Figure MDe-3; Table MDe-1). This field was selected to represent the shallow marine trend in Ohio. Hydrocarbons have been produced from the Berea Sandstone at depths ranging from 836 to 2,126 feet. A total of 732 gas and combination wells have been drilled in this field. Total productive area is estimated at 9,080 acres. Production from many of the wells is commingled with production from the underlying Devonian shales and the siltstones. From 1901 to 1972, cumulative gas production from 104 Berea wells totalled 9 bcf. Heterogeneity in the Barnesville Consolidated field is due primarily to permeability barriers resulting from facies changes and diagenetic factors. Localized structural features such as paleotopographic highs and noses also may affect the heterogeneity of the Berea in this field. Initial open flows ranged from 2 to 5,253 Mcf/d and averaged 619 Mcf/d. Initial reservoir pressure was 780 psi. Pay thicknesses range from 3 to 22 feet and average 10 feet. Figure MDe-16 represents the type geophysical log for the Berea Sandstone in this field. Porosity ranges from 3 to 18 percent and averages 10 percent. Gas wells in the Barnesville Consolidated field were either completed naturally, shot with nitroglycerin, or perforated and hydraulically fractured.

Nora field: Situated in Wise and Dickenson counties, Virginia, the Nora field was discovered in 1948 (Figure MDe-3; Table MDe-1). This field, the largest Berea field in Virginia, was selected to represent the shallow marine trend. Depths to the top of the Berea range from 4,000 to 5,500 feet, with an average pay thickness of 71 feet. A total of 368 Berea wells were drilled in this field, of which 358 were productive. Initial open flows averaged around 100 Mcf/d, and the initial reservoir pressure of the early wells ranged from 500 to 850 psi. Final open flows commonly ranged from 100 to 1,400 Mcf/d. A scatter plot of the total cumulative gas production from 64 Berea wells located in Buchanan, Dickenson, and Tazewell counties, Virginia, shows cumulative production ranging from 5 to 5,617 MMcf (Figure MDe-17). Figure MDe-18 is a decline curve constructed from production data obtained from the 64 Berea wells in Virginia. Fluctuations in the decline curve reflect the effects of periodic shut-ins over the life of the wells. Development of primary porosity on the east side of the field and thinning of the sandstone to the east and south are the primary factors that control cumulative gas production (Hyde, oral commun., 1995). Nolde and Milici (1993) also believe production is stratigraphically controlled, and the Berea produces where it is greater than 60 feet thick. Figure MDe-19 is an isopach map of the Berea Sandstone in southwestern Virginia. Average porosity is 5.68 percent and average permeability is 0.014 md. The primary drive mechanism in this field is solution gas. Production from the Berea is commingled with production from the Devonian shale units. Most wells in this field were completed by shooting with nitroglycerin or perforating and hydraulic fracturing.

Gay-Fink Consolidated field: Located in Doddridge, Lewis, Ritchie, Jackson, and Roane counties, West Virginia, the Gay-Fink Consolidated field was discovered in 1909. (Figure MDe-3; Table MDe-1). This field was selected to represent the fluvial-deltaic trend of the Berea in West Virginia. The Berea Sandstone ranges in depth from 2,100 feet to 2,700 feet. Berea Sandstone within the Gay-Fink Consolidated field represents channel fill deposits ranging in

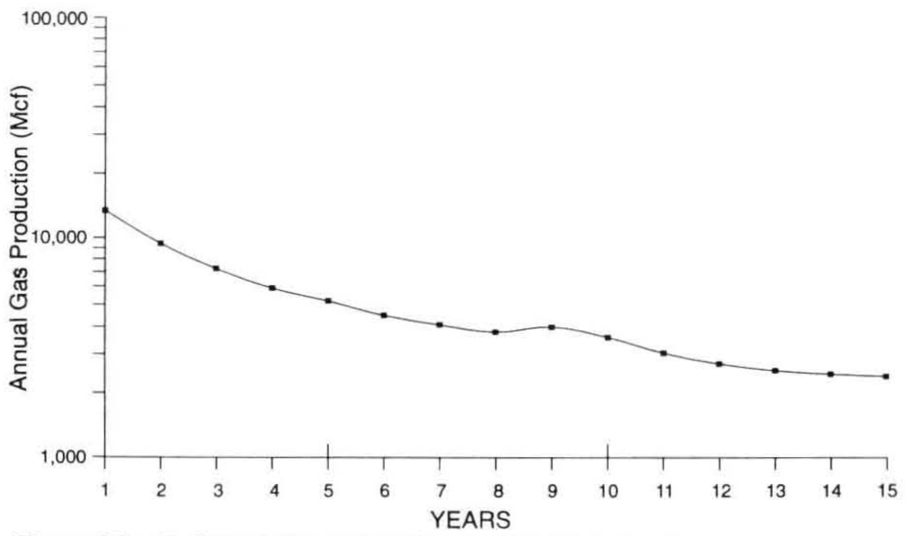


Figure MDe-13. Cumulative production decline curve for 39 gas wells from 12 Berea fields in Ohio. These wells represent the typical decline for Berea wells associated with the fluvial-deltaic facies.

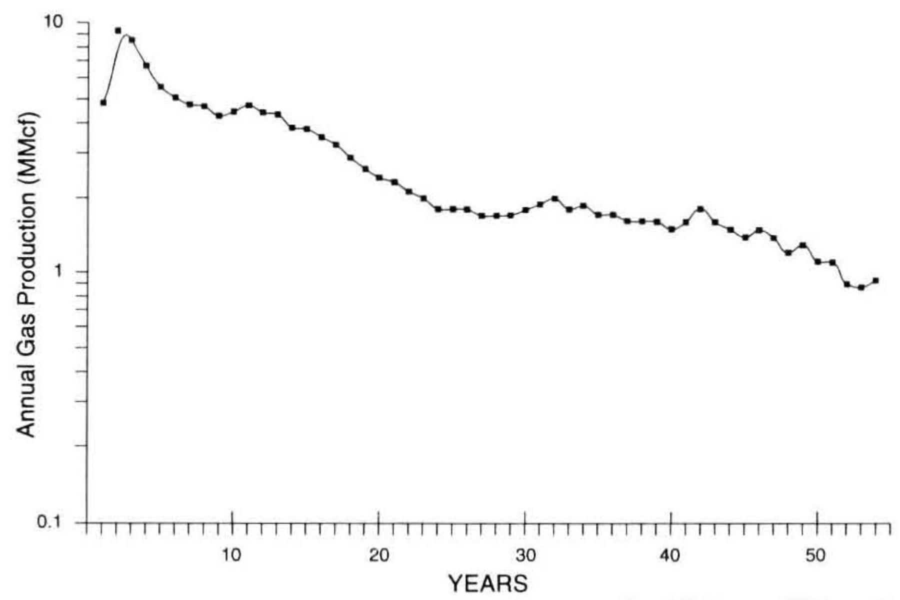


Figure MDe-14. Cumulative production decline curve for 111 Second "Berea" gas wells from the Cheshire Consolidated field in southeastern Ohio. Modified from Tomastik and Cavender (1990). Average cumulative production from these wells was 134 MMcf. These wells represent typical decline for wells associated with the barrier island facies.

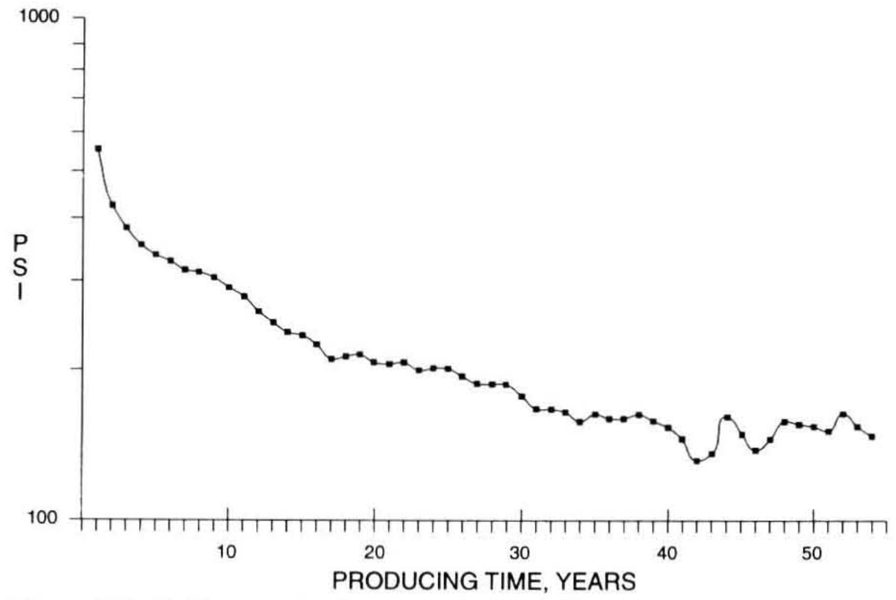


Figure MDe-15. Pressure decline curve for the 111 Second "Berea" wells from the Cheshire Consolidated field in southeastern Ohio. Modified from Tomastik and Cavender (1990). Slight irregularities in the wellhead pressures indicate periodic shut-in and/or restimulation by hydraulic fracturing. These wells represent typical decline for wells associated with the barrier island facies.

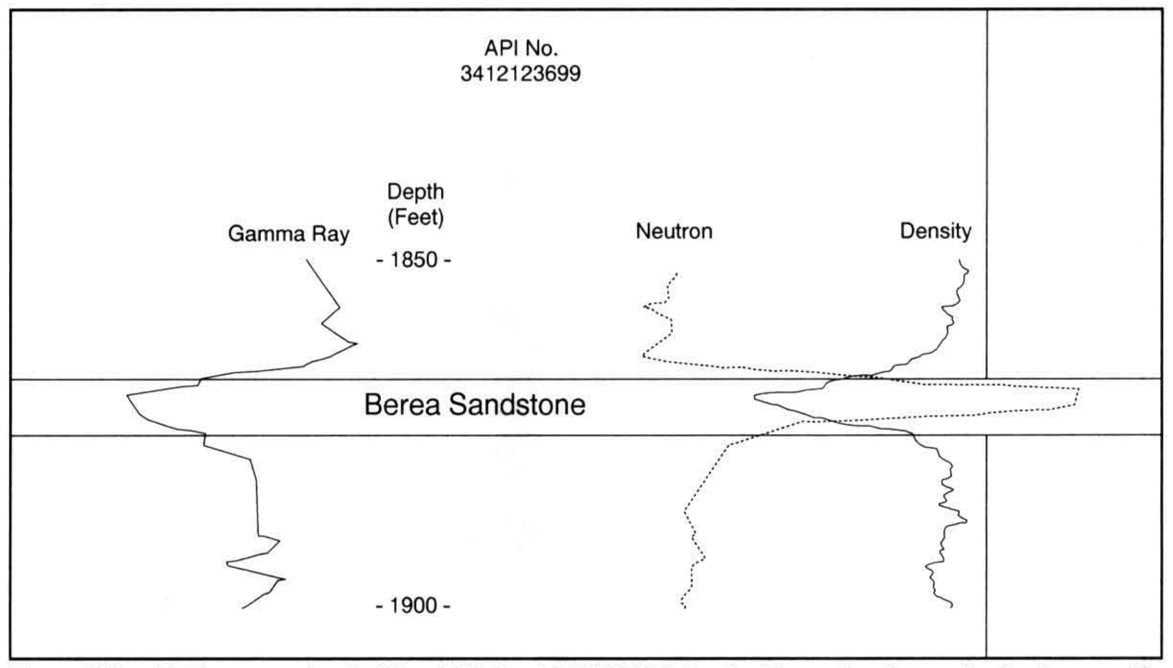


Figure MDe-16. Type geophysical log (API No. 3412123699) for the Berea Sandstone in the Barnesville Consolidated field in southeastern Ohio. This log represents the Berea shallow marine facies of southeastern Ohio.

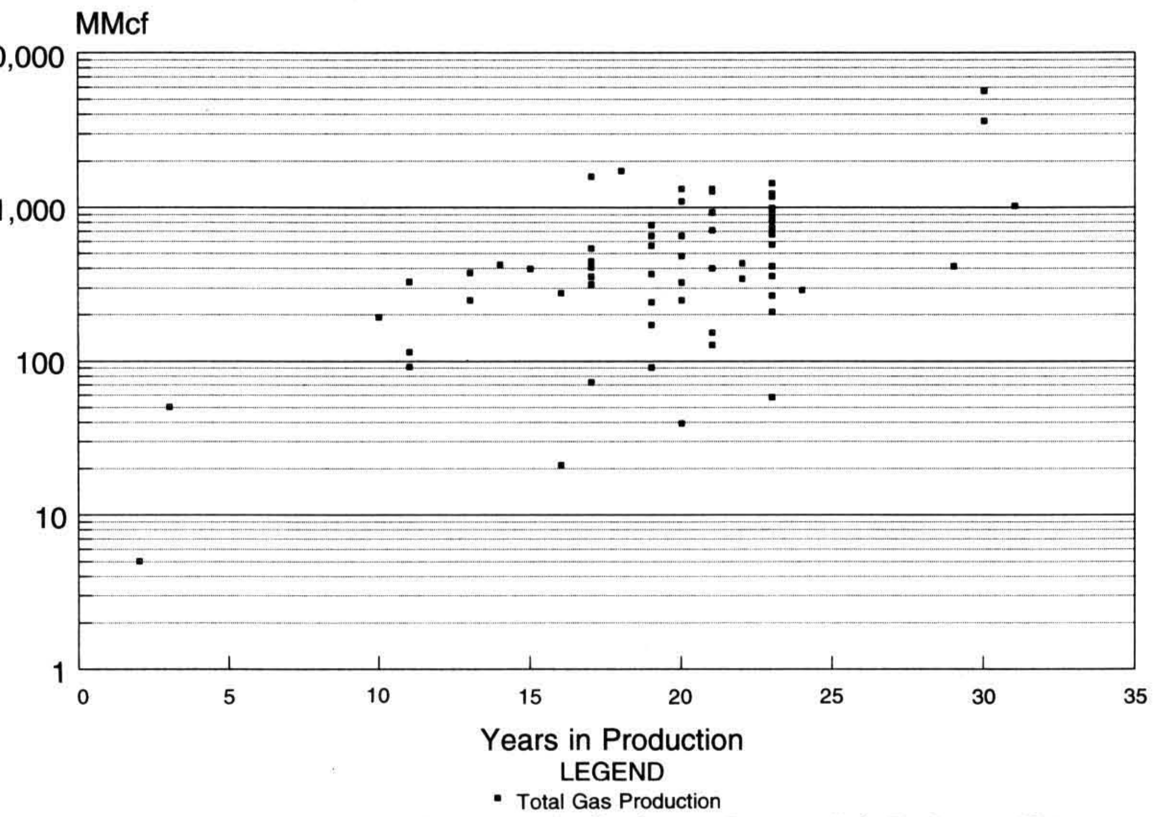


Figure MDe-17. Scatter plot of cumulative gas production from 64 Berea wells in Buchanan, Dickenson, and Tazewell counties, Virginia. Cumulative production ranges from 5 to 5,617 MMcf. Production is controlled by primary porosity development and thickness of the sandstone unit.

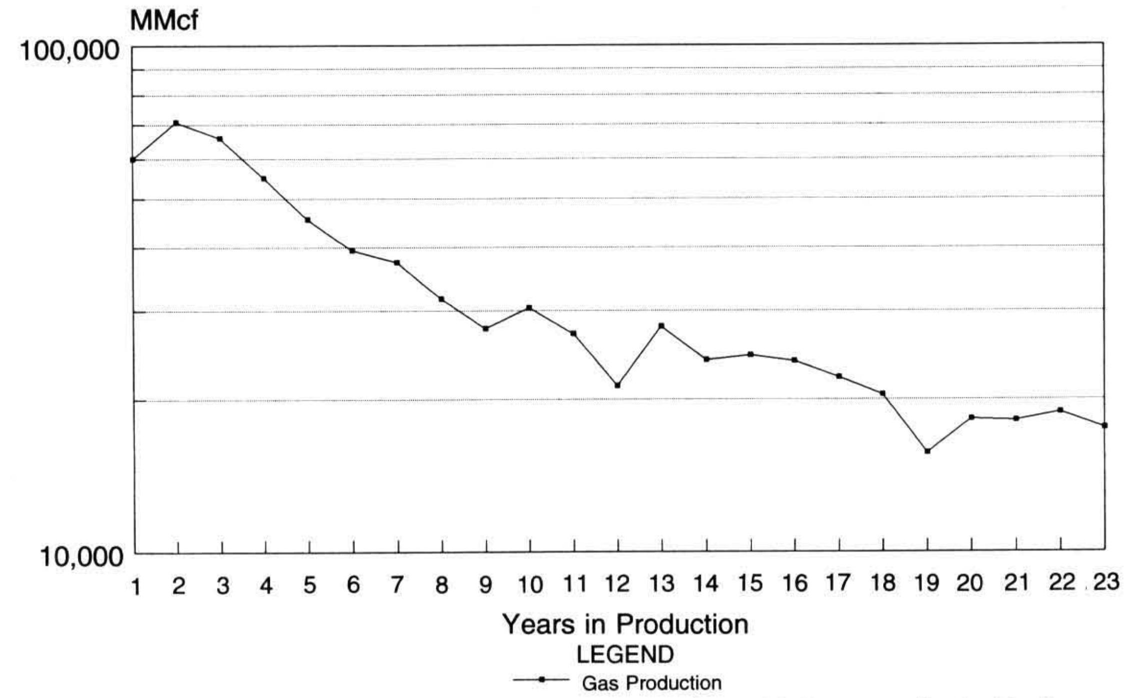


Figure MDe-18. Cumulative production decline curve from 64 Berea wells in Buchanan, Dickenson, and Tazewell counties, Virginia. Fluctuations in the decline curve reflect periodic shut-ins over the life of the wells.

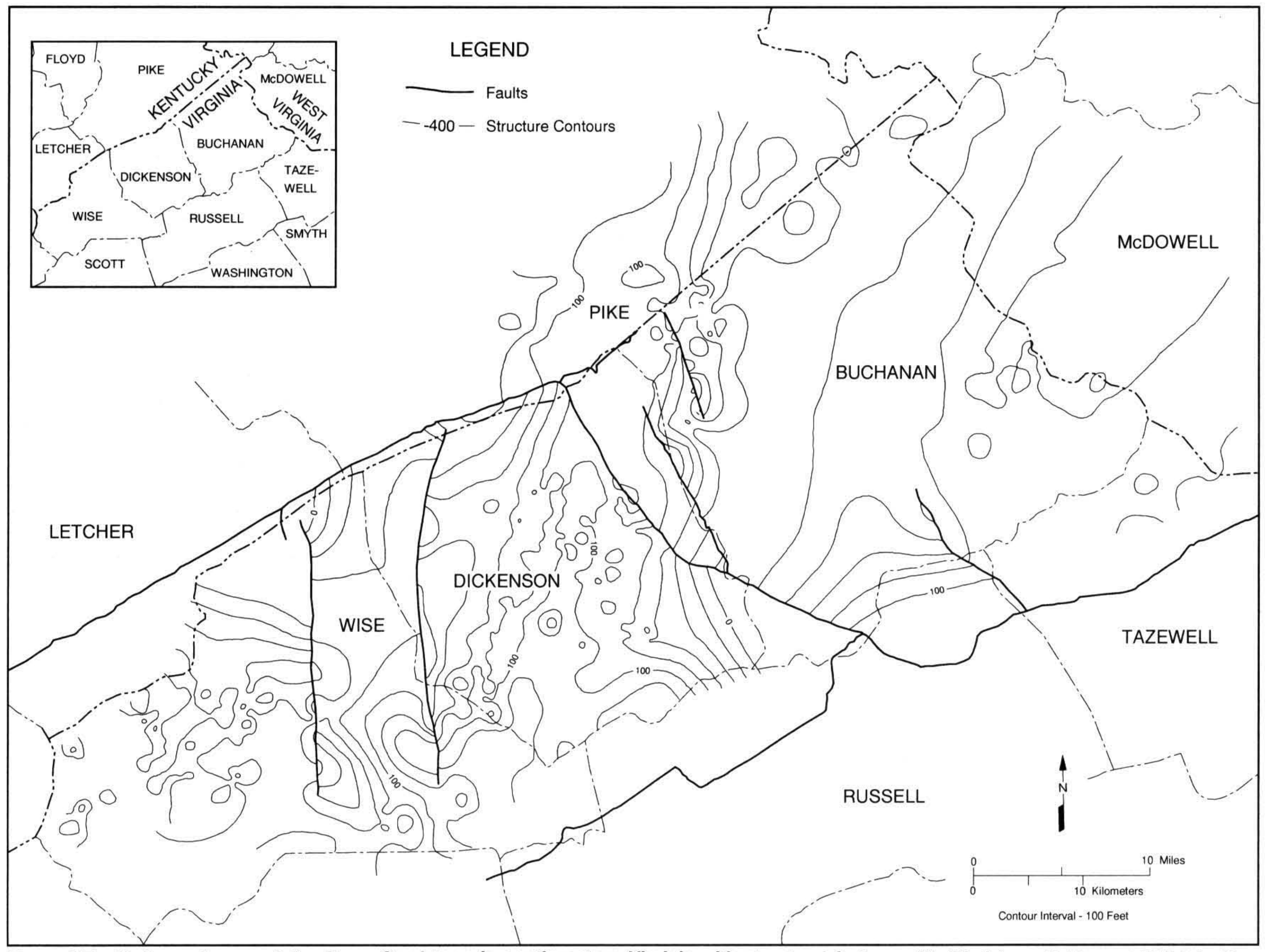


Figure MDe-19. Isopach map of the Berea Sandstone in southwestern Virginia with structural features. Modified from Nolde and Milici (written commun., 1994).

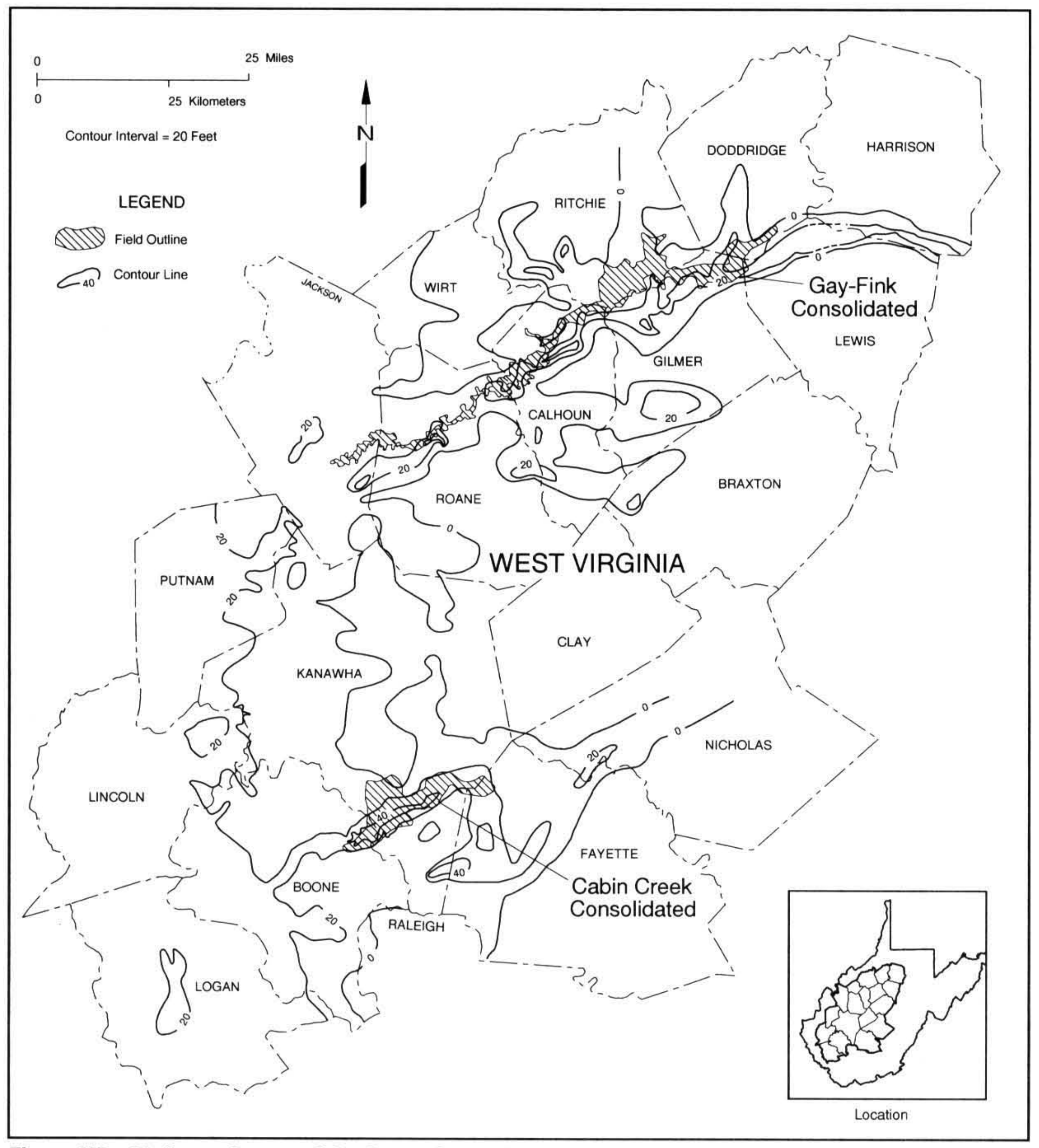


Figure MDe-20. Isopach map of the Berea Sandstone showing the location of the Gay-Fink and Cabin Creek Consolidated fields in West Virginia. Modified from Larese (1974).

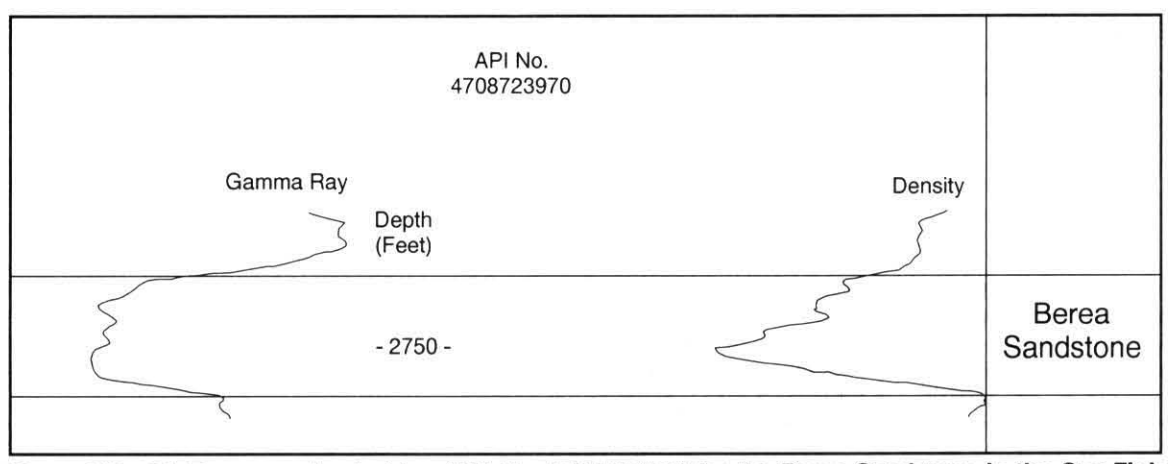


Figure MDe-21. Type geophysical log (API No. 4708723970) for the Berea Sandstone in the Gay-Fink Consolidated field in Doddridge, Lewis, Ritchie, Jackson, and Roane counties, West Virginia. This log is a typical example of the fluvial-deltaic facies in this field.

thickness from 1 to 60 feet (Larese, 1974). Figure MDe-20 shows the extent of these channel fill deposits and the field outlines of the Gay-Fink Consolidated and Cabin Creek Consolidated fields.

A total of 113 wells have been drilled in this consolidated field. Estimated productive area is 13,017 acres. Heterogeneity is due to variability in porosity and permeability caused by diagenetic factors such as cementation, feldspar, solutioning, and compaction (Larese, 1974). Facies changes from channel fill deposits to less permeable units also affects the heterogeneity of the Berea in this field. Most of the hydrocarbon entrapment in the Gay-Fink Consolidated field is stratigraphic, although monoclinal structure may play a role (Larese, 1974; Cardwell and Avary, 1982). Porosity from cores ranges from 3.7 to 11.7 percent and averages 7 percent (Larese, 1974). The average pay thickness is 8 feet and initial reservoir pressure was 543 psi. Figure MDe-21 is the type geophysical log for the Berea Sandstone in this field. Initial open flows ranged from 300 to 12,000 Mcf and average 3,503 Mcf. Cumulative gas production from 40 wells in this field from 1916 to 1992 is 28 bcf. Oil production exceeded 7 million barrels of oil. The primary driving mechanisms are solution gas and water. Wells developed in this field were produced naturally or shot with nitroglycerin.

Cheshire Consolidated field: Located in Morgan, Athens, Meigs, and Gallia counties, Ohio, the Cheshire Consolidated field was discovered in 1904 (Figure MDe-3; Table MDe-1). The Cheshire Consolidated field is the main producing field in the Second "Berea" barrier island trend. Figure MDe-22 shows the extent of the Second "Berea" trend and the limits of the Cheshire Consolidated field within the trend. Oil and gas have been produced from the Second "Berea" and Berea sandstones at depths ranging from 1,081 to 1,910 feet. Most of the production is obtained from the Second "Berea" Sandstone. The Berea Sandstone is commonly charged with large quantities of salt water and is usually not economically productive. Occasionally, however, localized subtle structures allow for gas to be produced from the Berea in this field. Since 1904, more than 2,697 gas and combination wells have been drilled in this field. Total productive area is estimated at 26,970 acres. Cumulative gas production from 823 wells from 1925 to 1992 totalled 50.2 bcf. The primary trapping mechanism in this field is stratigraphic. The Second "Berea" trend is a long, linear, porous and permeable sandstone body that is enclosed by impermeable shales. Figure MDe-23 illustrates the north-south extent of the Second "Berea" trend and its gradation into impermeable shales. Heterogeneity in the Cheshire Consolidated field is due to facies changes and diagenetic factors. Production of natural gas from the Second "Berea" is, in part, controlled by both the thickness of the sandstone body and by the grain size of the sand (Pepper and others, 1944). Initial open flows ranged from 1 to 2,500 Mcf/d and averaged 114 Mcf/d. The best well in this field produced more than 500 MMcf. Initial reservoir pressure was 700 psi, and average pay thickness is 12 feet. Porosity ranges from 2 to 23 percent and averages 12 percent. Table MDe-3 compares and contrasts the main reservoir characteristics of the Second "Berea" trend with the other trends. Figure MDe-24 shows the breakdown of the major constituents in natural gas from 27 Second "Berea" wells in this field. Methane is the primary constituent, with minor constituents being ethane, propane, butane, and nitrogen. (Tomastik and Cavender, 1990). Wells in the Cheshire Consolidated field were either produced naturally, shot with nitroglycerin, or stimulated by hydraulic fracturing.

Oakford field: Located in Westmoreland County, Pennsylvania, the Oakford field was discovered in 1885 (Figure MDe-3; Table MDe-1). This field is representative of the Berea structural-fluvial-deltaic trend. The Oakford field (formerly called Grapeville) is in the form of an ellipse and covers an area of 12 square miles (Cummins, 1892). Most of the gas produced from this field came from the Murrysville sandstone at depths ranging from 1,199 to 2,130 feet. A total of 648 wells have been drilled and completed in this field. Estimated productive area is 24,962 acres. The Oakford field occupies the crown of the Grapeville anticline. From the center of the field to the southwest and to the northeast, the surface elevation of the field drops 200 feet in 4 miles (Cummins, 1892). Hydrocarbon entrapment in the Oakfield field is a result of the structure associated with the Grapeville anticline and facies changes (Jefferies, 1952; Lytle, 1963). The Murrysville sandstone is approximately 100 feet thick with a pay thickness of 50 feet (Cummins, 1892; Jefferies, 1952). Figure MDe-25 is the type geophysical log for the Murrysville in the Oakford field. Initial reservoir pressure was 550 psi (Cummins, 1892). Initial open flows ranged from 10 to 40 MMcf/d. The Oakford field was converted to gas storage in 1951, and the total reservoir capacity of the Murrysville is 88 bcf (Lytle, 1963). This gas storage capacity closely represents the field cumulative production from 1885 to 1951. Porosity from logs range from 2 to 26 percent and average 17 percent. Both solution gas and water seem to be the principal drive mechanisms in this field. The gas-water contact is approximately 250 feet below sea level (Cummins, 1892). Murrysville wells in this field were either produced naturally, shot with nitroglycerin, or acidized.

Resources and Reserves

Original gas-in-place and reserve calculations were estimated from decline curves, average cumulative well production data, and standard industry formula calculations. Estimated original gas-in-place and proven reserves are summarized in Table MDe-4.

Proven reserves for Ohio, West Virginia, Virginia, and Kentucky were calculated using an average cumulative production per well and assuming a 65 percent recovery factor. This recovery factor was based upon conservative estimates by assuming a higher recovery rate in the early wells and lower recovery factor for developmental and infill drilling. Total proven gas reserves were estimated at 1,885 bcf. Production data from Pennsylvania is unavailable.

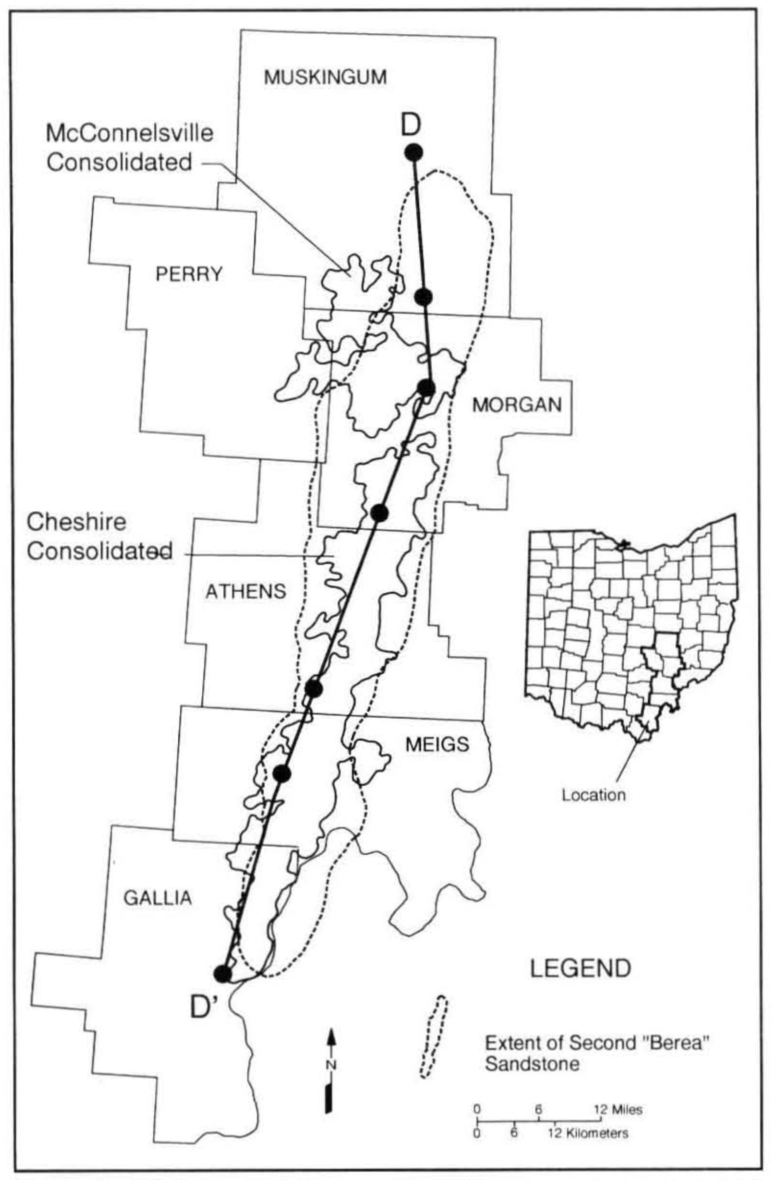


Figure MDe-22. Approximate extent of the Second "Berea" trend in the Cheshire Consolidated and McConnelsville Consolidated fields in southeastern Ohio and the location of cross section D-D' showing the gamma-ray characteristics and the north-south extent of the Second "Berea" trend in southeastern Ohio.

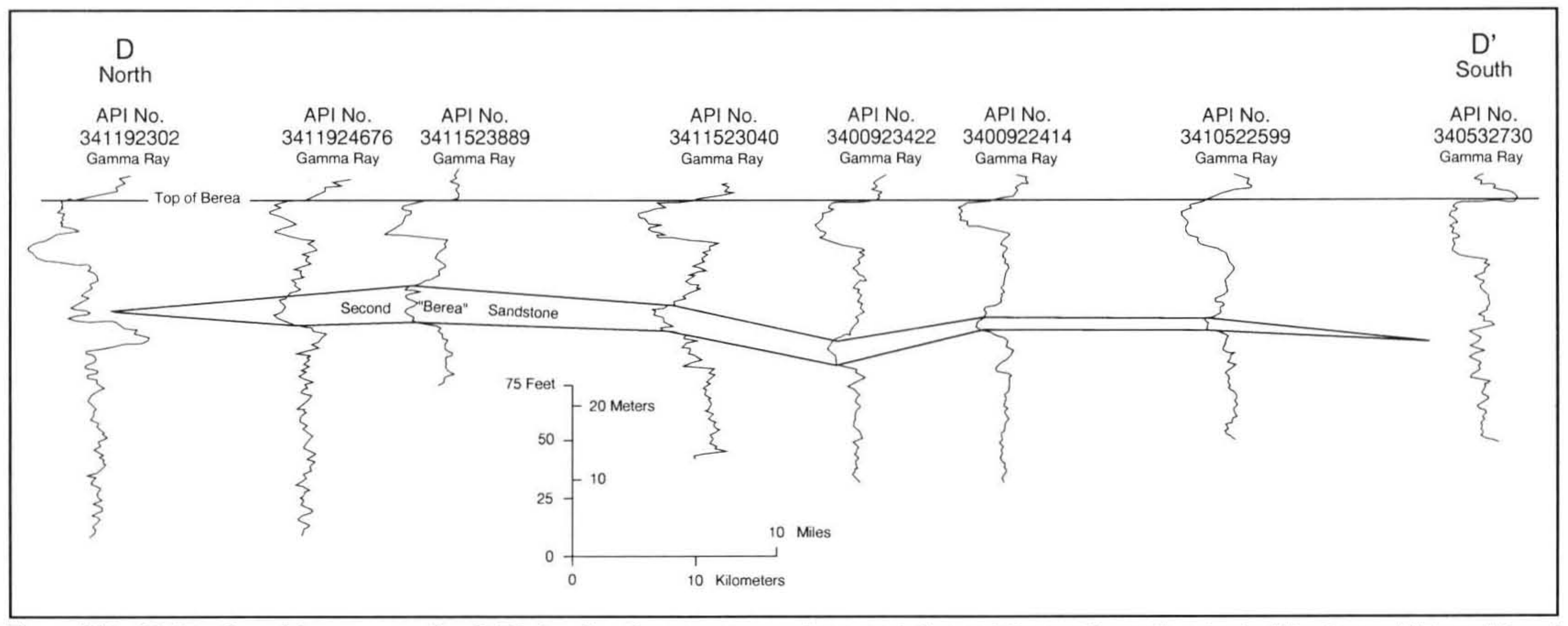


Figure MDe-23. Stratigraphic cross section D-D' showing the gamma ray characteristics and the north-south extent of the Second "Berea" trend in southeastern Ohio. See Figure MDe-22 for location of cross section.

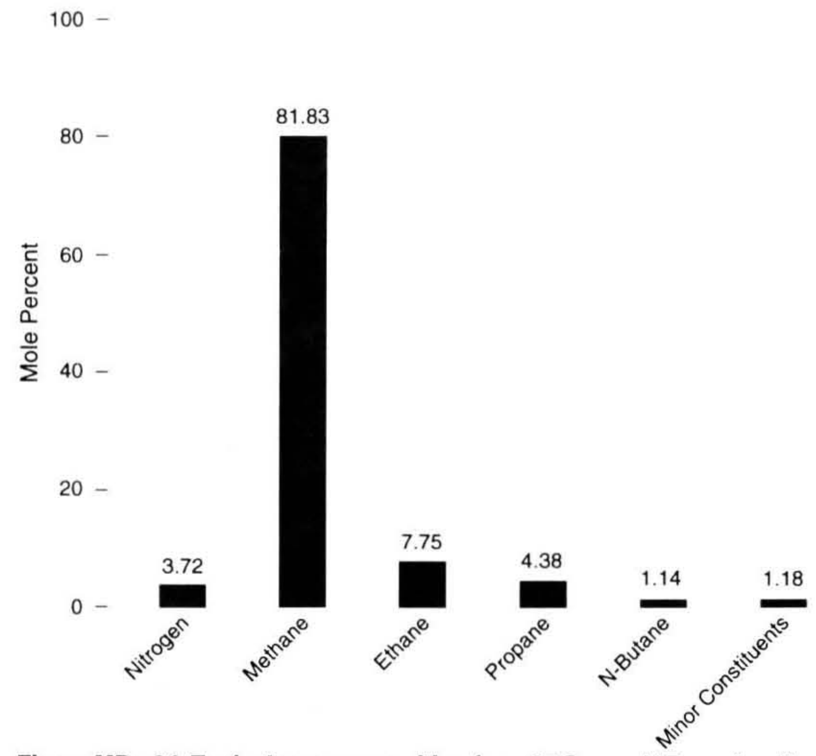


Figure MDe-24. Typical gas composition from 27 Second "Berea" wells in the Cheshire Consolidated and McConnelsville Consolidated fields in southeastern Ohio. Modified from Tomastik and Cavender (1990).

Future gas resources were identified for the Lower Mississippian-Upper Devonian Berea and equivalent sandstones based on fairways delineated throughout the Appalachian basin (Figure MDe-26). Classifications have been established by the Potential Gas Committee (1990) for unconfirmed and undiscovered recoverable gas resources: probable resources (for extensions and new pools) and possible resources. The limits of the "probable" and "possible" fairways have been arbitrarily defined based on the extent and reservoir history of this play. Probable resources will occur as extensions of the present producing trend delineated by the existing Berea fields and pools. Table MDe-5 summarizes the undiscovered resources for the Berea Sandstone and equivalent rocks in the Appalachian basin. Probable and possible gas resources for the Lower Mississippian-Upper Devonian Berea and equivalent shelf and shallow marine sandstones were calculated using the methods developed by the Potential Gas Committee (1990). The maximum estimated recoverable gas resources were calculated for each resource type. Assumptions were made in regard to reservoir conditions and probability of traps.

Future Trends

Exploration and development of the fluvial-deltaic, shallow marine, barrier island, and structural-fluvial-deltaic Berea Sandstone and equivalent rocks will continue along the main producing trends in the Appalachian basin. New field development will most likely continue in the southwestern Virginia area. Development and infill drilling of existing fields will continue in southeastern Ohio, eastern Kentucky, and southwestern West Virginia. Most development in the Berea Sandstone will likely concentrate in the southwestern West Virginia and southwestern Virginia areas, where proven gas reserves from the Berea range from 400 to 600 MMcf. Advancements in technology and increases in gas prices may also allow for renewed activity in some of the older fields.

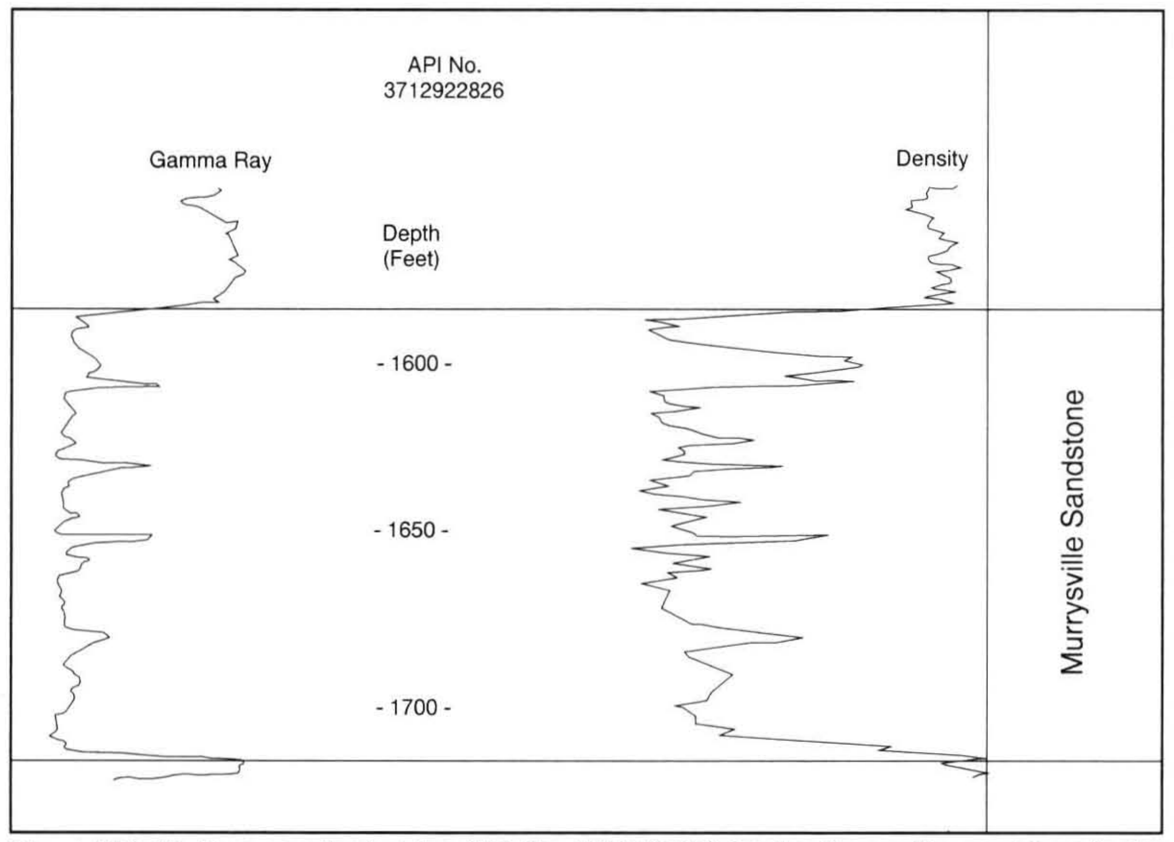


Figure MDe-25. Type geophysical log (API No. 3712922826) for the Murrysville sandstone in the Oakford field, Westmoreland County, Pennsylvania.

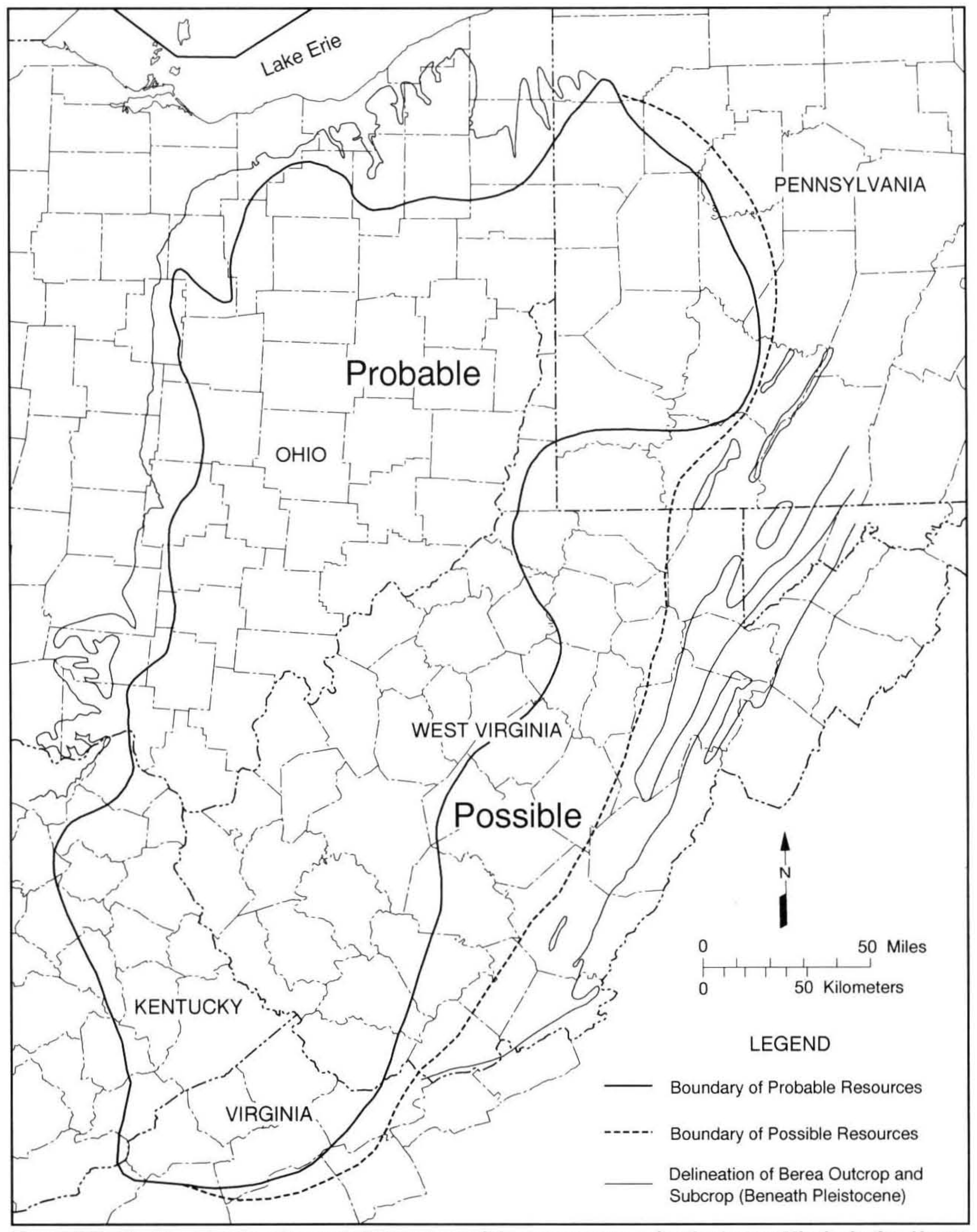


Figure MDe-26. Map showing the probable and possible gas resources for the Lower Mississippian-Upper Devonian Berea and equivalent rocks in the Appalachian basin.

Table MDe-4. Summary of reservoir characteristics for existing proven fields of the Berea and equivalent rocks in the Appalachian basin.

Reservoir	Total Number of Wells	Estimated Cumulative Production Per Well (MMcf)	Recovery Factor (%)	Total Estimated Drainage Area for All Wells (in acres)	Original Gas in Place (bcf)	Original Gas Reserves (bcf)	Average Life of Well (years)
Berea Sandstone and equivalent rocks	15,834	119	65	1,866,509	2,899	1,885	40

Table MDe-5. Undiscovered recoverable gas resources for the Berea and equivalent rocks in the Appalachian basin. Data was calculated from methods derived by the Potential Gas Committee (1990).

Resource Type	Gross Area of Entire Resource Type (square miles)	Estimated Net Productive Area (square miles)	Average Proved Reserves (bcf per square mile)	Yield Factor (bcf per cubic mile)	Average Pay Thickness (in feet)	Probability of Trap (%)	Probability of Trap Filled (%)	Maximum Estimated Recoverable Gas Resources
Probable	34,688	26,131	0.68	151	24	60	50	5,327 bcf
Possible	8,232	8,232	0.50	111	24	40	25	411 bcf

PLAY Dvs: UPPER DEVONIAN VENANGO SANDSTONES AND SILTSTONES

by Ray Boswell, EG&G TSWV, Inc.; L. Robert Heim, Atlas Energy Group; Gregory R. Wrightstone, Eagle Resources Inc.; and Alan Donaldson, West Virginia University

Location

Natural gas production from the Upper Devonian Venango sandstone and siltstone reservoirs extends from southern West Virginia to north-central Pennsylvania and is largely confined to the eastern half of the structural basin (Figure Dvs-1). The largest fields, which are generally inactive or converted to storage, occur in the north-south-trending shallow gas belt where production was obtained from numerous stacked, marginal-marine sandstones with excellent reservoir quality (Figure Dvs-2). Current activity is focused in outlying areas where low-permeability parallic, coastal plain, and marine shelf reservoirs serve as stand-alone targets or as contributing formations in wells with commingled production.

The Venango play is the shallowest and most sandstone-rich of three quasi-chronostratigraphic plays that bracket major progradational episodes of the Catskill delta complex (Figure Dvs-3). The Venango play is defined to include all reservoirs occurring between the horizons of maximum regional transgression marked by the Chadakoin Formation of Pennsylvania (equivalent to the informal Warren shale of West Virginia) and the marine shales directly underlying the Berea Sandstone.

Production History

The modern petroleum industry began in 1859 with the production of oil from coarse-grained, shallow sandstones at the very top of the Venango play at the Drake well, located along Oil Creek in northern Venango County, Pennsylvania (Giddens, 1948). Within a decade, 5,500 wells, 1,186 of which were oil producers (Moyer, 1933), had been drilled in the Venango district (Figure Dvs-2). Initial production rates of 1,000 barrels of oil per day were common. As production around Oil Creek declined in the early 1870s, wildcatters moved to the south, discovering several large oil fields in Clarion and Butler counties (the "Lower Region"). Oil production from Venango reservoirs was extended into southwestern Pennsylvania by 1880. In 1886, a well drilled on the Gordon farm, Washington County, Pennsylvania, reported an IP of 600 barrels of oil per day from a sandstone at 2,392 feet and became the world's deepest producing oil well (Clapp, 1907). In 1891, the Guffey and Jennings No. 1 Matthews well (Figure Dvs-2), McDonald field, Allegheny County, Pennsylvania, was completed with an estimated IP of 12,000 to 21,000 barrels of oil per day, which is still an Appalachian basin record for initial potential of oil (Harper and Cozart, 1992).

In the 1860s and 1870s, virtually all gas produced in the basin was found unintentionally during the search for oil and was used either to support oil field operations or vented into the atmosphere. However, as markets for gas developed, Venango reservoirs were tracked to the south and east of the oil-producing regions where drilling depths increased and the sandstones generally became more gas-prone. One of the earliest substantial gas wells on record was the 1882 McGuigan well in the Hickory-Buffalo Consolidated field, Washington County, Pennsylvania (Figure Dvs-2). This well had an estimated IP of 30,000 Mcfg/d, the largest flow of gas in the world up to that date (Ashley and Robinson, 1922). By 1890, Venango reservoirs were under development in northern West Virginia. Continued development throughout the region resulted in numerous high-volume wells from multiple Venango sandstones, most notably the Gordon and Gordon stray in northwestern West Virginia, and the Fifty-Foot, Gordon, Fifth, Bayard, and Elizabeth sandstones across a large region stretching from Allegheny County, Pennsylvania, to Lewis County, West Virginia.

Development drilling in the early 1900s resulted in the progressive consolidation of the original gas fields into numerous superfields. By 1915, major new field discoveries had become rare, resulting in a decline in both the drilling and productivity of new Venango wells (Wyer, 1918) that has continued to the present. For the past several decades, the main contribution of Venango reservoirs has been to provide subsidiary production in wells targeted for deeper reservoirs. Drilling for Venango targets within the shallow gas belt (Figure Dvs-2) has been limited to the development of small pockets of bypassed reserves, gas storage, and enhanced oil recovery projects. To the east, lower Venango reservoirs (Fifth and Bayard) are commonly produced along with Bradford reservoirs in the main Bradford production area of Indiana County, Pennsylvania, and surrounding counties (see R. Boswell and others, Upper Devonian Bradford sandstones and siltstones, this atlas). There is also occasional exploration of shoreline/distributary channel deposits of uppermost Venango sandstones and fluvial channel equivalents of the main Venango reservoirs. Also, several hundred wells (primarily targeted for the Devonian Shale) have produced gas from fine-grained marine facies located to the west and south of the shallow gas belt since 1980.

Production data for the Venango play is limited. Many of the fields were developed prior to 1910, and well data generally are not available. Furthermore, recent Upper Devonian gas production from the three Catskill delta complex plays is typically commingled, rendering it impossible to assess accurately the production from specific reservoirs or plays. It is not unreasonable, however, that Venango play reservoirs may account for roughly one-third of the estimated 9 tcfg cumulative production from Upper Devonian and younger reservoirs in Pennsylvania (Harper and Cozart, 1992) and a similar proportion of the 11.7 tcfg estimated production through 1973 from correlative units in West Virginia (Cardwell and Avary, 1982). The resulting estimate of 7 to 8 tcfg cumulative production from Venango reservoirs compares well with the estimate of 6.7 tcfg provided by the U. S. Department of Energy's Morgantown Energy Technology Center (A. Zammerilli, written commun., 1994).

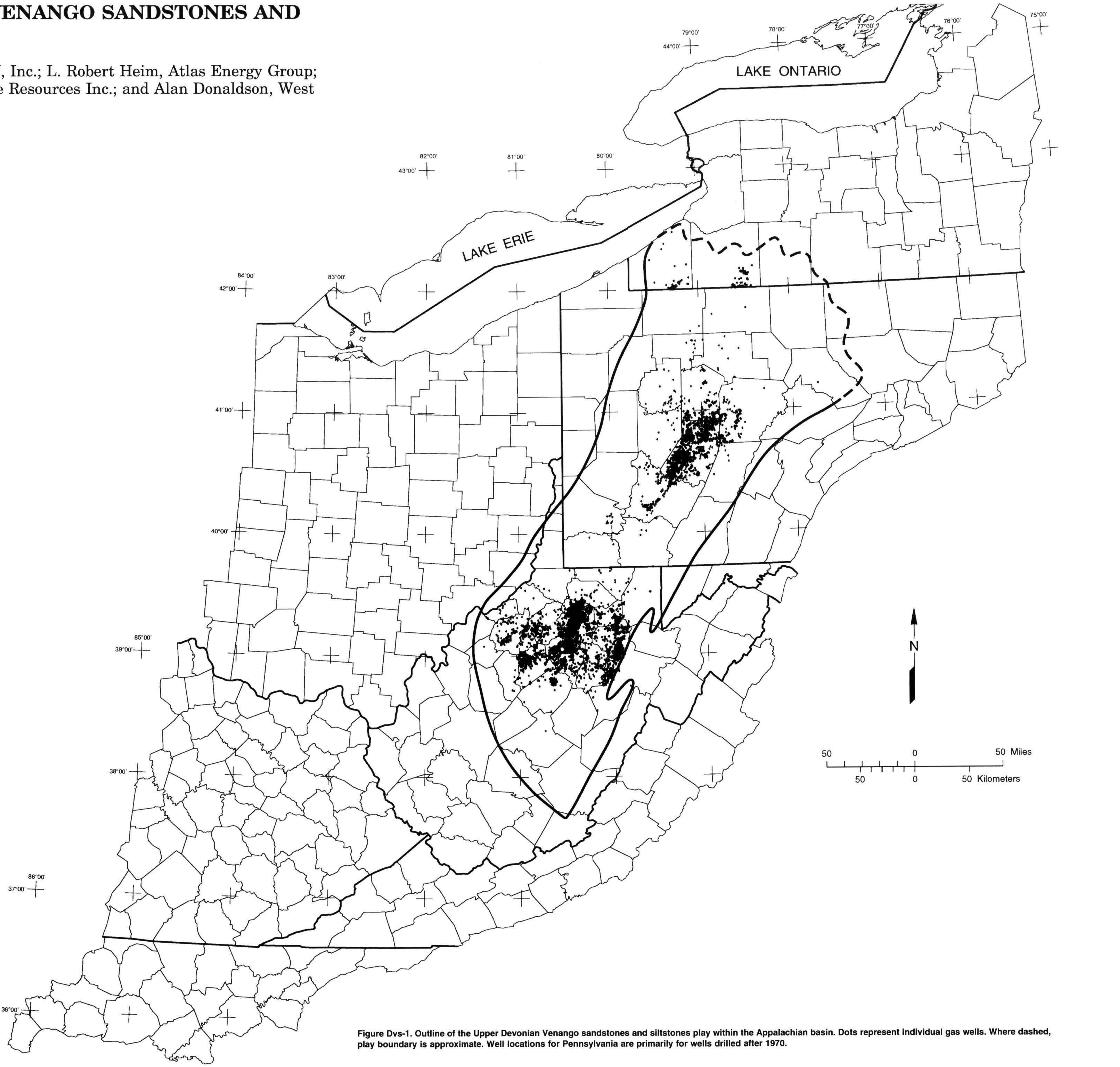


Figure Dvs-1. Outline of the Upper Devonian Venango sandstones and siltstones play within the Appalachian basin. Dots represent individual gas wells. Where dashed, play boundary is approximate. Well locations for Pennsylvania are primarily for wells drilled after 1970.

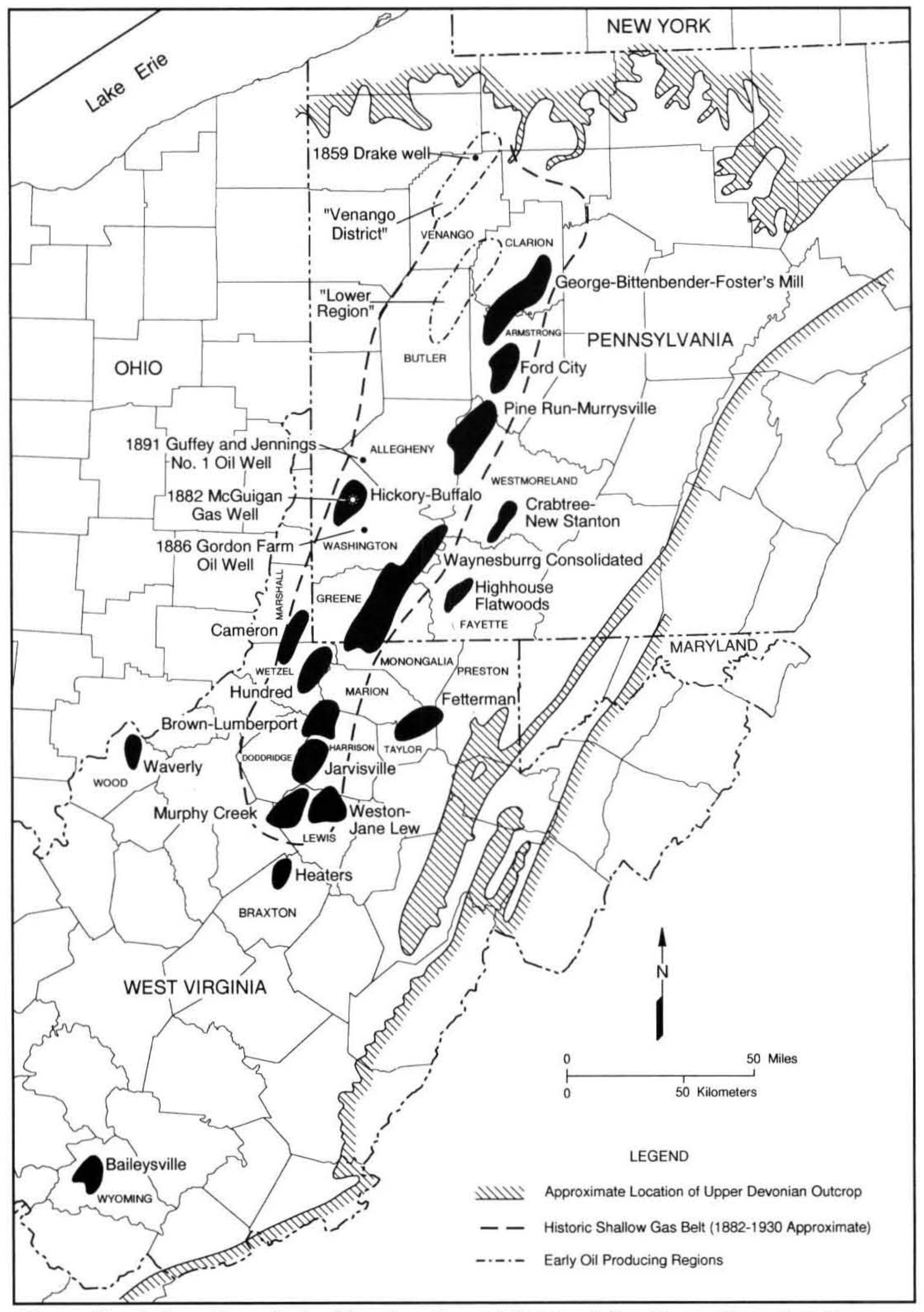


Figure Dvs-2. Location of significant wells and fields of the Upper Devonian Venango sandstones and siltstones play. Other productive areas illustrated in Figure Dvs-1 are not shown.

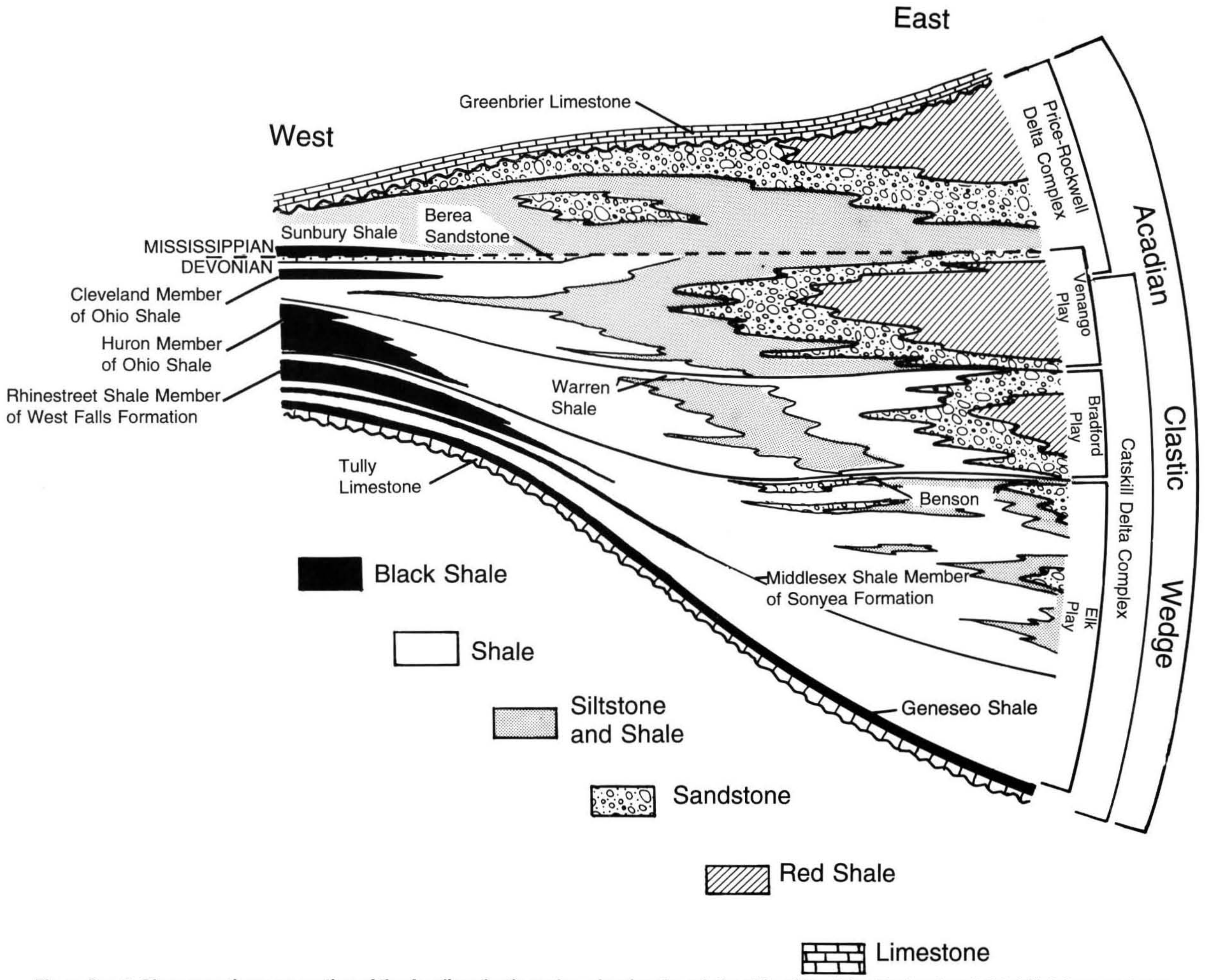


Figure Dvs-3. Diagrammatic cross section of the Acadian clastic wedge, showing the relationship of the Price-Rockwell and Catskill delta complexes, the three sandstone and siltstone plays with key bounding units noted, and the general lithologic framework.

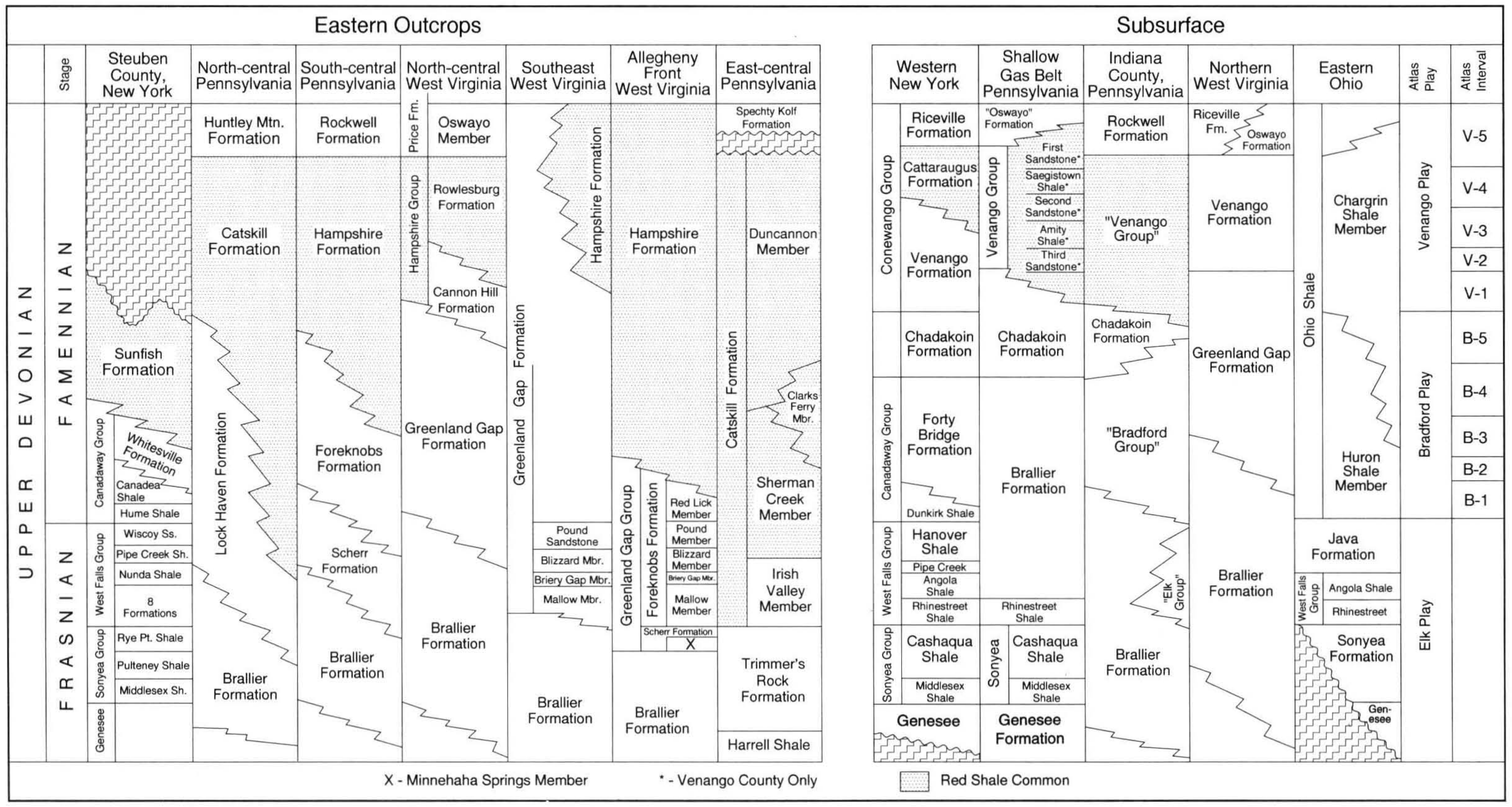


Figure Dvs-4. Regional lithostratigraphic nomenclature for the gas productive regions and surrounding outcrops of the Venango play. The correlation of formations to the stages is approximate and has not been consistently reported in the literature. The subsurface terminology given for the shallow gas belt in Pennsylvania and Indiana County, Pennsylvania (see Figure Dvs-2 for location) has not been formalized. The formations of the Venango Group given in the shallow gas belt column were used in numerous publications in the 1940s (see Dickey and others, 1943) but may not be traceable outside Venango County. The geographic extent of the major Venango play lithostratigraphic units is shown in Figure Dvs-13. After Boswell and others (1987) and Woodrow and others (1988).

Stratigraphy

The Venango play encompasses all sandstone reservoirs deposited during the upper half of the Famennian stage of the Devonian period (European usage; Bradford or Conewangoan stage of North American usage). Along the northeast and east outcrop belts, Venango play strata are non-marine red shales and enclosed fluvial sandstones of the Hampshire, Catskill, or Sunfish formations. In Ohio and Kentucky outcrops, the interval is represented by the distal marine shales of the Chagrin, Ohio, and Chattanooga shales. In southern and central West Virginia, the play is represented by the shelf shales, siltstones, and sandstones of the Brallier and Greenland Gap formations. Unfortunately, exposures of marginal-marine, reservoir-bearing facies are rare, located far from most gas fields, and perhaps not representative of the subsurface lithology. As a result, the lithostratigraphy of Venango play reservoirs throughout most of the basin interior remains unsettled (Figure Dvs-4).

The pioneering stratigraphic work of James Hall (New York) and Henry Rodgers (Pennsylvania) and others in the 1830s and 1840s established the basic Upper Devonian stratigraphic succession of the Appalachian region as Portage (oldest), Chemung, and Catskill (youngest). Carll (1876; 1880) and Ashburner (1880) conducted the first surveys of the Venango oil fields and placed the reservoirs within an informal "Venango oil-sands group" of the Catskill Formation. It should be noted that this usage of "group" occurred in an era before standard nomenclatural procedures were developed and at a time when it was widely believed that basic rock formations such as Catskill represented specific and uniform periods of time.

In the early 1900s, the recognition of the diachroneity of Catskill delta complex strata rendered the status of most previously recognized "formations" suspect (see Williams, 1900; Barrell, 1913; Caster, 1934). Subsequently, stratigraphers working in the subsurface of Pennsylvania generally used either terminology derived from the New York-Pennsylvania outcrop belt (Conewango Group, incorporating the Riceville, Oswayo, Venango, Cattaraugus, and other formations in various combinations) or have reverted to the terminology of Carll and Ashburner ("Venango Group", with First, Second, and Third sandstone formations; see Dickey and others, 1943). However, like Catskill, the definition of Conewango is heavily tied to concepts of time (see Harper and Laughrey, 1987), causing the term to fall out of favor, leaving only the informally named "Venango Group" with no formations assigned to it, to serve as the current lithostratigraphic name in the subsurface of Pennsylvania until more detailed correlations are accomplished (Harper and Laughrey, 1980; Berg and others, 1983; Woodrow and others, 1988).

In West Virginia, the main reservoir sandstones of the Venango play are generally considered to lie within the distal pinchout of the Hampshire Formation (Woodrow and others, 1988), although these rocks differ significantly in lithology from the red-shale-dominated Hampshire in its type section in western Maryland. Kammer and Bjerstedt (1986) recognized non-red Upper Devonian sandstones in the area and assigned them to the Oswayo Member of the Price Formation. An attempt to refine and extend this usage into the subsurface of northern West Virginia resulted in a proposed lithostratigraphic framework incorporating the terms Venango Formation and Oswayo Formation as depicted in Figure Dvs-5 (Boswell and others, 1987).

Sandstone reservoirs of the Venango play are best known relative to an informal system of drillers' names that gradually emerged during the development of the oil and gas fields of Pennsylvania (Figure Dvs-6). Although numerous nomenclatural and correlation errors persist, these names have been widely documented in the publications of the Pennsylvania Bureau of Topographic and Geologic Survey and the West Virginia Geological and Economic Survey. In West Virginia, which was developed essentially as a single district, a relatively consistent nomenclature emerged. However, each separate producing region of Pennsylvania retains nomenclatural relicts from the earliest stages of oil field development. The reservoir names initially developed in the Venango district were based on a simple top-to-bottom counting method (that is, First Venango through Third Venango sandstones). As production spread, some operators attempted to extend this terminology (hence Fourth, Fifth, and Sixth sandstones). As noted by Carll (1890), this method was highly prone to error in areas where units were missing or where additional units occurred. Other operators elected to create new names based on the lease of the discovery well (Gantz, Gordon, Bayard, and McDonald, for example), or some other attribute of the producing reservoir.

Here, the authors retain the drillers' names as they are used in the various producing districts as referenced to an informal basin-wide stratigraphic zonation (see Figure Dvs-6). The Venango play is divided into five quasi-chronostratigraphic intervals of approximately equal thickness designated V-1 through V-5 as illustrated on regional stratigraphic cross sections (Figures Dvs-6, Dvs-7, Dvs-8). In general, the lower intervals (V-1 and V-2) mark periods of rapid and irregular regression characterized by highly lenticular sandstones that generally are limited to the easternmost portions of the subsurface (Figure Dvs-9). Interval V-3 includes two major strike-trending progradational units (Fifth and Bayard of Pennsylvania) that are correlatable over large areas. Interval V-4 includes the Second Venango/Gordon sandstones and includes the regressive maxima of the Catskill coastal plain. This interval is characterized by an extremely well-developed belt of multiple amalgamated sandstones with conspicuous overall strike-trend that can be correlated from the oil fields of northwestern Pennsylvania to central West Virginia (Figure Dvs-10). The uppermost interval (V-5) contains the First Venango/Fifty-Foot sandstones and corresponds to a regional transgression that is marked by the development of the black Cleveland Shale on the western margin of the basin and the Riceville and Oswayo formations in the basin interior.

Structure

The overwhelming majority of Venango play gas production is obtained from stratigraphic or combined stratigraphic-structural traps. Although the relationship of structure to hydrocarbon occurrence had been presented as early as 1861 by Hunt (see White, 1904), the theory was not supported by experience in the Venango district where production was controlled by the combination of southeast regional dip and northwestward disappearance of the reservoirs (Carll, 1890). The tendency for Venango production to occur along elongated northeast-trending streaks was generally attributed to zones of greater porosity related to the northeast orientation of shoreline-parallel depositional systems. Nonetheless, based on the work of White (1885), these productive trends generally became attributed to structural features, which also exhibit a regional northeast trend throughout the basin. White's anticlinal theory was successfully applied in West Virginia (see D. Matchen and A. Vargo, Lower Mississippian Weir sandstones, this atlas) where many fields were found with a normal segregation of oil and gas in rough conformance to structure (White, 1904; Reger, 1929). As the theory regained converts in the Venango fields of southwestern Pennsylvania, a large number of successful wells were drilled along fold axes, suggesting that the distribution of oil and gas in the area was controlled by structure (Wagner and Lytle, 1976). However, Harper and Laughrey (1987) suggested that the distribution of fields may be more an artifact of the early drillers' belief in the anticlinal theory than a true indicator of structural control.

Although the influence of structure on production remains unclear, there is evidence that basement structures influenced the distribution of reservoir facies. The vertical stacking of the main Venango sandstones in central West Virginia (Boswell, 1988a) and southwestern Pennsylvania (Harper and Laughrey, 1987) has been attributed to differential subsidence along basement faults marking the active eastern margin of the Rome trough (Figure Dvs-11). Similarly, the location of prograding fluvial-deltaic systems may have been controlled by basement structures somehow related to postulated cross-strike discontinuities (Boswell and Donaldson, 1988). No reports of enhanced productivity from Venango reservoirs due to natural fractures are available, although it is likely that such fractures do exist.

Reservoir

The Catskill delta complex of the central Appalachian basin consists of a massive, eastward-thickening wedge of clastic rocks that was deposited in response to the Middle and Upper Devonian Acadian orogeny (Friedman and Johnson, 1966; Woodrow and Sevon, 1985). Natural gas reservoirs of the Venango play include sandstones and siltstones formed in fluvial, deltaic, interdeltaic shoreline, shelf, and slope environments at the close of Catskill deposition (Figures Dvs-12, Dvs-13). The total Venango sandstone isolith map for northern West Virginia (Figure Dvs-14) shows map patterns typical of the marine, transitional, and non-marine lithofacies. Table Dvs-1 presents available data for selected gas fields. Table Dvs-2 provides typical gas composition data.

Reservoirs within the shallow gas belt exhibit a variety of trends and geometries due in part, perhaps, to episodic reworking of mouth-bar sand bodies into strike-trending belts during regional transgression (Dennison, 1971). However, recurrent changes in the balance of marine and fluvial energies related to transgressive-regressive cycles of varying scale may have forced alterations in regional depositional style between fluvial and marine domination (Boswell and Donaldson, 1988), resulting in varied reservoir geometries. The most productive and highest quality Venango reservoirs are typically elongated in a north-south (West Virginia) to northeast-southwest (western Pennsylvania) direction, parallel to regional depositional strike (Figures Dvs-15a, Dvs-15b). These sandstones are interpreted as forming along or near the shorelines of wave-dominated deltas during periods of stillstand that marked apexes of delta complex progradation

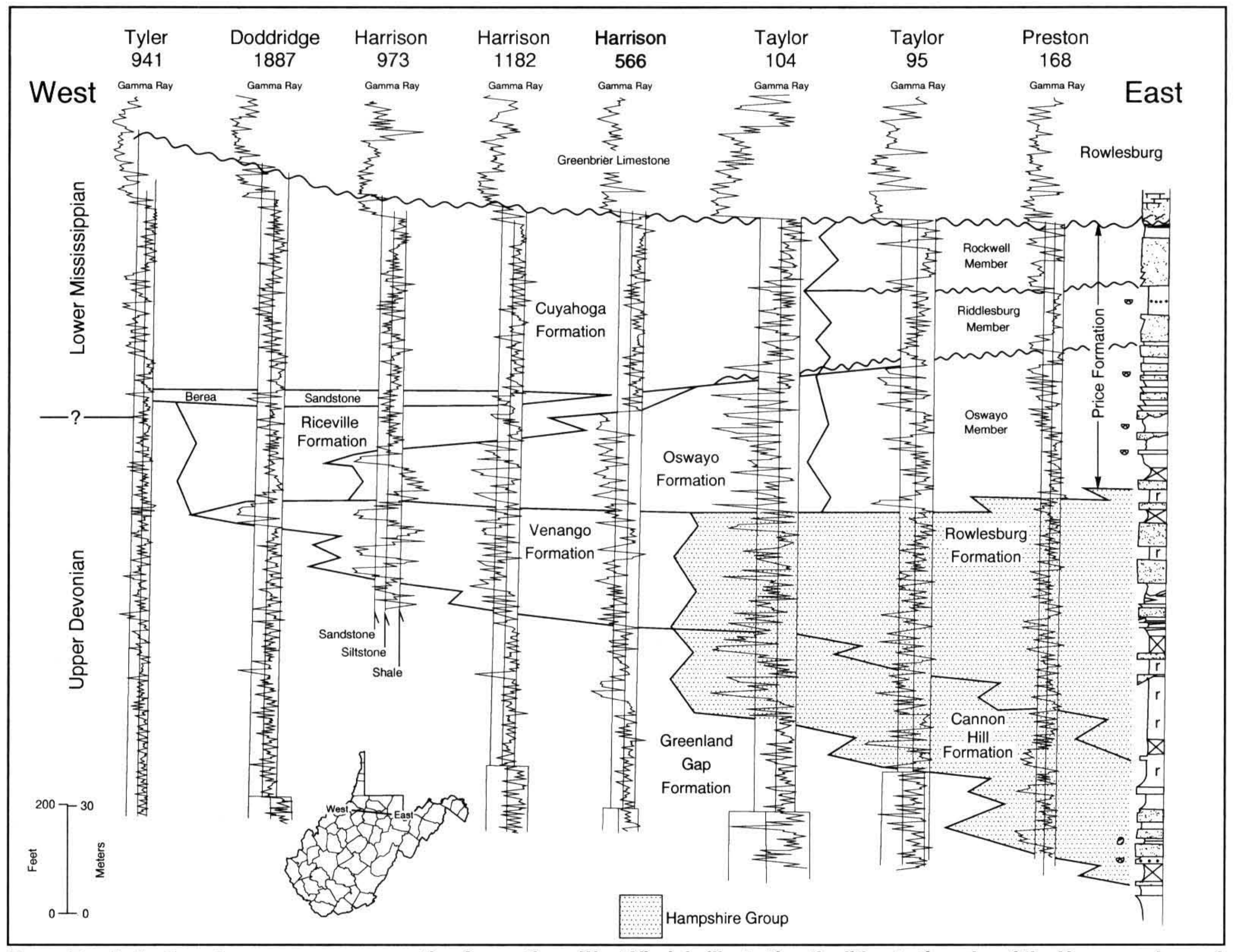


Figure Dvs-5. East-west gamma-ray cross section for northern West Virginia illustrating the lithostratigraphy of the Venango play and its correlation to an outcrop at Rowlesburg, Preston County. Modified from Boswell and others (1987). Areas on the outcrop diagram marked with "r's" are red shales and mudstones. In Pennsylvania, the entirety of the sandstone wedge is typically called the Venango Group, although no internal formations have yet been identified outside the Venango district. Price Formation stratigraphy after Kammer and Bjerstedt (1986). The main reservoirs in this area are the sandstones of the Venango and Oswayo formations at the western terminus of the clastic wedge.

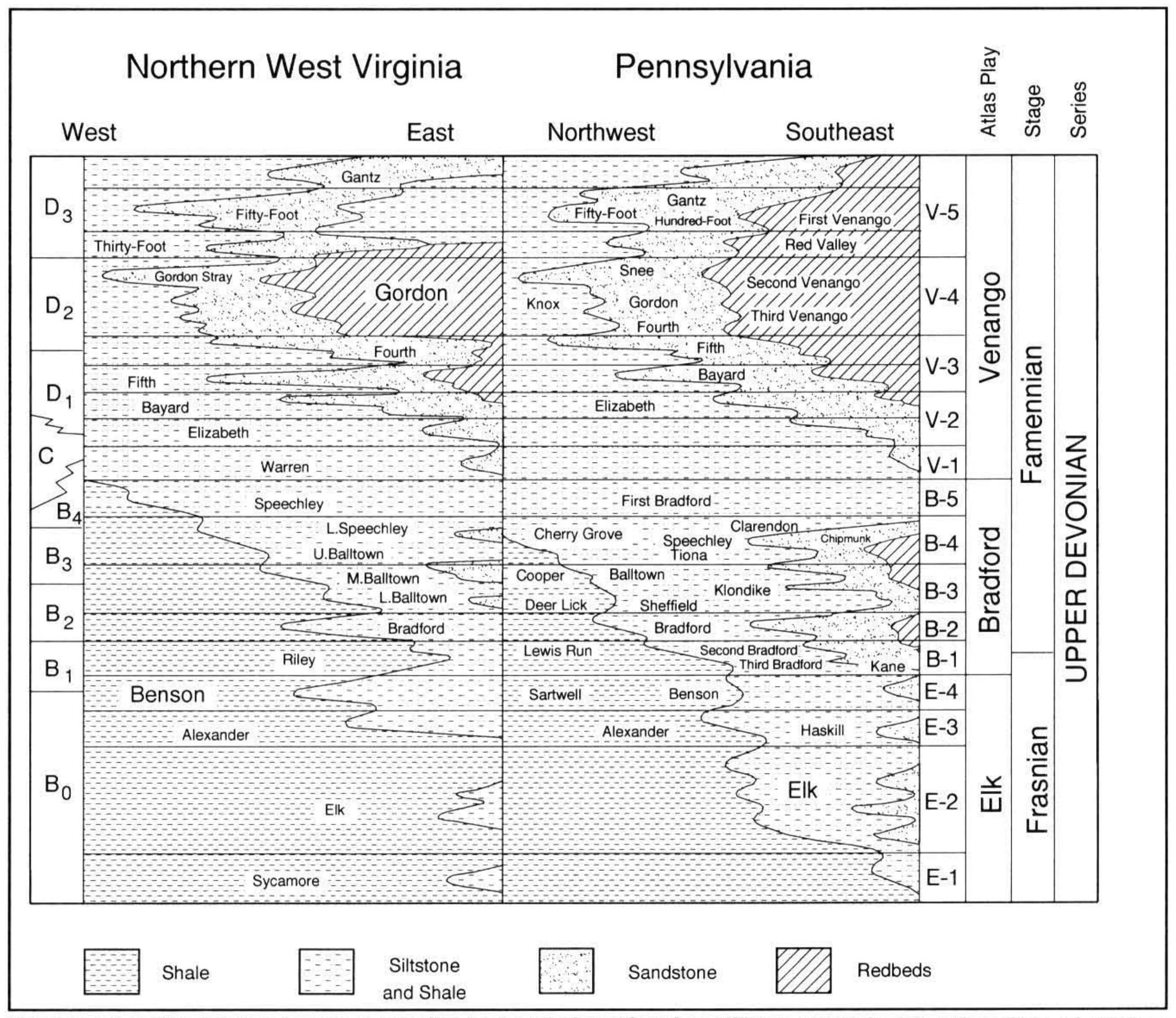
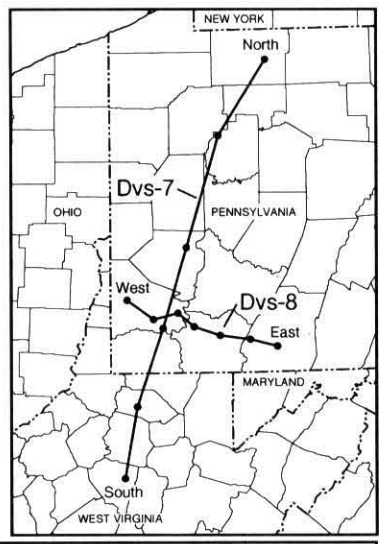


Figure Dvs-6. The sequence and approximate correlation of major drillers' sands in the subsurface of western Pennsylvania and northern West Virginia. Pennsylvania correlations taken largely after Fettke (1938b), Dickey and others (1943), Wolfe (1963), and Harper and Laughrey (1987). West Virginia correlations after Cardwell (1982a), Filer (1985), and Boswell and others (1987). Atlas designations are shown in the column on the right. The terminology of Kelley and Wagner (1970) is given on the left.



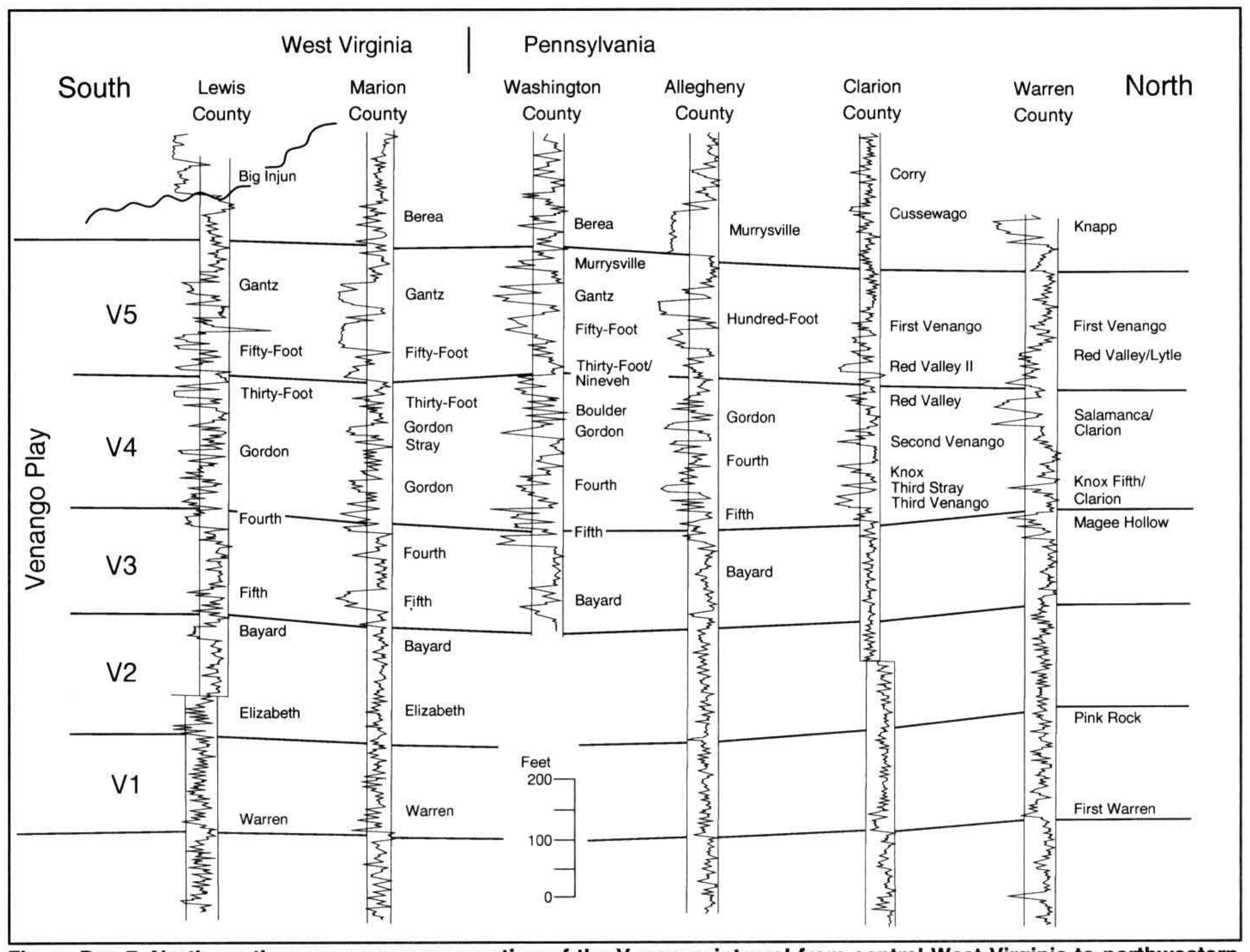


Figure Dvs-7. North-south gamma-ray cross section of the Venango interval from central West Virginia to northwestern Pennsylvania. Designation of intervals V-1 through V-5 are based on regional correlation of Boswell and others (1993). Drillers' names reflect the names most commonly used at that particular horizon in each area. A prominent historical correlation error is the expanded use of the term Gordon in West Virginia, which has resulted in the misnaming of the subadjacent Fifth, Fourth, and Bayard sandstones relative to their original positions in southwestern Pennsylvania. Drillers' names are based on the following: Lewis County, West Virginia, Cardwell (1980); Washington and Allegheny counties, Pennsylvania, McGlade (1967) and Harper and Laughrey (1987); Clarion County, Pennsylvania, Kelley (1967); and Warren County, Pennsylvania, Lytle (1965). No datum or horizontal scale. See locator map for line of cross section.

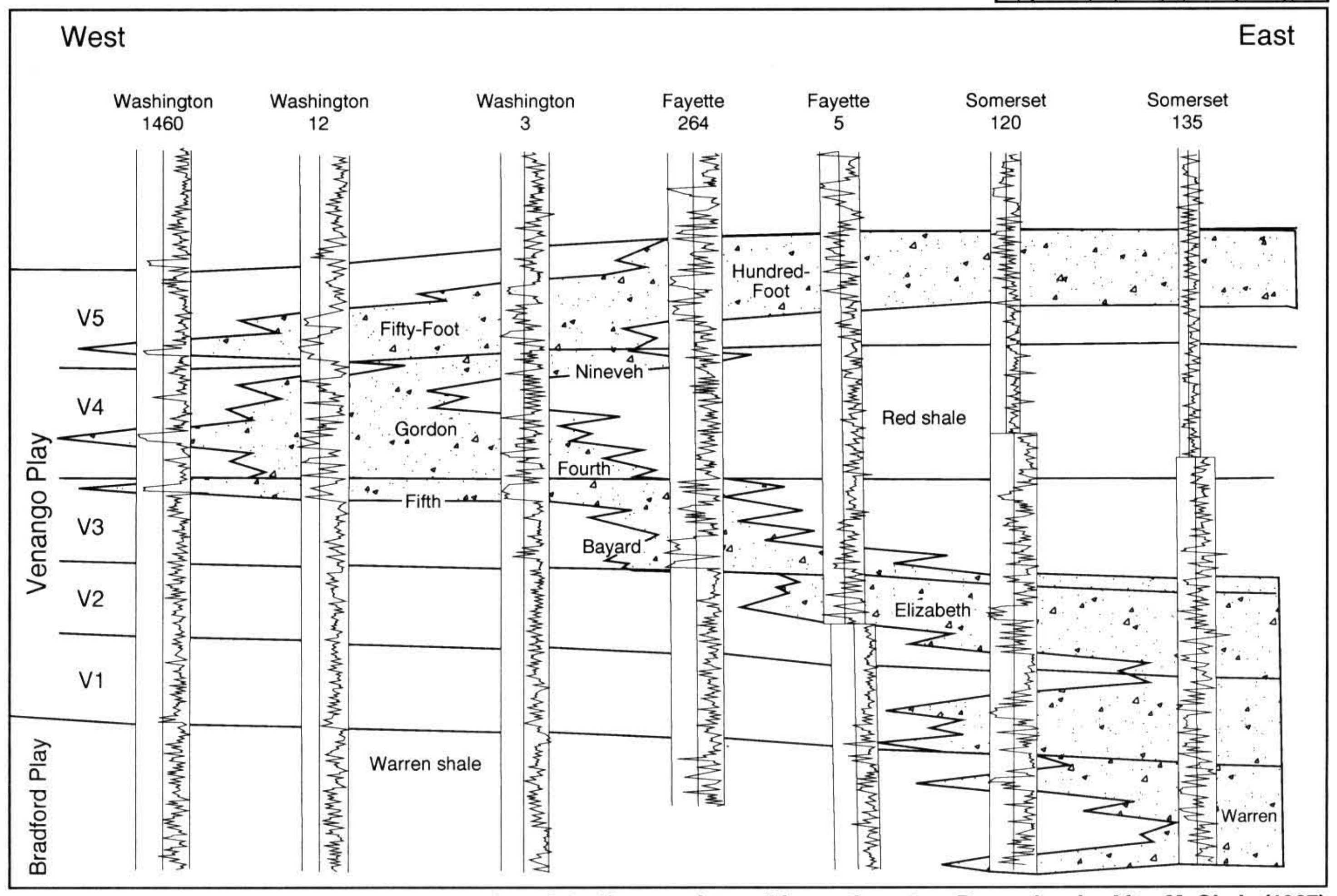


Figure Dvs-8. East-west gamma-ray cross section of the Venango interval in southwestern Pennsylvania. After McGlade (1967) and Harper and Laughrey (1987). Wells are identified by county permit numbers. No datum or horizontal scale. See locator map for line of cross section.

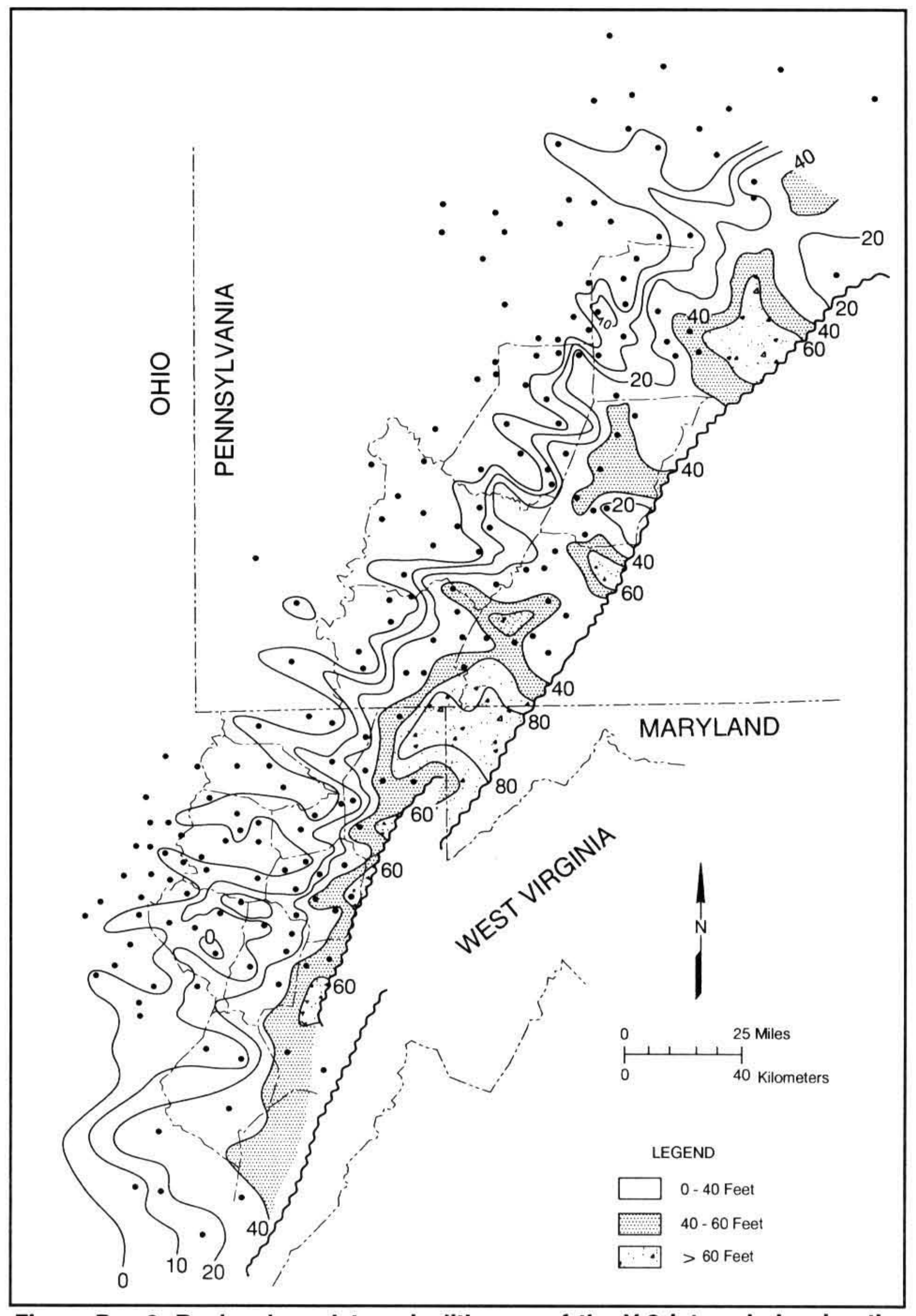


Figure Dvs-9. Regional sandstone isolith map of the V-2 interval showing the irregular, dip-trending nature of regional sandstone distribution typical of lower Venango intervals. Sandstone was determined using 50 percent clean sand gamma-ray baseline method. From Boswell and others (1993). Dots indicate gamma-ray well logs used in the construction of the map.

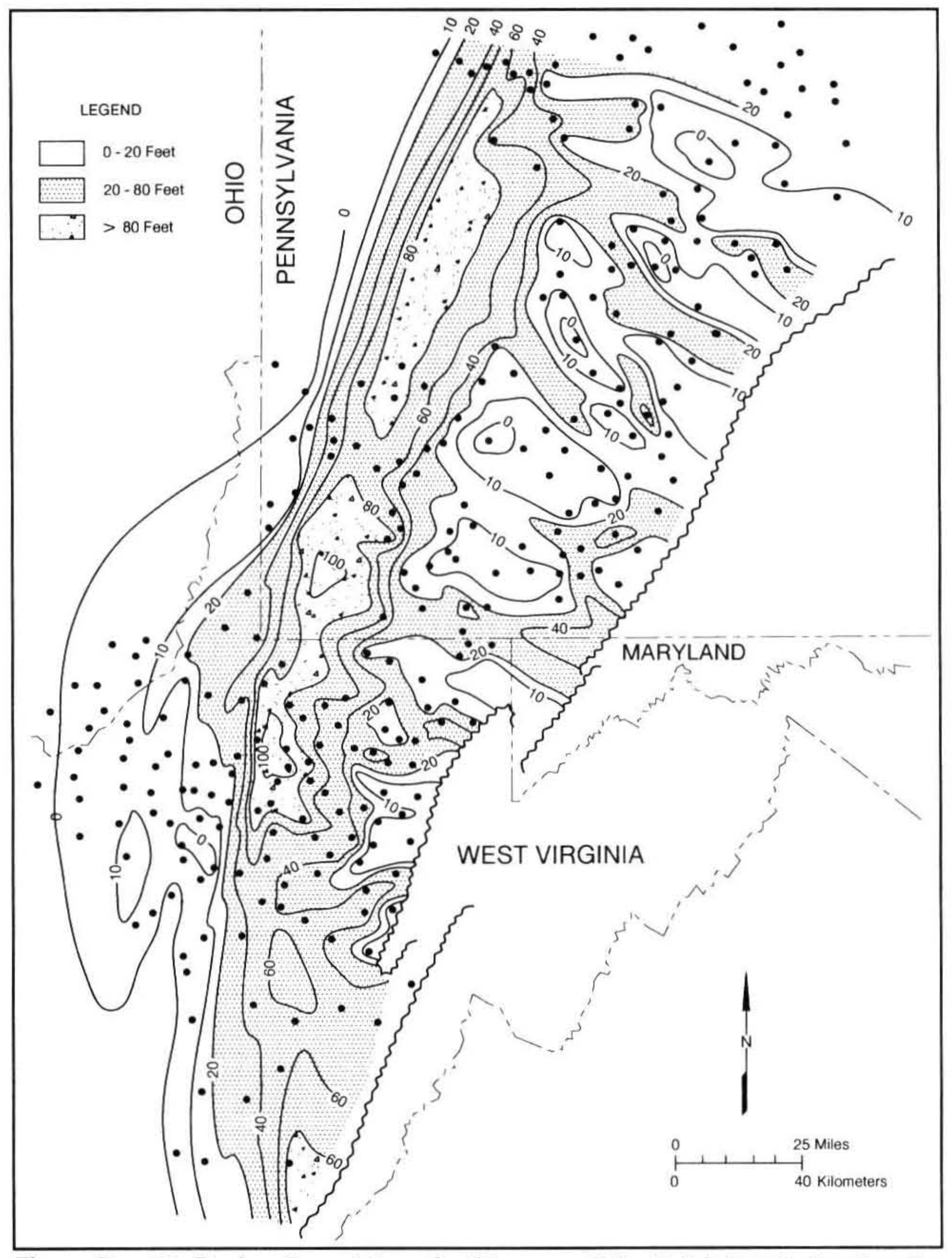
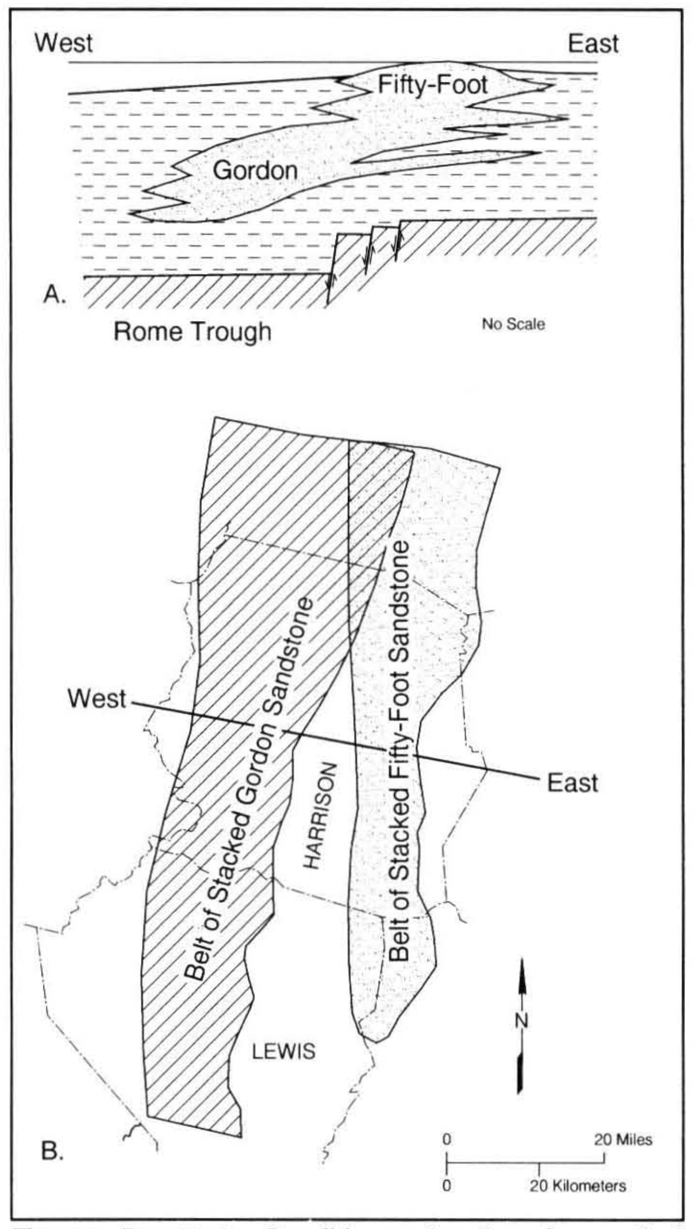


Figure Dvs-10. Regional sandstone isolith map of the V-4 interval showing the strike-trending nature of the unit. Sandstone was determined using 50 percent clean sand gamma-ray baseline method. From Boswell and others (1993). Dots indicate gamma-ray logs used in the construction of the map.



Figures Dvs-11a-b. Possible explanation for vertical stacking of Gordon (V-4) and Fifty-Foot (V-5) sandstones in northern West Virginia as the consequence of differential subsidence across the eastern margin of the Rome trough. From Boswell (1988a). Progradation of regressive Gordon shoreline sandstones may have been halted by a linear zone of subsidence, resulting in vertically stacked sandstones in a linear trend to the west of the inferred basement fault. During subsequent regional transgression, offshore sandbars are localized over relative structural high. Figure Dvs-5 shows the relationship between these units and an outcrop to the east, most notably the transition from non-marine to marine facies at the boundary between the Gordon and Fifty-Foot units.

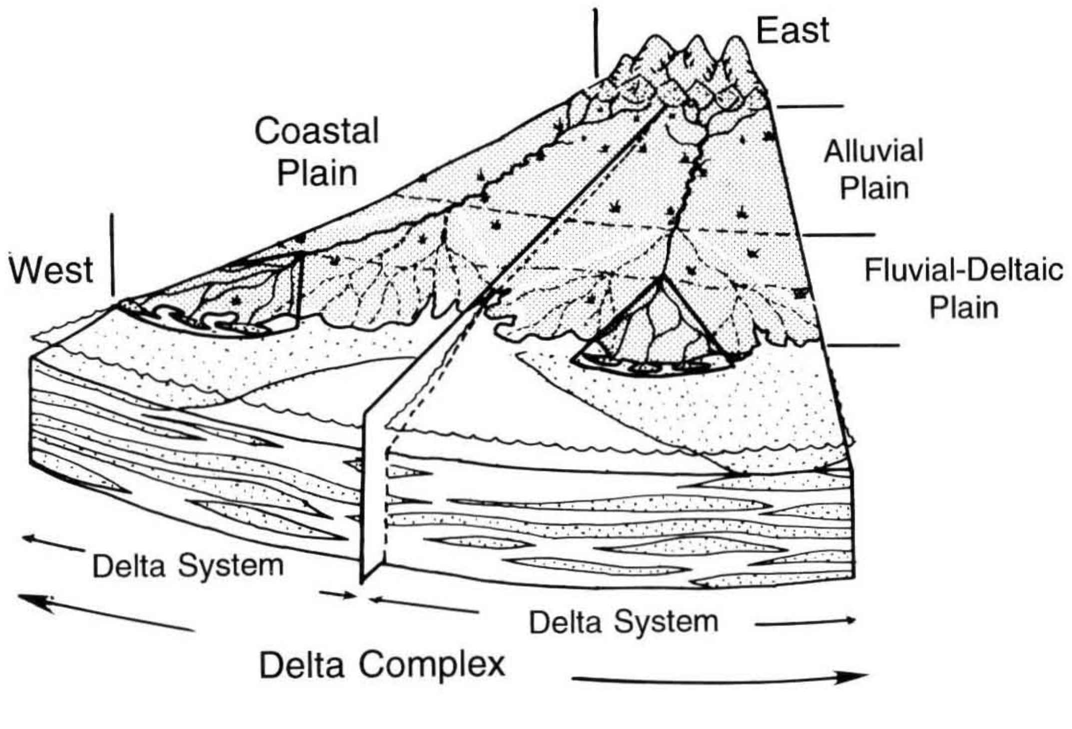


Figure Dvs-12a.

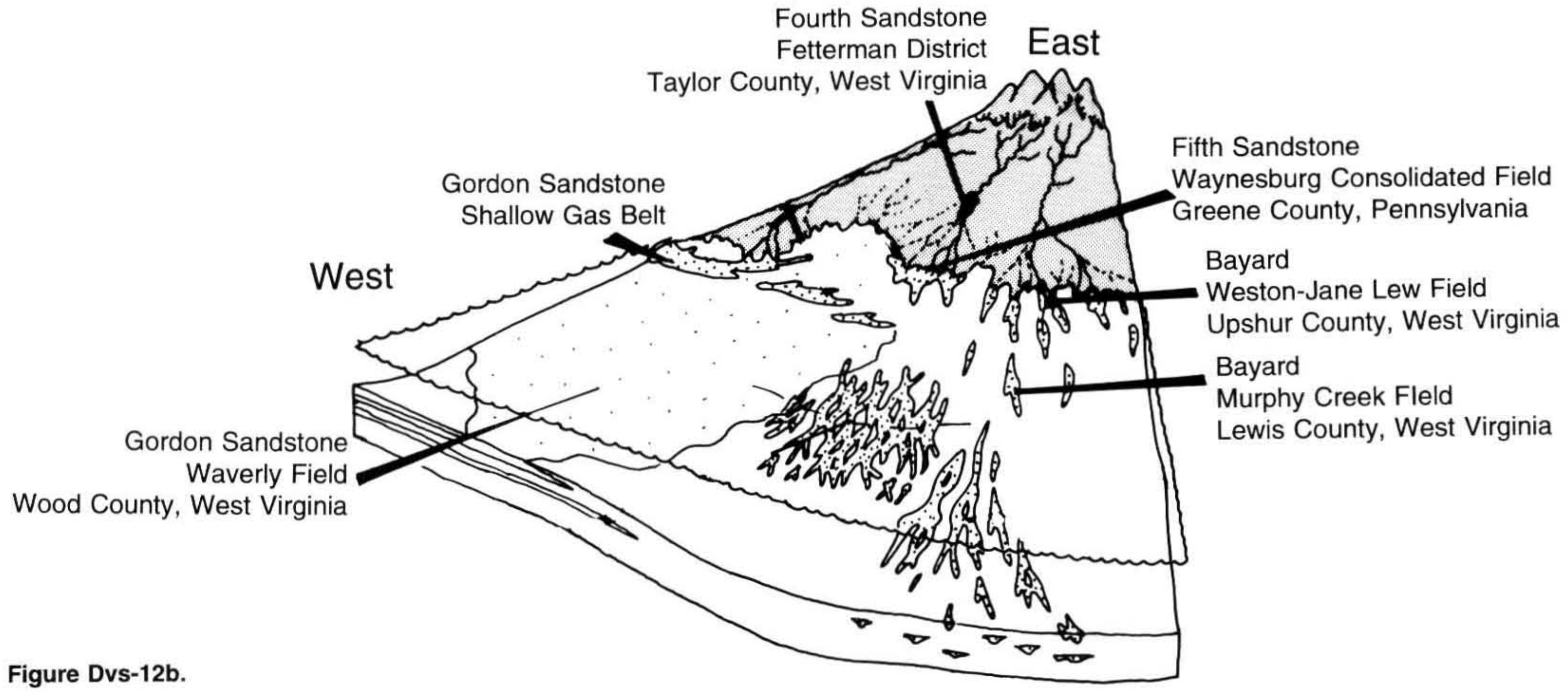


Figure Dvs-12b.

Figures Dvs-12a-b. Dvs-12a. Schematic diagram of interpreted Catskill delta complex depositional environments showing the multiple-river architecture (Boswell and Donaldson, 1988). Dvs-12b. Schematic illustration of the variation in reservoir geometry observed in Venango reservoirs. Modified from Boswell and Jewell (1988).

(Boswell and Donaldson, 1988). Conglomerates are not uncommon in these units. Such strike trends may occur at any level, but are most common in intervals V-3, V-4, and V-5. In contrast, progradational units, such as those typical of the V-1 and V-2 intervals, are commonly more digitate in shape, reflecting greater fluvial dominance over the distribution of sand delivered to the shoreline (Boswell and Jewell, 1988). These dip trends also contain good quality reservoirs; however, they are more lenticular, resulting in erratic production.

Venango reservoirs occur at depths ranging from less than 1,000 feet in northern Pennsylvania to roughly 3,500 feet in central West Virginia. The total thickness of sandstone in the interval varies from 0 to more than 200 feet and decreases rapidly westward and more slowly eastward of the main sandstone belt. Individual sandstones in excess of 50 feet are rare, with 15 to 20 feet being most common. Reservoir quality is also highest within the main belt, with the reservoirs rapidly shaling out to the west and becoming more lenticular, immature, and well cemented to the east. Original rock pressure varies widely (see Wyer, 1918), although values between 500 and 600 psi are most common (Moyer, 1933). Porosity is generally intergranular (Harper and Laughrey, 1987). Maximum porosities within the shallow gas belt commonly range from 18 to 25 percent; permeabilities are also high, ranging from 10 to 500 md with some values in excess of 1,000 md (Dickey, 1941; Harper and Laughrey, 1987). However, porosity and permeability to the east and west of the shallow gas belt rarely exceeds 6 percent and 0.1 md, respectively (see Laughrey and Harper, 1986). The results of a regional averaging of the characteristics of Venango reservoirs (Boswell and others, 1993) are presented in Table Dvs-3.

Production data for typical wells completed in Venango reservoirs are greatly limited. Shaw and Munn (1911) report that many early Venango wells in northern Washington County, Pennsylvania, reported initial potentials ranging from 5,000 to 30,000 Mcfg/d and that it was not uncommon for wells to produce from 50 to 500 Mcfg/d 10 or 20 years later. On the other hand, McGlade (1967) reported that Fifty-Foot sandstone and Bayard sandstone wells in southern Washington County reported typical IPs of 500 Mcfg/d. Cardwell (1978) reported that cumulative production from the Gordon sandstone in the Cameron field, Marshall County, West Virginia, was 75 bcfg for 357 wells, or 212 MMcfg per well, which may be typical of the early fields.

Description of Key Fields

Waynesburg Consolidated field: The Waynesburg Consolidated field, Greene County, Pennsylvania (Figure Dvs-2), is typical of the prolific gas fields within the main strike-trending Venango sandstone belt. The field includes seven gas fields that were discovered and developed from 1889 to 1930 (Harper and Laughrey, 1987). Production began with the discovery of high-volume wells in the Fifth (V-3), Bayard (V-3), and Elizabeth (V-2) sandstones. By 1905, more than 1,000 wells had been drilled in Greene County (Stone and Clapp, 1907). Ashley and Robinson (1922) reported that one early well had an IP as high as 60,000 Mcfg/d. From 1922 to 1927, natural gas production from Greene County averaged 17.9 bcf per year from roughly 1,700 wells (Moyer, 1933). By 1930, development

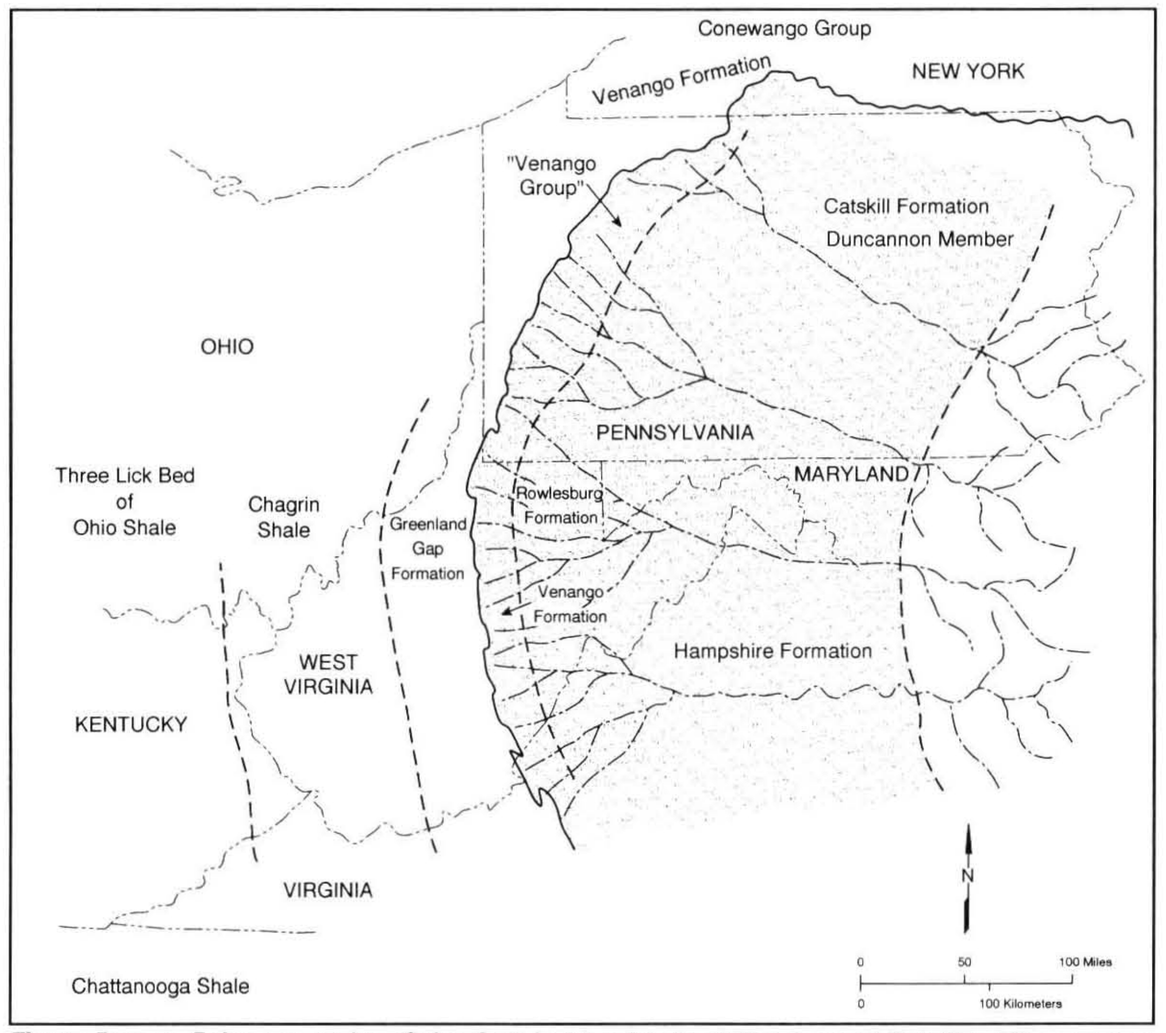


Figure Dvs-13. Paleogeography of the Appalachian basin at the apex of Catskill delta complex progradation (deposition of the Gordon/Second Venango sandstones (V-4)). From Boswell (1988b). The prolific oil and gas reservoirs form a narrow belt that parallels the interpreted shoreline trend. Stratigraphic terminology is based largely on Boswell and others (1987) and Woodrow and others (1988). Shaded area represents land.

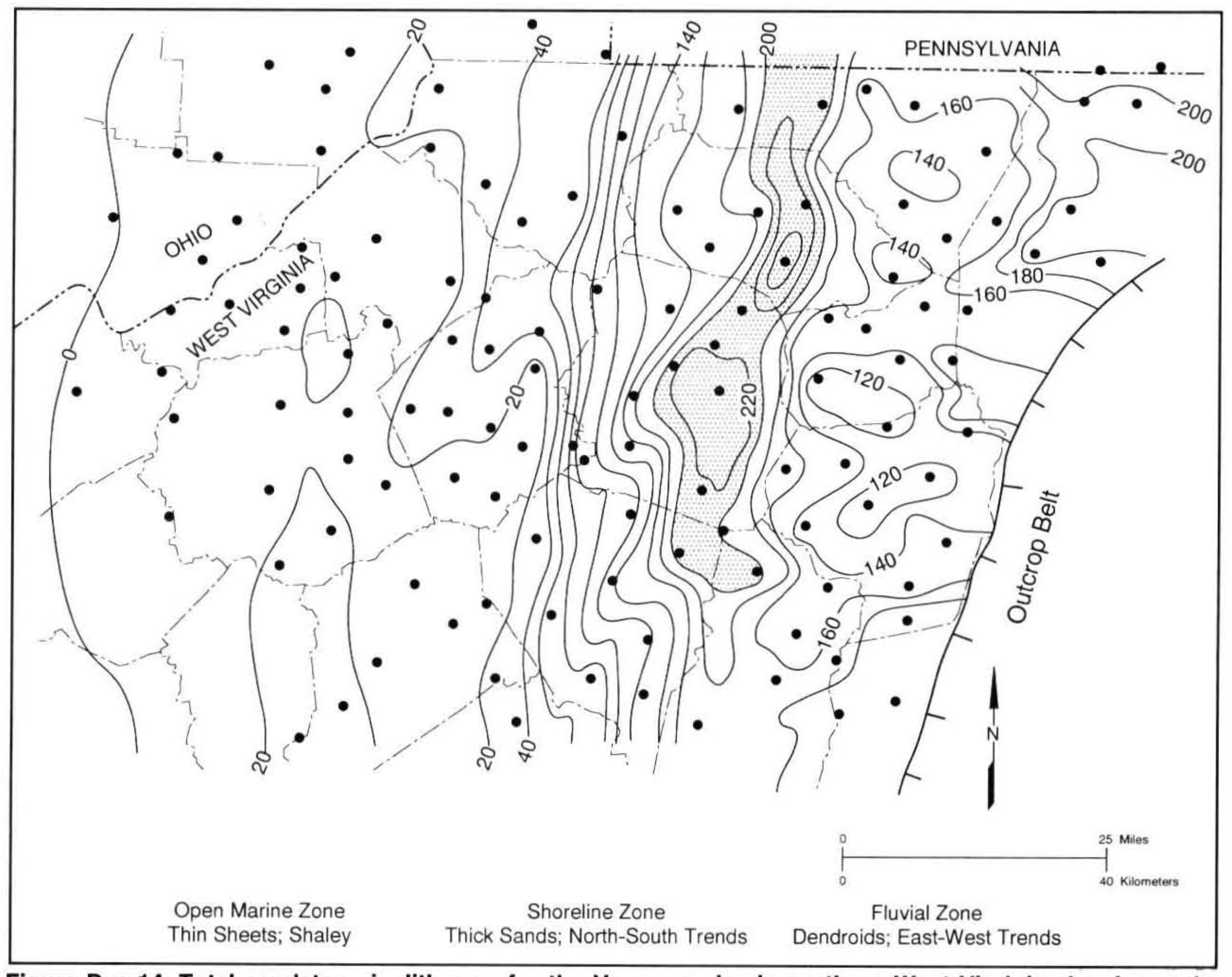


Figure Dvs-14. Total sandstone isolith map for the Venango play in northern West Virginia showing major facies of sandstone occurrence. The marine shelf facies is dominated by siltstone with only minor sandstone. The shoreline facies is represented by thick belts of stacked, coarse-grained sand that was deposited along or parallel to the shoreline. Further to the east, landward facies consist of interlocked dendroids of sandstone encased in red shale. Sandstone was determined using 50 percent clean sand gamma-ray baseline method. See Figure Dvs-5 for the relationship between this interval and the lithologies recorded in an outcrop at Rowlesburg. Stippling indicates greater than 200-foot thickness. Contour interval = 20 feet.

TABLE Dvs-1		Murphy Creek WV	Murphy Creek WV	Wolf Summit WV	Fetterman WV	Weston-Jane Lew WV	Waynesburg PA	Latrobe PA
BASIC RESERVOIR DATA	POOL NUMBER	47150423	47150419	47106419	47373421	47153423		
	DISCOVERED	1910	1900	1897	1985	1911	1895	1907
	DEPTH TO TOP RESERVOIR	2,650	2,372	2,646	2,139	2,445	2,544	2,540
	AGE OF RESERVOIR	Upper Devonian	Upper Devonian	Upper Devonian	Upper Devonian	Upper Devonian	Upper Devonian	Upper Devonian
	FORMATION	Greenland Gap	Venango	Venango	Hampshire	Greenland Gap	Venango	Venango
	PRODUCING RESERVOIR	Bayard	Gordon	Gordon	Fourth	Bayard	All	All
	LITHOLOGY	sandstone/ siltstone	sandstone/ siltstone	sandstone/ siltstone	sandstone/ siltstone	sandstone/ siltstone	sandstone	sandstone
	TRAP TYPE	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic
	DEPOSITIONAL ENVIRONMENT	nearshore	nearshore	nearshore	nearshore	nearshore	shoreline	shoreline
	DISCOVERY WELL IP (Mcf)						10,000	
	DRIVE MECHANISM	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion
	NO. PRODUCING WELLS	152	107	12	53	41	158	71
	NO. ABANDONED WELLS	3	154	11	0	19	46	6
	AREA (acreage)				3,392		38,000	2,802
	OLDEST FORMATION PENETRATED	Helderberg	Helderberg		Brallier		Helderberg	Bradford
	EXPECTED HETEROGENEITY DUE TO:	stratigraphic	stratigraphic				stratigraphic	stratigraphic
RESERVOIR PARAMETERS	AVERAGE PAY THICKNESS (ft.)	9	10.8	24.8	25	11	39	41
	AVERAGE COMPLETION THICKNESS (ft.)	10	13	27	29	13		
	AVERAGE POROSITY–LOG (%)	10.37	10.54	6.26		9.6		7.5
	MINIMUM POROSITY–LOG (%)	6.7	5.2	4	8	12.63	10	3.9
	MAXIMUM POROSITY–LOG (%)	17.91	20.63	7.5	15	17.01	30	15.6
	NO. DATA POINTS	78	30	5		19		
	POROSITY FEET	0.9	1	1.6				
	RESERVOIR TEMPERATURE (°F)	83	79		78	91		
	INITIAL RESERVOIR PRESSURE (psi)	1,020	900		665	1,085	725	1,146
	PRODUCING INTERVAL DEPTHS (ft.)	2,230-3,192	1,950-2,900	2,200-2,970	1,774-2,507	2,100-3,658		
	PRESENT RESERVOIR PRESSURE (psi) / DATE	364/1984	96/1968	133/1980		513/1986		
FLUID & GAS PROPERTIES	Rw (Ωm)	0.05	0.05	0.05	0.05	0.05		
	GAS GRAVITY (g/cc)		0.727					
	GAS SATURATION (%)	54.67	55.15	61.86		62.79		
	WATER SATURATION (%)	45.33	44.85	38.14		37.21		
	COMMINGLED	yes	yes	no	yes	no		
	ASSOCIATED OR NONASSOCIATED	associated	associated	associated	nonassociated	associated		
	Btu/scf		1,260					
VOLUMETRIC DATA	STATUS (producing, abandoned, storage)	producing			producing			
	ORIGINAL GAS IN PLACE (Mcf)							
	ORIGINAL GAS RESERVES (Mcf)							
	PRODUCTION YEARS	1978-1993	1901-1993	1982-1992	1985-1992	1978-1993		
	REPORTED CUMULATIVE PRODUCTION (Mcf)	1,538,200	3,070,700	11,900	1,637,500	507,600		
	NO. WELLS REPORTED	19	26	2	15	11		
	ESTIMATED CUMULATIVE PRODUCTION (Mcf)							
	REMAINING GAS IN PLACE (Mcf)/DATE							
	REMAINING GAS RESERVES (Mcf)/DATE							
	RECOVERY FACTOR (%)							
	INITIAL OPEN FLOW (Mcf/d)	440	6,540		109	177		
	FINAL OPEN FLOW (Mcf/d)	565	475		1,574	594		

Table Dvs-2. Representative compositional analyses of natural gases from Venango reservoirs. Sources are 1, White (1904); 2, Hickock (1933); 3, Laughrey and Harper (1986); and 4, Harper and Laughrey (1987).

Source	County	Pool	Reservoir	Btu/ft	Meth	Eth	Othe	He	H_2	N_2	CO	CO_2	H_2S	O_2
2	Greene, Pennsylvania		Gantz	1,005	90.5	4.9	0.4	0.20		4.0				
2	Washington, Pennsylvania	Amity	Gantz	1,169	83.8	7.5	5.9	0.12		2.5		0.1	0.1	
2	Washington, Pennsylvania	Rodfield	Gantz	1,071	92.1	4.9	1.8	0.07		0.9		0.2		
4	Harrison, West Virginia	Shinnston	Fifty-foot	1,065	86.5	7.7	0.6			4.9	0.5			0.3
2	Allegheny, Pennsylvania	Forward	Fifty-foot	1,085	91.9	4.0	2.4	0.11		1.4		0.1		0.1
2	Greene, Pennsylvania	McCracken	Fifty-foot	1,330	75.4	11.1	11.4	0.10		1.8		0.2		
2	Washington, Pennsylvania	Vanceville	Fifty-foot	1,095	91.5	4.3	2.6	0.09		1.3		0.1	0.1	
2	Washington, Pennsylvania	Rodfield	Fifty-foot	1,069	93.8	2.9	1.9	0.15		1.2		0.1		
2	Allegheny, Pennsylvania	Rennerdale	Gordon	1,269	80.1	10.9	7.9	0.10		0.8		0.1	0.1	
2	Greene, Pennsylvania	New Freeport	Gordon	1,227	71.8	27.8	0.0	0.11		0.1		0.1		0.1
4	Harrison, West Virginia	Shinnston	Gordon	1,144	80.9	14.9	0.5		0.1	3.5	0.4			0.1
2	Washington, Pennsylvania	Amity	Fifth	1,088	89.5	6.0	2.4	0.11		1.7		0.2		0.1
4	Harrison, West Virginia	Lumberport	Fifth	1,131	80.7	14.4	0.4		0.1	4.0	0.4	0.1		0.3
2	Allegheny, Pennsylvania	Forward	Bayard	1,045	93.8	3.5	1.0	0.07		1.4		0.2		
2	Greene, Pennsylvania	Jefferson	Bayard	1,056	92.0	3.9	0.6	0.12		3.0		0.1		0.3
2	Greene, Pennsylvania	Fordyce	Bayard	1,076	91.9	5.2	1.6	0.09		1.0		0.1	0.1	
2	Greene, Pennsylvania	Waynesburg	Bayard	1,099	82.8	14.4	0.0	0.10		1.8				0.9
2	Greene, Pennsylvania	Garrison	Bayard	1,614	56.3	21.3	21.5	0.05		0.8		0.1		
4	Marion, West Virginia	Fairmont	Bayard	1,136	81.6	14.1	0.6		0.2	3.2	0.4	0.1		0.2
2	Allegheny, Pennsylvania	Elizabeth	Elizabeth	1,131	88.3	6.2	3.9	0.09		1.4		0.1		
2	Allegheny, Pennsylvania	Mifflin	Elizabeth	1,062	93.1	3.5	1.7	Trace		1.6				0.1
2	Greene, Pennsylvania	Carmichaels	Elizabeth	1,133	88.2	6.6	3.9	0.08		1.1		0.1		
2	Greene, Pennsylvania	Jefferson	Elizabeth	1,108	90.2.	5.2	3.0	0.10	0.1	1.2		0.1	0.1	

Table Dvs-3. Average reservoir characteristics of Venango reservoirs in the Appalachian basin based on analysis of 280 randomly selected well log suites. After Boswell and others (1993). These data represent the average characteristics of Venango sandstones in areas outside the shallow gas belt.

	Interval				
	V-1	V-2	V-3	V-4	V-5
Porosity (%)	7.0	7.2	7.9	7.9	6.9
Water Saturation (%)	54	49	53	52	47
Sandstone (ft.)	16.4	16.8	21.5	18.0	51.0
Pay Thickness (ft.)	8.8	9.8	13.1	10.0	26.0

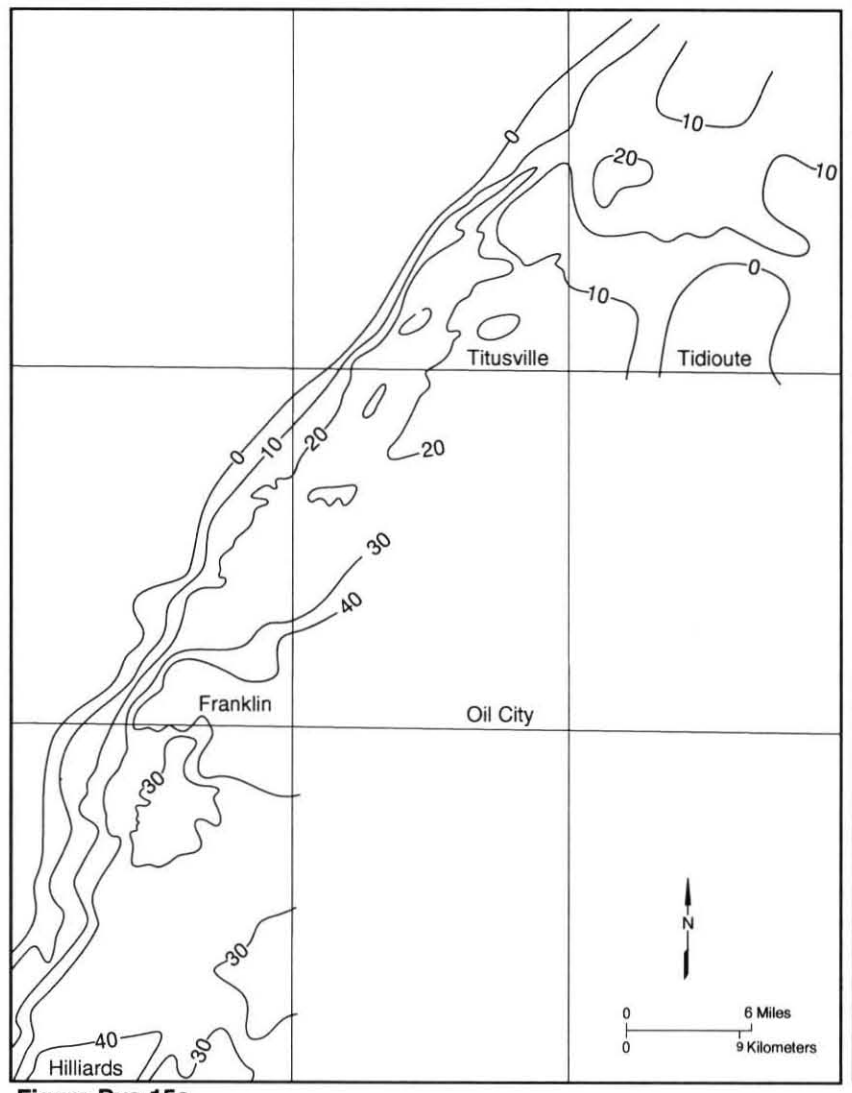


Figure Dvs-15a.

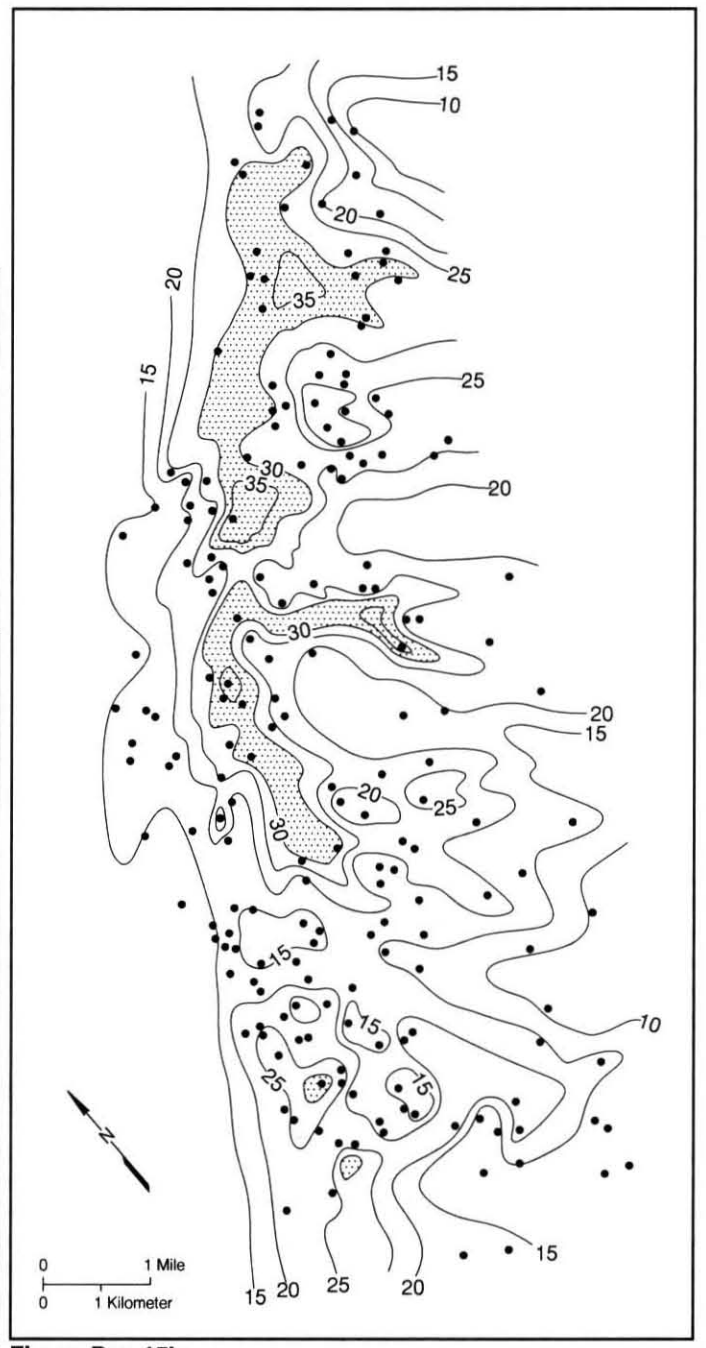


Figure Dvs-15b.

Figures Dvs-15a-b. Examples of strike-trending sandstones typical of the historic Venango oil and gas fields. Dvs-15a. Second Venango sandstone (V-2), Venango County, Pennsylvania. Names refer to 15-minute quadrangles. After Dickey and others (1941). See Figure Dvs-17 for location. Dvs-15b. McDonald (Fifth) sandstone (V-3), McDonald field, Allegheny and Washington counties, Pennsylvania. After Ingham and others (1949). Stippling indicates greater than 30-foot thickness. See Figure Dvs-17 for location. Contour interval = 5 feet.

drilling around the major early fields showed most of the intervening areas also to be productive (Stone, 1932).

In general, gas production in southwestern Pennsylvania was obtained from the western edges of the basal sandstones present in the Venango section. Although the overall belt of sandstone and the area of production are extensive, individual productive sandstones are lenticular (Figure Dvs-16). In the western half of Greene County, production was derived mainly from the Gordon and Fifty-Foot sandstones (V-4 and V-5), whereas to the east the bulk of the production was derived from the Fifth and Bayard sandstones (V-3). A regional sandstone isolith of the V-3 interval is presented as Figure Dvs-17. Harper and Laughrey (1987) correlated the productive units of the area to nearby outcrops (Figure Dvs-18). Porosities in shoreline sandstones ranged from 10 to 30 percent with average permeability of roughly 200 md, whereas fluvial channel facies were found to have porosities ranging from only 2 to 12 percent, with an average permeability of 9.2 md. Reservoir pressures probably ranged between 650 and 800 psi. Presently, the Venango reservoirs of Greene County are largely depleted, with several sections converted to gas storage.

Fetterman district: Recent development of the Fourth sandstone in Taylor County, West Virginia (Figure Dvs-2), provides an example of current exploration strategies for Venango reservoirs outside the shallow gas belt. In the late 1980s, exploration of the deeper Benson sandstone (see A. Donaldson and others, Upper Devonian Elk sandstones, this atlas) revealed porous and permeable Upper Fourth sandstone (V-3) at depths of approximately 2,000 feet. Delineation drilling and regional correlation throughout neighboring Marion, Monongalia, and Preston counties suggested that the sandstone occurred in a channel morphology (Figure Dvs-19). Several productive trends with varying orientations have been identified. Net sandstone and net pay maps of a portion of the unit reveal narrow, elongate, and remarkably straight zones of gas-charged sandstone (Figures Dvs-20, Dvs-21). The productive area is roughly 1 mile wide; however, the best reservoir quality is restricted to a zone commonly only 1,500 feet wide. Petrographic analyses show that the quartz grains are highly angular. Furthermore, the grains are coated with hematite, which gives the rock a pale red color and increases formation conductivity so that the unit appears water-saturated on the resistivity log. The unit may be regional in extent: correlative low-resistivity sandstones have produced gas in east-central Fayette County, Pennsylvania (Figure Dvs-22). Core-derived porosities and permeabilities from the pay zone range from 8 to more than 15 percent and from 0.1 to 2.9 md, respectively. The majority of the wells are hydraulically fractured, although exceptional wells have produced economically without stimulation. Reported initial potentials range from 20 to 200 Mcfg/d before treatment and from 500 to 1,500 Mcfg/d after treatment.

Murphy Creek and Weston-Jane Lew fields: The historic Murphy Creek and Weston-Jane Lew fields of northern Lewis and Upshur counties, West Virginia (Figure Dvs-2), have recently obtained production from a porous lens of Bayard sandstone (V-4) that lies less than 100 feet stratigraphically below the main Fifth sandstone (V-3) reservoir (Figure Dvs-23). The Bayard was not fully appreciated in this area until the mid-1980s when extensive log data from deeper Benson drilling was utilized. The sandstone differs significantly from the overlying units in that it is oriented east-west (Figure Dvs-24). Cores revealed that the unit contains thick sections of clean, very fine-grained sandstone with porosity ranging from 7 to 14 percent (Figure Dvs-25). This sandstone formed during a major regional regression and is interpreted to progress through distributary channel, mouth bar, and prodelta submarine channel environments as traced westward across northern Lewis and Upshur counties, West Virginia (Figure Dvs-26). Sporadic wells within the Bayard were found to be depleted,

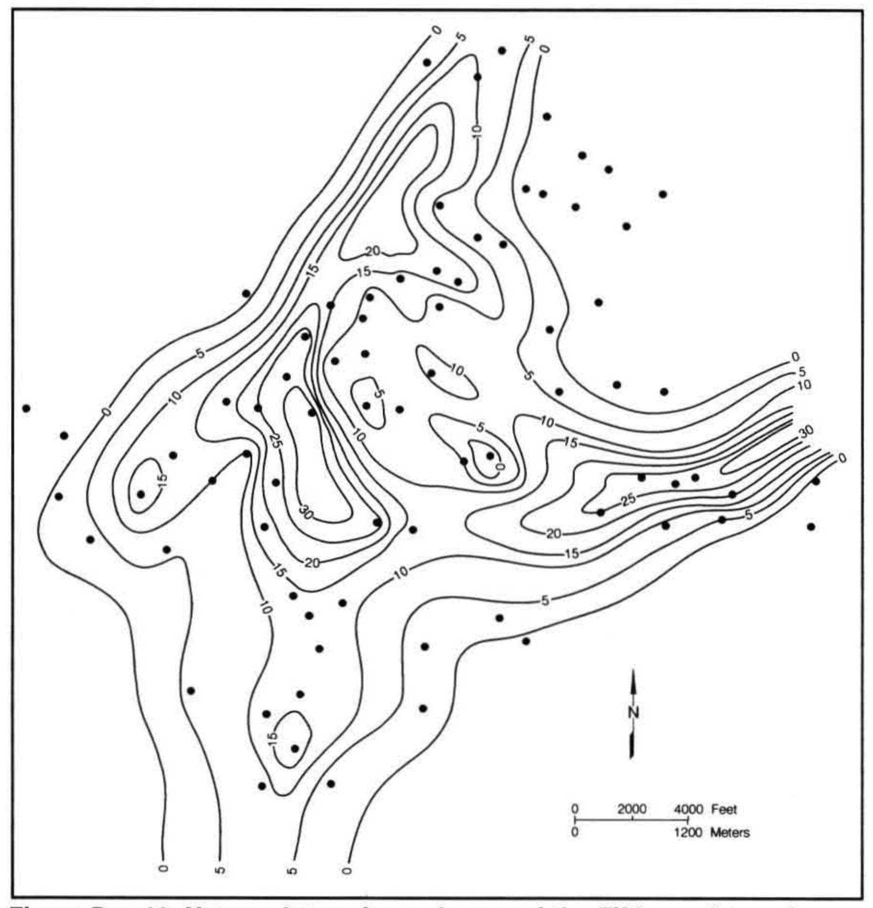


Figure Dvs-16. Net sandstone isopach map of the Fifth sandstone in one part of the Waynesburg Consolidated field, Greene County, Pennsylvania. The unit shows an overall strike-trend that thins to the north and south and is modified by a major dip-trending accumulation. Name and location of the field held confidential upon request. Sandstone was determined using 75 percent baseline gamma-ray method. Dots represent gamma-ray well log control. Contour interval = 5 feet.

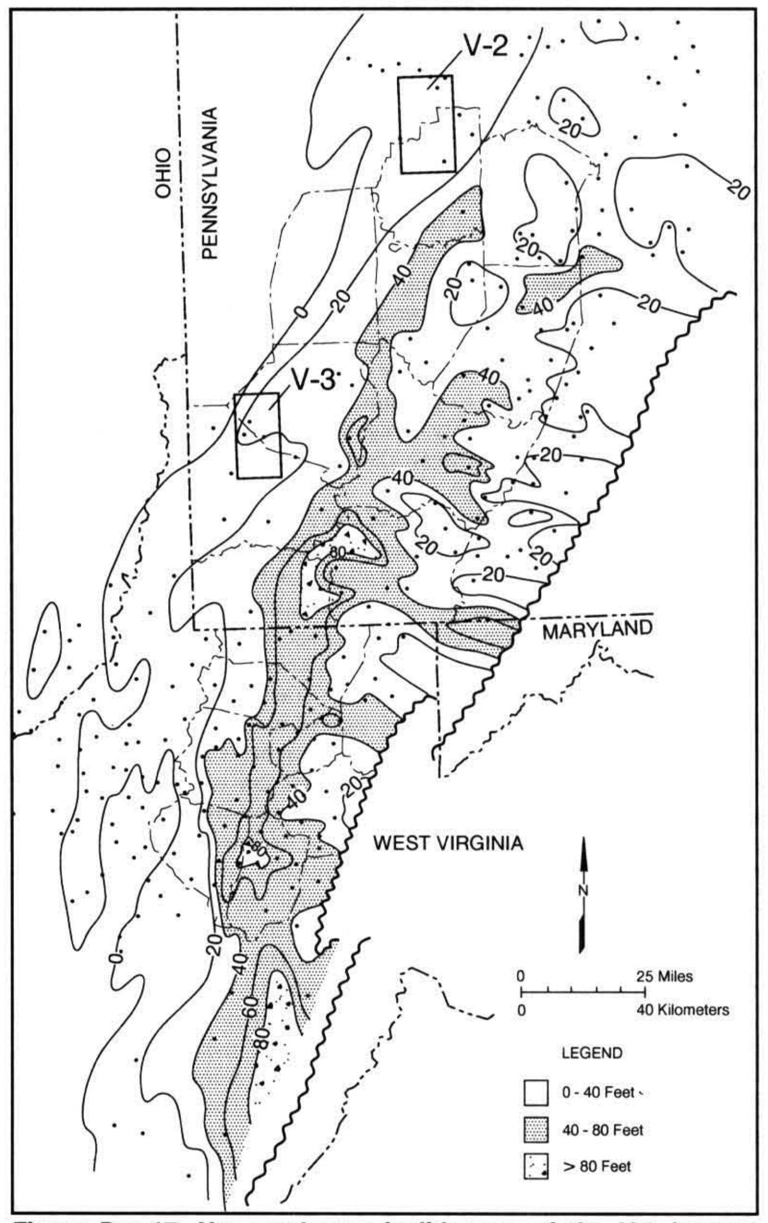


Figure Dvs-17. Net sandstone isolith map of the V-3 interval (Fourth and Fifth of West Virginia; Fifth and Bayard of Pennsylvania). Sandstone was determined using 50 percent clean sand gamma-ray baseline method. After Boswell and others (1993). This interval includes the productive sandstones within the eastern half of Greene County, Pennsylvania. See Figure Dvs-7 to note the change in typical drillers' names for reservoirs within this interval along strike. Location of Figures Dvs-15a (V-2) and Dvs-15b (V-3) are also shown.

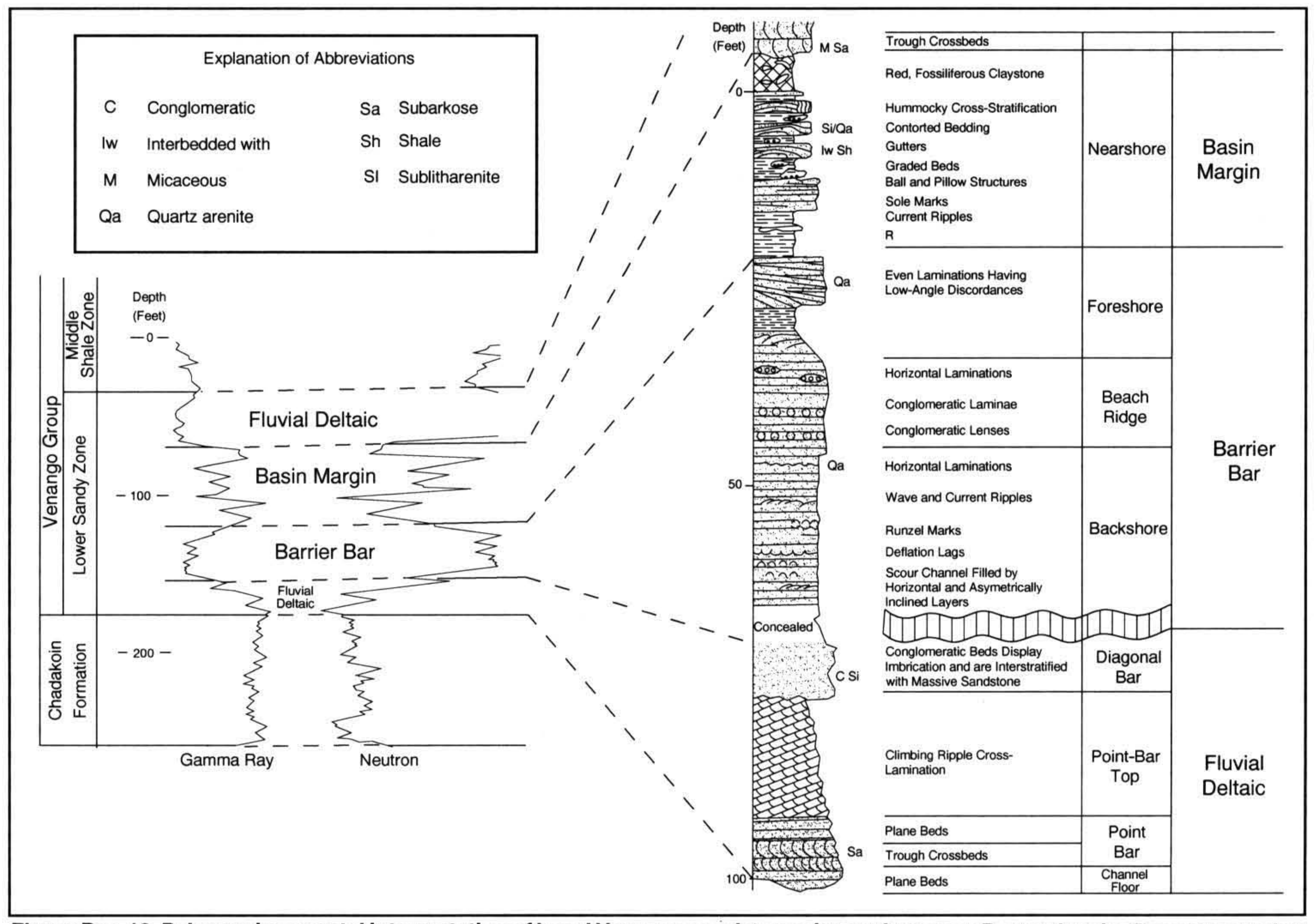


Figure Dvs-18. Paleoenvironmental interpretation of basal Venango sandstones in southwestern Pennsylvania. The units studied in outcrop are analogous to the younger productive sandstones in the Waynesburg Consolidated field. After Harper and Laughrey (1987).

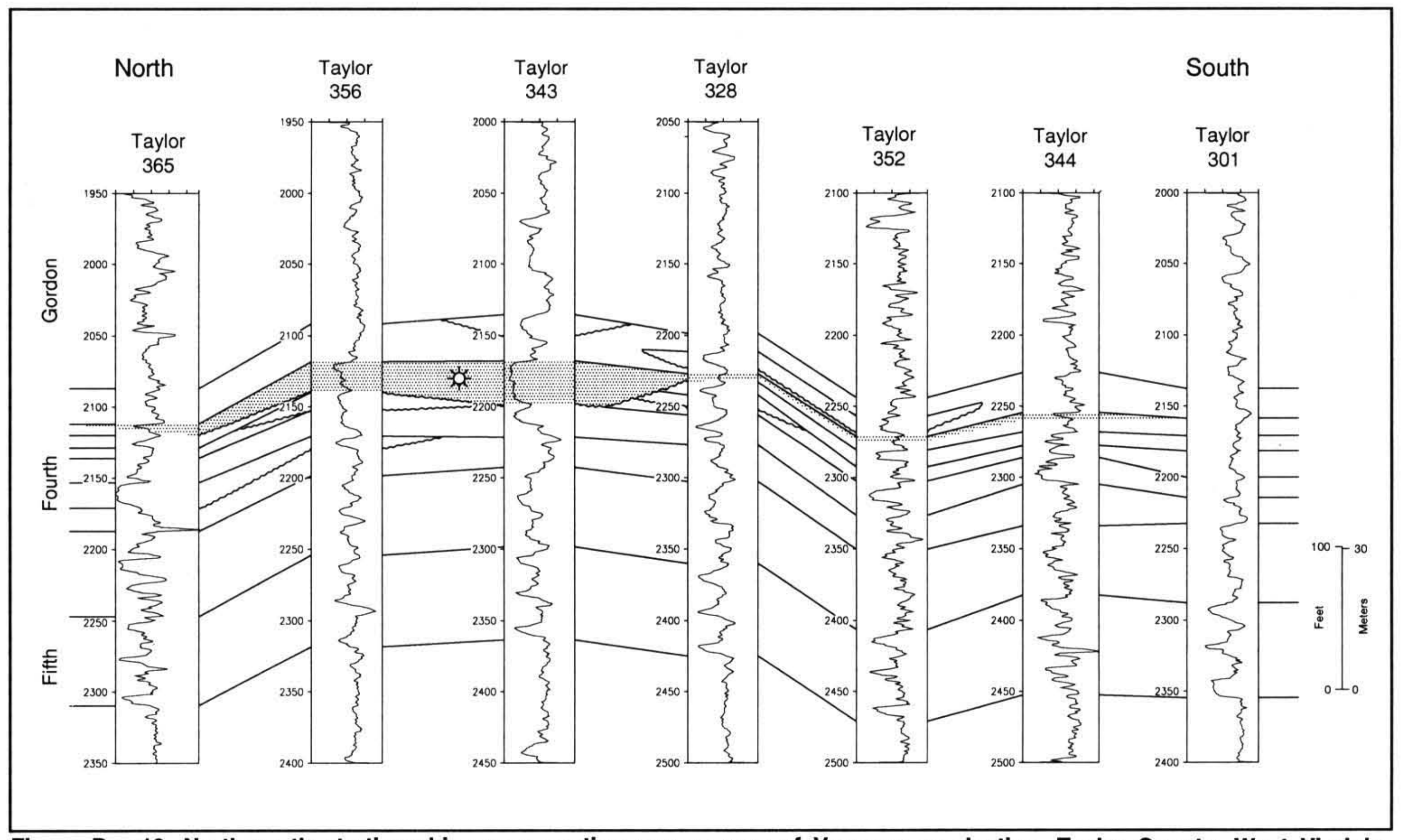


Figure Dvs-19. North-south stratigraphic cross section across area of Venango production, Taylor County, West Virginia. Productive upper part of the Fourth sandstone is indicated by stippling.

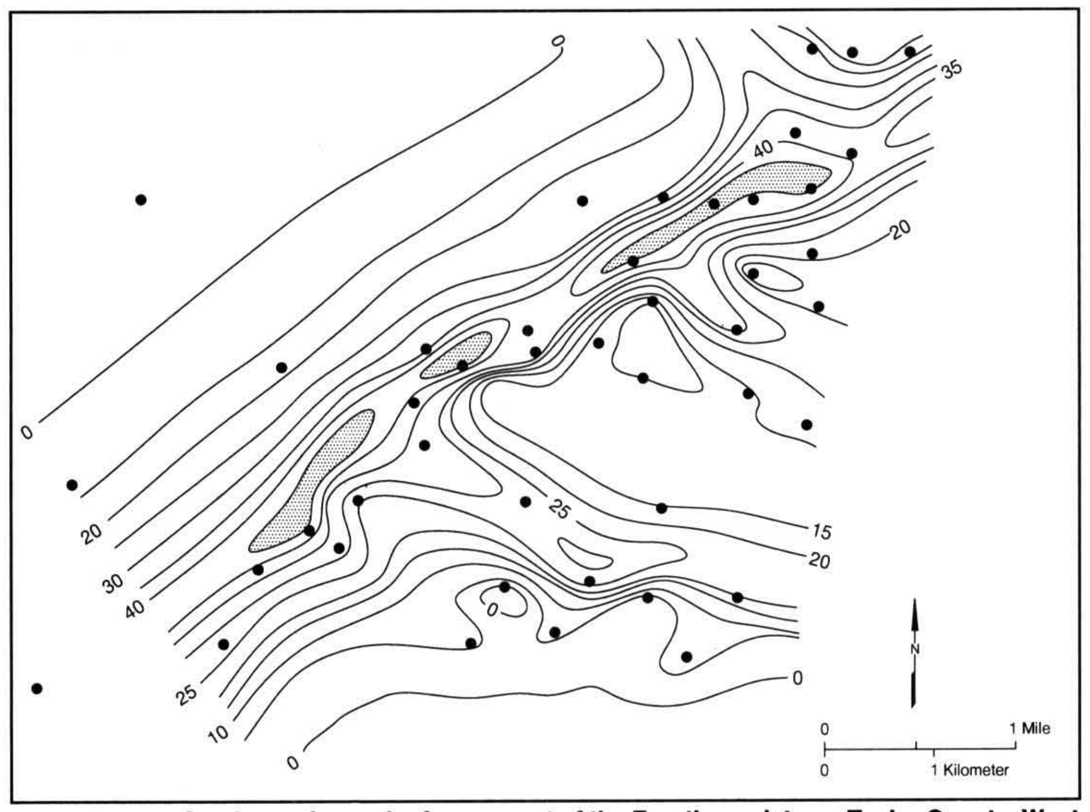


Figure Dvs-20. Sandstone isopach of upper part of the Fourth sandstone, Taylor County, West Virginia. The lenticular branching pattern, as well as the downward thickening morphology (see Figure Dvs-19) support a channel origin for this unit. Age-equivalent strike-trending shoreline sandstones occur approximately 20 to 30 miles west of this location. Sandstone was determined using 50 percent clean sand gamma-ray baseline method. Stippling indicates greater than 45-foot thickness. See Figure Dvs-2 for location. Contour interval is variable.

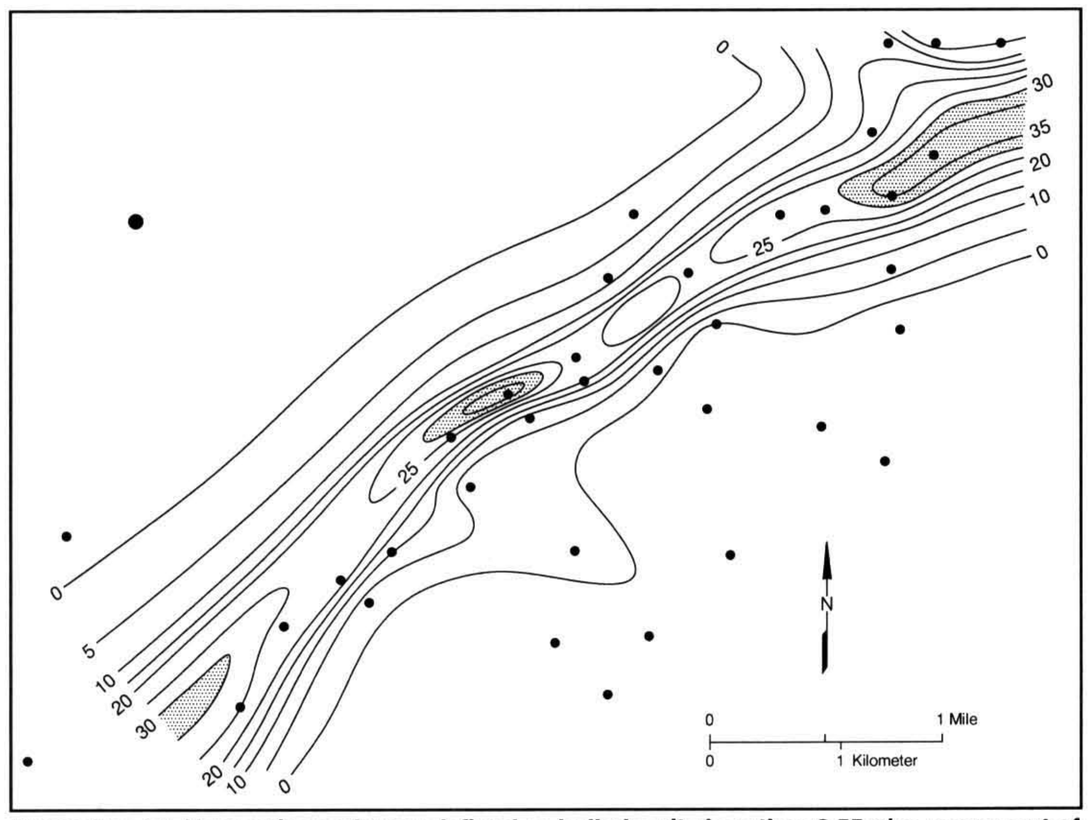


Figure Dvs-21. Net pay isopach map defined as bulk density less than 2.55 g/cc, upper part of the Fourth sandstone, Taylor County, West Virginia. Stippling indicates greater than 30-foot thickness. See Figure Dvs-2 for location. Contour interval is variable.

suggesting gas loss through fractures that were produced during nitroglycerin fracturing of nearby Fifth sandstone wells in the early 1900s. Typical production data for the wells have not been obtained.

Wood County, West Virginia: Two major siltstone bundles can be traced far to the west (basinward) of the main Venango shoreline trends. The lower bundle, generally named the Warren (V-1), marks the base of the Venango play in West Virginia. The upper siltstone package is thicker, coarser-grained, and correlates with the zone of the Upper Fourth, Gordon, and Fifty-Foot sandstones (V-4 and V-5) of northern West Virginia (Filer, 1985). As opposed to the areally restricted strike-trending belts of turbiditic siltstone and fine-grained sandstone observed in the productive Bradford units of West Virginia (see R. Boswell and others, Upper Devonian Bradford sandstones and siltstones, this atlas), the Gordon and Warren siltstones occur as broad sheets that extend far westward into eastern Ohio (Filer, 1985; Boswell, 1988b). The Gordon unit was deposited at the height of Catskill progradation when basin slopes were low and large areas of the shelf may have been above storm-wave base (Filer, 1985). Spurred by Devonian shale credits, more than 200 wells contributed production from the Gordon siltstone zone (Filer, 1985) in fields such as Waverly (Figure Dvs-2) in western West Virginia and eastern Ohio from 1979 through 1985. In Wood County, West Virginia, porosity in the Gordon zone (Figure Dvs-27) ranges from 3.9 percent to 5.1 percent, irreducible water saturation is 64 percent, drilling depth is 2,430 feet, and permeabilities are significantly less than 0.1 md. Average natural open flow from Gordon wells in Wood County is 5 Mcfg/d. Nearly all wells are hydrofractured with varying success, and final open flows from 14 wells that produce solely from the Gordon ranged from 50 to 2,750 Mcfg/d (West Virginia Tight Formations Committee, 1982). Analogous productive siltstones and fine-grained sandstones occur as far south as the Baileysville field, Wyoming County, West Virginia (see Figure Dvs-2).

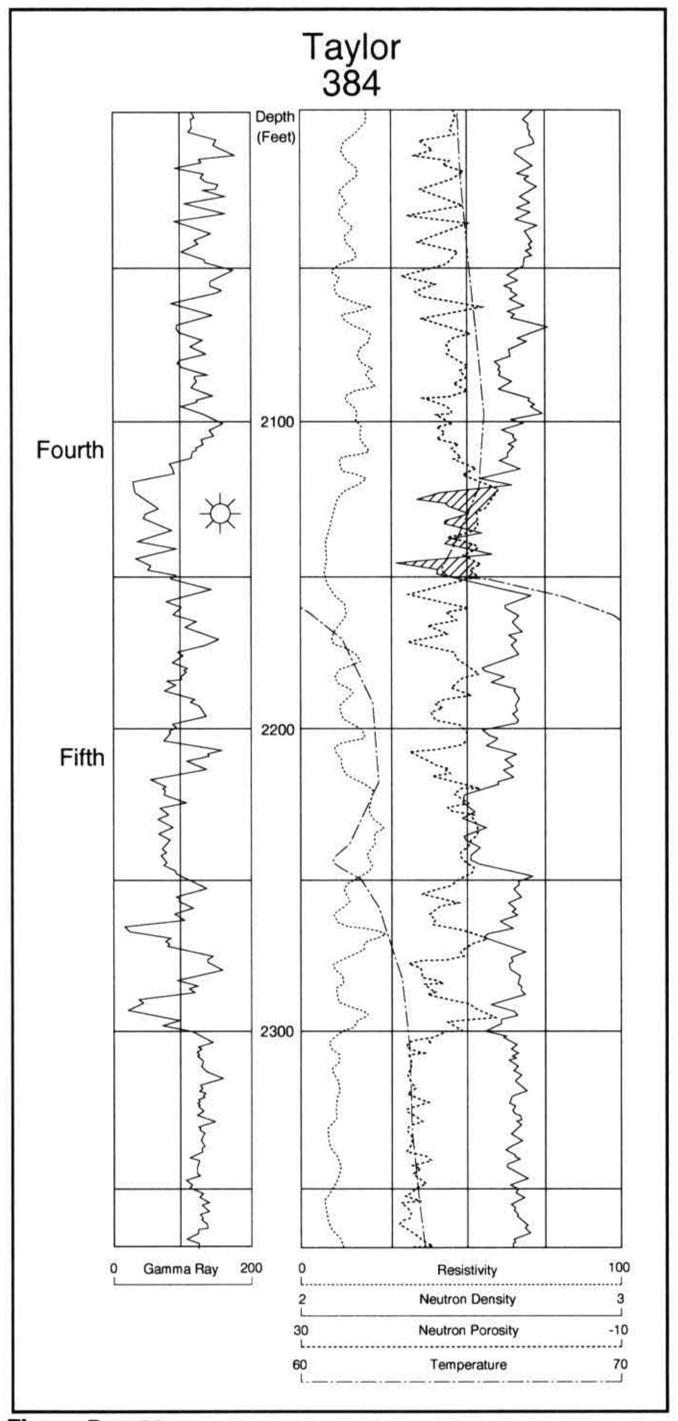


Figure Dvs-22a.

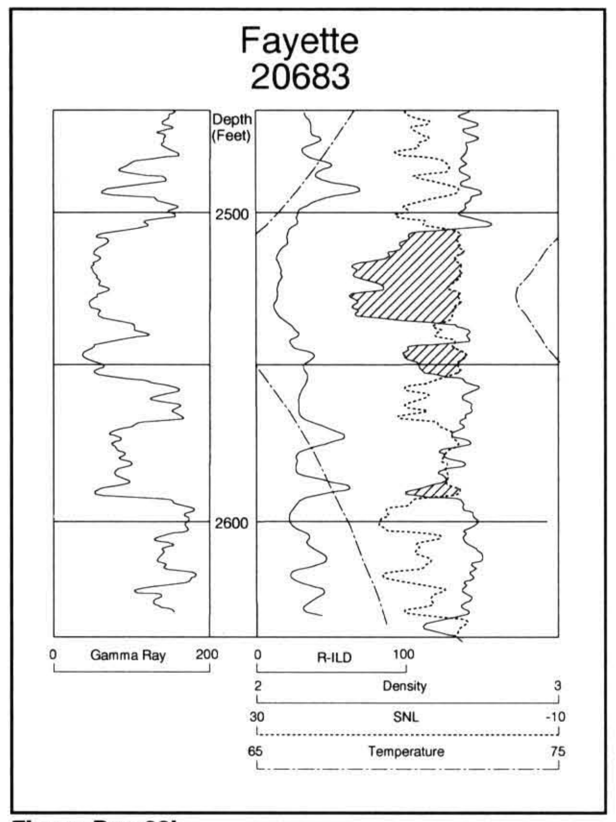
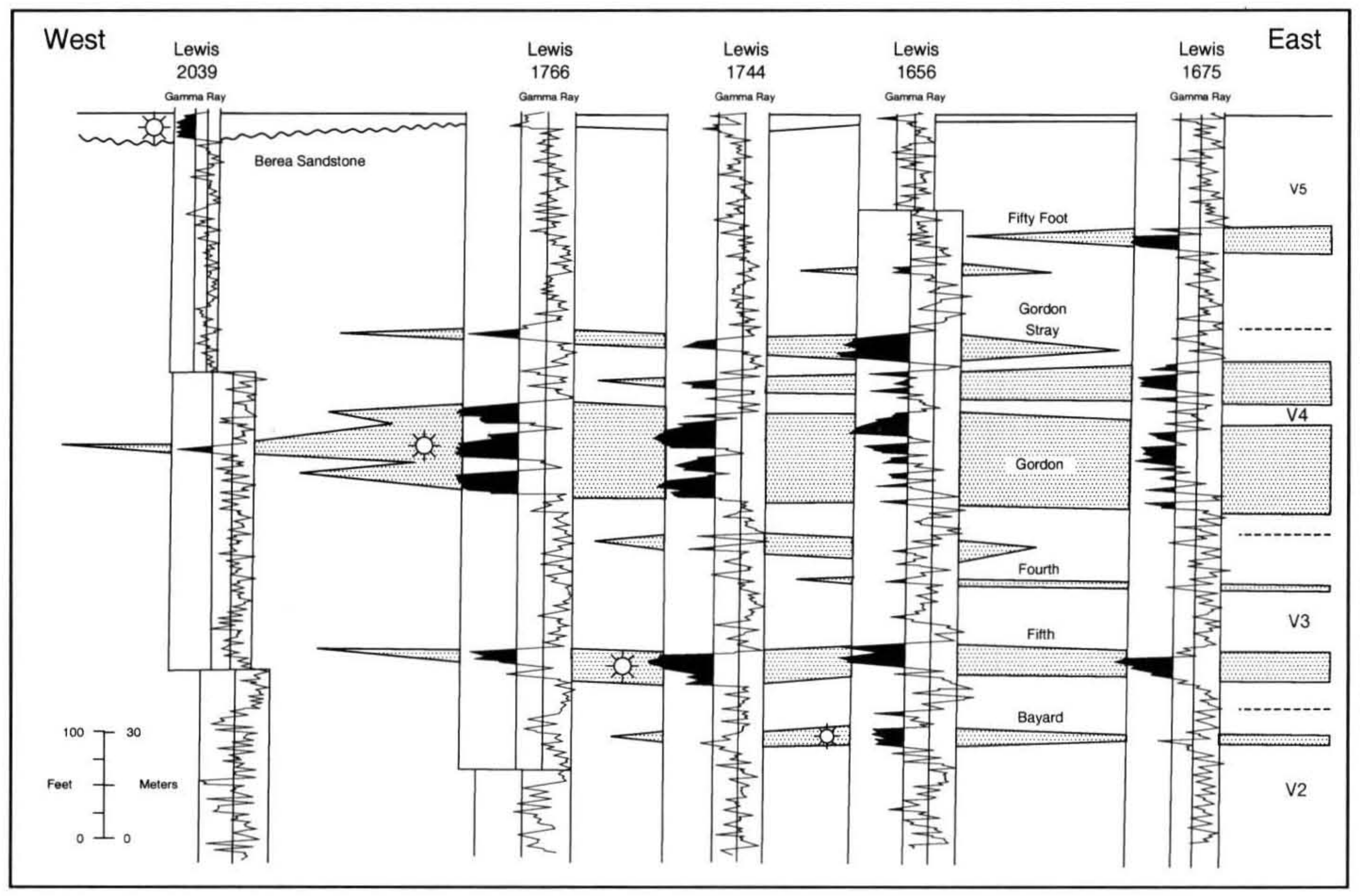


Figure Dvs-22b.

Figures Dvs-22a-b. Dvs-22a. Type log of the upper part of the Fourth sandstone, Taylor County, West Virginia. Dvs-22b. Similar reservoir characteristics have been observed in the Fifth sandstone in east-central Fayette County, Pennsylvania (correlative to the upper Fourth of northern West Virginia). Log supplied by T. Murin, Castle Exploration Company.



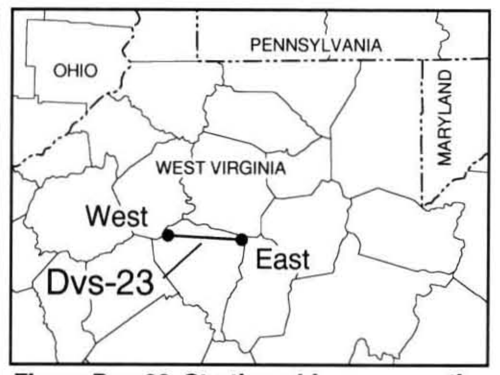


Figure Dvs-23. Stratigraphic cross section across the Weston-Jane Lew and Murphy Creek fields, north-central West Virginia, showing the relationship of the Bayard sandstone (upper V-2) to the main field pays (Fifth/V-3 and Gordon/V-4). Isolith maps of the overlying units exhibit north-south trends, in marked contrast with the geometry of this unit. Strike-trending units within the Bayard interval are located well to the east, suggesting that this unit was deposited offshore. Datum is the top of Berea Sandstone.

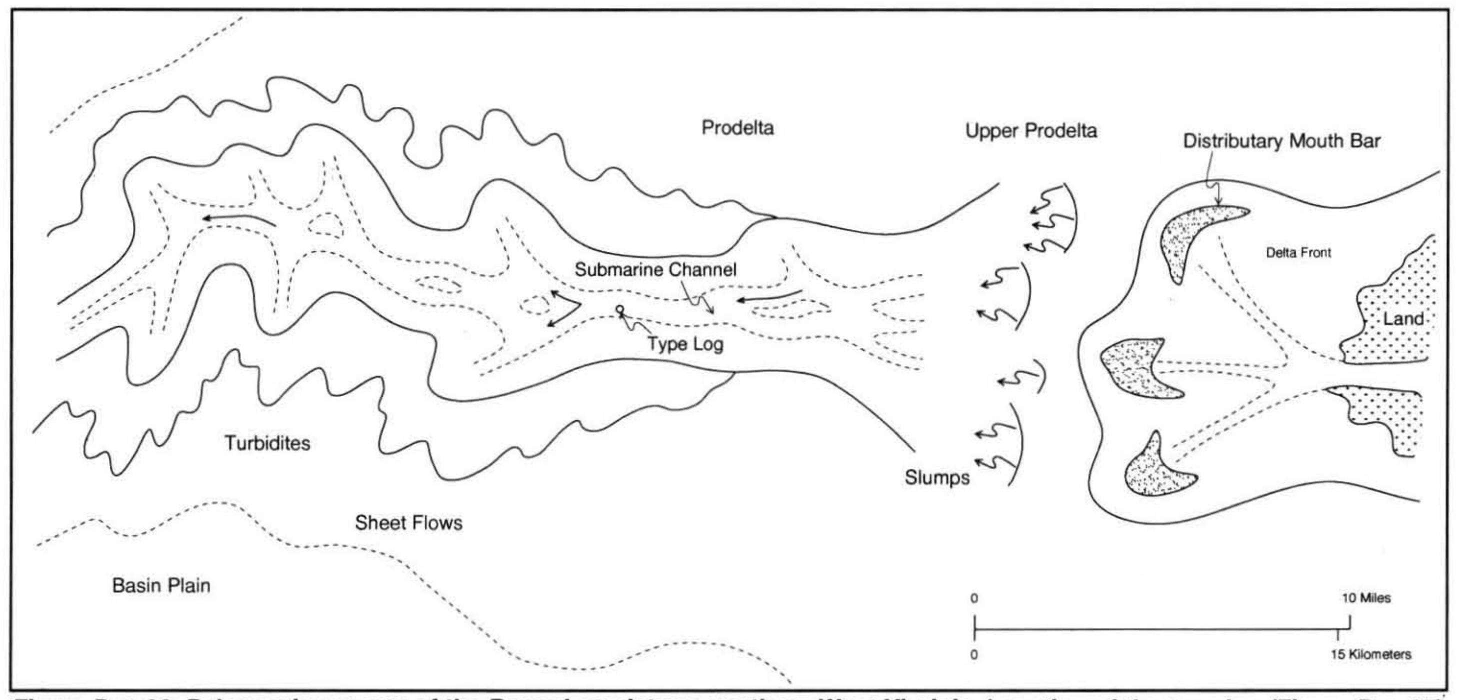


Figure Dvs-26. Paleoenvironments of the Bayard sandstone, northern West Virginia. Location of the type log (Figure Dvs-27) is indicated. Deposition is interpreted to have occurred within a submarine channel fed by periodic upper prodelta slumps associated with a major fluvial-deltaic sediment input system located to the east. From Heim (1987).

Resources and Reserves

Despite a vast quantity of gas having been produced from Venango sandstones, substantial recoverable reserves likely remain. Although no published accounts of natural gas reserves specifically attributed to Venango reservoirs exist, the U.S. Department of Energy's Morgantown Energy Technology Center (US DOE/METC) utilized a regional reservoir characterization data set based on 250 well logs (Boswell and others, 1993) to provide an estimate of 10.4 tcfg originally in-place in Venango reservoirs (A. Zammerilli, written commun., 1994). Of an estimated 3.69 tcfg remaining gas-in-place, DOE/METC suggests that approximately 2.3 tcfg may be recoverable. In comparison, the undiscovered recoverable resources for all Upper Devonian and Mississippian reservoirs in Pennsylvania has been estimated by Briggs and Tatlock (1983) at 3.61 tcfg, of which 1.64 tcfg was classified probable, 1.240 tcfg possible, and 0.73 tcfg speculative. The National Petroleum Council (1992) estimated the total undiscovered resources of Appalachian basin reservoirs at depths less than 5,000 feet at 6.22 tcfg at current technologies.

Future Trends

The thick, porous Venango sandstones that contributed much of the historic production from the shallow gas belt have been penetrated by more than 100,000 wells. At present, many of the high-quality reservoirs have been depleted, limiting current and future activity primarily to gas storage and enhanced oil recovery projects. In Pennsylvania, lower Venango reservoirs (Fifth and Bayard) to the east of the shallow gas belt will continue to be important contributors of gas within the primary Bradford play area of Indiana County and surrounding counties. Present and future exploration within the Venango play likely will concentrate on similar low-permeability reservoirs along the eastern margin of the basin, as well as on small pockets of bypassed reserves in the basin center and, less likely, on thin-bedded, marine facies to the west (Figure Dvs-28). In all cases, drilling activity may depend heavily on the possibilities for combining production from Venango targets with deeper intervals. However, as the examples above show, good quality Venango reservoirs may still be located and produced at shallow depths. However, these targets are much more lenticular than the reservoirs in the old fields and therefore contain substantial geologic risk. Extensive geologic mapping is needed in order to determine the geometry of the reservoirs.

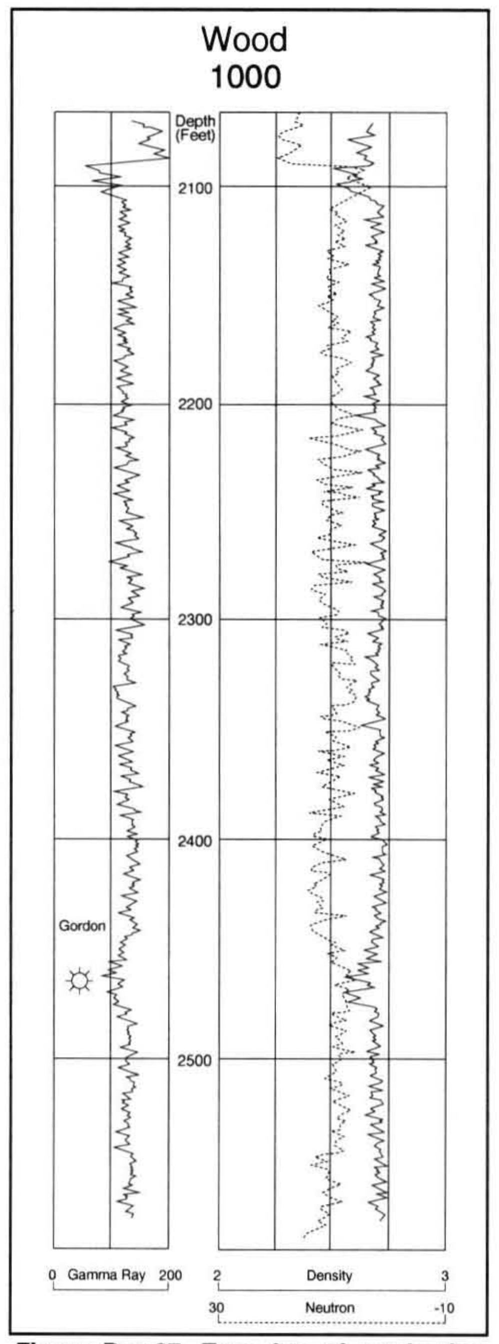


Figure Dvs-27. Type log of productive marine facies of the Gordon (V-4) siltstone, Wood County, West Virginia. These units are located 30 to 50 miles west (seaward) of age-equivalent strike-trending, coarse-grained sandstones believed to mark the paleoshoreline trend. Porosity in the Gordon is probably related to winnowing of shelf sediments during storms. Similar faces produce gas in Kanawha, Raleigh, and McDowell counties in southern West Virginia.

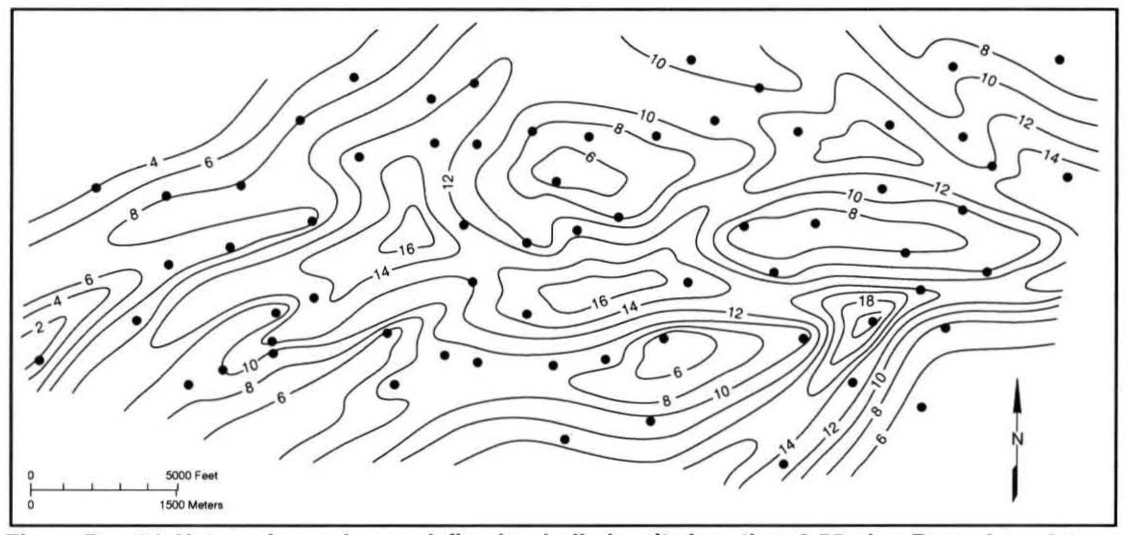


Figure Dvs-24. Net pay isopach map defined as bulk density less than 2.55 g/cc, Bayard sandstone (V-2), north-central West Virginia. This map reveals the predominant east-west geometry of the unit, and was produced based on information provided by B. Staub, COG Production Company. Approximate location shown on Figure Dvs-2; exact location is held confidential upon request.

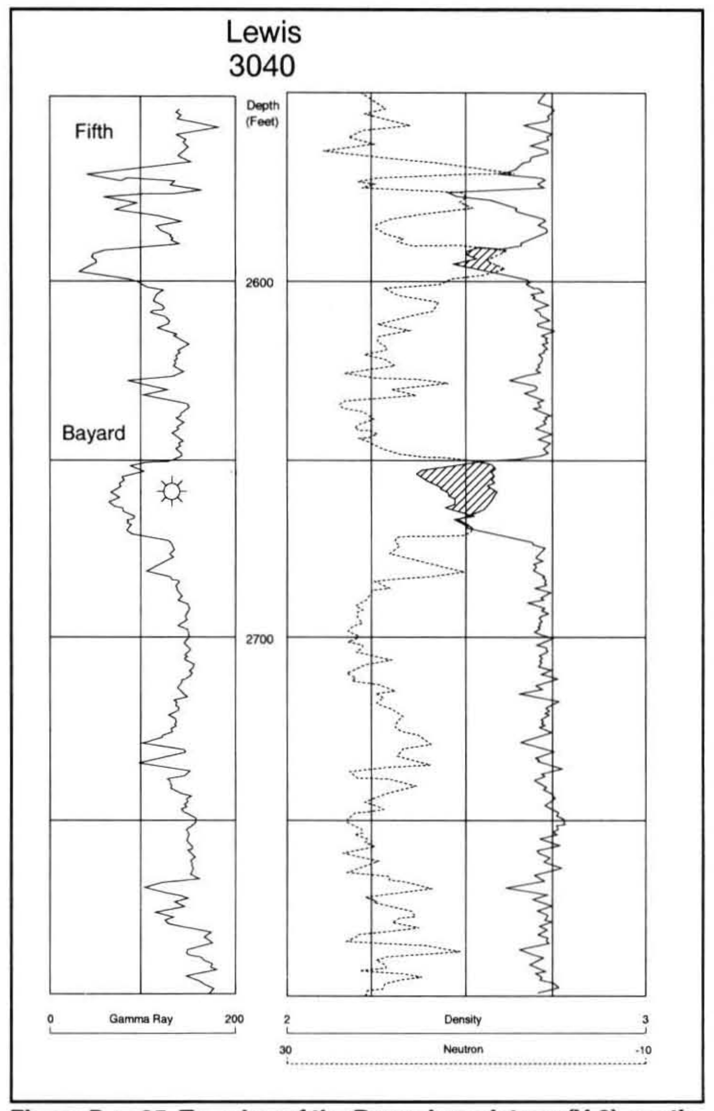


Figure Dvs-25. Type log of the Bayard sandstone (V-2), north-central West Virginia. The base of the Fifth sandstone is at 2,600 feet.

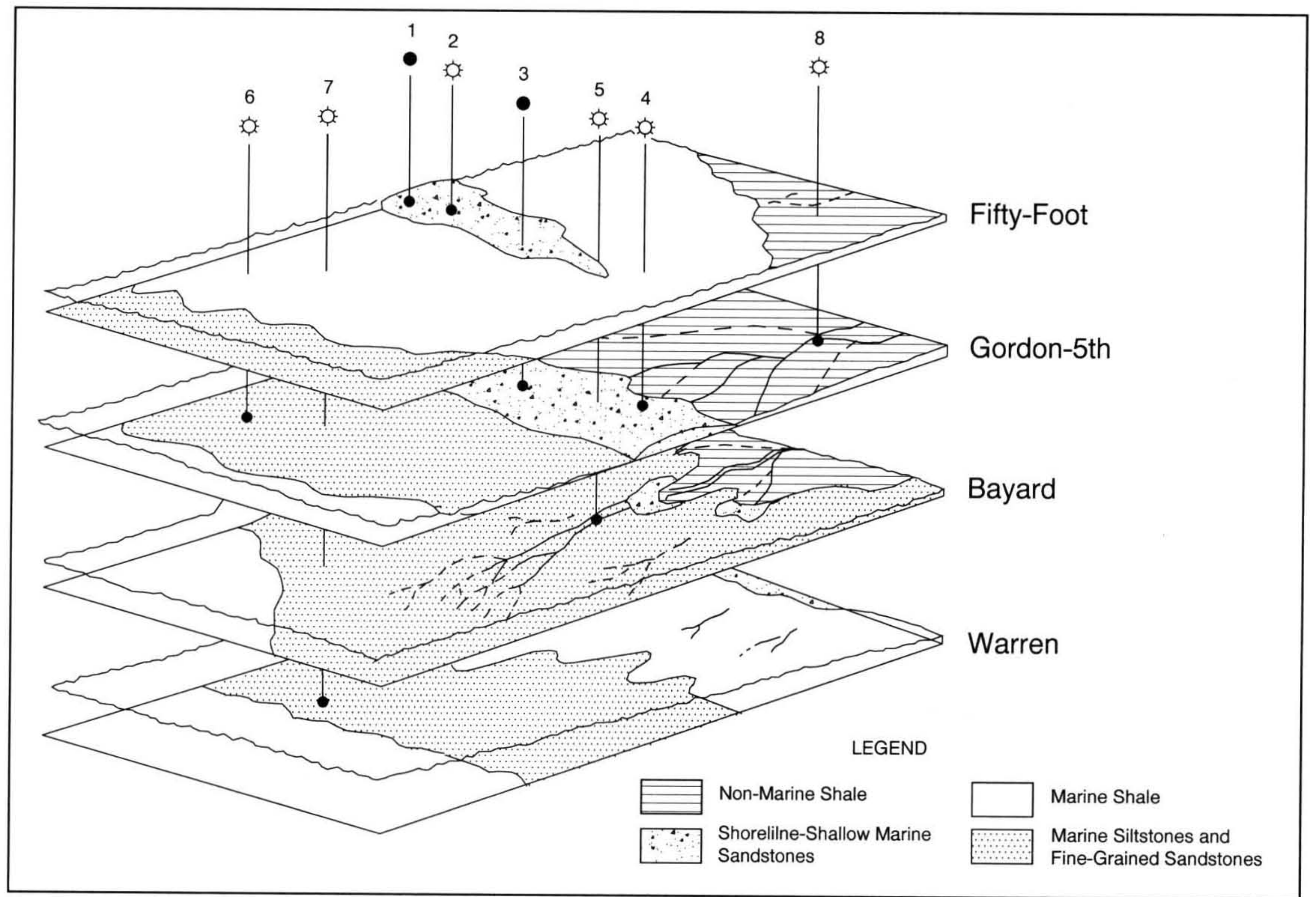


Figure Dvs-28. Schematic depiction of typical exploration strategies for Venango reservoirs: 1, 2, 3, and 4) Oil and gas wells in strike-trending Fifty-Foot and Gordon sandstones. These reservoirs are now mostly depleted, although there are significant gas storage and secondary oil recovery projects, as well as occasional discovery of bypassed reserves; 5) gas wells in high-risk, dip-trending nearshore sandstones formed during periods of fluvially dominated conditions; 6) gas wells in distal shelf storm deposit equivalents of the Gordon through Fifth intervals; 7) gas wells in turbidites of basal Venango (Warren) intervals; and 8) gas wells in high-risk, dip-trending fluvial channel sandstones along the eastern margin of the basin.

PLAY Dbs: UPPER DEVONIAN BRADFORD SANDSTONES AND SILTSTONES

by Ray Boswell, EG&G TSWV, Inc.; Bradley W. Thomas, Exploration Partners, Inc.; R. Brandon Hussing, Parker and Parsley Development Co., Inc.; Timothy M. Murin, Castle Exploration Co., Inc.; and Alan Donaldson, West Virginia University

Location

Natural gas potential from sandstone and siltstone reservoirs of the Bradford play exists throughout a broad belt that stretches along the eastern margin of the Appalachian basin from southwestern New York to southern West Virginia (Figure Dbs-1). Bradford play sandstones are the main producing reservoirs in many historic oil fields at shallow depths in McKean and Warren counties, Pennsylvania, and adjacent Allegany County, New York. However, from the 1890s to the present, production from the play has been dominated by large volumes of natural gas produced from multiple shelf and nearshore sandstones throughout Armstrong, Indiana, and neighboring counties of west-central Pennsylvania (Figure Dbs-2). More recently, previously bypassed shelf and basinal siltstones of the Bradford play have been found capable of providing economic production within a large number of gas fields in northern West Virginia (Figure Dbs-2).

The Bradford play is the intermediate of three Upper Devonian sandstone and siltstone plays that represent major progradational episodes of the Catskill delta complex. The base of the Bradford play is defined as the horizon of maximum transgression marked in the western half of the play area by the Dunkirk Shale and equivalents, and corresponding closely to the Frasnian-Famennian stage boundary (Figure Dbs-3). The upper boundary of the play coincides with mid-Famennian transgression marked by the Chadakoin Formation of western Pennsylvania and the Warren shale of northern West Virginia (Figure Dbs-3). As traced westward and southward, the Bradford play interval grades laterally into a sequence of thinly-interbedded siltstones and gray, green, and black shales that are productive where sufficiently fractured (see R. Milici, Upper Devonian fractured black and gray shales, this atlas).

Production History

As drilling opportunities in the Venango oil district (Figure Dbs-2) dwindled during the 1860s (see R. Boswell and others, Upper Devonian Venango sandstones and siltstones, this atlas), numerous wildcat wells were drilled throughout northwestern Pennsylvania. Attempts to extend Venango production to the north and east were generally unsuccessful until a well drilled near the town of Bradford in northern McKean County in 1871 produced 10 barrels of oil per day from a sandstone at a depth of 1,110 feet. The oil potential of the area was proven in late 1874 when the No. 1 Butts well produced 70 barrels of oil per day from the same sandstone (Figure Dbs-2). Development of the Bradford field proceeded rapidly. By 1880, it was recognized that the field was not producing from Venango sandstones, as had generally been assumed, but instead from a new and distinct package of sandstones that lay up to 1,000 feet stratigraphically below the lowest Venango reservoir. Annual production from the Bradford field peaked in 1881 with 11,200 wells producing a total of 22.9 million barrels of oil, or 77 percent of the global oil production at the time (Fettke, 1938b). Production continues at present at about 500,000 barrels per year. Total cumulative production is slightly more than 675 million barrels, more than half of which was obtained through water-flooding operations (see Fettke, 1950).

Crowded conditions in the Bradford oil field prompted drillers to look elsewhere in the early 1880s, resulting in the successful extension of erratic production that had been obtained and abandoned in Glade Township, Warren County, from 1875 to 1877 (Lytle and Goth, 1970). Activity in the new Warren district (Figure Dbs-2) climaxed in 1881 and 1882 with the discovery of the Balltown, Sheffield, Clarendon, and numerous other productive, yet short-lived, oil pools.

The earliest utilization of Bradford natural gas may have occurred in the Sheffield field, eastern Warren County, in 1875 (Ingham and others, 1956). However, most early Bradford gas discoveries were considered a nuisance to oil exploration and the gas was not gathered. For example, a well drilled within the Bradford oil field in early 1877 was metered at more than 24 MMcfg/d, but was vented to the atmosphere until oil began flowing nearly five years later (Fettke, 1938b). It was not until the late 1880s that a market for natural gas evolved sufficient to encourage development of Bradford gas reservoirs. Perhaps the earliest substantial Bradford gas field was discovered on the Speechley farm, in eastern Venango County, in 1885 (Figure Dbs-2). Large flows of gas were obtained from a sandstone 800 feet below the main Venango reservoir section. The discovery well was still producing more than 55 years later, and the Speechley gas field eventually accommodated more than 1,000 wells (Dickey and others, 1943).

From 1885 to the present, exploration for Bradford reservoirs generally has progressed downdip of the original oil fields. Most activity in the early 1900s was focused on a broad and irregular belt of sandstone with apparent northeasterly trend in eastern Armstrong County (Figure Dbs-4). Development continued at a modest pace until the mid-1950s with roughly 20 to 30 percent of the wells drilled in any year being unproductive. Drilling for Bradford reservoirs accelerated through the 1950s and 1960s as rising gas prices and improved production practices, such as multiple-zone hydrofracturing and commingling, dramatically lowered dry hole rates and increased average well productivity (Kelley and others, 1970). Hydrofracturing was particularly important, resulting in a typical improvement in initial production ranging from 30 to 50 times natural rates (Lytle and others, 1961). In recent years, activity has concentrated

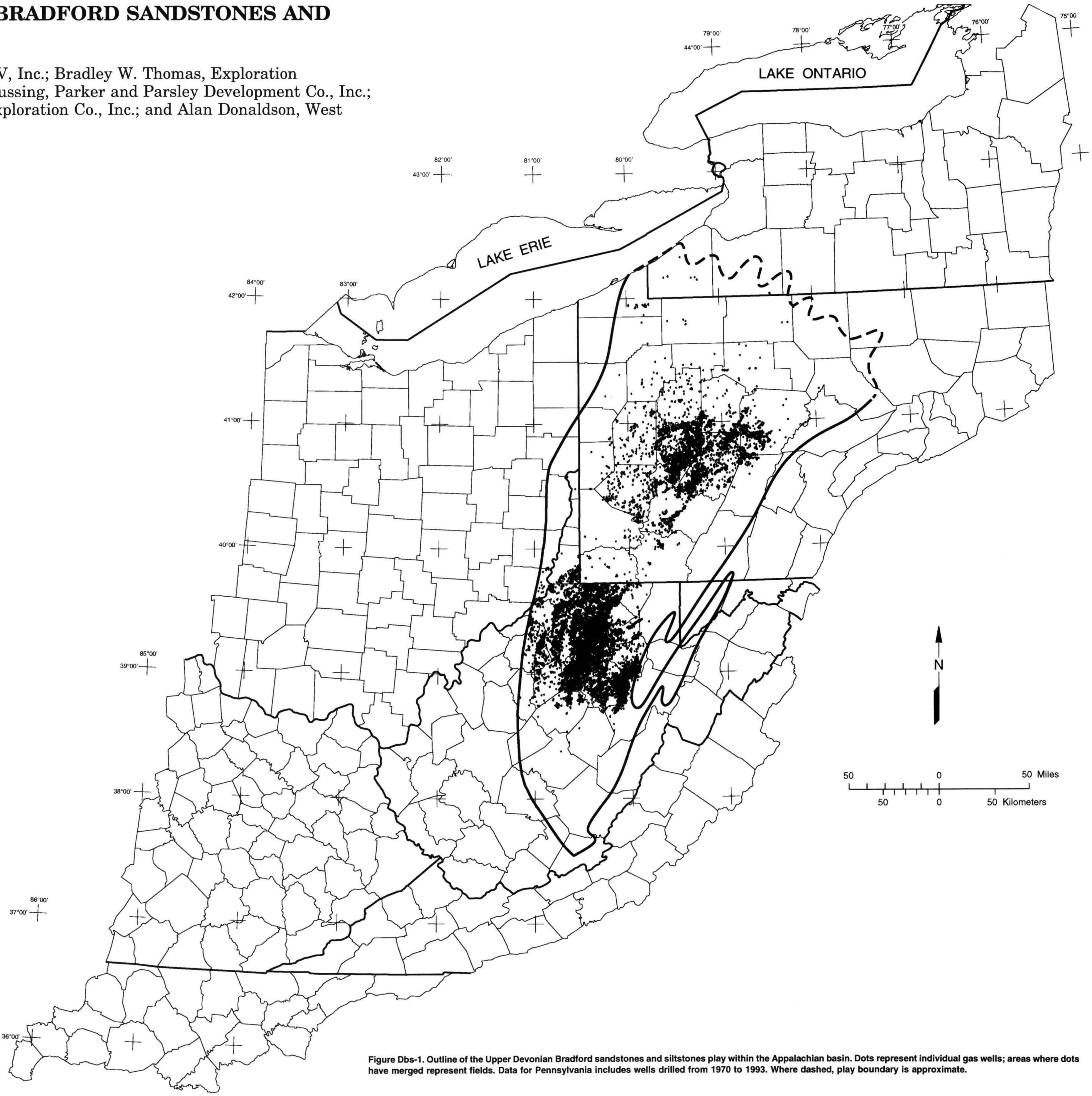


Figure Dbs-1. Outline of the Upper Devonian Bradford sandstones and siltstones play within the Appalachian basin. Dots represent individual gas wells; areas where dots have merged represent fields. Data for Pennsylvania includes wells drilled from 1970 to 1993. Where dashed, play boundary is approximate.

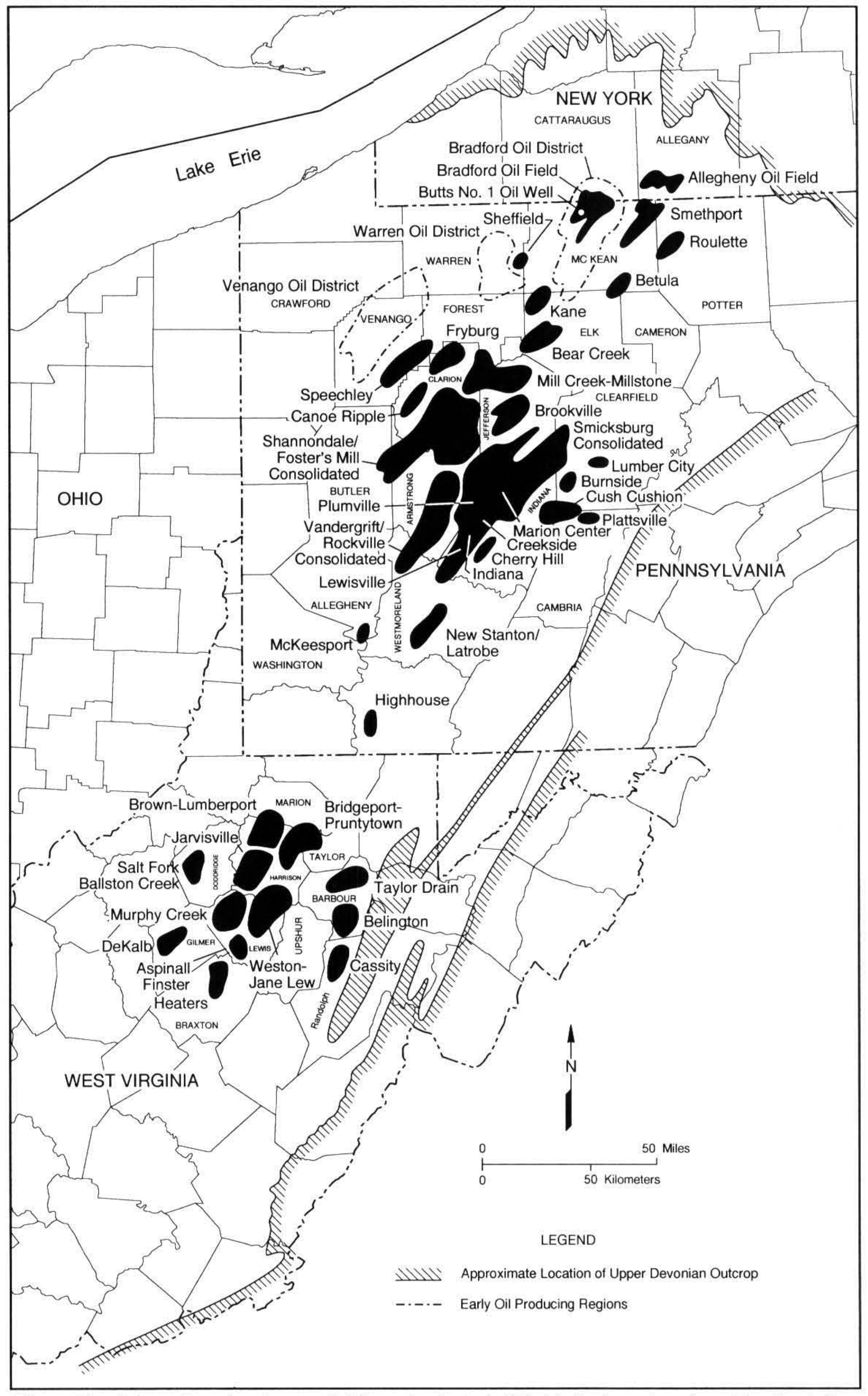


Figure Dbs-2. Location of major gas fields and selected oil fields that produce from Bradford play reservoirs. Reservoir data for selected fields are presented in Table Dbs-1.

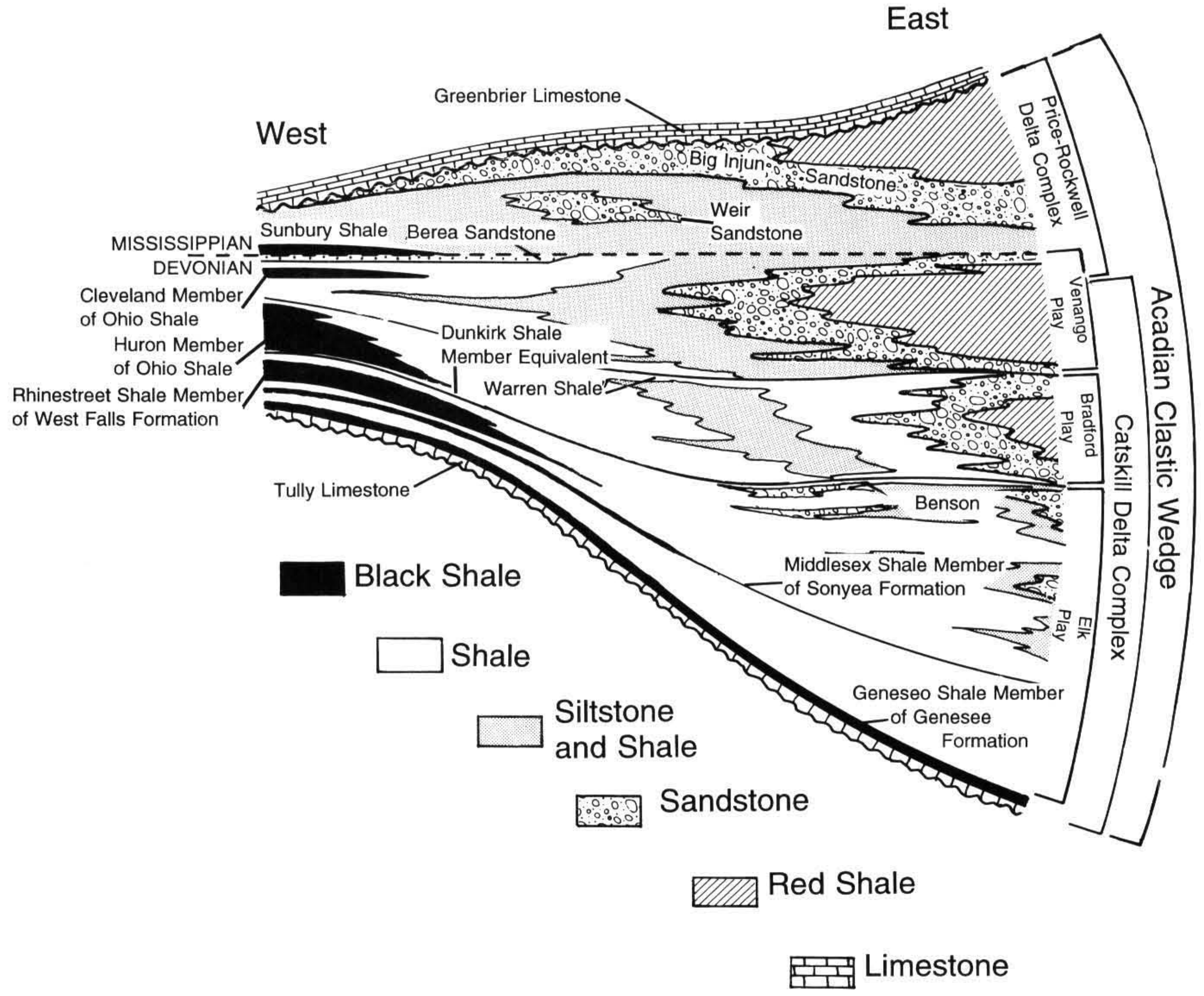


Figure Dbs-3. Diagrammatic cross section of the general lithologic framework of the Acadian clastic wedge showing the relationship of the Price-Rockwell and Catskill delta complexes and the Venango, Bradford, and Elk plays defined in this atlas. The Bradford play represents all the coarse-grained clastic reservoirs occurring between the horizons of maximum regional transgression within the Chadakoin Formation of northern Pennsylvania (equivalent to the informal Warren shale of West Virginia) and the shales just below the Kane sandstone of Pennsylvania (roughly equivalent to the shales immediately overlying the Benson sandstone in northern West Virginia).

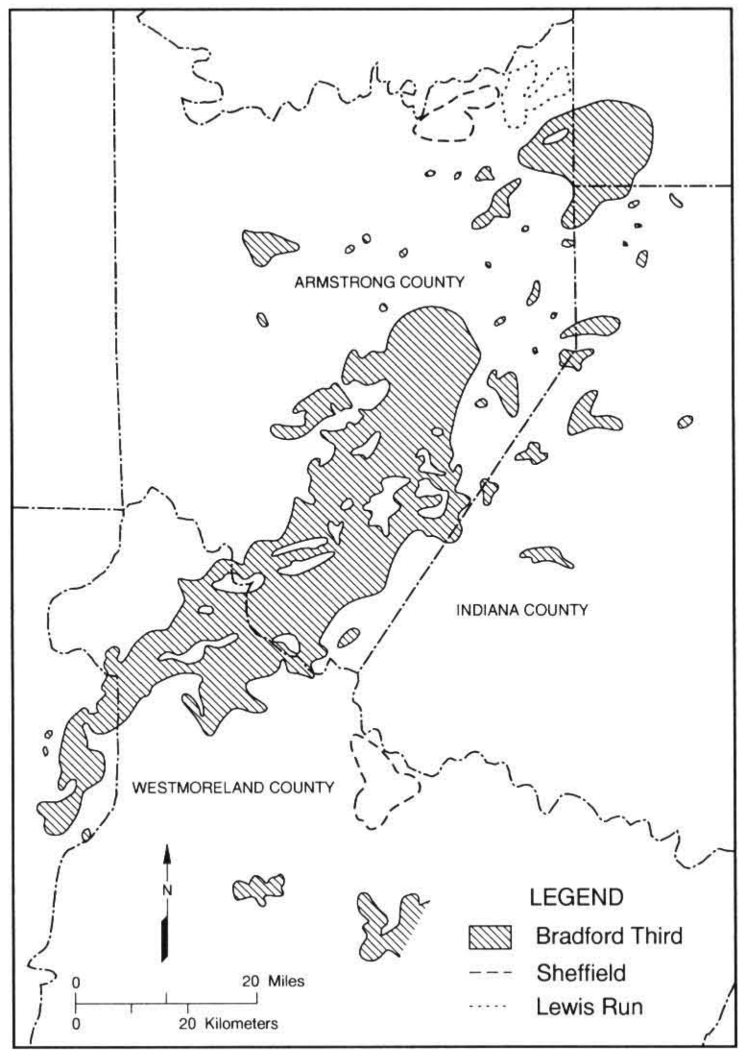


Figure Dbs-4. Areas of various Bradford play sandstone gas production in the primary Bradford producing area of eastern Armstrong County, Pennsylvania, and surrounding areas as of 1960. From Lytle and others (1961).

on delineating the highly-lenticular sandstone reservoirs and extending the limits of the Armstrong County gas province both eastward and southward across Jefferson and Indiana counties. Currently, more than 95 percent of Bradford play wells will produce gas; however, it is unclear what percentage produces well enough to be considered economically successful by investors.

One notable exception to the general southeastward progression of Bradford play development is the discovery and exceptionally rapid development of a Speechley sandstone reservoir at the McKeesport (Long Run) pool (Figure Dbs-2), Allegheny County, Pennsylvania, during the winter of 1919-1920. After modest production from the first two wells drilled in the field, the third well began production at 4,000 Mcfg/d and increased to a staggering 56,117 Mcfg/d within one month. As cumulative production from this well eclipsed 5 bcfg within four months, an unprecedented drilling boom erupted that resulted in the drilling of roughly 650 wells (approximately 450 dry holes) into the 850-acre field within a one-year period. Although total cumulative production was approximately 21 bcfg, the feverish development of the field resulted in a net loss to investors of more than $9,500,000 (see Johnson, 1929).

Reservoir-quality sandstones such as those that produce in Pennsylvania are largely absent from the Bradford play in the subsurface of West Virginia. Consequently, drilling rarely proceeded below the Venango sandstones during the early 1900s. However, development of the sub-Bradford Benson reservoir beginning in the 1950s (see A. Donaldson and others, Upper Devonian Elk siltstones and sandstones, this atlas) resulted in the drilling of thousands of wells through the Bradford section. At many locations, gas was encountered within thinly-bedded and fine-grained marine sandstones and siltstones within the Bradford interval; however, these zones were not always rigorously evaluated. Presently, much of the Benson trend is developed, and many operators are re-examining the potential of the Bradford intervals. For the past several years, the Balltown-Speechley reservoirs in Harrison and Lewis counties have been among the most active plays in the state.

Summary production data for the Bradford play is limited. Many of the fields are very old and well data generally are not available. Furthermore, the widespread commingling of Bradford gas production with shallower units in Pennsylvania and deeper units in West Virginia renders it impossible to assess accurately the production from the play or from any specific Bradford reservoir. However, it may be reasonable to assume that the Bradford play represents roughly two-thirds of the total estimate of 9 tcfg cumulative production from Upper Devonian and younger reservoirs in Pennsylvania (Harper and Cozart, 1992) and perhaps 10 percent of the estimated 11.7 tcfg production through 1973 from the same interval in West Virginia (Cardwell and Avary, 1982). These assumptions compare favorably with an estimate of 7.7 tcfg produced from Bradford reservoirs provided by the U.S. Department of Energy Morgantown Energy Technology Center (A. Zammerilli, written commun., 1994).

Stratigraphy

As defined here, the Bradford play represents all lower Famennian sandstone and siltstone gas reservoirs in the Appalachian basin with the exception of those in western West Virginia in which interbedded fractured shales are a significant component of production (see R. Milici, Upper Devonian fractured black and gray shales and siltstones, this atlas). As traced from east to west, lower Famennian rocks grade from non-marine red shales of the Catskill and Hampshire formations, through a number of variably well-defined marginal-marine and shallow-marine units once widely associated with the term "Chemung," into basinal shales and siltstones of the Chagrin and Brallier formations, and ultimately into the black Huron Member of the Ohio Shale (Figure Dbs-5). The following discussion will focus on the "Chemung" unit, which encompasses all significant Bradford play gas production.

During the initial development of the Bradford oil field, well drillers assumed that the main oil reservoir correlated with the "Third sandstone" of the Venango district; consequently, the unit became known as the Bradford Third sandstone formation. However, Carll (1875) and Ashburner (1880) showed this correlation to be incorrect. In accordance with the divisions of the Upper Devonian series established by Hall (1839) and others, these workers assigned the Venango units to the Upper Devonian Catskill and the Bradford Third sandstone to the middle of the underlying Chemung. Ashburner (1880) further designated the Bradford Third sandstone as the basal unit within a "McKean (or Bradford) oil-sands group" within the middle Chemung. In a similar fashion, Carll (1890) assigned the reservoirs of the Warren district to the "Warren oil-sands group" of the upper Chemung. It should be noted that at this time, there was no distinction made between rock units and time units, and there was no standardized terminology for unit rank. Therefore, it is probably best to substitute the word "sequence" for "group" as used by Carll and Ashburner to obtain the equivalent modern meaning.

In the early 1900s, Appalachian basin stratigraphers began to appreciate the negative ramifications of the previously unrecognized time-transgressive nature of lithologies on the existing faunally based formations. The Chemung could not be adequately restated in lithologic terms and was transformed into a stage of the Upper Devonian by Cooper and others (1942) before being ultimately discarded as a rock unit in its type locality. Unfortunately, the Canadaway and Conneaut groups that were often used to replace parts of the Chemung also relied heavily on faunal transitions and likewise do not meet the current standards for lithostratigraphic units (Frakes, 1963; Manspeizer, 1963). More recent designations for the Upper Devonian transitional marine facies from central Pennsylvania outcrops (such as Lock Haven Formation) have only been applied in the extreme eastern sections of the subsurface and have not been traced westward into the gas-producing regions. As a result, stratigraphers at the Pennsylvania Bureau of Topographic and Geologic Survey have chosen to revert to the informal name Bradford oil-sands group, incorporating both the McKean and Warren oil-sand groups of Ashburner (1880) and Carll (1875) to refer to the main reservoir-bearing section of the Bradford play (Harper and others, 1982; Berg and others, 1983). Obviously, formal lithostratigraphic definition in the subsurface of western Pennsylvania is needed.

Lithostratigraphy in the subsurface of West Virginia is better established. The term Chemung Formation was replaced along the Allegheny front in Maryland and eastern West Virginia by Dennison (1970b), who redesignated the thick sequence of marine sandstones and shales below the Catskill (Hampshire Formation) redbeds as the Foreknobs and Scherr formations of the Greenland Gap Group. Subsequently, Boswell and others (1987) traced these units westward into the subsurface as the Greenland Gap Formation, documenting the time-transgressive nature of the contacts of the unit (Figure Dbs-6). The major gas-productive areas of the Bradford, Balltown, Speechley, and Warren intervals in West Virginia occur primarily within the Greenland Gap Formation.

The informal subsurface stratigraphic nomenclature for the productive sandstone and siltstone reservoirs of the Bradford play is shown schematically in Figure Dbs-7. The play contains numerous named units that correspond to separate packages of sandstone that were deposited during small-scale, transgressive-regressive cycles (interpreted as sixth-order by Flaherty, 1994) (see Figure Dbs-8). Each of these packages contains many individual sandstones that are limited in extent; however, when taken as a whole, each sandstone package can be confidently correlated across large areas. In western Pennsylvania, these correlations are aided by the presence of transgressive, silty limestones that serve as local marker beds (Wolfe, 1963; Murin, 1988; Flaherty, 1994). In northern West Virginia, prominent shale units such as the Warren shale and the Speechley shale are reliable and extensive marker beds (see Figure Dbs-6).

Throughout western Pennsylvania, a general sequence that includes an upper Speechley zone, an intermediate Balltown zone, a lower Bradford zone, and a basal Kane zone is consistently used (Figure Dbs-9). However, other terms such as First, Second, or Third Bradford sandstone are used haphazardly at best. Along the eastern edge of the basin in particular, as many as 20 potential reservoirs may be encountered by any given well, rendering the exact assignment of any one reservoir to a specific drillers' term highly problematic.

To allow the regional description of units, Boswell and others (1993) divided the Bradford sequence into five intervals (B-1, B-2, B-3, B-4, B-5). The basal B-1 interval marks a major regional regression marked by the Kane sandstones (Riley of West Virginia) and including the Second and Third Bradford sandstones of the gas-producing regions of west-central Pennsylvania. Interval B-2 includes the prolific First Bradford sandstone of Indiana County at the base (correlative with the distinctive Bradford siltstone of northern West Virginia) and contains a widespread transgressive, silty limestone at the top. Interval B-3 records an overall regression that is most pronounced in Jefferson and Elk counties, Pennsylvania, and recorded in the Balltown and equivalent sandstones. Interval B-4 marks the westernmost progradation of sandstones within the Bradford play, including the Glade, Clarendon, and Speechley sandstones of Pennsylvania (Upper Balltown or Lower Speechley of West Virginia). Sandstones in interval B-5 are commonly called Warren or upper Speechley; however, the interval is largely transgressive and relatively sandstone-poor throughout much of the basin.

Structure

The productive areas of the Bradford play are characterized by discontinuous northeast-southwest-trending anticlines and synclines with amplitudes decreasing northwestward from nearly 1,000 feet along the eastern margin of the basin to several hundred feet at the western boundary of the play. However, virtually all Bradford gas reservoirs are purely stratigraphic traps. Along the eastern margin of the basin, the occurrence of reservoir sandstones may be complicated by thrust faults with displacements of up to 150 feet and strike-slip faults of unknown displacement (Murin, 1988; Hussing, 1994). Fracturing associated with these features may be important in enhancing the productivity of certain wells (Murin, 1988). Murin (1988) reported that dip-trending sandstone units cluster around interpreted strike-slip faults, suggesting a syndepositional topographic effect. On a larger scale, the proliferation of Bradford play sandstones along strike in the Indiana-Armstrong county area may be related to regional cross-strike basement features that compartmentalized rates of subsidence along depositional strike (Harper, 1989).

Reservoir

Bradford play reservoirs are sandstones and siltstones deposited in a variety of environments of the Catskill delta complex. In general, the productive reservoirs of west-central Pennsylvania are thicker, shale-poor sandstones that are interpreted to have formed primarily in proximal marine environments. In contrast, Bradford play reservoirs in West Virginia are finer-grained, more argillaceous, and more thinly bedded, and are generally interpreted to represent distal shelf and slope turbidite deposition (Figure Dbs-10). The reservoir characteristics of selected gas fields are presented in Table Dbs-1. Selected gas composition data are provided in Table Dbs-2.

The oil reservoirs of McKean and Warren counties, Pennsylvania, have been the most studied reservoirs of the Bradford play. The Bradford Third reservoir (B-1) of the Bradford oil field consists of fine- to very fine-grained, angular quartz sand, with clay content typically between 3 and 10 percent. Porosity is typically from 13 to 17 percent with permeability from 2 to 40 md (Figures Dbs-11, Dbs-12). Reported core analyses for oil reservoirs including the Glade (B-5), Clarendon (B-4), Balltown (B-3), and Cooper (B-3) sandstones in Forest and Warren counties show a wide range in permeability (0.2 to 760 md) and porosity (9.8 to 18.6 percent) (Ingham and others, 1956; Overbey and Evans, 1965).

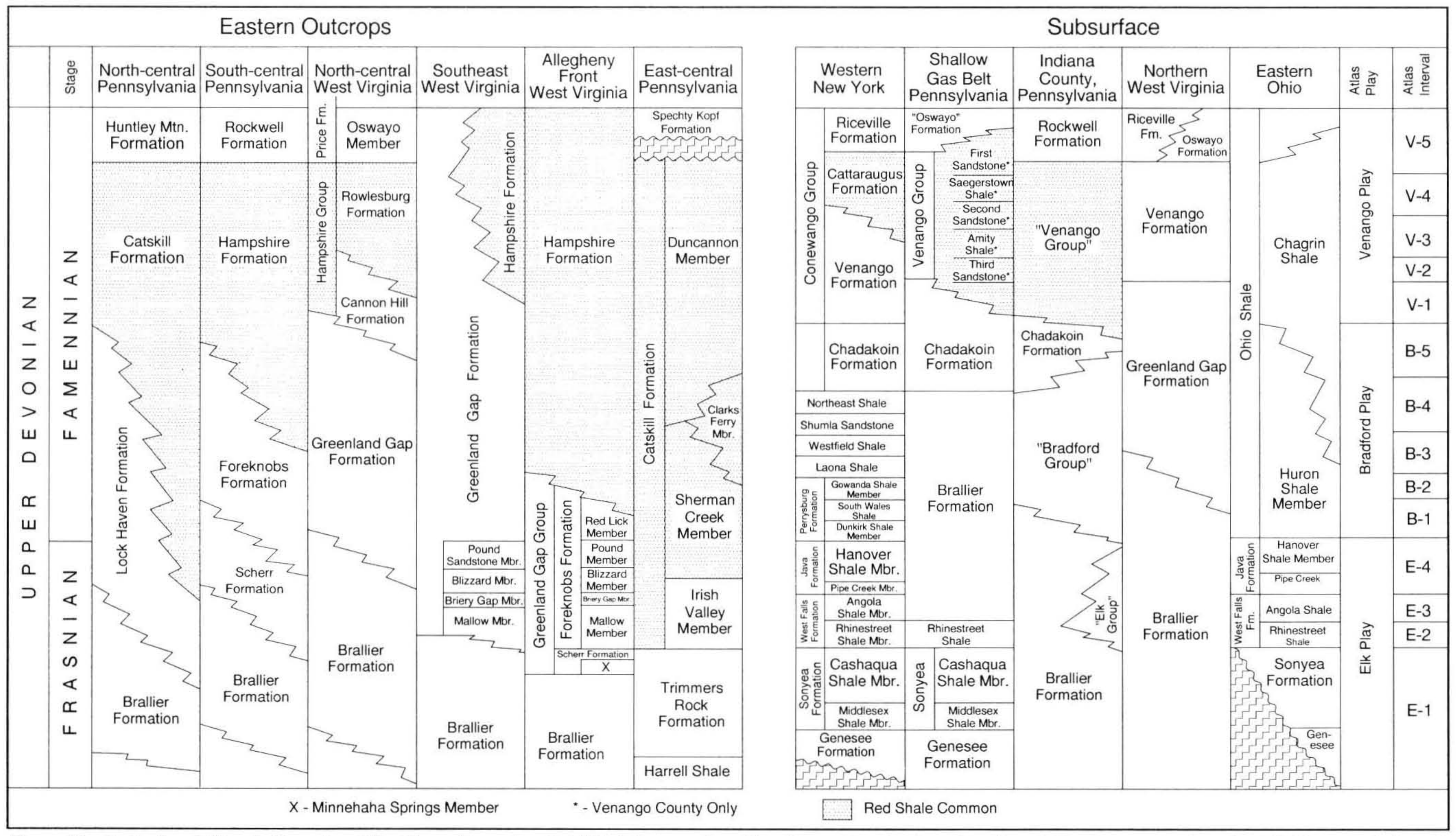
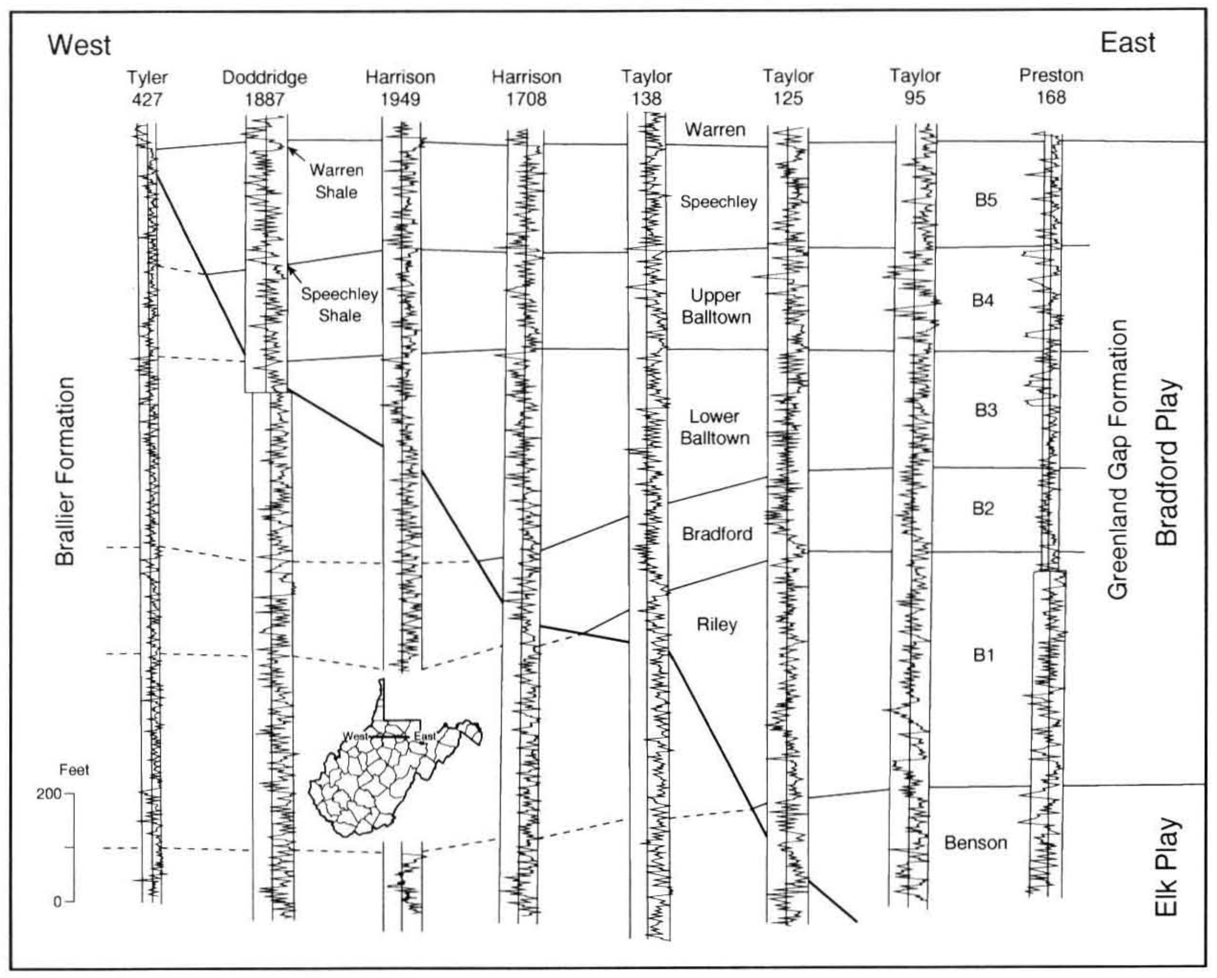


Figure Dbs-5. Regional lithostratigraphy of the Upper Devonian Catskill delta complex. After Boswell and others (1987) and Woodrow and others (1988). The correlation of formations to the stages is approximate and has not been consistently reported in the literature.

Figure Dbs-6. West-east stratigraphic cross section of the Bradford play in northern West Virginia. Informal interval designations are based on Cardwell (1980; 1982a). Left line on logs represents 50 percent clean sandstone and center line represents 25 percent clean sandstone (considered equivalent to siltstone) based on the gamma-ray base-line method. Lateral transition from Greenland Gap to Brallier Formation occurs where lithology grades from siltstone-dominated to shale-dominated. Modified from Boswell and others (1987). The Warren and Speechley shales cross larger Catskill lithofacies at low angles, approximating time lines, and can be recognized across large areas.



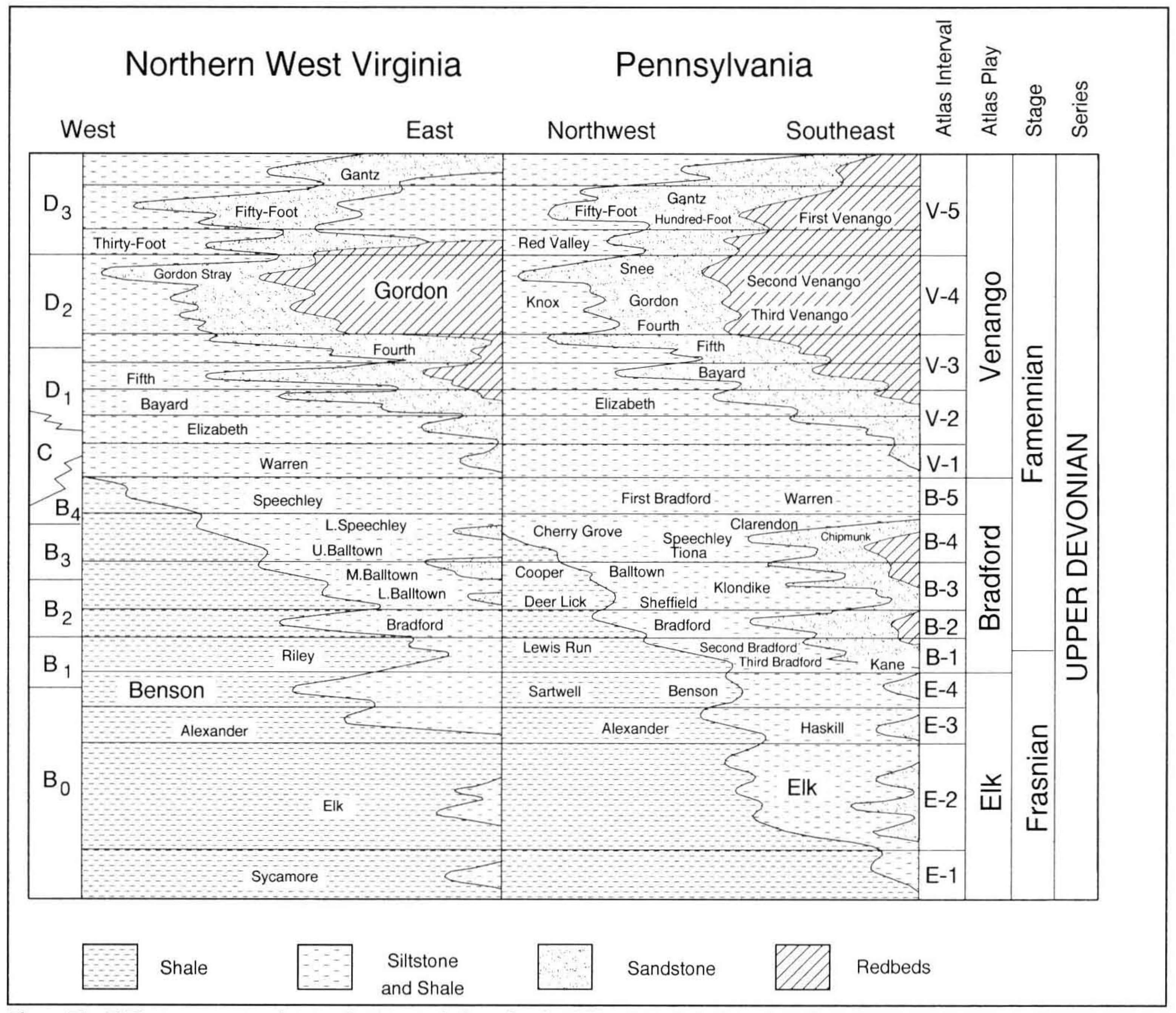


Figure Dbs-7. The sequence and approximate correlation of major drillers' sands in the subsurface of western Pennsylvania and northern West Virginia. Because the Bradford reservoirs have a longer and more successful production history in Pennsylvania, a more complex terminology has developed in that area. Pennsylvania correlations taken largely after Fettke (1938b), Dickey and others (1943), Wolfe (1963), and Harper and Laughrey (1987). West Virginia correlations after Cardwell (1982a), Filer (1985), and Boswell and others (1987). Far left column shows terminology introduced by Kelley and Wagner (1970).

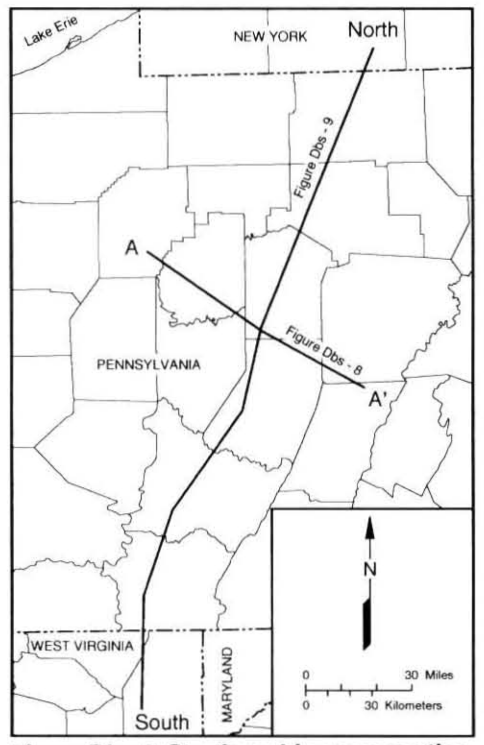
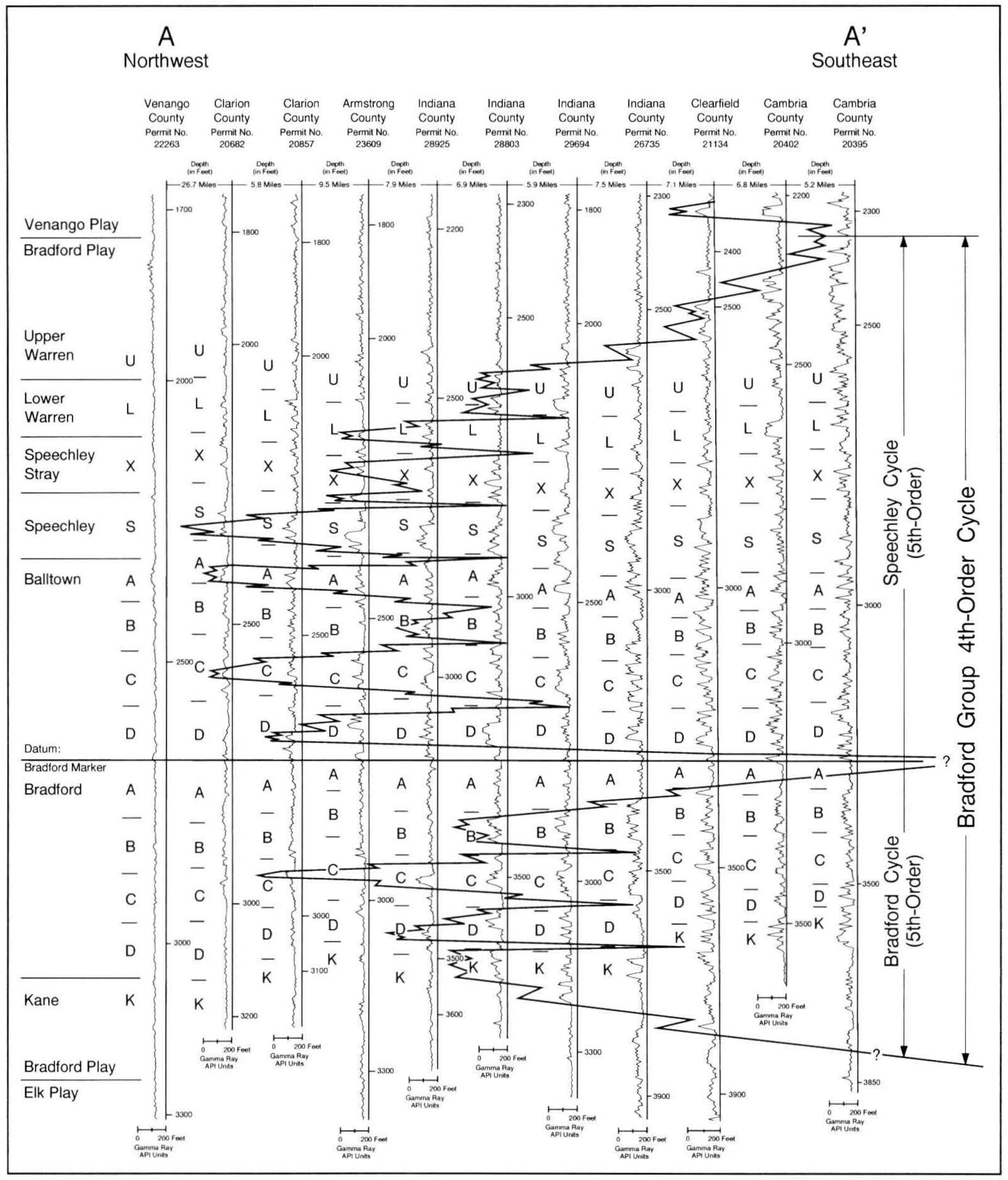


Figure Dbs-8. Stratigraphic cross section A-A' of the Bradford play in Pennsylvania prepared by Flaherty (1994). Based on a network of similar cross sections, Flaherty interpreted two primary transgressive-regressive cycles within the Bradford play, which he named the Bradford cycle (intervals B-1 and B-2) and the Speechley cycle (intervals B-3, B-4, and B-5). Smallest-scale cycles are considered to be sixth order. Figure modified slightly to show atlas intervals. Location of north-south cross section (Figure Dbs-9) is also shown.



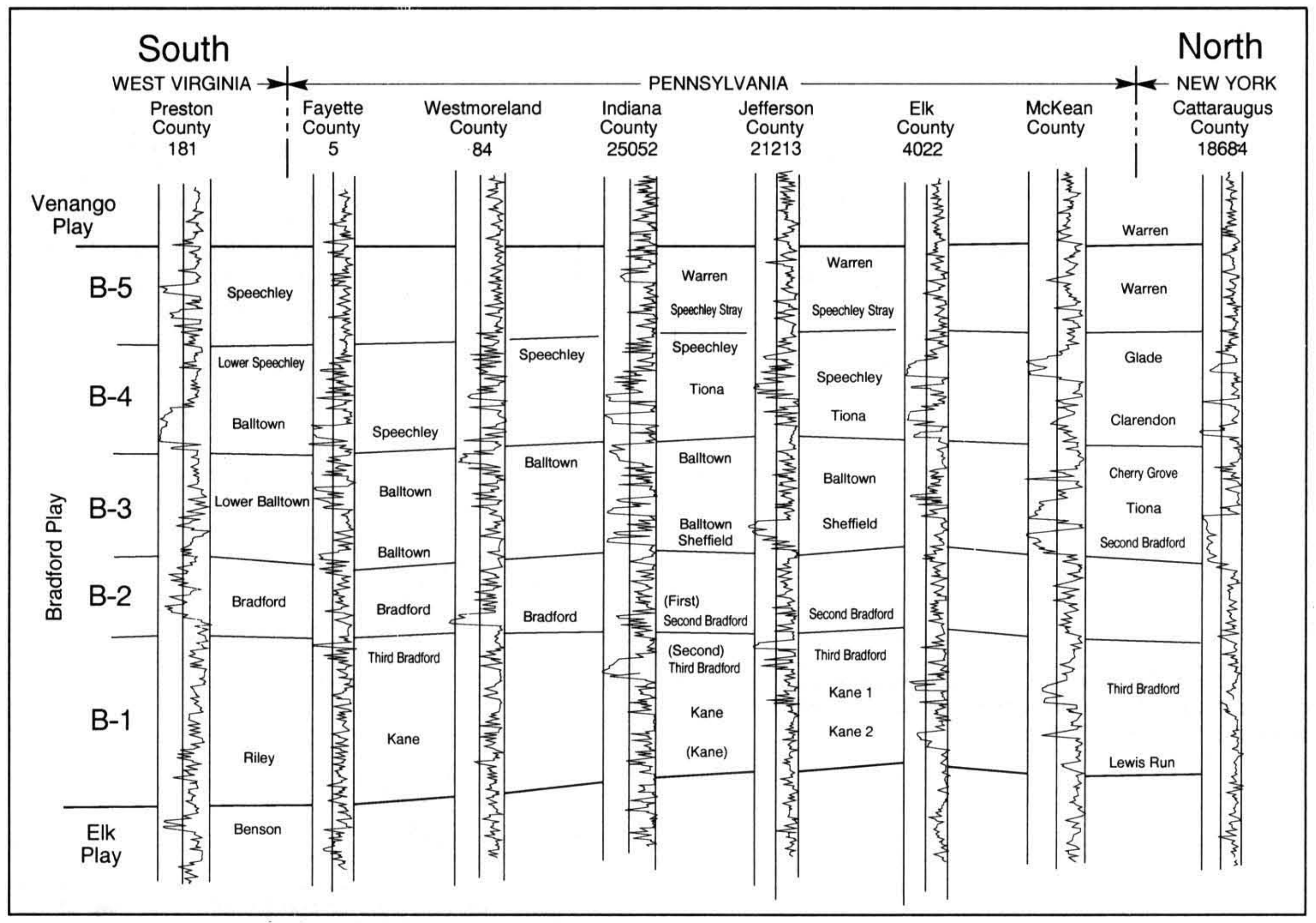


Figure Dbs-9. North-south stratigraphic cross section of the Bradford play. Center line on logs represents 50 percent clean sandstone using gamma-ray base-line method. References for informal sandstone designations are as follows: Preston County, West Virginia, Lewis (1983); Fayette County, Pennsylvania, Hickock and Moyer (1933); Indiana County, Pennsylvania, Wolfe (1963); Jefferson County, Pennsylvania, Shaffner (1946); Elk County, Pennsylvania, based on Ingham and others (1956); McKean County, Pennsylvania, Lytle and Goth (1970). Informal names indicate the most common name used in that locality; for example, note that Second Bradford is used to designate a sandstone in interval B-3 in the oil fields of McKean County and for a sandstone in the upper B-1 interval in the gas fields of Indiana County. Furthermore, Second Bradford has also been used to designate basal B-2 sandstones in Armstrong County to the west of this line. See locator map (Figure Dbs-8) for location of cross section.

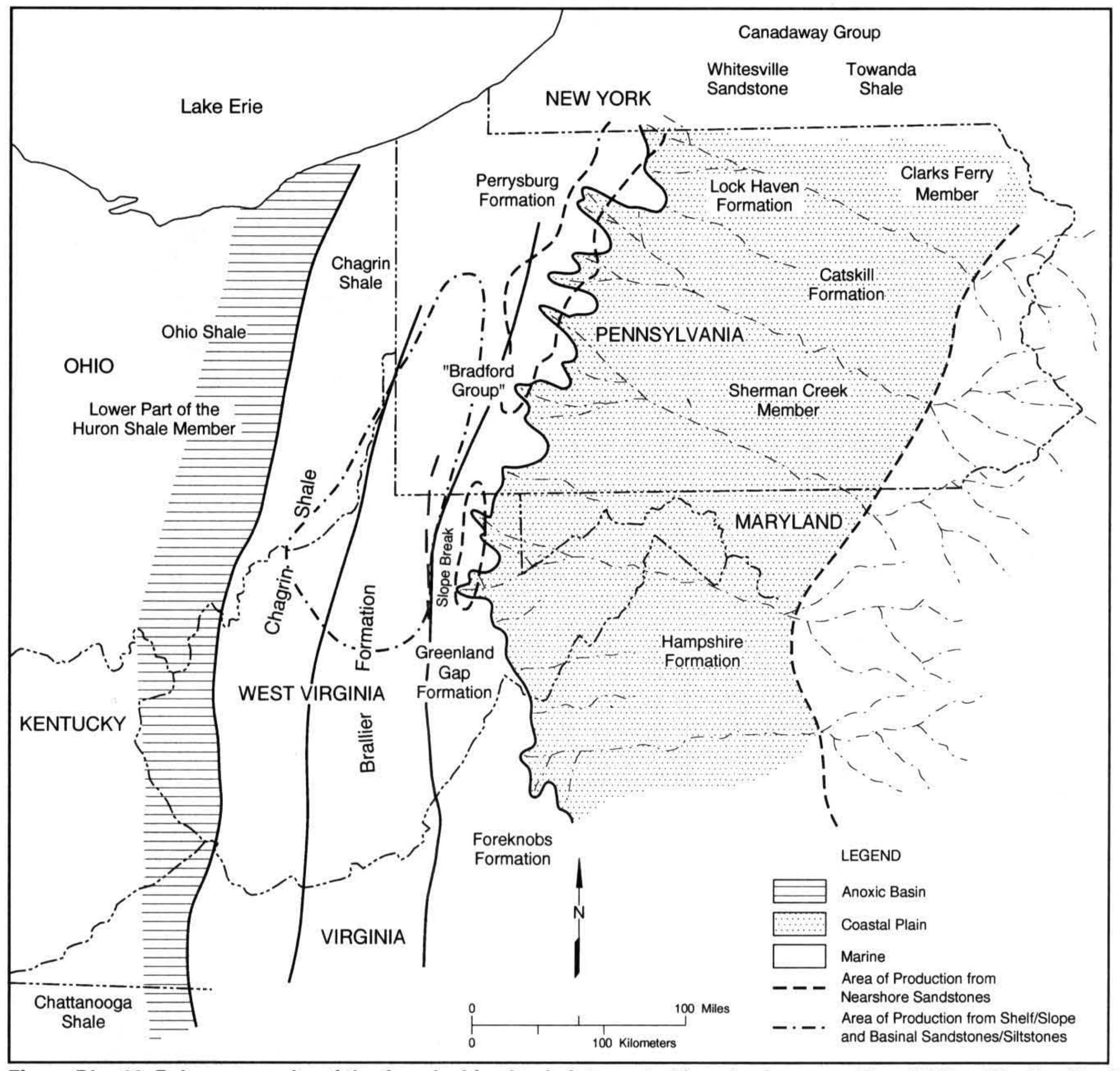


Figure Dbs-10. Paleogeography of the Appalachian basin interpreted for a horizon near the middle of the Bradford play. The figure represents conditions during deposition of the Balltown interval. Balltown reservoirs in Pennsylvania are highly-lenticular sandstones interpreted to have formed in shallow marine environments adjacent to a fluvially dominated shoreline. The same interval is productive from shelf and slope marine units in northern West Virginia. More wave-dominant conditions may have prevailed in other intervals of the Bradford play. After Boswell (1988a).

TABLE Dbs-1		Murphy Creek WV	Murphy Creek WV	Jarvisville WV	Brown-Lumberport WV	Bridgeport-Pruntytown WV	Weston-Jane Lew WV	Belington WV	Brookville PA	Creekside Area of Smicksburg Consolidated PA
BASIC RESERVOIR DATA	POOL NUMBER	47150433	47150432	47151432	47104433	47110	47153433	47297433		
	DISCOVERED	1920	1906	1914	1902	1912	1925	1973	1884	1900
	DEPTH TO TOP RESERVOIR	3,388	3,201	3,357	3,153	3,190	3,198	2,932	2,647	2,558
	AGE OF RESERVOIR	Upper Devonian	Upper Devonian	Upper Devonian	Upper Devonian	Upper Devonian	Upper Devonian	Upper Devonian	Upper Devonian	Upper Devonian
	FORMATION	Greenland Gap	Greenland Gap	Greenland Gap	Greenland Gap	Greenland Gap	Greenland Gap	Greenland Gap	Bradford	Bradford
	PRODUCING RESERVOIR	Balltown	Speechley	Balltown	Balltown	Speechley Balltown	Balltown	Balltown	All	All
	LITHOLOGY	sandstone/ siltstone	sandstone/ siltstone	sandstone/ siltstone	sandstone/ siltstone	sandstone/ siltstone	sandstone/ siltstone	sandstone/ siltstone	sandstone	sandstone
	TRAP TYPE	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic
	DEPOSITIONAL ENVIRONMENT	shallow shelf	shallow shelf	shallow shelf	shallow shelf	shallow shelf	shallow shelf	shallow shelf	marine	marine
	DISCOVERY WELL IP (Mcf)				237					
	DRIVE MECHANISM	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion
	NO. PRODUCING WELLS	278	181	328	244	168	172	241	190	351
	NO. ABANDONED WELLS	4	4	7	36	8	2	2	68	13
	AREA (acreage)	30,738				16,016	23,490	17,010	33,180	18,805
	OLDEST FORMATION PENETRATED	Helderberg	Helderberg	Helderberg	Marcellus	Helderberg	Juniata	Helderberg	Bradford	Brallier
	EXPECTED HETEROGENEITY DUE TO:	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic
RESERVOIR PARAMETERS	AVERAGE PAY THICKNESS (ft.)	11	7	16	4	8	13			
	AVERAGE COMPLETION THICKNESS (ft.)	90	59	35	32	54	60	58	25	188
	AVERAGE POROSITY–LOG (%)	8.99	12.62	8.40	7.21	7.86	6.80		8.90	8.10
	MINIMUM POROSITY–LOG (%)	4.91	4.94	4.48	5.98	6.44	5.60		6.2	3.3
	MAXIMUM POROSITY–LOG (%)	13.10		21.18	8.44	8.93	9.20		11.6	12.5
	NO. DATA POINTS	66	25	75	2	5	35			
	POROSITY FEET	1	1.3	1.9	2.7					
	RESERVOIR TEMPERATURE (°F)	92	90	92	89	87		85		87
	INITIAL RESERVOIR PRESSURE (psi)		1,100	1,625	900	1,400	1,375	900	635	957
	PRODUCING INTERVAL DEPTHS (ft.)	2,772-4,215	2,604-3,763	2,956-4,382	3,022-4,384	2,376-4,346	2,666-4,242	2,140-3,858		
	PRESENT RESERVOIR PRESSURE (psi) / DATE	280/1970		241/1965	113/1980		239/1983			
FLUID & GAS PROPERTIES	Rw (Ωm)	0.05	0.05	0.05	0.05	0.05	0.05	0.05		0.05
	GAS GRAVITY (g/cc)			0.645						0.596
	GAS SATURATION (%)	54.22	53.81	56.21	56.24	65.13	55.62		60.2	57.6
	WATER SATURATION (%)	45.78	46.19	43.79	44.76	34.87	44.38		39.8	42.4
	COMMINGLED	yes	yes	yes	yes	yes	yes	yes	yes	yes
	ASSOCIATED OR NONASSOCIATED	associated	associated	associated	associated	associated	associated	associated		
	Btu/scf			1,100						1,062
VOLUMETRIC DATA	STATUS (producing, abandoned, storage)	producing	producing	producing	producing	producing	producing	producing	producing	producing
	ORIGINAL GAS IN PLACE (Mcf)									
	ORIGINAL GAS RESERVES (Mcf)									
	PRODUCTION YEARS	1978-1993	1978-1993	1978-1993	1930-1993		1979-1993	1980-1993	1884-1993	1900-1993
	REPORTED CUMULATIVE PRODUCTION (Mcf)	1,854,300	970,500	1,995,200	7,223,300		575,400	527,000		
	NO. WELLS REPORTED	19	17	44	69		7	16		
	ESTIMATED CUMULATIVE PRODUCTION (Mcf)	16,300,000		13,800,000	31,200,000	6,700,000	9,400,000	5,600,000		
	REMAINING GAS IN PLACE (Mcf)/DATE									
	REMAINING GAS RESERVES (Mcf)/DATE									
	RECOVERY FACTOR (%)									
	INITIAL OPEN FLOW (Mcf/d)	62			39	175		389	13	23
	FINAL OPEN FLOW (Mcf/d)	843		548	65	553	790	872	129	557

TABLE Dbs-1		Millstone PA	Indiana Area of Smicksburg Consolidated PA	Lewisville Area of Smicksburg Consolidated PA	Marion Center Area of Smicksburg Consolidated PA	Plumville Area of Smicksburg Consolidated PA	Plattsville PA	Lumber City PA	Cush Cushion PA	Cherry Hill PA
BASIC RESERVOIR DATA	POOL NUMBER									
	DISCOVERED	1885	1885	1900	1891	1908	1975	1976	1978	1927
	DEPTH TO TOP RESERVOIR	1,979	2,800	2,785	2,554	2,733	2,771	2,554	3,563	2,339
	AGE OF RESERVOIR	Upper Devonian	Upper Devonian	Upper Devonian	Upper Devonian	Upper Devonian	Upper Devonian	Upper Devonian	Upper Devonian	Upper Devonian
	FORMATION	Bradford	Bradford	Bradford	Bradford	Bradford	Bradford	Bradford	Bradford	Bradford
	PRODUCING RESERVOIR	Speechley	All	All	All	All	All	All	Kane	All
	LITHOLOGY	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone
	TRAP TYPE	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic
	DEPOSITIONAL ENVIRONMENT	marine	marine	marine	marine	marine	marine	marine	marine	marine
	DISCOVERY WELL IP (Mcf)							3	10,000	
	DRIVE MECHANISM	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion
	NO. PRODUCING WELLS	153	976	443	634	512	148	350	139	359
	NO. ABANDONED WELLS	70	16	6	7	22	6	15	5	26
	AREA (acreage)	27,868	18,015	19,450	7,696	23,365	5,532	15,240	3,541	7,452
	OLDEST FORMATION PENETRATED	Bradford	Bradford	Bradford	Elk	Helderberg	Bradford	Elk	Elk	Bradford
	EXPECTED HETEROGENEITY DUE TO:	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	fractures/ stratigraphic	stratigraphic
RESERVOIR PARAMETERS	AVERAGE PAY THICKNESS (ft.)								20	
	AVERAGE COMPLETION THICKNESS (ft.)	28	151	147	148	89	69	205	20	179
	AVERAGE POROSITY–LOG (%)	11.9								
	MINIMUM POROSITY–LOG (%)	9	6						8	
	MAXIMUM POROSITY–LOG (%)	14	11						30	
	NO. DATA POINTS									
	POROSITY FEET	3.3								
	RESERVOIR TEMPERATURE (°F)	77			92			80		
	INITIAL RESERVOIR PRESSURE (psi)	257	1,074	1,016	770	953	1,338	960		955
	PRODUCING INTERVAL DEPTHS (ft.)									
	PRESENT RESERVOIR PRESSURE (psi) / DATE									
FLUID & GAS PROPERTIES	Rw (Ωm)	0.05	0.05							
	GAS GRAVITY (g/cc)	0.714	0.587	0.587		0.587				
	GAS SATURATION (%)	83.2	60							
	WATER SATURATION (%)	16.8	40							
	COMMINGLED	yes	yes	yes	yes	yes	yes	yes	yes	yes
	ASSOCIATED OR NONASSOCIATED									
	Btu/scf	1,244	1,050	1,047		1,056				
VOLUMETRIC DATA	STATUS (producing, abandoned, storage)	producing	producing	producing	producing	producing	producing	producing	producing	producing
	ORIGINAL GAS IN PLACE (Mcf)									
	ORIGINAL GAS RESERVES (Mcf)									
	PRODUCTION YEARS	1885-1993	1885-1993	1900-1993	1891-1993	1908-1993	1975-1993	1976-1993	1927-1993	
	REPORTED CUMULATIVE PRODUCTION (Mcf)									
	NO. WELLS REPORTED									
	ESTIMATED CUMULATIVE PRODUCTION (Mcf)									
	REMAINING GAS IN PLACE (Mcf)/DATE									
	REMAINING GAS RESERVES (Mcf)/DATE									
	RECOVERY FACTOR (%)									
	INITIAL OPEN FLOW (Mcf/d)	48	13	37	56	128	138	38		
	FINAL OPEN FLOW (Mcf/d)	101	785	817	1,507	506	1,426	516	421	708

A regional sandstone isolith map of the B-2 interval (Figure Dbs-13) reveals a pronounced strike-trending accumulation in east-central Indiana County and a less well-developed strike trend displaced approximately 20 miles to the west (seaward) in Armstrong County. Both units have been prolific gas reservoirs. Murin (1988) interpreted the Indiana County unit (First Bradford) as delta front sandstones that formed during transgression by the reworking of fluvially dominated deltas. The Armstrong County accumulation was interpreted by Murin (1988) as coeval submarine fans dominated by dip-trending sandstones (Figure Dbs-14). Alternatively, Wolfe (1963) interpreted the Armstrong County trend (which he referred to as Second Bradford) (see Figures Dbs-9, Dbs-15) as the product of a regressive nearshore bar system dissected by tidal channels. Although the western belt of sandstone is more lenticular, it exhibits reservoir quality that is equal or superior to that of the sandstone belt to the east (Figure Dbs-16).

Throughout the Indiana-Armstrong area, Bradford production from B-2 sandstones is supplemented by gas commingled from numerous subsidiary reservoirs. Production from these reservoirs is erratic, probably due to extreme reservoir heterogeneity. Nonetheless, where these reservoirs are well-developed, reservoir quality is equal to that of the main regional reservoirs (Figure Dbs-17). Laughrey and Harper (1986) summarized core and log data for several secondary Bradford reservoirs in an Indiana County well and reported porosities typically ranging between 6 and 9 percent (Figure Dbs-18).

With the increased utilization and effectiveness of multiple zone completion and stimulation, the average productivity of new Bradford wells in western Pennsylvania has gradually increased. In the 1930s and 1940s, IPs commonly ranged from 50 to 500 Mcfg/d (Shaffner, 1946). By 1957, average after-stimulation IPs for Armstrong County wells had improved to 650 Mcfg/d (Lytle and others, 1959). Presently, an average well in Indiana County is expected to test between 700 and 1,000 Mcfg/d initially (Laughrey and Harper, 1986). During an expected well life of up to 20 years, good wells can produce an average of 180 MMcfg (Figure Dbs-19) (Harper and others, 1996).

Bradford reservoirs in northern West Virginia are typically siltstones and thin-bedded, fine-grained sandstones (Figure Dbs-20). Deposition of these units took place on marine slopes approximately 30 to 50 miles offshore of the paleoshoreline (Boswell, 1988a). The role of natural fractures in increasing the porosity and permeability of certain units is not clear. Sandstone as interpreted from gamma-ray well logs is uncommon in the interval, perhaps owing to the thinness of the units relative to the resolution of the logging tools. An isopach of

Table Dbs-2. Representative compositional analyses of natural gas produced from the Bradford play. Sources are 1, Hickock (1993); 2, Laughrey and Harper (1986); and 3, Harper and Laughrey (1987).

Source	County	Pool	Reservoir	Btu/ft³	Meth (%)	Eth (%)	Other (%)	He (%)	H_2 (%)	N_2 (%)	CO_2 (%)	O_2 (%)
2	Allegheny, Pennsylvania	Forward	Speechley	1,049	92.8	3.0	1.8	0.12		2.2	0.1	
2	Allegheny, Pennsylvania	Mifflin	Speechley	1,056	92.7	3.1	2.0	0.13		2.0	0.1	
2	Washington, Pennsylvania	Rodfield	Speechley	1,061	93.6	4.2	1.2	0.10		0.8	0.1	
1	Butler, Pennsylvania		Speechley	1,420	53.3		45.8			0.9		
3	Westmoreland, Pennsylvania	Bagdad	Speechley	1,081	92.3	4.9	1.9	Trace		0.8	0.11	
3	Armstrong, Pennsylvania	Plumville	Tiona	1,056	94.9	3.4	1.2			0.5	Trace	
3	Indiana, Pennsylvania	Blairsville	Balltown	1,083	92.5	4.1	2.5	0.10		0.7	0.1	
3	Elk, Pennsylvania	Halltown	Sheffield	1,244	78.2	13.1	7.4			1.1	0.06	0.1
3	Westmoreland, Pennsylvania	Saltsburg	Bradford	1,016	95.5	2.4	0.5			1.5	0.09	Trace
1	Clarion, Pennsylvania		Bradford	1,189	80.5		17.8			1.7		
1	Forest, Pennsylvania		Bradford 3rd	1,279	70.8		28.2			1.0		
2	Greene, Pennsylvania	Waynesburg	Bradford	1,123	89.5	6.6	3.5			0.4		
2	Washington, Pennsylvania	Lone Pine	Bradford	1,184	83.8	10.4	5.4			0.4		
3	Jefferson, Pennsylvania	Sigel	Kane	1,141	89.6	6.3	2.6	0.10		1.2	0.06	0.1

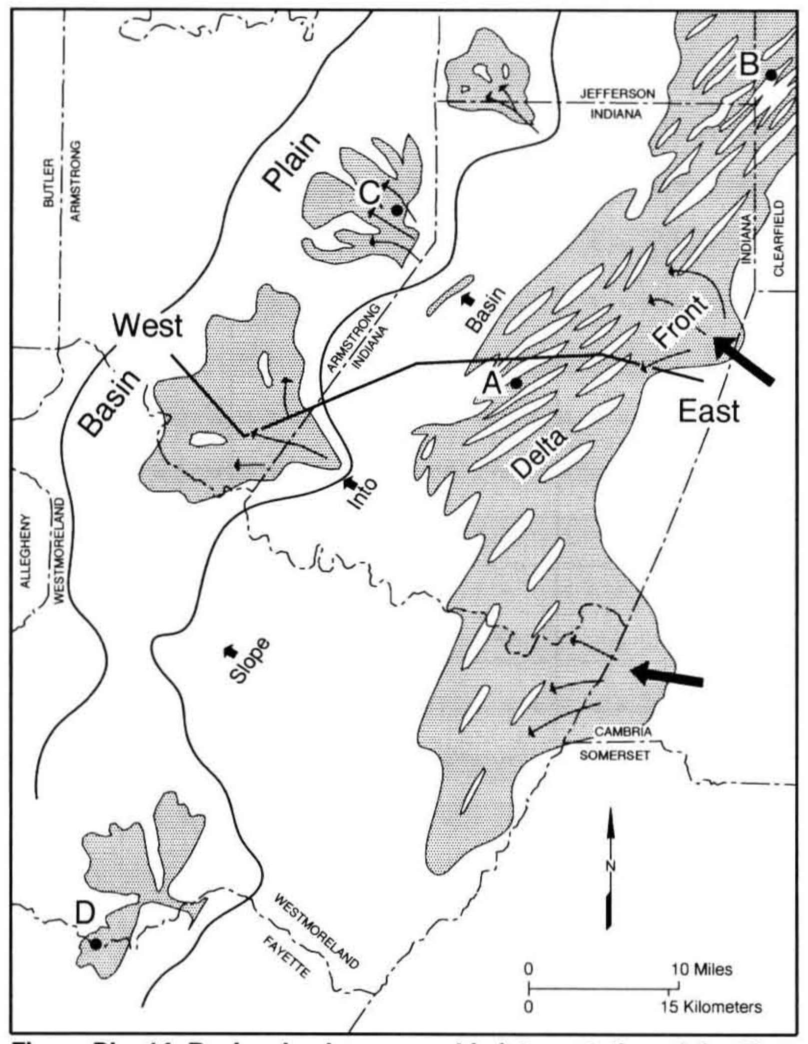


Figure Dbs-14. Regional paleogeographic interpretation of the First Bradford (B-2) sandstone in Indiana County, Pennsylvania, and surrounding areas. The eastern strike-trending sandstones are interpreted as reworked delta front deposits; the lobate units to the west are interpreted as submarine fans (Murin, 1988). An alternative interpretation is that the western sandstone is a progradational shoreline unit with the eastern sandstones slightly older delta front deposits formed during regional transgression. The relationship of the two units can be seen in Figure Dbs-15. Letters A, B, C, and D refer to core descriptions provided in Figure Dbs-16.

a Balltown sandstone from the Jarvisville field, Harrison County, reveals a unit less than 5 feet thick that is restricted to sinuous channels often no more than 1,000 feet in width (Figure Dbs-21). The overall trend of the reservoir-bearing facies in northern West Virginia is north-south and was probably controlled by a shelf-slope break that paralleled depositional strike (Figures Dbs-22a, Dbs-22b, Dbs-23).

Balltown reservoirs in West Virginia have low porosities and permeabilities and are routinely hydrofractured. Typical after-stimulation IPs of recent Balltown wells in Lewis and Harrison counties range from 500 to 1,000 Mcfg/d. Natural open flow data collected by the West Virginia Tight Formations Committee (1982) indicated that only 38 of 1,467 completions in the Bradford interval in Harrison and Lewis counties exceeded 105 Mcfg/d. In all of these areas, Balltown production is commonly commingled with that from Big Injun, Venango, Benson, or other Bradford units.

Description of Key Fields

Smicksburg Consolidated field: The Smicksburg Consolidated field encompasses numerous historical gas fields that were developed in eastern and northern Indiana County, Pennsylvania, and surrounding areas beginning in the early 1900s. The area subsequently has been penetrated by thousands of wells with a typical spacing of roughly 20 to 80 acres. Drilling continues at present, and is focused on further extending the eastern margin of the field as well as better delineating the more lenticular sandstones within the field. The primary Bradford reservoirs in the area (the lower Balltown (B-3), First Bradford (B-2),

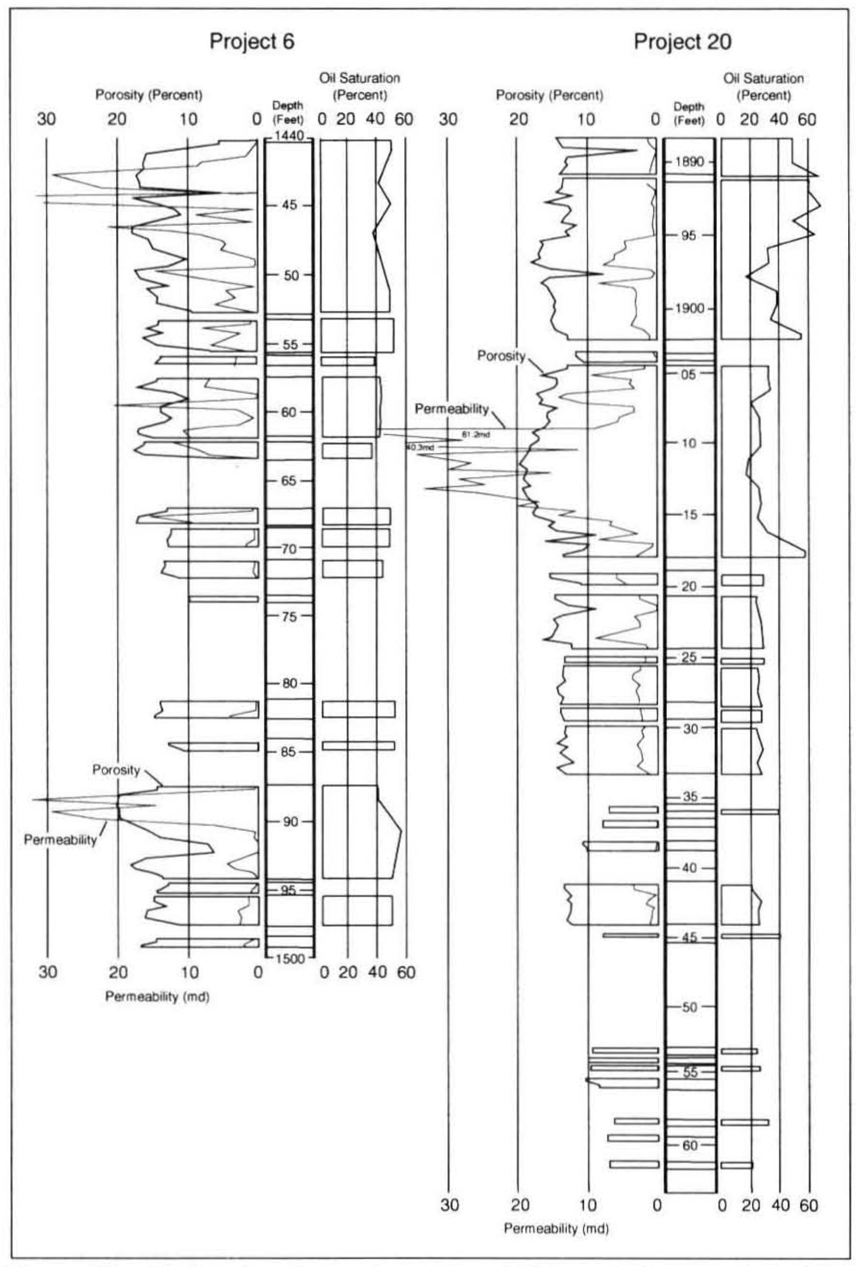


Figure Dbs-11. Graphs of porosity, permeability, and oil saturation of the Bradford Third sandstone (B-1) derived from core analysis of two wells in the Bradford oil field, McKean County, Pennsylvania. From Fettke (1950).

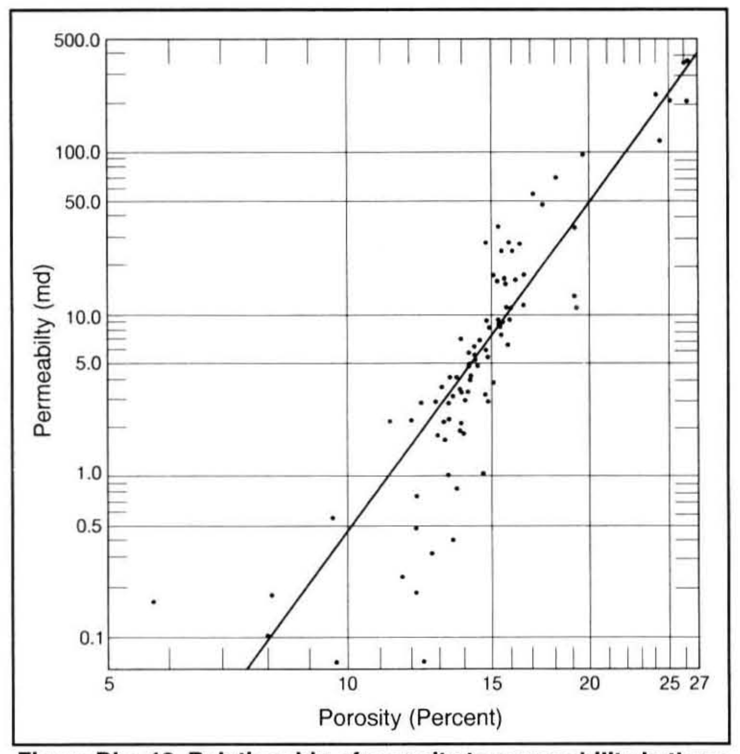


Figure Dbs-12. Relationship of porosity to permeability in three cores of the Bradford Third sandstone reservoir in the Bradford oil field. From Fettke (1938b).

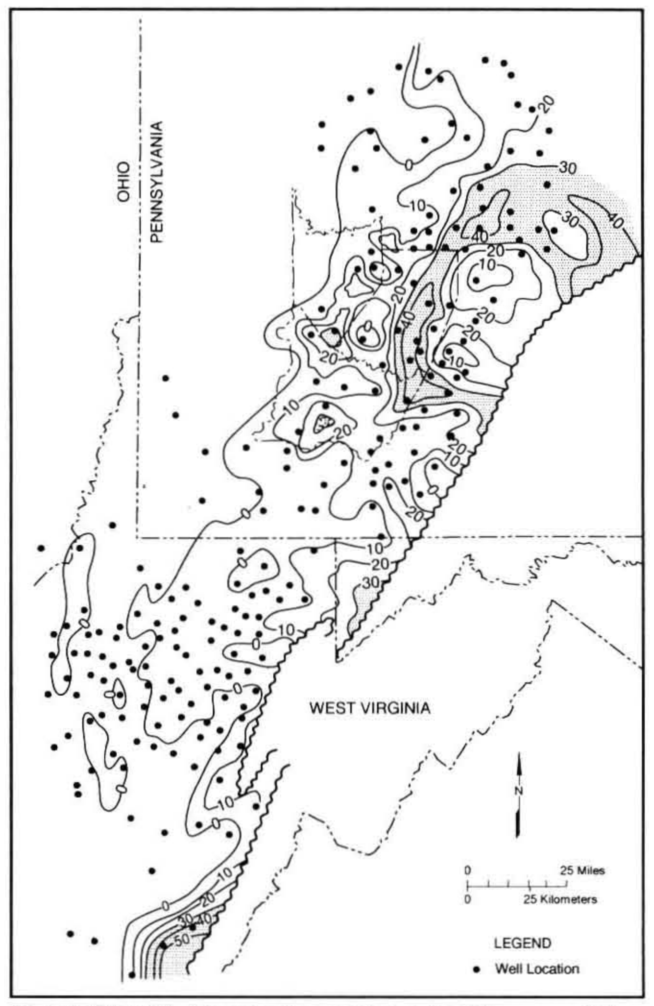


Figure Dbs-13. Regional sandstone isolith map of the B-2 interval. Note the strike-trending sandstones of east-central Indiana County, Pennsylvania. Contour interval = 10 feet. The lobate units located to the west of the main trend have been interpreted as submarine fan complexes (Murin, 1988) and nearshore marine bars (Wolfe, 1963). Modified from Boswell and others (1993).

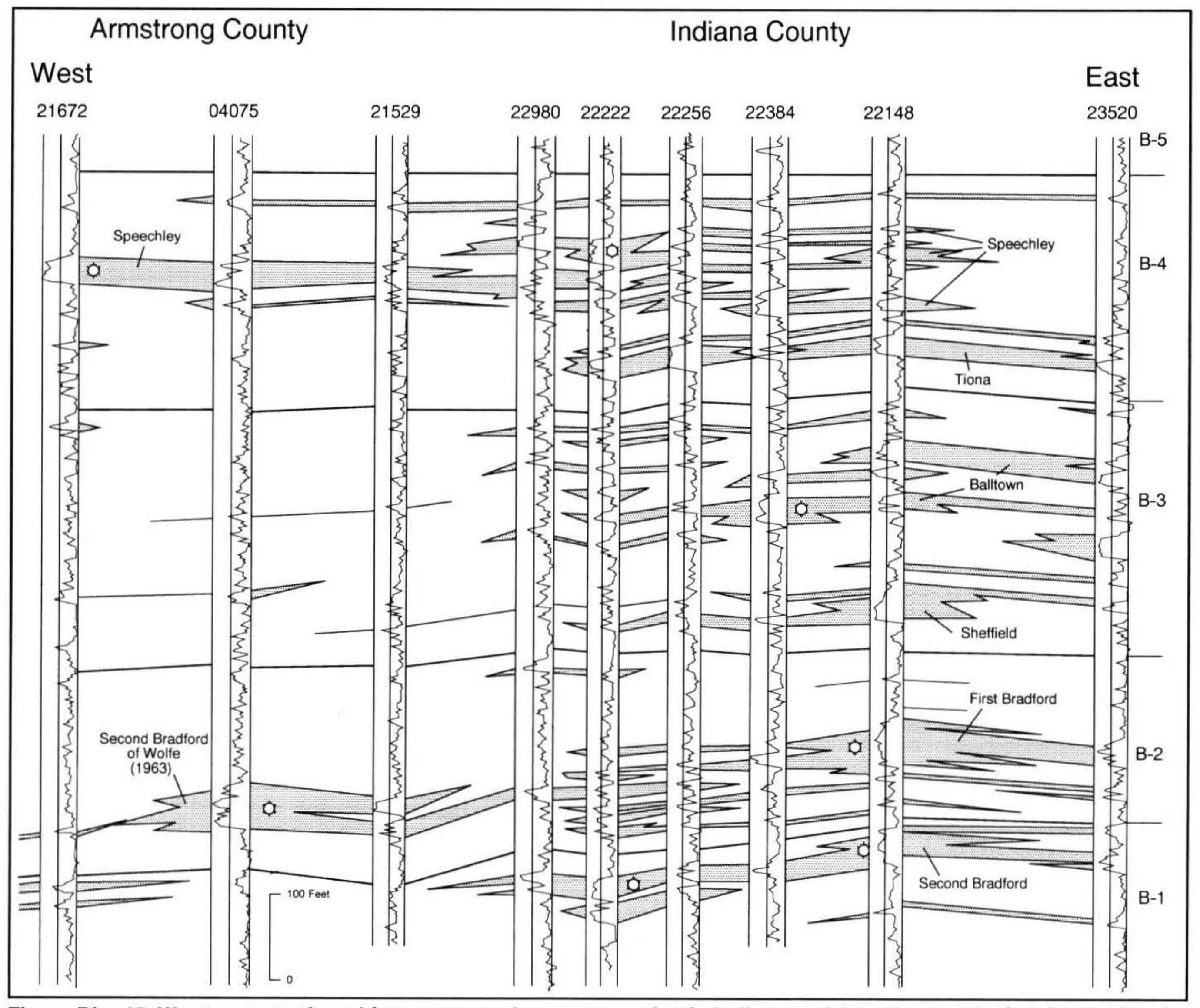
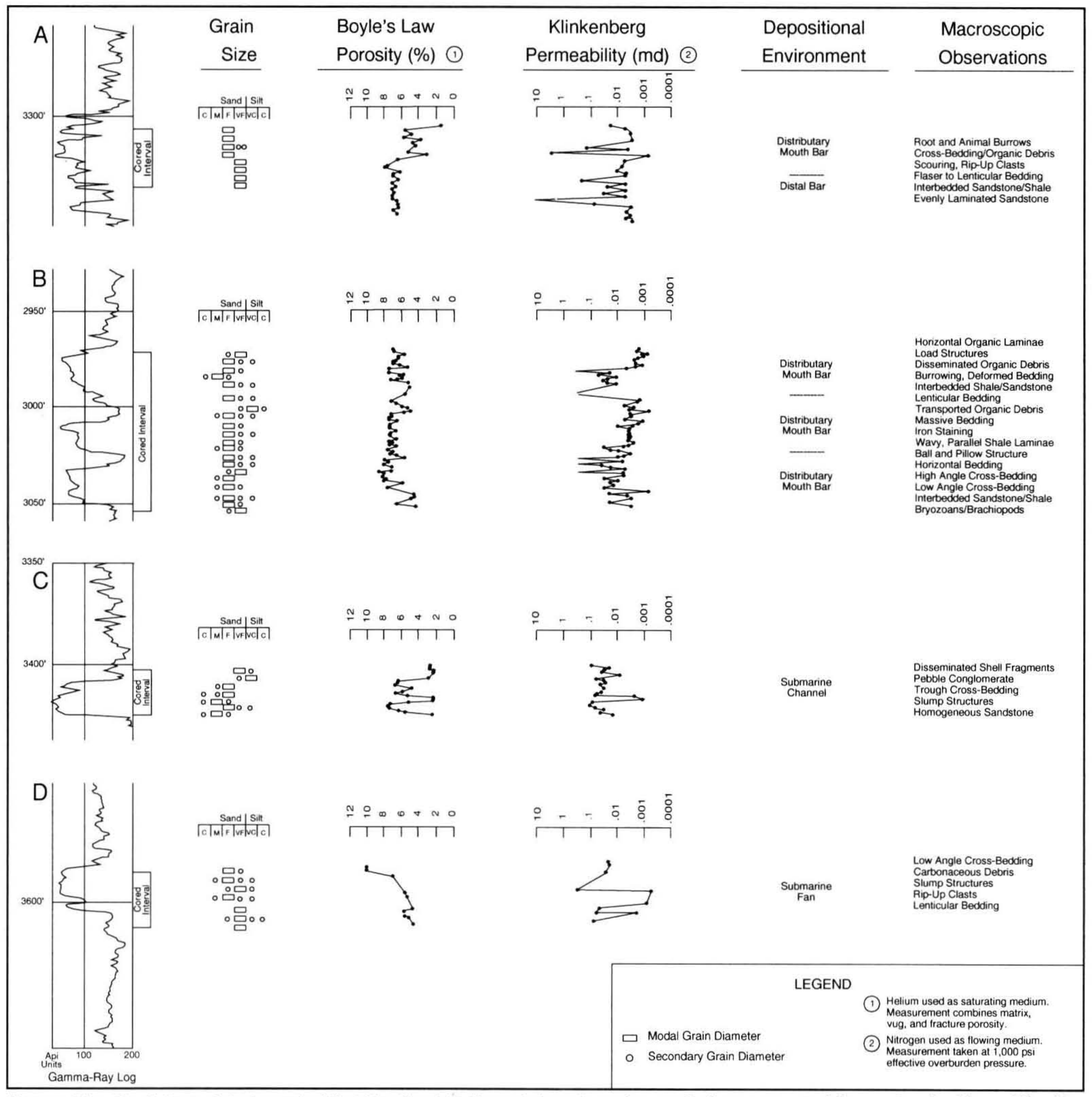


Figure Dbs-15. West-east stratigraphic gamma-ray log cross section in Indiana and Armstrong counties, Pennsylvania, showing the distribution of the Bradford reservoirs across the primary gas-producing area. The correlated units represent 50 percent clean sandstone using the gamma-ray base-line method. Wells are identified using county permit numbers. The First Bradford Sandstone represents the delta front deposits shown in Figure Dbs-14. The Second Bradford of Wolfe (1963) is identified in Figure Dbs-14 as basin plain deposits. Location of cross section is shown in Figure Dbs-14.



Figures Dbs-16a-d. Core data from the First Bradford (B-2) sandstone from four wells in west-central Pennsylvania; Figure Dbs-16a. No. 1 Good, Lahr, and Kaufman (Indiana County No. 25084). Figure Dbs-16b. No. 1 Beatty (Clearfield County No. 21356). Figure Dbs-16c. No. 3 Stewart (Armstrong County No. 22349). Figure Dbs-16d. No. 1 Shirer (Westmoreland County No. 21640). Modified from Murin (1988).

and Second Bradford (B-1) sandstones) trend roughly parallel to regional depositional strike and are interpreted to have formed in nearshore environments (Murin, 1988). These main strike-trending sandstones are fine-grained, offset-stacked, and separated by thick, shaley sequences characterized by numerous, highly lenticular sandstones that provide subsidiary production (Figure Dbs-15). The bulk of these secondary reservoirs, such as the upper Balltown (B-3), exhibit distinct east-west trends (Figure Dbs-24) that are typically less than 1 mile wide. A structural cross section through the Tiona and Balltown intervals shows that the units are in channel morphology suggesting origin in deltaic distributary and subaqueous shelf channels (Figure Dbs-25). Log-derived porosities within pay sandstones of strike and dip orientation range from 6 to 11 percent; however, data provided by Laughrey and Harper (1986) indicate that core-calibrated porosities for Bradford sandstones are generally lower than log values (see Figure Dbs-18). Almost no Bradford sandstones are water-wet; gas saturation typically ranges between 60 and 85 percent. Data provided by Shaffner (1946) indicate that of the more than 1,100 gas wells drilled in the Smicksburg quadrangle (northwest Indiana County) by 1945, slightly more than 65 percent were productive gas wells. Typical rock pressures for Bradford or Balltown wells in the quadrangle ranged as high as 900 psi from an average of roughly 500 psi. Drilling depths throughout the area range from 2,500 to 3,500 feet. A log of a typical well located in the Indiana quadrangle (southwestern Indiana County) shows 19 separate Bradford units that have been perforated for production in the Smicksburg Consolidated field (Figure Dbs-26).

Brown-Lumberport Consolidated field: In the Brown-Lumberport Consolidated field, Harrison County, West Virginia, Balltown (B-3 and B-4) and Speechley (B-4 and B-5) strata were deposited as turbidites upon sloping shelves approximately 30 to 50 miles west (seaward) of the inferred paleoshoreline (Boswell, 1988a). The main Balltown reservoir occurs as a relatively porous zone near the top of the B-3 interval (Figure Dbs-27). However, unlike the fields in Pennsylvania, the reservoir appears very shale-rich and thinly bedded on the gamma-ray log. The unit is 50 to 100 feet in gross thickness, with generally 30 feet of pay or less (Figure Dbs-28). Petrographic analysis of a similar Balltown reservoir in western Taylor County revealed clay content from 19 to 25 percent with feldspars accounting for an additional 9 to 12 percent. Chlorite was the dominant clay mineral present (46 to 52 percent) with substantial amounts of illite (34 to 38 percent) and mixed layer clays (14 to 18 percent). Porosity in the well was 10 percent; permeability ranged from 0.2 to 0.3 md.

Cush Cushion field: In 1980, unusually high IPs were encountered in the Kane sandstone (B-1), escalating local drilling activity in the Cush Cushion field of Cambria, Clearfield, and Indiana counties, Pennsylvania. The discovery well had an initial flow to atmosphere of 10,000 Mcfg/d without the aid of fracture stimulation. In subsequent wells, natural and after-fracture-stimulation IPs of this magnitude were common, with the highest in the field reported at 29,000 Mcfg/d. Production rates from individual wells were equally impressive (Figure Dbs-29), with some wells exceeding 1,000 Mcfg/d. Isopach maps of the Kane sandstone during early development of the field revealed a dominant east-west trend that was interpreted to represent a distributary channel system (Laughrey, 1982). Hussing (1994) interpreted the Kane sandstone as a prograding river or distributary mouth bar. This interpretation is based on the predominance of a coarsening-upward gamma-ray log profile along the main depositional axis of the field, the digitate morphology of the unit as revealed on isopach maps (Figure Dbs-30), and the vertical "climbing" of the unit through the stratigraphic section relative to two time-stratigraphic marker beds (Hussing, 1994) (Figure Dbs-31). Pay thickness ranges from less than 10 feet to more than 30 feet. Log-derived porosities range from 8 percent to the scaled maximum of 30 percent (Figure Dbs-32). Laughrey (1982) surmised that the high porosity in the Kane sandstone was primarily from open natural fractures and that these fractures may be related to a documented cross-strike structural discontinuity that extended from the overthrust belt into the Appalachian Plateau. Hussing (1994) identified numerous vertical faults subparallel to the depositional axis of the Cush Cushion field. These faults are transverse to the regional structural grain and associated with the cross-strike structural discontinuity.

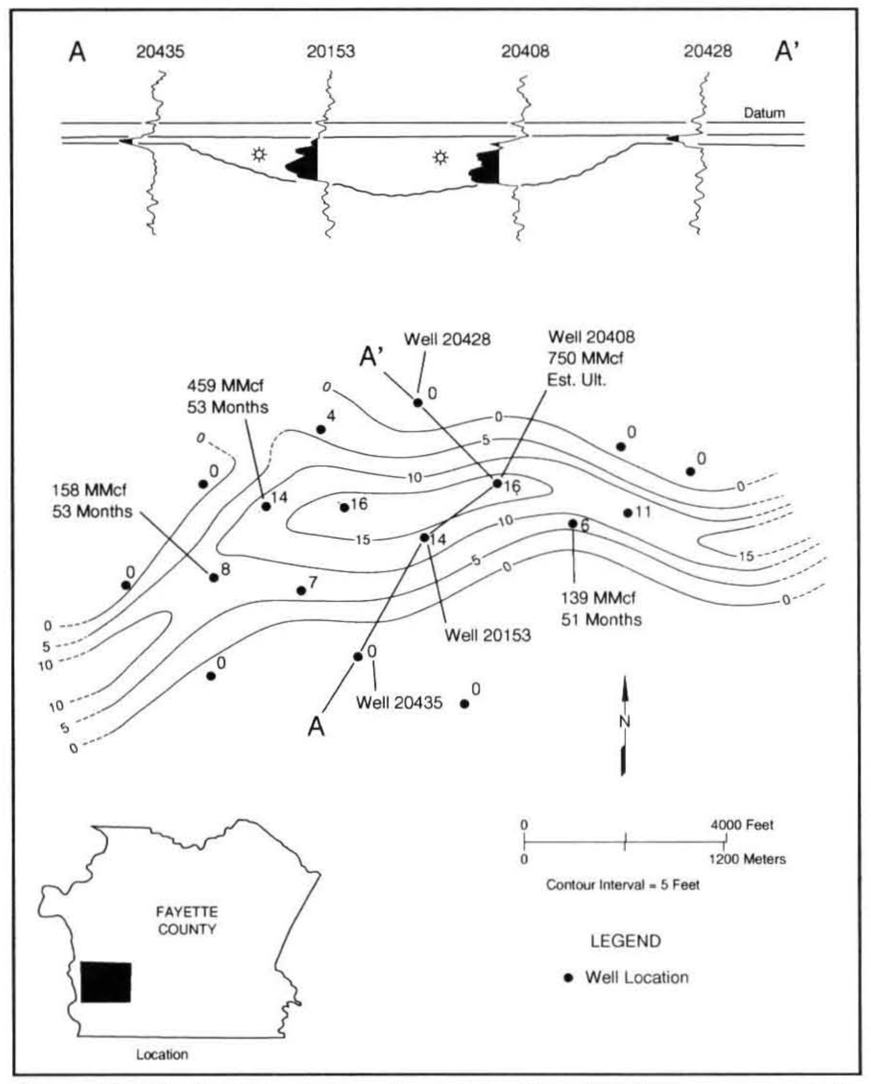


Figure Dbs-17. Isopach map and cross section showing an example of highly lenticular, channelized Bradford play reservoirs in the area outside the primary historical Armstrong-Indiana County producing area. The unit is a Speechley (B-2) sandstone that occurs in a narrow east-west trend. Wells in axial positions are good producers but can be closely offset by dry holes. Example from the Highhouse field area in eastern Fayette County, Pennsylvania. Values given are total feet of clean sandstone.

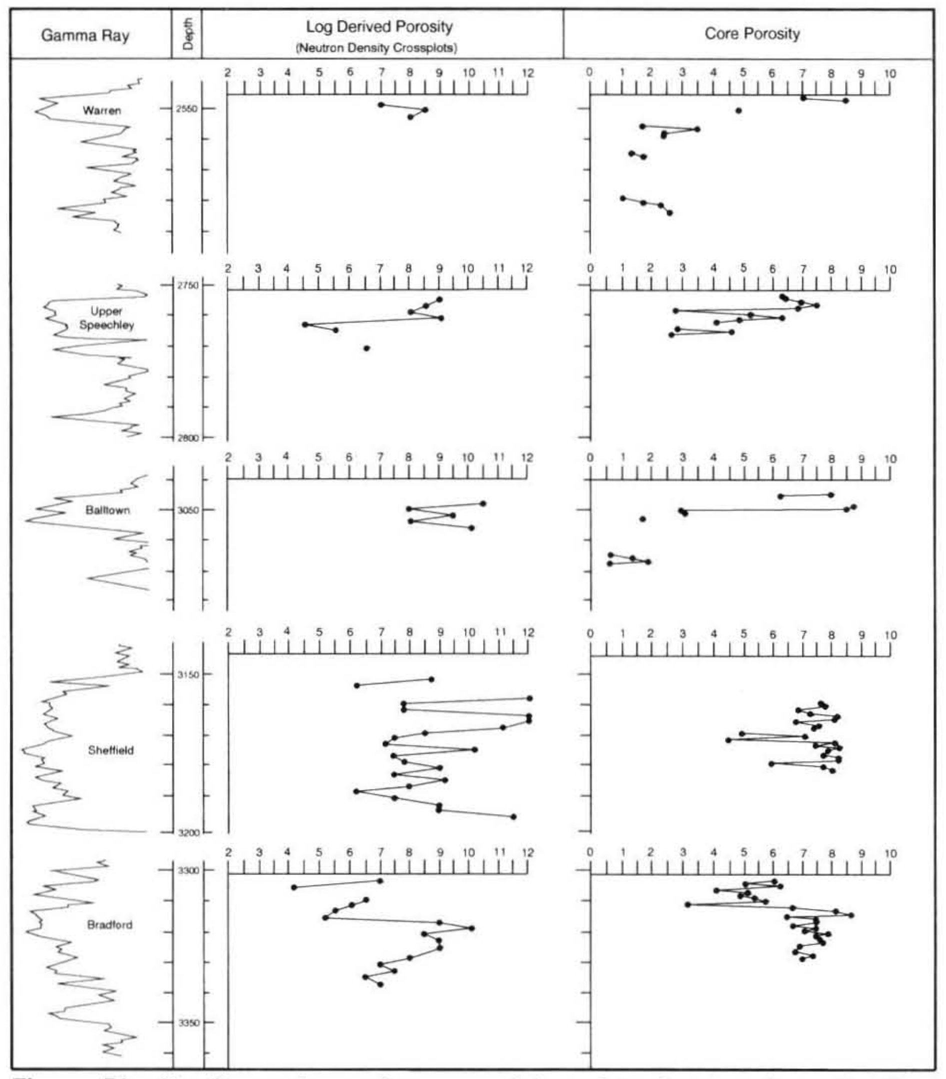


Figure Dbs-18. Comparison of core and log data from various Bradford sandstones in the No. 1 Good, Lahr, and Kaufman well, Indiana County, Pennsylvania. Data taken from Laughrey and Harper (1986). In general, log-derived porosities are greater than core porosities for this well.

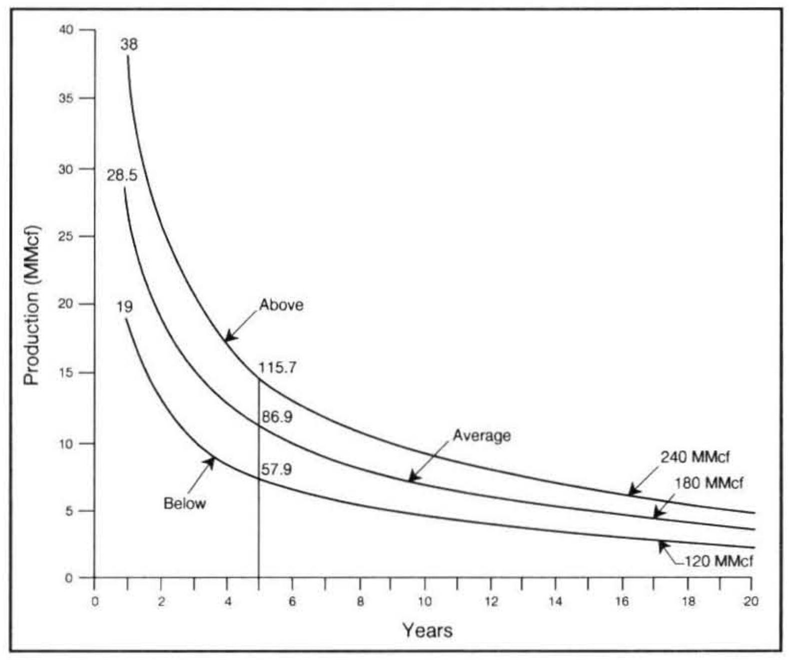


Figure Dbs-19. Typical production decline curve for Bradford wells in Indiana County, Pennsylvania. Profiles for above-average, average, and below-average producing wells are provided. Modified slightly from Harper and others (1996), based on information provided by J. Wigal.

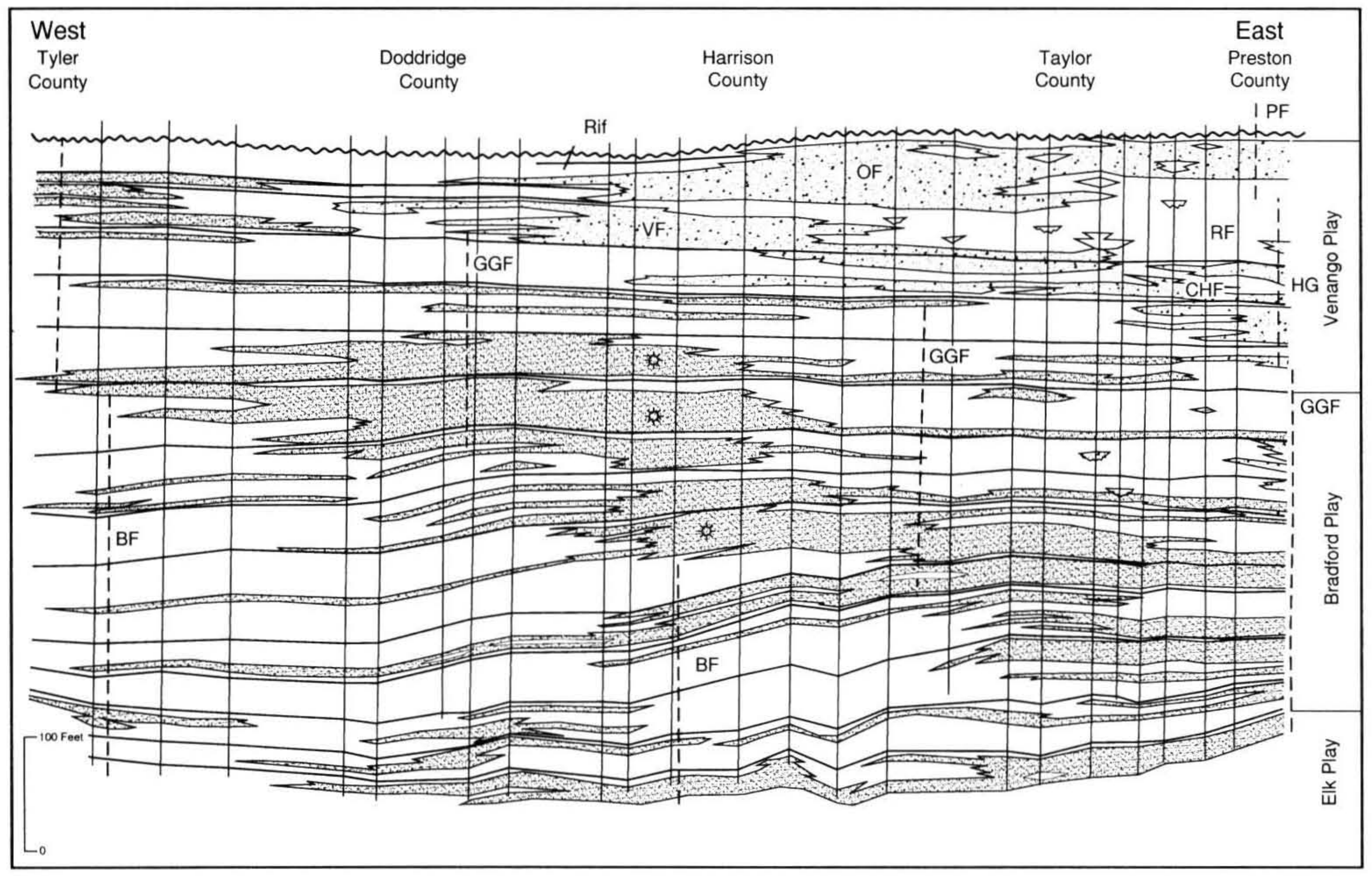


Figure Dbs-20. West-east stratigraphic cross section illustrating the occurrence of fine-grained shelf, slope, and basinal reservoirs within the Bradford play of northern West Virginia. Note the presence of an intervening shale-rich zone between the productive Bradford siltstones and the shoreline units that existed to the east. After Boswell (1988a). Coarse stippling indicates sandstone; light stippling indicates thin-bedded, fine-grained sandstones and siltstones. Vertical lines indicate position of well logs. GGF = Greenland Gap Formation; BF = Brallier Formation; HG = Hampshire Group, including Cannon Hill Formation (CHF) and Rowlesburg Formation (RF); VF = Venango Formation; OF = Oswayo Formation; RiF = Riceville Formation; PF = Price Formation. Section based on gamma-ray logs. See Figure Dbs-22a for location of cross section.

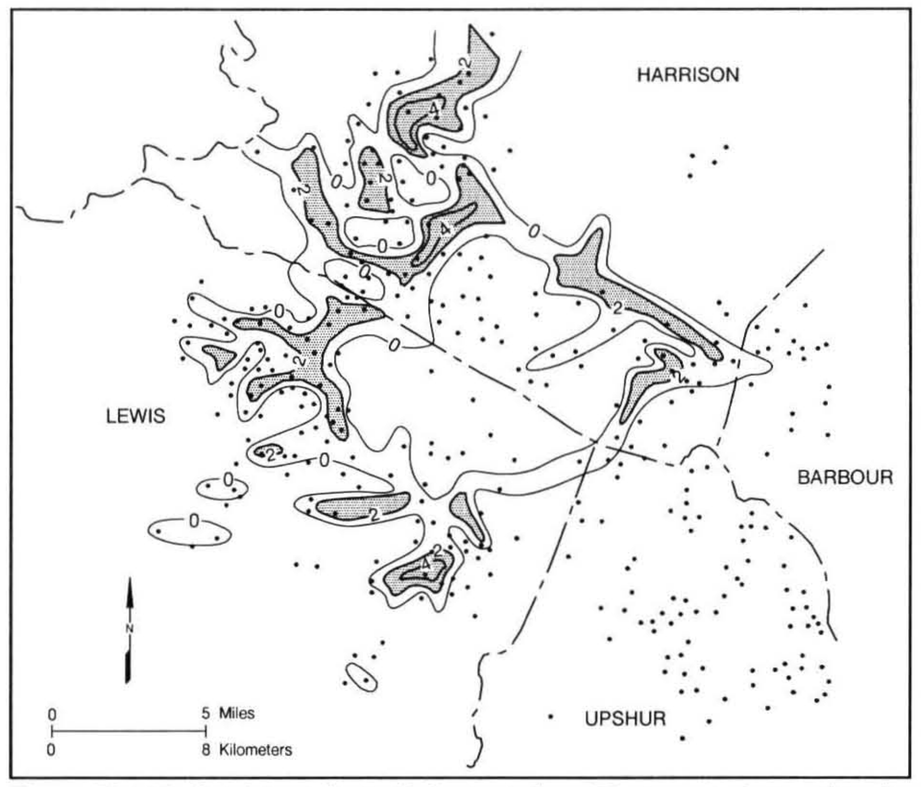


Figure Dbs-21. Sandstone isopach (greater than 50 percent clean using the gamma-ray base-line method) of an upper Balltown sandstone (B-4) in southern Harrison County, West Virginia. From Horsey (1978). Small dots indicate log control. Contour interval = 2 feet.

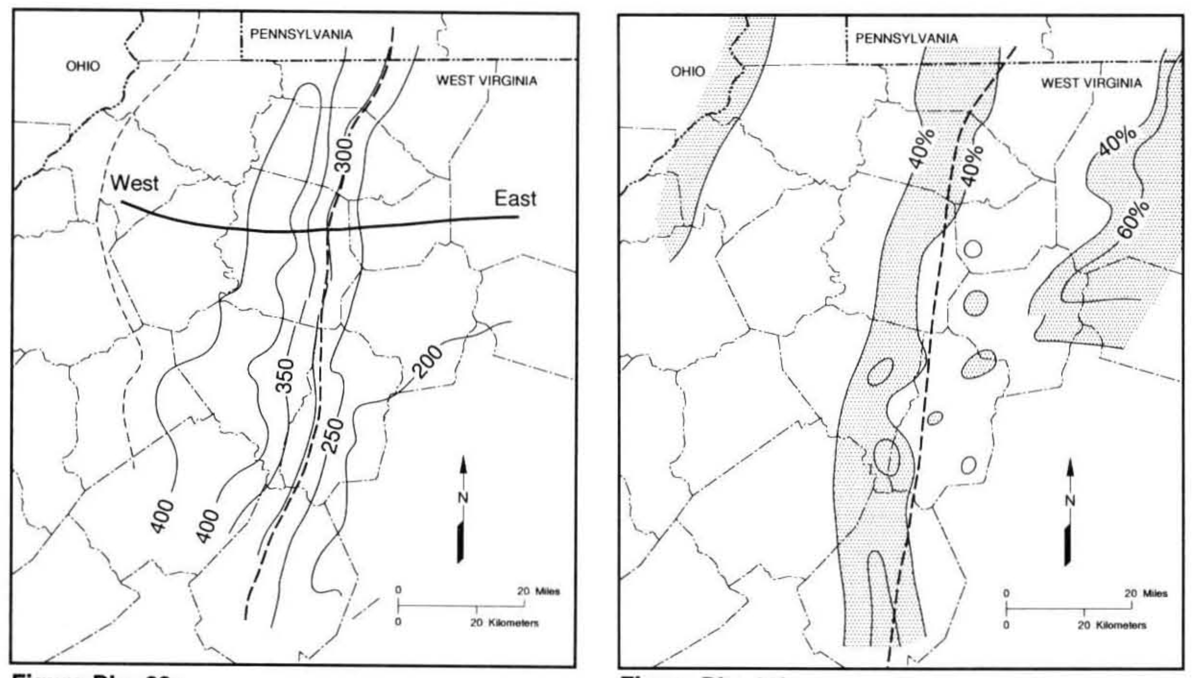


Figure Dbs-22a. Figure Dbs-22b.

Figures Dbs-22a-b. Relation of net siltstone occurrence and trends in interval thickness in the upper part of the lower Balltown interval (B-3) in northern West Virginia. Figure Dbs-22a. Total interval isopach map indicating a marked zone of thickening trending parallel to depositional strike. This trend (dashed line) is interpreted to mark syndepositional tectonism that produced a shelf-slope break beginning in B-3 time. Location of west-east cross section (Figure Dbs-20) is shown. Figure Dbs-22b. Net siltstone isolith map (percentage of interval as 25 percent or greater clean sand using the gamma-ray base-line method) showing that siltstones within this portion of the Bradford play are concentrated within a linear belt aligned with the proposed shelf-slope break and separated from time-equivalent marginal-marine sandstones (build-ups along eastern margin of the basin) by a shale-rich shelf 20 miles or more in width (Boswell, 1988b). Detailed mapping of siltstone occurrence within the strike-trending belt suggests that the belt is comprised of numerous, side-by-side, turbiditic fans similar to those described by Lundegaard and others (1985) for the Brallier Formation.

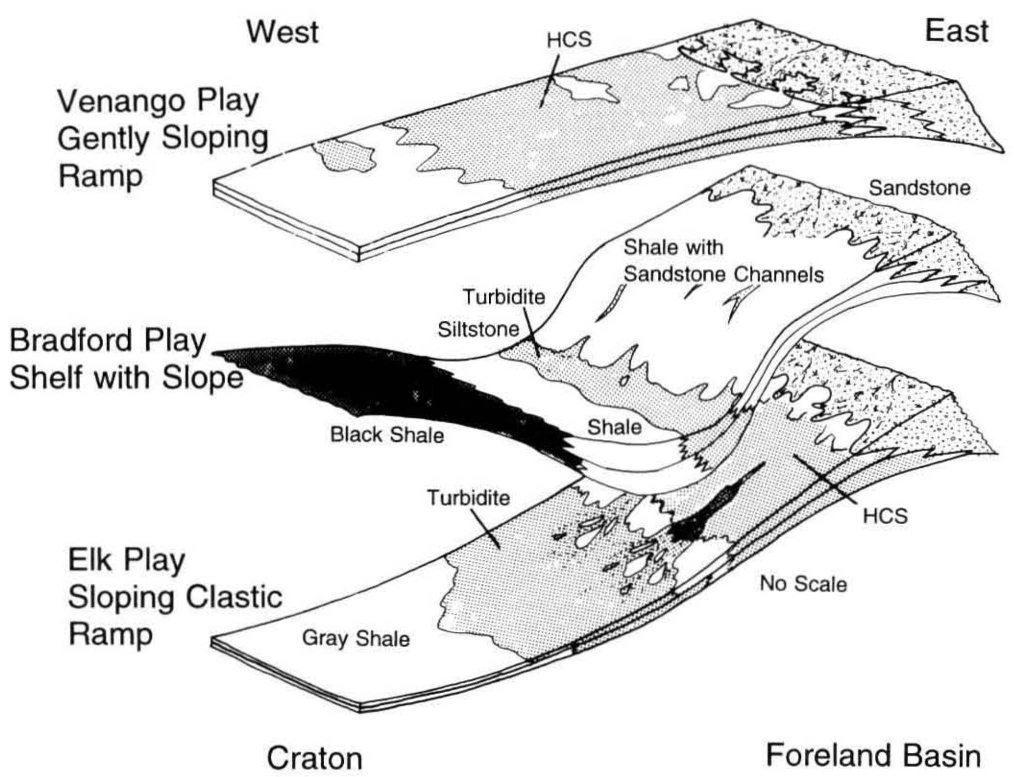


Figure Dbs-23. Schematic diagram contrasting the strike-trending Bradford play siltstones in the productive area of northern West Virginia with more lobate and sheet-like marine siltstone deposits of the underlying Elk and overlying Venango plays. The changing geometry of the units is related to progressive shallowing of sea-floor slopes combined with syndepositional tectonism along the eastern margin of the Rome Trough during Bradford play time. From Boswell (1988b). HCS indicates hummocky cross-stratified, shelf-storm deposits.

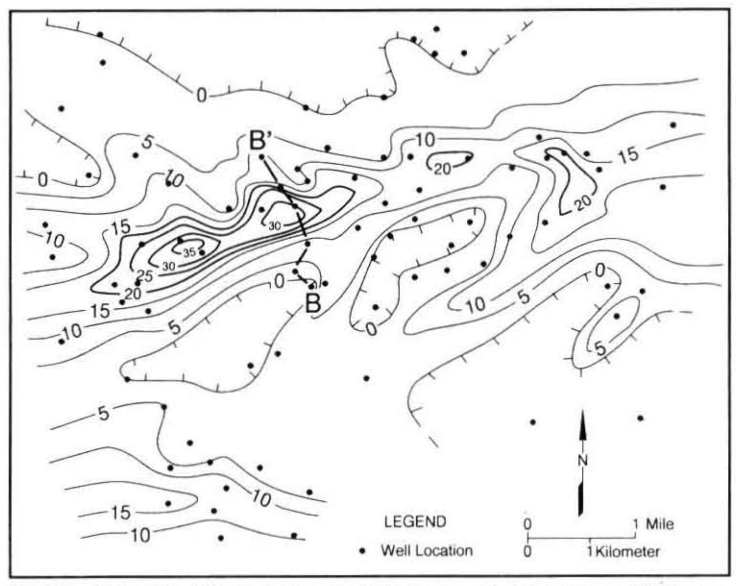


Figure Dbs-24. Sandstone isolith map of an upper Balltown interval (B-3) in the area of the Smicksburg Consolidated field, Indiana County, Pennsylvania. Contour interval = 5 feet. Line of cross section (Figure Dbs-25) is shown. See Figure Dbs-2 for location.

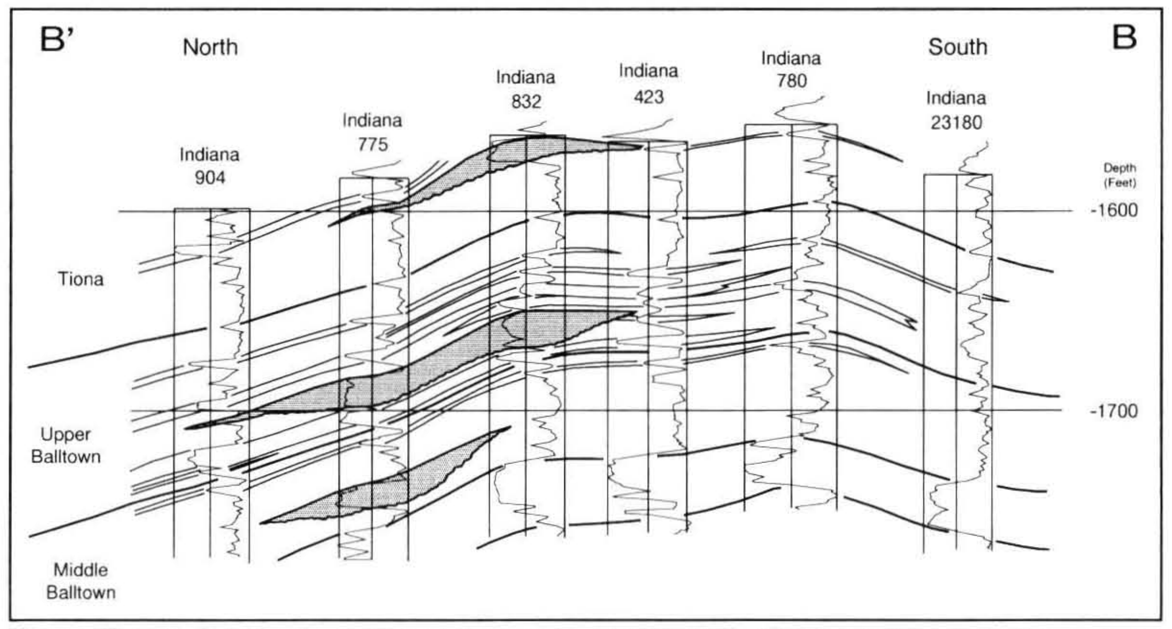


Figure Dbs-25. Structural gamma-ray log cross section B-B' showing three productive channel sandstones in the Tiona (basal B-4), upper Balltown (B-3), and middle Balltown (B-3) intervals within the Bradford play, Indiana quadrangle, Indiana County, Pennsylvania. The lower Balltown unit (B-3) is a major strike-trending reservoir that is an important regional gas producer. Line of cross section is indicated in Figure Dbs-24.

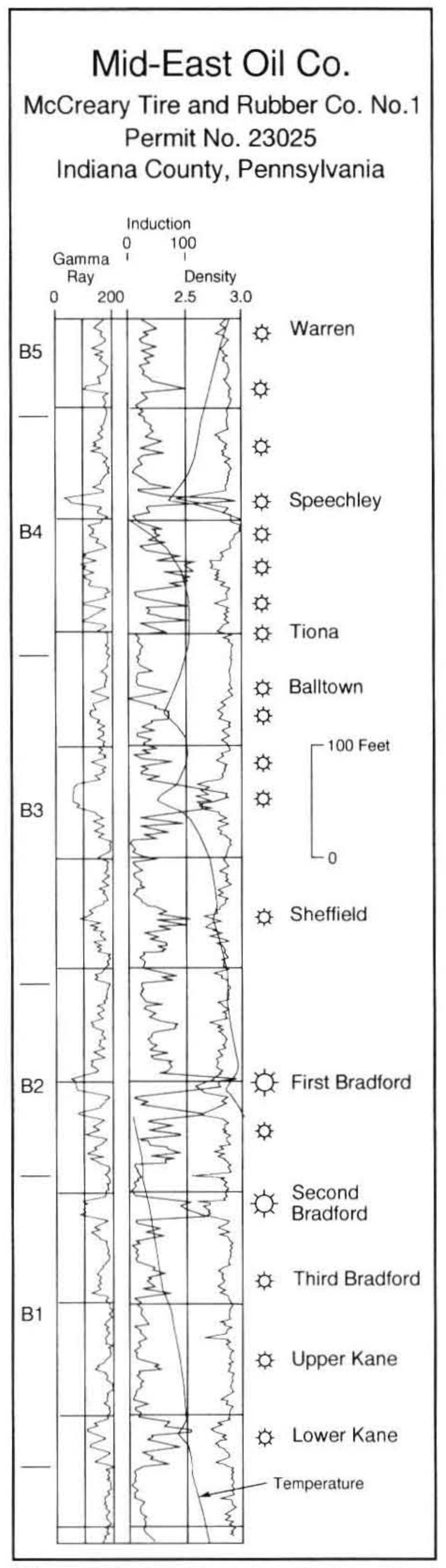


Figure Dbs-26. Type log for Bradford production, Indiana County, Pennsylvania. Gas well symbols indicate all horizons at which gas has been produced in south-central Indiana County. Wells in this area typically are perforated in six or more sandstones.

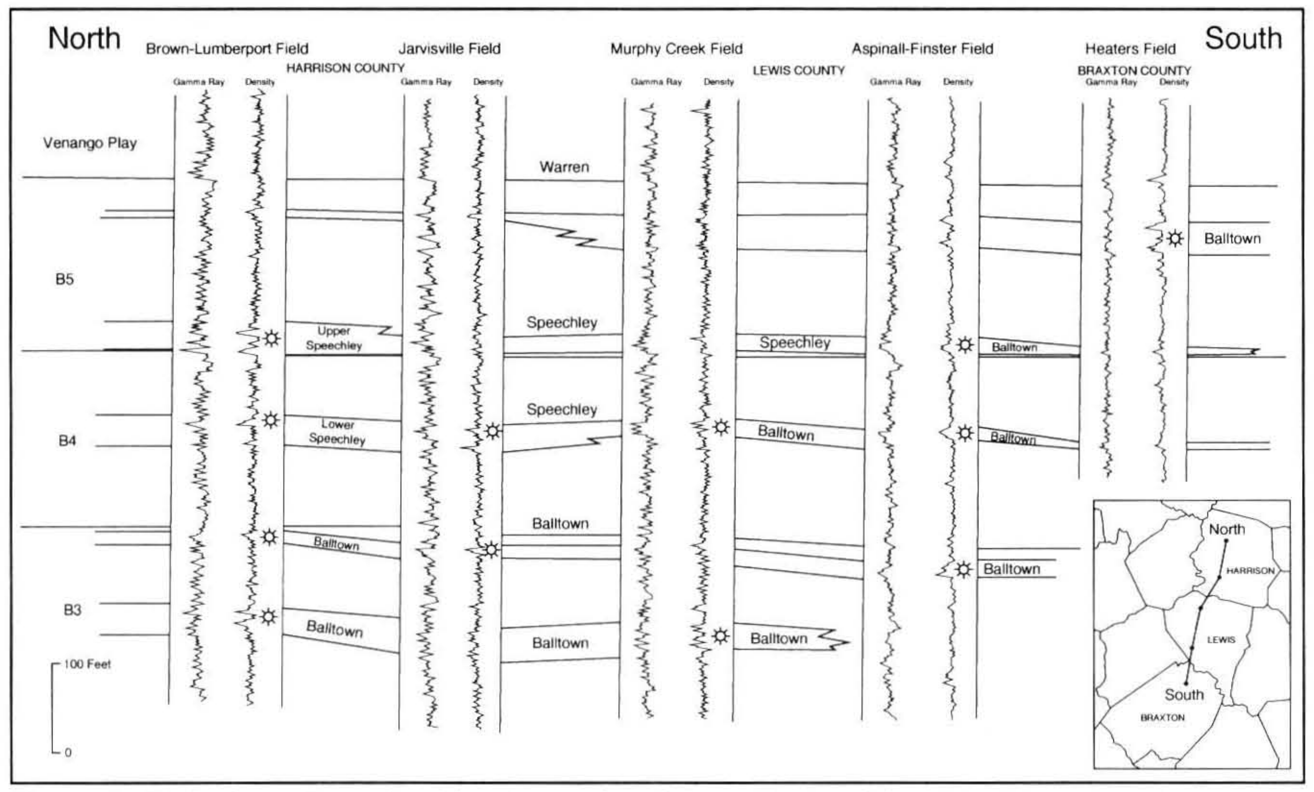


Figure Dbs-27. North-south stratigraphic cross section of the upper part of the Bradford play in Harrison, Lewis, and Braxton counties, West Virginia. The informal drillers' name marked next to each log represents the most common name associated with that unit on well completion reports. The uppermost B-3 unit is the primary reservoir in most areas; the B-4 unit also is productive over large areas.

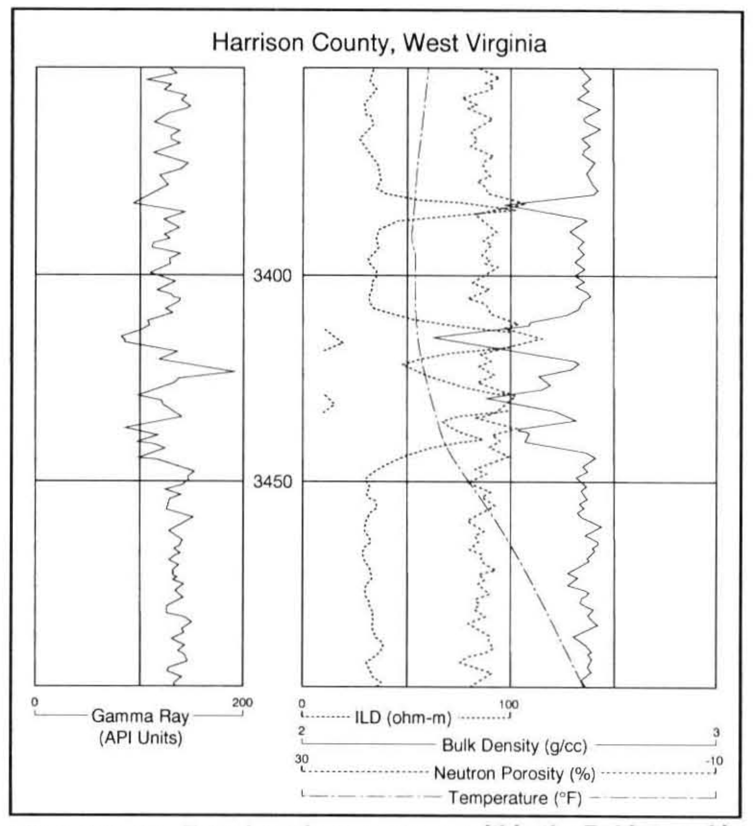


Figure Dbs-28. Type log of porous zone within the B-4 interval in northern Harrison County, West Virginia. Well log name and number held confidential upon request.

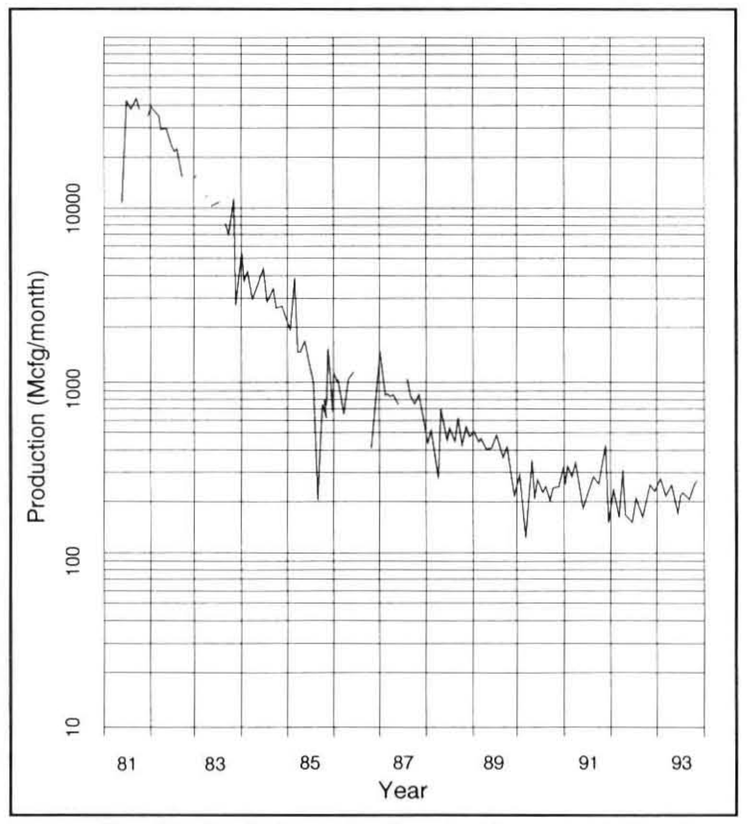


Figure Dbs-29. Typical production decline curve for Kane fractured sandstone (B-1) wells in the Cush Cushion field, eastern Indiana County, Pennsylvania. From Hussing (1994).

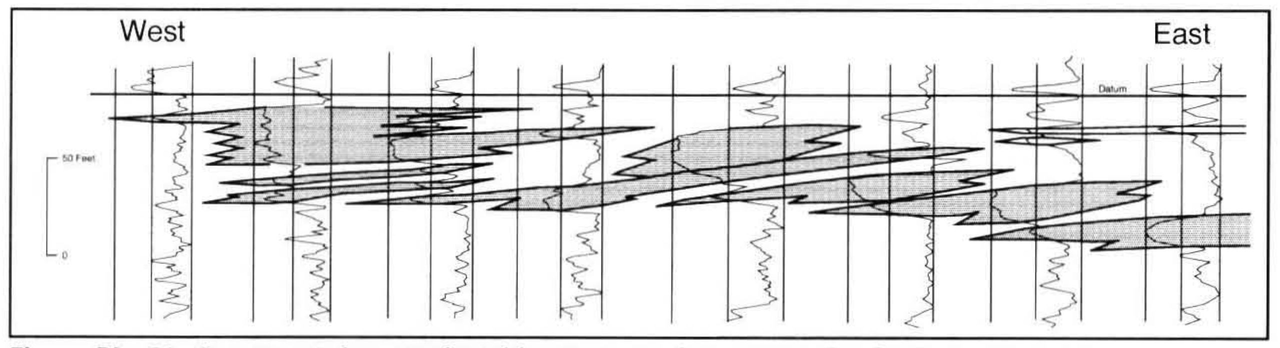


Figure Dbs-31. Gamma-ray log stratigraphic cross section across the Cush Cushion field showing the prograding nature of the productive Kane (B-1) sandstone. Modified from Hussing (1994). See Figure Dbs-2 for location of Cush Cushion field. Well log locations held confidential upon request.

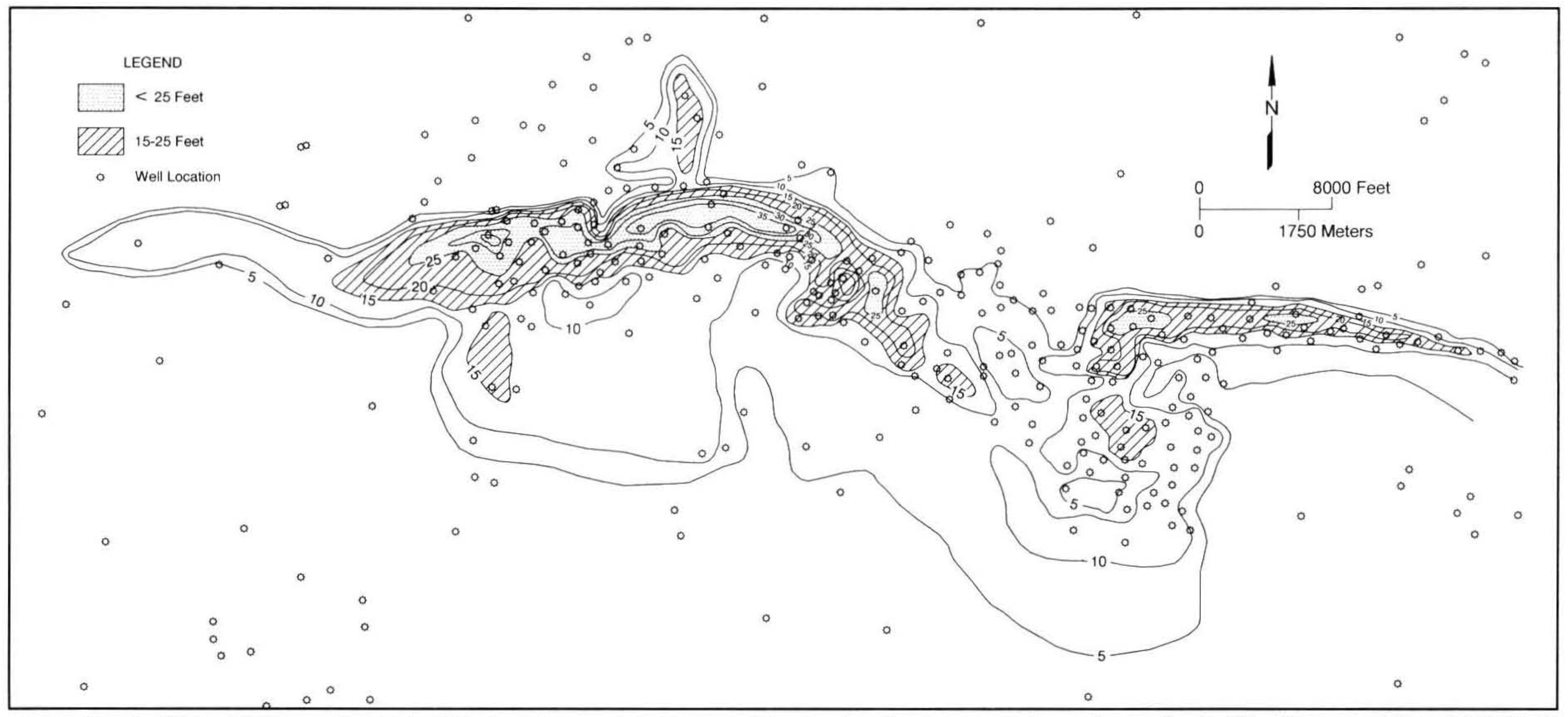


Figure Dbs-30. Sandstone isopach map (greater than 60 percent clean sandstone using the gamma-ray base-line method) of the Kane sandstone (B-1), Cush Cushion field, Clearfield, Indiana, and Cambria counties, Pennsylvania. From Hussing (1994). Contour interval = 5 feet. See Figure Dbs-2 for location.

Reserves and Resources

Published accounts of natural gas reserves specifically attributed to Bradford reservoirs do not exist. The U.S. Department of Energy Morgantown Energy Technology Center utilized data collected by Boswell and others (1993) to calculate that 17.96 tcfg was originally in-place in Bradford reservoirs; of an estimated 10.24 tcfg remaining in-place, approximately 7.58 tcfg may be recoverable (A. Zammerilli, written commun., 1994). Other published resource estimates tend to group all Upper Devonian reservoirs together. In comparison, the undiscovered recoverable resources for all Upper Devonian and Mississippian reservoirs in Pennsylvania has been estimated by Briggs and Tatlock (1983) at 3.61 tcfg, of which 1.64 tcfg was classified probable, 1.24 tcfg possible, and 0.73 tcfg speculative. The National Petroleum Council (1992) estimated the total undiscovered resources of all Appalachian basin reservoirs at depths less than 5,000 feet at 6.22 tcfg at current technologies. The average depth to Bradford play reservoirs is less than 5,000 feet.

Future Trends

The Bradford play presents numerous exploration opportunities. Unfortunately, the enormous gas reserves represented by the play are distributed among a multitude of low-permeability reservoirs scattered over a huge area. Consequently, many of these reservoirs are incapable of producing economic volumes of gas at current conditions. Therefore, the best wells typically commingle production from several reservoirs. Future Bradford production also will likely rely on extensive multiple completions. In Pennsylvania, there appears to be gas potential in the Bradford play along depositional strike both to the north and south of the shallow gas belt. Also, significant volumes of gas may remain in low-quality Bradford siltstone reservoirs below the shallow Venango gas fields of western Pennsylvania. In West Virginia, Bradford production is largely limited to the areas above Benson fields, where the abundant well log data provide sufficient control to allow detailed mapping of the highly lenticular Bradford reservoirs. Future Bradford exploration will be a geologically intensive exercise, as detailed mapping of the reservoirs should allow numerous good wells to be drilled within old field boundaries and in new areas.

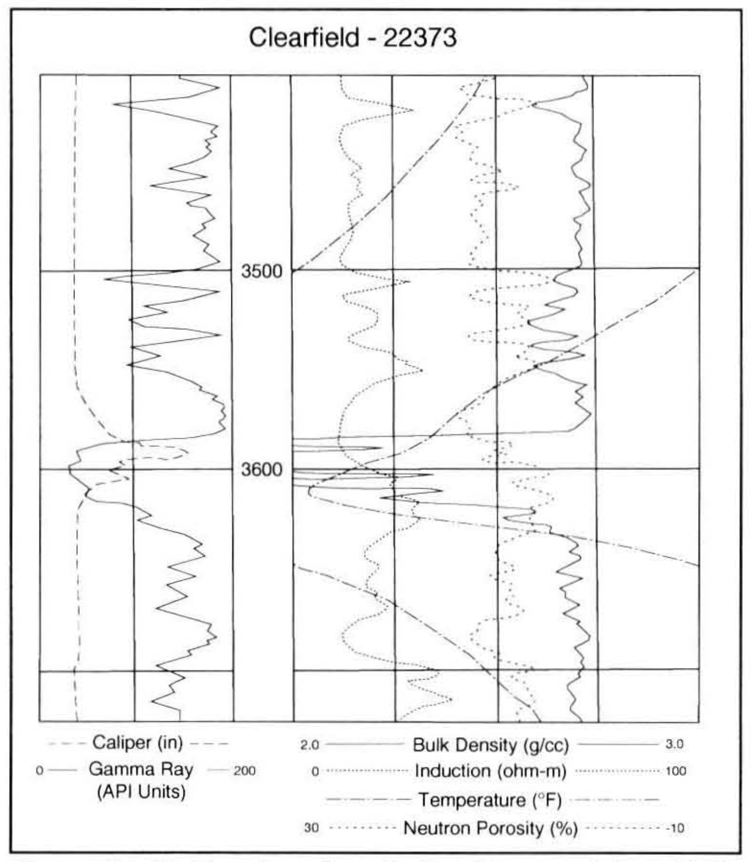


Figure Dbs-32. Type log of productive Kane sandstone (B-1), Cush Cushion field, Clearfield, Indiana, and Cambria counties, Pennsylvania. The anomalous log porosities and high production rates suggest a fractured reservoir.

PLAY Des: UPPER DEVONIAN ELK SANDSTONES AND SILTSTONES

by Alan Donaldson, West Virginia University; Ray Boswell, EG&G TSWV, Inc.; Xiangdong Zou, CBM, Inc.; Larry Cavallo, Dominion Appalachian Development, Inc.; L. Robert Heim, Atlas Energy Group; and Michael Canich, Eastern States Exploration Co.

Location

The Upper Devonian Elk sandstones and siltstones play occurs throughout the eastern half of the gas-producing part of the Appalachian basin (Figure Des-1). In West Virginia, the play is dominated by fine-grained sandstone and siltstone reservoirs that represent turbidites and distal shelf deposits. Thirty gas fields in northern West Virginia are productive from the Elk play (Figures Des-2, Des-3; Tables Des-1, Des-2). The vast majority of this production has come from a thin, widespread unit at the very top of the interval, known informally as the Benson siltstone.

Gas production from similar fine-grained marine units has been obtained from numerous wells scattered throughout western Pennsylvania (Figure Des-1); however, these reservoirs are generally of much poorer quality than those in West Virginia. Coarse-grained shoreline and terrestrial sandstones of Elk age in the subsurface are limited to areas adjacent to its eastern outcrop belt in western Maryland and Pennsylvania and have been significant gas producers only in the Council Run field, Centre and Clinton counties, Pennsylvania (Figure Des-2).

Production History

The first production from Elk play reservoirs was oil obtained from a 15-foot-thick, fine-grained, and dark-colored sandstone in two wells drilled near Smethport, McKean County, Pennsylvania, in the mid-1870s (Figure Des-2). However, this reservoir, or any of the other subsequent Elk reservoirs developed at the stratigraphic levels below the prolific Bradford Third sandstone (see R. Boswell and others, Upper Devonian Bradford sandstones and siltstones, this atlas), were not exceptionally large or productive. As the overlying Bradford and Venango production was gradually extended southward throughout the 1880s and 1890s, the depth to the Elk play reservoirs increased, and very few wells penetrated below the Bradford into the Elk section. Those deep wells that were drilled generally showed very little promise owing to a lack of reservoir quality in the section. As a result, very little Elk play gas production was obtained in Pennsylvania.

The first well (Barbour County No. 998 well) to produce gas from what would become the prolific Benson trend of the Elk play in northern West Virginia was drilled in 1909 on the Benson farm, west-central Barbour County. Several offsets of this early well were drilled during the next several decades; however, full development of the field did not occur until the implementation of hydrofracturing techniques in the mid-1950s. By 1970, Benson production was well established throughout Upshur, Barbour, Lewis, and Harrison counties, West Virginia. Rapidly, the Benson became a favorite target of gas well drillers in the Appalachian basin in West Virginia (Table Des-2). Benson production was eventually extended throughout most of north-central West Virginia (Figure Des-3), with the best production occurring in northwesterly trends in northern Lewis and central Harrison counties that can be traced as far westward as Tyler County and eastward to the edges of the play.

In late 1973, Harrison County well No. 716 penetrated 18 feet of gas-saturated sandstone at a depth of 6,190 feet (Lytle and others, 1974). This unit, which has become known as the Sycamore siltstone, established the first sub-Benson Upper Devonian Elk play production in West Virginia. In 1975, a thin reservoir named the Alexander siltstone was discovered 350 feet below the Benson in Upshur County well no. 1592 (Lytle and others, 1975) drilled by Seneca-Upshur. In 1976 and 1977, additional sub-Benson production from the Elk play was achieved by a series of successful wells drilled in Barbour, Randolph, Doddridge, and Gilmer counties that encountered reservoirs such as the Alexander as well as deeper Elk sandstones and siltstones (Lytle and others, 1977; Patchen and others, 1978). However, after 15 years of delineation, none of these deeper reservoirs has approached the Benson in terms of extent, reservoir quality, or economics.

At present, attempts to extend Benson and Alexander production northward into Pennsylvania have been largely unsuccessful. An aggressive drilling program in Greene County Consolidated field (Figure Des-2) in the early 1980s by Kepco and others indicated the presence of gas-saturated Elk play reservoirs at depths of 4,600 feet and more. However, poor reservoir quality has generally limited after-treatment IPs to less than 300 Mcf/d (Harper and Laughrey, 1987), and drilling in the trend has, at least temporarily, been abandoned.

Although very few coarse-grained, shallow-water Elk Play units are preserved within the basin interior, Eastern States Exploration Company discovered 36 feet of clean, porous, gas-saturated sandstone at a depth of 4,600 feet in Centre County on Pennsylvania Tract 231 in 1982 (Figure Des-2). The reservoir, informally named the Fifth Elk sandstone, tested a reported natural open flow of gas of 1,958 Mcf/d. The field has been fully developed, and now occupies 70 square miles. To date, no other accumulation of Elk play gas in coarse-grained sandstone facies has been discovered.

Total estimated cumulative production for the Benson reservoir of northern West Virginia is approximately 3 tcf from 6,700 wells, or 450 MMcf per well. Fifth Elk production for approximately 60 percent of the Council Run field is roughly 10.2 bcf from 40 wells (J. Walker, written commun., 1994). To date, these two units represent about 3 tcf of Elk play cumulative production.

Stratigraphy

The Upper Devonian Elk sandstones and siltstones play consists of the lower sandstone and siltstone portion of the Upper Devonian Acadian clastic wedge (Figure Des-4). The Elk play is defined to include all reservoirs of Frasnian age

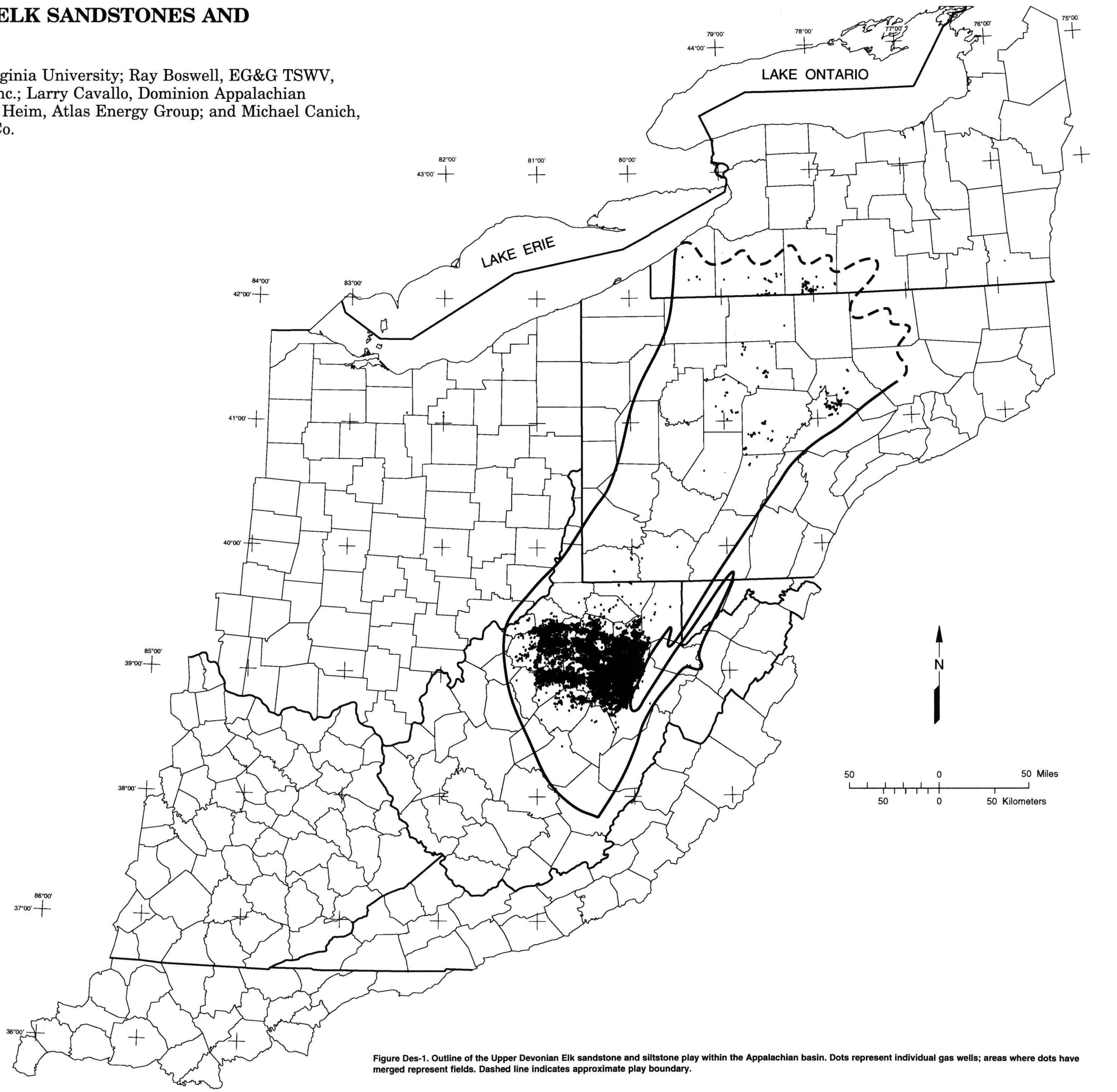


Figure Des-1. Outline of the Upper Devonian Elk sandstone and siltstone play within the Appalachian basin. Dots represent individual gas wells; areas where dots have merged represent fields. Dashed line indicates approximate play boundary.

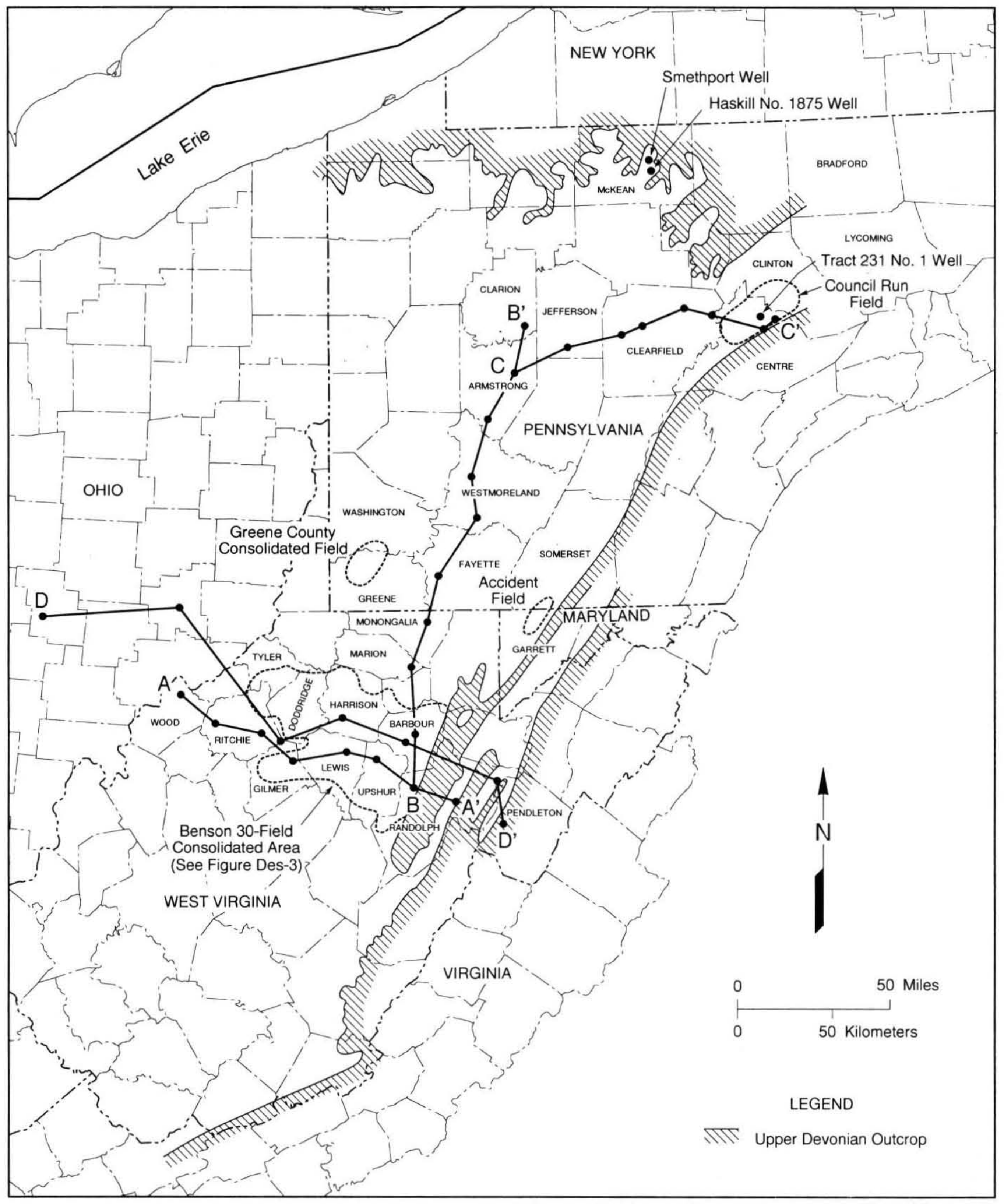


Figure Des-2. Location of Upper Devonian Elk sandstone and siltstone fields mentioned in text or listed in Table Des-1. Cross sections A-A' (Figure Des-10), B-B' (Figure Des-11), C-C' (Figure Des-12), and D-D' (Figure Des-14) are also shown.

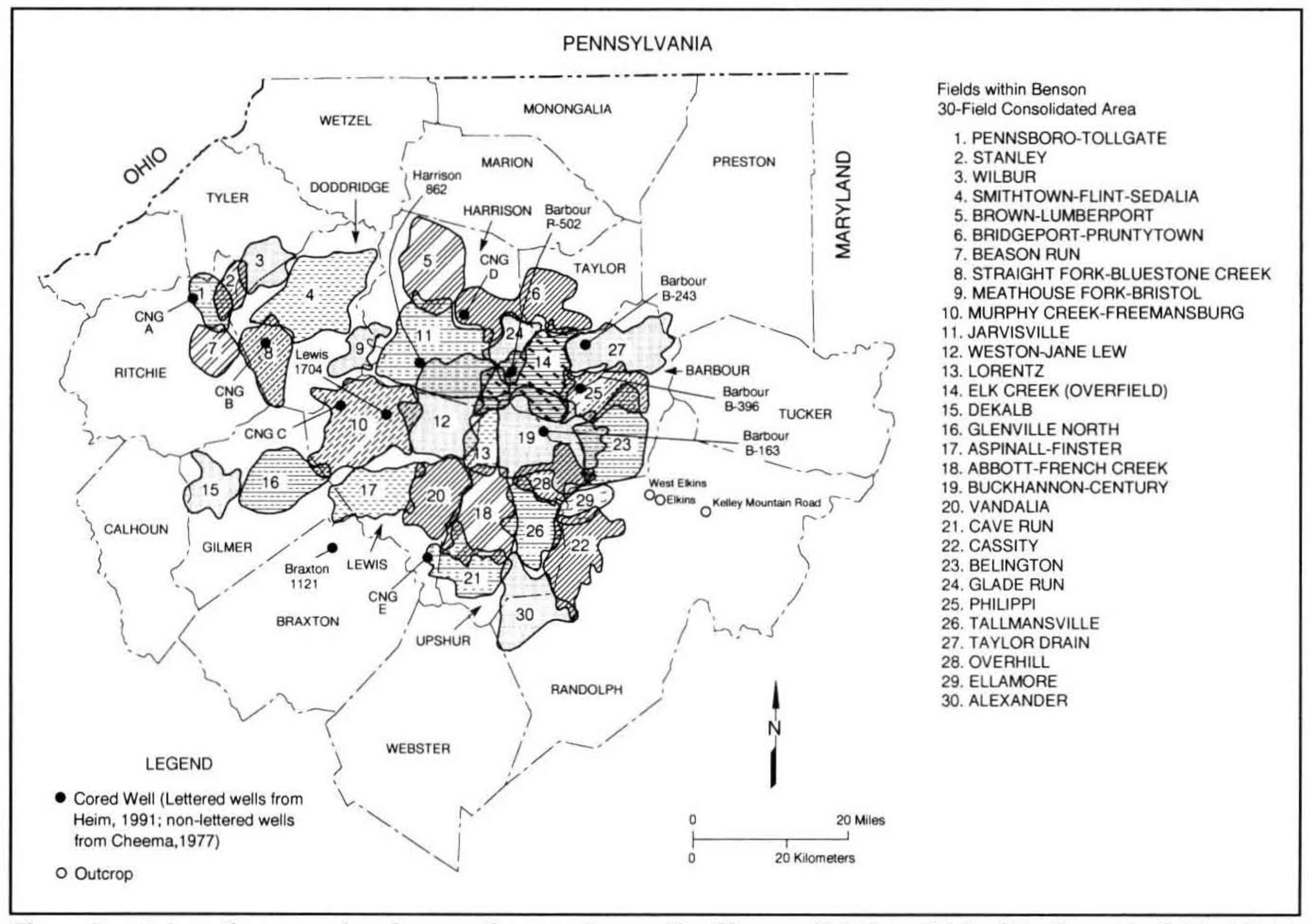


Figure Des-3. Location map of surface sections, wells used by Cheema (1977) and Heim (1991), and individual fields in the E-4 Benson 30-field consolidated area of north-central West Virginia. See Figure Des-2 for regional location.

TABLE Des-1		Jarvisville WV	Jarvisville WV	Weston-Jane Lew WV	Meathouse Fork-Bristol WV	Meathouse Fork-Bristol WV	Murphy Creek Freemansburg WV	Murphy Creek Freemansburg WV	Straight Fork Bluestone Creek WV	Straight Fork Bluestone Creek WV	Wilbur WV	Council Run PA
BASIC RESERVOIR DATA	POOL NUMBER	47151435	47151439	47153435	47146435	47146439	47150435	47150439	47133435	47133439	47092435	
	DISCOVERED	1959	1979	1909	1972	1972	1917		1977	1977	1917	1982
	DEPTH TO TOP RESERVOIR	4,500	5,043	4,338	5,020	5,350	4,430	4,900	4,740	5,090	4,900	4,600
	AGE OF RESERVOIR	Upper Devonian	Upper Devonian	Upper Devonian	Upper Devonian	Upper Devonian	Upper Devonian	Upper Devonian	Upper Devonian	Upper Devonian	Upper Devonian	Upper Devonian
	FORMATION	Brailler	Brailler	Brailler	Brailler	Brailler	Brailler	Brailler	Brailler	Brailler	Brallier	Lock Haven
	PRODUCING RESERVOIR	Benson	Alexander	Benson	Benson	Alexander	Benson	Alexander	Benson	Alexander	Benson	Fifth Elk
	LITHOLOGY	sandstone siltstone	sandstone siltstone	sandstone siltstone	siltstone silty sandstone	siltstone silty sandstone	siltstone silty sandstone	siltstone silty sandstone	siltstone silty sandstone	siltstone silty sandstone	siltstone silty sandstone	sandstone
	TRAP TYPE	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic
	DEPOSITIONAL ENVIRONMENT	slope/ turbidite	slope/ turbidite	slope/ turbidite	slope/ turbidite	slope/ turbidite	slope/ turbidite	slope/ turbidite	slope/ turbidite	slope/ turbidite	slope/ turbidite	slope/ turbidite
	DISCOVERY WELL IP (Mcf)											1,950
	DRIVE MECHANISM	gas expansion	water	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	
	NO. PRODUCING WELLS	351	60	400	121	105	222	29	149	259	245	321
	NO. ABANDONED WELLS	2	0	29	0	0	2	0	1	0	0	29
	AREA (acreage)	34,594		43,329	8,349	7,245				20,202		18,800
	OLDEST FORMATION PENETRATED	Helderberg	Helderberg	Helderberg	Alexander	Alexander	Helderberg	Helderberg	Juniata	Juniata	Helderberg	
	EXPECTED HETEROGENEITY DUE TO:											
RESERVOIR PARAMETERS	AVERAGE PAY THICKNESS (ft.)	9	8	11	7	7	8	8	4	11	8	23
	AVERAGE COMPLETION THICKNESS (ft.)	11	32	12	16	30	15	65	31	44	8	64
	AVERAGE POROSITY--LOG (%)	7.2	7.49	8.43	5.67	6.29	6.67	6.65	6.08	6.02	2.6	9.14
	MINIMUM POROSITY--LOG (%)	5	5.01	5.49	0	5.4	4.8	6.1	5.42	0	6.25	3.81
	MAXIMUM POROSITY--LOG (%)	16.55	8.6	68.7	8.78	11.2	10.2	6.1	9.44	8.29	10.09	50
	NO. DATA POINTS	69	84	74	12	19	31	32	29	69	11	3
	POROSITY FEET											
	RESERVOIR TEMPERATURE (°F)	104	113	102	108	112	102	109	106	109	109	101
	INITIAL RESERVOIR PRESSURE (psi)	1,980	1,800	1,980	1,760	2,050	1,960	1,375	2,108	1,950	2,100	1,740
	PRODUCING INTERVAL DEPTHS (ft.)	3,326-5,133	4,450-5,482	3,331-5,466	4,601-5,318	4,961-5,652	4,004-5,041	4,348-5,569	4,205-5,231	4,775-5,563	4,700-5,100	3,500-5,500
	PRESENT RESERVOIR PRESSURE (psi) / DATE	448/1972		383/1983	280/1962		368/1977			1,075/1980	1,450/1994	
FLUID & GAS PROPERTIES	Rw (Ωm)	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
	GAS GRAVITY (g/cc)	0.665		0.651			0.694				0.0687	0.584
	GAS SATURATION (%)	59.72	59.28	67.75	54.18	55.53	59.83	59.48	48.64	50.63	58.87	87.3
	WATER SATURATION (%)	40.28	40.72	32.25	45.82	44.47	40.17	40.52	51.36	49.37	47.13	12.7
	COMMINGLED	yes	yes	yes	no	no	yes	yes	no	no	no	
	ASSOCIATED OR NONASSOCIATED	associated	associated	nonassociated	associated	associated	associated	associated	associated	associated	nonassociated	nonassociated
	Btu/scf	1,168		1,146			1,214				1,150	1,038
VOLUMETRIC DATA	STATUS (producing, abandoned, storage)	producing	producing	producing	producing	producing	producing	producing	producing	producing	producing	producing
	ORIGINAL GAS IN PLACE (Mcf)											
	ORIGINAL GAS RESERVES (Mcf)											
	PRODUCTION YEARS	1978-1993	1983-1993	1970-1993	1978-1993	1980-1993	1967-1993	1982-1986	1979-1983	1979-1993	1980-1993	
	REPORTED CUMULATIVE PRODUCTION (Mcf)	12,302,500	335,800	19,743,000	7,104,500	880,100	11,512,300	3,700	1,829,500	6,644,100	2,314	
	NO. WELLS REPORTED	100	3	191	72	9	85	1	29	74	40	
	ESTIMATED CUMULATIVE PRODUCTION (Mcf)											
	REMAINING GAS IN PLACE (Mcf)/DATE											
	REMAINING GAS RESERVES (Mcf)/DATE											
	RECOVERY FACTOR (%)											
	INITIAL OPEN FLOW (Mcf/d)	166		1,409			1,838			383	151	55
	FINAL OPEN FLOW (Mcf/d)	891	553	1,693	440	840	2,063	567	1,093	1,007	739	712

and is therefore not directly tied to depositional environment. The upper boundary of the play is marked by a major transgressive horizon that corresponds with the base of the Huron Member of the Ohio Shale (Dunkirk Shale Member of the Perrysburg Formation) within the western half of the basin and the base of the Red Lick Member of the Foreknobs Formation (Greenland Gap Group) along the Allegheny Front in northeastern West Virginia (Figure Des-5). This upper boundary is not well defined as traced northward into Pennsylvania, but generally is equated with the shaley zone that occurs beneath the widespread Kane sandstone in the main Bradford gas-producing area in and around Indiana County, Pennsylvania. The base of the play is marked by the Middlesex Shale Member of the Sonyea Formation and its equivalents (Figures Des-4, Des-5). The drillers' terminology of the gas reservoirs of the Elk, Bradford, and Venango plays is indicated in Figure Des-6.

The first description of Elk play sandstones may have been by Carll (1890), who noted minor oil production from sandstone reservoirs below the main Bradford Third sandstone of Warren County, Pennsylvania. These lower sandstones were reported to have a darker color than the younger units, and were assigned by Carll to an informal Elk oil-sands group within the lower portion of the Chemung division of the Upper Devonian series. The remainder of the clastic interval below these sandstones and above the black Marcellus Shale was thought to be dominated by marine shale and was identified as Portage. In the 1920s and 1930s, stratigraphers abandoned both Portage and Chemung as lithostratigraphic units and assigned the interval to a variety of different units. However, none of these designations has proven to be applicable to the subsurface sandstone reservoirs in Pennsylvania. Consequently, the Pennsylvania Bureau of Topographic and Geologic Survey has elected to revive the term "Elk group" (Figure Des-5). As now recognized, the informal "Elk group" of Pennsylvania includes the relatively sandstone- and siltstone-rich section below the Kane sandstone, which marks the basal sandstone throughout the main Bradford gas-producing region of Indiana County (Harper and others, 1982). The boundary corresponds closely to the top of the Frasnian stage. The remainder of the interval, once known as Portage, is generally assigned to the Brallier Formation (Figure Des-5). However, in areas of north-central Pennsylvania where the marked northeastward swing of the structural front preserves more eastwardly facies of the Elk play, units are assigned to the Lock Haven Formation. A paleogeographic representation of the Appalachian basin at the end of Elk deposition is provided in Figure Des-7.

Dennison (1970b) refined the Frasnian stratigraphy along the Allegheny Front in northern West Virginia and western Maryland. The basal shale-rich portion is assigned to the Brallier Formation, and the overlying coarser-grained units are designated as the Greenland Gap Group (Figure Des-5). Correlation westward into the subsurface by Lewis (1983) and Filer (1994) connected the Benson sandstone and siltstone reservoir with Dennison's (1970b) Pound Sandstone Member. However, because the overall interval is much finer-grained than the outcrop equivalents, most of the Benson production is from reservoirs within the Brallier (Boswell and others, 1987), which is a clay-rich turbidite slope-apron deposit (Figure Des-8). Elk play strata grade westward into the Sonyea and West Falls formations in West Virginia (Figure Des-9). Transgressive units, marked by eastward extensions of the black shale lithofacies (Figures Des-4, Des-9) can be correlated far into the basin center, and commonly are used to subdivide the otherwise monotonous shale-siltstone sequence (Filer, 1988). Here, the authors recognize four discreet stratigraphic units, designated E-1 through E-4, based largely on the work of Filer (1988; 1994). The basal E-1 unit contains all but the youngest of at least five prospective Sycamore sandstones and siltstones and is bounded above by the transgressive base of the Rhinestreet Shale Member of the West Falls Formation (Figure Des-9). The top of the thick E-2 interval, which contains the informal Elk, Fox, and Haverty reservoirs, is defined by a regional shale marker that extends from the base of the Angola Shale Member of the West Falls Formation (Figure Des-9) eastward to a position within the Mallow Member of the Foreknobs Formation (Figures Des-5, Des-9). The Pipe Creek Shale Member of the Java Formation marks the top of the E-3 interval (Figure Des-9). This interval contains the lower Alexander sandstones and siltstones, which have been correlated with the Briery Gap Sandstone Member of the Foreknobs Formation by Filer (1994). The uppermost E-4 interval contains the Pipe Creek Shale at its base and the drillers' Leopold and overlying Benson sandstones and siltstones (westward lateral equivalents of the Pound Sandstone Member of the Foreknobs Formation) at its top (Figure Des-9). The top of the E-4 is marked by the base of the Huron Member of the Ohio Shale, the base of the Dunkirk Shale Member of the Perrysburg Formation of New York, and their equivalents (Figures Des-5, Des-9).

Three regional stratigraphic cross sections of the Elk play (Figures Des-10, Des-11, Des-12), using gamma-ray curves for correlation, indicate the vertical and lateral changes of this lower part of the Acadian clastic wedge. Figures Des-10 and Des-12 are east-west sections across northern West Virginia and central Pennsylvania, respectively, and both show an increase in siltstone and sandstone for all four Elk intervals toward the east as well as from E-2 upward to E-3 and E-4. The lower two intervals, E-1 and E-2, show greatest thickening toward the east and the least amount of sandstone and siltstone in the middle part of the E-2 interval. A north-south regional cross section (Figure Des-11) intersects common wells of the east-west sections for the E-4 and E-3 intervals and documents nearly uniform thicknesses and siltstone content along its extent for these upper two intervals of the Elk play. Figures Des-10, Des-11, and Des-12 indicate that the Elk sandstones and siltstones extend beyond their proven gas-productive areas of north-central West Virginia for the E-4 interval (the principal gas-bearing interval, although subordinate gas is contributed from underlying E-3 and E-2 sandstones and siltstones), and of central Pennsylvania for the E-2 uppermost sandstones. The Elk sandstones and siltstones mainly occur as vertically stacked units that intertongue with marine shales westward (Figure Des-6).

A regional isolith map (Figure Des-13) of net sandstone within the E-4 interval (generally the upper 200 feet of the play) shows that thicker sandstones of the Benson and Leopold are restricted to the eastern margin of the play. The Benson has been studied in detail both in outcrop and in the subsurface. Lewis (1983) interpreted the fine-grained Benson sandstones and siltstones exposed at Elkins, West Virginia (Figure Des-3), as shelf-storm deposits. Correlative sandstones (such as the Pound Sandstone Member) exposed farther to the east along the Allegheny Front at Briery Gap (Figure Des-14) were interpreted by Filer (1988) to be barrier island deposits. Dennison (1985) extended this ancient shoreline northward into Pennsylvania and its position is shown in Figure Des-7. In the subsurface, the Benson (uppermost E-4) consists of fine-grained sandstones and siltstones that occur mainly west of the 70-foot-thickness contour of the Benson-interval isopach map (Figure Des-15). Those units where the thickness map exhibits strike-trending contours in eastern Barbour and Upshur counties are interpreted as storm deposits (Heim, 1987), and northwesterly dip-trending lobes are interpreted as turbidite deposits (Cheema, 1977; Heim, 1987). The turbidity flows probably were generated from delta-front storm deposits that exhibit soft-sediment deformation structures in the outcrop belt (Lewis, 1983) in Benson-equivalent rocks in Randolph County, West Virginia. Cheema (1977) and Heim (1987) recognized evidence of turbidites in cores of the Benson that included a variety of Bouma structures, trace fossils, and textural characteristics. Heim (1987) also suggested the turbidite deposits accumulated on steepened slopes presumably caused by reactivation of faults along the eastern border of the Rome trough and, to a lesser extent, the adjacent cross-over rift zone (Figure Des-15).

Cheema (1977) subdivided the Benson interval into the informal lower (18 to 50 feet thick), middle (0 to 25 feet thick), and upper (20 to 60 feet thick) units (Figure Des-16), noting their thinning westward and the replacement of the

Table Des-2. Number of E-4 Benson completions in West Virginia. Columns represent separate fields; rows indicate decades. Data obtained from West Virginia Geological and Economic Survey.

Benson	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	%
Pre-1930											2	27		8				1	2								2				0.631
1930s												3	3	1				5	4		1										0.255
1940s												13	50	27			1	54	32	11	12				2	2					3.06
1950s											1	11	13	2		1	3	46	105	35	10	1				1					3.44
1960s					3	11				56	8	99	10	128			4	140	310	197	18		4	5	11	62	26	16	22		16.9
1970s			7	41	126	24	15	21	27	74	211	148	8	146	5	181	28	77	143	66	54	53	157	61	64	189	117	58	37	87	33.4
1980s	31	152	214	91	62	191	46	101	56	91	127	87	29	50	114	152	158	47	47	45	125	169	189	37	69	35	139	20	40	93	42.2
TOTAL	31	152	221	132	191	226	61	122	83	221	349	388	113	362	119	334	194	370	643	354	200	223	350	103	146	289	284	94	99	180	6,654*

* Indicates the total number of wells for all fields through the 1980s.

Field Names

1 = Pennsboro-Tollgate
2 = Stanley
3 = Wilbur
4 = Smithton-Flint-Sedalia
5 = Brown-Lumberport
6 = Bridgeport-Pruntytown
7 = Beason Run
8 = Straight Fork-Bluestone Creek
9 = Meathouse Fork-Bristol
10 = Murphy Creek-Freemansburg
11 = Jarvisville
12 = Weston-Jane Lew
13 = Lorentz
14 = Elk Creek (Overfield)
15 = Dekalb
16 = Glenville North
17 = Aspinall-Finster
18 = Abbott-French Creek
19 = Buckhannon-Century
20 = Vandalia
21 = Cave Run
22 = Cassity
23 = Belington
24 = Glade Run
25 = Philippi
26 = Tallmansville
27 = Taylor Drain
28 = Overhill
29 = Ellamore
30 = Alexander

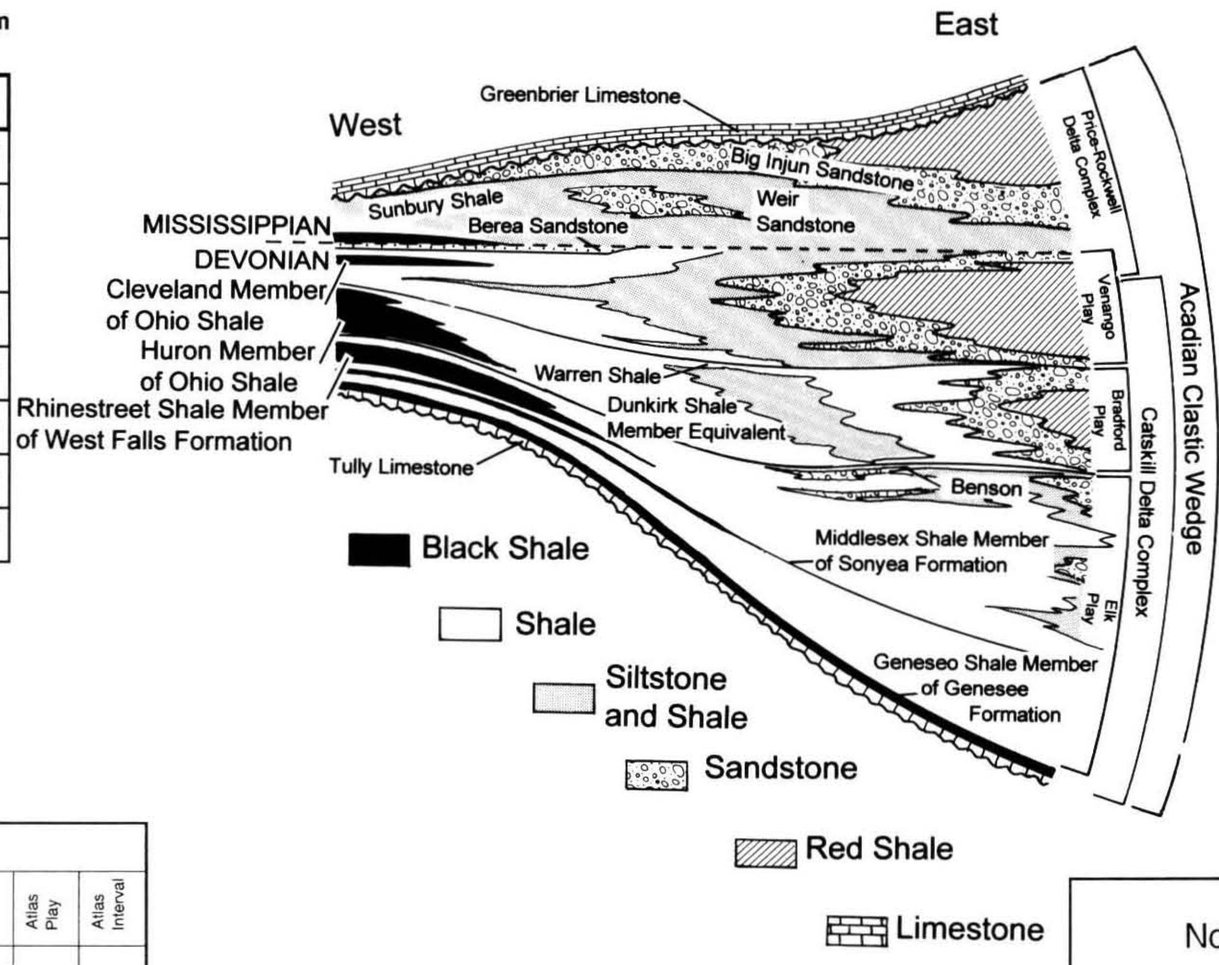


Figure Des-4. Schematic diagram of the Acadian clastic wedge, showing the relationship of the Price-Rockwell and Catskill delta complexes, three Upper Devonian sandstone and siltstone plays with their key bounding units noted, and the general lithologic framework. The Elk sandstone and siltstone play is the basal part of the Catskill delta complex.

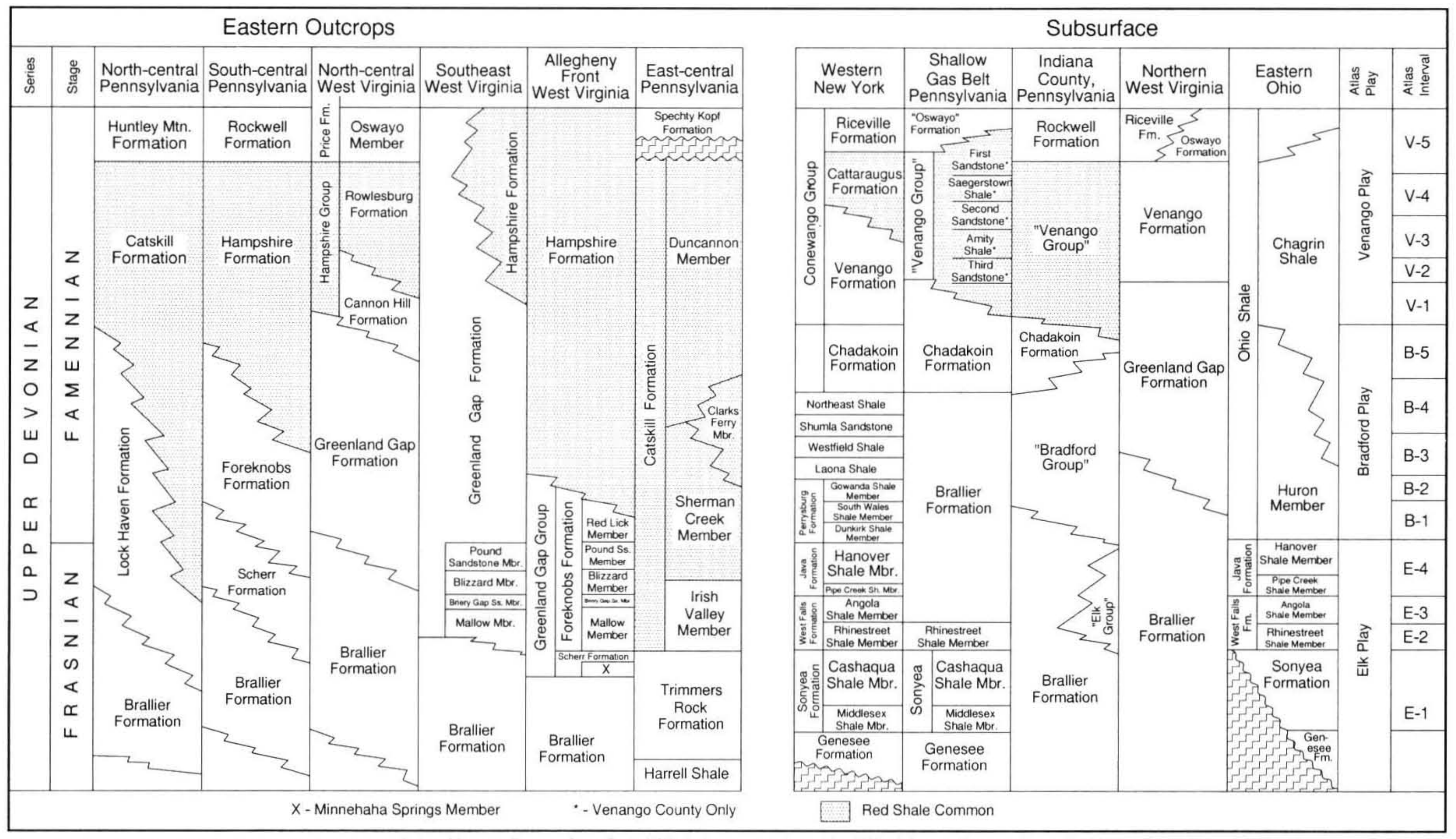


Figure Des-5. Regional correlation chart of the Upper Devonian Catskill delta complex. Modified from Boswell and others (1987) and Woodrow and others (1988).

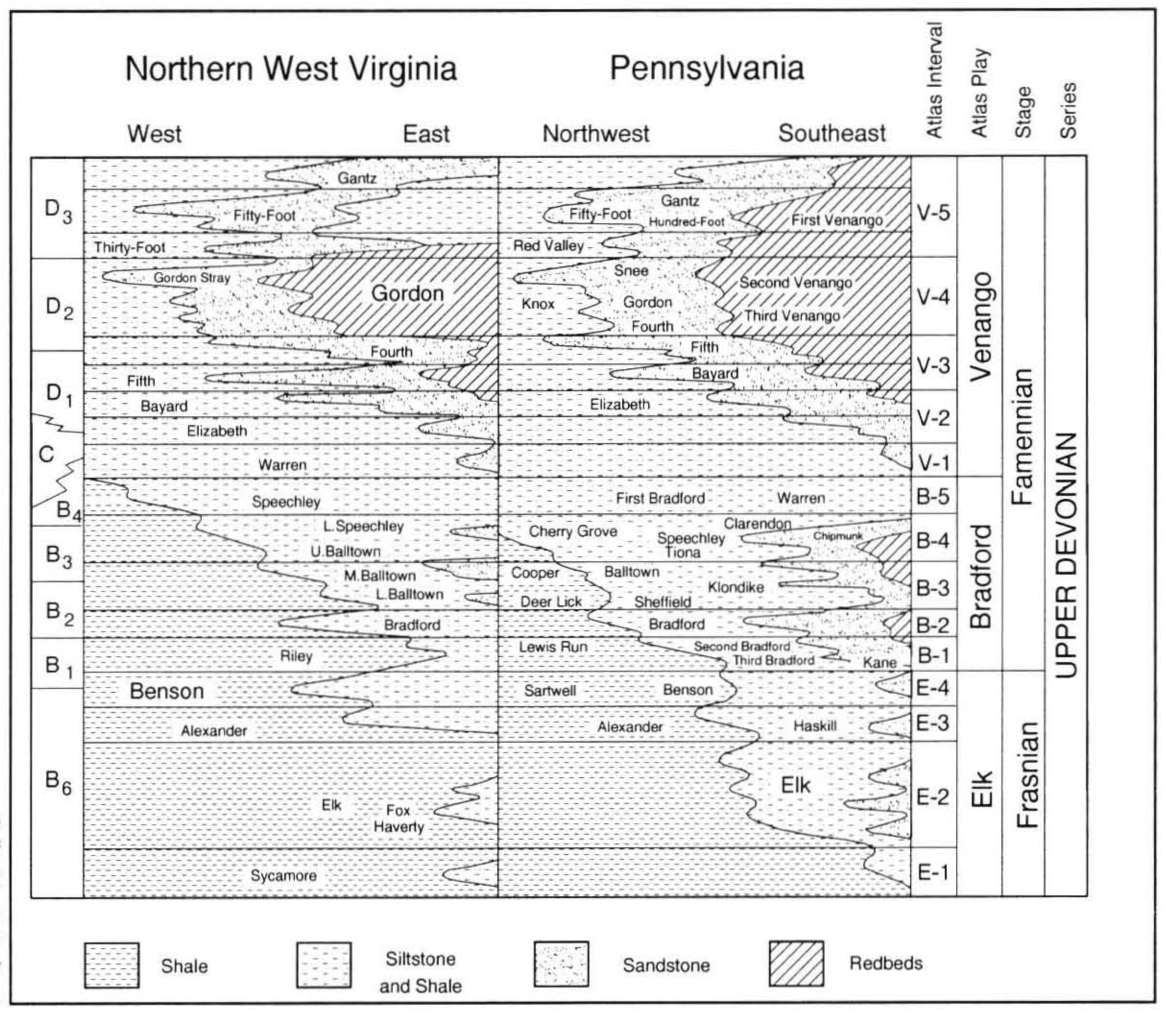


Figure Des-6. Generalized stratigraphic section showing the sequence and approximate correlation of major drillers' units in the subsurface of western Pennsylvania and northern West Virginia. Pennsylvania correlations taken largely after Fettke (1938b), Dickey and others (1943), Wolfe (1963), and Harper and Laughrey (1987). West Virginia correlations after Cardwell (1982a), Filer (1985), and Boswell and others (1987). Far left column shows terminology introduced by Kelley and Wagner (1970).

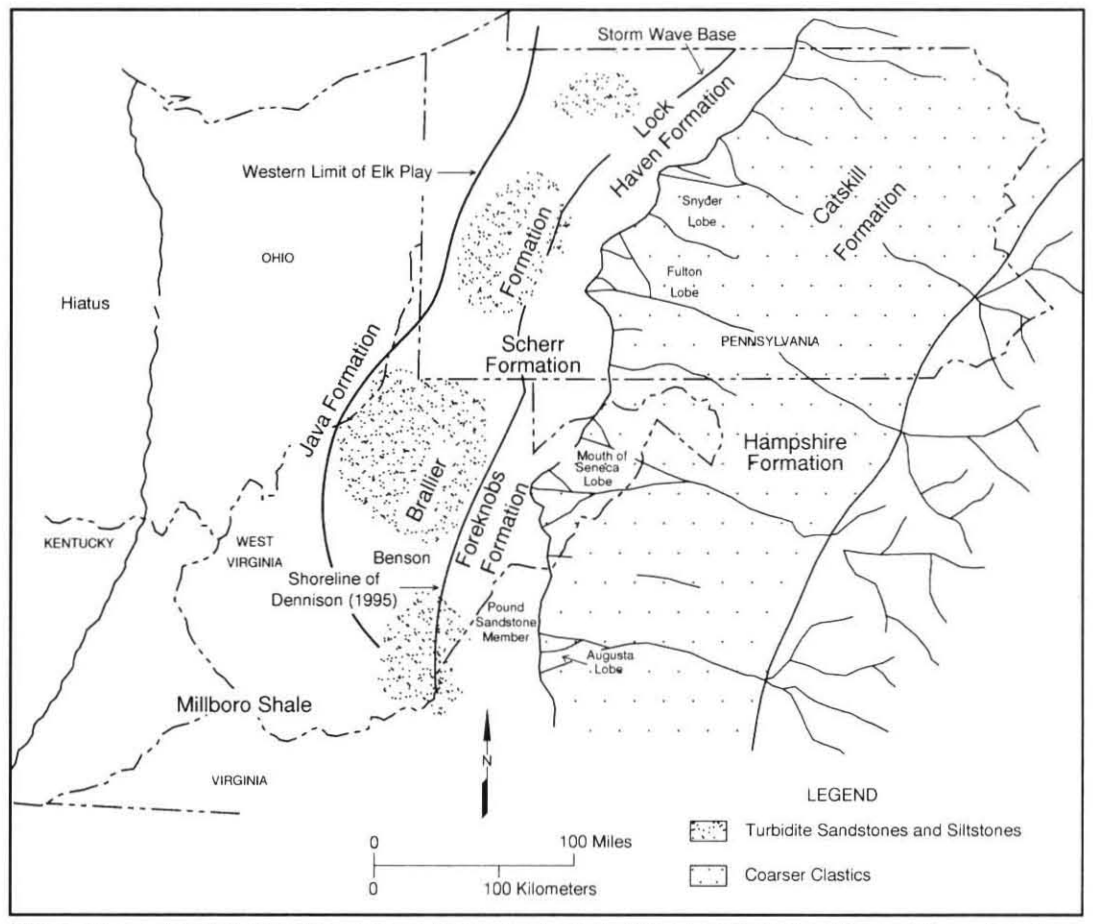


Figure Des-7. Regional paleogeography of the Appalachian basin at the close of Frasnian time, during Benson E-4 deposition. Modified from Boswell (1988b).

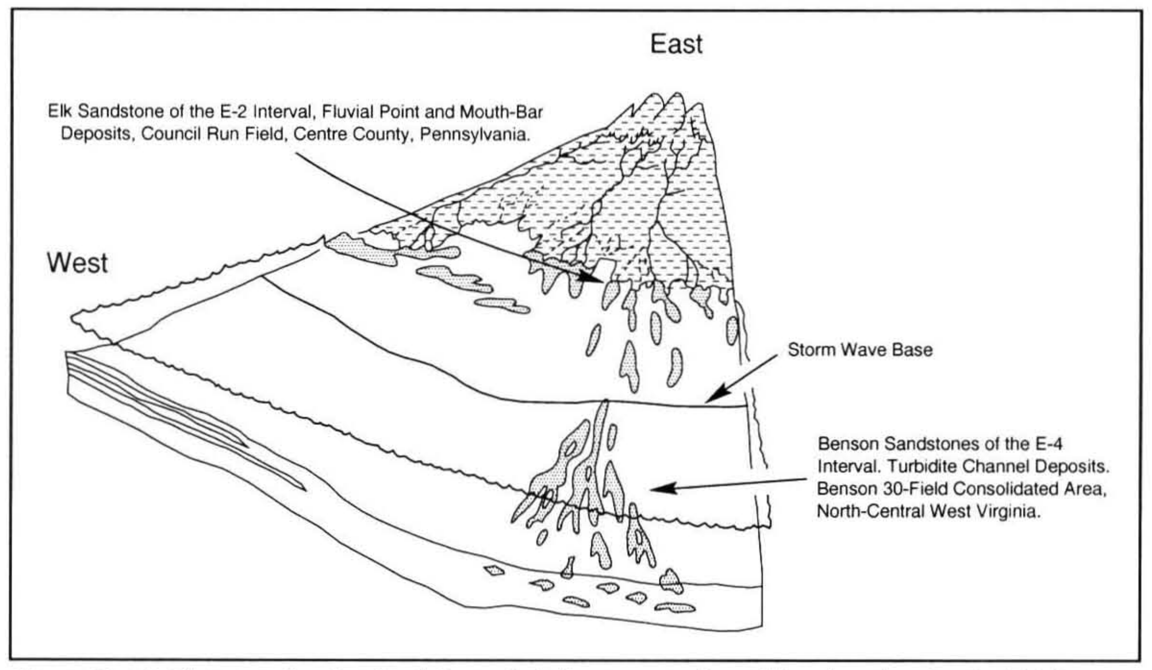


Figure Des-8. Diagram showing the interpreted slope apron depositional setting for the E-4 Benson in the 30-field consolidated area of north-central West Virginia and the shoreline-delta plain setting of the E-2 sandstone in the Council Run field of north-central Pennsylvania.

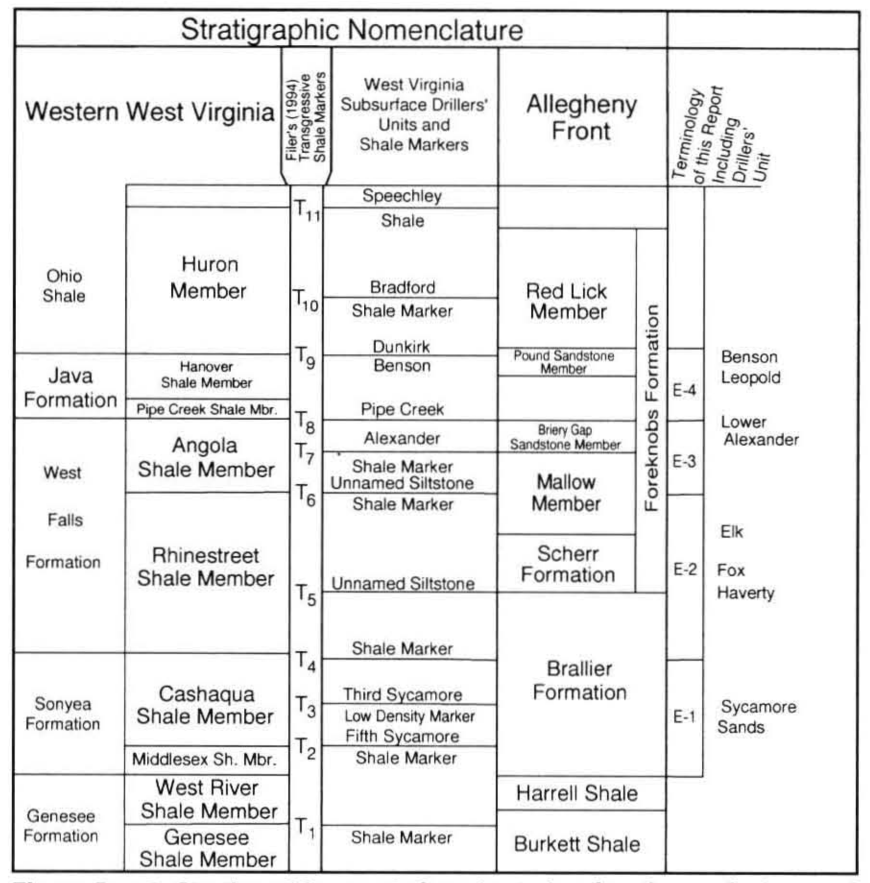


Figure Des-9. Stratigraphic correlation chart showing the equivalence of units and major subsurface marker beds (modified from Filer, 1994), and the Elk interval terminology for West Virginia.

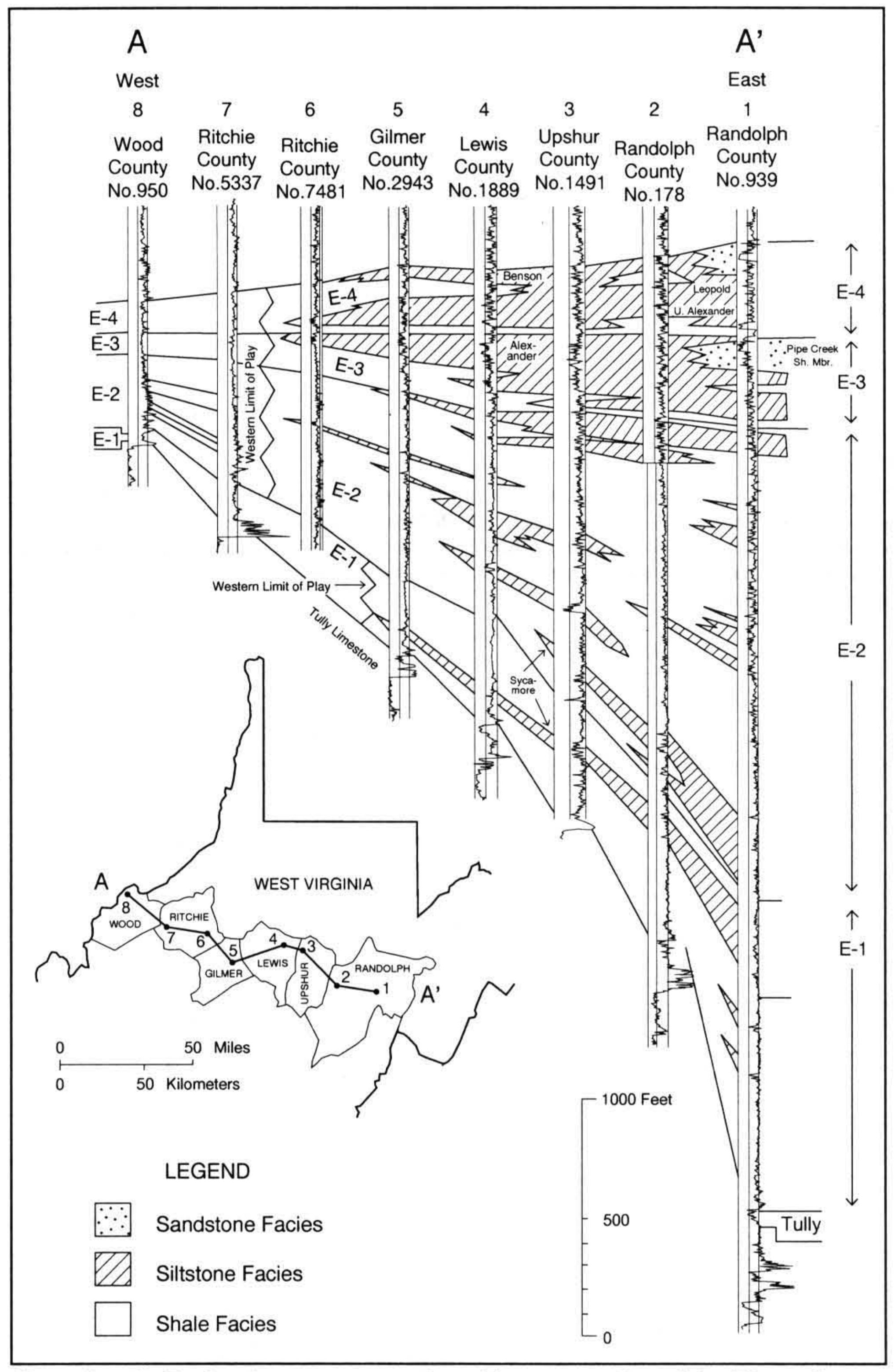


Figure Des-10. Regional gamma-ray stratigraphic cross section of the Elk sandstone and siltstone in north-central West Virginia. The section thins rapidly from east to west. The primary productive reservoir, the Benson, occurs at the top of interval E-4. Other productive units include the Leopold (E-4), Alexander (E-3), various Elks (E-2), and the Sycamore (E-1 and lowermost E-2). See Figure Des-2 for regional location.

middle Benson by shale. Heim (1987) preferred to lump Cheema's middle Benson with the lower unit because of their similar bioturbated and low porosity character compared with the more porous and less bioturbated upper Benson, as observed in cores. Here, the lower and middle Benson of Cheema (1977) are also the distal facies of the turbidite slope apron in the gas-productive area (Benson 30-field consolidated area of Figures Des-2 and Des-3), whereas the upper Benson is interpreted as the proximal facies of the turbidite slope apron (Figure Des-16), which prograded rapidly westward over its distal part during a drop in sea level.

Within the proximal facies, increased concentrations of fine-grained sandstones and siltstones overlie the broader part of the lobes consisting of the distal facies of the turbidite slope apron. Three subfacies of the proximal facies of the upper Benson were mapped by Cheema (Figure Des-17a). The inner lobe subfacies consists of the increased concentrations of fine-grained sandstones, which also occur in west-northwest-oriented narrow elongated lobes. The slope apron interpretation is preferred to fan, as these lobes parallel each other rather than radiate from a point source. A cross section across one of these elongated lobes (Figure Des-17b) indicates the gamma-ray signatures for the three subfacies. The upper Benson facies is indicative of turbidity flows.

Heim (1987) reported from core examination that amalgamation of successive turbidite-graded beds converted previously 2- to 6-inch beds of fine-grained sandstone into several foot-thick sandstone beds bearing shale rip-ups. Cheema (1977) de-emphasized deep scour by these turbidity flows, claiming that the bulk of core samples displayed thin shales vertically separating thin graded beds. He did, however, cite log evidence for 6 feet of channel scour within the inner lobe subfacies in the eastern part of the Benson gas-producing area.

Cheema (1977) also recognized seven different sandstone units (bundles or aggregates of sandstone/siltstone-rich graded beds) for the entire Benson interval, and these plus two additional sandstones units recognized west of his study area are: sandstone units a, b, c, and d for the lower Benson; sandstone unit e of the middle Benson; and sandstone units 1, 2, 3, and 4 for the upper Benson (Figure Des-18). This east-west stratigraphic cross section shows the progradational down-dip migration westward of the four sandstone units of the upper Benson (Figure Des-16), as well as the change from storm to turbidite deposits (Figure Des-18).

In summary of the Benson portion of the E-4 interval, there are three ways to describe its stratigraphic framework: overall, the porous upper Benson mainly is the proximal facies of a slope apron turbidite deposit, which overlies the abundantly bioturbated, low-porosity distal facies of the lower and middle

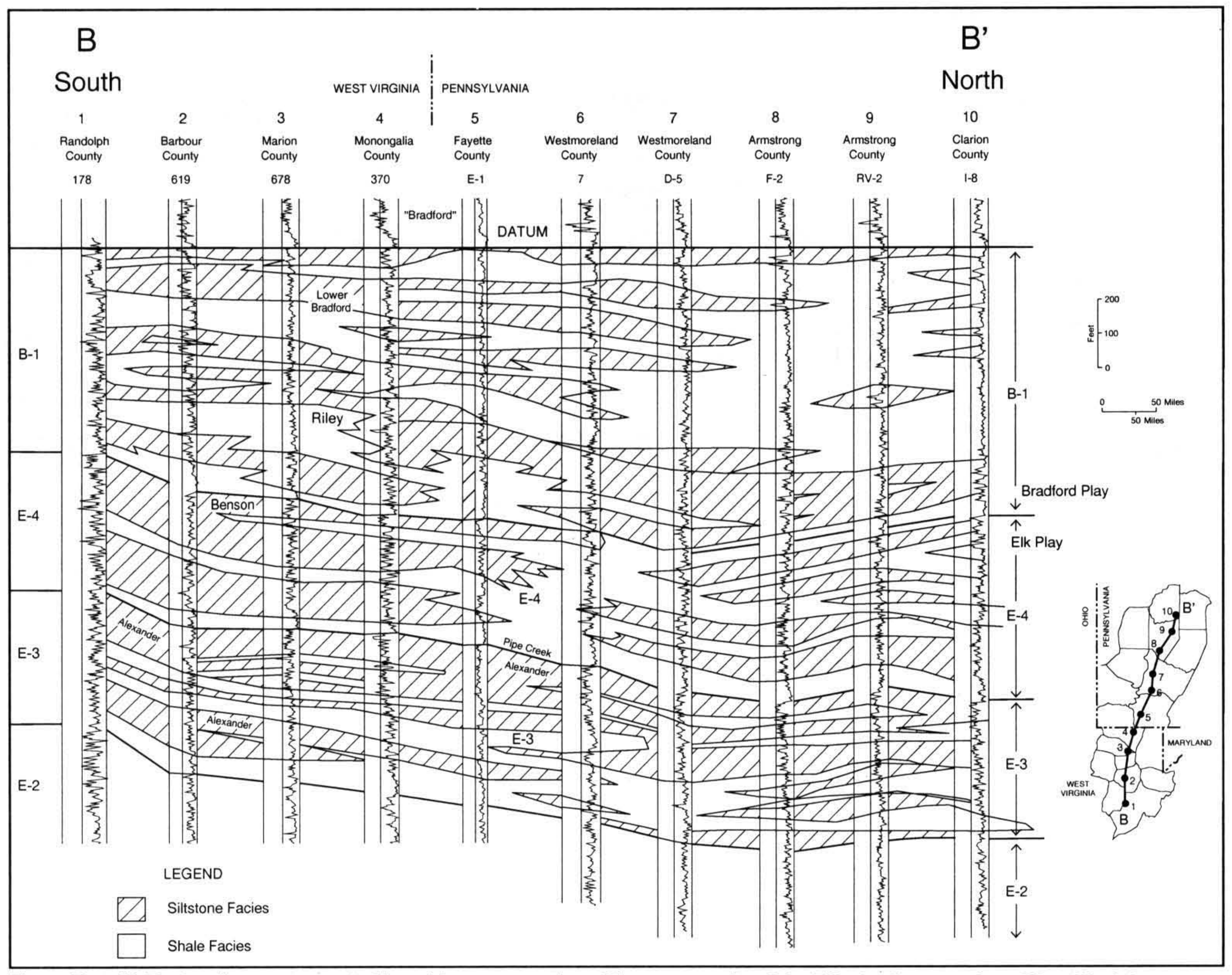


Figure Des-11. Regional gamma-ray stratigraphic cross section of the upper units of the Elk play from northern West Virginia to west-central Pennsylvania. See Figure Des-2 for regional location.

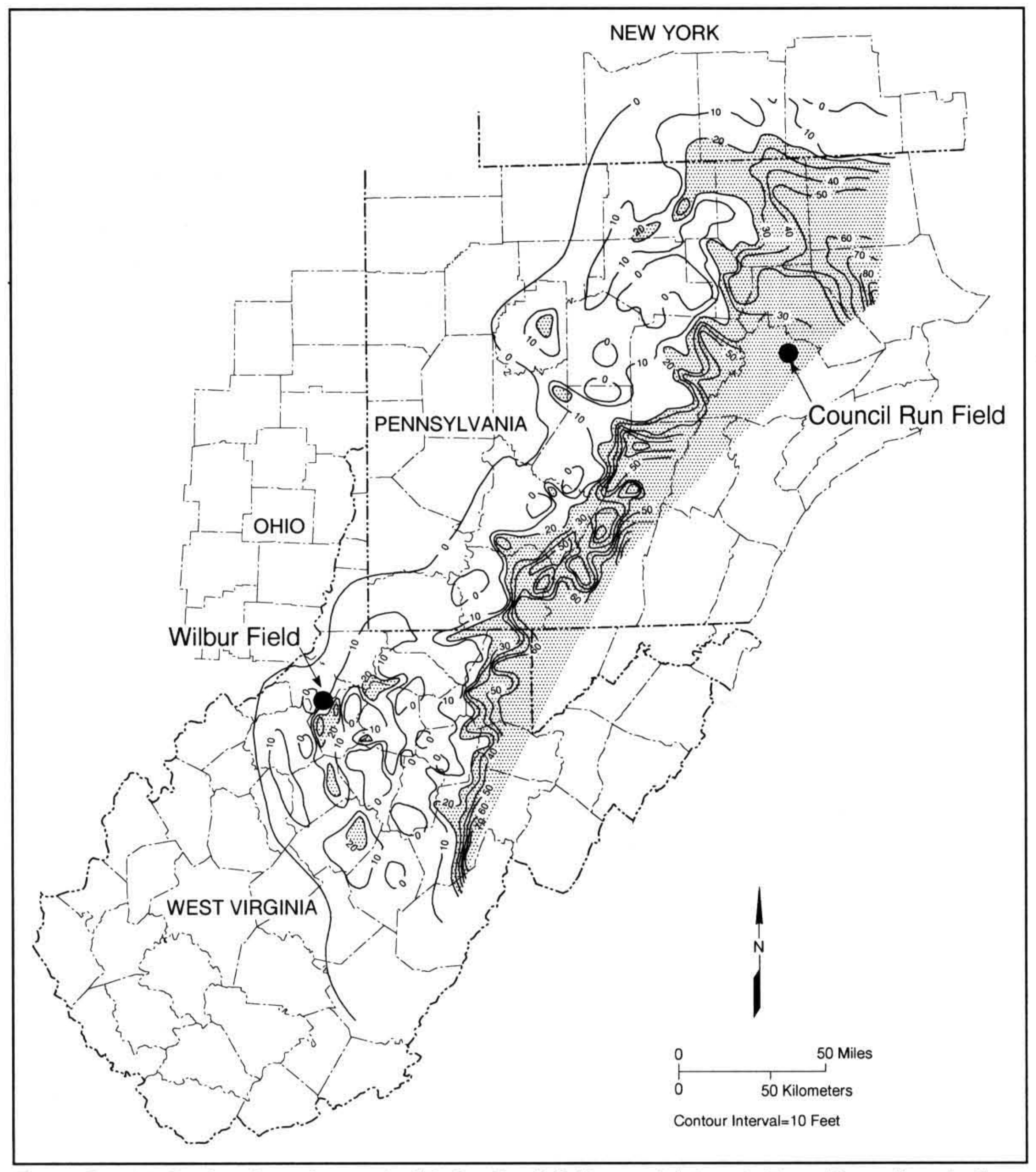


Figure Des-13. Regional sandstone isolith for the E-4 (Benson) interval. From Boswell and others (1993). Shading indicates area where sandstone is 20 feet or greater in thickness based on 50 percent gamma-ray baseline method.

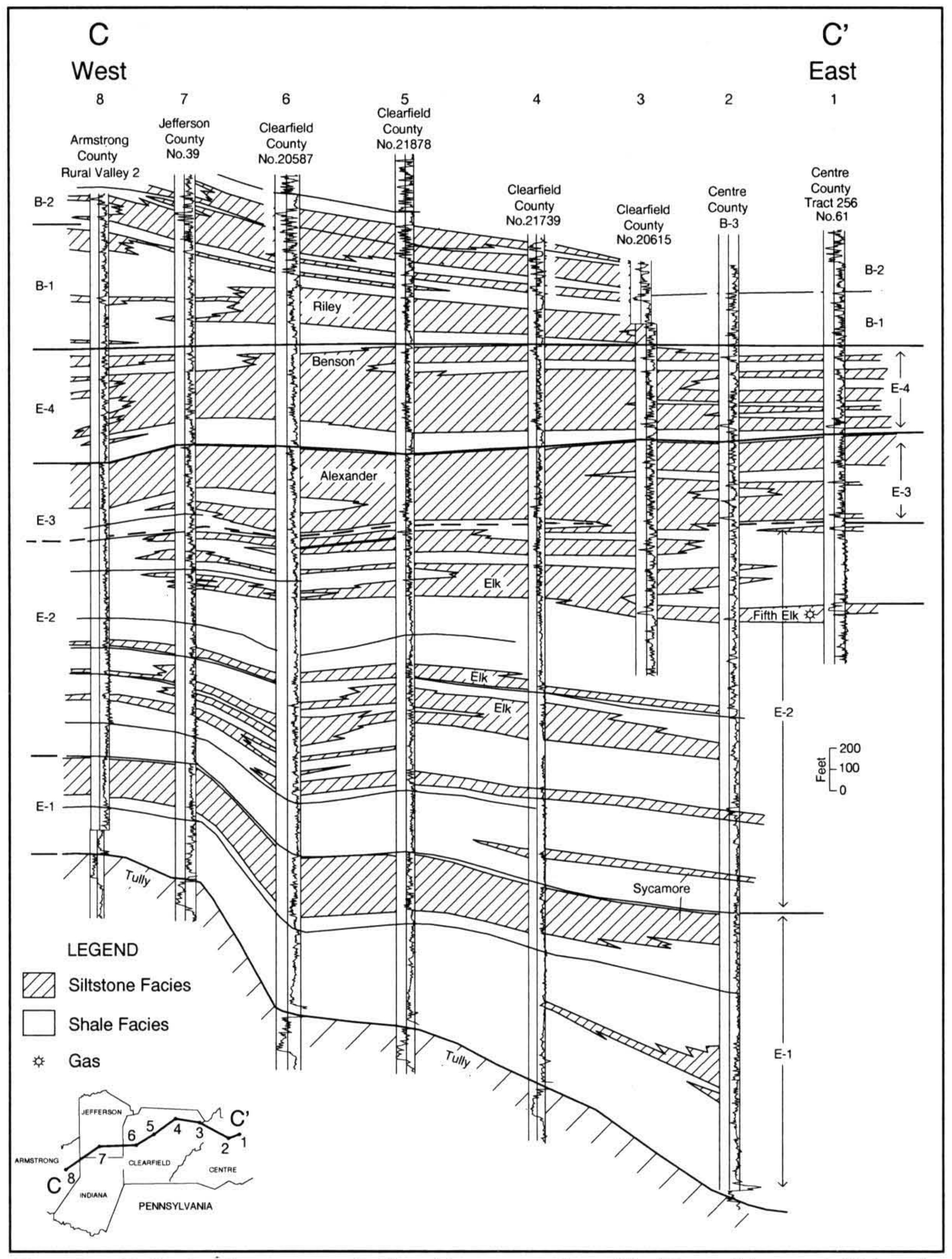


Figure Des-12. Regional gamma-ray stratigraphic cross section of the Elk sandstone and siltstone in western Pennsylvania. The sequence thins rapidly from east to west. The primary productive reservoir, the Fifth Elk of the Council Run field in Centre and Clinton counties, Pennsylvania, occurs within the E-2 interval. See Figure Des-2 for regional location.

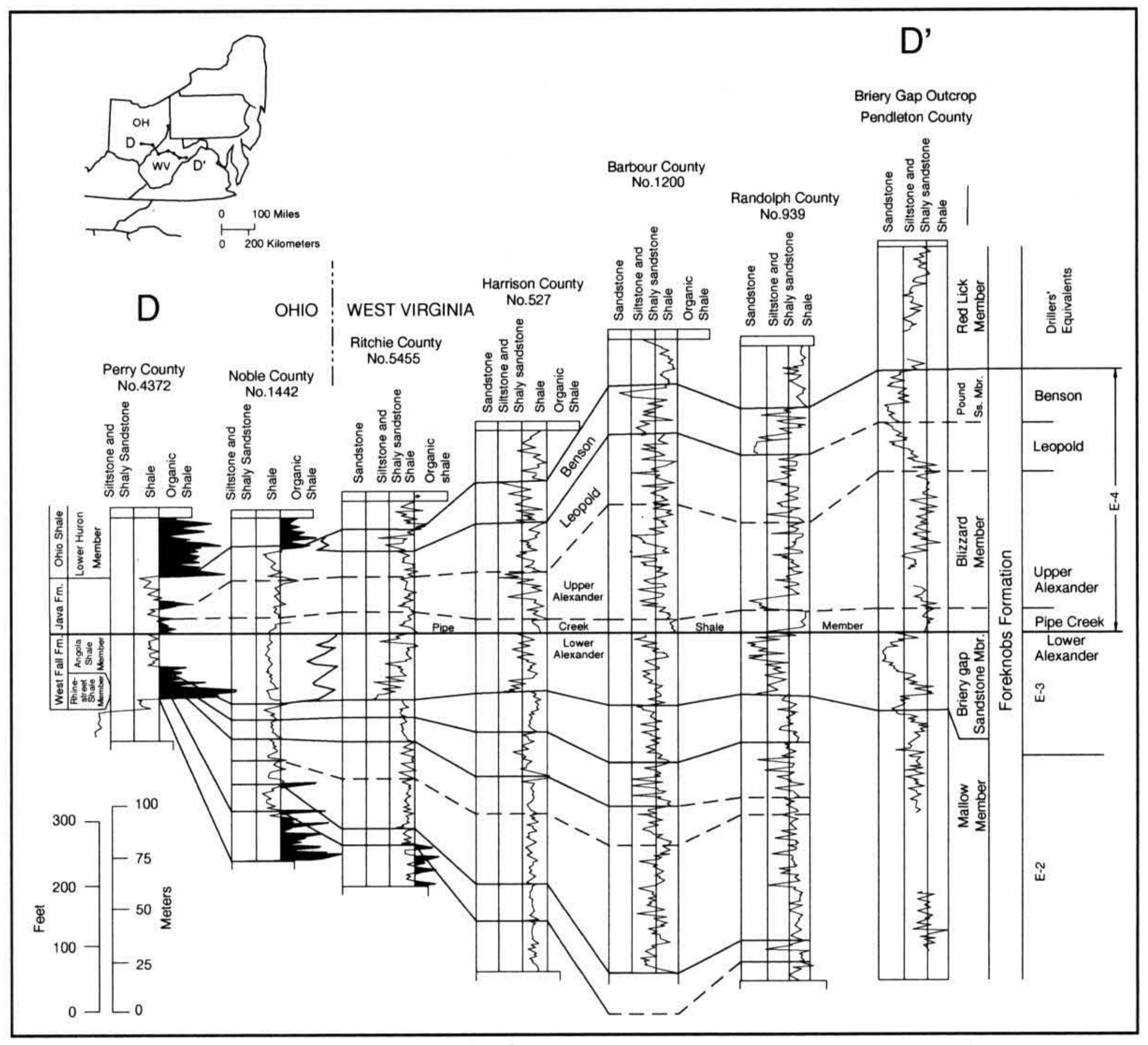


Figure Des-14. Correlation of the E-3 and E-4 intervals from eastern Ohio to an outcrop in eastern West Virginia. From Filer (1994). See Figure Des-2 for regional location.

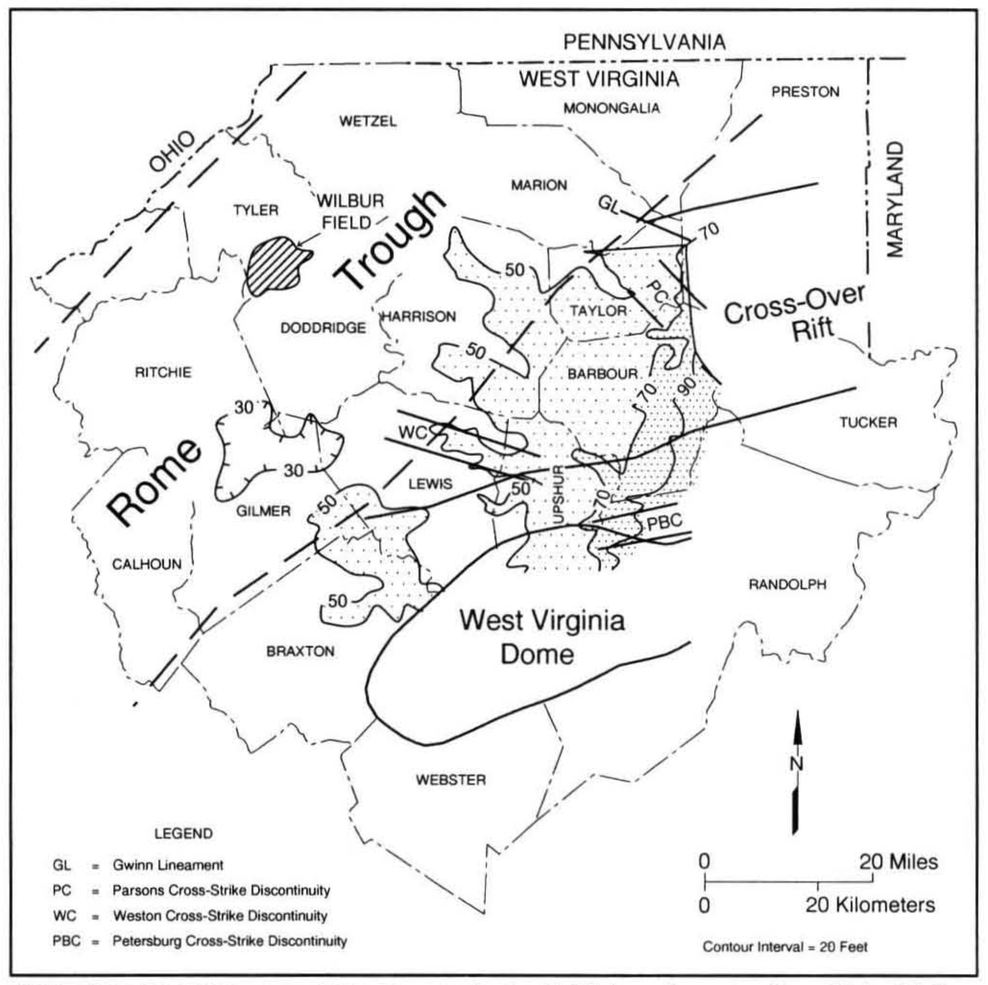


Figure Des-15. Thickness of the Benson in the E-4 interval greater than 30 feet (after Heim, 1987) is shown. Thickness contour of 70 feet approximates the eastern limit of turbidite and western limit of storm deposits for the upper Benson. Location of Wilbur field is indicated.

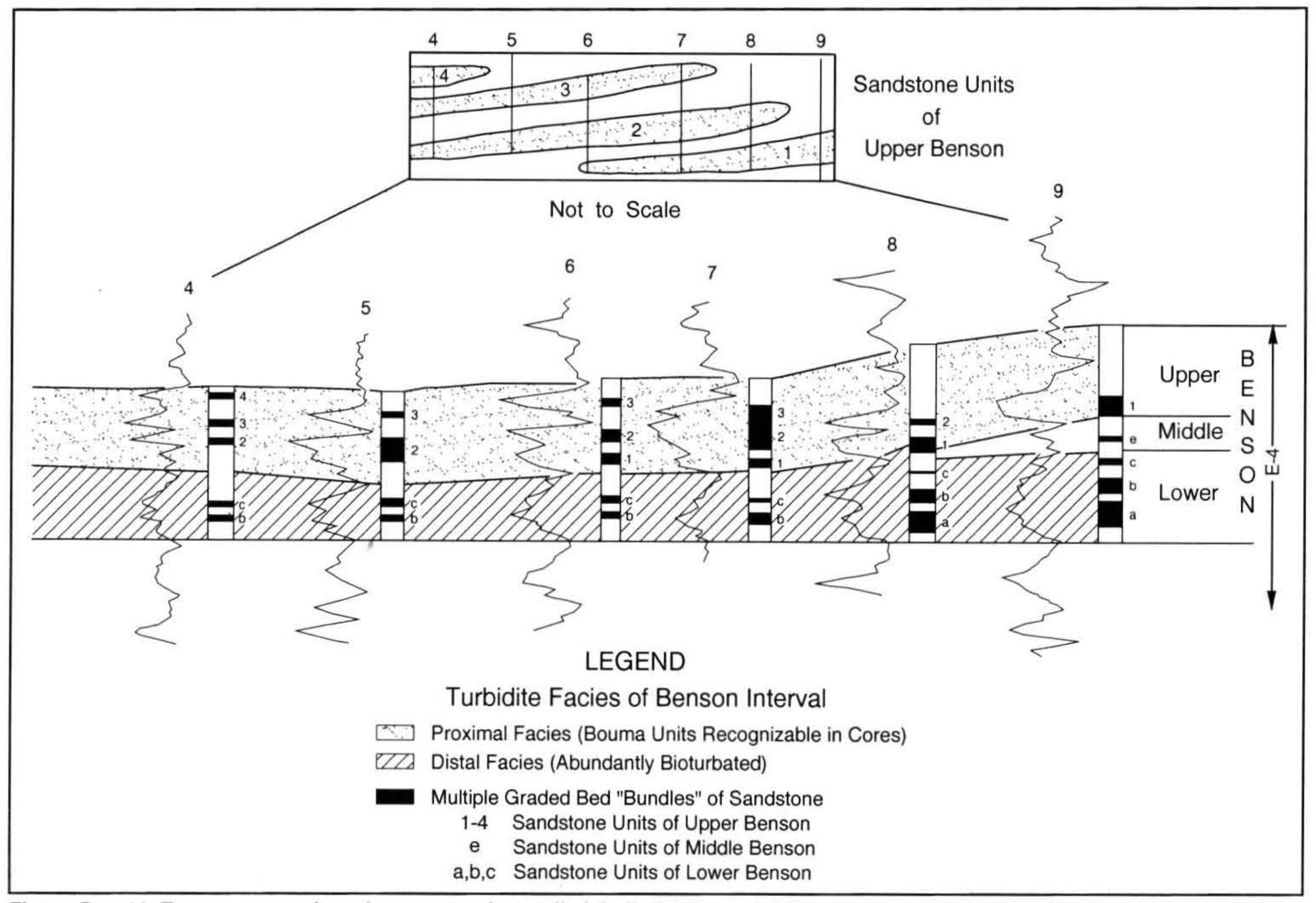


Figure Des-16. Two cross sections (segment using wells labelled 4 through 9 from cross section B-B' of Figure Des-18) oriented west-east show the westerly progradation of the E-4 Benson turbidite sandstones and siltstones. In the lower section, distal and proximal facies of a turbidite slope-apron are indicated for the entire Benson interval using gamma-ray signatures from six wells. The interpretation of the upper section focuses on the proximal facies of the upper Benson and indicates imbricated down-dip positions of four sandstone units, each consisting of thin multiple graded beds. See Figure Des-17a for location of cross section. From Cheema (1977).

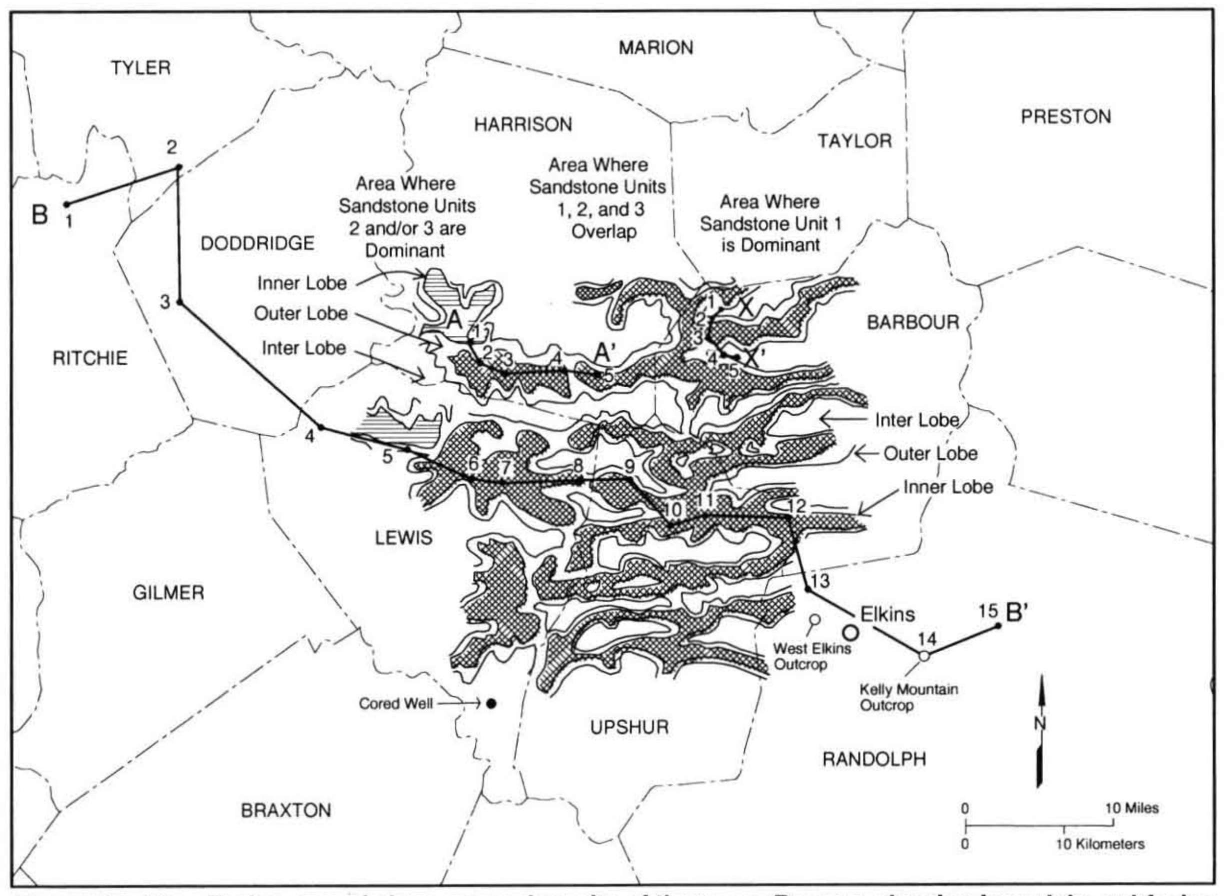


Figure Des-17a. Facies map of slope apron deposits of the upper Benson, showing inner lobe subfacies of maximum sandstone/siltstone thickness (also best gas production) in narrow west-northwest trends. Modified from Cheema (1977). Westward progradation of the slope apron is indicated by dominance of oldest sandstone unit 1 (of Figure Des-16) in eastern area; overlapping of sandstone units 1, 2, and 3 in the middle area; and sandstone units 2 and 3, then only 3 in the western area of Benson production. Location of cross sections in Figures Des-16, Des-17b, and Des-20b are indicated.

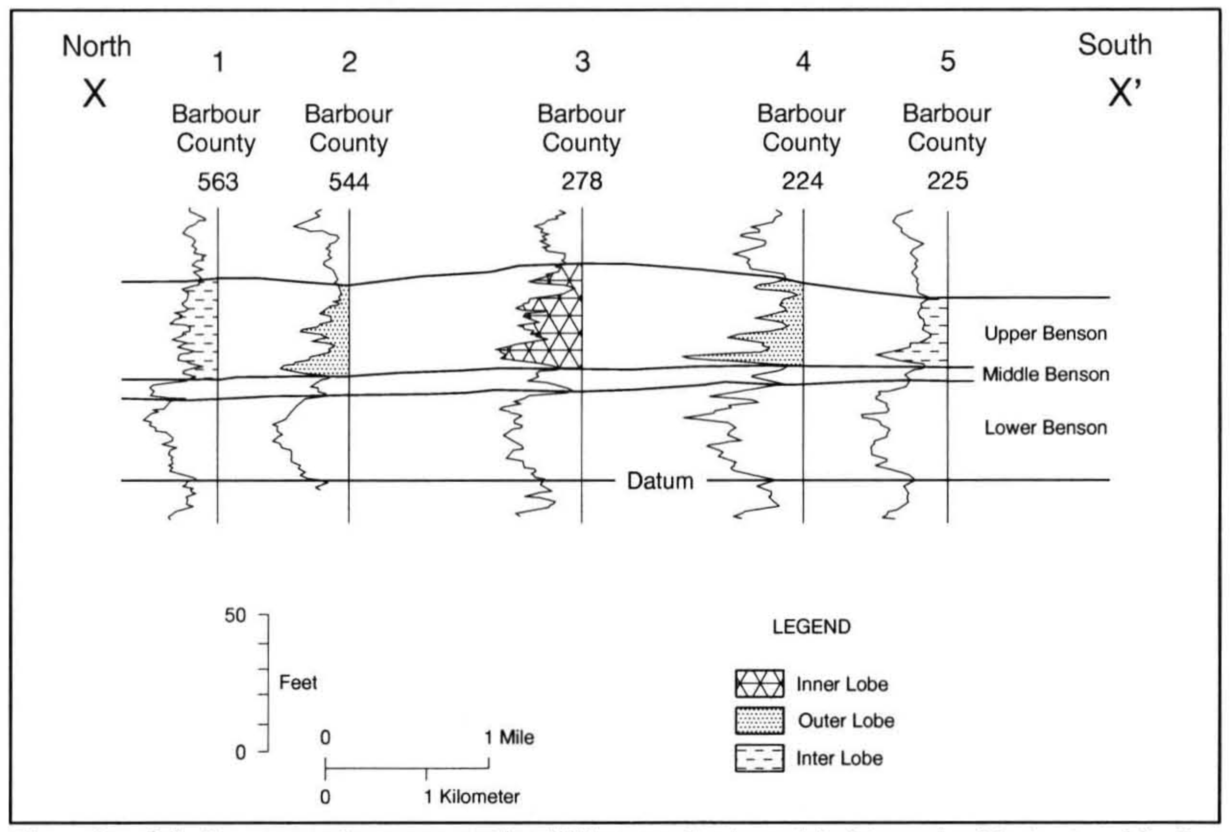


Figure Des-17b. Gamma-ray log cross section X-X' across the inner lobe/channel subfacies trend for the upper Benson reservoir. Note log signatures for the three subfacies of the proximal facies of the slope apron deposits. See Figure Des-17a for location of cross section.

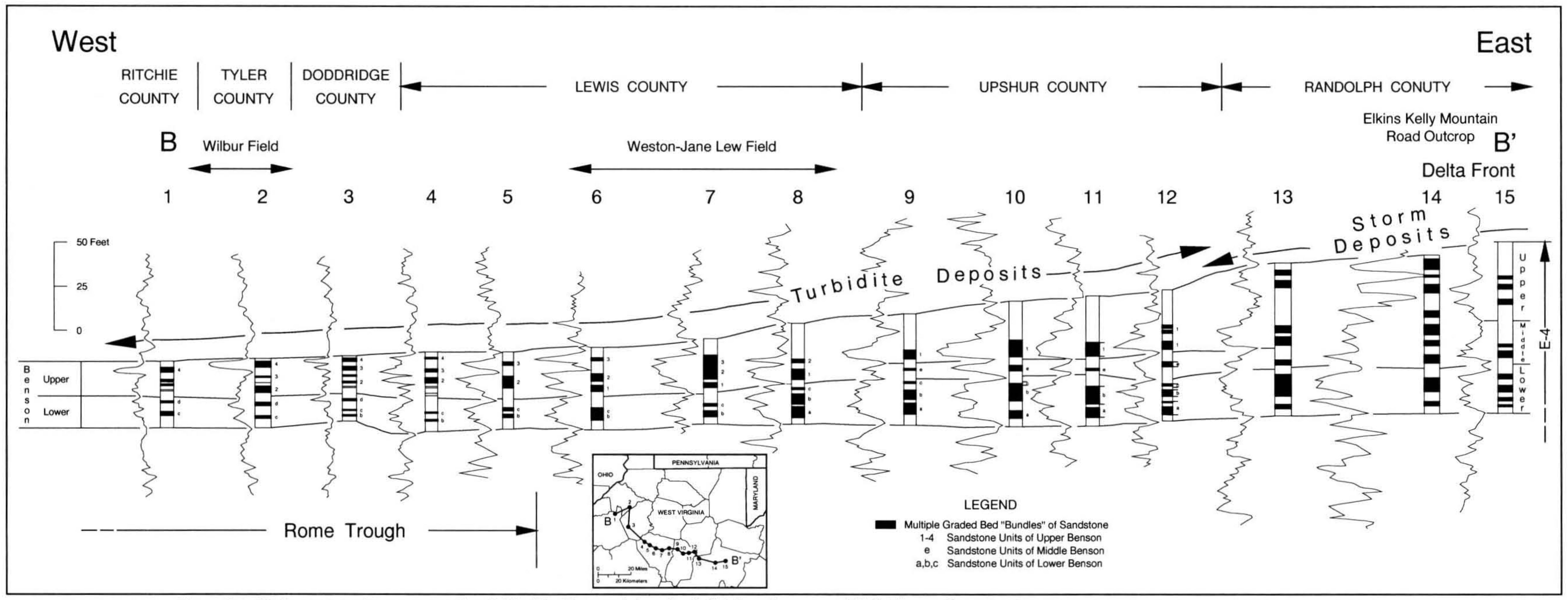


Figure Des-18. Gamma-ray log cross section B-B' of the Benson interval subdivisions (uppermost E-4). The section extends west-east across the Benson 30-field consolidated area, including the Weston-Jane Lew and Wilbur fields. Surface section log at Kelly Mountain Road from Schwietering (1979).

Benson; the upper Benson (proximal facies) can be subdivided into subfacies based on net sandstone/siltstone content and the inner lobe subfacies occurs in narrow elongate belts trending west-northwest; and the upper Benson contains three units of aggregated multiple thin-graded beds of sandstones and siltstones, which show downdip offlap and westward progradation of the interpreted turbidity deposits in the gas-productive area. The proximal facies of the upper Benson grades laterally eastward into interpreted storm deposits (Figures Des-15, Des-18).

The detailed stratigraphy of the underlying E-3 to E-1 intervals is poorly understood compared with the Benson in the E-4 interval, with the exception of the uppermost E-2 interval in central Pennsylvania where the Council Run gas field is located. In general, the depositional environments interpreted for the Benson in its paleogeographic reconstruction (Figure Des-7) apply to the older units in the Elk play, realizing that sea-level fluctuations during the deposition of an Elk interval resulted in shoreline shifts of 1 to 25 miles, comparable to shoreline changes documented by Boswell and Donaldson (1988) for overlying Bradford and Venango units. Throughout Elk time, the western limit of the shoreline during maximum shoreline regressions probably coincided with the position shown for the Benson in the E-4 interval (Figure Des-7), and frequently tens of miles east of this position (Dennison, 1985). Therefore, the Alexander of the E-3 interval, various drillers' Elks (mainly E-2), and Sycamore (mainly E-1) sandstones and siltstones are interpreted as either offshore storm or slope turbidite deposits underlying the Benson 30-field consolidated area (Figure Des-2), whereas the Fifth (or Sixth) Elk (uppermost E-2) sandstones of the Council Run and Accident fields are interpreted as shoreline deposits.

The gas reservoir of the E-2 unit in Pennsylvania was named the Fifth Elk sandstone by Eastern States Exploration Company in the Council Run field of Centre and Clinton counties (Figures Des-2, Des-12) in 1982, but geologists with Consolidated Natural Gas (CNG) referred to it as the Lock Haven Sixth Elk (Kelleher and Johnson, 1991). Initially, Eastern States Exploration Company interpreted these coarse-grained deposits to be offshore slope turbidites, similar to the finer-grained sandstones and siltstones of the Benson (E-4) in its gas-producing area of West Virginia, but later reinterpreted them as ancient coastal deposits of deltaic and fluvial channel environments. Follador (1993) interpreted the strike-trending equivalent Elk sandstones and siltstones of the Accident field of western Maryland to have been deposited in shoreline (shoreface) environments during a regression related to a drop in sea level. Al-Mugheiry (1995) interpreted three facies for the Elk reservoir sandstone of the Council Run field: fluvial to distributary channel facies in the southeastern part; strike-oriented lowstand shoreface deposits that rest on a wave-cut bench in the eastern part; and marine shelf deposits in the western part. The shoreline setting is indicated in Figure Des-8.

Structure

Fold structures associated with the Allegheny orogeny have not been a major factor in petroleum exploration of Elk sandstones and siltstones at the field scale in West Virginia. Pre-existing basement structures that may have been active during Late Devonian time apparently have affected the distribution of the Benson (E-4) reservoir facies (Figures Des-15, Des-19) and probably the underlying Alexander (E-3) and Elk (E-2) units. The occurrence of the Elk gas-bearing reservoirs in the Benson 30-field consolidated area (Figures Des-2, Des-3) in northern West Virginia, where no analogous units have yet been discovered on strike either to the north or to the south, suggests the importance of a dip-trending basement low, such as the cross-over rift discussed by Donaldson and Shumaker (1981). The major dip-trending inner lobe subfacies, consisting of the thickest pay zone of the upper Benson, parallels the cross-over rift east of the Rome trough, then realigns perpendicular to the eastern border fault within the Rome trough. Vertical stacking of lower and upper Benson net sandstones and siltstones also was noted by Cheema (1977). The Weston cross-strike discontinuity is occupied by a major dip-trending inner lobe subfacies in the upper Benson (Figures Des-15, Des-19) and the site of the Weston-Jane Lew field (Figure Des-3). In addition, production in the Benson may be enhanced by fracturing that is expressed by surface lineaments (Silbaugh, 1985).

On a regional scale for the E-2 sandstones along the structural front of Pennsylvania and Maryland, Kelleher and Johnson (1991) suggested present-day structures were active during their deposition, causing barred deposition to the west and accumulation of sands in a northeast-southwest fairway, further thickened where intersected by cross-strike discontinuities. Within the Council Run field, production in the Elk sandstones also may be enhanced by fracturing that is expressed by surface lineaments and related to structure (J. Walker, written commun. 1994; J. Harper, written commun.,1995).

Reservoir

The Elk play is dominated by stratigraphic traps of highly lenticular reservoirs, consisting of E-2 deltaic and shoreline Elk sandstones in the Council Run field of north-central Pennsylvania; and E-2, E-3, and especially E-4 marine slope apron, fine-grained sandstones and siltstones mainly occurring in the Benson 30-field consolidated area of northern West Virginia (Figures Des-2, Des-3). Although the Sycamore siltstones (E-1 and lowermost E-2) of West Virginia have been tested, to date only marginal production has been reported.

The Benson consolidated area consists of mostly contiguous fields, commonly with poorly defined to overlapping boundaries. The following description is an expanded discussion of the geological characteristics of the reservoir for the consolidated area and, in this respect, serves to compare and contrast all 30 of its fields. The Benson (E-4) has been an important gas producer from all 30 fields, and the dominant reservoir in all but 3 fields. The Alexander (E-3) has produced gas from 60 percent and Elk/Brallier (E-2) sandstones and siltstones from 27 percent of the fields in the 30-field consolidated area. The E-2 reservoirs are the principal target in two fields (No. 22 Cassity of Randolph and Upshur counties, and No. 23 Belington of Barbour County), whereas the Alexander (E-3) is the main target in one field (No. 8 Straight Fork-Bluestone Creek of Doddridge County) (Figure Des-3). The E-2 reservoirs are productive in fields along the

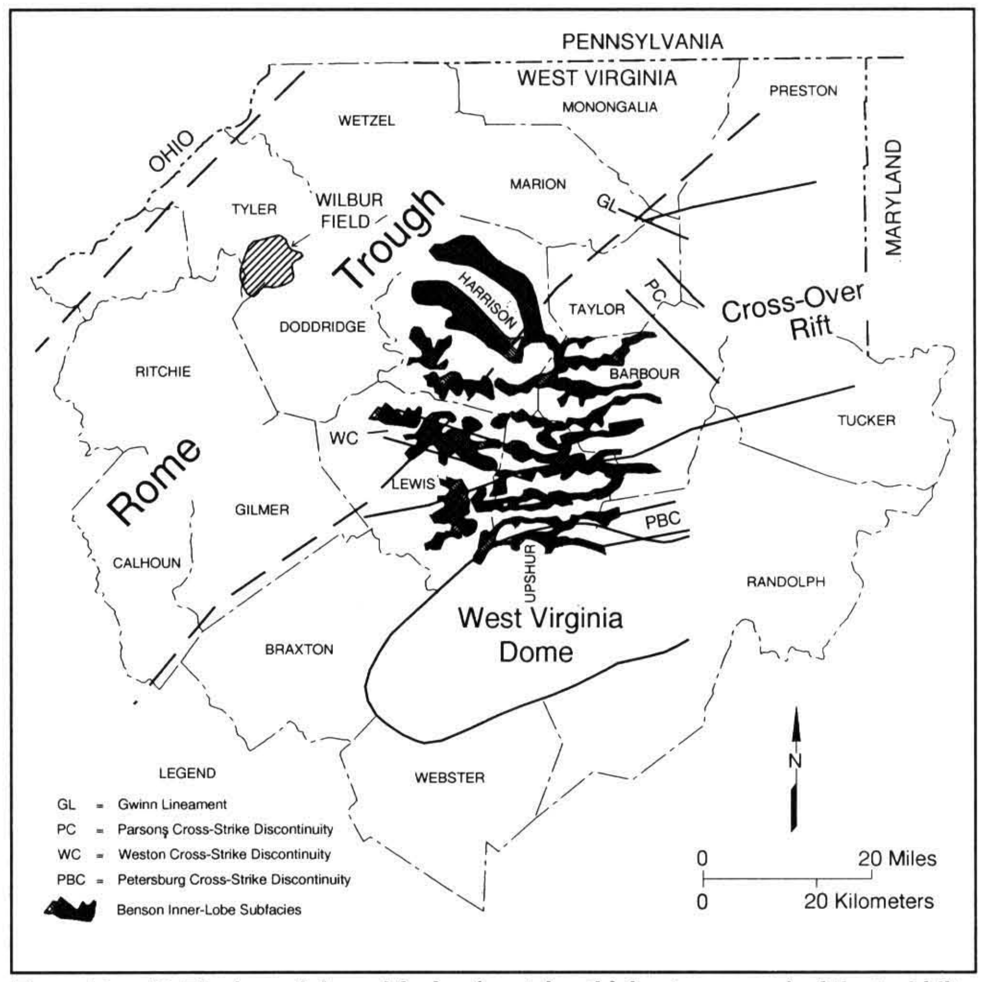


Figure Des-19. The inner lobe subfacies (contains thickest pay zone) of the turbidite proximal deposits of the upper Benson (E-4) is superposed on selected structural elements. The Weston-Jane Lew field is located within the Weston cross-strike discontinuity.

Table Des-3. Typical gas production from different subfacies of the proximal facies of the E-4 upper Benson, an interpreted turbidite slope apron deposit. Characteristics indicating the geometry of upper Benson reservoir are from cores located in Figure Des-3, correlations indicated in Figure Des-18, and map of Figure Des-17a.

	INNER LOBE/CHANNEL	OUTER LOBE/LEVEE	INTERLOBE (flaking position)
AVERAGE WIDTH	0.75 miles	0.33 miles	0.75 miles
LENGTH: Total Dip-Trending Length	55 miles	55 miles	55 miles
Approximate Sandstone unit length #4 = 5+ miles #3 = 25 miles #2 = 18 miles #1 = 25 miles	18 to 25 miles		
Average "Tear-Drop" Shape Segment of Sandstone Unit Length	6 miles		
NET SANDSTONE THICKNESS	> 10 feet	5-10 feet	< 5 feet
FIRST-YEAR PRODUCTION	> 75 MMcf	25-74 MMcf	< 25 MMcf
GRADED BED THICKNESS	0.4-55 inches		
REPRESENTATIVE CORES From Different Subfacies	Barbour No. 502 Lewis No. 1704 Harrison No. 862	Barbour No. 243	Barbour No. 396

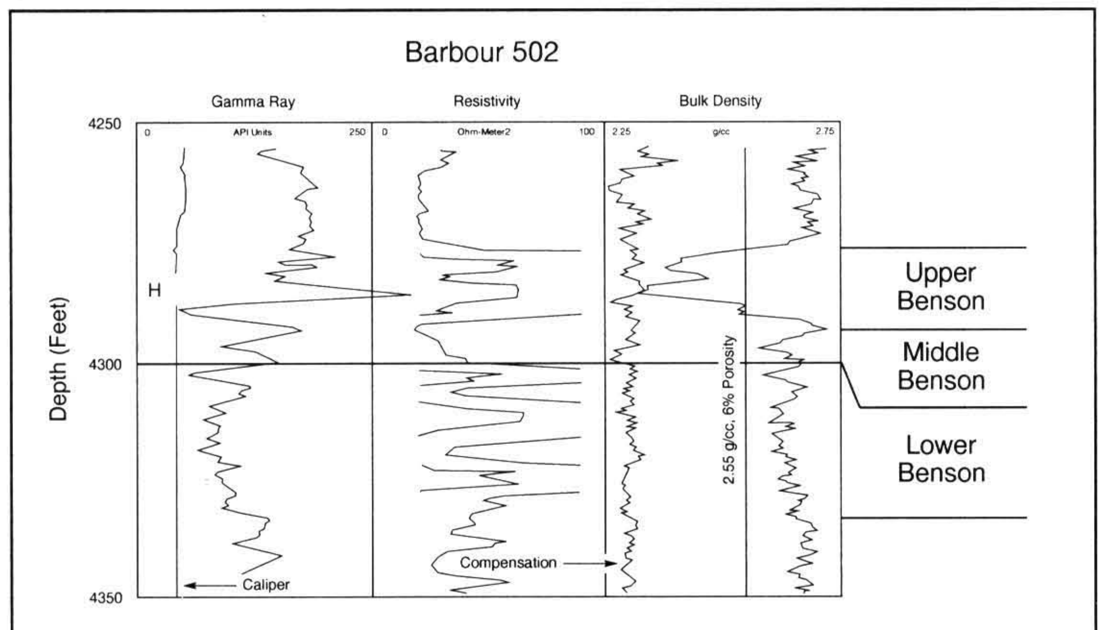


Figure Des-20a.

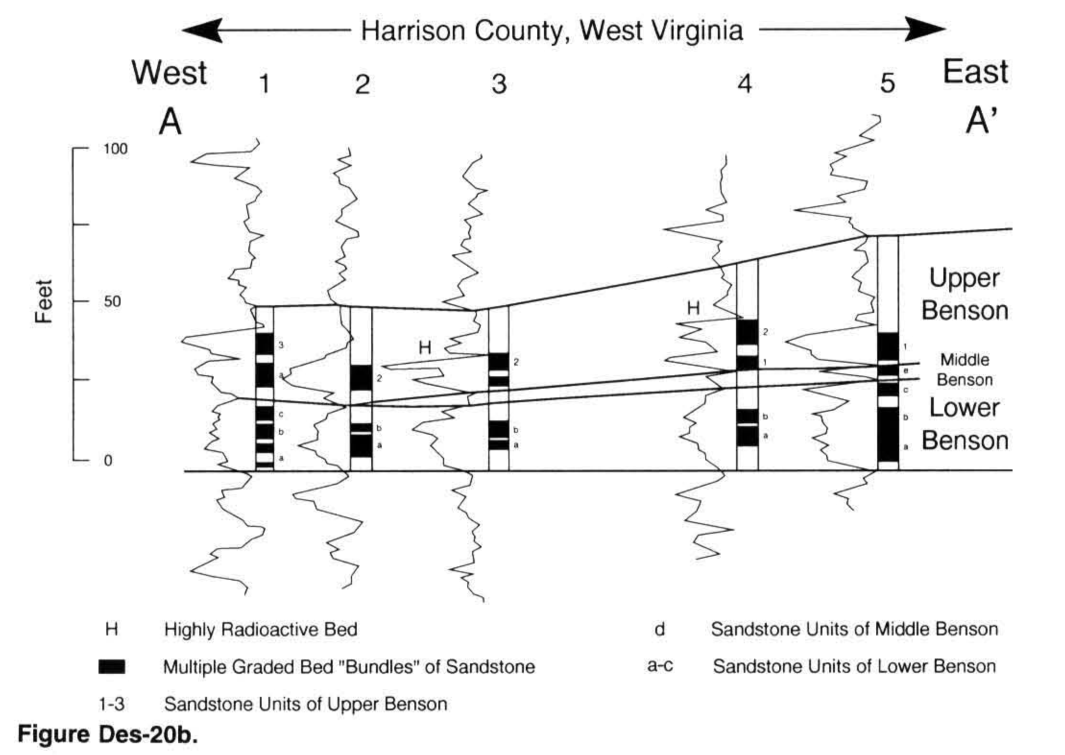


Figure Des-20b.

Figures Des-20a-b. Figure Des-20a. Geophysical log responses of the Benson interval (uppermost E-4 interval) for cored Barbour County well No. 502. Figure Des-20b. Cross section of the Benson interval including the highly radioactive bed. See Figure Des-17a for location of cross section.

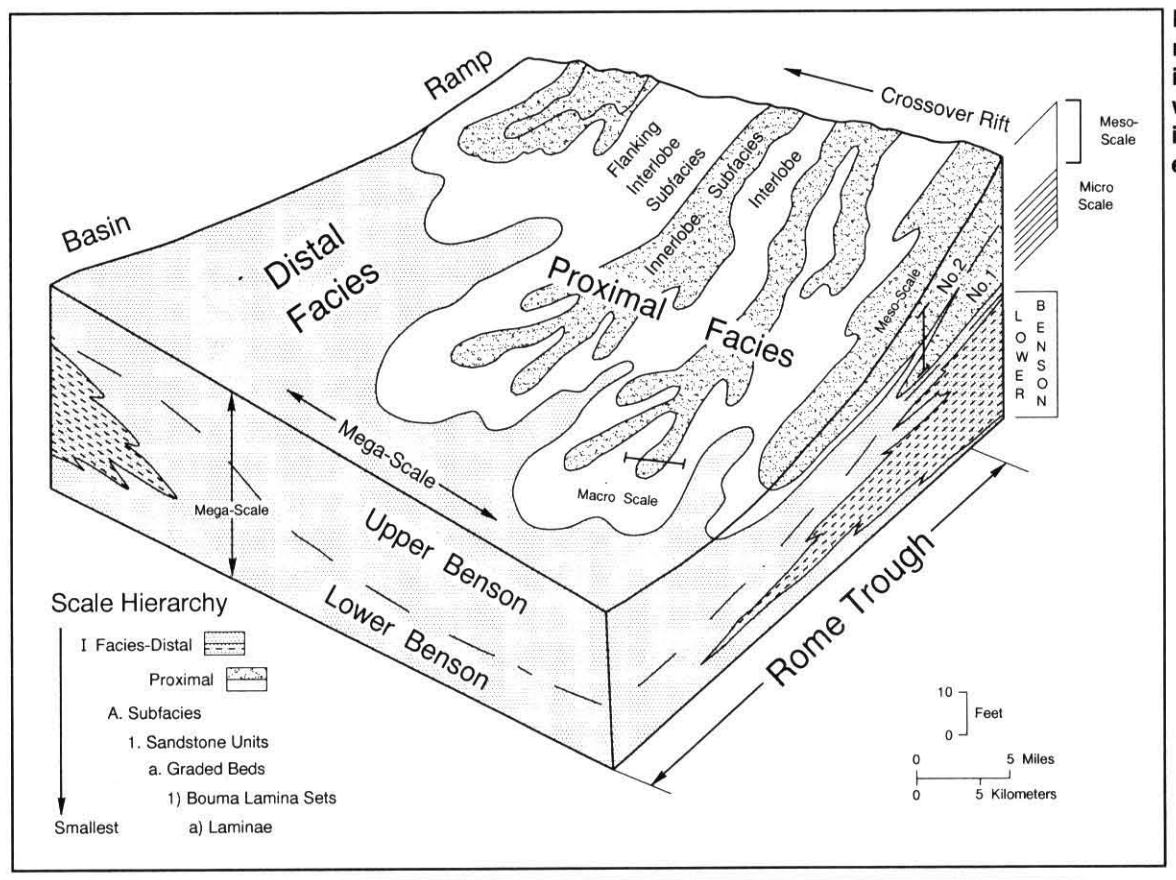


Figure Des-21. Model of the heterogeneities and spatial relations of the sandstone reservoirs in the Benson E-4 interval at different scales (between fields, between wells, and within wells). Subfacies dimensions are indicated in Table Des-3. See legend (below) for explanation.

SCALE	HETEROGENEITY IN INTERGRANULAR POROSITY

Mega — Between Fields
Facies:
1. Distal facies — sandstones and siltstones less than shales unless abundantly bioturbated.
2. Proximal facies — sandstones and siltstones dominant over shale interbeds, with recognizable Bouma structures and common bioturbation.

Macro — Between wells within field
Subfacies:
1. Subfacies of distal facies
   a. dominant shales basinward.
   b. abundantly bioturbated siltstones and sandstones of graded beds.
2. Subfacies of proximal facies — recognizable Bouma structures.
   a. inner lobe — sandstone and siltstone dominant in multiple graded beds; thickest sandstone units; channel-like.
   b. outer lobe — siltstones of multiple thin graded beds about equal to shale beds; levee-like.
   c. outer lobe (flanking outer lobe) — shales equal or greater than thin siltstones of multiple graded beds; bioturbation masks Bouma couplets.

Meso — Between wells within field and within well
A. Sandstone/siltstone units mainly of inner lobe subfacies of proximal facies or abundantly bioturbated siltstone subfacies of distal facies:
   1. sandstone units (siltstones included in unit) consist of multiple graded beds where sandstone or siltstone are dominant.
      a. upper Benson — sandstone units 1 (oldest) to 4 (youngest); usually one or two units per facies per well of proximal facies.
      b. middle Benson — sandstone unit d, found in eastern 30-field consolidated area, of distal facies.
      c. lower Benson — sandstone units a (oldest) to c (youngest) of distal facies.
B. Shale partings between graded beds — laminae sets.

Micro — Within well — laminae scale
Fabric of illite-rich, argillaceous and micaceous sandstones and siltstones (>18% matrix); average percent framework grains is 74%, with 5 to 15% porosity in pay-zone inner lobe subfacies.

eastern part of the area (Randolph, Barbour, and Upshur counties). The best Alexander production is in the western part of the 30-field consolidated area.

The organic-rich black shales, which intertongue with and mainly thicken west of Elk play sandstones and siltstones, are the source rocks. These shales are Late Devonian in age. Gas from the Fifth Elk (E-2) reservoir of the Council Run field in north-central Pennsylvania contains 98.4 percent hydrocarbon gases (95.1 percent methane) and 1.6 percent nonhydrocarbon gases (1.2 percent nitrogen). According to Laughrey (written commun., 1995), this thermogenic associated gas (isotopic composition) indicates a compositional change due to shallow migration and oil-associated methane. This methane was generated in the upper oil window during the principal phase of oil generation in the source rock. Within the Benson 30-field consolidated area of northern West Virginia, the Benson contains 99.3 percent hydrocarbon gases (83.3 percent methane, 10.9 percent ethane in Wilbur field; 87.9 percent methane, 7.9 percent ethane in Aspinall-Finster field) and 0.7 percent nonhydrocarbon gases (0.65 percent nitrogen in Wilbur field, 0.68 percent in Aspinall-Finster field), with Btu dry values of 1,183.3 and 1,127.9, respectively, for the Wilbur and Aspinall-Finster fields.

For the Benson (E-4), the immediately overlying Huron Member of the Ohio Shale (equivalent basal Riley shales mainly in productive area) represents a transgressive marine flooding event (Filer, 1994), which also serves as a reservoir seal.

The interpreted depositional environment for the multiple pays in the Benson 30-field consolidated area is slope turbidites and the lithologies are highly argillaceous fine-grained sandstones and siltstones. Depth to the multiple pay zones in the Benson 30-field consolidated area, in terms of average and range, are 4,750 feet, ranging from 3,666 to 5,041 feet for the Benson (E-4); 5,050 feet, ranging from 4,138 to 5,230 feet; and 5,350 feet, ranging from 4,600 to 5,500 feet for the Alexander (E-3) and uppermost Elk (E-2). The average pay thickness for the Benson is 11.4 feet, and ranges from 7.6 to 16 feet, although the completion thickness ranges from 6 to 39 feet with an average of 15 feet. The average completion thickness for the Alexander is 34 feet, and ranges from 4 to 72 feet. The Elk (uppermost E-2) completion thickness averages 196 feet and ranges from 6 to 465 feet. The average rock pressure for the Benson is 869 psi, ranging from 485 to 1,455 psi. The initial open flow for the Benson averages 273 Mcf/d and ranges from 10 to 1,400 Mcf/d for the 25 fields with data. The initial open flow for the E-2 Elk reservoir from five fields averages 586 Mcf/d, ranging from 58 to 1,439 Mcf/d. The final open flow for the Benson averages 1,243 Mcf/d and ranges from 446 to 2,116 Mcf/d. The final open flow for the Alexander averages 643 Mcf/d and ranges from 189 to 1,007 Mcf/d for 12 fields. The final open flow for the E-2 Elk averages 820 Mcf/d and ranges from 302 to 1,417 Mcf/d for nine fields. Table Des-3 indicates representative first-year production from cored wells of the upper Benson related to its three subfacies of the proximal facies: greater than 75 MMcf for inner lobe subfacies (channelized turbidity flow); 25 to 74 MMcf for outer lobe (levee); and less than 25 MMcf for the flanking interlobe subfacies.

Typical Benson reservoir rock in the 30-field consolidated area of northern West Virginia is coarse silt size (0.57 mm), containing greater than 18 percent matrix (mostly illite), 5 to 10 percent porosity, and permeabilities of 0.1 to 2.0 md (Table Des-1). Permeability from cores of the inner lobe subfacies decreases westward from 0.45 md at the Barbour No. 502 well to 0.1 to 0.356 md over a distance of about 12 miles. To the southwest, the permeability of the pay zone in the Braxton No. 1121 well decreases to 0.04 md. Calcite can account for 10 to 20 percent of some fine-grained sandstones. Throughout this consolidated field area, intergranular porosity is most important and is generally best developed in the thicker units.

Cheema (1977) described lateral changes in lithology for the Benson that correlated with gas production, concluding that the inner lobe subfacies of the upper Benson is the favored part of the reservoir. It is characterized by more than 10 feet of aggregate sandstone, more than 5 feet of pay zone, more than 75 MMcf of first-year production, and more than 0.4 gas production index (gas production index equals pay zone thickness multiplied by average percent porosity multiplied by percent gas saturation). The pay zone is that part of the sandstone/siltstone interval that has a bulk density of less than 2.55 g/cc on the formation density log and is water free (Cheema, 1977). Common practice for determining minimum reservoir thickness is 4 feet of 8 percent log porosity. Generally, a simple relationship exists between increased sand grain framework, decreased argillaceous matrix, and increased effective porosity. Heim (1987) also observed lower porosity where sandstones and siltstones are abundantly bioturbated and credited the higher porosity of the upper Benson compared with the lower/middle Benson to its lesser bioturbated nature.

The geometry and trend of the inner lobe subfacies controls heterogeneity within fields in the Benson 30-field consolidated area. These subfacies extend westward across the Benson 30-field consolidated area as multiple narrow belts. Figures Des-19, Des-20a, and Des-20b compare structural elements and subfacies trends, and the positive correlation between them indicates growing structures during sedimentation, which can be used as a strategy for exploration. For example, east of the Rome trough, the various belts of the inner lobe subfacies parallel the cross-over rift and West Virginia dome, but change to a northwest orientation upon crossing the eastern border fault of the Rome trough. Heim (1987) mapped five dip-oriented narrow lobes of thick upper Benson (greater than 20 feet, but including shale interbeds), which extend into the area above the Rome trough perpendicular to its eastern border fault.

Although thicknesses of upper Benson exceeding 20 feet (or more than 10 feet of aggregate sandstone/siltstone) commonly are important in the 30-field consolidated area for locating the good gas-bearing part of the Benson reservoir, fracture porosity slightly enhances the reservoir particularly within the area affected by the Weston cross-strike discontinuity, where the Weston-Jane Lew field occurs in Lewis County (Figures Des-2, Des-19); and near the western extent of Benson within the Wilbur field (Figures Des-3, Des-15, Des-19), where the Benson underlies a Big Injun/Keener storage field.

Cheema (1977) also reported the positive correlation between a highly radioactive sandstone bed within the productive inner lobe subfacies that occurs as a single bed (4 feet thick in the Barbour No. 502 well) (see Figure Des-3) in the eastern part of the Benson 30-field consolidated area, but is replaced by as many as three thin, highly radioactive beds in the west where multiple pay zones are present. Cheema surmised that, "after sand deposition, fluids containing radioactive material circulated preferentially through areas of thicker and more porous-permeable sands and left behind radioactive residues that now cause the hot streak" (p. 27). This positive correlation between gas production and presence of the highly radioactive thin bed can be used as a development strategy.

Heterogeneity of the Benson reservoir occurring between and within fields is related to changes in lithologic subfacies (inner lobe, outer lobe, and interlobe) (Figure Des-17a) and to discontinuity of the sandstone units (Figures Des-18, Des-20b). These factors probably account for several thin pay zones in a well. On a smaller scale, within a well, the thin shales that separate turbidite deposits can impede flow of gas. A model of the Benson reservoir depicting heterogeneity at different scales is presented in Figure Des-21 and Table Des-3.

The reservoir quality of the Elk slope turbidites (Benson, Alexander, and E-2 Elk) decreases along strike both north and south of the Benson 30-field consolidated area. Heim (1987) reported that the Benson thickens north of the productive area but low porosities render it nonproductive. Harper and Laughrey (1987) also noted the low porosity and permeability of the E-4 interval siltstones in Greene County, Pennsylvania (Figure Des-2). Here, the greatest gas production is from the margins of the turbidite slope deposits in the silt-laminated shales and interbedded burrowed claystones, where matrix porosity in the siltstone laminae ranges from 1.9 to 3.0 percent and matrix permeability ranges from 0.12 to 0.39 md. Fracture-enhanced porosity and permeability are as high as 4.2 percent and 1.18 md, respectively. Water saturation, measured by core analysis, ranges from 58.3 to 91.7 percent, indicating nonproductive quality in the upper range. Harper and Laughrey (1987) concluded that the channel-fill siltstones, unlike the comparable inner lobe subfacies of the Benson 30-field consolidated area, usually are nonproductive, with porosities of 2.0 to 3.0 percent (as high as 10 percent where fracture-enhanced), average permeabilities less than 0.02 md, and water saturations of 82 to 91 percent. Extensive calcite cementation is responsible for the reduction of porosity and permeability. Harper and Laughrey (1987) also considered the large amounts of clays present, including the highly expandable mixed-layer illite-smectite, a potential problem during development. They recommended foam fracs, although hydrofracturing of these reservoirs has been successful, because of their lower total liquid volume, low fluid loss, and additional driving force for fluid return to the wellbore. At best, the reservoir characteristics in the Greene County consolidated area are not as favorable as in the Benson 30-field consolidated area.

Three geological conditions are present where slope-turbidite reservoirs have demonstrated their best gas production: low calcite content in fine-grained sandstones and siltstones; high radioactivity in sandstone of pay zone; and underlying basement structures reactivated periodically during Elk sedimentation and its burial history. These conditions dominate within an area the size of the Benson 30-field consolidated area, although considerable variation in these attributes exists within it. Recognition of the inner lobe subfacies of the multiple dip-trending lobes in the upper Benson, for example, is important in reservoir development within the 30-field consolidated area.

Reservoir properties for Elk (E-2, Lock Haven Formation) shoreline sandstones are based on the productive Council Run field of Clinton and Centre

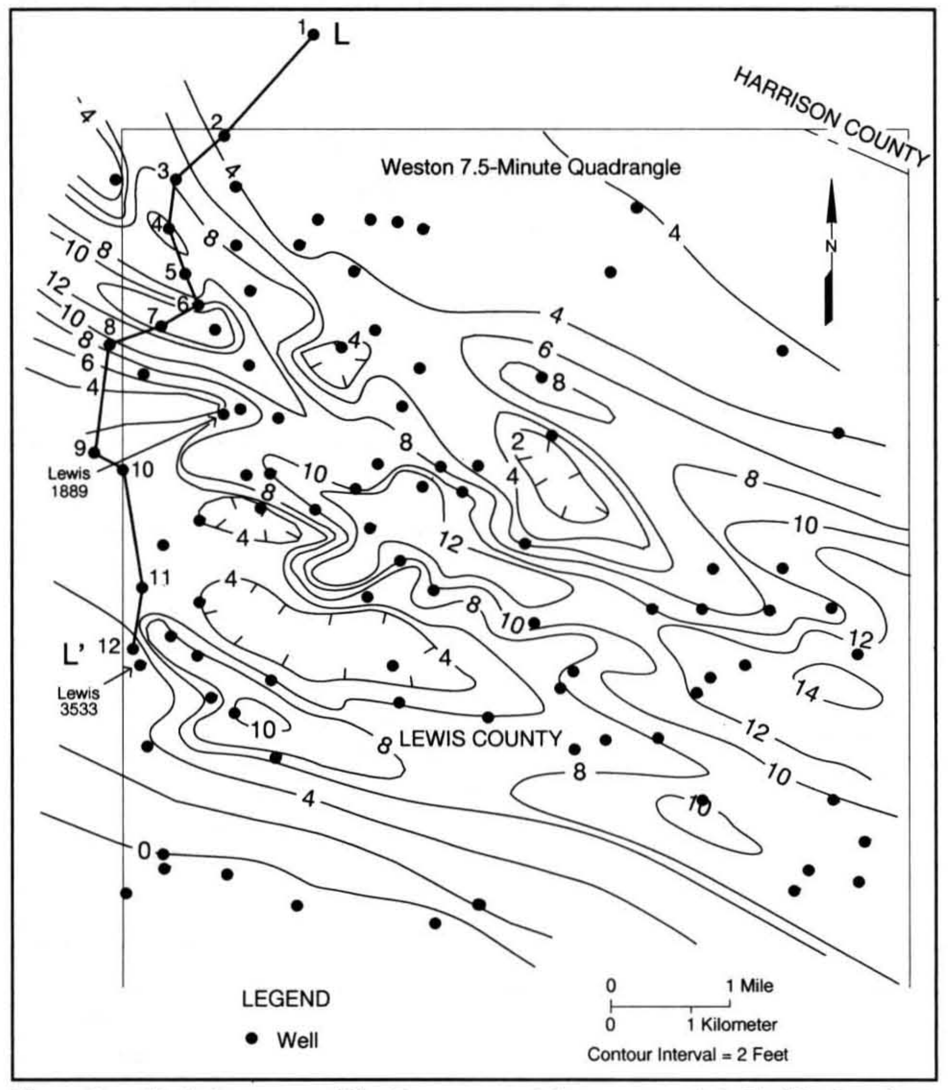


Figure Des-22. Net pay map of the Benson sandstone reservoir in the Weston-Jane Lew field, Lewis County, West Virginia. Location of productive trend occurs within the Weston cross-strike discontinuity in Figure Des-19.

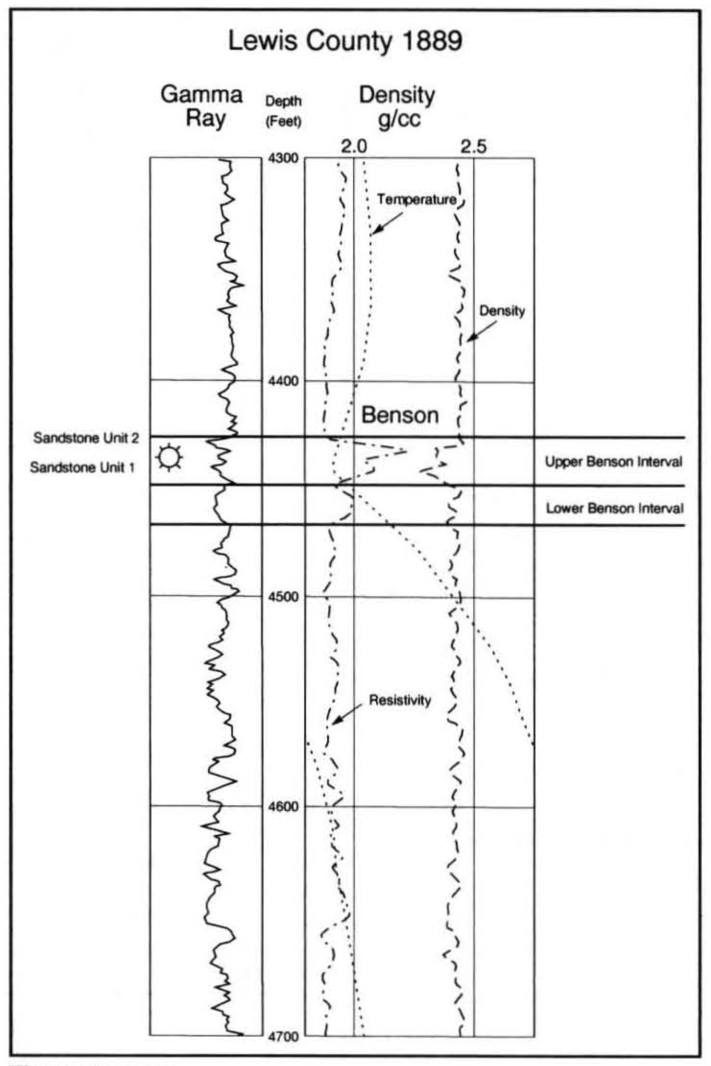


Figure Des-23a.

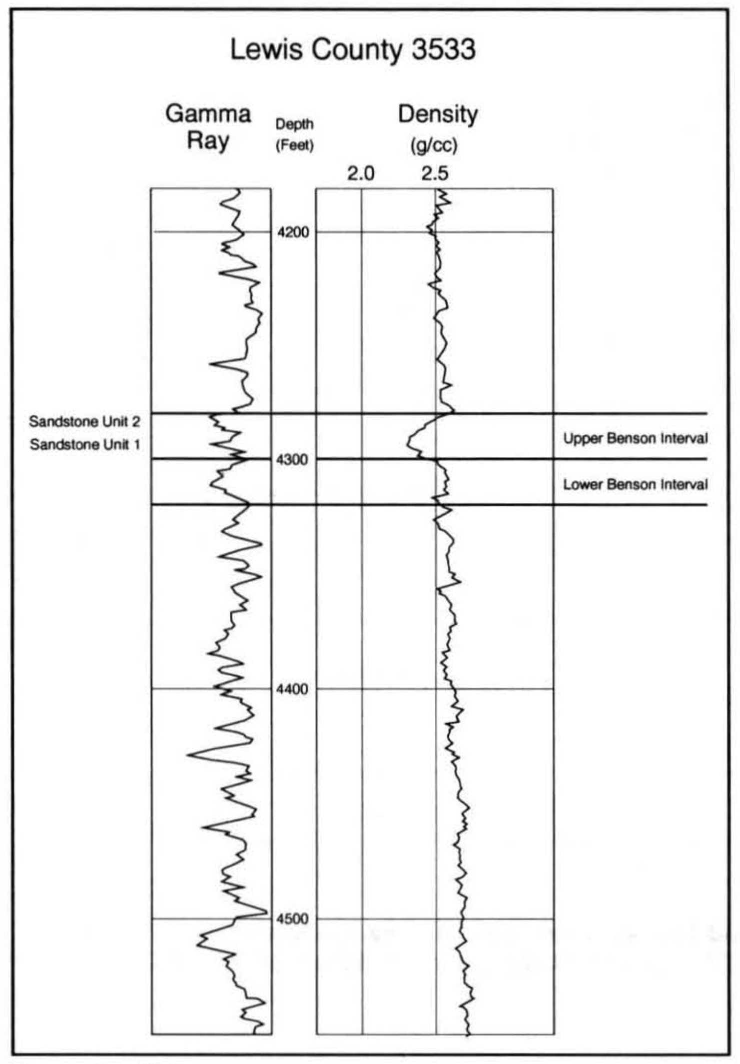


Figure Des-23b.

Figures Des-23a-b. Type logs of the Benson E-4 interval in the Weston-Jane Lew field, Lewis County, West Virginia. See Figures Des-22 and Des-24 for location.

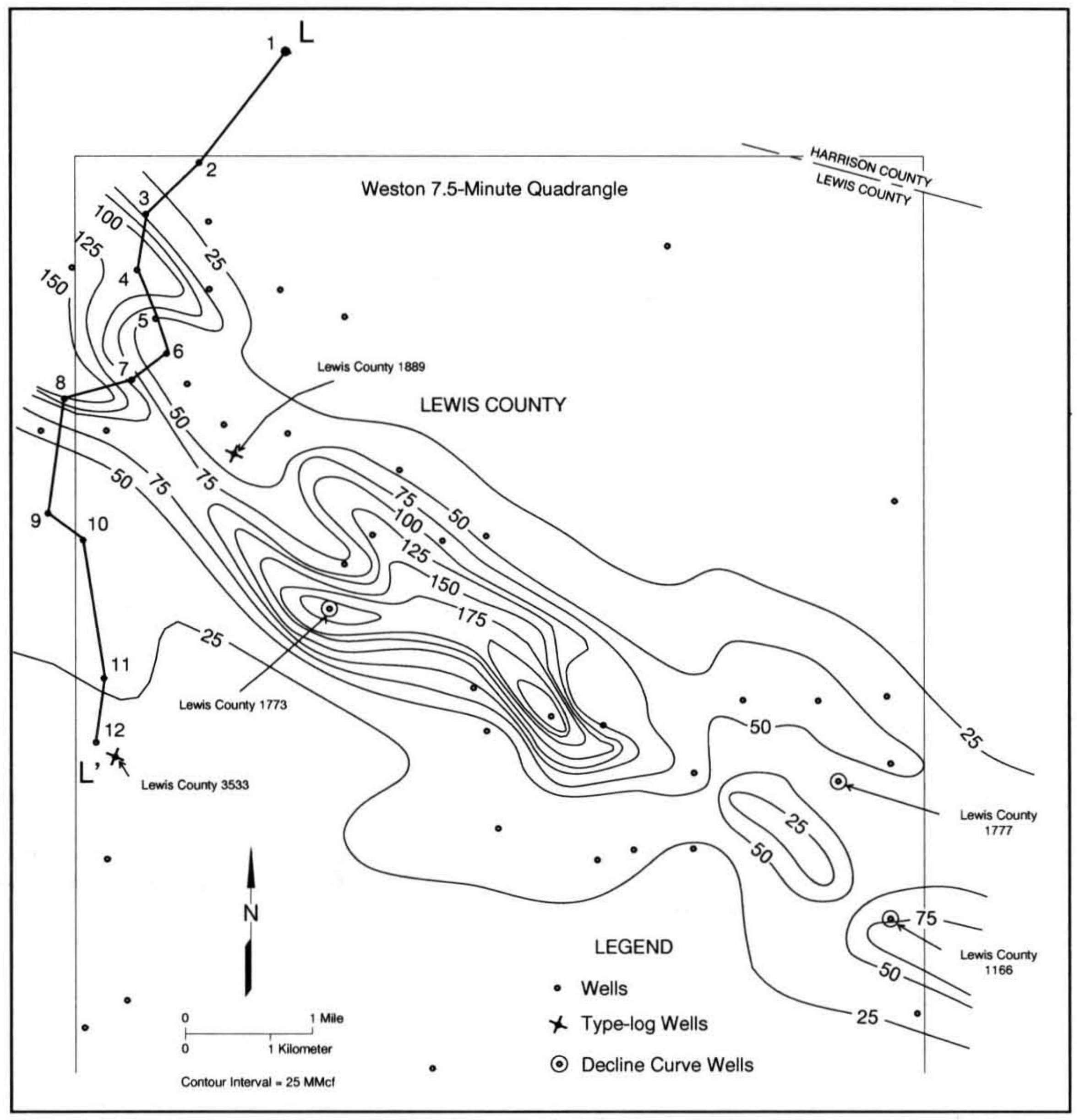


Figure Des-24. Isoline map showing the cumulative production for the first year from the Weston-Jane Lew field, Lewis County, West Virginia. Units are in MMcf. Locations of type-log wells in Figures Des-23a and Des-23b and decline curve wells in Figure Des-25 are shown.

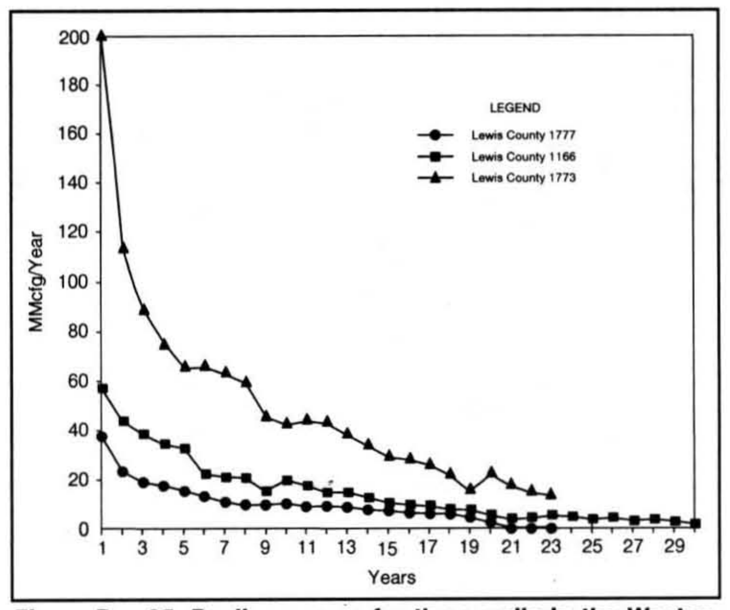


Figure Des-25. Decline curves for three wells in the Weston-Jane Lew field, Lewis County, West Virginia. Locations of wells are shown in Figure Des-24.

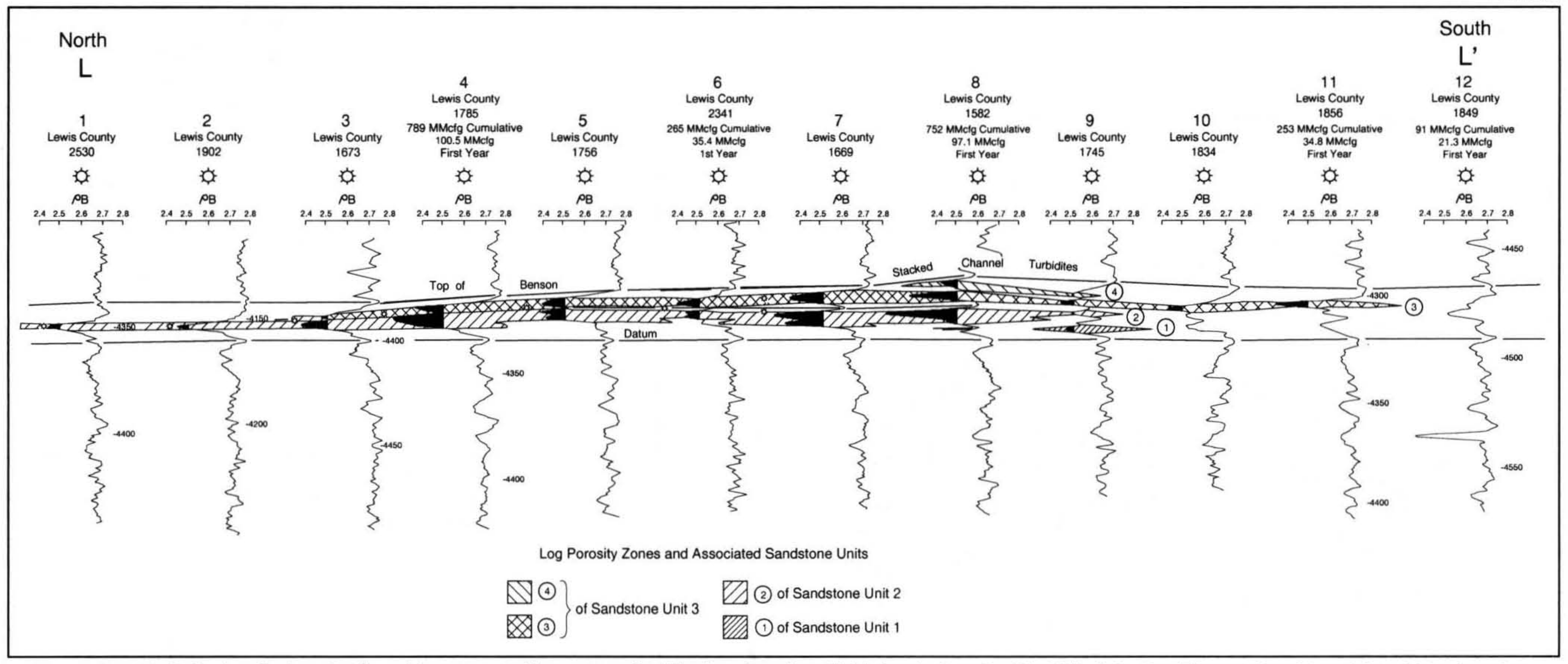


Figure Des-26. Bulk density log stratigraphic cross section across the Weston-Jane Lew field, Lewis County, West Virginia. See Figures Des-22 and Des-24 for location.

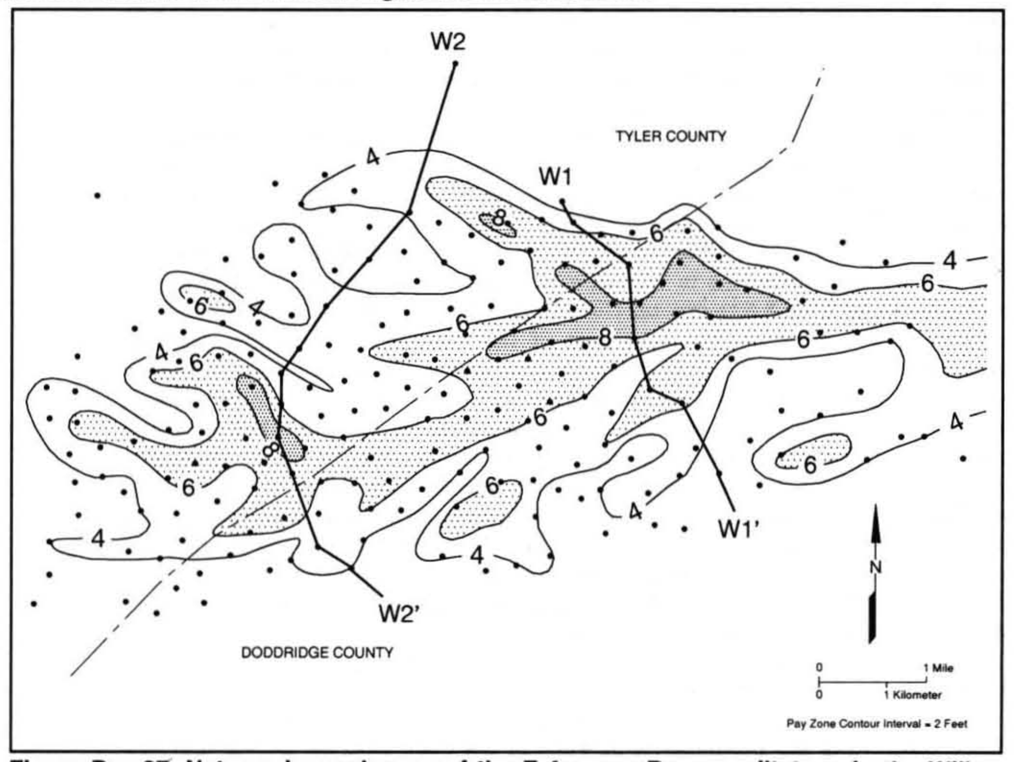


Figure Des-27. Net pay isopach map of the E-4 upper Benson siltstone in the Wilbur field, Doddridge and Tyler counties, West Virginia. Log density value of 2.55 g/cc approximates 8 percent porosity, with every 0.05 density decrease corresponding to an increase of 3 percent porosity (Schlumberger Log Interpretation Charts, 1989). Minimum reservoir thickness is 4 feet of pay zone of at least 8 percent porosity. Locations of cross sections W1-W1' (Figure Des-29a) and W2-W2' (Figure Des-29b) are also shown.

counties in north-central Pennsylvania as well as a laterally equivalent Elk sandstone (basal Foreknobs Formation of Greenland Gap Group) in the Accident field of Garrett County, Maryland (Follador, 1993), where it is nonproductive. Follador (1993) correlated this Elk sandstone of the Accident field to the Lower Jennings Conglomerate, exposed at Johnsburg, Pennsylvania, in nearby Somerset County. The Elk (E-2) shoreline sandstones of these two fields occur in a strike-trending belt, maintaining a relatively uniform thickness of 30 to 60 feet for miles along strike but thinning rapidly westward into marine shales. The sandstone ranges from fine- to coarse-grained, exhibits both sharp (interpreted as scour) and gradational basal contacts, and coarsening upward characteristics near the western limit. In both fields, the Elk (Fifth or Sixth) occurs between 4,000 and 5,000 feet below the surface. At Council Run field, the depth to the reservoir at the discovery well (No. 1 Centre County) is 4,600 feet, its pay thickness 36 feet, and natural open flow is 1.9 MMcf/d. Although called a stratigraphic trap, the porosity can be as high as 50 percent, where faults or fractures are suspected. Follador (1993) considered similar reservoir properties between the Elks of the Council Run and Accident fields. He suggested that the lack of gas production in the Accident field from the Elk might be from a significant decrease noted regionally in black shale source beds compared with the Council Run field area, and/or that thrust faults along the crest of the Accident anticline have broken the seal for the reservoir and allowed the gas to escape.

Description of Key Fields

Weston-Jane Lew field: Gas production from this field in northeastern Lewis County, West Virginia (Figure Des-3), began in the late 1800s from Upper Devonian Venango sandstones. By 1930, 27 Benson (E-4) wells had been drilled in the area. However, activity was slow through the 1940s and 1950s; it was not until effective stimulation methods could be employed that drilling began in earnest. In the 1960s and 1970s, nearly 250 Benson wells were drilled in the field (Table Des-2; Figure Des-3). At the time of this report, activity is again declining.

Data from more than 60 Benson gas wells in the Weston 7.5-minute quadrangle indicate a highly lenticular reservoir with west-northwest trend (Figure Des-22) that occurs within the inner lobe subfacies (Figure Des-17a) located along the Weston cross-strike discontinuity zone (Figures Des-19). The best reservoir quality is restricted to a highly complex belt that is roughly two miles in width. Porosity development is restricted to the uppermost sandstones within a larger siltstone package (Figure Des-23) of approximately 600-foot thickness, and values between 10 to 16 percent are common, yet the average is about 7 percent. Maximum pay thickness is approximately 15 feet, averaging 12.5 feet, and completion thickness averages 30 feet. Production is highly variable (Figure Des-24), and is distributed in a similar fashion with areas of higher pay thickness (Figure Des-22). Well lives in excess of 40 years are common, and very few wells last less than 20 years. Production decline curves from typical marginal, medium, and good wells (Figure Des-25) indicate that cumulative production of more than 500 MMcf is common for good wells and attainable for medium-quality wells. Log cross sections from the area show that porosity is developed in four separate, vertically stacked units within the three sandstone units recognized by Cheema (1977) (Figure Des-26). Each pay zone ranges from 2 to 8 feet in thickness. In general, the thickness of sandstone as read from the gamma-ray log increases toward the center of the productive belt and represents the inner lobe subfacies. In detail, there is no solid correlation between the occurrence of porous zones and log-interpreted decreasing shale content. In many cases, porous zones are represented by high gamma-ray reading relative to a clean sandstone reading. This high reading can be due to high-radioactivity zones (Figure Des-20) within the sandstones (Cheema, 1977). The porous zones generally correlate with the three sandstone units recognized by Cheema for this area. The correspondence between the producing trend and the sedimentation trend influenced by the Weston cross-strike discontinuity is significant (Figure Des-19) for the Weston-Jane Lew field and the main reason for its selection as a key field. Production from the Weston-Jane Lew field shows that highest gas production is associated with the proximal facies of a slope-apron turbidite of the upper Benson where overlapping of sandstone units 1, 2, 3 occurs within inner lobe subfacies (Figures Des-16, Des-17a, Des-18); and within the zone of the Weston cross-strike disconformity about where the cross-strike discontinuity meets the eastern border fault of the Rome trough (Figure Des-19).

Wilbur field: The Wilbur field, located in Tyler and Doddridge counties, West Virginia (Figure Des-3), was discovered in 1972 and developed largely by Stonewall Gas Company (now Dominion Appalachian Development, Inc.) since 1987. The field represents the distal (westward) margin (Figure Des-18) of Benson (E-4) production in northern West Virginia. The average depth to the top of the Benson reservoir is 4,900 feet. The 214 wells drilled into the reservoir delineate an east-west-trending digitate unit showing consistent westward bifurcation (Figure Des-27) of slope turbidite siltstones. Maximum pay thickness of 8 feet occurs in a single, siltstone-rich unit (Figure Des-28) within the center of the field, whereas the average pay thickness and average completion thickness are 6 feet and 15 feet, respectively. Two stratigraphic cross sections normal to the trend of the reservoir are presented in Figure Des-29. The narrow pay zone trends across fold axes (Figure Des-30) without obvious change in reservoir properties. Projecting 30-year well lives, the best cumulative production per well is 419 MMcf and the average is approximately 257 MMcf. An average upper Benson well in Wilbur field produced 96.5 MMcf in slightly less than four years with minor shut-ins, and its ultimate economic reserves are estimated at 278 MMcf over duration of 39 years. Its decline curve is similar to the decline curve of Lewis County well No. 1777 (Figure Des-25) in the Weston-Jane Lew field. Therefore, an average quality well in the Wilbur field compares with a marginal quality well in the Weston-Jane Lew field.

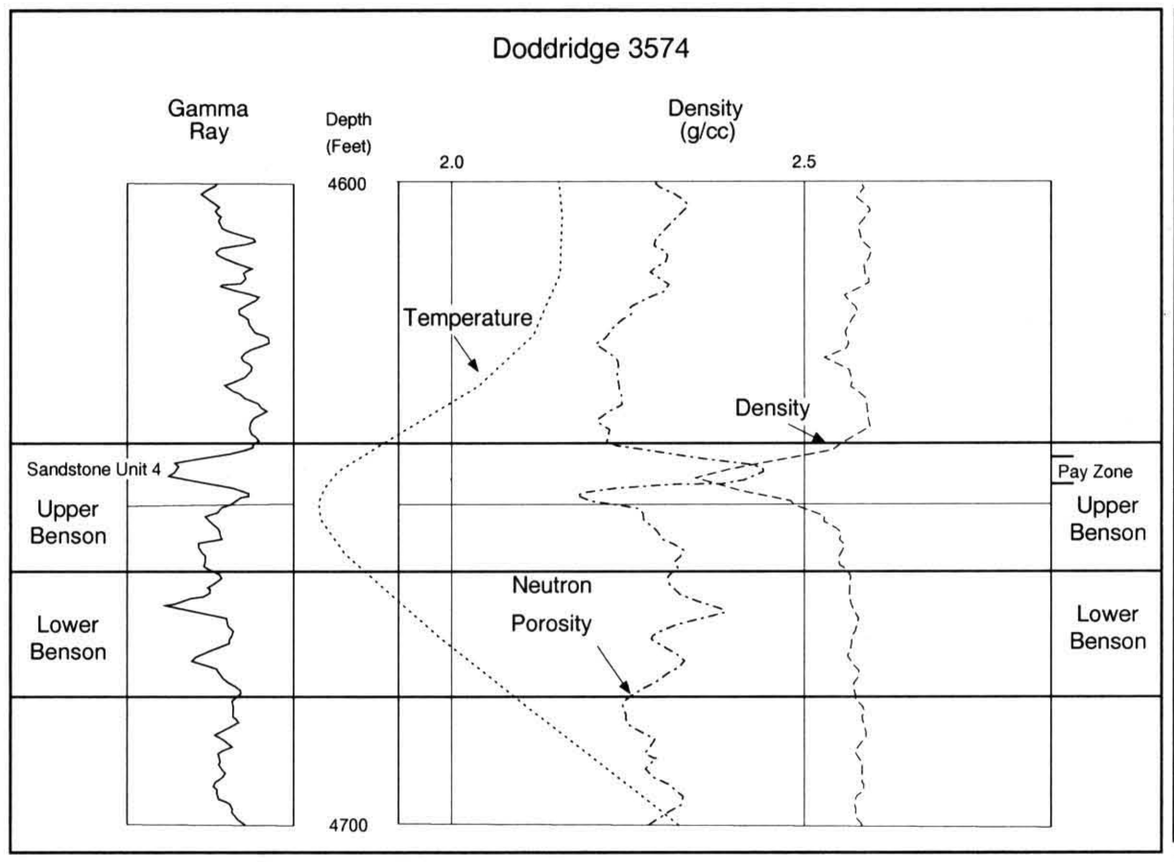


Figure Des-28a.

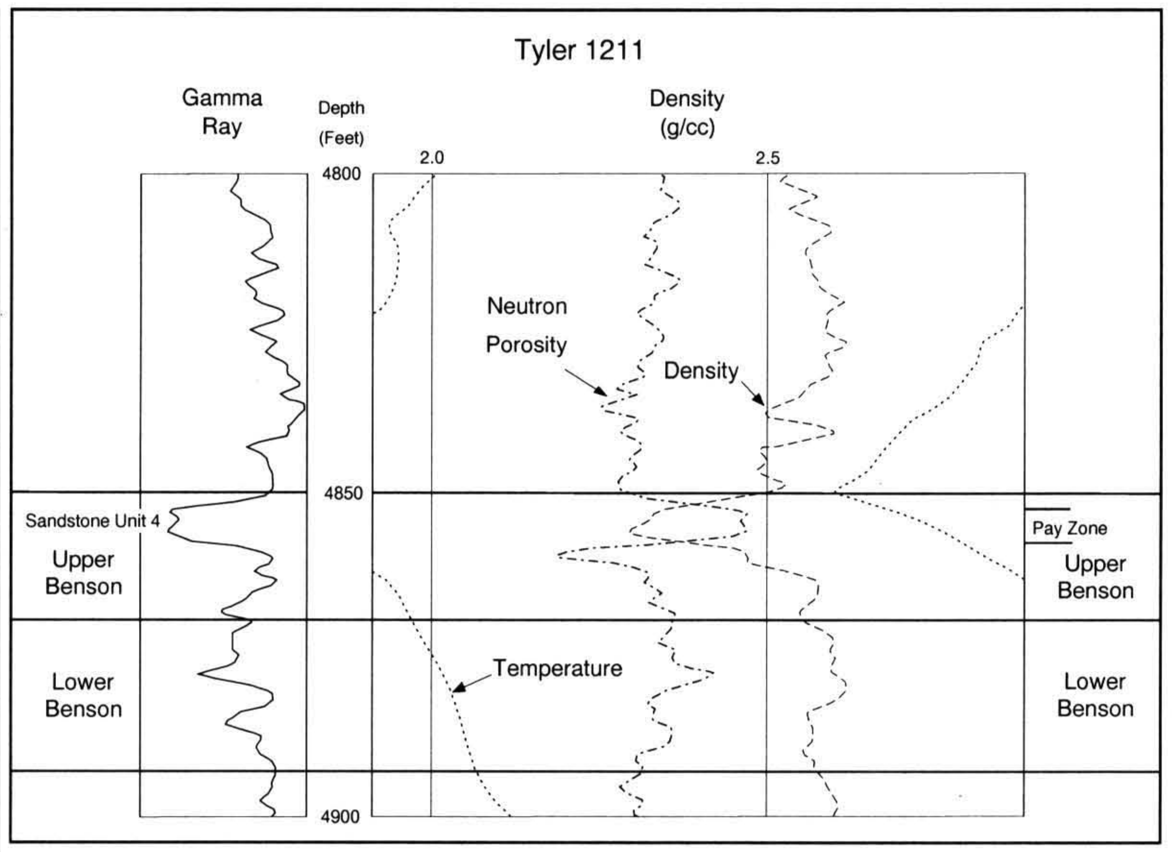


Figure Des-28b.

Figures Des-28a-b. Type logs of the E-4 upper Benson siltstone in the Wilbur field, Doddridge and Tyler counties, West Virginia, are located on profile W2-W2' in Figure Des-27 and located along W2-W2' in Figure Des-29b. Log of Doddridge County well no. 3574 shows 4 feet of pay zone, and the log for Tyler County well no. 1211 indicates 7 feet of pay zone.

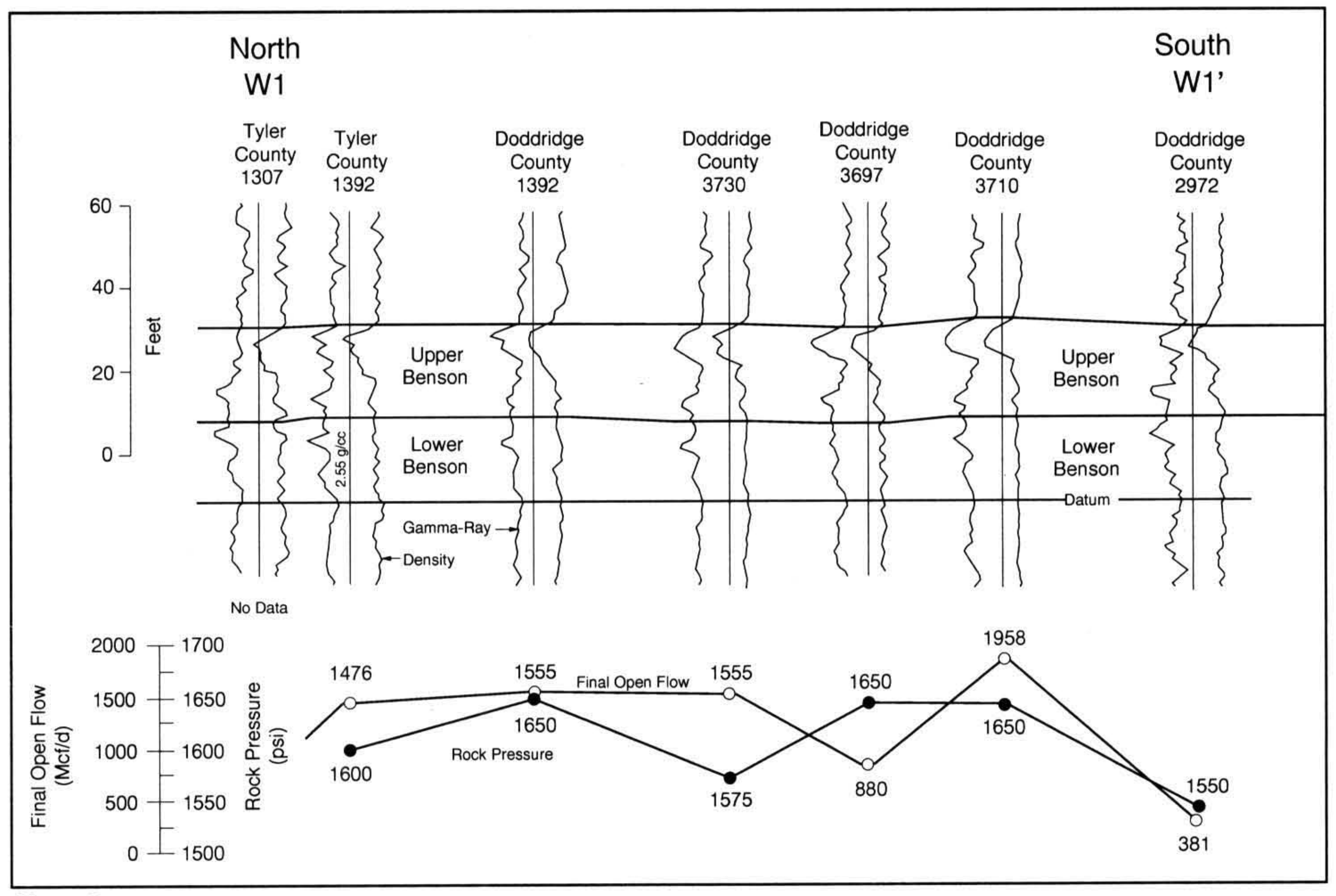


Figure Des-29a.

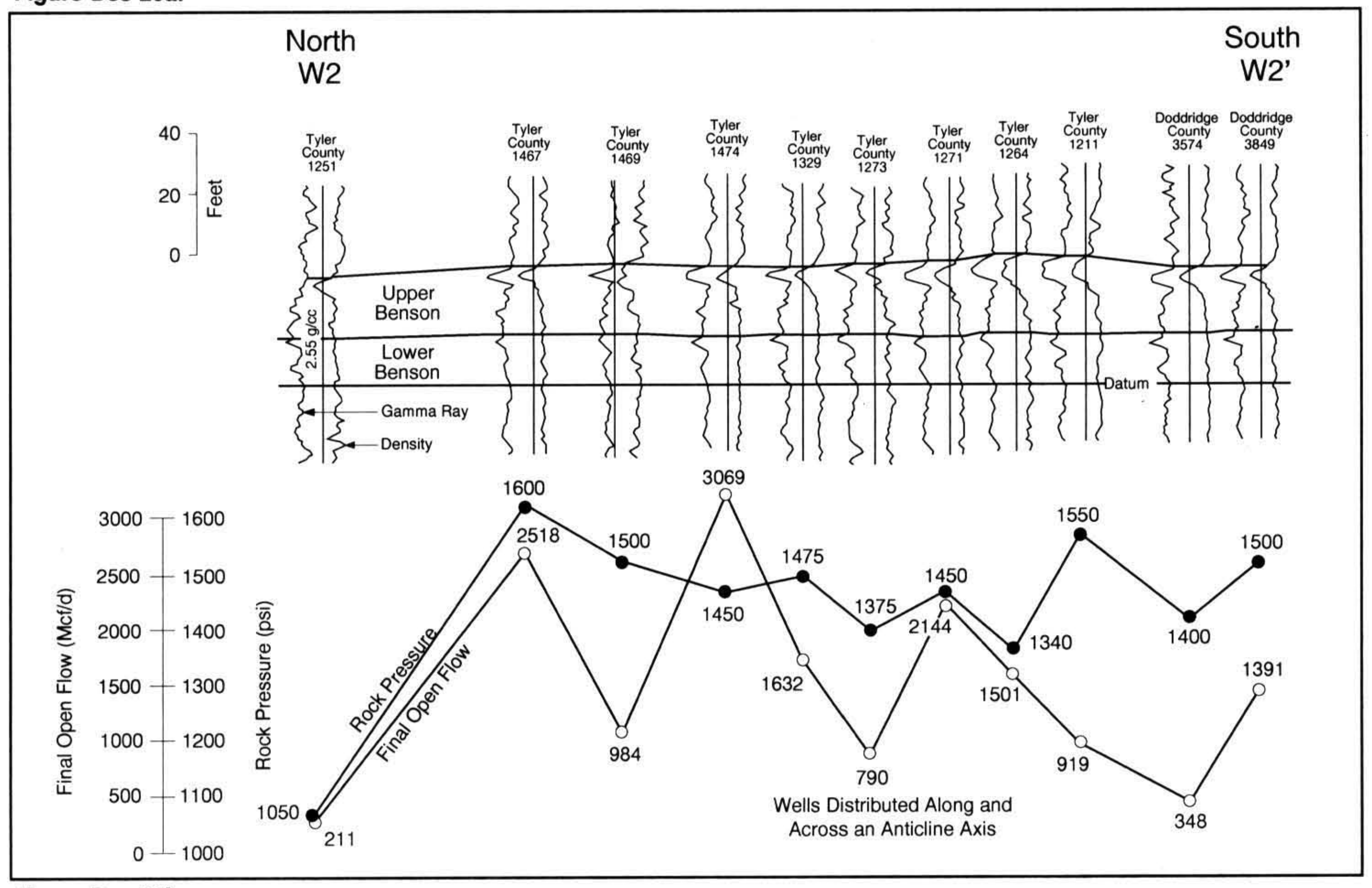


Figure Des-29b.

Figures Des-29a-b. Stratigraphic cross sections across the Wilbur field, Doddridge and Tyler counties, West Virginia, showing final open flow and rock pressure.

Council Run field: The Council Run field, located in Centre and Clinton counties, Pennsylvania (Figure Des-2), was discovered in 1982 when Eastern States Exploration Company drilled the Commonwealth of Pennsylvania, No. 1 Tract 231, penetrating 36 feet of E-2 Lock Haven sandstone at a depth of 4,600 feet. This field is located well to the east of any previous significant Upper Devonian sandstone production, and fueled considerable optimism for a new phase in Upper Devonian exploration.

The discovery well tested a natural open flow of 1,958 Mcf/d. Currently, the reservoir is delineated by 550 wells that encompass 18,800 acres. The reservoir rock, which crops out only 5 miles to the southeast of the discovery well, is designated the Fifth Elk sandstone (Figure Des-12) by the operator. Areally, the reservoir has an overall lobate shape with westward bifurcation (Figure Des-31). The average pay thickness is 23 feet and completion thickness is 64 feet. Log porosity ranges from 3.8 to greater than 50 percent (probably fractured), and the average is 9.1 percent. The best part of the reservoir is a single, massive sandstone (Figure Des-32) with complex internal variations in reservoir quality at the top of the Fifth Elk. Regional cross sections illustrate the rapid lateral thickness changes (Figure Des-33). Based on palynological and other data, the pay sandstone is interpreted by Eastern States Exploration Company geologists to have been deposited in fluvial point-bar deposits flanked to the north and south by crevasse-splay and similar units. Two stratigraphic cross sections across the field show the blocky gamma-ray signature of the Fifth Elk, the sharp base, and a general downward thickening observed in the central portion of the field (Figure Des-34). To the west, the reservoir facies grades into river-mouth-bar sandstones and offshore shelf sandstones and shales.

According to Eastern States Exploration Company geologists, the trapping method in the field is mostly stratigraphic. Natural fracturing occurs in certain locations, mainly along cross-strike discontinuities, but is generally not a major factor controlling the productivity of wells in the field. Diagenesis has played a significant role in porosity development, and natural fractures may have been important in allowing the delivery of mineral-rich fluids, as well as hydrocarbons, in and out of the reservoir. Dead oil has been observed in side-wall cores. Rock pressure ranges from 1,400 to 2,000 psi. Typical final open flow of gas is 8 MMcf/d from fluvial channel and river-mouth-bar facies, and 1.2 MMcf/d from flanking facies. Declines curves of selected wells, their net earnings, and payout are presented in Figure Des-35.

Resources and Reserves

According to Heim (1987), approximately 100 bcf of gas resources remain within the E-4 Benson sandstone and siltstone reservoirs in northern West Virginia. Resource and reserve estimates for the remainder of the Elk play are problematic.

An estimate of the sub-Benson in-place gas resources of the Elk play in northern West Virginia is based on the cumulative production to date from the overlying Benson and the authors' assumptions that the sub-Benson reservoirs are one-half the area of the Benson and are one-half as productive. The cumulative Benson production is approximately 3 tcf, 25 percent of which would yield about 750 bcf in-place for the sub-Benson reservoirs in northern West Virginia.

In Pennsylvania, the Benson (E-4) and the Alexander (E-3) of the Greene County Consolidated field are thought to have about 2 bcfg remaining in-place after producing an estimated 6 bcfg. The mature Council Run field and adjacent areas in Centre and Clinton counties have produced about 30 bcfg from the Elk sandstones of the E-2 interval. Assuming similar geology and production characteristics as in the Council Run area, it is estimated that an equal amount of gas, 30 bcf, can be produced from the Elk interval to the northeast along strike in Lycoming and Bradford counties, Pennsylvania.

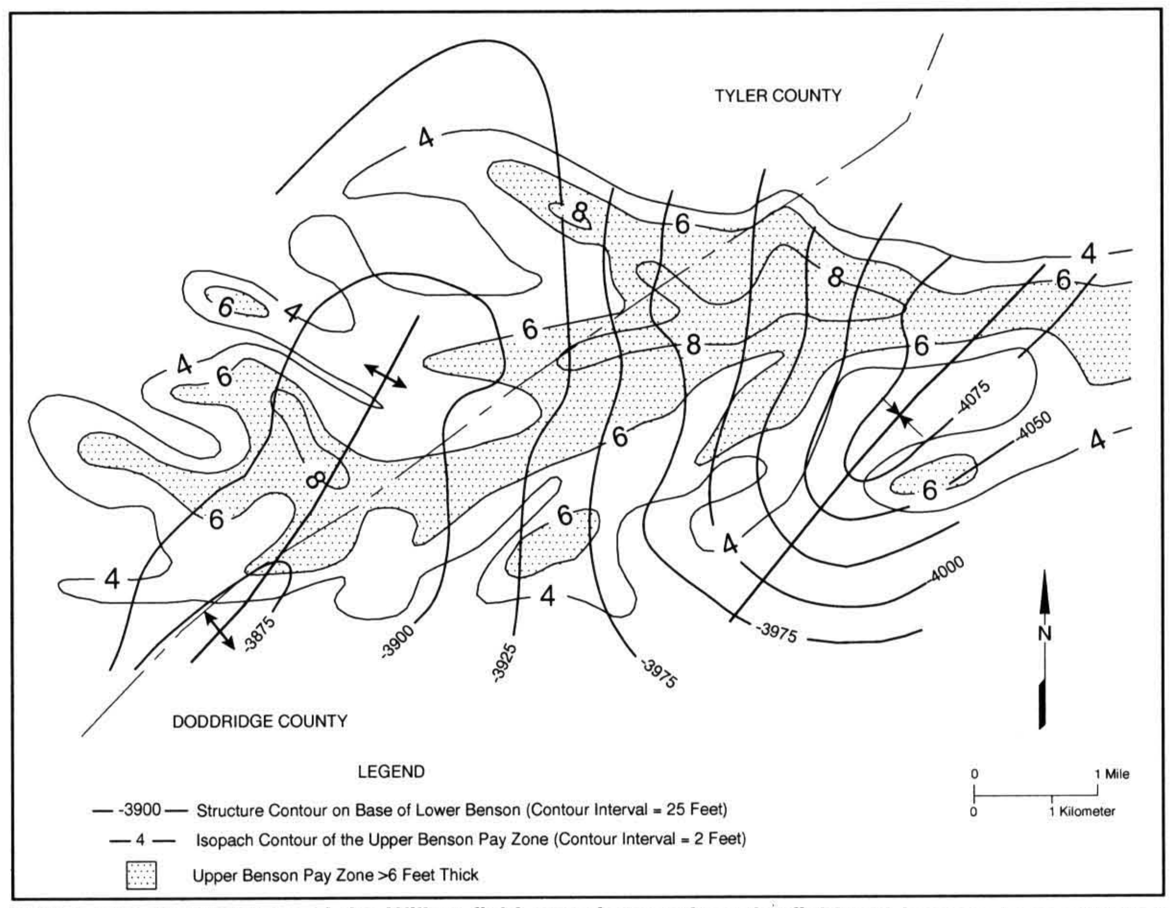


Figure Des-30. Structure of the Wilbur field superimposed on the field pay isopach map. Stippled pattern indicates the pay-zone thickness greater than 6 feet, and the 4-foot contour represents the outer boundary of the producing upper Benson reservoir.

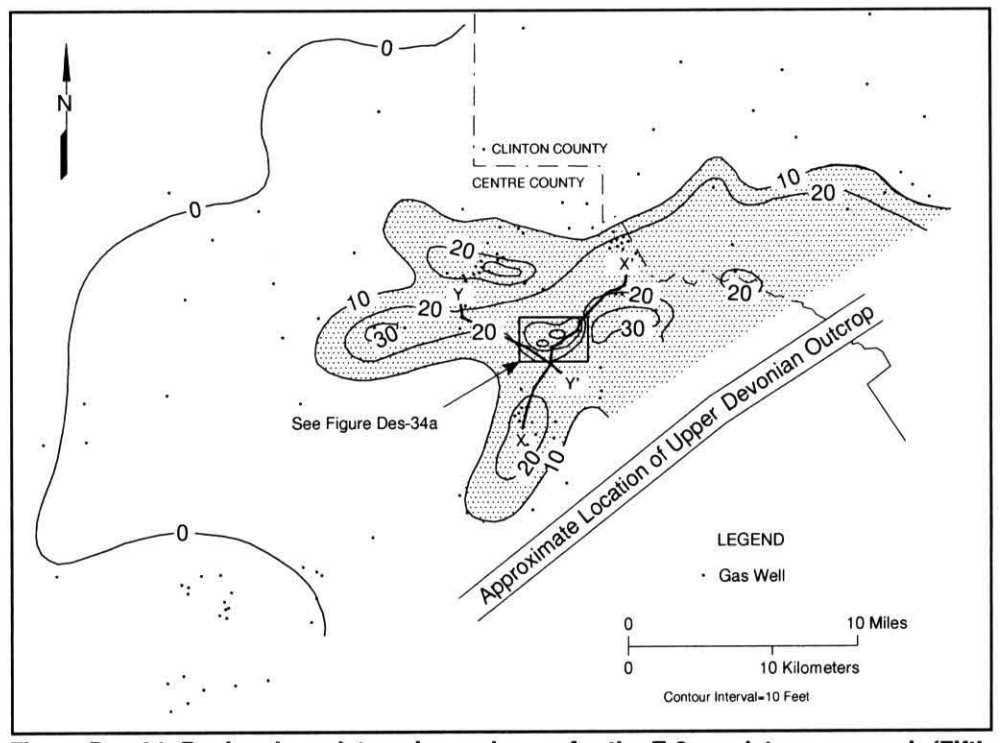


Figure Des-31. Regional sandstone isopach map for the E-2 sandstone reservoir (Fifth Elk of drillers) of the Council Run field, Centre and Clinton counties, Pennsylvania. Locations of cross sections X-X' and Y-Y' (Figure Des-33) are shown.

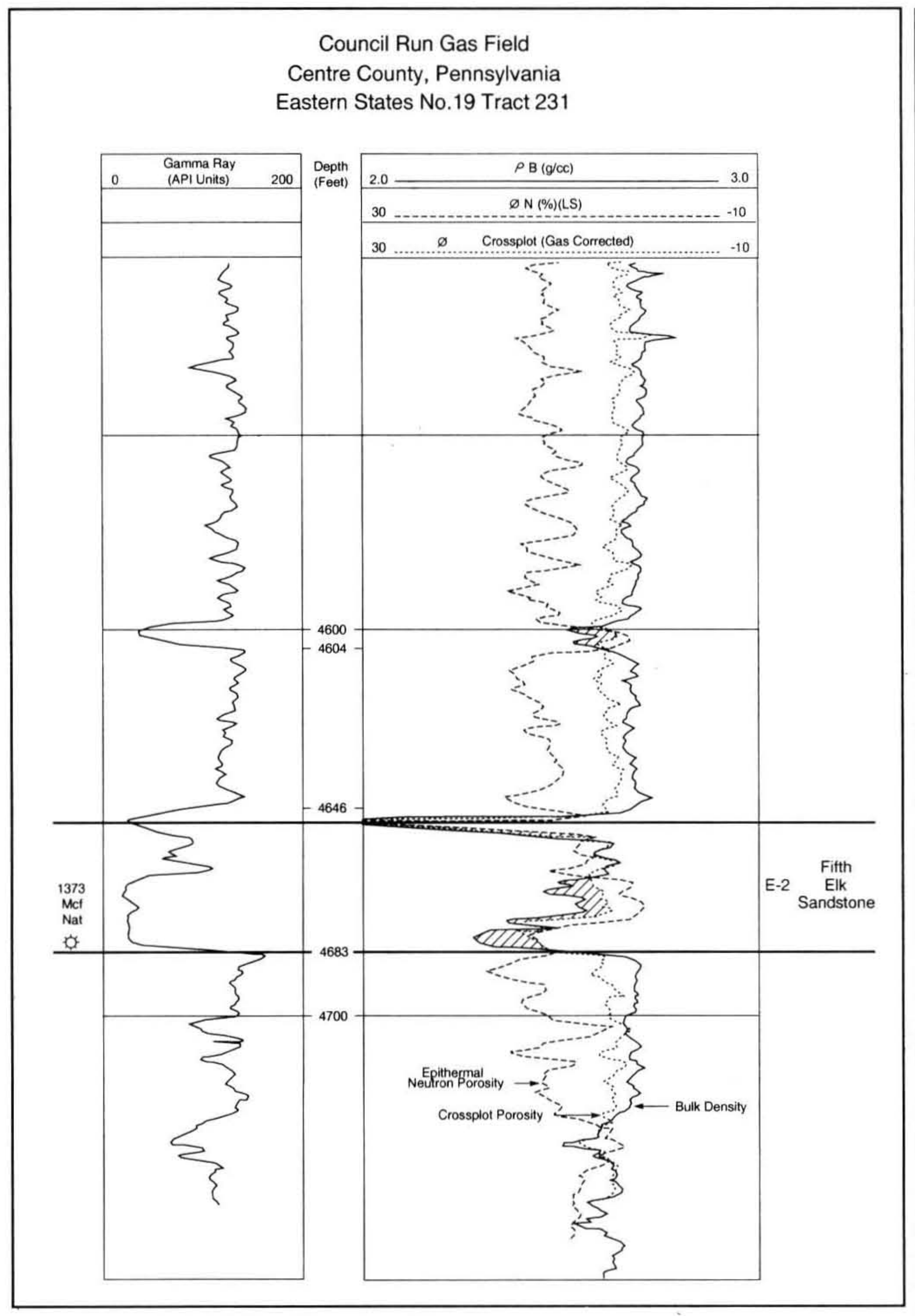


Figure Des-32a.

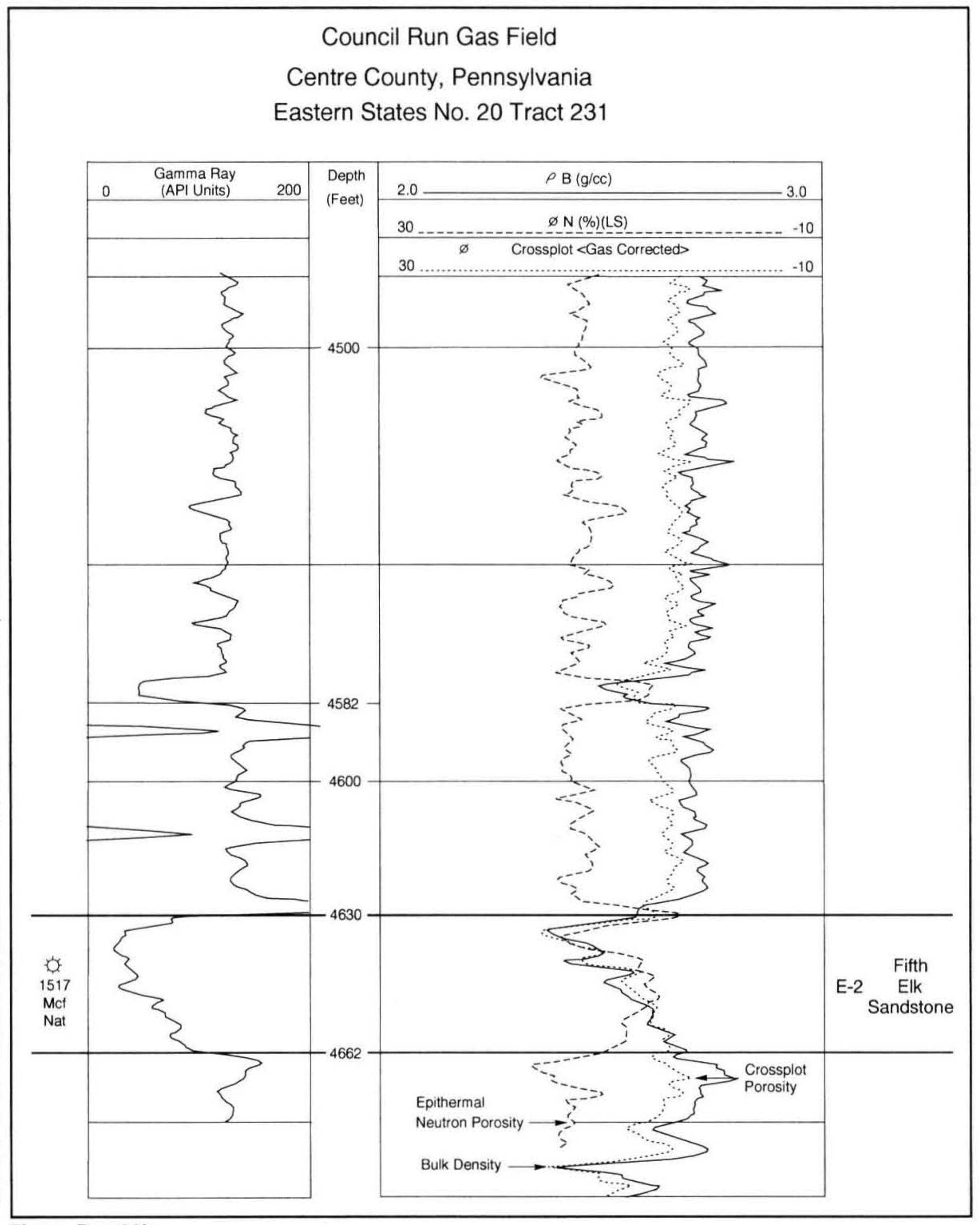


Figure Des-32b.

Figures Des-32a-b. Type logs for two wells in the Council Run field. See Figure Des-34a for location of wells.

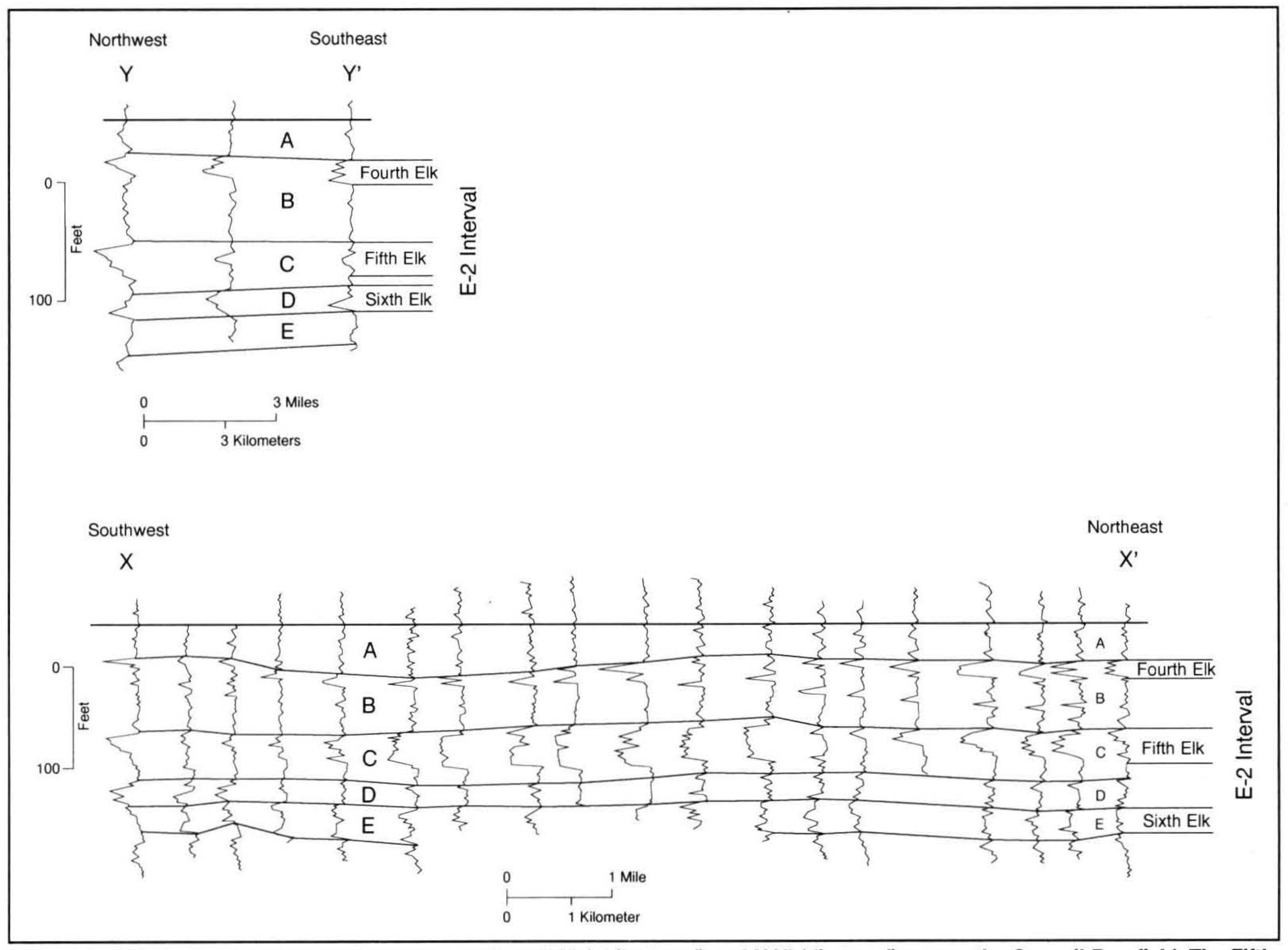


Figure Des-33. Regional gamma-ray log cross sections X-X' (strike trend) and Y-Y' (dip trend) across the Council Run field. The Fifth Elk is the main reservoir. See Figure Des-31 for location of cross sections.

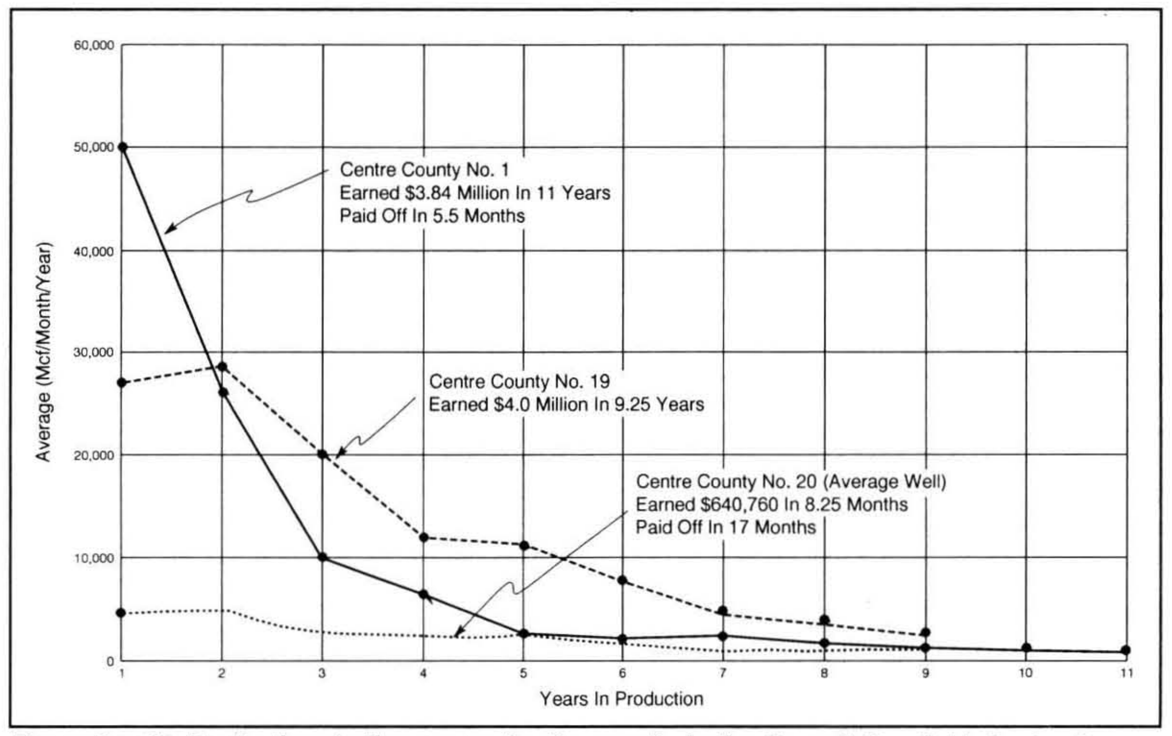


Figure Des-35. Production decline curves for three wells in the Council Run field, Centre County, Pennsylvania.

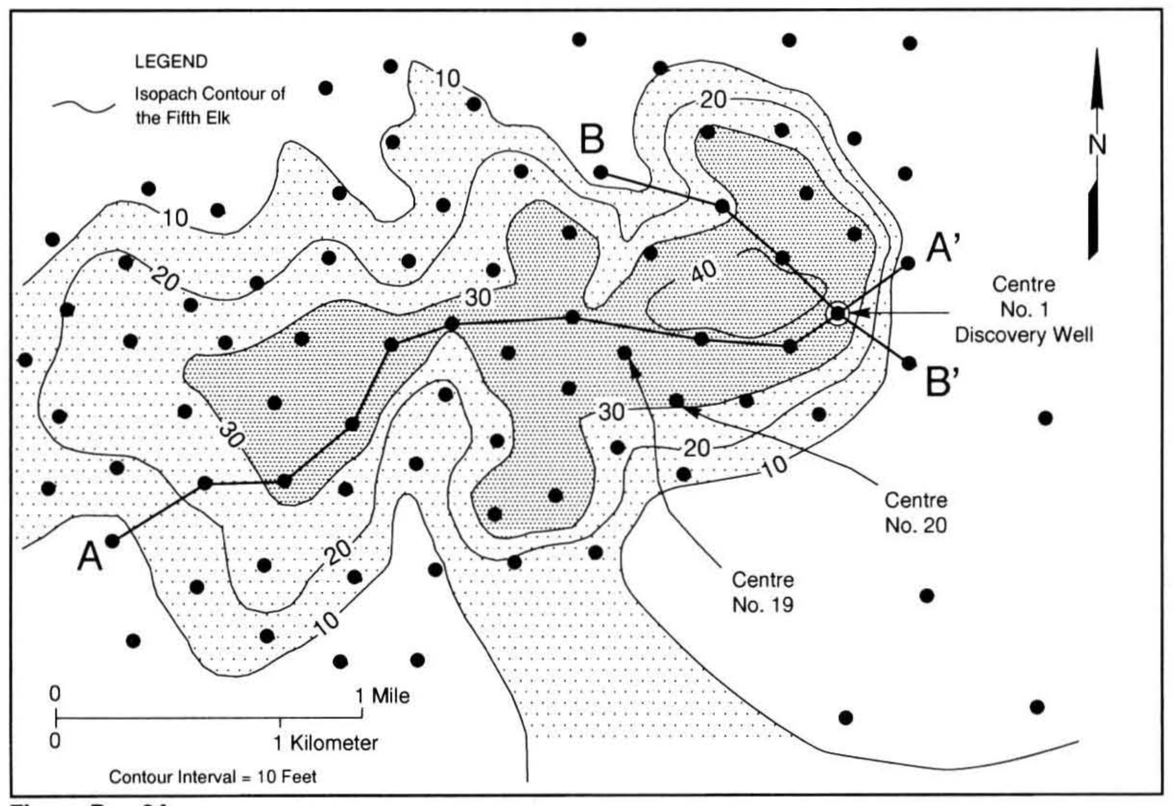


Figure Des-34a.

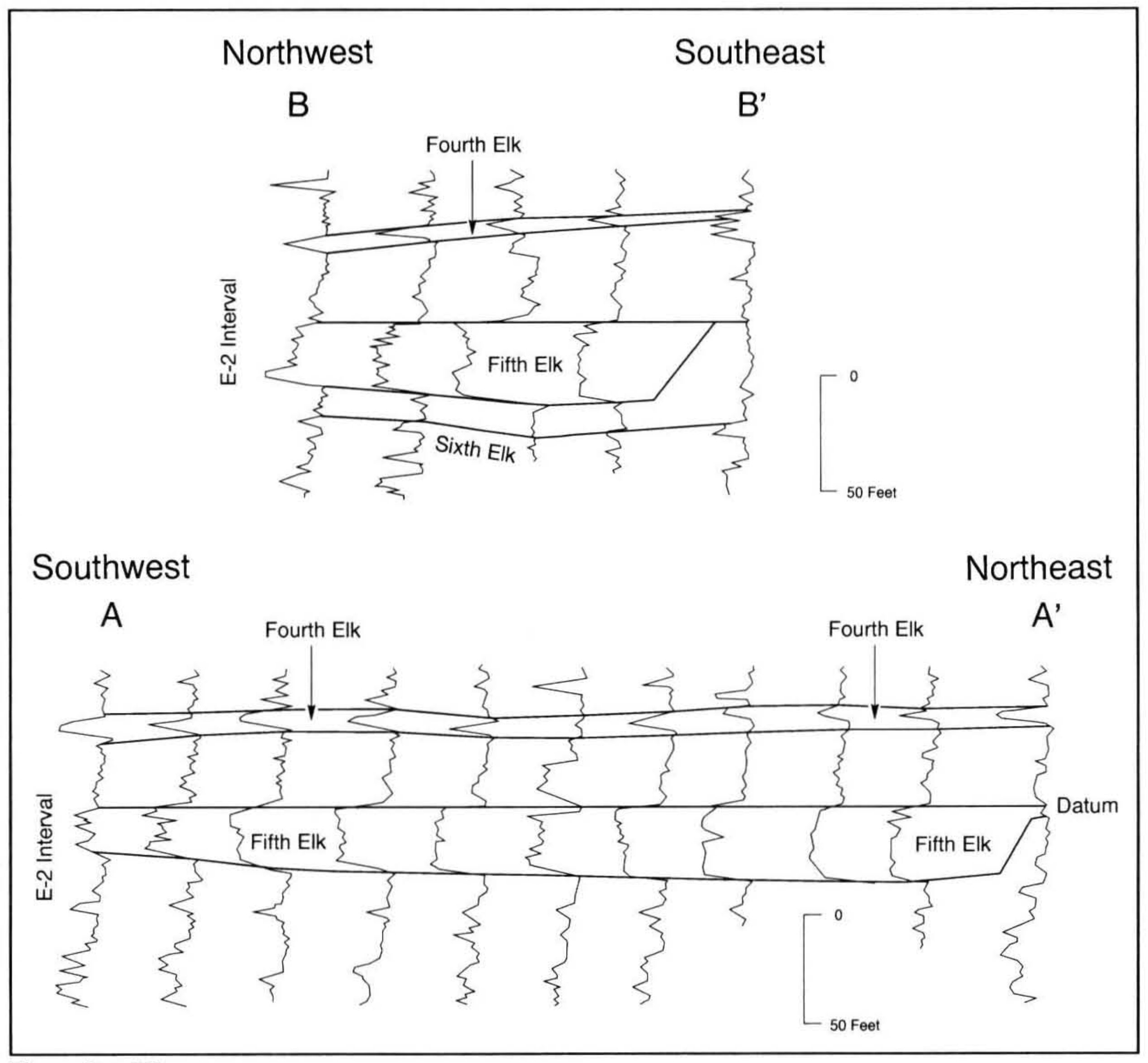


Figure Des-34b.

Figures Des-34a-b. Figure Des-34a. Isopach map of the Fifth Elk sandstone reservoir in the E-2 interval of the Council Run field, Centre County, Pennsylvania. Figure Des-34b. Gamma-ray log cross sections across Council Run field. The geometry of the Fifth Elk suggests a fluvial point-bar deposit. See Figure Des-34a for location of cross sections.

Future Trends

The Benson reservoir (E-4) is currently in a mature stage of development in West Virginia. Operators will likely continue to search for other, as yet undiscovered, porous zones in turbidite slope fine-grained sandstones and siltstones, both in E-4 (Benson) equivalents in Pennsylvania, and in older E-1 to E-3 units along its depositional strike throughout the basin. Also, operators will continue to search for comparable reservoirs consisting of E-2 shoreline sandstones and conglomerates similar to the Council Run field, both along strike in age-equivalent units and, perhaps, farther to the east in older shoreline units. The location of the Council Run field coincides with the position of the Snyder Lobe (Figure Des-7) of Willard (1934), indicating that prospects for exploration may occur northeast along strike (Wyoming Lobe in Lycoming and Bradford counties). To date, exploratory wells have been relatively few, partly because of low pipeline pressures and drilling logistics, and partly because the few wells also have been poor. However, additional drilling is warranted. To the southwest, gas production from correlative Elk sandstones in the Accident field, Garrett County, Maryland, is generally poor (Follador, 1993).

PLAY Dbg: UPPER DEVONIAN FRACTURED BLACK AND GRAY SHALES AND SILTSTONES

by Robert C. Milici, U. S. Geological Survey

Location

Natural gas and oil fields in the Upper Devonian fractured black and gray shales and siltstones play generally produce hydrocarbons from fractured gray and greenish-gray shales and siltstones that are interbedded with gray and black shales. This play is intermediate, both geologically and geographically, between the autogenic (self-sourced) fractured black and gray shale reservoirs of the Upper Devonian black shales play (R. Boswell, this atlas) to the west, and reservoirs that produce gas from the siltier and sandier delta front turbidite deposits of the Upper Devonian Bradford sandstones and siltstones play (R. Boswell and others, this atlas) to the east (Figures Dbg-1, Dbg-2a, Dbg-2b). In contrast with the gas produced from autogenic reservoirs of fractured shale in the Upper Devonian black shales play, much of the gas produced in this play appears to have migrated into the silty shale and siltstone reservoirs from the intercalated black shale source beds (Broadhead, 1993; Patchen and Hohn, 1993).

Over much of the central Appalachian basin, the boundaries among the Upper Devonian sandstones and siltstones plays, this play, and the Upper Devonian black shales play are defined by stratigraphic and geochemical parameters. By definition, this play occurs generally in a transition zone along the Catskill delta front, where basinal shale facies on the west interfinger eastward with delta front turbidites. Geographically, this intermediate zone may be defined approximately by using stratigraphic criteria. It lies generally between the easternmost limits of the Rhinestreet Shale Member of the West Falls Formation below, and the upper black shale unit of the Huron Member of the Ohio Shale above (de Witt and others, 1993) (Figure Dbg-3). Of the two, the eastern limit of the Rhinestreet Member of the West Falls Formation appears to constitute a practical eastern boundary for this play.

The boundary between this play and the Upper Devonian black shales play, however, cannot be defined adequately by using a single stratigraphic parameter. Therefore, the western boundary of this play in the Big Sandy area is defined by the relative mass of organic carbon, in kilograms per square centimeter (kg C/cm^2), in the Devonian shale section (Milici, 1993; Schmoker, 1993) (Figures Dbg-4a, Dbg-4b). The 0.8 kg C/cm^2 isoline of Schmoker (1993) separates the more productive black shale sequence in eastern Kentucky and southwestern West Virginia from the less productive interbedded gray and black shale sequence in the emerging area of west-central West Virginia and parts of adjacent Ohio. To the north, this isoline also divides the shoreline fields in two. For the purpose of this atlas, however, the play boundary is moved arbitrarily several miles to the west so that all shoreline fields may be discussed together as a part of this play.

The interbedded black shale and gray shale and siltstone reservoirs of the Lake Erie shoreline region (Figure Dbg-2a) (Broadhead, 1993) are more similar lithologically to reservoirs in the emerging area of Patchen and Hohn (1993) in west-central West Virginia and southeastern Ohio than they are to the predominantly black shale autogenic reservoirs of the Big Sandy gas field in eastern Kentucky and southwestern West Virginia. Nevertheless, the geologic controls and production characteristics of the shoreline fields are sufficiently different from those of the gas fields in west-central West Virginia (Table Dbg-1), so they will be considered herein as a subset of this play.

Thus defined, the Upper Devonian fractured black and gray shales and siltstones play encompasses a large area within the Appalachian basin in which the stratigraphy, thickness, organic geochemistry, and thermal maturity of the Devonian shale sequence ranges widely. The play is defined, however, by shale gas reservoirs that consist generally of fractured black shale source rocks that are interbedded with gas-producing gray shales and siltstones.

Production History

The first well dug specifically for natural gas in the U.S. was drilled in 1821 at Fredonia, on the banks of Canadaway Creek near the Main Street bridge, in Chautauqua County, New York. The well bottomed in the Dunkirk Shale Member of the Perrysburg Formation (Devonian) at a depth of 27 feet (Ashburner, 1886; Weeks, 1886; Orton, 1899; Van Tyne, 1983; de Witt and others, 1993). Initially, the well produced enough gas to light 30 burners and was sufficient to light an inn. The well was later drilled deeper, to about 70 feet, and produced enough gas to provide lighting for the streets and public buildings of Fredonia. Several more wells were drilled in the next few decades, and by 1880 the Fredonia Natural Gas Company was producing about 110 Mcfg each month (Ashburner, 1886).

This well, the initial discovery for the fields along the southern shores of Lake Erie, sparked a local interest in drilling for natural gas that spread episodically from Fredonia, New York, to Erie County, Pennsylvania, by 1860, and then into north-central Ohio to Lorain County by 1880 (Van Tyne, 1974; Janssens and de Witt, 1976; Piotrowski and Harper, 1979; Harper, 1980; de Witt, 1986). In populated areas, wells commonly were drilled closely together and much of the gas from these shallow, low-pressure, low-yield wells was used domestically (Janssens and de Witt, 1976).

There is little specific production data for the early wells in the shoreline fields. Janssens (1977b), however, reported gross statistics for shale gas production in Cuyahoga County, Ohio, for the years 1911 to 1915. In 1911, 609 wells produced 116 MMcf, averaging 190 Mcf per well; in 1912 and 1913, 578 wells produced 96.9 MMcf, averaging 168 Mcf per well; and in 1914 and 1915, an estimated 567 wells produced an estimated 101 MMcfg annually, averaging 178 Mcf per well.

According to Van Tyne (1983), most of the 300 or more wells that produced gas from the Dunkirk Shale Member in the shoreline region of New York were drilled in the late 1800s and early 1900s. Of the eight shale gas fields that had been discovered in New York between 1821 and 1964, only the Naples, Dansville,

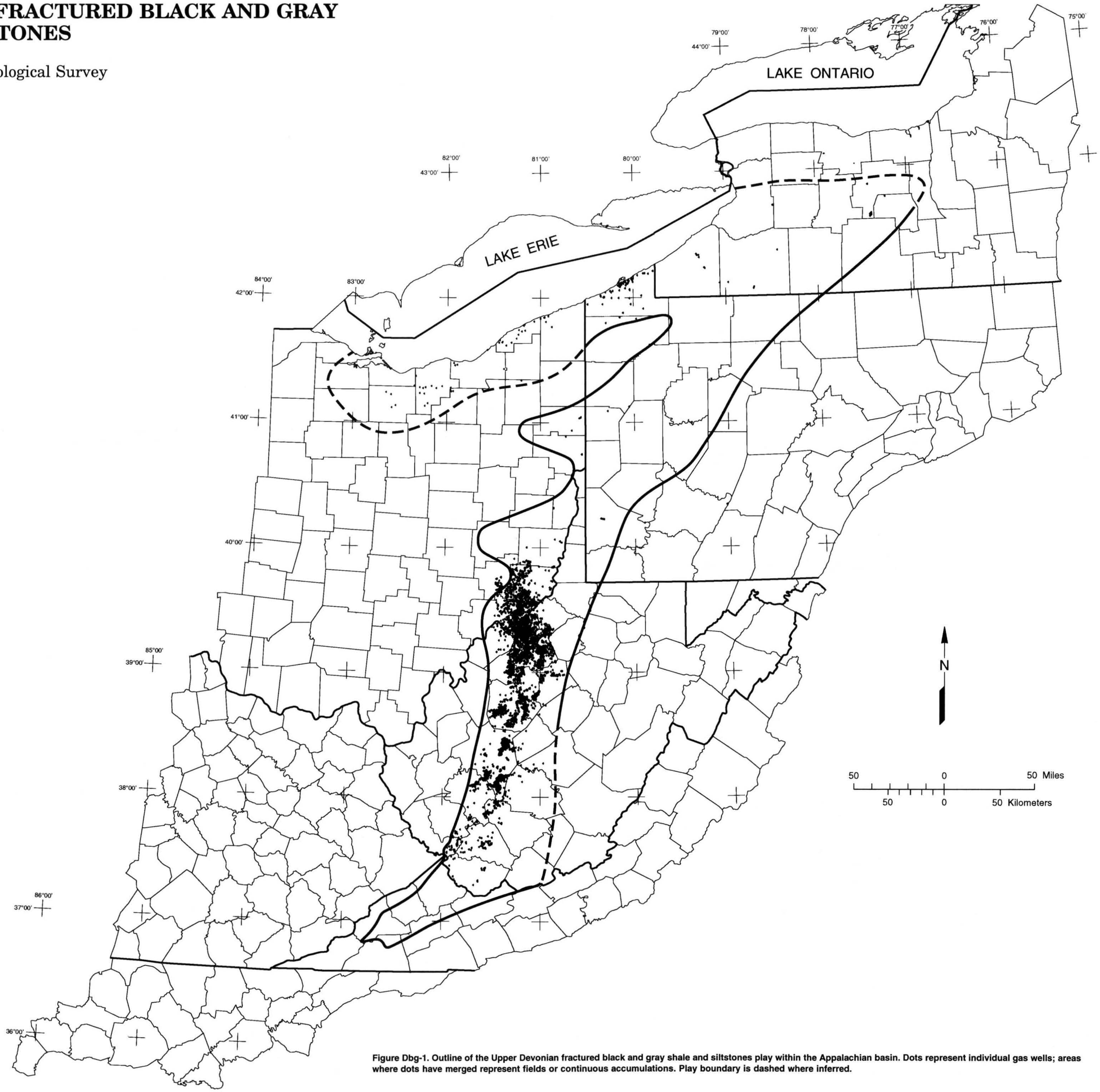


Figure Dbg-1. Outline of the Upper Devonian fractured black and gray shale and siltstones play within the Appalachian basin. Dots represent individual gas wells; areas where dots have merged represent fields or continuous accumulations. Play boundary is dashed where inferred.

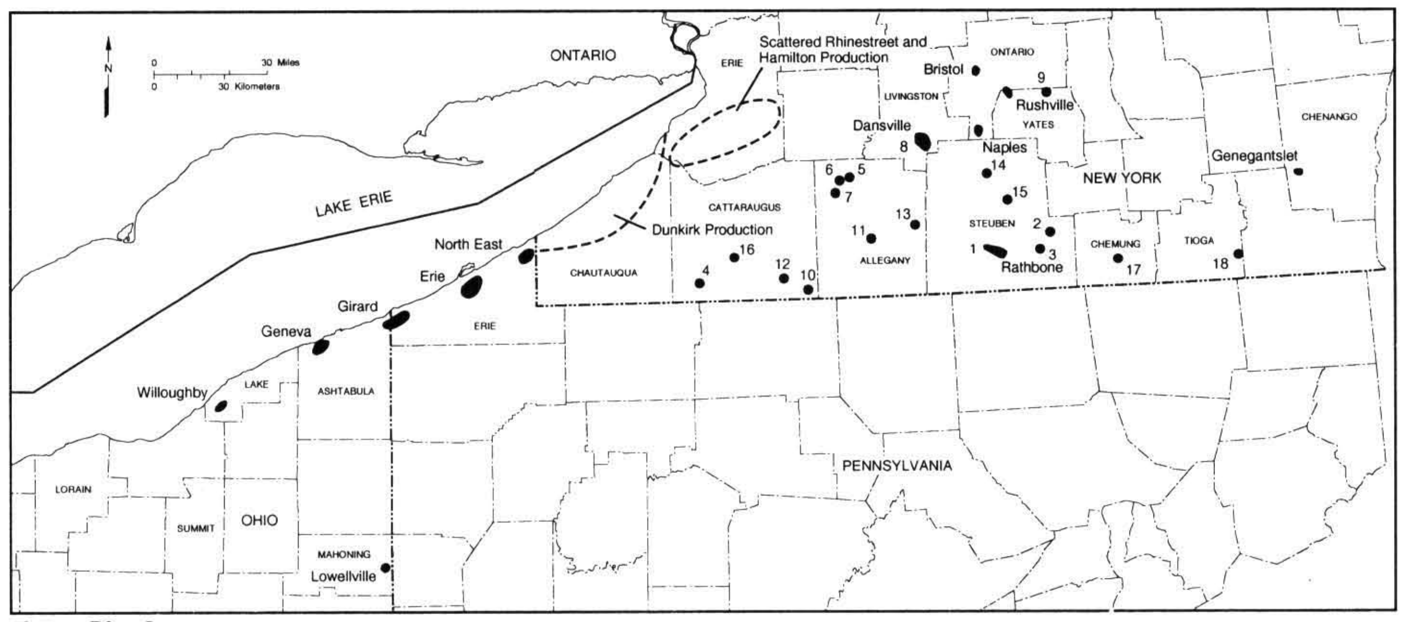


Figure Dbg-2a.

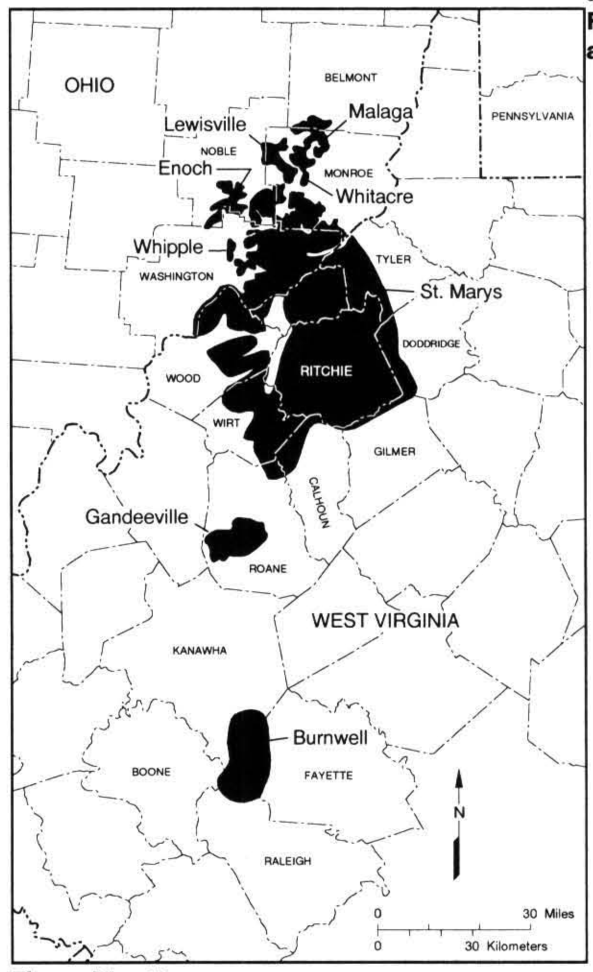


Figure Dbg-2b.

Figures Dbg-2a-b. Location of fields and boundaries mentioned in text or in Table Dbg-1. Figure Dbg-2a. Fields along shoreline of Lake Erie and western New York. Numbers refer to wells listed in Table Dbg-2. Figure Dbg-2b. Fields and continuous accumulations in the emerging area of Ohio and West Virginia.

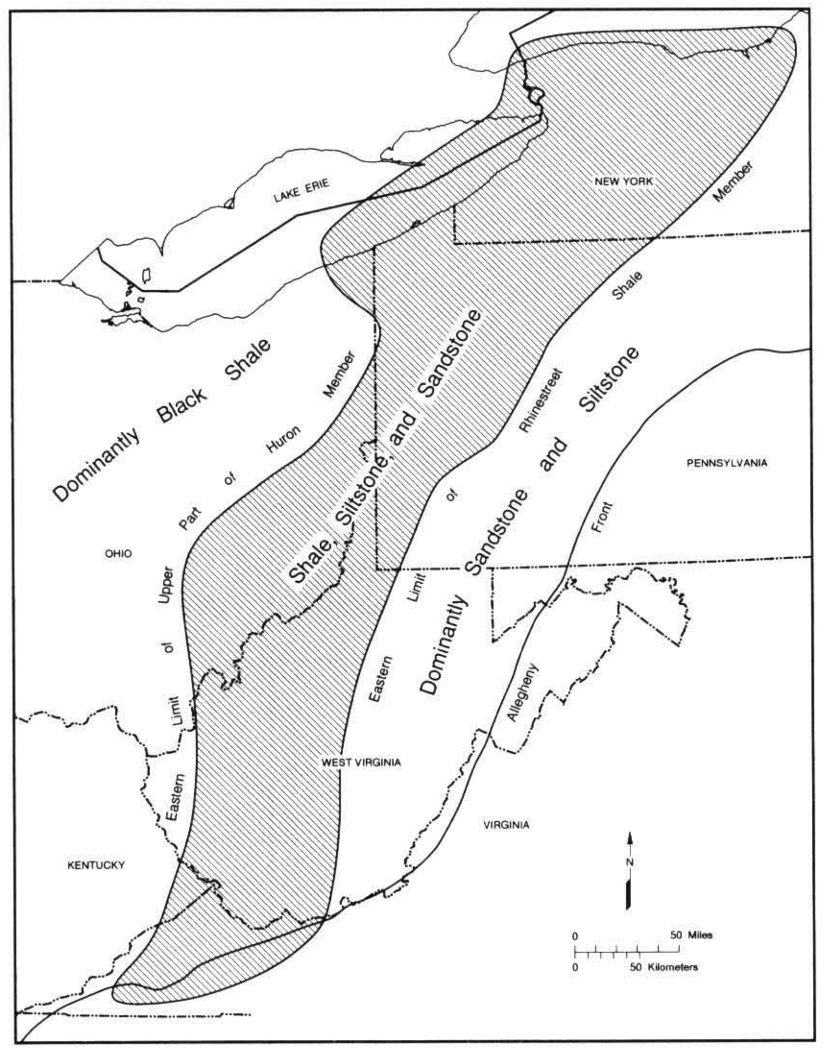


Figure Dbg-3. Generalized facies map of the Devonian shale sequence in the Appalachian basin.

TABLE Dbg-1	Burnwell WV	Burnwell WV	St. Marys WV	St. Marys WV	Gandeeville WV	Gandeeville WV	Gandeeville WV	Burnwell WV	St. Marys WV
BASIC RESERVOIR DATA									
POOL NUMBER	47262813	47262404	470077404	470077813	47371404	47371813	47371	47262	47077
DISCOVERED	1981	1976	1968	1968	1981	1952	1952	1976	1968
DEPTH TO TOP RESERVOIR	4,670	3,461	2,673	3,638	2,910	4,043	3,608	3,914	3,530
AGE OF RESERVOIR	Upper Devonian	Upper Devonian	Upper Devonian	Upper Devonian	Upper Devonian	Upper Devonian	Upper & Middle Devonian	Upper & Middle Devonian	Upper & Middle Devonian
FORMATION	Ohio Shale	Ohio Shale	Ohio Shale	Ohio Shale	Ohio Shale	Ohio Shale	Ohio Shale Hamilton Group	Ohio Shale Hamilton Group	Ohio Shale Hamilton Group
PRODUCING RESERVOIR	Lower Huron	Upper Devonian undifferentiated	Upper Devonian undifferentiated	Lower Huron	Upper Devonian undifferentiated	Lower Huron	Upper Devonian Marcellus	Upper Devonian Marcellus	Upper Devonian Marcellus
LITHOLOGY	shale	shale siltstone	shale siltstone	shale	shale siltstone	shale	shale	shale	shale
TRAP TYPE	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic
DEPOSITIONAL ENVIRONMENT	marine	marine	marine	marine	marine	marine	marine	marine	marine
DISCOVERY WELL IP (Mcf)	21								
DRIVE MECHANISM	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion
NO. PRODUCING WELLS	127	123	138	281	81	85	123	160	315
NO. ABANDONED WELLS	1	2	3	4	1	2	2	4	4
AREA (acreage)	15,233	13,730	9,964	18,016	7,231	7,516	12,777	16,071	18,711
OLDEST FORMATION PENETRATED	McKenzie	McKenzie	Juniata	Juniata	Onondaga	Onondaga	Onondaga	McKenzie	Juniata
EXPECTED HETEROGENEITY DUE TO:	fractures	fractures	fractures	fractures	fractures	fractures	fractures	fractures	fractures
RESERVOIR PARAMETERS									
AVERAGE PAY THICKNESS (ft.)									
AVERAGE COMPLETION THICKNESS (ft.)	284	512	248	296	615	505	1,364	1,219	563
AVERAGE POROSITY--LOG (%)									
MINIMUM POROSITY--LOG (%)									
MAXIMUM POROSITY--LOG (%)									
NO. DATA POINTS									
POROSITY FEET									
RESERVOIR TEMPERATURE (°F)	113	97	89	97	86	97			
INITIAL RESERVOIR PRESSURE (psi)	1,125	758	1,250	1,800		1,200	1,340	1,325	1,850
PRODUCING INTERVAL DEPTHS (ft.)	3,869-5,991	2,786-4,755	1,501-3,738	2,324-4,799	2,569-3,810	3,323-4,978	2,569-5,868	2,786-7,027	1,501-5,670
PRESENT RESERVOIR PRESSURE (psi) / DATE									
FLUID & GAS PROPERTIES									
Rw (Ωm)	0	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
GAS GRAVITY (g/cc)									
GAS SATURATION (%)									
WATER SATURATION (%)									
COMMINGLED	yes	yes	yes	yes	yes	yes	no	yes	no
ASSOCIATED OR NONASSOCIATED	nonassociated	nonassociated	associated	associated	nonassociated	nonassociated	nonassociated	nonassociated	associated
Btu/scf									
VOLUMETRIC DATA									
STATUS (producing, abandoned, storage)	producing	producing	producing	producing	producing	producing	producing	producing	producing
ORIGINAL GAS IN PLACE (Mcf)									
ORIGINAL GAS RESERVES (Mcf)									
PRODUCTION YEARS	1983-1993	1976-1993	1980-1993	1980-1993	1982-1993	1981-1993	1981-1993	1976-1993	1980-1993
REPORTED CUMULATIVE PRODUCTION (Mcf)	40,013	676,472	2,354,712	2,287,357	4,065,046	2,140,606	6,647,918	14,911,432	5,095,697
NO. WELLS REPORTED	2	5	112	133	78	32	119	158	277
ESTIMATED CUMULATIVE PRODUCTION (Mcf)							6,871,378	15,000,184	5,794,745
REMAINING GAS IN PLACE (Mcf)/DATE									
REMAINING GAS RESERVES (Mcf)/DATE									
RECOVERY FACTOR (%)									
INITIAL OPEN FLOW (Mcf/d)			225	316		63	331	458	395
FINAL OPEN FLOW (Mcf/d)		267	165	183		534	348	899	276

TABLE Dbg-1	Girard PA	North East PA	Enoch OH	Geneva OH	Lewisville OH	Lowellville OH	Malaga OH	Whipple OH	Whitacre OH	Willoughby OH
BASIC RESERVOIR DATA										
POOL NUMBER	37140	37251	3400056	3400319	3400069	3400985	3400100	3400014	3400045	3400988
DISCOVERED	1878	1865	1979	1880	1980	1974	1968	1980	1968	
DEPTH TO TOP RESERVOIR	600		3,600	550	3,100	916	3,850	3,100	3,275	975
AGE OF RESERVOIR	Upper Devonian	Upper Devonian	Upper Devonian	Upper Devonian	Upper Devonian	Upper Devonian	Upper Devonian	Upper Devonian	Upper Devonian	Upper Devonian
FORMATION		Ohio Shale	Chagrin	Ohio Shale	Ohio Shale	Ohio Shale	Ohio Shale	Ohio Shale	Chagrin	Ohio Shale
PRODUCING RESERVOIR	Ohio Shale	Ohio Shale	Chagrin	Ohio Shale	Ohio Shale	Ohio Shale	Ohio Shale	Ohio Shale	Chagrin	Ohio Shale
LITHOLOGY	shale	shale	shale	shale	shale	shale	shale	shale	shale	shale
TRAP TYPE	stratigraphic	stratigraphic	fractured	fractured	fractured	fractured	fractured	fractured	fractured	fractured
DEPOSITIONAL ENVIRONMENT	shallow marine	shallow marine	anoxic basin	slope turbidite	slope turbidite	slope turbidite	slope turbidite	anoxic basin	slope turbidite	slope turbidite
DISCOVERY WELL IP (Mcf)			10		50	350	50	50	150	
DRIVE MECHANISM	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion
NO. PRODUCING WELLS	15	538	39	5	48	4	85	5	7	1
NO. ABANDONED WELLS		28	0	0	2	0	1	0	0	3
AREA (acreage)	2,558	6,658	762	47	1,001	47	1,725	100	140	4
OLDEST FORMATION PENETRATED	Ohio Shale	Ohio Shale	Queenston	Queenston	Queenston	Queenston	Oriskany	Medina	Ohio	Queenston
EXPECTED HETEROGENEITY DUE TO:	fractures	fractures	fractures	fractures	fractures	fractures	structure fractures	fractures	fractures	fractures
RESERVOIR PARAMETERS										
AVERAGE PAY THICKNESS (ft.)			450		300	69	150	200	70	
AVERAGE COMPLETION THICKNESS (ft.)										
AVERAGE POROSITY--LOG (%)			8		6	5	4	6		
MINIMUM POROSITY--LOG (%)			7		2	3	2	4		
MAXIMUM POROSITY--LOG (%)			8		8	7	6	8		
NO. DATA POINTS										
POROSITY FEET										
RESERVOIR TEMPERATURE (°F)			102		89		119	91		
INITIAL RESERVOIR PRESSURE (psi)	251	51					125			
PRODUCING INTERVAL DEPTHS (ft.)										
PRESENT RESERVOIR PRESSURE (psi) / DATE				70/1974						
FLUID & GAS PROPERTIES										
Rw (Ωm)										
GAS GRAVITY (g/cc)										
GAS SATURATION (%)			20							
WATER SATURATION (%)			18							
COMMINGLED	no	no	yes	yes	yes	no	yes	yes	yes	no
ASSOCIATED OR NONASSOCIATED	nonassociated	nonassociated	associated	nonassociated	associated	nonassociated	associated	associated	associated	nonassociated
Btu/scf										
VOLUMETRIC DATA										
STATUS (producing, abandoned, storage)	producing	producing	producing	producing	producing	producing	producing	producing	producing	producing
ORIGINAL GAS IN PLACE (Mcf)			3,900,000	500,000	5,000,000	400,000	8,600,000	500,000	700,000	400,000
ORIGINAL GAS RESERVES (Mcf)			1,950,000	250,000	2,500,000	200,000	4,300,000	250,000	350,000	200,000
PRODUCTION YEARS			1982-1992		1982-1992		1981-1992		1988-1990	
REPORTED CUMULATIVE PRODUCTION (Mcf)			346,000		330,000		102,000		49,000	
NO. WELLS REPORTED			31		20		8		4	
ESTIMATED CUMULATIVE PRODUCTION (Mcf)										
REMAINING GAS IN PLACE (Mcf)/DATE			3,120,000/1994	400,000/1994	4,000,000/1994	320,000/1994	6,880,000/1994	400,000/1994	560,000/1994	320,000/1994
REMAINING GAS RESERVES (Mcf)/DATE			1,170,000/1994	150,000/1994	1,500,000/1994	120,000/1994	2,580,000/1994	150,000/1994	210,000/1994	120,000/1994
RECOVERY FACTOR (%)			50	50	50	50	50	50	50	50
INITIAL OPEN FLOW (Mcf/d)	807		65	300	50		250		30	85
FINAL OPEN FLOW (Mcf/d)		81	100		115	350	270	90	490	

and Genegantslet fields were in production in 1983 (Van Tyne, 1983). In response to the U.S. Department of Energy (US DOE) Eastern Gas Shales Project that was initiated in the mid-1970s, however, 25 shale gas tests were drilled in western New York in the late 1970s and early 1980s. Of these, 22 were completed as shale gas producers and most of them produced from the lowermost black shale unit, the Marcellus Shale (Figures Dbg-2a, Dbg-3; Table Dbg-2).

In Pennsylvania, shale gas is produced from the Girard, Erie, and Northeast fields along the shores of Lake Erie (Figures Dbg-2a, Dbg-4a, Dbg-4b). These fields were discovered between 1860 and 1880 and are still productive (Tetra Tech, n.d. a). Open flow rates of some 20 wells drilled in 1941 in the Girard field in Erie County, Pennsylvania, by the Ohio Oil Company ranged from 116 Mcf/d to 4.17 MMcf/d, with gas production occurring from depths of 800 feet or less. A dozen or more wells were drilled in western Pennsylvania, generally to the south of the shoreline fields, during the late 1970s and early 1980s, and most of these wells either produced natural gas or have the potential to produce gas from the Devonian shale and siltstone sequence (Tetra Tech, n.d. a; Piotrowski, 1978; Harper, 1980).

In addition to the natural gas produced from the fields in Lorain, Summit, Lake, and Ashtabula counties, Ohio, near and along the southern shore of Lake Erie, oil and associated gas is produced from this play in Monroe, Washington, and Noble counties in east-central Ohio and in adjacent West Virginia (Figure Dbg-2b). As of 1994, 3,360 wells have been drilled to test the Ohio Shale in Ohio since records were first kept in 1888 (McCormac, 1994).

Prior to 1980, exploration for shale gas in West Virginia had been confined to the northeastward extension of the Big Sandy field into the southwestern part of the state from eastern Kentucky. Indeed, there had been little or no concentrated exploration for natural gas in Devonian shale and siltstone reservoirs in a six-county area which includes Roane, Calhoun, Wirt, Ritchie, Wood, and Pleasants counties (Figure Dbg-2b; Table Dbg-1); this area in western West Virginia was in subsequent years to be called the emerging area by Patchen and Hohn (1993) (Tetra Tech, n.d. c). In the latter part of the 1970s, however, exploration for shale gas in the Appalachian basin was stimulated by research sponsored by US DOE and by the Gas Research Institute (GRI), in cooperation with several state geologic surveys, the U.S. Geological Survey, and industry. This extensive research program, together with favorable tax credits, led to much exploration for shale gas in the emerging area of western West Virginia during the early half of the 1980s, as well as in many other parts of the Appalachian basin. Subsequently, because of a sharp downturn in oil and gas prices in the mid 1980s, exploration for shale gas declined significantly in the Appalachian basin. Nevertheless, as of the mid-1980s, approximately 2,800 new wells had been completed in the Devonian shale sequence in the six-county emerging area of West Virginia.

Stratigraphy

In general, the Upper and Middle Devonian stratigraphic sequence in the area of this play consists of black and dark gray shale units that are interstratified with gray and greenish-gray shales and siltstones and, in places, with very fine-grained sandstones (de Witt and others, 1993). The darker-colored shales, rich in organic matter, commonly contain small but significant amounts of uranium, are more radioactive than intercalated formations of gray and greenish-gray shales and siltstones, and are easily identified on well logs.

The stratigraphic nomenclature used herein is modified from that used by state geological surveys in their reports on local areas (Figure Dbg-5). A type log from the Gandeeville field in Roane County, West Virginia (Figure Dbg-6), shows the Devonian shale sequence in the emerging area of Patchen and Hohn (1993). This sequence extends from the base of the Berea Sandstone (Mississippian) downward to the top of the Onesquethaw Group (Middle Devonian). The thickness of the Devonian shale sequence ranges considerably in and near the area encompassed by this play, from about 2,000 feet on the western side of the play to 3,000 feet or more on the east, toward the interior of the Appalachian basin. A significant hiatus, the Acadian disconformity (Wheeler, 1963), occurs within the Devonian shale sequence so that the Middle Devonian Hamilton Group and Tully Limestone are overlain by Upper Devonian shale and siltstone beds that range stratigraphically from the Genesee Formation to the Rhinestreet Member of the West Falls Formation. The hiatus, which becomes progressively greater to the west toward the crest of the Cincinnati arch, reflects the progressive onlap of the Upper Devonian part of the shale sequence to the west, to where Upper Devonian shales unconformably overlie Lower Devonian carbonate strata commonly called "Corniferous" (de Witt and others, 1993).

The Devonian shale sequence was deposited during episodes of subsidence (relative sea-level rise) and eastward transgression of the marine environments in which the black and dark gray shales rich in organic matter were preserved. Commonly, each transgression was followed by an episode of deltaic progradation and deposition of coarser-grained green and gray siliciclastics that contain lesser amounts of organic matter. In general, basinal black and dark gray shale units dominate the lower part of the Devonian shale sequence in the area of this play. Prodelta and deltaic siliciclastic units did, with time, prograde westward over these black shales as the basin filled, so that the coarser beds constitute most of the upper part of the Devonian section (de Witt and others, 1993) (Figure Dbg-7).

In eastern parts of Ohio and adjacent western West Virginia, the Upper Devonian part of the shale and siltstone sequence contains little or no black shale and cannot be divided into the standard stratigraphic units of the Ohio Shale. This gross stratigraphic unit, informally called the Upper Devonian undivided,

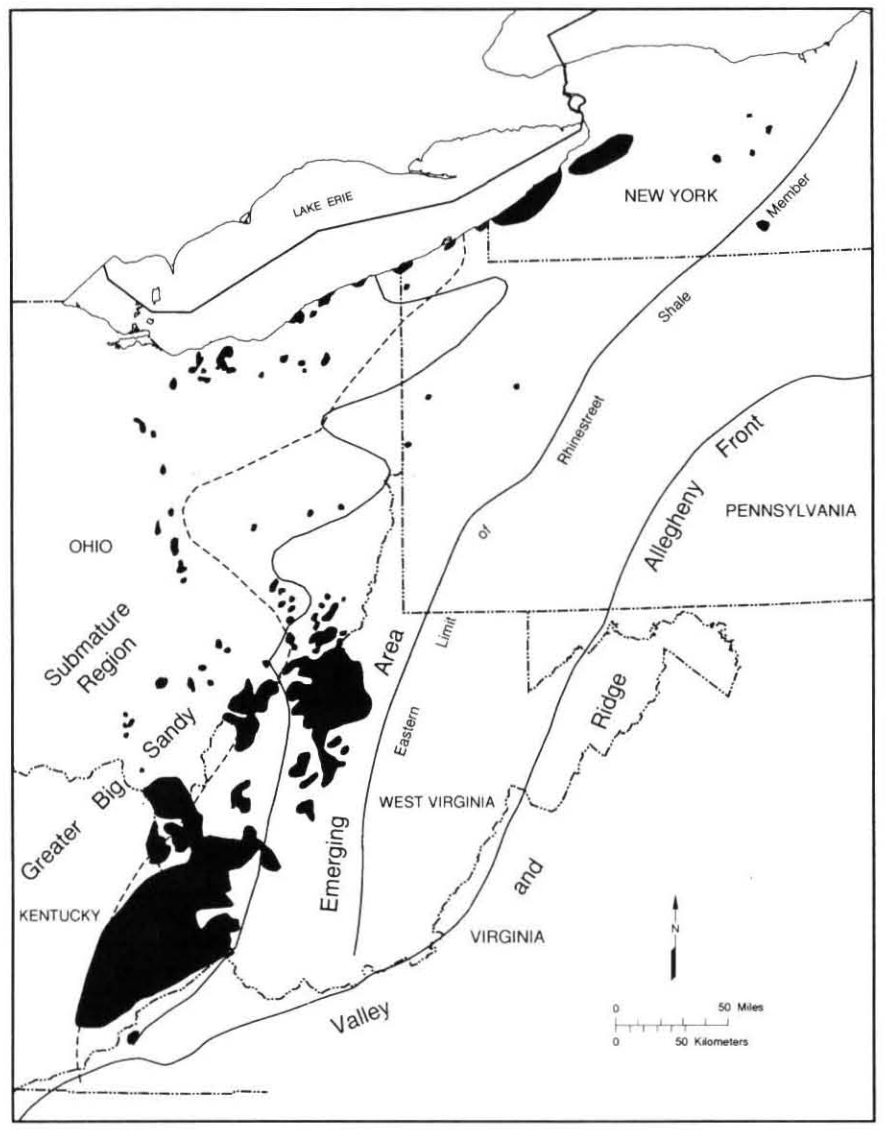


Figure Dbg-4a.

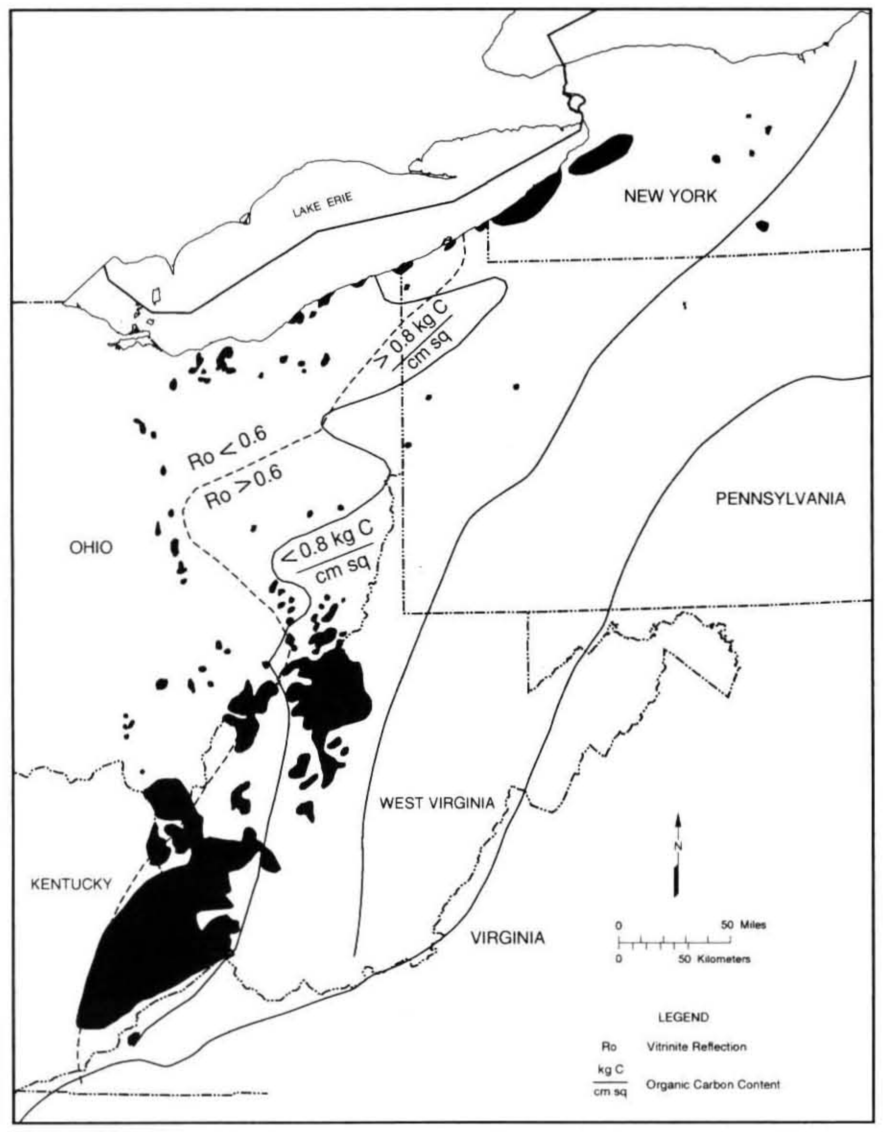


Figure Dbg-4b.

Figure Dbg-4. Generalized maps of areas producing gas from the Devonian shales of the Appalachian basin. Figure Dbg-4a. Location of major features. Figure Dbg-4b. Thermal maturation (Ro) and organic carbon content indicators (0.8 kg C/cm² isoline).

Table Dbg-2. Devonian shale gas tests in western New York. Data from Van Tyne (1983, 1993). See Figure Dbg-2 for well location numbers.

Well Location Number	County	Date Drilled	Field	Producing Formation	IP (Mcf/d)	Cumulative Production Through 1986 (Mcf)
1	Steuben	1980	Rathbone	Marcellus	110	3,453 (turned over to land owner)
2	Steuben	1980		None	Abandoned	
3	Steuben	1980		Rhinestreet	10	18,346 (drilled deeper to Oriskany,1986)
4	Cattaraugus	1981		Rhinestreet/Marcellus	Fair	
4	Cattaraugus	1981		Marcellus	?	
5	Allegany	1979		Marcellus	130	24,750
6	Allegany	1981		Marcellus	23	788 (plugged and abandoned)
7	Allegany	1983		Marcellus	?	
8	Livingston	1980	Dansville	Hamilton/Marcellus	95	4,914 (turned over to landowner)
Unnumbered	Livingston	1980	Dansville	Hamilton	175	
Unnumbered	Livingston	1980	Dansville	Hamilton	50	
Unnumbered	Livingston	1982	Dansville	Hamilton	Fair	
9	Yates	1980		Hamilton	50	
10	Cattaraugus	1981		Marcellus	18	1,130 (plugged and abandoned)
11	Allegany	1981		Marcellus	72	
12	Cattaraugus	1981		Marcellus	14	4,135 (producing)
13	Allegany	1981		Marcellus	40	
14	Steuben	1981		Marcellus	500	2,592 (plugged and abandoned)
14	Steuben	1982		Marcellus	Good	
15	Steuben	1981		Marcellus	274	
15	Steuben	1981		Marcellus	194	
15	Steuben	1981		Marcellus	149	
16	Cattaraugus	1982		Marcellus	Fair	
17	Chemung	1982		Marcellus	89	
18	Tioga	1982		Marcellus	23	

is bounded at the top by the Berea Sandstone or, where the Berea is absent, by the Sunbury Shale or Bedford Shale. The Upper Devonian undivided unit extends stratigraphically downward to the top of the uppermost black shale bed in the lower part of the Huron Member of the Ohio Shale. In general, the Upper Devonian undivided consists of about 1,000 to 1,300 feet of gray shales and siltstones in this area. The amount of siltstone increases eastward and upward within the unit and reflects the overall progradation of the Acadian Catskill delta from east to west across the Appalachian basin (Filer, 1985; Sweeney, 1986; Caramanica, 1988; de Witt and others, 1993). Siltstone bundles (Filer, 1985) occur near the base (Upper Speechley), near the middle (Warren), and near the top of the Upper Devonian shale and siltstone unit (Gordon, post-Gordon interval) (Figures Dbg-7e, Dbg-7f). These coarser-grained strata are interpreted to represent turbidites that were deposited in prodelta environments along the distal margins of the Catskill delta front (Filer, 1985). Filer (1985) suggested that the "Gordon" and post-Gordon siltstones correlate with nearshore, shallow water deposits in western Pennsylvania, the "D" sandstone deposits of Piotrowski and Harper (1979); similarly, the "Speechley/Balltown" turbiditic siltstones lower in the section correlate generally with the shallow water "B" sandstone of Piotrowski and Harper (1979) in western Pennsylvania.

In the eastern part of the Lake Erie shoreline region, the Upper Devonian section is subdivided into the Cleveland Member of the Ohio Shale at the top, the Chagrin Shale, the lower part of the Huron Member of the Ohio Shale, and the upper part of the Olentangy Shale and its equivalents, the Java and West Falls formations of New York (Broadhead, 1993). The Cleveland Member, up to 70 feet of dominantly black to olive-black shale, overlies up to about 1,000 feet of gray shales and siltstones of the Chagrin. The lower part of the Huron Member is a 70-foot-thick dark gray to black shale. To the west, the Chagrin Shale thins significantly and splits into two gray shale and siltstone tongues, the Three Lick Bed and the middle part of the Huron Member, that are separated by the dark gray and black shales of the upper part of the Huron Member of the Ohio Shale (Broadhead, 1993). The upper part of the Olentangy Shale lies above the pre-Upper Devonian unconformity and consists of gray, green, and black shales that are equivalent to the Java and West Falls formations of New York. Combined, their maximum thickness is about 300 feet. Below the pre-Upper Devonian unconformity, the lower part of the Olentangy Shale (Middle Devonian) contains gray shale and black shale equivalents of the Mahantango Formation and Marcellus Shale of Pennsylvania and New York. Together, these formations are about 200 feet thick. This unit grades westward into about 130 feet of calcareous, fossiliferous gray shale.

In eastern Ohio, black shale formations are interstratified with lighter colored shales and siltstones in the upper part of the Ohio Shale. From the top down, the stratigraphic units are the Cleveland Member of the Ohio Shale; the Chagrin Shale, which grades westward and southward into the Three Lick Bed; and the black and gray shale beds of the Huron Member of the Ohio Shale (Figure Dbg-5). The Ohio Shale overlies the upper part of the Olentangy Shale (Baranoski and Riley, 1988), which in turn is divisible into the Java and West Falls formations. Gray shales and siltstones in the upper part of the Java Formation overlie black shales of the Pipe Creek Shale Member. The West Falls Formation is divisible into an upper gray Angola Shale Member and a lower black Rhinestreet Shale Member. The Rhinestreet unconformably overlies the Middle Devonian Onondaga Limestone in much of the area of this play.

The combined thickness of the stratigraphic units from the base of the Huron Member to the top of the Cleveland Member of the Ohio Shale is much less in

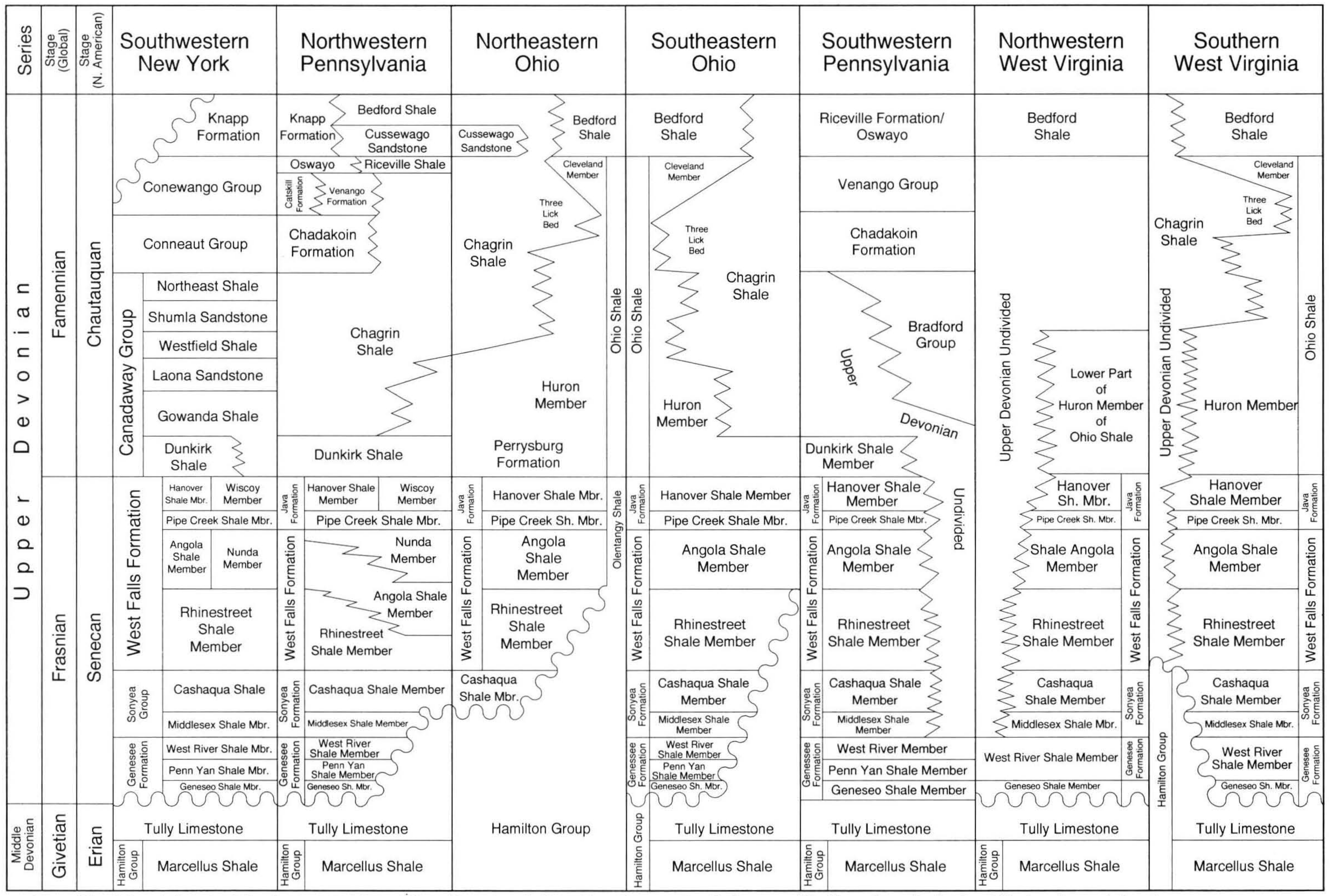


Figure Dbg-5. Correlation chart showing nomenclature of Upper Devonian stratigraphic units recognized in the area of the Upper Devonian fractured black and gray shales play. Modified from Patchen and others (1985a).

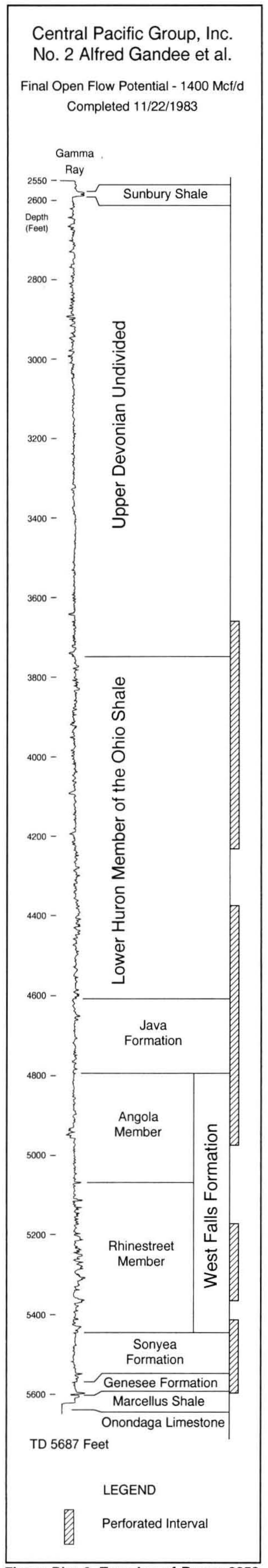


Figure Dbg-6. Type log of Roane 3850 well in the Gandeeville field. Several thick perforated zones are typical of completion practices in the field.

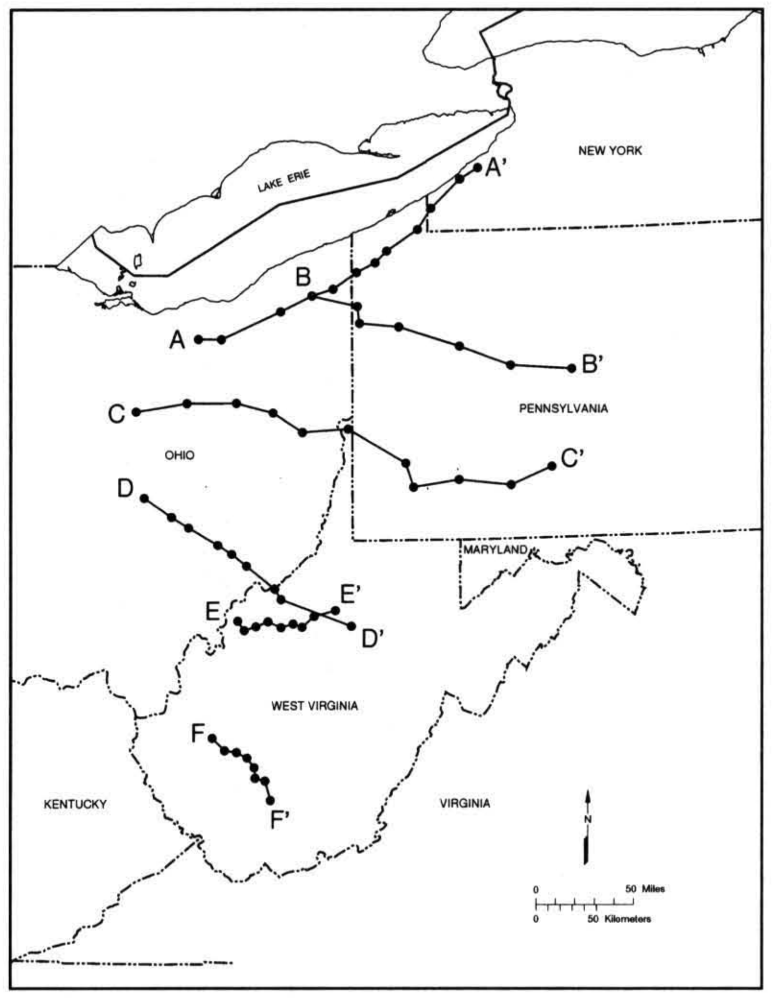


Figure Dbg-7a.

Figures Dbg-7a-g. Stratigraphic sections across the Upper Devonian fractured black and gray shales and siltstone play. Figure Dbg-7a. Location map. Figure Dbg-7b. Cross section A-A' along the south shore of Lake Erie. Modified from Roen and de Witt (1984) and de Witt and others (1993). Figure Dbg-7c. Cross section B-B' across western Pennsylvania. Modified from Roen and de Witt (1984) and de Witt and others (1993). Figure Dbg-7d. Cross section C-C' across eastern Ohio and western Pennsylvania. Modified from Roen and de Witt (1984) and de Witt and others (1993). Figure Dbg-7e. Cross section D-D' across eastern Ohio and West Virginia. Modified from Roen and de Witt (1984) and de Witt and others (1993). Figure Dbg-7f. Cross section E-E' across western West Virginia. Modified from Filer (1985). Figure Dbg-7g. Cross section F-F' across southern West Virginia. Modified from Caramanica (1988). Datum for Figures Dbg-7a, Dbg-7b, Dbg-7c, and Dbg-7d is the top of the Onondaga Limestone.

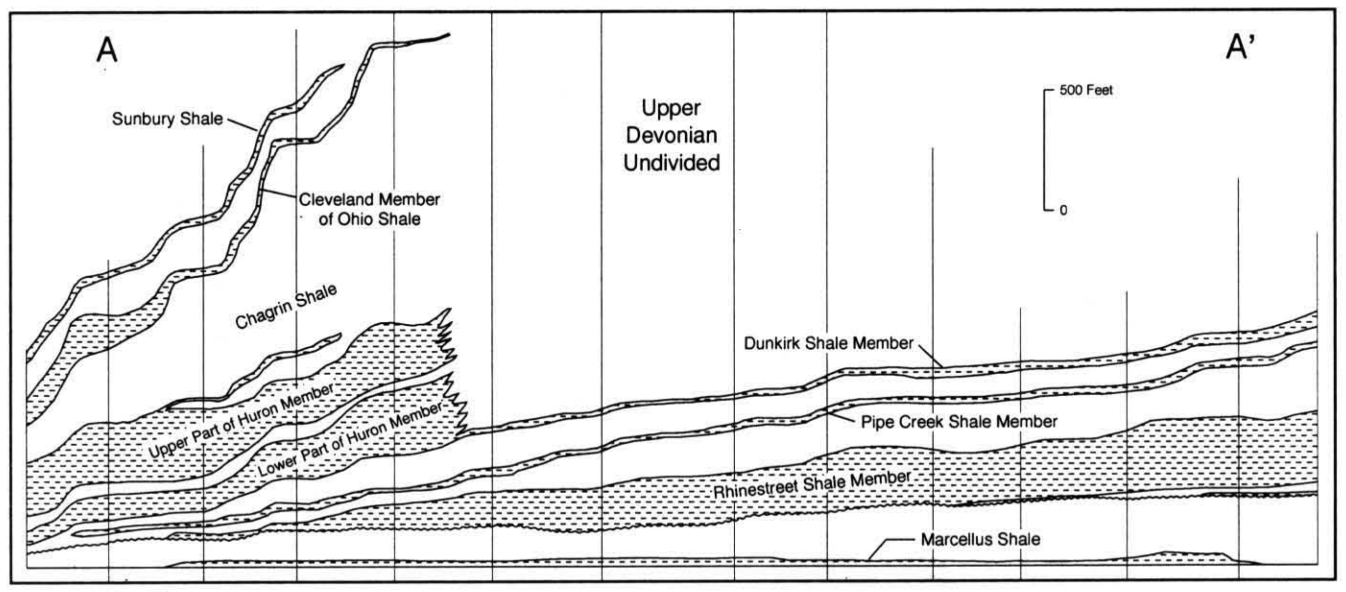


Figure Dbg-7b.

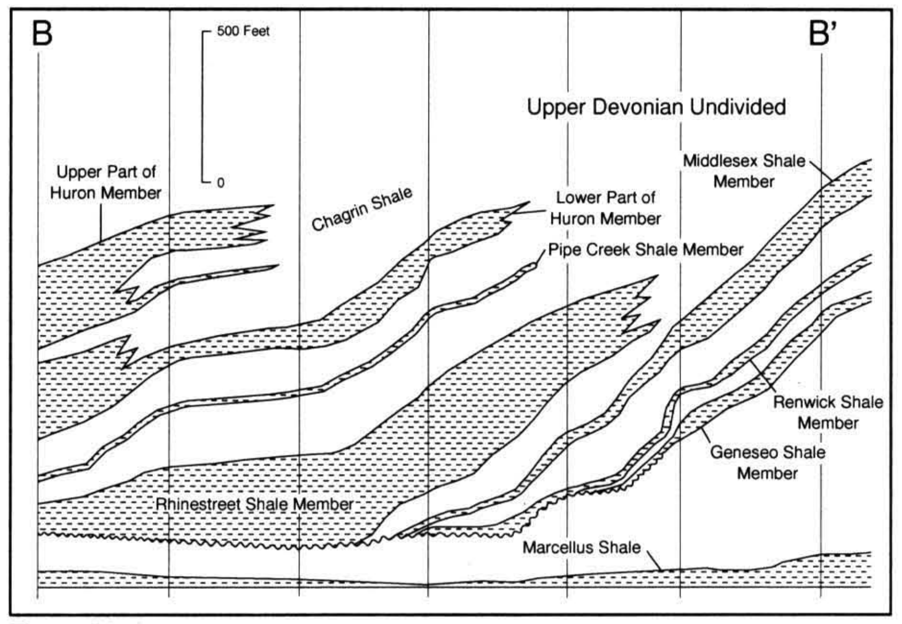


Figure Dbg-7c.

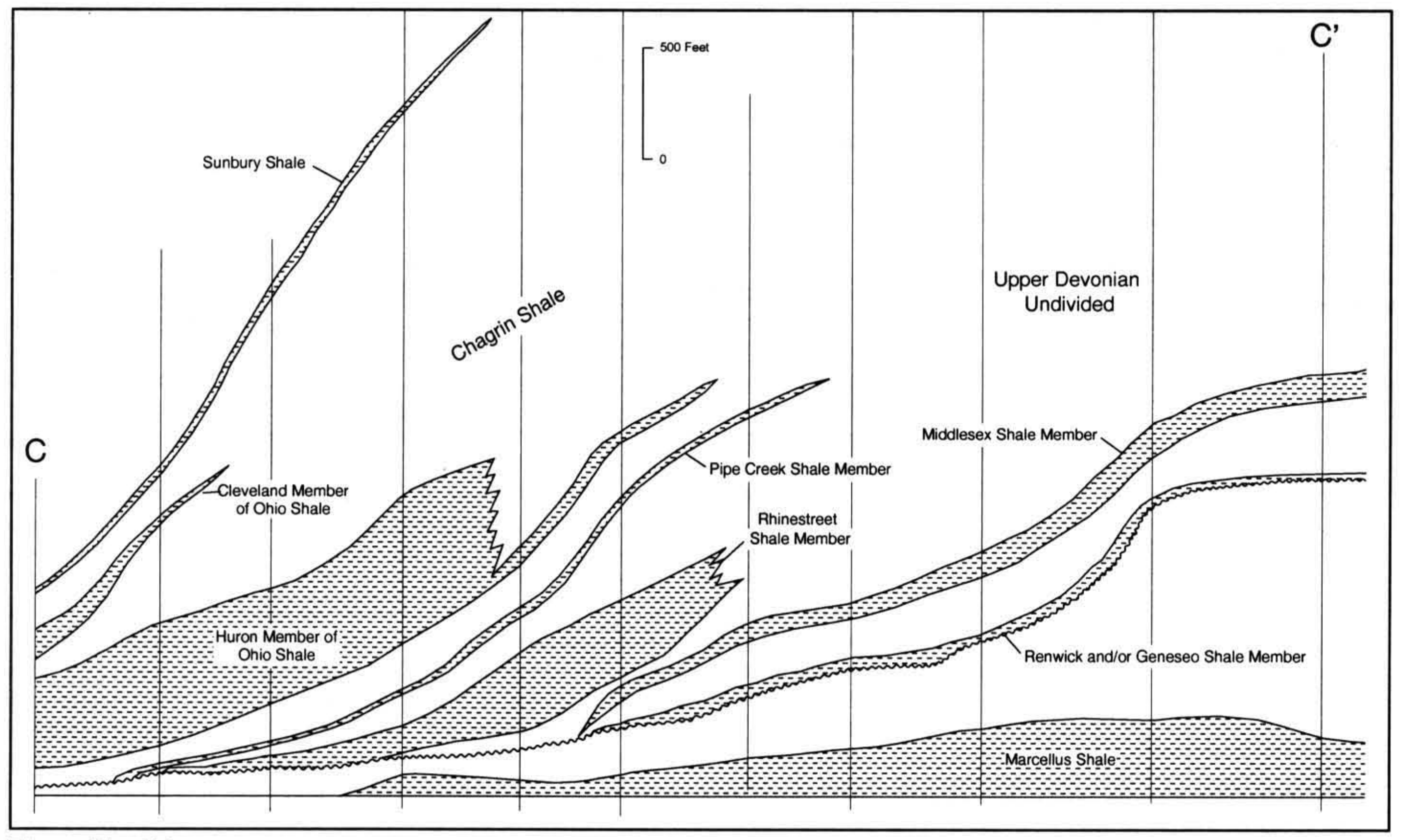


Figure Dbg-7d.

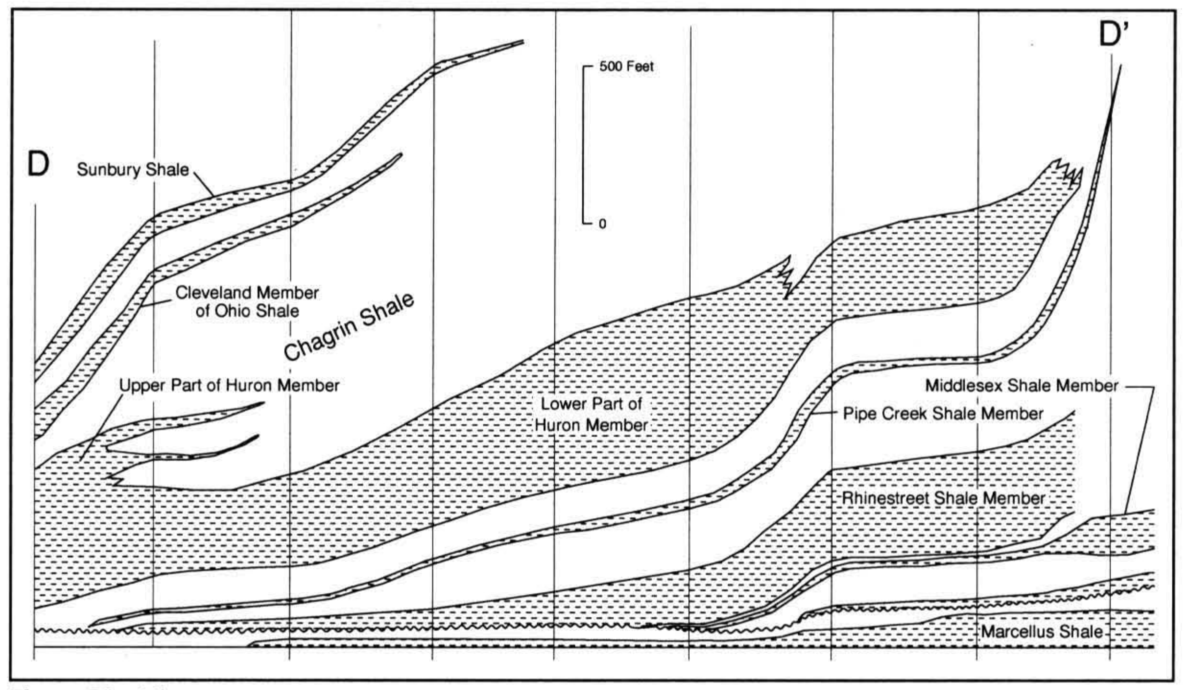


Figure Dbg-7f.

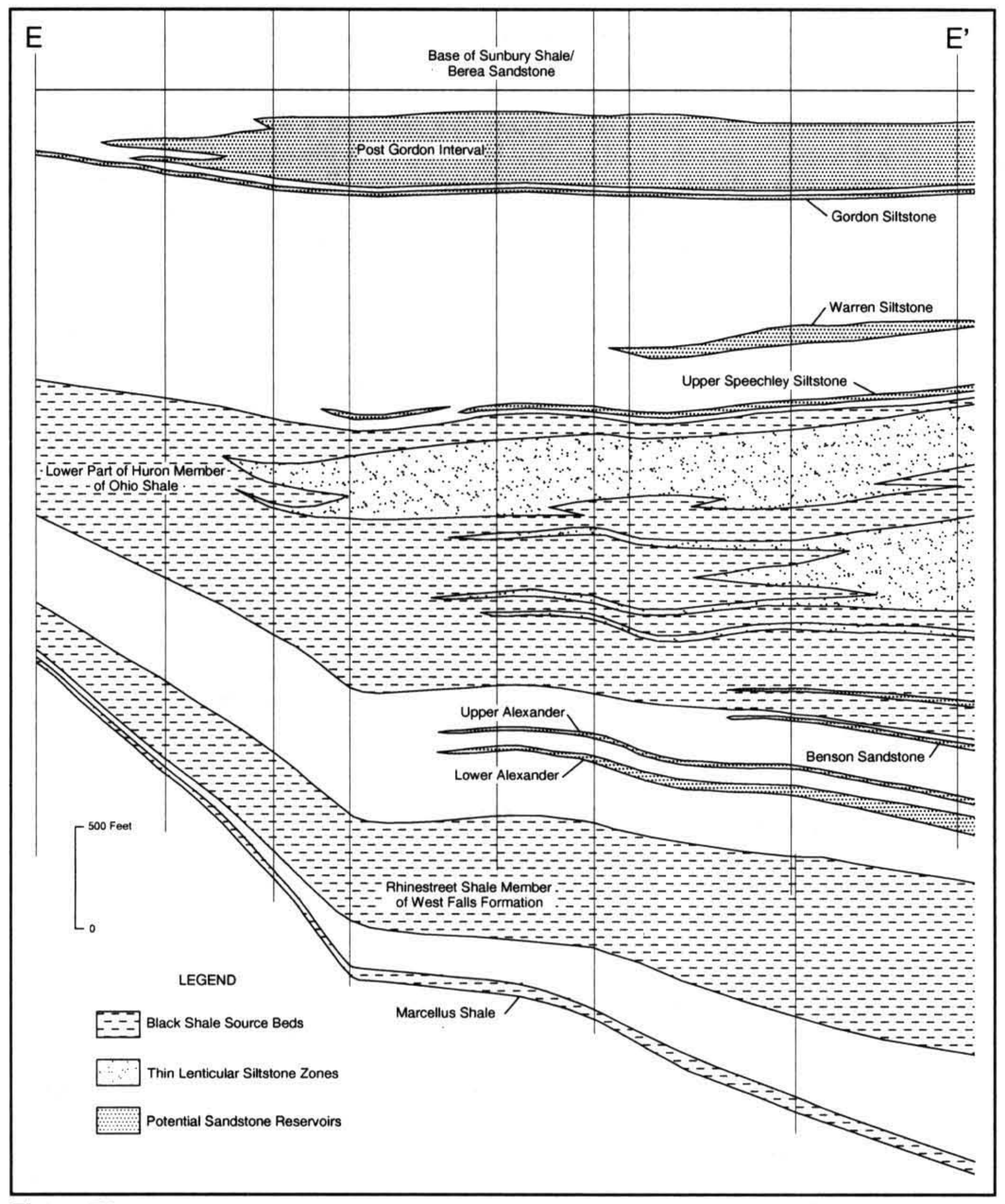


Figure Dbg-7e.

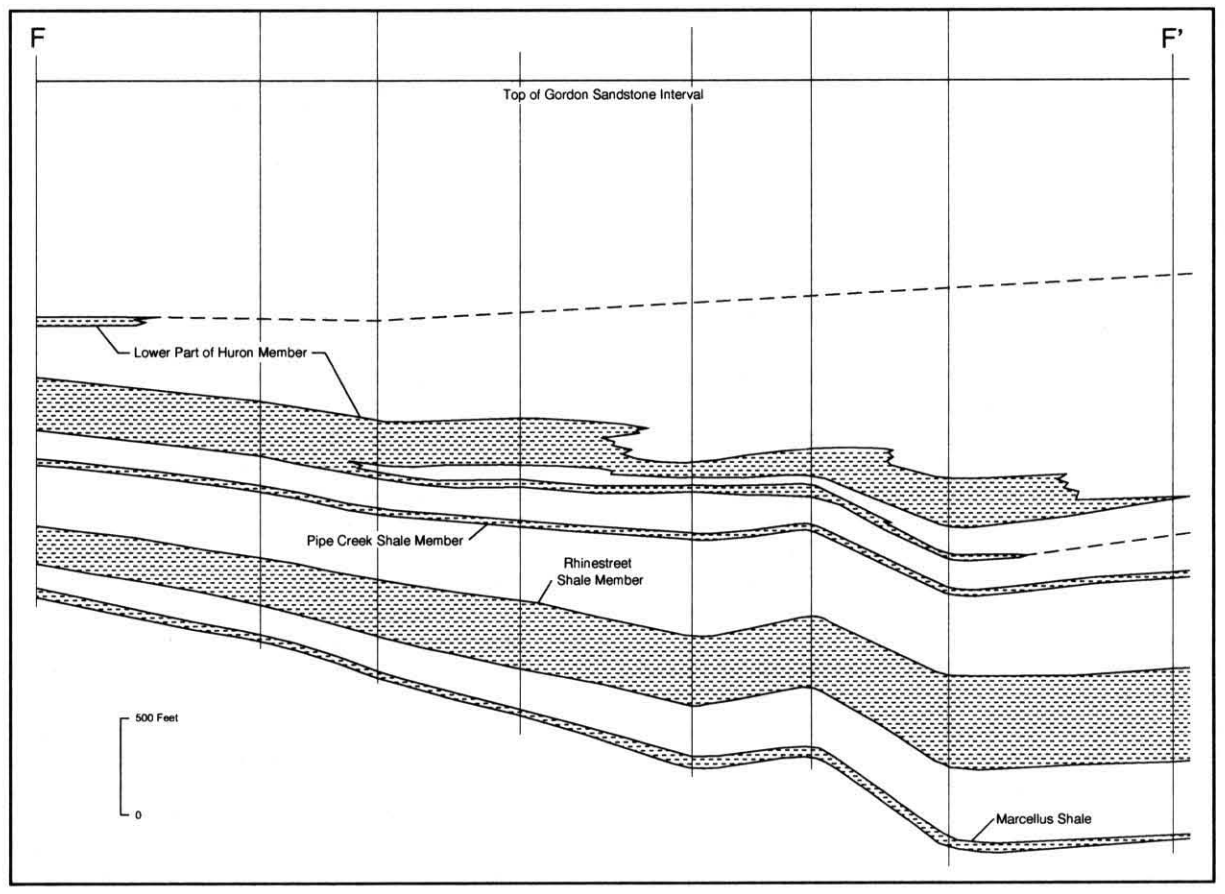


Figure Dbg-7g.

southeastern Ohio, where it ranges from about 500 to 900 feet (Baranoski and Riley, 1988), than is the thickness of the correlative Upper Devonian shales and siltstones in western West Virginia, which are about 2,200 feet thick. At the base of the Upper Devonian section in southern Ohio, the Olentangy Shale and its equivalents range from about 130 to 275 feet thick (Baranoski and Riley, 1988).

In western West Virginia, the Sonyea and Genesee formations occur beneath the Rhinestreet Member; they generally are not preserved above the pre-Upper Devonian unconformity to the west (Figure Dbg-5). The Sonyea consists of up to 200 feet of massive gray to dark gray shale and contains the thin black Middlesex Shale Member at its base. The underlying Genesee Formation, which occurs at the base of the Upper Devonian sequence in western West Virginia, consists of up to 200 feet of gray and black shale. The Genesee is divisible into the upper gray West River Shale Member, and the lower dark gray to black Geneseo Shale Member.

In general, siliciclastic strata of Middle Devonian age are absent in the western part of the play area, where Upper Devonian siliciclastic rocks commonly overlie the Onondaga Limestone (Middle Devonian) unconformably. In the eastern part of the play, however, Middle Devonian strata of the Hamilton Group and Tully Limestone intervene between these Upper Devonian strata and the unconformity (Sweeney, 1986). The Hamilton Group consists of the Mahantango Formation and the Marcellus Shale. In the subsurface of western West Virginia, the combined thickness of the Mahantango and Marcellus is only about 50 to 60 feet, and the two formations are practically indistinguishable. There, the Marcellus Shale is a calcareous, black fissile shale that contains concretions and thin beds of limestone. The overlying Mahantango consists of dark to very dark shale that apparently has less organic matter and radioactivity than the underlying Marcellus (Sweeney, 1986).

Structure

In general, the major geologic structure of the region is that of the Appalachian basin, which extends from the crest of the Cincinnati arch on the west to and beneath crystalline rocks of the Blue Ridge thrust sheet on the east (Figure Dbg-8). Devonian gas shales incline eastward from near the crest of the Cincinnati arch at approximately 55 feet per mile, from a narrow outcrop band that trends almost north-south across central Ohio, downward deep into the basin interior to where they are at a depth of about 5,500 feet in western West Virginia (de Witt and others, 1993).

In the central part of the Appalachian basin, the almost uniform trend of the

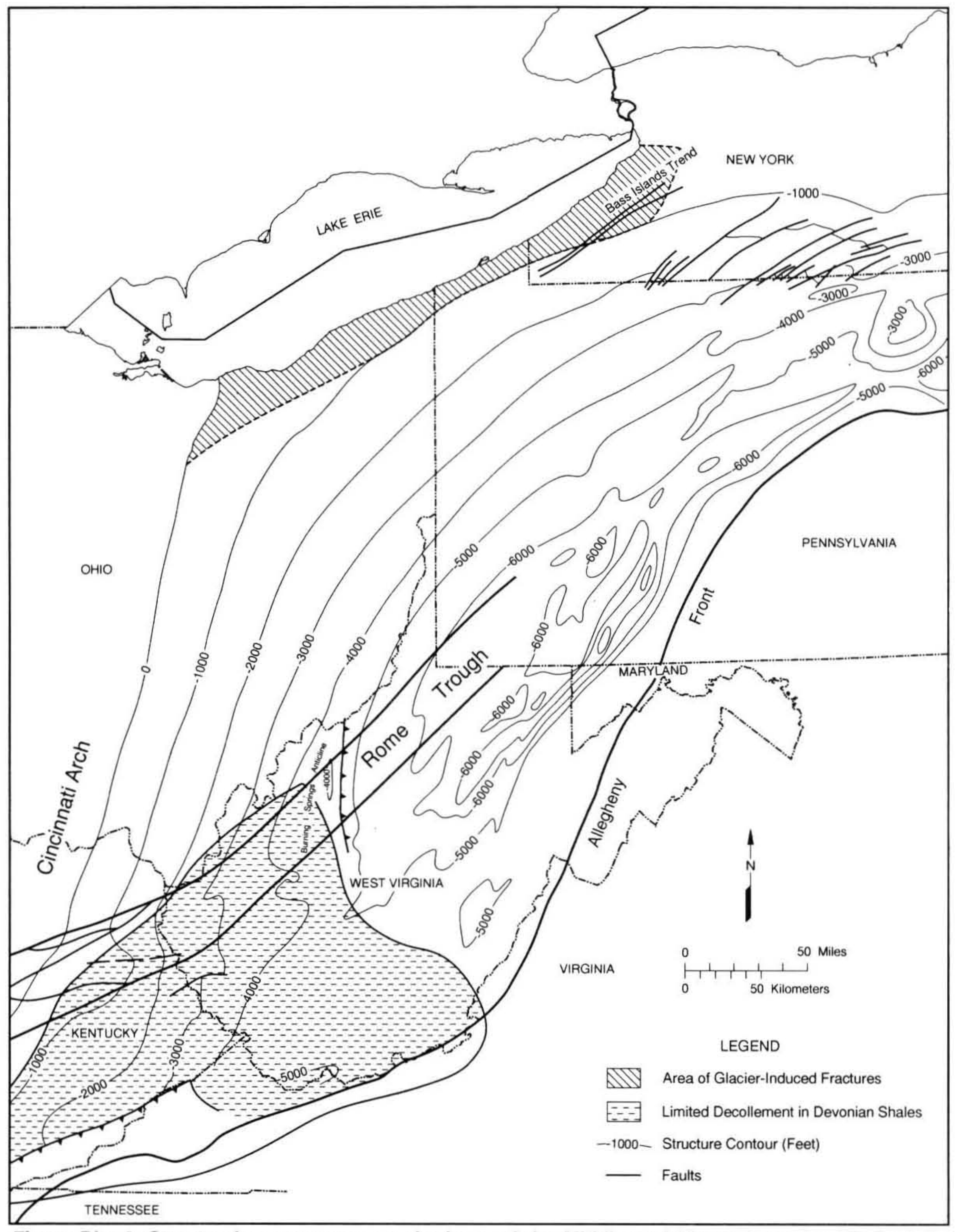


Figure Dbg-8. Structural contour map on the base of the Middle and Upper Devonian black shale sequence of the central part of the Appalachian basin. Adapted from Roen and de Witt (1984).

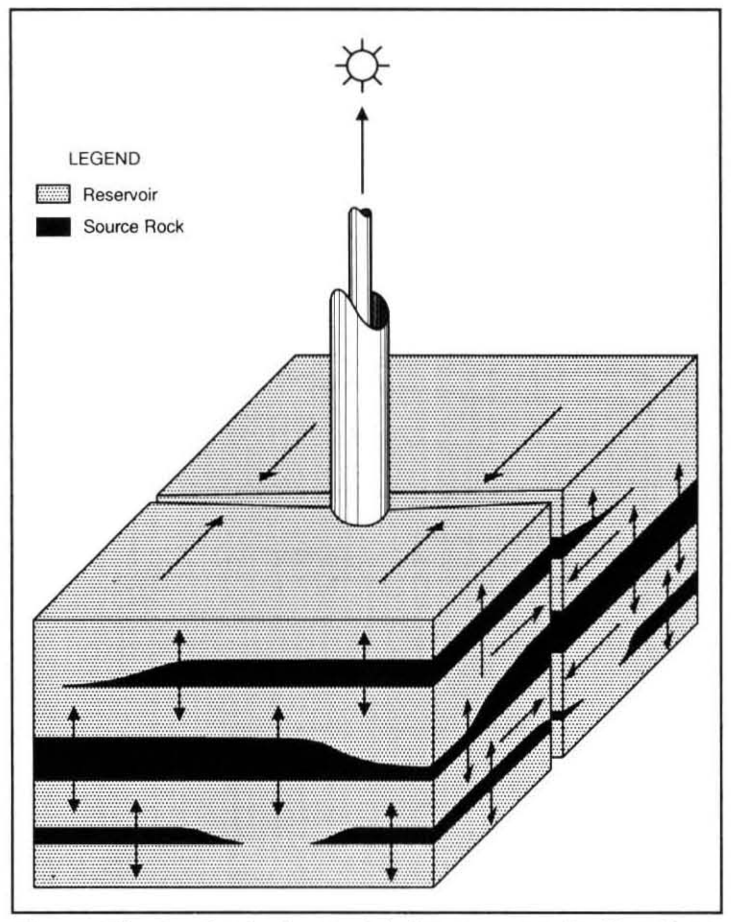


Figure Dbg-9. Geologic model for gas production from Devonian shale/siltstone turbidites in the Upper Devonian black and gray shales and siltstones play. From Caramanica (1988). Arrows show direction of gas flow.

regional structural contours is deflected around decollement-related superficial anticlines, such as the faulted Burning Springs anticline in western West Virginia, the Cow Run anticline in Ohio (Baranoski, 1993b), and the Bass Islands trend (Chautauqua anticline) in westernmost New York (Beinkafner, 1983) (Figure Dbg-8). These structures appear to mark the western limit of the decollement in the Salina salt beds in the Appalachian basin (Rodgers, 1963; Filer, 1985; Sweeney, 1986).

In the emerging area of Patchen and Hohn (1993), the elongate superficial anticlines with the greatest structural relief appear to be related to splay thrusts, or tectonic ramps, that extend upward and westward from decollement in the Silurian salt measures, whereas lower relief folds appear to be related to decollement within the Devonian shales. Shumaker (1982), reiterated by Filer (1985), suggested that a down-to-east basement fault underlies the Burning Springs anticline and acted locally either as the western boundary of the Silurian salt basin or structurally offset the salt. In either way, the edge of the salt basin apparently acted as a buttress that deflected the Salina decollement upward to form the anticline. Fortuitously, the western limit of decollement lies within and follows the trend of the western boundary of this play from West Virginia across eastern Ohio and western Pennsylvania to New York.

Fracture porosity in the emerging area of Patchen and Hohn (1993) generally is related to three types of geologic structures: folds and growth faults adjacent to and within the deep-seated Rome trough (Caramanica, 1988; Shumaker, 1993); fractured superficial anticlines that were formed by thrusting from decollement in Silurian salt measures (Filer, 1985; Sweeney, 1986); and decollement-related fractures formed by subhorizontal thrusting and movement within the Devonian shale reservoir (Shumaker, 1980; Milici, 1993).

The Rome trough is a keel-like structure beneath the Appalachian basin that is filled with an overthickened section of Cambrian siliciclastics. These rocks are correlated generally with the Rome Formation in the Appalachian Valley and Ridge, hence the name of the trough. Overthickening of the strata within the trough indicates that it subsided intermittently from the Cambrian at least into the Devonian (Harris, 1978). Indeed, recent seismic activity indicates that some faults associated with the Rome trough may be active today (Costain and others, 1987). The trough extends across western West Virginia in a broad arc that trends northeasterly from the Big Sandy area in eastern Kentucky to southwestern and central Pennsylvania. Shumaker (1993) speculated that movement along faults associated with the Rome trough may have contributed to fracture porosity in Devonian shale reservoirs in western West Virginia, which includes the six-county emerging area. In addition, Caramanica (1988) provided evidence that supports a deep-seated origin for some of the major fold trends in the southern part of the emerging area, in Kanawha and Boone counties, West Virginia.

An area of limited decollement in the lower part of the Devonian shale section occurs in much of southwestern West Virginia, generally in the area to the south of the Burning Springs anticline and the decollement in Silurian salt measures (Milici, 1993) (Figure Dbg-8). Decollement in Devonian strata was first described by Young (1957) beneath the Pine Mountain fault in southwestern Virginia. Drilling indicates that extensive fracturing occurs primarily within the hydrocarbon-rich lower part of the Huron Member of the Ohio Shale in southwestern Virginia and southeastern West Virginia (Shumaker, 1980; Wilson and others, 1980; Jacobeen, 1992). The area of limited decollement within the Plateau region of southern West Virginia and eastern Kentucky to the northwest of the Pine Mountain block was documented in several places by cores of the Devonian shale studied by Wilson and others (1980) and Shumaker (1980). They described the decollement-generated fracture porosity in these autogenic black shale reservoirs as a "porous fracture facies."

Where subhorizontal deformation is relatively large, such as beneath the Pine Mountain block in Virginia and eastern Kentucky, the shale is extensively deformed, fractured, and slickensided (Young, 1957). When drilled, these deformed shales, the blowout zone of Young (1957), yield gas in a short, violent, explosive event. Northeast and west of the Pine Mountain block, the amount of subhorizontal slippage within the Devonian shales apparently is diminished and the integrity of the reservoir has not been destroyed. Instead, optimal tectonic deformation has resulted in a shale gas reservoir that is characterized by a laterally extensive and integrated fracture network.

Decollement-induced extensional/contractional fracture networks described from exposures of Paleozoic strata by Harris and Milici (1977) and from Devonian shale outcrops by Milici (1980b) serve as structural analogues for fracture porosity in subsurface Devonian shale reservoirs in the south-central part of the Appalachian basin. In almost every case in the Valley and Ridge of eastern Tennessee and southwestern Virginia, deformation in the immediate hanging wall of exposed thrust sheets consists of a mixture of extensional and contractional faults regardless of the stratigraphic age and lithology of the thrust sheet rocks. In places where these faults are closely spaced and abundant, fracture porosity is significantly enhanced.

Almost all of northern Ohio and adjacent parts of Pennsylvania and nearby New York were subjected to several episodes of Pleistocene continental glaciation within the last million years. White (1992) suggested that the southeastward movement of a 4,000- to 6,500-foot-thick continental ice sheet would effectively produce a southeastward-moving decollement in Silurian salt measures and form southeastward verging salt-cored anticlines (Fry, 1973) around the periphery of the Laurentide ice lobe in the western and northern parts of the Appalachian basin. Indeed, glacial loading and post-glacial isostatic rebound in the shale gas-producing regions to the south of Lake Erie appear to have created fractured pathways for gas to have migrated from black shale source rocks into intercalated brittle silty and sandy reservoirs, as well as to have fractured and enhanced the storage capacity of the shale reservoirs (Figure Dbg-9).

Reservoir

The unconventional hydrocarbon accumulations in the autogenic gas shales of the Appalachian basin are best described as continuous accumulations (Gautier and others, 1995). Generally, the Devonian shale sequence produces gas almost everywhere it is drilled so that fields, initially separated by several miles or more during the early phases of development, tend to grow together as the region is explored. Continuous accumulations differ from conventional hydrocarbon accumulations in several ways. They do not occur above a base of water and they commonly are not density stratified within the reservoir. Although production is significantly affected by fracturing, gas accumulations generally occur independently of broad anticlinal structures. The distribution of producing areas and the production characteristics of gas-shale reservoirs depend greatly on several factors, including the nature and amount of the organic matter, thermal maturation, and enhancement of reservoir porosity and permeability by natural fracture systems. In places, production may occur over relatively thick stratigraphic intervals and generally is greatest in naturally fractured black shale reservoirs rich in organic matter.

Source rocks in the Devonian shale and siltstone sequence are generally the dark gray to black shales rich in organic matter. The regional thermal maturation patterns of the Devonian shales were summarized by de Witt (1986). In the western part of the Appalachian basin, on the east flank of the Cincinnati arch and including the area of the fields along the southern shores of Lake Erie, Devonian shales were buried less deeply by younger Paleozoic deposits than they were to the east and, thus, are thermally less mature. Consequently, in the western part of the Appalachian basin, they yield biogenic and early catogenic gasses with carbon isotope ratios ($\Delta^{13}C$) ranging from -90 to -55 permil (‰) (Claypool and others, 1978). In a broad area that extends from western New York to eastern Kentucky, the shales yield wet gas that in places is associated with liquid hydrocarbons. For example, oil is commonly associated with gas produced from Devonian shales in southeastern Ohio and adjacent West Virginia. In this region, which includes much of the area of this play, the $\Delta^{13}C$ ratio ranges from -55 to -50 ‰. Where the Devonian shales are even more deeply buried under the eastern half of the Appalachian basin, generally in the area of the Upper Devonian Elk sandstones and siltstones play (see A. Donaldson and others, this atlas), they yield dry methane with $\Delta^{13}C$ that ranges from -50 to -35 ‰ (Claypool and others, 1978).

The emerging area in western West Virginia and adjacent Ohio is of considerable economic interest for exploration, primarily because it produces oil as well as gas from the Devonian shale sequence (Filer, 1985). The occurrence of both liquid and gaseous hydrocarbons in the Devonian shale sequence of the Appalachian basin in this region is a result of the almost unique coincidence of suitable source rock composition, thermal maturity, matrix porosity in fine-grained siliciclastics, and abundant fracture porosity (Zielinski and McIver, 1982). To the east, in the general area of the Upper Devonian Elk sandstones and siltstones play (see A. Donaldson and others, this atlas), organic material is chiefly of terrestrial origin and is gas prone. Thermal maturity is relatively high and the eastern part of the Appalachian basin is within the dry gas window (de Witt, 1986). Although organic matter is more marine to the west and is oil prone, thermal maturity of the Devonian shale sequence in the area of the Upper Devonian black shales play (R. Boswell, this atlas) is relatively low and is not sufficient to have generated large amounts of liquid hydrocarbons. It is only in western West Virginia and in adjacent counties in Ohio that significant amounts of liquid hydrocarbons have been generated together with natural gas, and occur preserved within fractured reservoirs in the Devonian shales. At present, there is little evidence to support a hypothesis for long-distance migration of hydrocarbons from where they were generated in the eastern part of the basin to reservoirs on the west, where source beds are immature. Instead, gas in the fields in the northwestern part of the basin appears to be of biogenic, rather than of thermogenic, origin (Claypool and others, 1978).

In general, hydrocarbons generated at the molecular level within black shale source beds are absorbed onto the surfaces of abundant clay minerals (Claypool and others, 1978; Caramanica, 1988). Natural fractures enable these hydrocarbons to migrate from these mineral surfaces into more porous siltstone and fine-grained sandstone reservoirs and, ultimately, to the well bore (Figure Dbg-9). Hydrocarbon generation and local migration apparently occurred first in the northeastern part of the Appalachian basin, where source rocks in the lower part of the Catskill delta were buried deeply during final phases of Acadian deposition. Subsequently, Devonian deposits were buried even more deeply, especially by Carboniferous deposits caused by the collision of Africa with North America during the onset of the Alleghanian orogeny.

Finally, in some places thrust loading may have been an important mechanism in hydrocarbon generation and migration. To the west of the Allegheny structural front, there is little or no post-depositional structural imbrication and thrust-loading of potential source beds as there is to the east of the structural front. Over much of the Appalachian basin, where thermal maturation trends follow regional isopachs rather than regional structure, structural duplication of the stratigraphic section appears to have had little or no effect on the thermal maturity of source beds and distribution of hydrocarbons. To the southeast, however, where the oil window enters the Valley and Ridge in northeastern Tennessee, burial of Devonian black shale source beds by low-angle thrust sheets may, indeed, have contributed to the local generation and subsequent migration of hydrocarbons during the final stages of the Alleghanian orogeny.

Drilling depths to the base of the Devonian shale sequence range from a few to a few tens of feet on the northwestern side of the Appalachian basin, where the Devonian shale sequence crops out, to 6,000 to 7,000 feet in eastern Ohio and western West Virginia (de Witt and others, 1993). In the fields along the shore of Lake Erie, the relatively more porous gray shale and siltstone beds of the Chagrin Shale and Three Lick Bed are completed for natural gas production instead of the dark gray and black shales of the Devonian sequence. Gas is produced from shallow, low-pressure reservoirs in this area that range from a few feet thick up to 200 feet or more thick (Broadhead, 1993). In some wells in the emerging area, the entire shale sequence from the Sunbury Shale through the Rhinestreet Shale Member is perforated, a stratigraphic interval that is about 3,000 feet thick. In other wells, selected formations, such as the lower part of the Huron Member of the Ohio Shale, are completed for intervals that range from a few hundred to about 1,000 feet thick.

Wells in the region along the southern shores of Lake Erie generally are long-lived, low-pressure, low-yield wells with initial open flows that range from 1 to 50 Mcf/d (Tetra Tech, n.d. b). A typical well, the first one drilled for natural gas in the area (de Witt, 1986), had an annual yield of about 3 MMcf and had produced about 195 MMcfg over a 65-year period when it was plugged and abandoned in 1885. In Erie County, Pennsylvania, 20 wells were drilled in the Girard field in 1941 to depths ranging from 500 to 800 feet (Piotrowski, 1978). Gauged open flow rates for these wells ranged from 116 to 4,168 Mcf/d. In 1976, another well drilled into the North East field to a depth of 900 feet had an open flow rate of 150 Mcf/d and a rock pressure of 80 psi after foam fracture. In 1977, a well drilled just west of the Erie field to a depth of 901 feet had three shows of gas that ranged from 1,300 to 1,700 Mcf/d. The well settled in at a flow rate of 975 Mcf/d and a rock pressure of 120 psi. In Beaver County, Pennsylvania, a short-lived well, which encountered the Devonian shale at a depth of 4,500 feet, had an IP of 150 Mcf/d at a rock pressure of 1,150 psi. It declined steadily and was nonproductive after 30 days (Piotrowski, 1978).

In West Virginia, reported rock pressures range generally from about 500 to 1,800 psi and average depths of production range from 1,900 to 6,400 feet. In New York, average wellhead pressures reported by Van Tyne (1983) for eight gas fields range from 35 to 565 psi and average depths of production range from 200 to 2,000 feet.

Initial open-flow potentials in the emerging area of West Virginia range from a few to several thousand Mcf/d. The mean IP for 239 wells studied by Sweeney (1986) in the emerging area was 385 Mcf/d. For 174 gas wells in this area, in which three or more formations were completed, mean IP was 395 Mcf/d. Isopotential maps for the emerging area in West Virginia show that IP values range from about 60 Mcf/d to a little more than 1,000 Mcf/d, with much of the area in the range of 100 to 400 Mcf/d (Hohn and Timberlake, 1988).

In general, the Devonian shale and siltstone gas reservoirs have low porosities and permeabilities. Porosities commonly range from 1 to 3 percent, and permeabilities from 0.1 to 10 microdarcies (de Witt, 1986). In a core from Lincoln County, West Virginia (Lincoln 1637), porosity values in formations from the Chagrin Shale to the Rhinestreet Shale Member range from 1.32 to 2.84 percent, with a mean of 1.98 percent (Neal, 1979). The porosity and permeability of the lower part of the Huron Member were tested in a core from Noble County, Ohio (Soeder and others, 1986); permeability was measured at 194 nanodarcies and porosity was less than 1 percent. One full-width crack and three short cracks were observed in the core. Oil occurred in the cracks. In general, because of the low-matrix porosity and permeability, Devonian shale and siltstone reservoirs are productive only where there is an extensively developed natural fracture system.

Completions commonly are in more than one formation, and gas production from several units may be commingled. Methods commonly employed in completing shale gas wells include natural, shot with explosives, foam frac, hydraulic frac, nitrogen frac, and nitrogen and foam frac. Prior to the mid-1960s, wells were commonly shot with explosives. Hydrofracing was utilized in western West Virginia during the late 1960s and 1970s, with sand commonly used as a proppant (Filer, 1985). Water introduced into the formation by the hydrofracing process, however, causes clay particles to swell and significantly reduces permeability. Nitrogen gas fracturing became popular in the late 1970s. This method has the advantage of keeping liquids from filling fractures in the shale reservoir, although the gas cannot carry proppants into induced fractures. According to Filer (1985), nitrogen commonly is used as a frac fluid in one of two ways, either in single-stage, short interval treatments, or in multiple stages over thicker intervals.

In Pleasants, Wood, and Ritchie counties, open-flow potentials after stimulation range up to 2,000 barrels of oil per day, and up to 2,000 Mcf/d, although most wells tested at much less (Filer, 1985). In Wirt, Roane, and Calhoun counties, mean initial open-flow potential was 385 Mcfg/d for 238 gas wells and 38 barrels of oil per day for 45 oil wells (Sweeney, 1986). Cumulative production data for 182 wells completed in Wirt, Roane, and Calhoun counties during the 1980s (Table Dbg-3) indicate that of the stimulated wells, those stimulated with nitrogen and no proppant had the highest average reported final open-flow potential. The only well in the data set stimulated with both nitrogen and carbon dioxide had a high reported cumulative gas production. The wells completed with nitrogen and no proppant and those stimulated with foam or a combination of nitrogen and foam had higher average per-well cumulative gas production than those wells stimulated with nitrogen together with a sand proppant.

Patchen and Hohn (1993) compared production decline curves for gas wells in three counties in southwestern West Virginia, in the area of long-term historical production where the Big Sandy gas field enters Kentucky, with production decline curves from the emerging area to the northeast (Figure Dbg-10). Patchen and Hohn (1993) determined that, in general, after one year wells in the emerging area were less productive than were wells in the historical area after 30 years of production and depletion. The apparent dilution of the total amount of organic carbon in the source beds in the emerging area, coupled perhaps with outmigration of hydrocarbons generated in this deeper part of the Appalachian basin, have significantly decreased the potential of the fractured Devonian shale and siltstone reservoirs of this play to produce substantial amounts of natural gas over the long term.

Description of Key Fields

In general, the gas accumulations in the Devonian shales of the Appalachian basin occur in continuous accumulations, rather than in discrete fields. Dark gray to black shales rich in organic matter serve both as a source for hydrocarbons, and where extensively fractured, as autogenic reservoirs. Two regions of this play, one along the southern shorelines of Lake Erie, and the other in western West Virginia and adjacent Ohio, are examples of this type of accumulation. The Gandeeville field in the emerging area of West Virginia, however, is a Devonian shale reservoir that currently exists as a discrete entity.

Lake Erie shoreline fields: The Lake Erie shoreline gas fields occur along the southern shores of Lake Erie from western New York, through the Pennsylvania corridor, and into north-central Ohio (Figure Dbg-2a). Like the fields in the emerging area, these fields occupy a transitional region, where the stratigraphic sequence of interbedded black shales and siltstones generally to the

Table Dbg-3. Comparison of completion methods and cumulative production for selected Devonian shale wells in Wirt, Roane, and Calhoun counties, West Virginia.

Completion Method	Number of Wells with Reported Gas Production	Average Per Well Initial Open Flow Potential (Mcf/d)	Average Per Well Final Open Flow Potential (Mcf/d)	Average Per Well Cumulative Gas Production Through 1993 (Mcf)	Number of Wells with Reported Oil Production	Average Per Well Cumulative Oil Production Through 1993 (bbls)	Average Number of Years of Production Data Per Well	Comments
Natural	7	881	none*	52,671	3	10,860	8.7	*For wells which were unstimulated or naturally completed, there is no final or post-stimulation open flow potential.
Shot	1	0	80	23,386	----	----	10	
Foam Frac	43	5	264	38,333	21	3,246	7.4	
Hydraulic Frac	2	0	40	20,155	2	1,703	5.5	
Nitrogen Frac without Sand	92	30	392	40,272	71	2,767	8.6	
Nitrogen Frac with Sand	27	42	368	35,538	15	423	7.4	
Nitrogen and Carbon Dioxide Frac	1	9	150	54,360	1	10,031	5	
Nitrogen and Foam Frac	9	50	226	76,356**	5	1,054	9.2	**One well had reported cumulative production of 354,924 Mcf. Average cumulative production of other 8 wells is 41,535 Mcf.

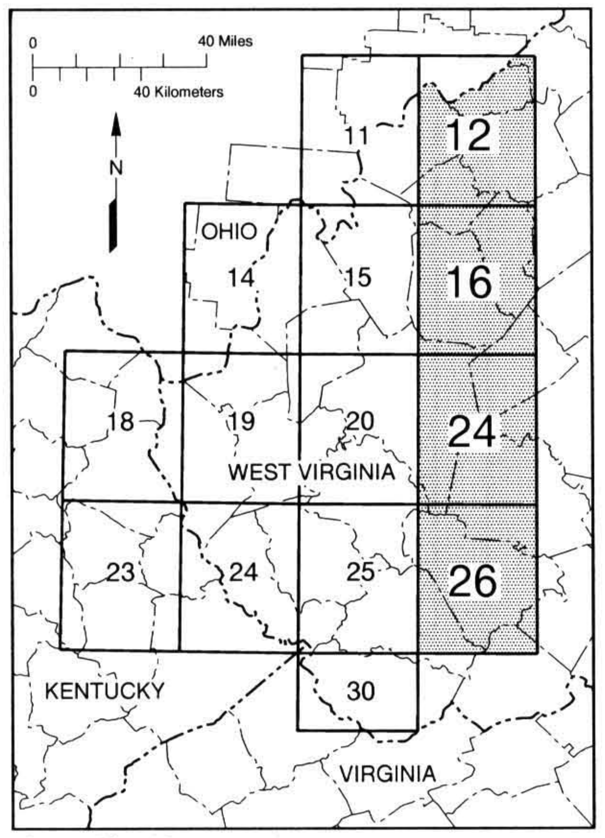


Figure Dbg-10a.

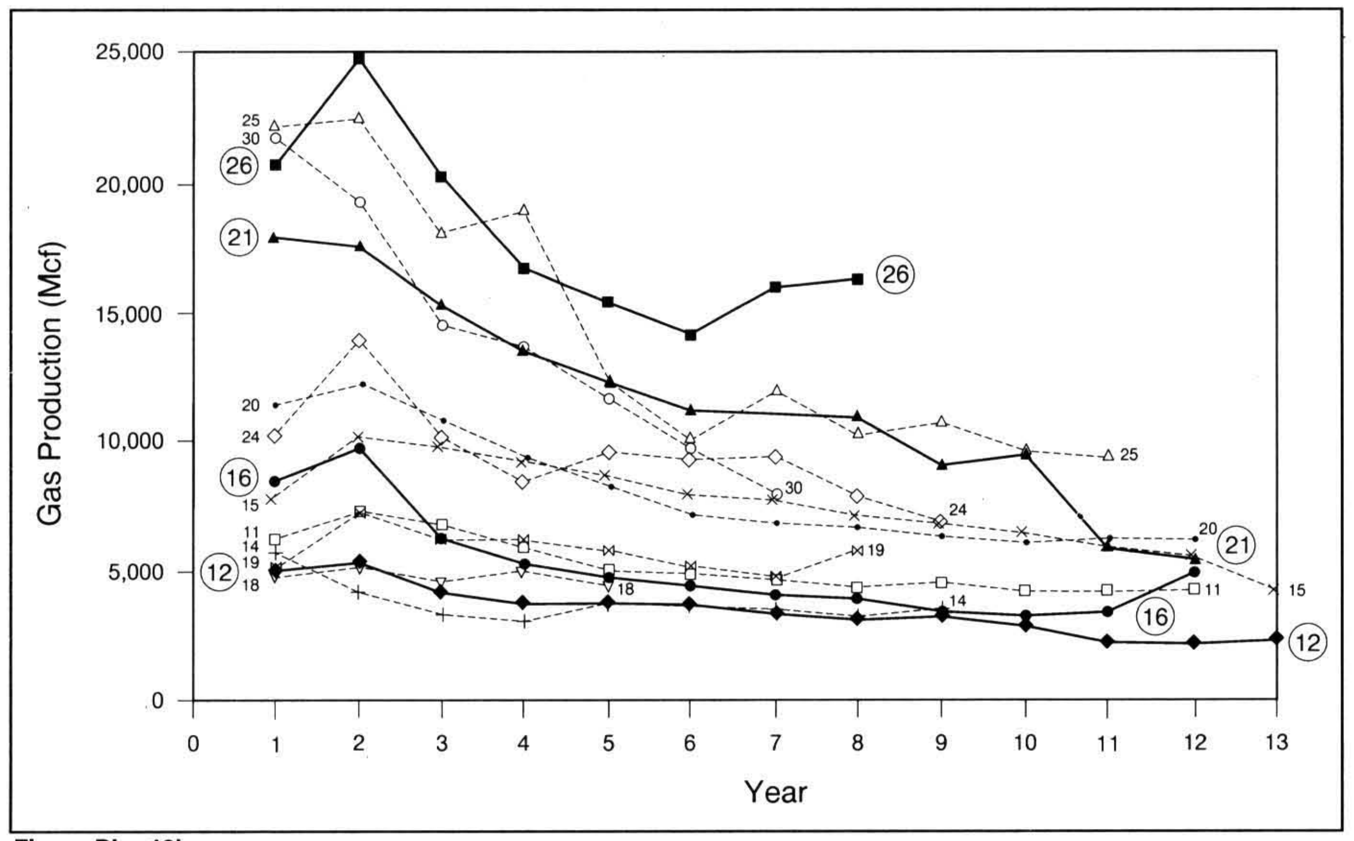


Figure Dbg-10b.

Figures Dbg-10a-b. Comparison of natural gas decline curves from wells in the Big Sandy field and the emerging area of western West Virginia. Figure Dbg-10a. Map showing approximate areas from which decline curves were constructed. Figure Dbg-10b. Decline curves for areas shown in Figure Dbg-10a.

east of Cleveland, Ohio (Three Lick Bed, Chagrin Shale), grade westward into a sequence dominated by black shale (Ohio Shale). Gas production in these fields is primarily from fractured gray siltstones that are intercalated with fractured black and gray shales (Broadhead, 1993). Otherwise, the geologic controls on gas produced from the shoreline fields bear little similarity to the controls on gas produced from the emerging area of northwestern West Virginia.

In the Lake Erie shoreline fields, the depth to productive parts of the Devonian shale sequence ranges from very near the surface (initial discovery in Chautauqua County, New York) to 800 feet or more in downdip areas to the south and east into the Appalachian basin. The maximum depth of significant shale gas production is dependent to a large degree on the capability which the Pleistocene ice sheets had to generate fractures beneath the surface of the earth, either by isostatic crustal warping caused by glacial loading and unloading or by horizontal stresses produced by southward movement of the ice sheets (White, 1992).

The stratigraphic thickness of units involved in this area ranges from a few hundred to 1,500 feet or more and generally increases eastward along the lake. This increase in thickness contributes little to gas production, however, because it is the result of an influx in coarser-grained siliciclastics that contain little organic matter and have a low source-rock potential. In general, these fields have low reservoir pressures; limited data indicate a current rock pressure of about 70 psi in one field. Initial open flows tend to be 50 Mcf/d or less, and the wells typically produce small amounts of gas (20 Mcf/d or less) for 30 to 50 years or more. It should be noted that gas production from wells in the shoreline fields declines slowly over a period of decades, in contrast with production from wells in the emerging area, which declines rapidly over a period of months.

Emerging area: The emerging area in western West Virginia and adjacent Ohio (Figures Dbg-2b, Dbg-10) is another example of an unconventional, or continuous, gas accumulation within the Devonian shale sequence. Devonian shale oil and gas fields and pools that were physically separated early in the development of the hydrocarbon resources of the region grew together as interfield areas were drilled and field boundaries met. At present, hydrocarbons are produced from a heterogeneous shale gas reservoir that is, to a great extent, areally continuous over the region.

In western West Virginia and eastern Ohio, drilling depths to the base of the black shale sequence range from about 4,000 to 6,500 feet deep (de Witt and others, 1993 (Figure Dbg-8). Although gas is produced from several stratigraphic zones within the shale sequence, the lower part of the Huron Member is the most important reservoir in the play (Filer, 1985; Sweeney, 1986; Caramanica, 1988). Based on detailed studies of wire-line logs by Truman and Campbell (1987), Caramanica (1988) presented a geologically based reservoir model for the lower part of the Huron Member in western West Virginia that is very likely applicable to other black Devonian shales in this part of the Appalachian basin. Examination of wire-line logs and cores has demonstrated that the lower part of the Huron Member consists chiefly of thin turbidite couplets consisting of black shale and more porous silty shales which contain much less organic matter. Gas generated from organic matter within the darker colored shales migrates to the more porous interbeds and from them into available fracture systems, either natural or induced (Figure Dbg-9). As gas is produced from wells fed by fracture networks, it is replaced by gas that subsequently migrates from kerogen-rich source beds into the coarser-grained fraction of the turbidite couplets.

Except for the Burning Springs anticline, the base of the Huron Member ranges from about -2,800 feet to -3,800 feet below sea level (Filer, 1985). Local relief on the Burning Springs anticline is up to 1,600 feet, and in places the base of the Huron occurs at subsea elevations as high as -2,000 feet. Although the total thickness of the Lower Huron in the emerging area ranges generally from 400 to 1,100 feet, total thickness of the black shale component of the unit exceeds 200 feet in only a few places in the western part of the play. Completion thicknesses range from a little less than 300 feet to a little more than 500 feet.

Production characteristics of Devonian shale reservoirs vary considerably from west to east, across the emerging area. In general, the area may be separated into three zones: the area west of Burning Springs anticline, the area eastward from the anticline to about 81°00', and the area to the east of 81°00' (Filer, 1985) (Figure Dbg-11). Stratigraphically, the area west of Burning Springs anticline is composed of black shales, rich in oil-prone organic matter, that are interbedded with lighter-colored shales that contain less organic matter. The area is relatively undeformed structurally so that a dense network of porous fractures has not been developed within the reservoir. Because of this lack of abundant fractures, permeability is low and very little oil is produced to the west of the Burning Springs anticline when compared to the region east of the anticline. Instead, to the west of the anticline, production is primarily gas, with initial open flows ranging from 25 to 350 Mcf/d. The oil-producing part of the play occurs

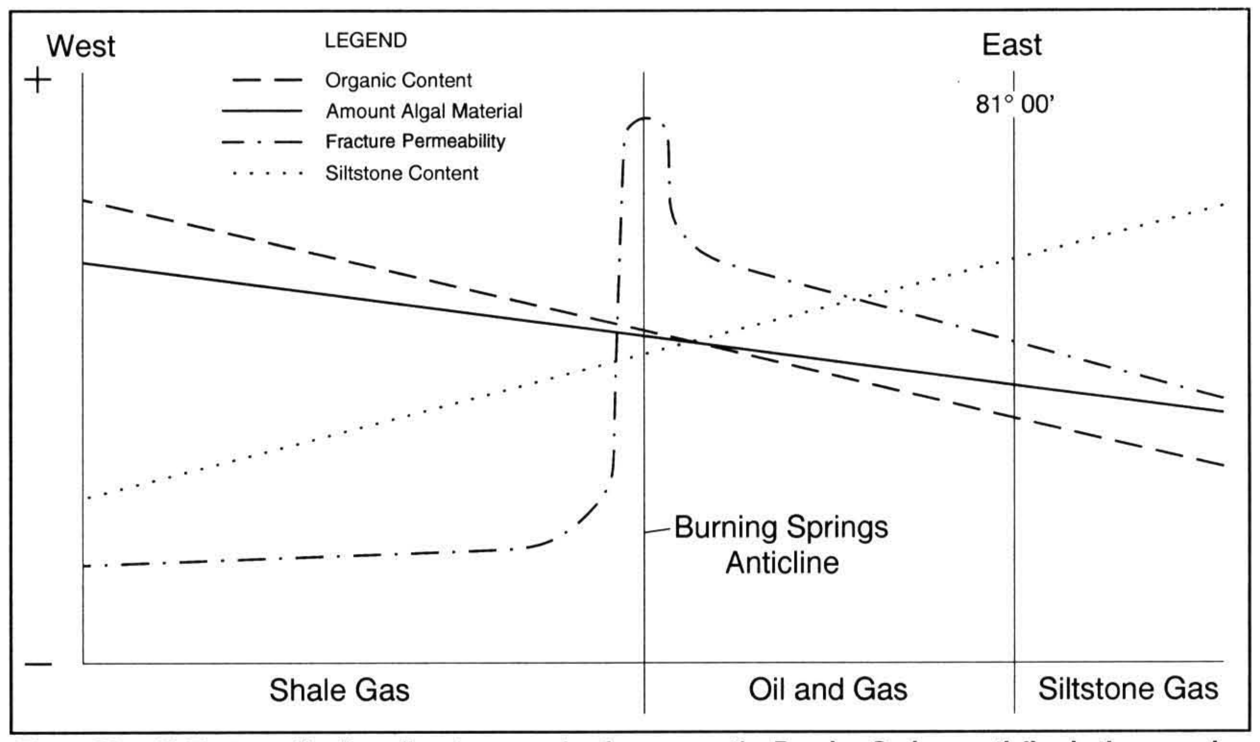


Figure Dbg-11. Factors affecting oil and gas production across the Burning Springs anticline in the emerging area. Modified from Filer (1985).

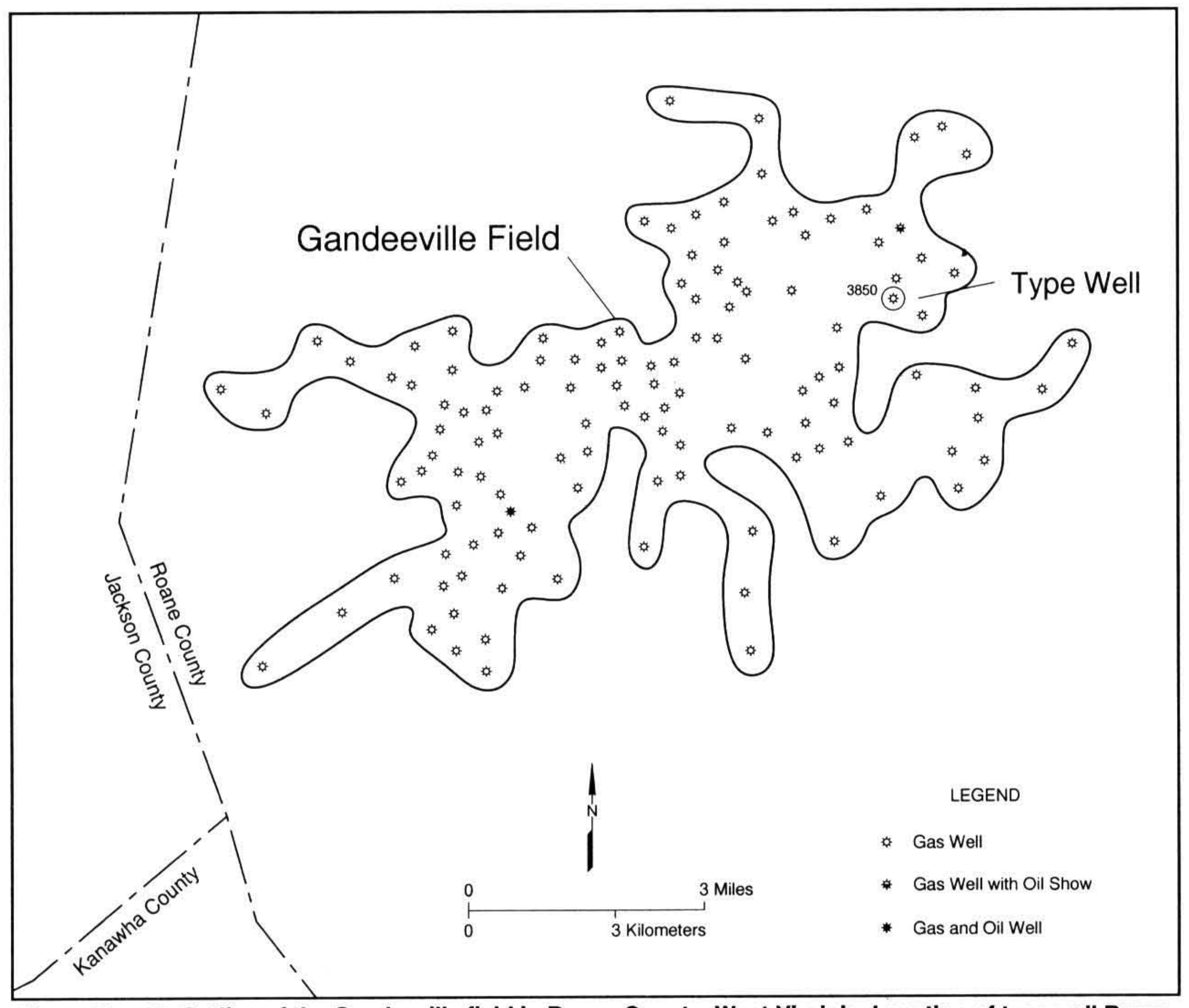


Figure Dbg-12. Outline of the Gandeeville field in Roane County, West Virginia. Location of type well Roane 3850 (Figure Dbg-6) is also shown. See Figure Dbg-2b for field location.

from the Burning Springs anticline eastward to about 81°00', where decollement-related fractures are abundant within the reservoir. East of 81°00', the reservoirs are siltier, organic content is lower and gas prone, thermal maturation is higher, and production is chiefly dry gas.

Reservoir and volumetric data for the Burnwell, St. Marys, and Gandeeville fields are summarized in Table Dbg-1. The Burnwell and St. Marys fields have coalesced with the continuous Devonian shale gas accumulation in western West Virginia. The Gandeeville field, however, still retains its identity.

Gandeeville field: The Gandeeville field is located in the southwestern part of Roane County, West Virginia (Figures Dbg-2b, Dbg-12). According to Sweeney (1986), most of the Devonian shale wells in this area are completed in the Upper Devonian undivided and in the lower part of the Huron Member. Other reservoirs include the Java Formation, the Angola Shale Member, and the Rhinestreet Shale Member of the West Falls Formation.

The Gandeeville field is located in an area beneath and between old, shallower oil fields (Flat Fork and Zona, which produce from the Pennsylvanian Salt sands to the north) and two lower Mississippian Big Injun sands oil fields (Walton [Rock Creek] and Clover-Rush Run-Fisher to the south and southeast).

The first well to penetrate the Devonian shales in the area of this field was Roane County, West Virginia, State Permit No. 602 (Roane 602). The No. 1 (26) F.A. Harper Bonnett Oil and Gas well was completed on July 9, 1952, at a total depth of 4,424 feet. The well was shot with nitroglycerin in the Lower Huron Member of the Ohio Shale, and the reported final open flow was 133 Mcfg/d. For nearly 30 years, no new shale wells were drilled in the area. Then, in 1981, 14 wells were drilled in the Gandeeville field, followed by 60 in 1982, five in 1983, 18 in 1984, 20 in 1985, and the final seven in 1986. One operator drilled 65 wells in the field, and a second operator drilled 31 wells. The remaining 29 wells were drilled by nine other operators who drilled between one and five wells each. This field is remarkable in that only two operators drilled more than 75 percent of the wells in the field. The small number of operators in Gandeeville field is quite a contrast to the St. Marys field in northwestern West Virginia (Figure Dbg-2), where 66 different operators drilled the 315 Devonian shale wells in the field. Of these 66 operators, 47 drilled between one and five wells each.

Elevations of the base of the Huron Member range generally from about 3,500 to about 3,750 feet below sea level, at a depth of about 4,500 feet (Figure Dbg-13). The Gandeeville field overlies a structural depression, rather than an anticlinal high. A type log for this field, Roane 3850 (Figure Dbg-6), illustrates four perforated intervals. This type of completion of several zones or stages up to several hundred feet thick was common in the emerging area.

Resources and Reserves

A way to calculate the resource potential of the play is to use existing well and field production data, estimated drainage areas for wells, and the area of the play. For the purposes of this assessment, this play is divided into three main areas: the region along the shoreline in Ohio, Pennsylvania, and New York; the emerging area of West Virginia and Ohio; and the broad area that extends from western New York through Pennsylvania to western West Virginia (Figures Dbg-4a, Dbg-4b). Production data are sufficient only in the area of the Lake Erie shoreline fields (Figure Dbg-2a) and in the emerging area (Figure Dbg-2b) to make an assessment of the potential amount of recoverable gas for this play.

Weight averaged data (National Petroleum Council, 1992) for the ultimate recovery of 49 wells in Roane and Kanawha counties near the emerging area of West Virginia is about 274 MMcf per well. In comparison, Brown (1976) studied more than 3,000 wells in West Virginia and calculated that, in an area of 1,500 square miles, ultimate recovery of shale gas in the state is 893 bcf, for an average ultimate recovery of about 300 MMcf per well (Patchen and Hohn, 1993). Patchen and Hohn (1993) assumed an average ultimate recovery of 350 MMcfg per well, although their estimate, like Brown's (1976), is generalized for Devonian shale gas production throughout West Virginia. In the Big Sandy area, in Mingo, Logan, and Lincoln counties, West Virginia (See R. Boswell, Upper Devonian black shales play, this atlas), the average shale well is estimated to produce 500 MMcf over a 40-year span (Patchen and Hohn, 1993). Recovery rates calculated by Brown (1976) and Avila (1976) for West Virginia and eastern Kentucky, respectively, range from 8.2 to 8.4 percent of the original gas-in-place.

In West Virginia, the emerging area encompasses Pleasants, Wood, Ritchie, Wirt, Roane, and Calhoun counties, and small parts of Kanawha and Boone counties. The area extends into adjacent counties in southern Ohio, including Washington, Monroe, Noble, and the southernmost part of Guernsey County. All told, the area of this subplay is about 3,447 square miles (Table Dbg-4). Table Dbg-4 lists the counties, areas, and available estimates on average ultimate recovery of gas for wells in the main part of the emerging area of West Virginia

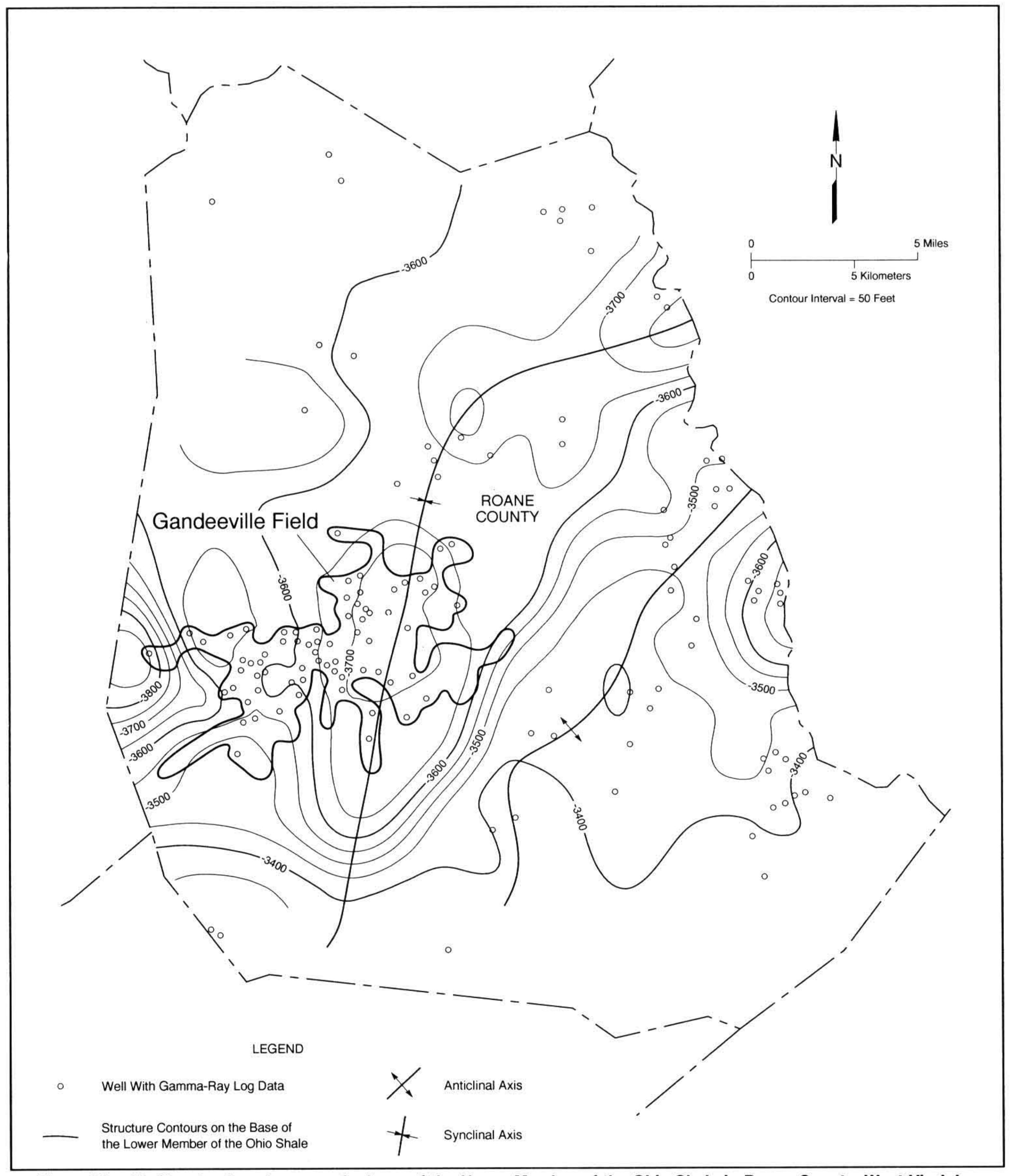


Figure Dbg-13. Structural contours on the base of the Huron Member of the Ohio Shale in Roane County, West Virginia.

Table Dbg-4. Estimated ultimate recovery of gas in emerging area of western West Virginia and eastern Ohio. Cumulative production estimated from production data given in Patchen and Hohn (1993).

County/State	Area (Square Miles)	Estimated Total Wells (60-acre spacing)	Estimated Ultimate Cummulative Production/Well (MMcf)	Total Estimated Ultimate Recovery (MMcf)
Pleasants, WV	131	1,397	70	97,813
Wood, WV	367	3,915	70	274,027
Ritchie, WV	454	4,843	70	338,987
Wirt, WV	235	2,507	140	350,933
Roane, WV	484	5,163	140	722,773
Calhoun, WV	280	2,987	140	418,133
SUBTOTAL (WV)	1,951	20,811	106	2,202,667
Washington, OH	640	6,827	100	682,667
Monroe, OH	457	4,875	100	487,467
Noble, OH	399	4,256	100	425,600
SUBTOTAL (OH)	1,496	15,957	100	1,595,733
TOTAL	3,447	36,768	103	3,798,400
Tested Area	328	3,500	126	441,000
Undiscovered Gas	3119	33,268	101	3,357,400

Total wells for achieving estimated ultimate recovery of the resource in these counties is given by the formula: Number of wells/county = (640 acres/square mile/60 acres/well) = 10.66 wells/square mile x number of square miles/county.

Table Dbg-5. Estimated ultimate recovery of gas in the shoreline region of Ohio, Pennsylvania, and New York. Cumulative production of 150 MMcf per well was calculated from an assumed average long-term production of 10 Mcf/d x 300 days per year x 50 years.

County/State	Area (Square Miles)	Estimated Total Wells (150-acre spacing)	Estimated Ultimate Cummulative Production/Well (MMcf)	Total Estimated Ultimate Recovery (MMcf)
Ashtabula, OH	703	3,023	150	453,435
Cuyohoga, OH	459	1,974	150	296,055
Lake, OH	231	993	150	148,995
Lorain, OH	495	2,129	150	319,350
Erie, PA	804	3,457	150	518,580
Chautauqua, NY	1,064	4,575	150	686,250
TOTAL	3,756	16,151	150	2,422,665
Tested Area	350	1,000	150	150,000
Undiscovered Gas	3,406	15,151	150	2,272,665

Total wells for achieving estimated ultimate recovery of the resource in these counties is given by the formula: Number of wells/county = (640 acres/square mile/150 acres/well) = 4.27 wells/square mile x number of square miles/county.

and Ohio.

Ultimate recoveries were estimated by extrapolating production estimates of about 20 Mcf/d for gas wells in Wirt, Roane, and Calhoun counties, and about 10 Mcf/d for wells in Ritchie, Wood, and Pleasants counties for a period of 20 years (for example, 10 Mcf/d x 365 days per year = 3,650 Mcf/year x 20 years = 73 MMcf). Approximate estimated ultimate recovery for the emerging area is calculated to be about 3.8 tcf. The U.S. Geological Survey (Milici, 1995), using somewhat different play boundaries and methodology, calculated a mean estimated ultimate recovery for this general area as 3.3 tcf.

A similar analysis for the area of the shoreline fields, with an estimated ultimate recovery per well of 150 MMcf, results in a total ultimate recovery approximately equal to 2.42 tcf for that area (Table Dbg-5). If as many as 1,000 wells have been drilled to date in the shoreline region, then 15,151 wells remain to be drilled and the amount of undiscovered gas is approximately 2.27 tcf. Of the estimated 3 tcfg produced from the Devonian shale basinwide, approximately 0.59 tcf will be produced from existing wells in the area of this play, 0.15 from the shoreline fields, and 0.44 tcf from the emerging area. Total undiscovered gas for the two areas is estimated to be 5.6 tcf (3.36 + 2.27).

Future Trends

Much of the Devonian shale section in the Appalachian basin has been drilled extensively: in the highly productive areas of the Big Sandy gas field in eastern Kentucky and southwest West Virginia; in the emerging area of western West Virginia and adjacent Ohio; along the southern shores of Lake Erie; and in the area of deeper plays, especially in the main area of production from the Clinton Sandstone play in central and eastern Ohio and adjacent Pennsylvania (Tetra Tech, n.d. b). Because the Clinton was the principal drilling target in this latter area, wells generally were not completed in the Devonian shales, and they remain largely untested. As Clinton wells play out, however, operators should consider plugging back and testing the Devonian shale section prior to abandoning the wells (Tetra Tech, n.d. b).

Better areas for hydrocarbon exploration in the Devonian shales of the Appalachian basin are anticipated to occur east of the 0.6 percent Ro isoline, west of the 1.5 percent Ro isoline, and where the aggregate hydrocarbon content of the Devonian shale section exceeds 0.8 kg C/cm^2 (Milici, 1993; Schmoker, 1993) (Figure Dbg-4b). Although most of the area of this play lies between the 0.6 percent Ro and 1.5 percent Ro isolines and is mature with respect to oil generation, total content of organic matter is less than 0.8 kg C/cm^2 by definition, and most wells decline rapidly within a year of completion and produce relatively little gas or oil (Patchen and Hohn, 1993).

In western West Virginia, southeastern Ohio, Pennsylvania, and New York, the middle and upper parts of the Devonian shale section are dominated by green and gray shales and siltstones (Chagrin) which contain relatively low amounts of organic matter. In contrast, the lower part of the Devonian shale section in the area of this play consists predominantly of black shales rich in organic matter, and is lithologically similar to the bulk of the Devonian shale section in the Big Sandy area. Where these black shales are not overmature in the deeper part of the play to the east, they may be prospective. Exploration strategies, thus, should be developed to locate areas with a maximum amount of total organic matter in the Devonian shale section, in areas which are mature with respect to oil and/or natural gas, and where the potential gas shale reservoirs are likely to be extensively fractured (Figure Dbg-14).

Technological improvements may greatly facilitate exploration and development of naturally fractured shale-gas reservoirs. It is anticipated that use of modern seismic technology to identify areas of low-density, gas-bearing, decollement-related fractured reservoirs may increase success ratios significantly during exploration. In addition, improvements in well drilling, stimulation, completion practices, and the use of directional drilling techniques may increase productivity so that in the future, more marginal wells will be completed as commercial.

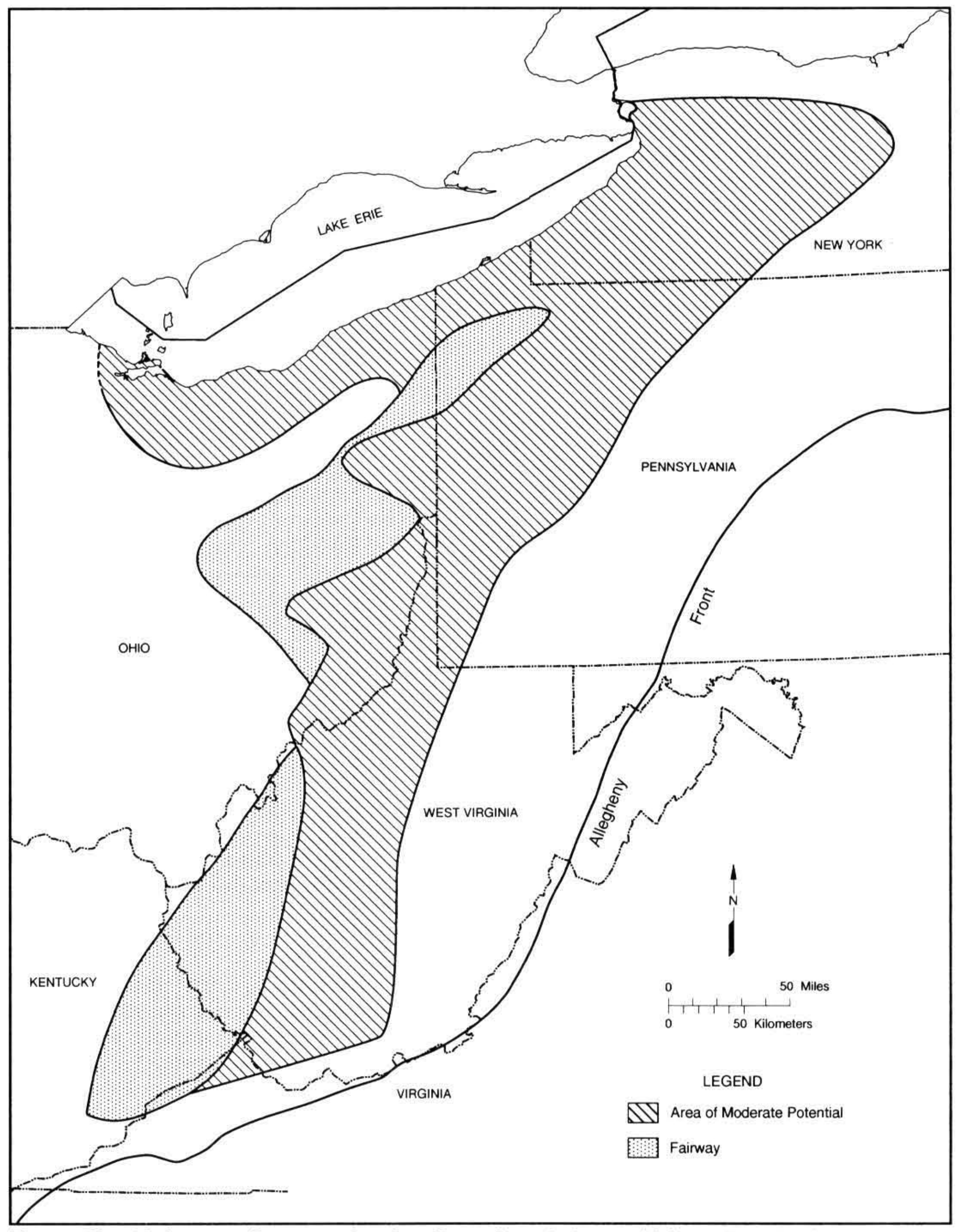


Figure Dbg-14. Interpretive map showing Devonian shale gas "fairway" and adjacent area of moderate potential.

PLAY UDs: UPPER DEVONIAN BLACK SHALES

by Ray Boswell, EG&G TSWV, Inc.

Location

The Upper Devonian black shale play encompasses natural gas production and potential from thick units of fractured, organic-rich, and highly-radioactive marine shales deposited as distal facies of the Acadian clastic wedge. Black shales ranging in age from Middle Devonian to Early Mississippian are potential reservoirs from western New York to southeastern Kentucky (Figure UDs-1). The majority of gas production from black shales to date is derived from the Big Sandy and associated fields of eastern Kentucky and southwestern West Virginia where the primary reservoir is the Huron Member of the Ohio Shale. Additional minor production has been obtained from the Upper Devonian Rhinestreet Member of the West Falls Formation, Dunkirk Shale Member of the Perrysburg Formation, and the Cleveland Member of the Ohio Shale, as well as the Mississippian Sunbury Shale and Lower Devonian Marcellus Shale at scattered locations throughout the basin.

As traced eastward, individual black shale units grade into and intertongue with distal turbidites and non-black shales of the Catskill delta complex. This zone of lateral facies change has proven to be productive through the commingling of thick intervals dominated by thinly interbedded black, gray, and gray-green shales and siltstones. This production is discussed fully by Milici (Upper Devonian fractured black and gray shales and siltstones play, this atlas).

Production History

Natural gas production from Upper Devonian black shales first occurred in 1821 from a well dug 27 feet into the Dunkirk Shale Member of the Perrysburg Formation at Fredonia, Chautauqua County, New York. Subsequent development along the southern shore of Lake Erie resulted in predominantly commingled siltstone and shale production (Broadhead, 1993). Several other small fields that produced primarily from the black shale were discovered in western New York state in the late 1800s and early 1900s. These fields produced from both the Marcellus Shale and the Rhinestreet Member of the West Falls Formation. The production from these wells was generally sufficient only for local use; therefore, very little data are available. See Milici (Upper Devonian black and gray shales and siltstones play, this atlas) for further discussion of the New York fields.

In 1921, unexpected gas flows of up to 1,000 Mcf/d from the Devonian shale sequence interrupted exploratory drilling for deeper Corniferous reservoirs in the Big Sandy area of eastern Kentucky. Subsequent drilling proved the shale to be a consistent producer and development was rapid. By the mid-1930s, numerous local discoveries had been consolidated, and the overall area of production expanded throughout a seven-county, 250,000-acre area in eastern Kentucky and southern West Virginia that was recognized as one of the largest gas accumulations in the U.S. (Ley, 1935). Attempts to extend shale production beyond the Big Sandy area resulted in significant new field discoveries at Ashland field (1912) in Kentucky, at Getaway field (1930) in southern Ohio, and at the Cottageville (1930) and Midway-Extra (1947) fields in West Virginia (Figure UDs-2; Tables UDs-1, UDs-2). However, the primary drilling area remained the Big Sandy field. Drilling at Big Sandy peaked in the 1940s when more than 1,400 wells were drilled (Hamilton-Smith, 1993).

The uniqueness of the black shale as a reservoir became evident early in the development of the play. Unlike the established sandstone reservoirs in the eastern half of the basin, the distribution of good and poor shale wells seemed disconnected to either stratigraphic changes in reservoir character or to local structure. Also, the stratigraphic location of shows within the shale sequence was erratic. Initial production declines were typically steeper than seen elsewhere in the basin, although production would often stabilize after several years and wells apparently could produce at low and near-constant levels almost indefinitely. Although the idea had been discussed earlier, it was not until the 1950s that the unique characteristics of shale gas production were widely attributed to natural fracturing in the reservoir (Hunter and Young, 1953).

Although gas production has been sporadically obtained from the Devonian shale during development of deeper horizons such as the Silurian "Clinton" sandstone in east-central Ohio (Janssens and deWitt, 1976), no significant new black shale fields have been discovered in recent decades. However, development of existing black shale fields was revitalized in the 1970s and 1980s, first in response to rising gas prices, and then later, to federal tax incentives. Both the Cottageville and Midway-Extra fields were extended during this period, and drilling in the Big Sandy field approached the record levels of the 1940s. In addition, a new area of drilling emerged in the vicinity of the Burning Springs anticline (north-central West Virginia and adjacent Ohio) with significant oil production (Filer, 1985; Patchen and Hohn, 1993). Because the thick perforated intervals in this new area typically include numerous interbedded non-black shales and siltstones, this area is described by Milici (Upper Devonian fractured black and gray shales and siltstones play, this atlas).

Cumulative production for the Devonian black shales in the Appalachian basin is estimated at approximately 3 tcfg (de Witt, 1986) from roughly 10,000 wells, or approximately 300 MMcfg/well. Of this total, it is likely that as much as 2.5 tcfg have been produced from the Big Sandy field (Charpentier and others, 1982).

Stratigraphy

For the first half-century of production from the black shales, much of the productive interval was stratigraphically undivided. Throughout the producing area, broad terms such as "Devonian shales" or "brown shales" were used to describe the entire rock sequence from the base of the Berea Sandstone to the top of the Onondaga Limestone. Schwietering's (1970) correlations in the subsurface of eastern Ohio were the first to relate the established outcrop lithostratigraphy with subsurface intervals. Further subsurface stratigraphic work in Ohio

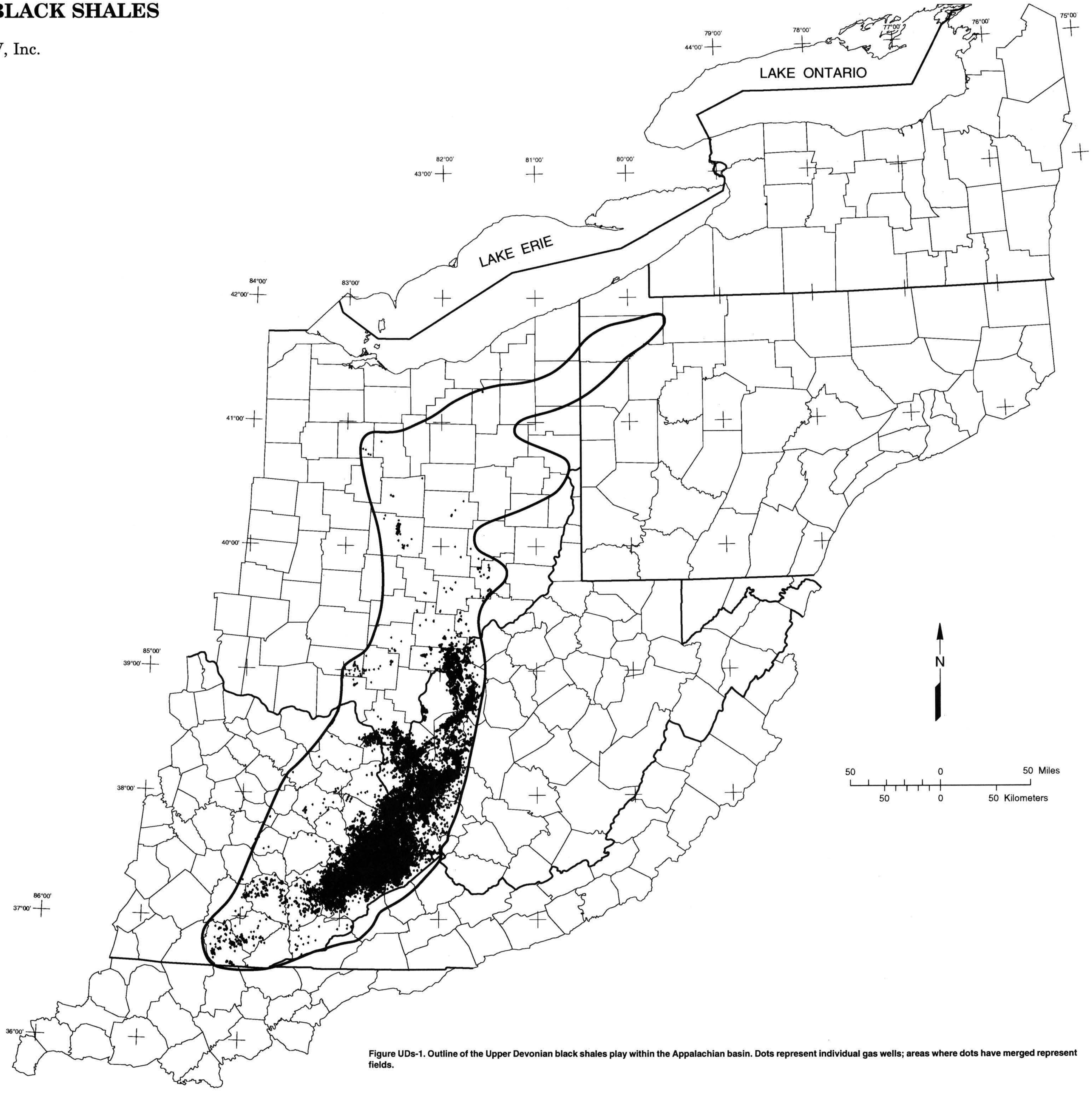


Figure UDs-1. Outline of the Upper Devonian black shales play within the Appalachian basin. Dots represent individual gas wells; areas where dots have merged represent fields.

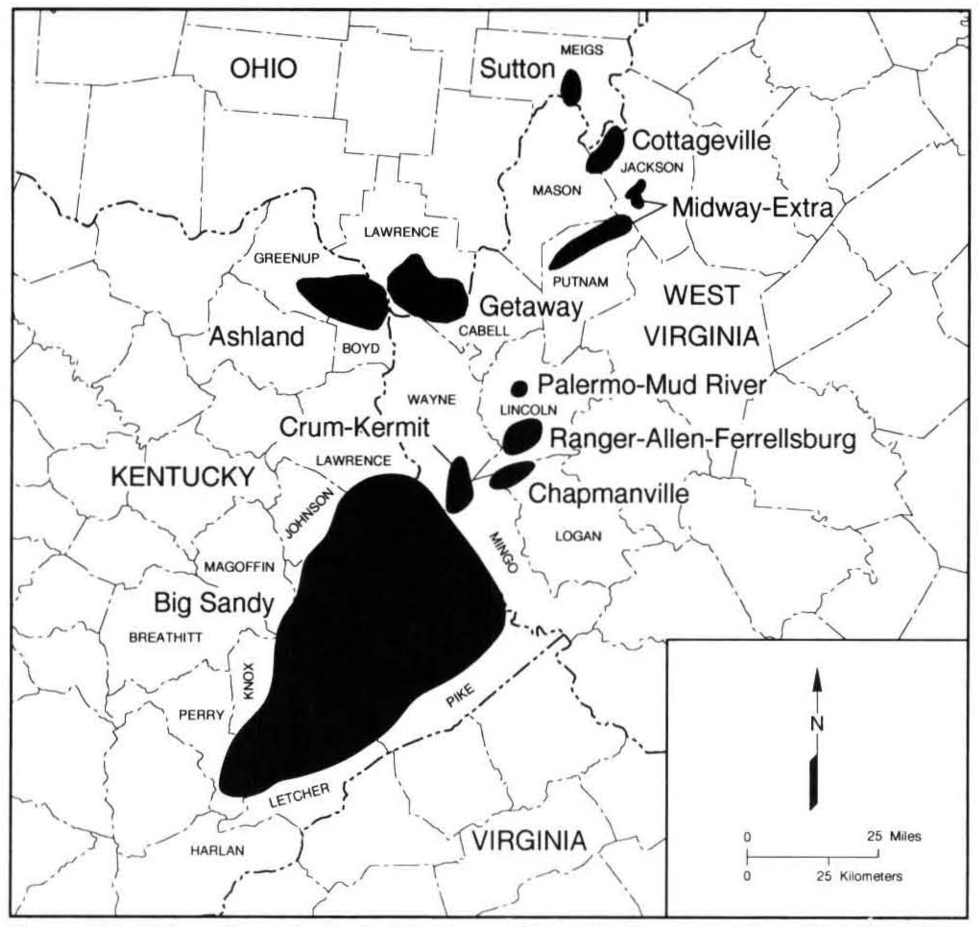


Figure UDs-2. Location of selected fields mentioned in the text or listed in Table UDs-1 producing from the Upper Devonian black shales play.

(Majchszak, 1980), southern West Virginia (Bagnall and Ryan, 1976; Patchen, 1977; Neal, 1979), Kentucky (Wilson and others, 1981), and basin-wide (West, 1978; Roen and others, 1978b; Wallace and others, 1978; de Witt and others, 1993) was initiated through the U.S. Department of Energy's (US DOE) Eastern Gas Shales Project (EGSP) administered by the Morgantown Energy Technology Center (METC) in Morgantown, West Virginia, and its predecessors. These studies provided a coherent subsurface stratigraphic framework based on the formal nomenclature standardized in the outcrop belts of western New York and central Ohio (Figures UDs-3, UDs-4). The lithostratigraphy for the Devonian black shale reservoirs is summarized in Figure UDs-5.

Deposition of black shales began within a linear, equatorial, foreland basin in which subsidence, sediment influx, and even climate were affected by the active Acadian orogenic belt to the east. During the early stages of the orogeny, basin slope at the distal edge of Catskill sedimentation was eastward toward the foreland basin from peripheral highs located along the present-day Cincinnati arch (Ettensohn and others, 1988). As a result, Middle and Lower Upper Devonian black shales pinch out as a result of nondeposition as traced westward upon the ascending craton margin (Figure UDs-6). Through four stages of orogeny, black shale deposition periodically spread and retreated within the basin (Ettensohn, 1985).

As Acadian tectonism waned in the latest Devonian, foreland basin subsidence abated and the basin was progressively filled, replacing the eastward slope with a gradual westward slope. In addition, the erosive removal of tectonic loads from the orogenic belt relaxed lithospheric flexure (peripheral bulge of Quinlan and Beaumont, 1984) that had supported the Cincinnati arch and other structures. Subsequently, deposition spread westward across the craton (Ettensohn and others, 1988), creating a continuous cratonic sea that accumulated organic-rich muds southward into Tennessee and Alabama (Chattanooga Shale), westward into the Illinois basin (New Albany Shale), northwestward into the Michigan basin (Antrim Shale), and beyond (Provo, 1977).

The basal unit within the black shale play is the Middle Devonian Marcellus Shale of the Hamilton Group. The Marcellus Shale is thickest in the northeastern part of the basin and thins to the south, west, and north (Figure UDs-7a). The Hamilton Group is separated from younger black shale-bearing units within the northeastern part of the basin by the Tully Limestone and within the western part of the basin by a depositional hiatus that decreases in magnitude eastward. In central Ohio, the hiatus is marked by a disconformity separating Middle Devonian shales of the lower Olentangy Shale (Hamilton-equivalent) from the Upper Devonian upper Olentangy shale (probably equivalent to some part of the Java and West Falls formations further to the east). Within the basin interior, much of the hiatus is represented by four Upper Devonian formations that onlap westward upon the unconformity and contain black shale members at the base. In ascending order, they are as follows: Genesee Formation, with basal, black Geneseo Shale Member; Sonyea Formation, with basal, black Middlesex Shale Member; West Falls Formation, with basal, black Rhinestreet Shale Member; and Java Formation, with basal, black Pipe Creek Shale Member. Of these four units, the Rhinestreet is the most extensive and significant gas producer, primarily in southwestern West Virginia. The Rhinestreet occurs as a thick, linear belt aligned with the depositional strike of the basin (Figure UDs-7b). The remaining units are important subsurface marker beds, but are generally too thin to stand alone as commercially viable gas reservoirs.

The Upper Devonian Ohio Shale includes two major black shale tongues: a basal Huron Member, which is the primary gas-producing black shale in the basin, and an overlying Cleveland Member. Both black shale tongues thicken as they grade into non-black shales as traced eastward from the Cincinnati arch toward the basin center (Figure UDs-7c). Notably, the lower part of the Huron Member grades eastward into gray Perrysburg Formation along a nearly vertical facies boundary. Only a thin basal black shale, the Dunkirk Shale Member of the Perrysburg Formation, persists further eastward into the subsurface where it closely marks the Frasnian-Famennian boundary. The Cleveland Member of the Ohio Shale (Figure UDs-7d) is separated from the underlying Huron Member by the Three Lick Bed (Provo and others, 1977) which represents the distal edge of the westward-thinning Chagrin Shale, as well as the interval of maximum progradation of the Catskill delta complex.

	TABLE UDs-1	Big Sandy KY	Ashland KY	Cottageville WV	Midway-Extra WV	Ranger-Allen-Ferrellsburg WV	Palermo WV	Crum-Kermit WV	Chapmanville WV	Getaway OH	Sutton OH	Nora VA	Roaring Fork VA
BASIC RESERVOIR DATA	POOL NUMBER			47158813	47278813	47275813	47234813	47243813	47245813				
	DISCOVERED	1915	1912	1930	1947	1943	1927	1929	1946	1930	1945	1949	1954
	DEPTH TO TOP RESERVOIR	3,144	1,800	3,425	3,709	3,104	3,280	2,963	3,082			3,990-6,304	4,225-6,480
	AGE OF RESERVOIR	Devonian	Devonian	Upper Devonian	Upper Devonian	Upper Devonian	Upper Devonian	Upper Devonian	Upper Devonian	Devonian	Devonian	Devonian	Devonian
	FORMATION	Ohio Shale	Ohio Shale	Ohio Shale	Ohio Shale	Ohio Shale	Ohio Shale	Ohio Shale	Ohio Shale	Ohio Shale	Ohio Shale	Chattanooga Shale	Chattanooga Shale
	PRODUCING RESERVOIR	Ohio Shale	Ohio Shale	Lower Huron Member	Lower Huron Member	Lower Huron Member	Lower Huron Member	Lower Huron Member	Lower Huron Member	Lower Huron Member	Ohio Shale	Chattanooga	Chattanooga
	LITHOLOGY	shale	shale	shale	shale	shale	shale	shale	shale	shale	shale	shale	shale
	TRAP TYPE	fracture	fracture	fracture	fracture	fracture	fracture	fracture	fracture	fracture	fracture	fracture	fracture
	DEPOSITIONAL ENVIRONMENT	prodelta	prodelta	prodelta	prodelta	prodelta	prodelta	prodelta	prodelta	prodelta	prodelta	prodelta	prodelta
	DISCOVERY WELL IP (Mcf)		500		251			387		839	1,600		
	DRIVE MECHANISM	gas	gas	gas	gas	gas	gas	gas	gas	gas	gas	gas	gas
	NO. PRODUCING WELLS	6,463	226	37	183	310	160	505	125	88	400	128	163
	NO. ABANDONED WELLS	580	15	58	12	30	51	70	7	19	16		
	AREA (acreage)	1,500,000		8,360	21,255	39,780	20,889	99,612	19,668		10,040		
	OLDEST FORMATION PENETRATED	Basal sandstone	Clinton	Juniata	Juniata	Upper Ordovician	Helderberg	Conococheague	Helderberg	Queenston		Onondaga	Wildcat Valley Sandstone
	EXPECTED HETEROGENEITY DUE TO:	fractures	fractures	fractures	fractures	fractures	fractures	fractures	fractures	fractures	fractures	fractures	fractures
RESERVOIR PARAMETERS	AVERAGE PAY THICKNESS (ft.)												
	AVERAGE COMPLETION THICKNESS (ft.)	532	189	316	421	542	384	360	402	200	20	361	633
	AVERAGE POROSITY–LOG (%)	4.3								7	7		
	MINIMUM POROSITY–LOG (%)	1.5								6	2		
	MAXIMUM POROSITY–LOG (%)	11								8	9		
	NO. DATA POINTS									7	7		
	POROSITY FEET												
	RESERVOIR TEMPERATURE (°F)	84	74				92						
	INITIAL RESERVOIR PRESSURE (psi)	800		865	710					475	651-858	350-1,100	1,100
	PRODUCING INTERVAL DEPTHS (ft.)	1,700-4,930		3,028-4,552	2,832-5,595	2,200-4,312	2,554-4,100	1,886-4,678	2,230-4,378	1,900-2,800	1,600-4,000	3,990-6,505	4,225-6,950
	PRESENT RESERVOIR PRESSURE (psi) / DATE	400/1993	505/1988	186/1985	400-950/1979						274-627/1982		
FLUID & GAS PROPERTIES	Rw (Ωm)												
	GAS GRAVITY (g/cc)	0.706			0.672	0.72		0.708	0.707				
	GAS SATURATION (%)	>50											
	WATER SATURATION (%)	<10											
	COMMINGLED	yes		no	no	yes	no	no	yes				
	ASSOCIATED OR NONASSOCIATED	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated
	Btu/scf	1,150			1,181	1,226		1,223	1,235				
VOLUMETRIC DATA	STATUS (producing, abandoned, storage)	producing		producing	producing	producing	producing	producing	producing	producing	producing	producing	producing
	ORIGINAL GAS IN PLACE (Mcf)	2,000,000,000											
	ORIGINAL GAS RESERVES (Mcf)	3,400,000,000			39,900,000								
	PRODUCTION YEARS	1921-1994		1948-1993	1950-1993	1945-1993	1939-1993	1929-1993	1953-1993				
	REPORTED CUMULATIVE PRODUCTION (Mcf)	2,500,000,000		10,994,200	17,566,400	26,550,000	22,340,000	37,719,000	5,290,000	1,760	8,300		
	NO. WELLS REPORTED			57	132	70	75	131	24				
	ESTIMATED CUMULATIVE PRODUCTION (Mcf)												
	REMAINING GAS IN PLACE (Mcf)/DATE	17,500,000								2,900/1994	13,800/1994		
	REMAINING GAS RESERVES (Mcf)/DATE	9,000,000								2,600/1994	12,500/1994		
	RECOVERY FACTOR (%)	17								50	50		
	INITIAL OPEN FLOW (Mcf/d)			519	28	1,927	101	1,053	470				0-show
	FINAL OPEN FLOW (Mcf/d)	299	281	412	252	234	175	234	865	190-225	79-148	50-1,600	112-190

The youngest of the black shales is the Mississippian Sunbury Shale. In much of the basin, the Sunbury Shale is separated from the Ohio Shale by the Berea Sandstone and Bedford Shale. Like the members of the Ohio Shale, the Sunbury thins eastward from a maximum thickness along the western margin of the basin. Because the underlying Bedford-Berea interval either also grades southward into black shale (Pashin and Ettensohn, 1987) or pinches out (de Witt and others, 1993), the Sunbury and Ohio shales coalesce and are recognized as the Gassaway Member of the Chattanooga Shale in southern Kentucky and eastern Tennessee (Roen, 1984).

Benthic fossils are virtually absent from the black shales. However, remains of the planktonic algae *Tasmanites* and the land plant *Protosalvinia (Foerstia)* are locally abundant. The latter form is restricted to a narrow zone within the lower Huron Member of the Ohio Shale and equivalents, and is commonly used as an aid to correlation (Kepferle, 1993). *Tasmanites*, however, is abundant at many horizons to the point that it obscures all other forms and imparts a brownish-red color to the rock.

The black shales of the Appalachian basin are marine units characterized by concentrations of organic carbon that locally approach 30 percent by weight of the rock (Zielinski and McIver, 1982). For deposits such as these, low rates of detrital influx must be combined with high rates of organic matter production. In addition, conditions must be established that hinder or stop the destruction of the organic matter before deep burial can be achieved. The most commonly cited mechanism for preservation of organic matter in the Devonian of the Appalachian basin is the establishment of oxygen-deficient (anoxic) bottom waters (see Ettensohn and Barron, 1981) related to water stagnation caused by density or temperature stratification in a closed or silled basin (Rhoads and Morse, 1971). As an alternative to basin stagnation, Robl and Barron (1988) invoked equatorial upwelling of nutrient-rich waters and resulting rapid oxygen withdrawal as a mechanism for the spread of anoxia recorded in the Cleveland Member of the Ohio Shale.

Many researchers suspect that water depths in the Appalachian basin during deposition of the black shales was similar to that seen in certain modern anoxic settings (150 meters or more) (Ettensohn and others, 1988; Kepferle, 1993). However, there is strong evidence that at least some Devonian black shales formed in relatively shallow water (see Schwietering, 1977; McCollum, 1988), indicating that the manner in which black shale deposition was established and the water depth at which it occurred might not necessarily be the same for all black shales (Provo, 1977).

Sedimentologic models aimed at describing the apparent cyclicity of black shale deposition usually focus on repetitive decreases in the rate of sediment influx. Ettensohn and Barron (1981) and Ettensohn (1985) related reductions in sediment supply to alternating wet and dry climates related directly to episodic tectonism in the Acadian orogenic belt. Other researchers argue that the primary cause of black shale cyclicity is periodic rises in sea level that promote water stagnation, distance basinal environments from sources of sediment supply, and reduce overall sediment supply by promoting deposition in nearshore and terrestrial environments (Dennison, 1985; Kepferle, 1993). Filer (1994) has shown that 11 separate and thin black shales within the Java and West Falls formations can be correlated regionally and represent events that would appear to be too short-lived to be tectonically derived. Boswell (1988b) also argued for eustatic control on shifting of the black shales within the Ohio Shale (Figure UDs-8) by showing the correlation between the shifting of those units, age-equivalent shoreline sandstones, and the global sea-level curve of Johnson and others (1985).

TABLE UDs-2	Big Sandy KY
AVERAGE POROSITY–CORE (%)	4.3
MINIMUM POROSITY–CORE (%)	0.4
MAXIMUM POROSITY–CORE (%)	8.6
NO. DATA POINTS	12
AVERAGE PERMEABILITY (md)	0.1

Structure

The various fields within the black shale play are complex combination traps. Production is controlled largely by the occurrence of zones of intense natural fracturing within a uniformly gas-saturated shale sequence. Unfortunately, the location, orientation, and intensity of natural fractures do not correlate well with the known near-surface fold and fault systems, and are therefore difficult to predict. However, research focusing on the role of reactivated basement faults (or fault zones) in causing fault- and/or flexure-related fracturing in overlying shale units has provided a workable exploration rationale (Negus-deWys, 1979; Lowry and others, 1990; Shumaker, 1993). Such fault zones can be seen directly on seismic lines or inferred from the structural configuration of overlying units. Many of these structures, particularly the bounding faults of the Cambrian-aged Rome trough (see R. Shumaker, Geologic structure of the Appalachian basin, this atlas) have shown evidence of reactivation throughout the Paleozoic (Negus-deWys, 1979; Lee, 1980; Shumaker, 1993).

Widespread, interconnected fractures in the black shale play are well-developed in eastern Kentucky and southwestern West Virginia. The extensive fracturing in this area may be related to the conjunction and periodic reactivation of several major basement structures combined with the position of this area relative to the western terminus of detached Alleghenian deformation (Figure UDs-9) (Kubik, 1993; Shumaker, 1993) (see Big Sandy field, below). Elsewhere, smaller isolated black shale fields may be cases in which fracturing occurs locally over specific, smaller-scale basement structures in the absence of a regional fracture network (see Midway-Extra and Cottageville fields, below).

The degree to which fractures are open and available for production may be closely tied to tectonic stress. In areas of high stress ratio (maximum horizontal stress divided by vertical stress), elevated horizontal stresses act to hold both natural and induced fractures closed. A compilation of measured stress ratios by Komar and Bolyard (1981) (Figure UDs-10) shows the correlation between low stress ratio and areas of historical production. Although fractures in the black shale fields are the result of structural events, the vertical distribution and intensity of fracturing is strongly influenced by the lithology of the shale (Figure UDs-11). Based on core studies conducted through US DOE and Gas Research Institute (GRI) initiatives (Martin and Nuckols, 1976; Kubik, 1993), fracture intensity seems to be greatest within, or along the contacts of, the most organic-rich layers. Among fractures, high-angle macrofractures may be the most important to production (Vinopal and others, 1979). Typical effective fracture widths measured in cores from Pike County, Kentucky, range from 0.3 to 2.4 microns (Ning and others, 1993). Secondary dolomite has often been cited as important to propping open natural macrofractures (Patchen and Larese, 1976; Larese and Heald, 1977). Lastly, fracturing in the shales may have been so intense in certain areas as to destroy the ability of the rock to seal, allowing the gas to fully escape the shale; an example of this phenomena has been reported from a section above the Warfield fault (Lowry and others, 1989). A synopsis of the orientations of natural fractures in cored wells in the play area and others not in the play area is presented in Figure UDs-12 (Shumaker, 1993).

Reservoir

The reservoirs in the black shale play are organic-rich, finely-laminated, gas-saturated shales that are unique (unconventional) reservoirs because they serve as the primary gas source rock, the reservoir, and the seal. Matrix porosity is low, perhaps ranging from 1.0 to 5.0 percent. Matrix permeability is virtually nonexistent: calculated values are typically on the order of from 10^{-8} or 10^{-9} md (Ning and others, 1993). Detrital materials represent from 60 to 98 percent of the black shales in eastern Kentucky in the following approximate proportions: silt and clay-sized quartz (42 percent), illite (34 percent), kaolinite (6 percent), and feldspar (4 percent) (Woock, 1982; Ettensohn and others, 1988). Authigenic minerals such as pyrite, dolomite, and others constitute 5 to 10 weight percent of the shales.

Gas content within the black shales varies regionally in accordance with changes in thickness, pressure, organic carbon content, and thermal maturity. Because the shale is virtually impermeable, commercially viable production to date has required an interconnected natural fracture system that can be accessed either by the wellbore or by induced fractures.

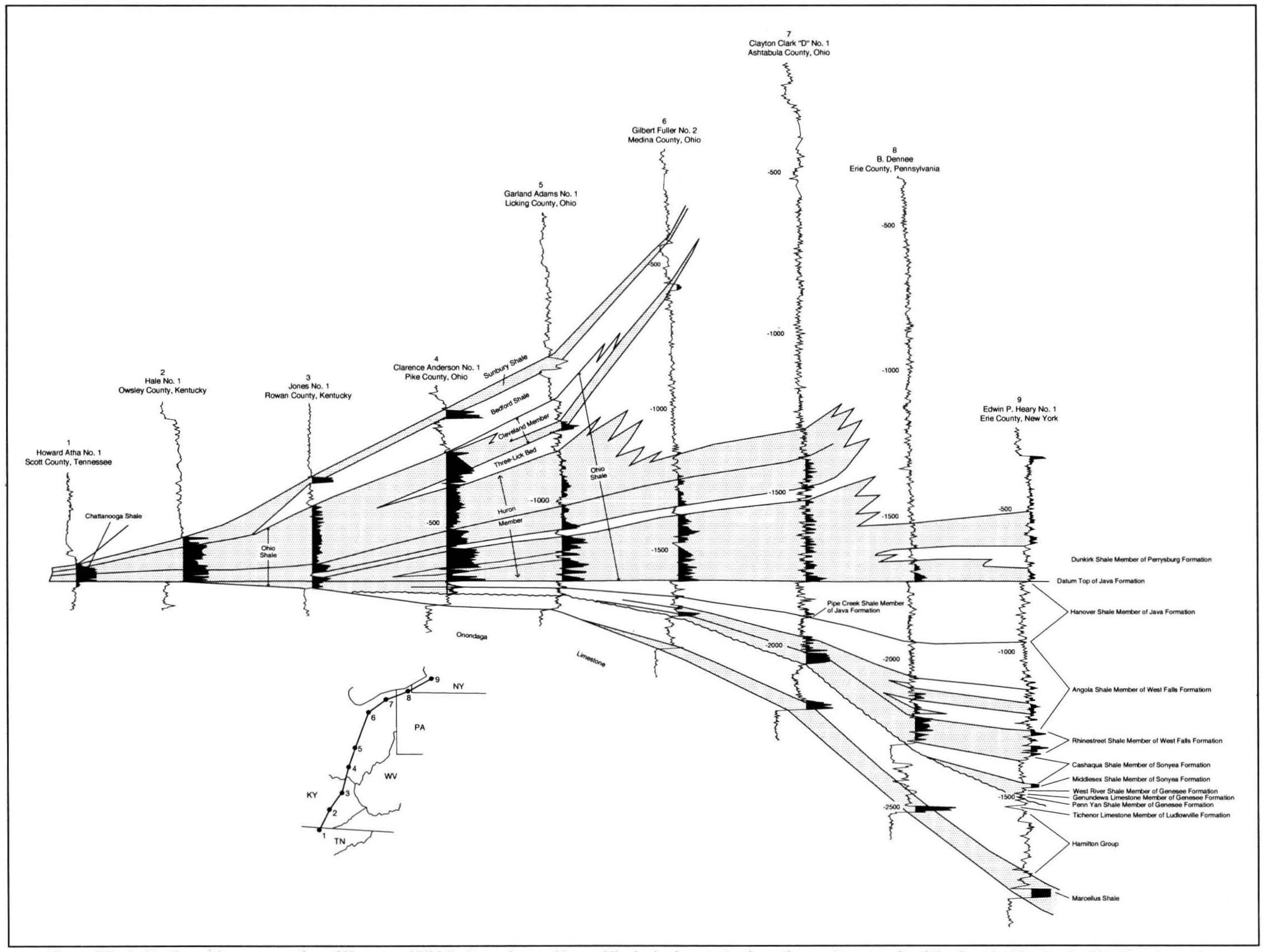


Figure UDs-3. Stratigraphic cross section of Upper and Middle Devonian and lower Mississippian strata along the western margin of the Appalachian basin. Shading shows the extent of the highly radioactive black shales. Modified from Roen and others (1978b). Depths are in feet.

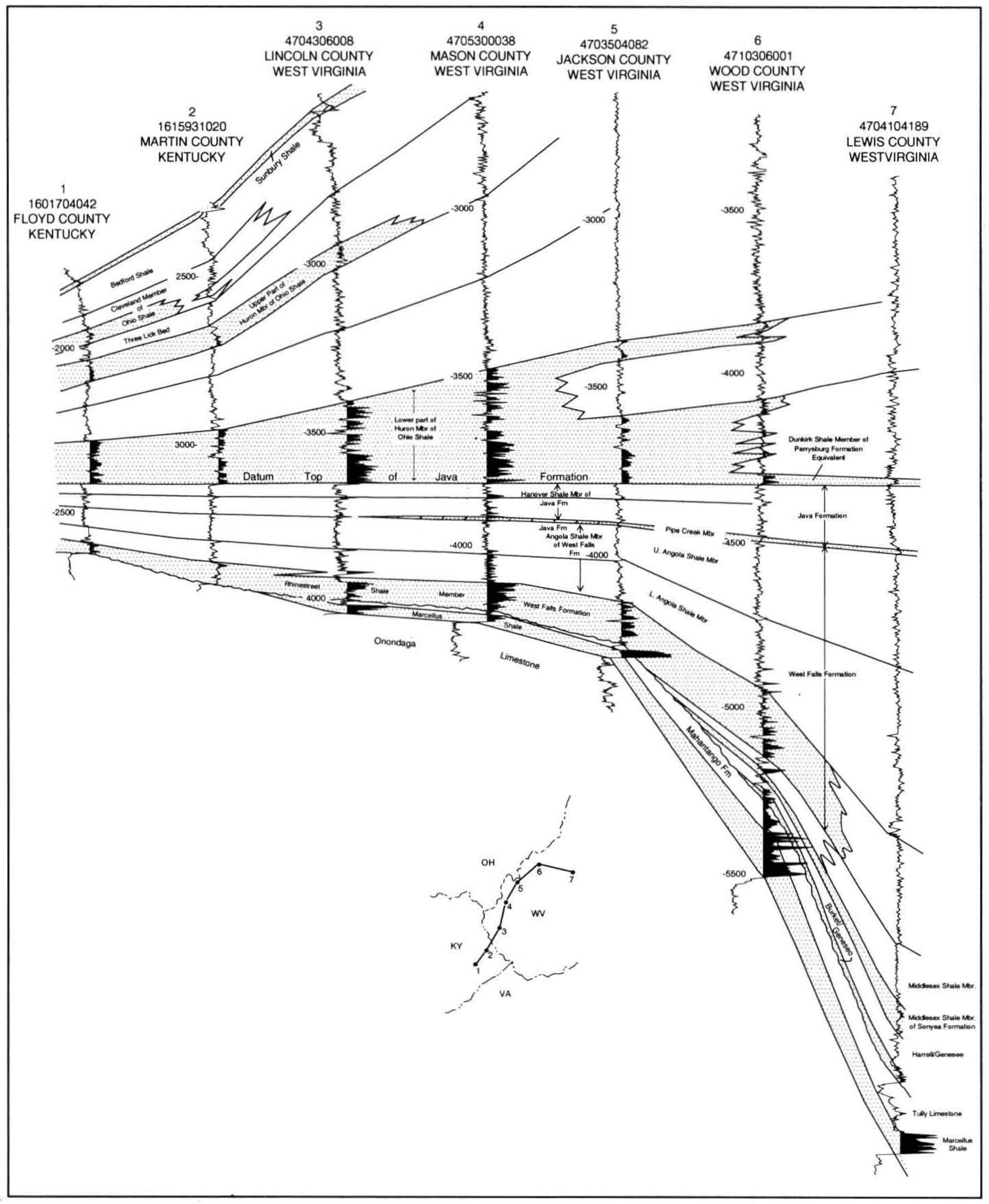


Figure UDs-4. Stratigraphic cross section of Upper and Middle Devonian and lower Mississippian strata in eastern Kentucky and southern West Virginia. Shading shows the extent of the highly radioactive black shales. Wells are identified by API number. Modified from Roen and others (1978b). Depths are in feet.

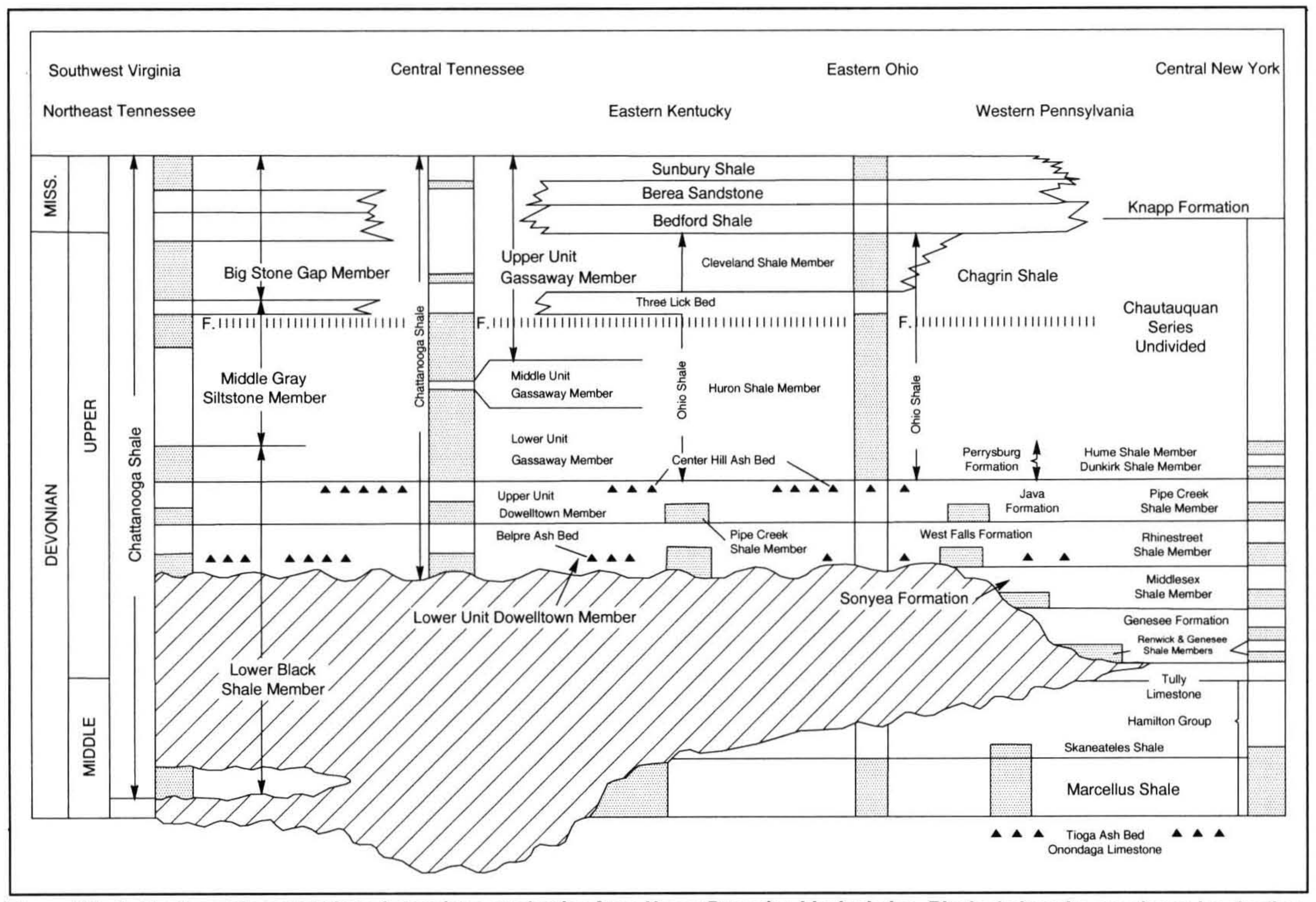


Figure UDs-5. Stratigraphic correlations for regions productive from Upper Devonian black shales. Black shale units are shown by shading. "F." indicates *Foerstia* zone; black triangles indicate significant ash beds. From de Witt and others (1993).

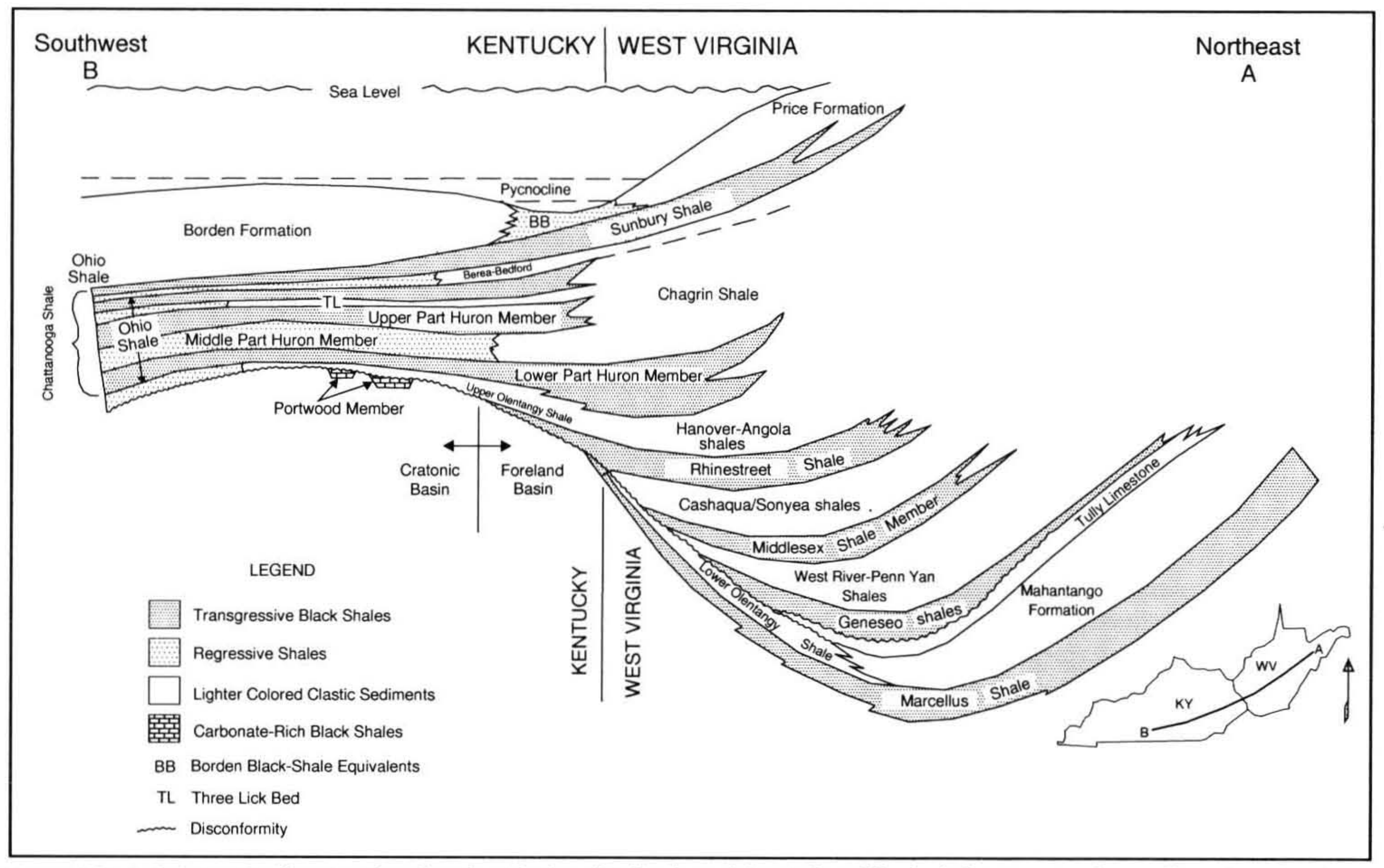
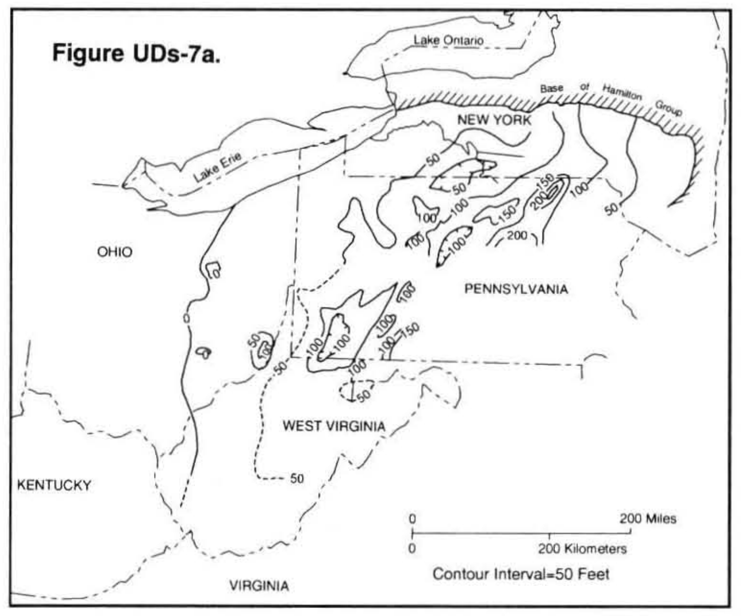
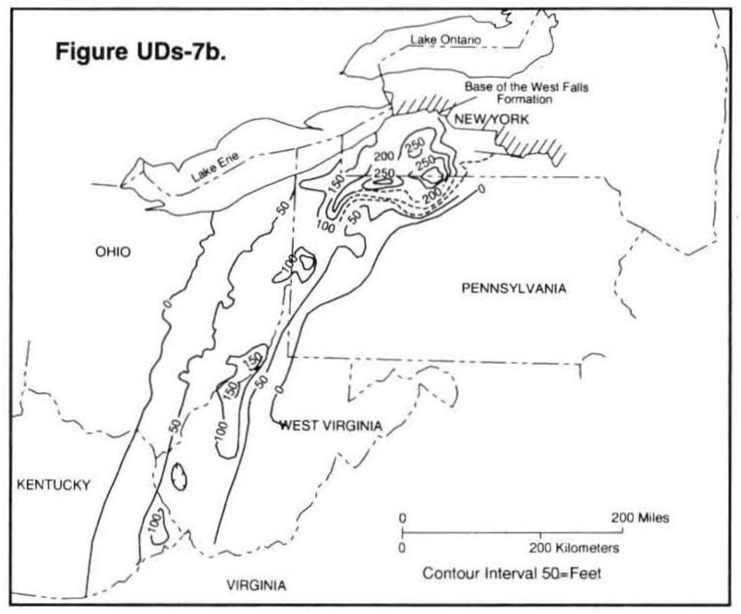


Figure UDs-6. Schematic diagram showing the relative distribution of the various black shale tongues along a line of section from eastern Kentucky to central West Virginia. The Marcellus, Geneseo, Middlesex, and Rhinestreet black shale tongues were deposited within a well-defined foreland basin and pinch out westward due to non-deposition upon a positive Cincinnati arch. The Huron and Sunbury shale units extend across the arch reflecting the infilling of the foreland basin perhaps coincident with subsidence along the arch. The eastward termination of the black shales in due to facies change related to dilution of organic material by clastics in locations nearer to shore. Modified from Ettensohn and others (1988).





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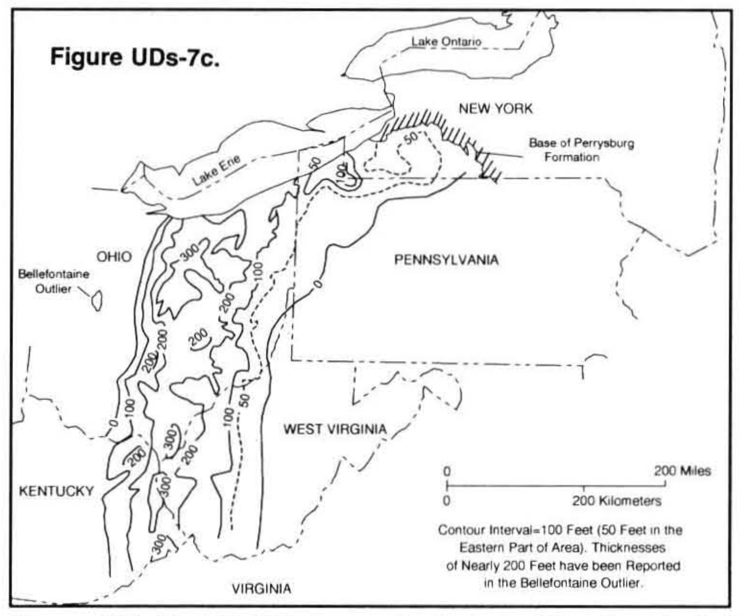
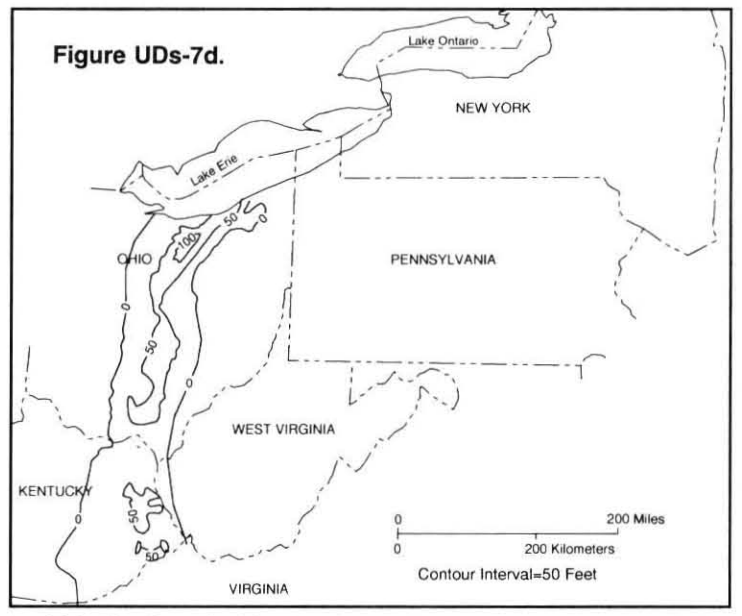




Figures UDs-7a-d. Net thickness of selected radioactive black shales within the Appalachian basin. From de Witt and others (1993). Figure UDs-7a. Hamilton Group (predominantly Marcellus Shale). Figure UDs-7b. West Falls Formation (predominantly Rhinestreet Shale Member). Figure UDs-7c. Perrysburg Formation (predominantly Dunkirk Shale Member in New York; Huron Member of Ohio Shale elsewhere). Figure UDs-7d. Cleveland Member of the Ohio Shale.

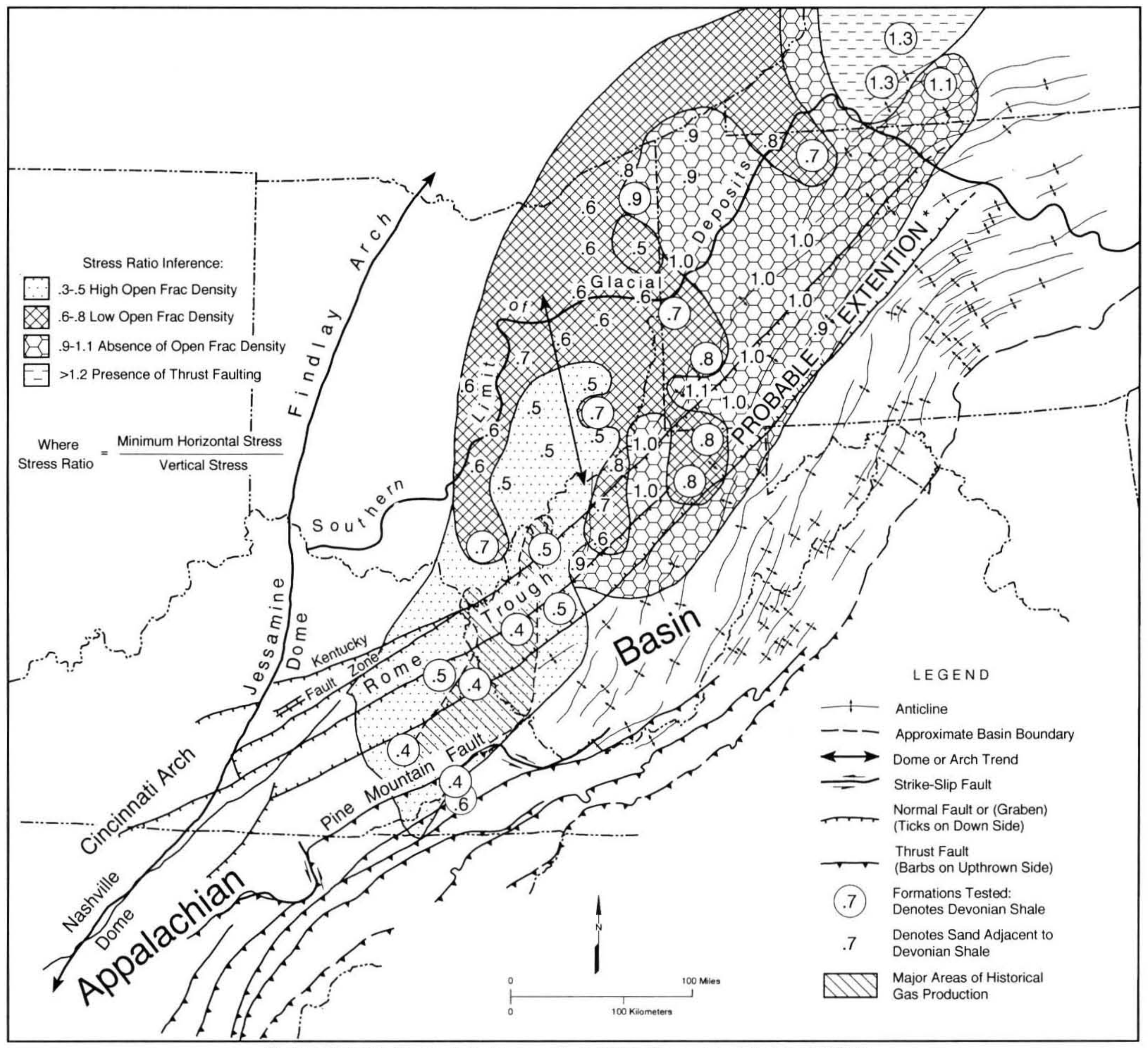


Figure UDs-10. Measured stress ratios. From Komar and Bolyard (1981).

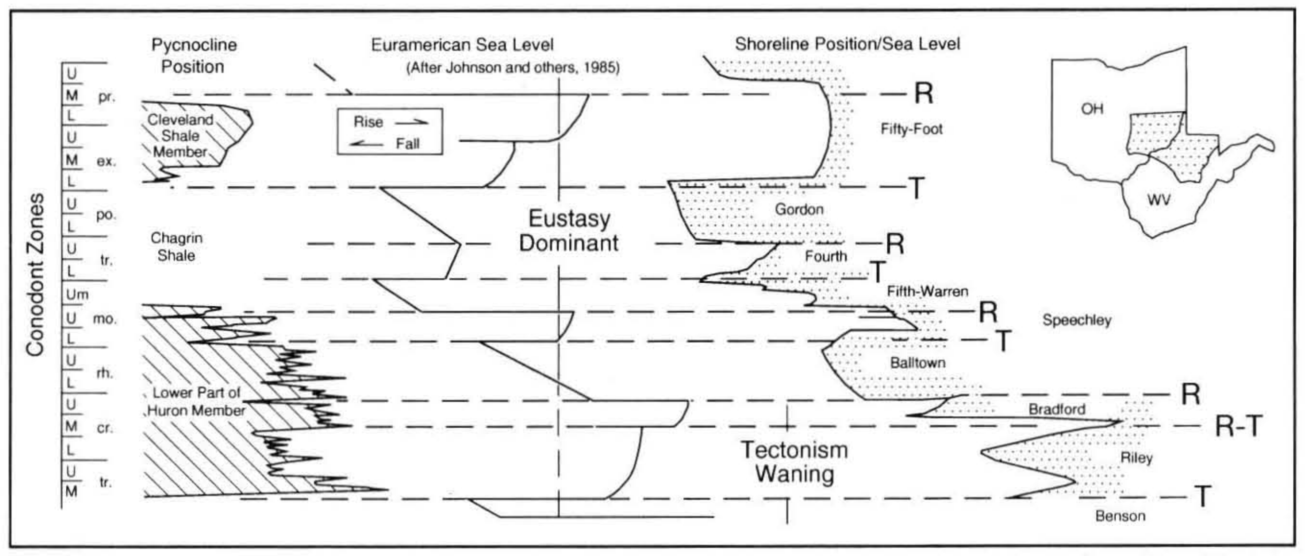


Figure UDs-8. Comparison of shifting of black shale and nearshore sandstone lithosomes in northern West Virginia and eastern Ohio with the composite Upper Devonian sea level curve of Johnson and others (1985) as modified by Boswell (1988b). The similarity in the curves suggests a dominant eustatic control on lithofacies migration. Major sea-level rises marked by "T"; major sea-level drops marked by "R."

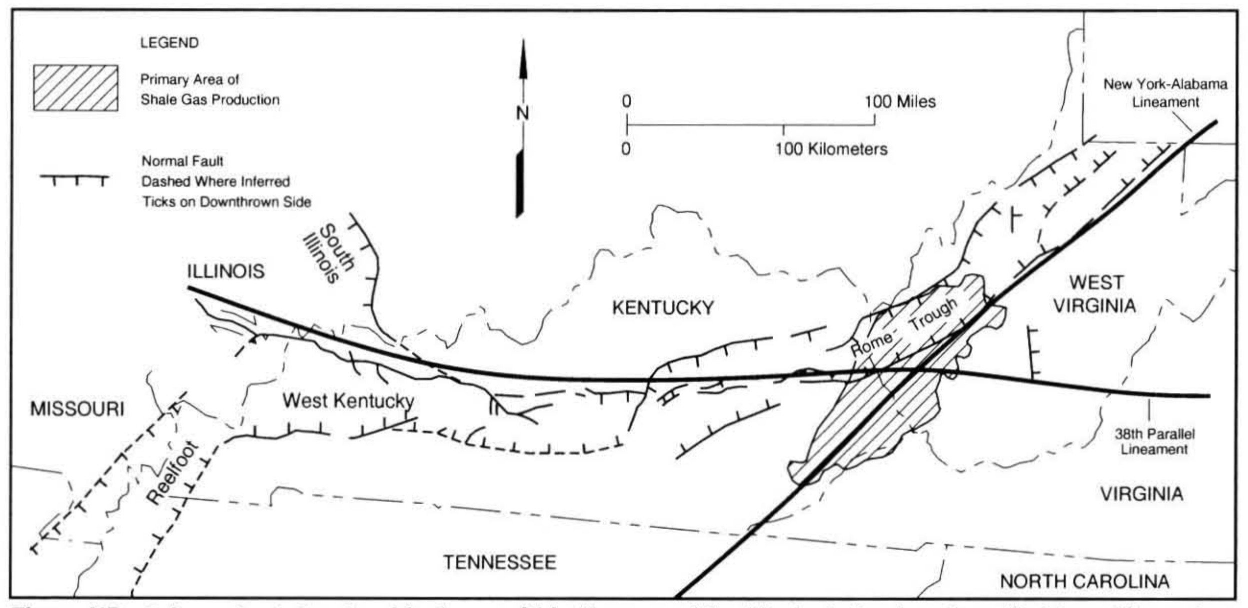


Figure UDs-9. Important structural features within the area of the black shale play. Compiled from Shumaker (1993). Many of these structures show evidence of motion throughout the Paleozoic and may be responsible for much of the faulting/fracturing in the black shales. Also, the proximity of thick black shale units to the western limit of detached Alleghenian deformation may be an important control on the production of interconnected fracture networks.

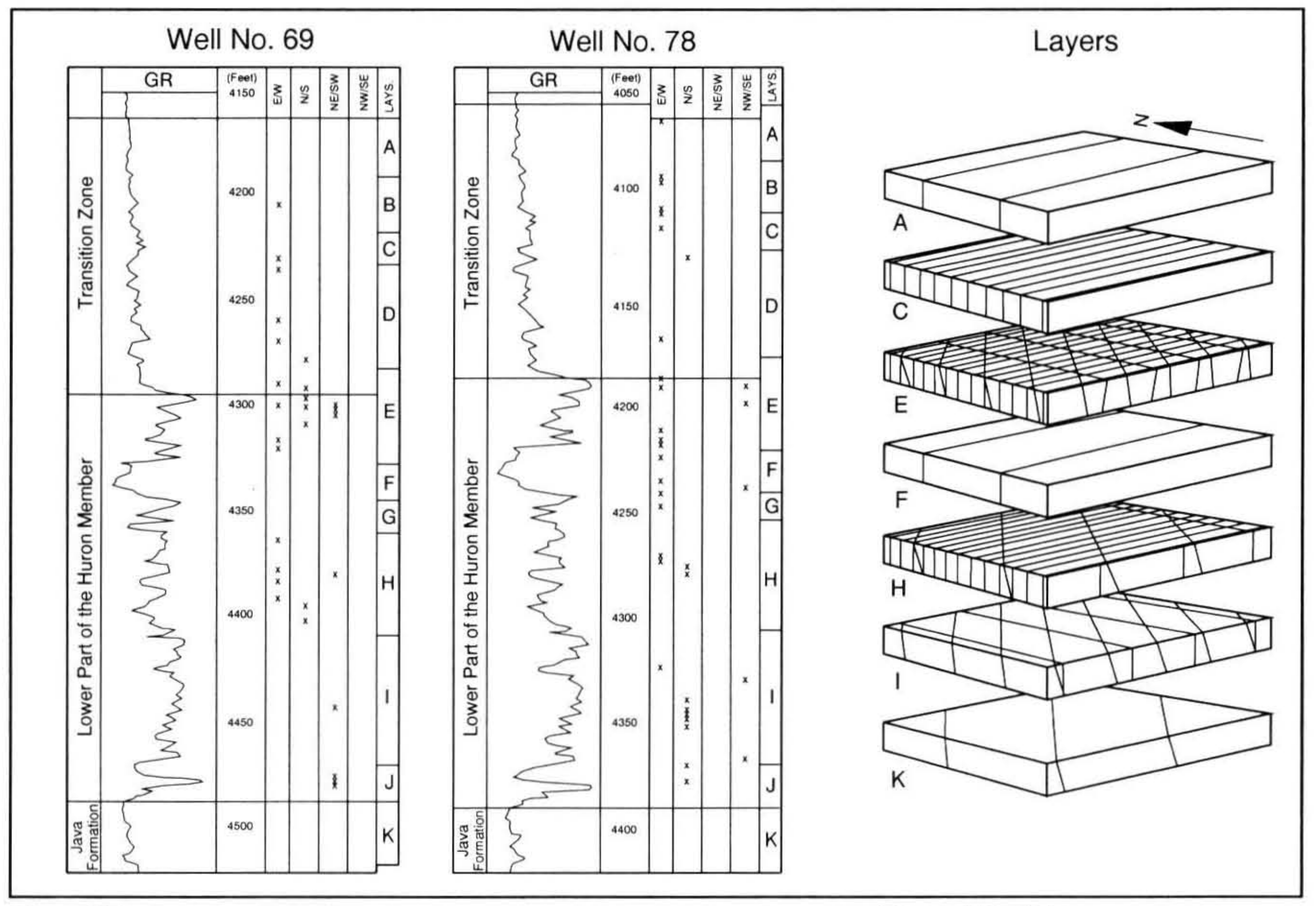


Figure UDs-11a.

Figure UDs-11b.

Figures UDs-11a-b. Correlation between fracture intensity and lithology in two cored wells within the Big Sandy field. Figure UDs-11a. Occurrence and orientation of fractures. Figure UDs-11b. Multi-layered representation of fracturing in the FMC No. 69 well. Modified from Kubik (1993). See inset map in Figure UDs-20 for location of wells.

Black shale reservoirs store gas in three modes: as free matrix gas within pore spaces in the rock matrix, as matrix gas adsorbed onto rock components, and as free gas within a variably developed system of open natural fractures. Schettler and Parmely (1990) estimated that roughly half of the total matrix gas is stored within matrix porosity and half is adsorbed, most prominently onto illite and organic carbon (Figure UDs-13). The initial flush of gas in most shale wells is probably due to the production of free gas through high-conductivity fractures (de Witt, 1986). Data from cores in Pike County, Kentucky, indicate that fracture permeabilities typically range from 20 to 300 md with some values as high as 2,556 md (Ning and others, 1993). Production is sustained by the continual diffusion of free matrix gas into fractures and the replenishment of free matrix gas by desorption of adsorbed gas with pressure decline (de Witt, 1986).

The main producing unit within the overall Devonian shale sequence was poorly known until recently. Analyses of gas production throughout the play has shown that the best production generally is associated with the highly radioactive, dark, and organic-rich zones. This correlation may be related to the greater abundance of organic matter that renders these units both more effective gas sources and better able to adsorb gas. Moreover, Patchen and Larese (1976) recognized numerous, discontinuous lenses enriched in silt-sized and coarser quartz and feldspar within the productive black shale intervals from a whole core taken in Lincoln County, West Virginia. These laminations represent preservation of original sedimentary structures that would have been destroyed by bioturbation in a more oxygen-rich environment. The enhanced (though still low) permeability provided by these laminae may be just as important as fracturing in providing pathways for production in West Virginia shale fields (Nuhfer and Vinopal, 1978). Furthermore, the siltstones may provide relatively brittle zones that enhance the formation of fractures in the surrounding shale during deformation. The abundance and permeability of porous laminae can be expected to increase eastward; however, the degree of bioturbation should also increase eastward.

Regional trends and local variations in organic carbon content, thickness of organic-rich zones, thermal maturity, and natural fracturing are critical to shale exploration. Organic carbon content of the black shales varies widely within each shale unit from less than 0.1 percent to as much as 27 percent with a mean value of 2.13 percent (Figure UDs-14a) (Zielinski and McIver, 1982). Organic carbon content in the Huron and younger shales decreases eastward from typical values of 10 percent along the western margin of the basin (Figure UDs-14b) (Roen, 1984; Schmoker, 1980; 1993) due both to progressive dilution from detrital material and decreased preservation. Organic carbon content in the Rhinestreet Shale decreases both to the east and west from high values of more than 3 percent in a narrow, north-south-trending belt that closely mimics the thickness trend of the unit (Figure UDs-14c) (Zielinski and McIver, 1982). Zielinski and McIver (1982) reported that organic carbon from the western half of the basin was dominantly of the algal type (Type I), whereas organic carbon from the eastern half of the basin was primarily of the woody-coaly variety (Type III).

Thermal maturity in the shales has been alternatively measured through changes in the following: the color of kerogen (Thermal Alteration Index) (Zielinski and McIver, 1982); the color of conodonts (Harris, 1978); the reflectance of vitrinite (Blanton and others, 1980; Maynard, 1981); and the crystallinity of illite (Hosterman, 1993). Each of these approaches has shown increasing maturity eastward into the basin, reflecting greater depth of burial (Figure UDs-15). The nature of gas produced is consistent with this west-to-east gradient; "wet" gas is produced predominantly along the western margin of the basin, whereas "dry" gas is produced in the basin center (Claypool and others, 1978). Vitrinite reflectance data show that all known gas production from the black shales lies in areas with Ro values between 0.6 and 1.5.

Drilling depths to the base of the black shale sequence increase eastward and southward from less than 500 feet along the northern and western margins of the basin to greater than 8,000 feet in areas near the structural front (Figure UDs-16) (de Witt and others, 1993). Depth to the uppermost shale tongue increases more rapidly eastward as the upper units progressively grade into more siltstone-rich facies. Reservoir pressures will increase with depth, potentially increasing the adsorptive capacity of the rock, but also reducing the likelihood of open natural fractures.

Cumulative production values for individual black shale wells range from 50 to more than 900 MMcfg, although the majority of wells produce less than 300 MMcfg (Patchen and Hohn, 1993). Initial open flows are a relatively good predictor of ultimate well performance in many areas (Bagnall and Ryan, 1976; Patchen and Hohn, 1993). A variety of well production decline curves for the various regions in the play are shown in Figure UDs-17. In general, the initial potential and cumulative production of shale wells decrease to the north and east of the Big Sandy area. Yost (1986) determined that 77 percent of wells in eastern Kentucky delivered final open flow potentials in excess of 300 Mcfg/d; for West Virginia, the probability is only 51 percent, whereas in Ohio, only 10 percent of wells demonstrate such potential.

Ultimate recovery efficiencies in black shale reservoirs are very low because only that portion of the gas resource contained as free gas within fractures or pores connected to the wellbore or adsorbed onto rock constituents in very close proximity to fractures or pores can be produced given current technologies. Brown (1976) reported that the typical shale well in West Virginia will only produce 8.2 percent of the gas within an 150-acre drainage area. Avila (1976) obtained very similar results based on Kentucky data.

From the mid-1920s to roughly 1950, approximately 90 percent of shale wells were stimulated through the detonation of 4,000 to 8,000 pounds of gelatinized nitroglycerin ("shooting") (Ray, 1976). Despite the long and costly cleanout jobs that were needed to remove shale rubble from the wellbore, this technique was highly effective, often resulting in commercial production from wells that had no show of gas on drilling. In only 11 percent of the cases was shooting unable to establish production in eastern Kentucky (Hunter, 1964). After 1950, new well stimulation technologies were introduced that used the forced injection of high-pressure water and sand ("hydrofrac") to induce and prop open fractures. Typical "frac" jobs on the periphery of the Big Sandy field (Moody, Johnston, and others, 1988; Moody, Kemper, and others 1988) consisted of approximately 14,000 gallons of water carrying 50,000 to 60,000 pounds of sand. More recently, nitrogen, nitrogen-foam, and CO_2 fracturing techniques have been investigated by various operators, US DOE (Yost and others, 1993), and GRI (Lancaster, 1990). Extensive well stimulation tests conducted as part of the EGSP indicated that borehole shooting and hydraulic fracturing may give roughly comparable results in areas

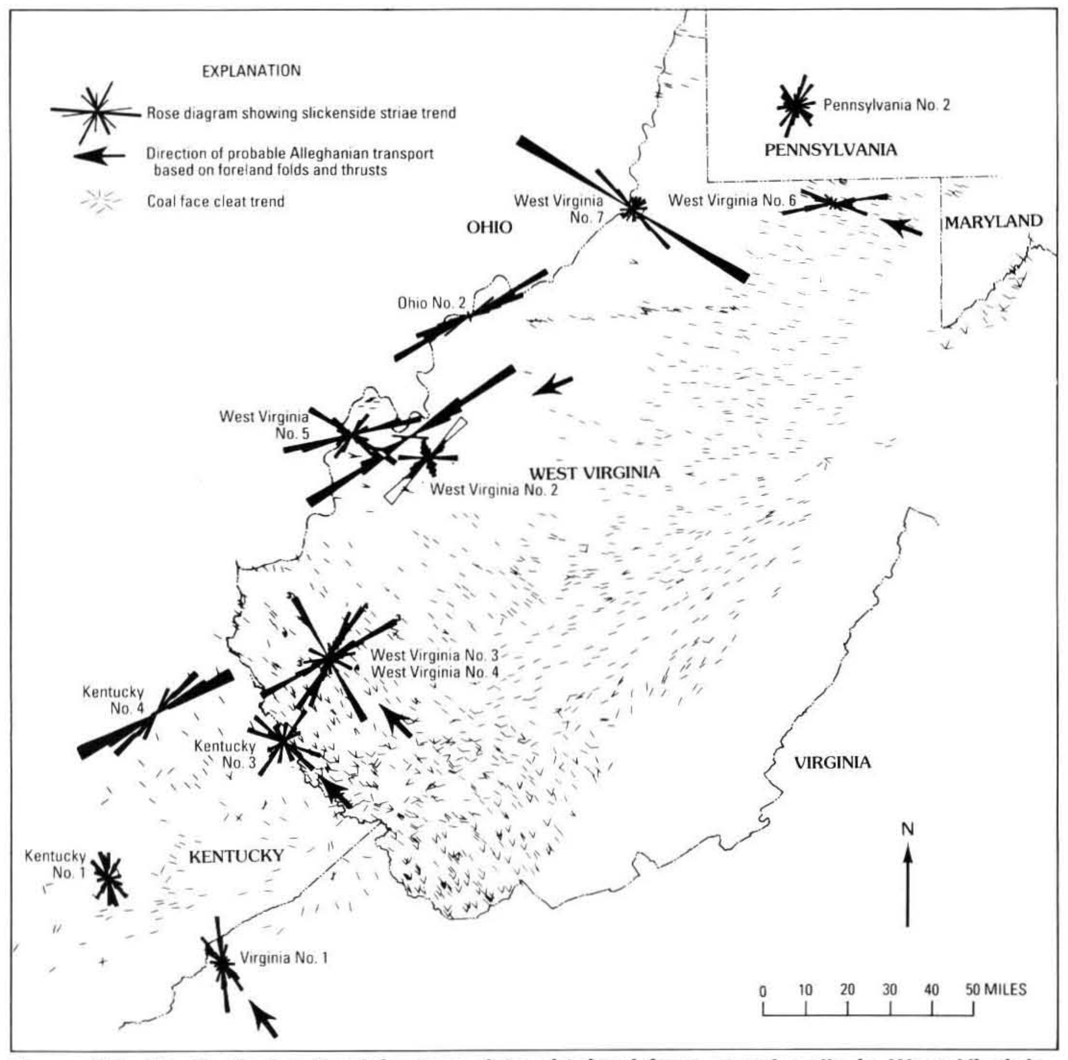
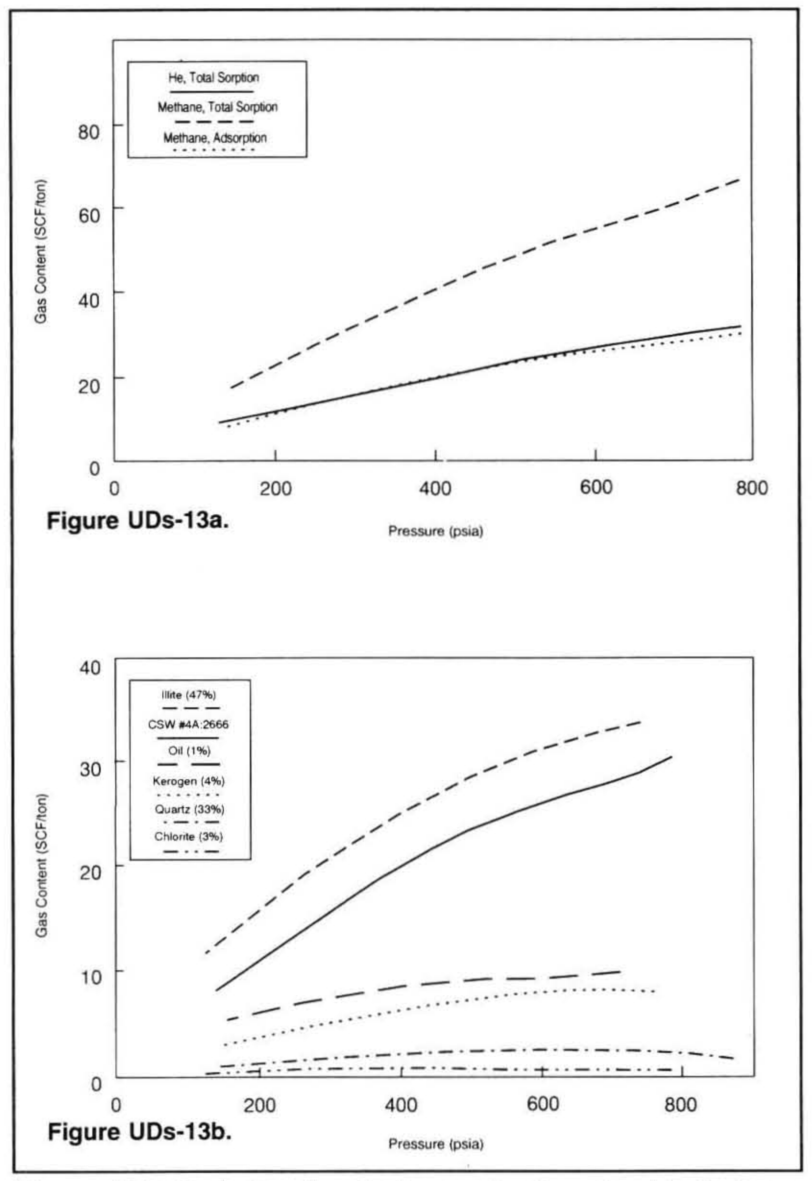
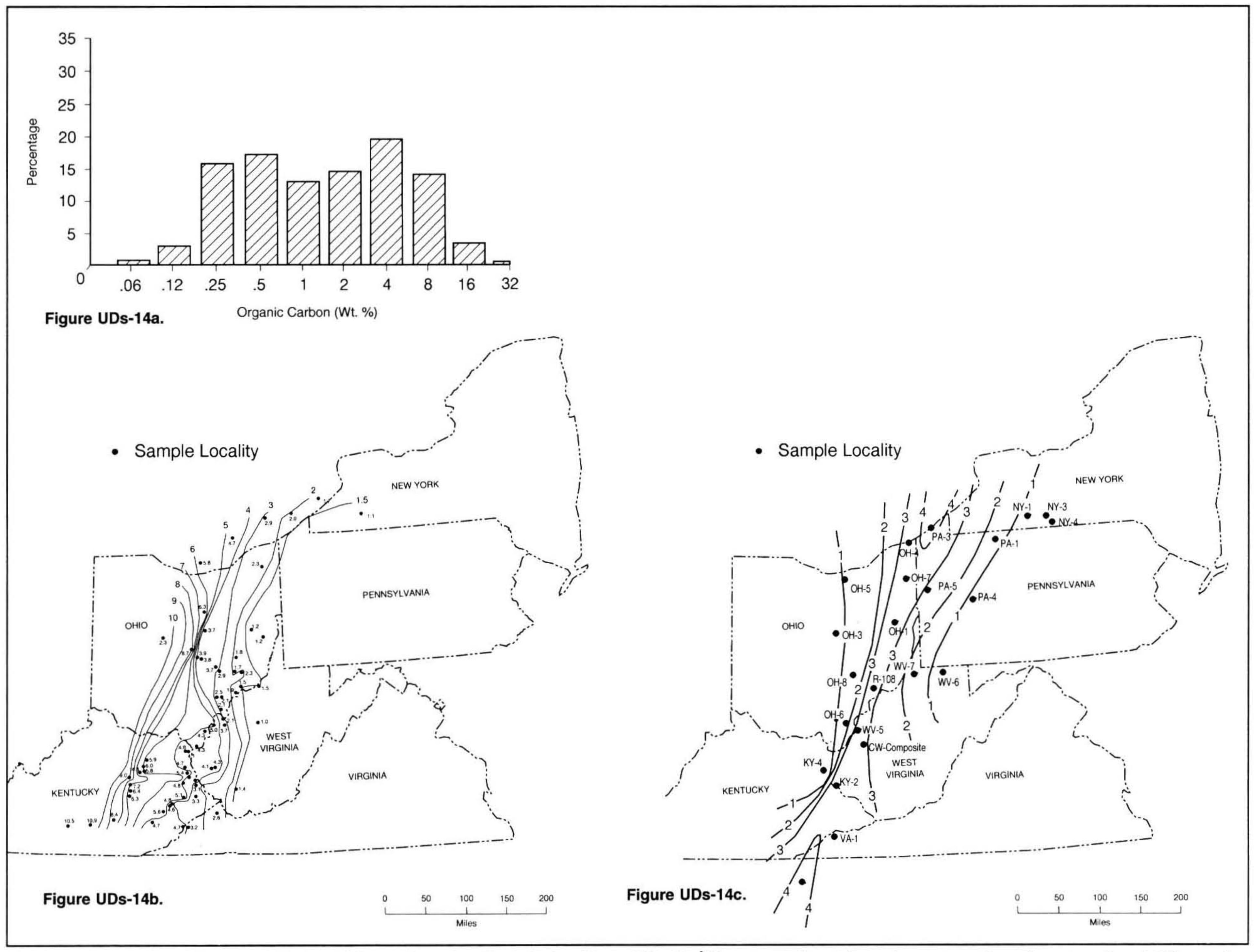


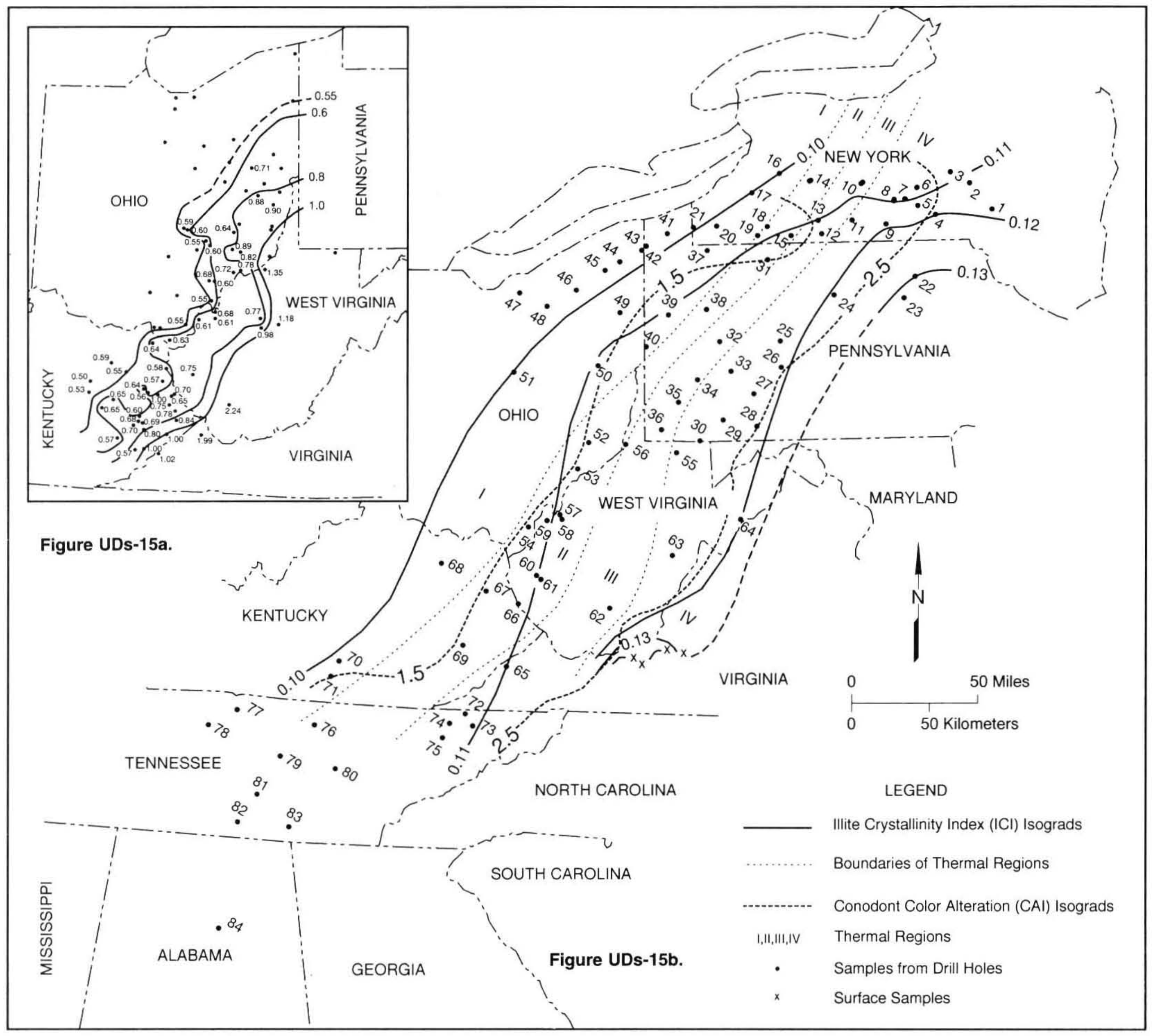
Figure UDs-12. Vertical natural fracture data obtained from cored wells in West Virginia, Kentucky, and Virginia. From Shumaker (1993) after modification from Evans (1979).



Figures UDs-13a-b. Sorption isotherms for Devonian black shale. Figure UDs-13a. Comparison of total methane sorption and adsorption isotherms for sample taken from GRI Cooperative Study Well No. 4A in Breathitt County, Kentucky, at a depth of 2,666 feet showing the components of free and adsorbed matrix gas. Figure UDs-13b. Comparison of adsorption isotherm for the same well with volume-weighted isotherms for various individual shale components showing the importance of illite to overall adsorptive capacity of the shale. From Schettler and Parmely (1990).



Figures UDs-14a-c. Organic carbon content of Upper Devonian black shales. Figure UDs-14a. Histogram of organic carbon content based on more than 2,000 samples of black shale obtained from 27 cores. From Zielinski and McIver (1982). Figure UDs-14b. Organic carbon content (in percent) of the Huron Member of the Ohio Shale. Compiled by T. Hamilton-Smith from the following: Smith and Young (1967), Lamey and Childers (1977), Maynard (1981), Bland and others (1982), Broadhead and others (1982), Zielinski and McIver (1982), and Curtis (1988). Figure UDs-14c. Organic carbon content (in percent) of the Rhinestreet Shale Member of the West Falls Formation. From Zielinski and McIver (1982).



Figures UDs-15a-b. Thermal maturation data for the black shales of the Appalachian basin. Figure UDs-15a. Vitrinite reflectance data from the Huron Member of the Ohio Shale. Compiled by T. Hamilton-Smith from the following: Maynard (1981), Curtis (1988), and Rimmer and Cantrell (1988). Figure UDs-15b. Compilation of illite crystallinity index (ICI) and conodont color alteration index (CAI) data. From Hosterman (1993).

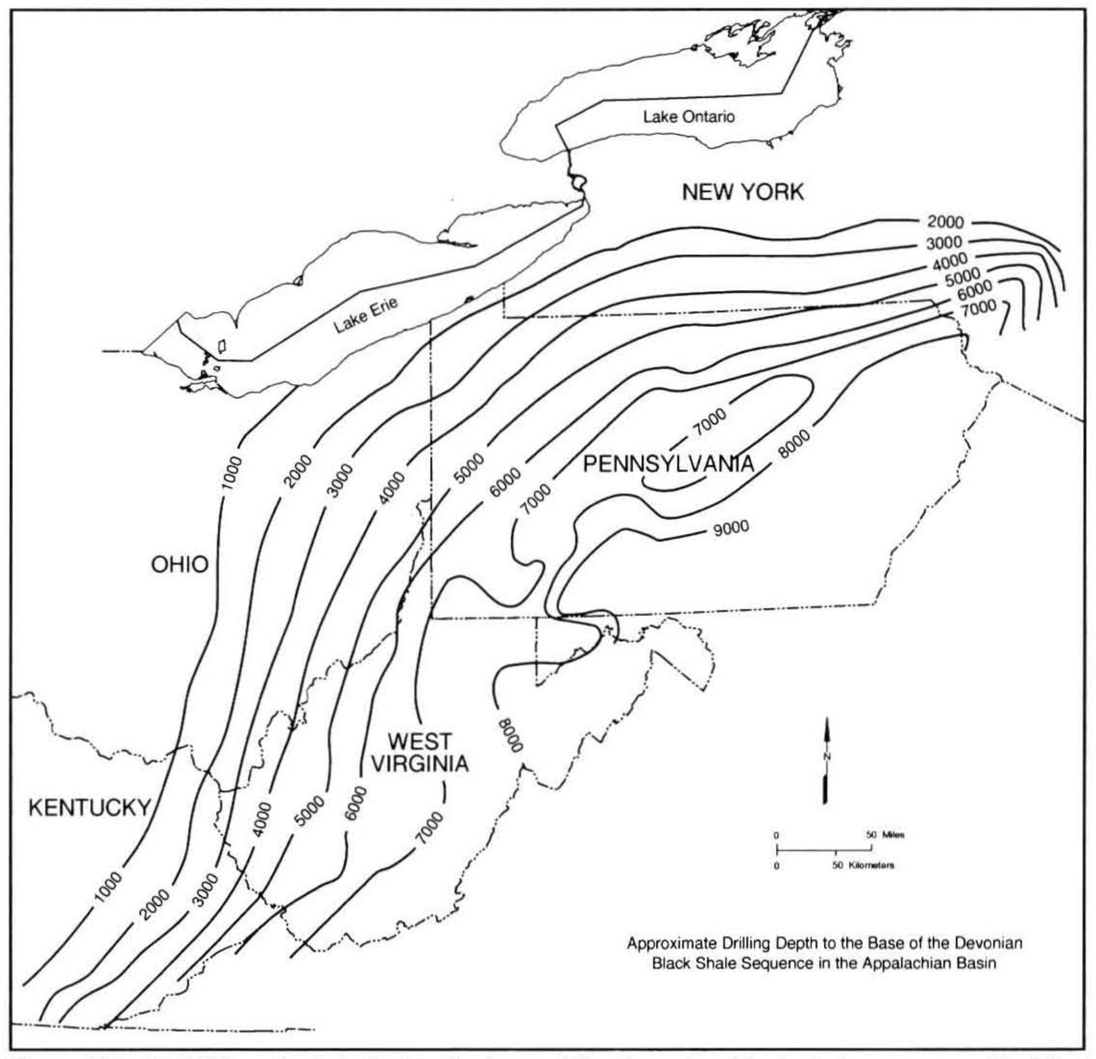
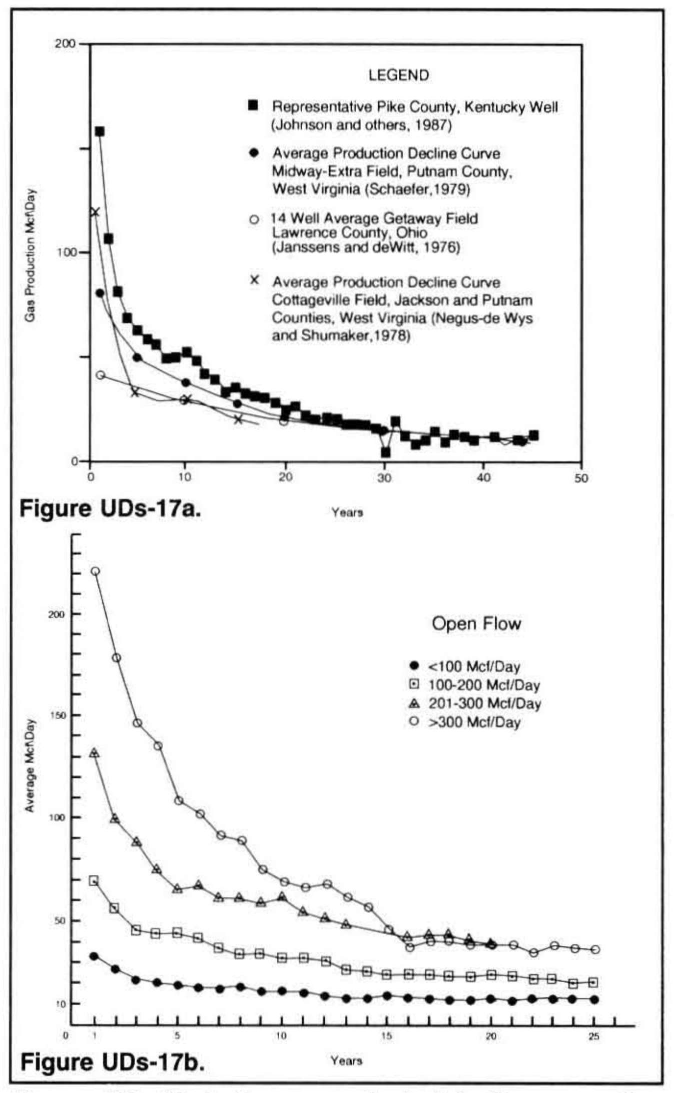


Figure UDs-16. Drilling depth in feet to the base of the Devonian black shale sequence. Modified from de Witt and others (1993).



Figures UDs-17a-b. Average or typical decline curves for Devonian shale wells. Figure UDs-17a. Various areas. Figure UDs-17b. Lincoln, Mingo, and Logan counties, West Virginia, summarized in four classes with differing initial open flow rates. From Patchen and Hohn (1993).

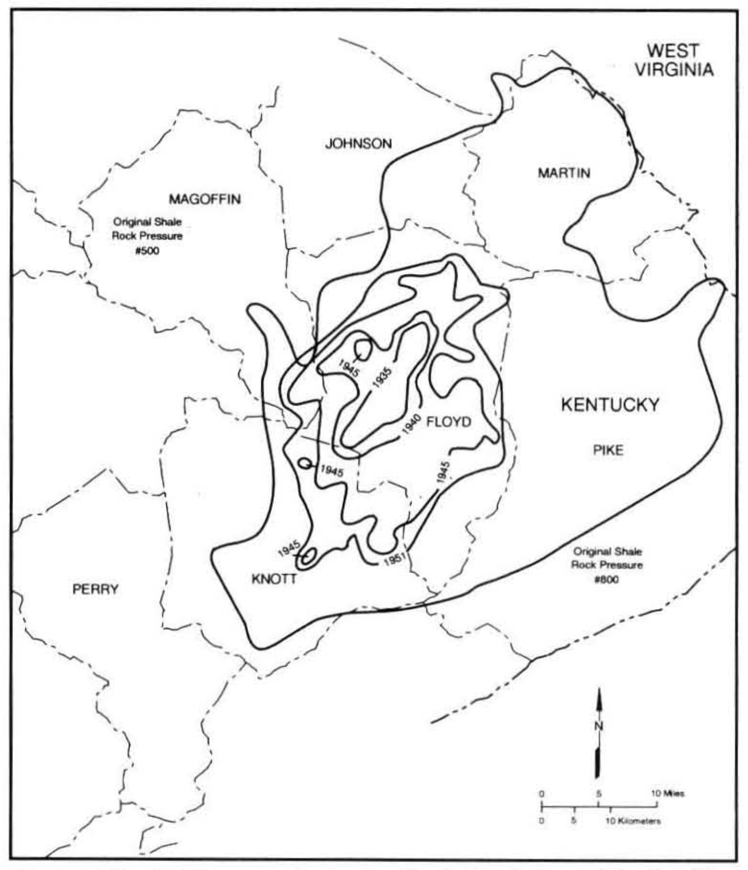


Figure UDs-18. Progressive growth of development in the Big Sandy field through 1950 as evidenced by the expanding area in which reservoir pressure has been reduced below 200 psi. Average original reservoir pressure was approximately 595 psi. Typical abandonment pressure is roughly 60 psi. Original shale rock pressures from 500 pounds in northwest Floyd County to 800 pounds in southeast Pike County (Hunter and Young, 1953). After Hunter and Young (1953), Negus-deWys (1979), and Shumaker (1993).

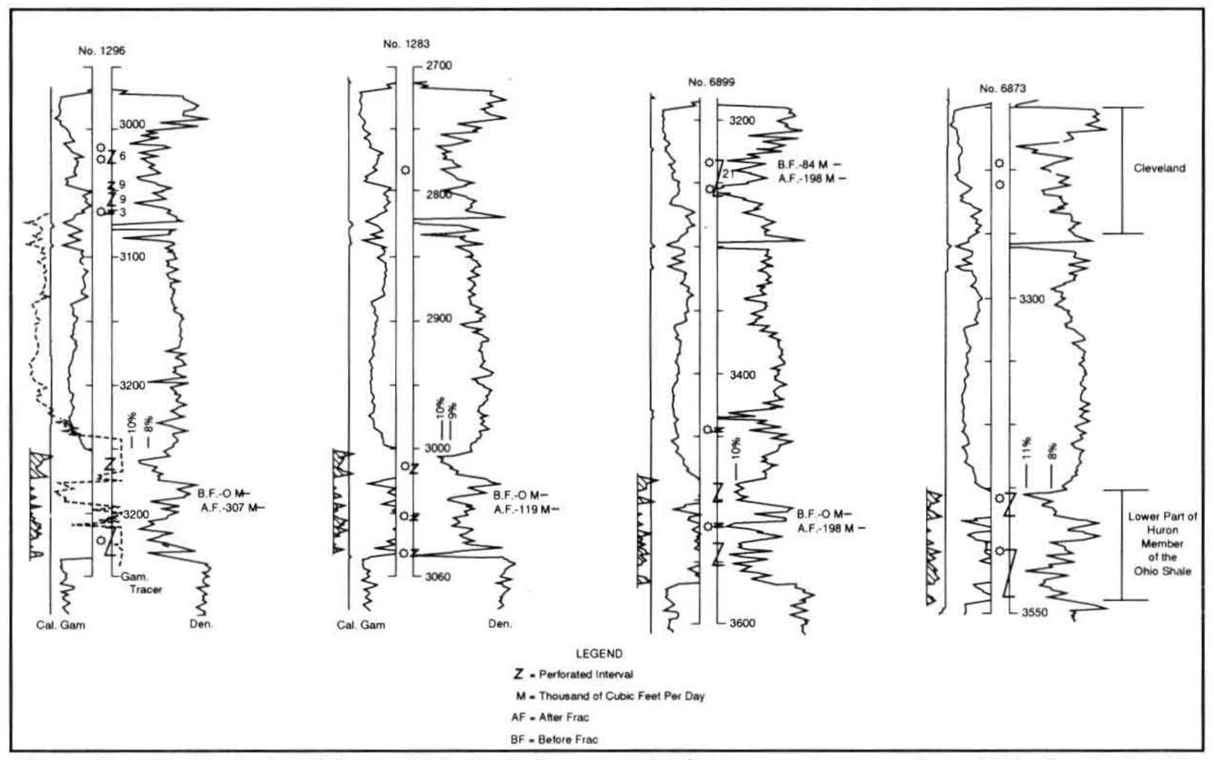


Figure UDs-19. Typical well logs of black shale reservoirs in the southern portion of Big Sandy field in Perry County, Kentucky. The logs exhibit the high gamma-ray and low density reading that typify black shale reservoirs. After Shumaker (1993).

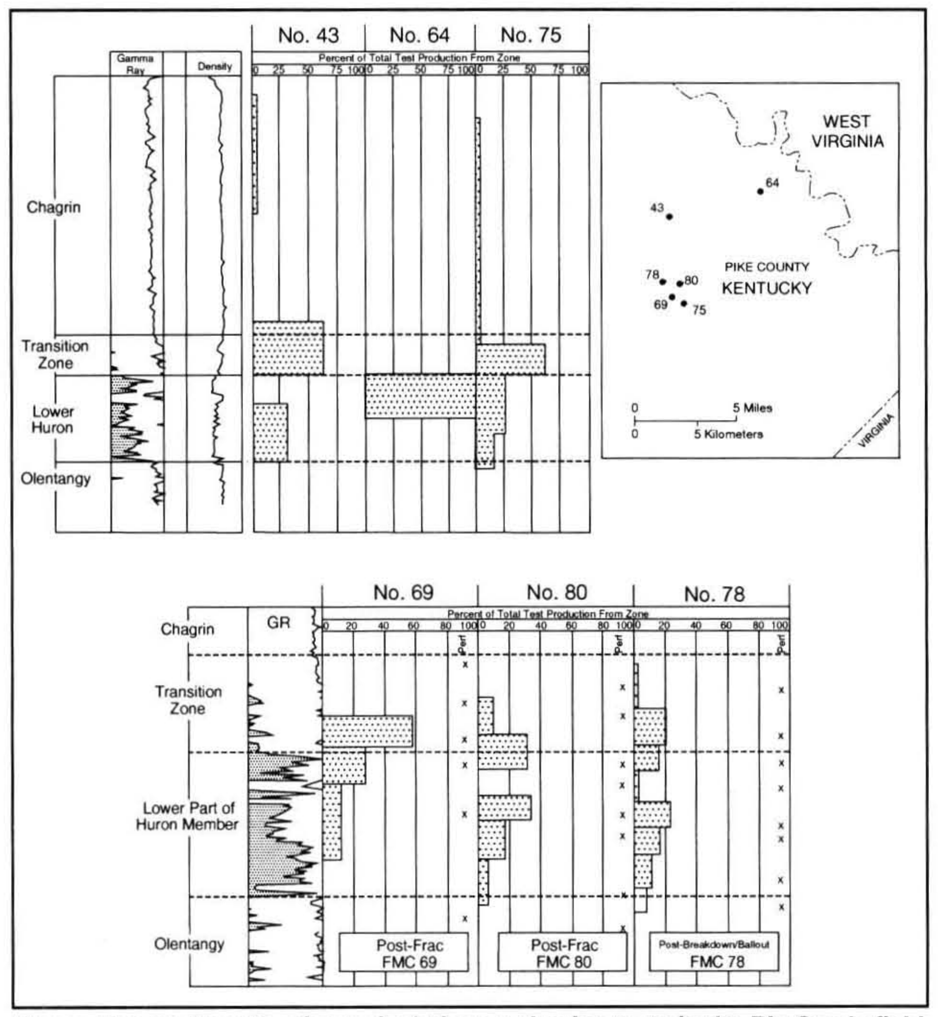


Figure UDs-20. Results of zone isolation production tests in the Big Sandy field of eastern Kentucky. The majority of production in these six wells is obtained from the lower Huron Member and the transition zone at the base of the middle Huron Shale. From Kubik (1993).

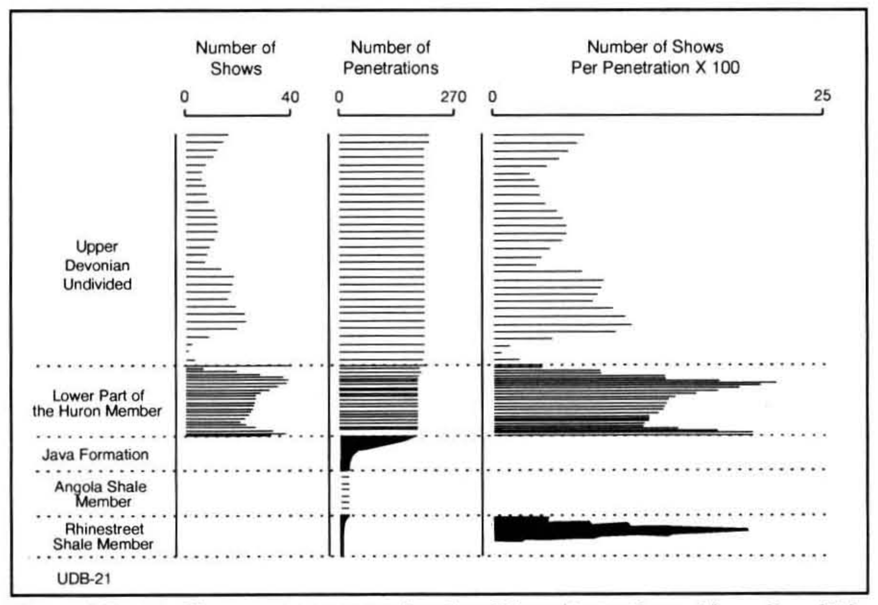


Figure UDs-21. Shows per penetration for different stratigraphic units within the Devonian shale sequence in Mingo, Logan, and Lincoln counties, West Virginia. The data show that the main productive zone is probably the black lower part of the Huron Member of the Ohio Shale. Notably, although few wells in the area are drilled to the Rhinestreet Shale Member of the West Falls Formation, the ratio of shows per penetration in that unit almost equals that observed in the lower Huron. From Patchen and Hohn (1993).

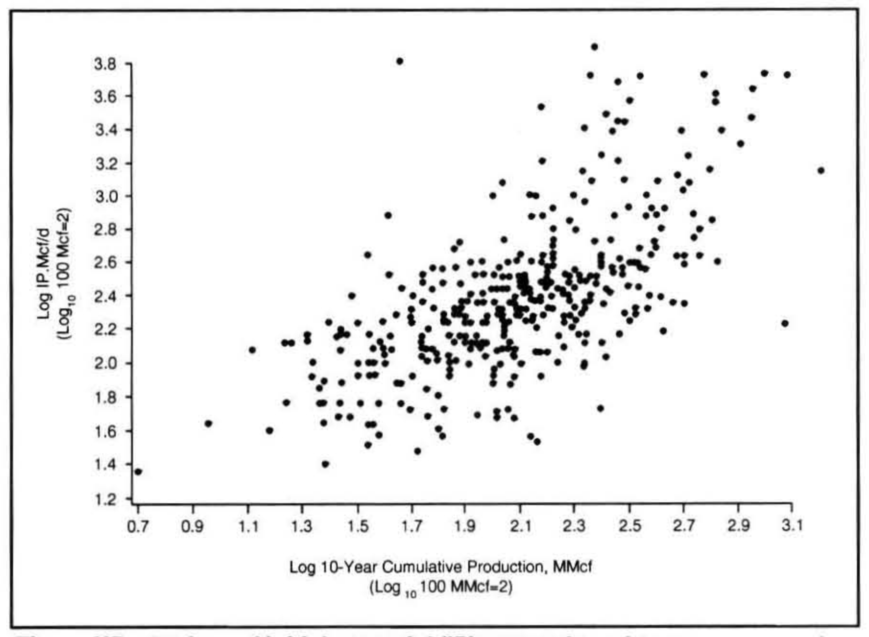


Figure UDs-22. Log of initial potential (IP) versus log of 10-year cumulative production for Devonian shale wells in the West Virginia portion of the Big Sandy field. From Patchen and Hohn (1993).

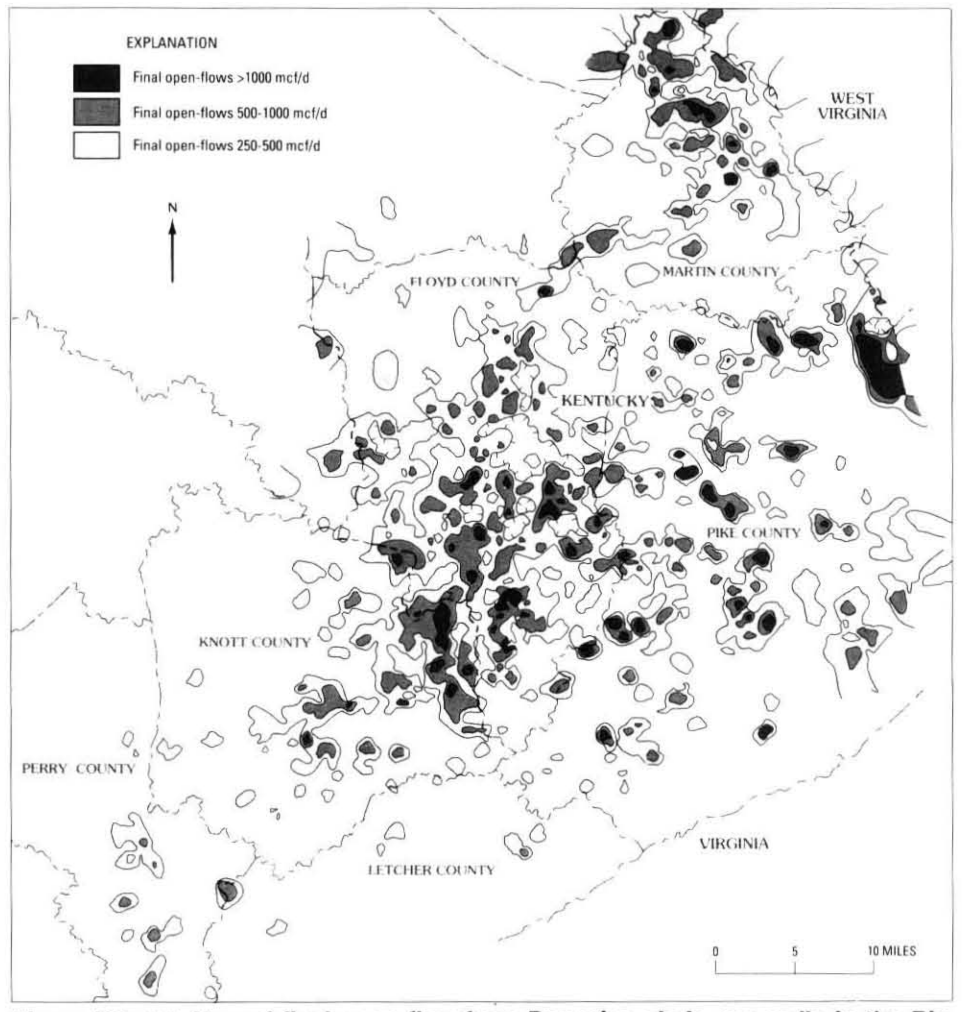


Figure UDs-23. Map of final open flow from Devonian shale gas wells in the Big Sandy field. Compiled by Shumaker (1993) from data collected by Negus-deWys (1979). The map shows the extreme lateral variations in well production potential that occurs over short distances, even within the best producing areas of the field.

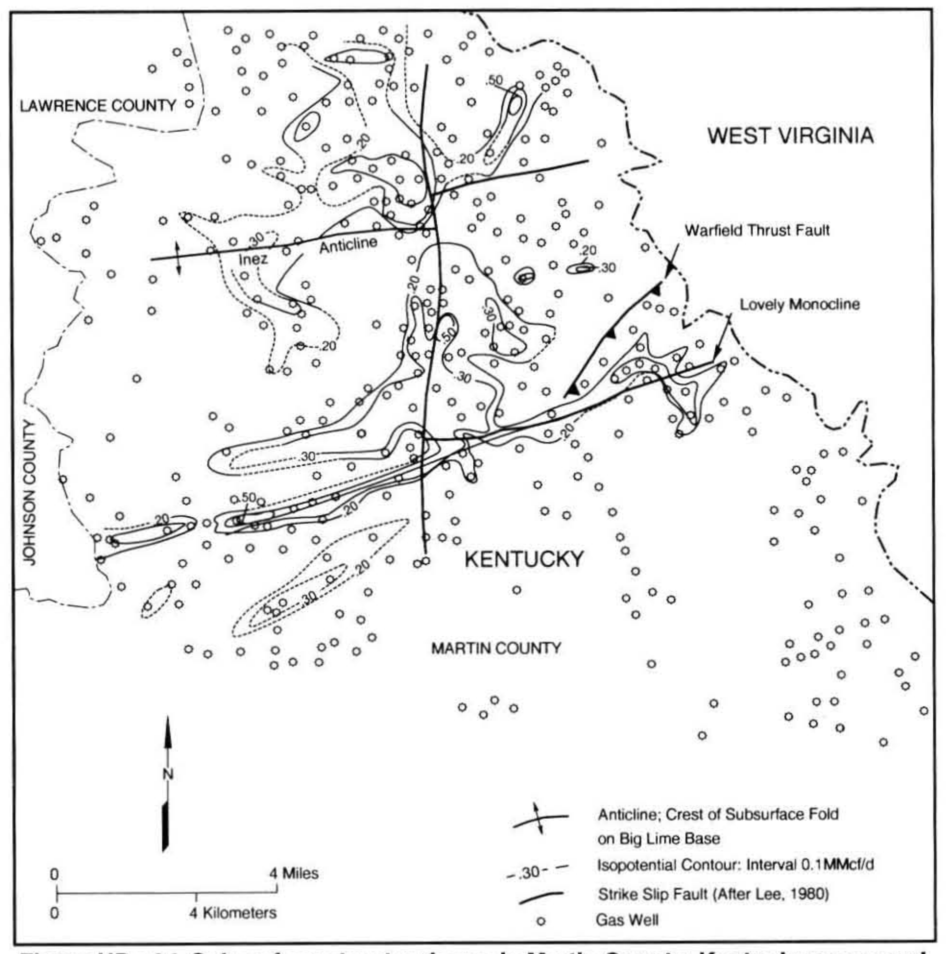
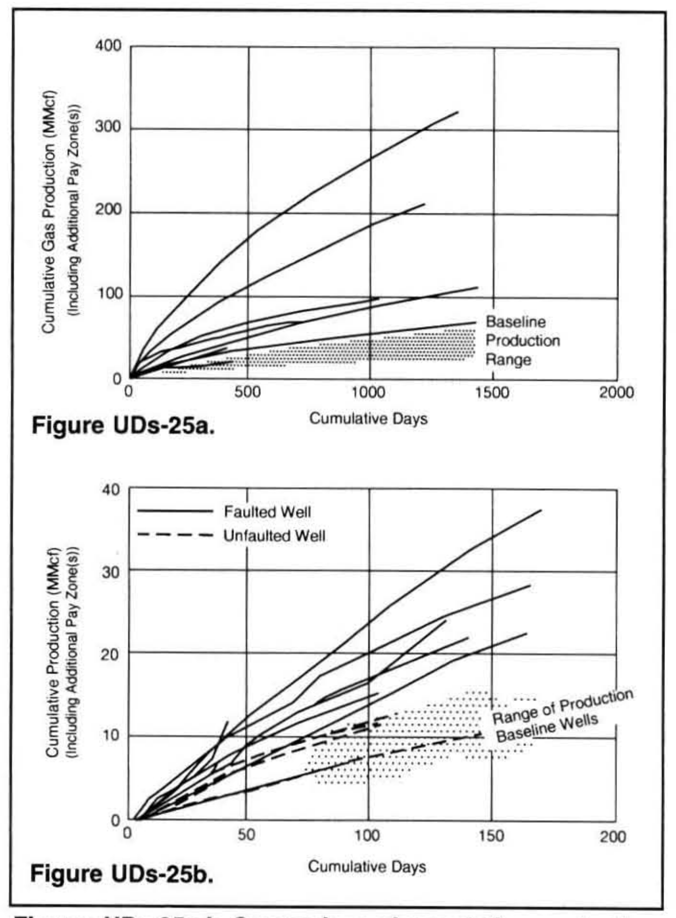


Figure UDs-24. Subsurface structural axes in Martin County, Kentucky compared with final production potential of wells. From Shumaker (1993), based on data collected by Lee (1980).



Figures UDs-25a-b. Comparison of cumulative production curves of wells marked by large-scale fractures or thrust faults interpreted from density and caliper logs with typical production ranges in the Big Sandy field illustrating enhanced production. Figure UDs-25a. Wells with density-log fractures. Figure UDs-25b. Comparison of production from faulted and unfaulted wells. From Kubik (1993).

with well-developed fracture networks; however, in areas of poorly developed fractures, hydraulic and/or foam fracturing techniques may be the most profitable choice (Horton, 1981). Additional technologies that have been investigated include horizontal well drilling (Yost and others, 1988), reduced-circulation air drilling (Graham and others, 1993), and improved well log evaluation (Guidry and others, 1990).

Description of Key Fields

Big Sandy field: The Big Sandy field of eastern Kentucky and southwestern West Virginia (Figure UDs-2; Table UDs-1) accounts for more than 80 percent of production from Upper Devonian black shales. More than 10,000 wells have been drilled into the Big Sandy field with an estimated cumulative production of 2.5 tcfg, averaging 250 MMcfg per well (de Witt, 1986). The field contains several original productive centers in eastern Kentucky (Figure UDs-18) that have subsequently been connected and extended both northeastward into West Virginia and southwestward.

The most commonly completed zones within the field are the Cleveland Member and the lower part of the Huron Member of the Ohio Shale (Figure UDs-19). Production isolation tests on six wells in eastern Kentucky (Kubik, 1993) show that the best production is associated with the upper part of the lower radioactive zone of the Huron and the overlying, less organic-rich, "transition zone" (Figure UDs-20).

Drilling depth to the Huron Member increases from roughly 2,000 to 4,000 feet southeastward across the field. Thickness of the radioactive lower Huron ranges from 100 to slightly more than 300 feet (de Witt and others, 1993). Total shale interval thickness ranges from 500 to 1,800 feet. Reported pay thickness may fall anywhere within this range, depending upon the practice of the operator. Although the lower Huron is recognized as the main field producer, the percentage of gas shows per penetration for the deeper, relatively untested Rhinestreet Shale Member of the West Falls Formation in the West Virginia portion of the field almost equals that of the Huron Member in adjacent fields in southern West Virginia (Figure UDs-21) (Patchen and Hohn, 1993).

Relatively few shale wells (4 to 6 percent) produce at high volumes naturally; the average initial open flow in the period before 1950 was approximately 60 Mcfg/d. As a result, wells are routinely stimulated. Typical minimum after-shot open flows before 1950 were 259 Mcfg/d (Hunter and Young, 1953; Hunter 1955). Data summarized in Patchen and Hohn (1993) indicate a positive correlation between initial potential and 10-year cumulative production (Figure UDs-22). Bagnall and Ryan (1976) described the production characteristics of the shale in adjacent West Virginia fields (Figure UDs-17b). Well productivity as gauged by final open-flow values illustrates the overall southwestern trend of the field, the primary areas of enhanced production, and the extreme heterogeneity of the reservoir (Figure UDs-23) (Shumaker, 1993).

A regional network of planar, high-angle joints localized within the lower Huron provides the basic permeability network for the reservoir (Kubik, 1993). Shumaker (1993) suggested that the proximity of the field to the western terminus of detached Alleghenian deformation occurring along decollements within the Ohio Shale may be significant in the formation of this regional fracture network. Overpressuring related to early gas generation within the shale may also be a contributing factor (Kubik, 1993). Areas of enhanced production seen locally within the field are attributed to the overprinting of the regional fracture network by fractures related to individual mappable structures (Figure UDs-24) (Shumaker, 1993). In addition, Kubik (1993) has shown a correlation between the occurrence of small thrust-faults and large-aperature fractures (density-log fractures) with above-average well production (Figure UDs-25).

Structure at the level of production represents the regional southeast dip of the basin (Figure UDs-26). Local faults and flexures are also present, including thrust and strike-slip faults associated with Alleghenian deformation and folds representing reactivation of basement structures (Shumaker, 1993).

Midway-Extra field: The Midway-Extra field in Putnam and Jackson counties, West Virginia (Figure UDs-2; Table UDs-1), produces gas from the lower part of the Huron Member of the Ohio Shale. The initial period of field development was from 1948 to 1952. From 1956 to 1959, the field was extended to the north. A third period of drilling occurred from 1974 to 1981 (Schaefer, 1979). Schaefer (1979) reported a mean initial open flow of 296 Mcf/d and an estimated cumulative production of 434 MMcfg per well over a 40-year period. An averaged production decline constructed from data from 39 wells is shown as Figure UDs-17a. Depth to pay averages 3,709 feet.

Schaefer (1979) demonstrated a clear correlation between geologic structure and final (post-stimulation) open-flow values. Final open flows and, presumably, natural fracture intensity are significantly higher along a trend paralleling the northwest limb of the Midway anticline (Figure UDs-27). The lower Huron Member is roughly 400 feet in thickness in this area, with approximately 250 feet of potential pay zones. Thickness maps of the lower Huron Member show thinning along the trend of the anticline, suggesting a growing structure related to reactivation of a basement fault (Figure UDs-28). A seismic line across the field reveals such a fault zone stepping down to the southeast. Shumaker (1993) suggested that the disparity in fracture intensity between the two limbs of the fold may be due to the intersection of the northeast-plunging Midway anticline with the southward-plunging Evans anticline. A structure map (Figure UDs-29) shows several small anticlinal features on the northwest limb of the Midway fold that parallel the trend of the Evans anticline. The greater production in this area may be due to increased permeability of the natural fracture network that resulted from the intersection of two fracture systems with different orientations.

Cottageville field: The Cottageville field in Jackson and Mason counties, West Virginia (Figure UDs-2; Table UDs-1), was discovered in 1930 by Cities Service. By 1975, the field had produced an estimated 15.8 bcfg from 90 wells at a spacing of approximately 76 acres (Martin and Nuckols, 1976). Average original rock pressure from 37 Consolidated Natural Gas wells drilled in the field during the peak development period from 1948 to 1950 was 595 psi, as compared to pressures of 190 to 350 psi in 1975 (Martin and Nuckols, 1976). Depth to pay averages 3,425 feet. Nitroglycerin shooting was used extensively, and resulted in an improvement in average open flow from 133 Mcf/d natural to 523 Mcf/d after stimulation for 37 Consolidated Natural Gas wells (Martin and Nuckols, 1976). Average cumulative production is 185 MMcfg per well (Martin and Nuckols, 1976). A composite decline curve for the field is given in Figure UDs-17a.

Production in the Cottageville field is obtained primarily from the lower portion of the Huron Member of the Ohio Shale (Figure UDs-30). Watts (cited in Patchen and Larese, 1976) provided core data from one good well and one poor well that allowed the comparison of the orientation of vertical fractures. Data from both wells share an east-northeast component; however, the more productive well contained a zone of intense fractures with four well-developed orientations, suggesting a greater interconnectivity of fractures (Figure UDs-31).

The best wells in the Cottageville field occur along an east-west trend (Figure UDs-32) that closely parallels the trend of basement faults interpreted from 3-D seismic data (Sundheimer, 1978). Shumaker (1993) presented evidence that the basement faulting may have contributed to the enhancement of natural fracturing in the field by complicating detached Alleghenian deformation occurring within the overpressured lower part of the Huron Member.

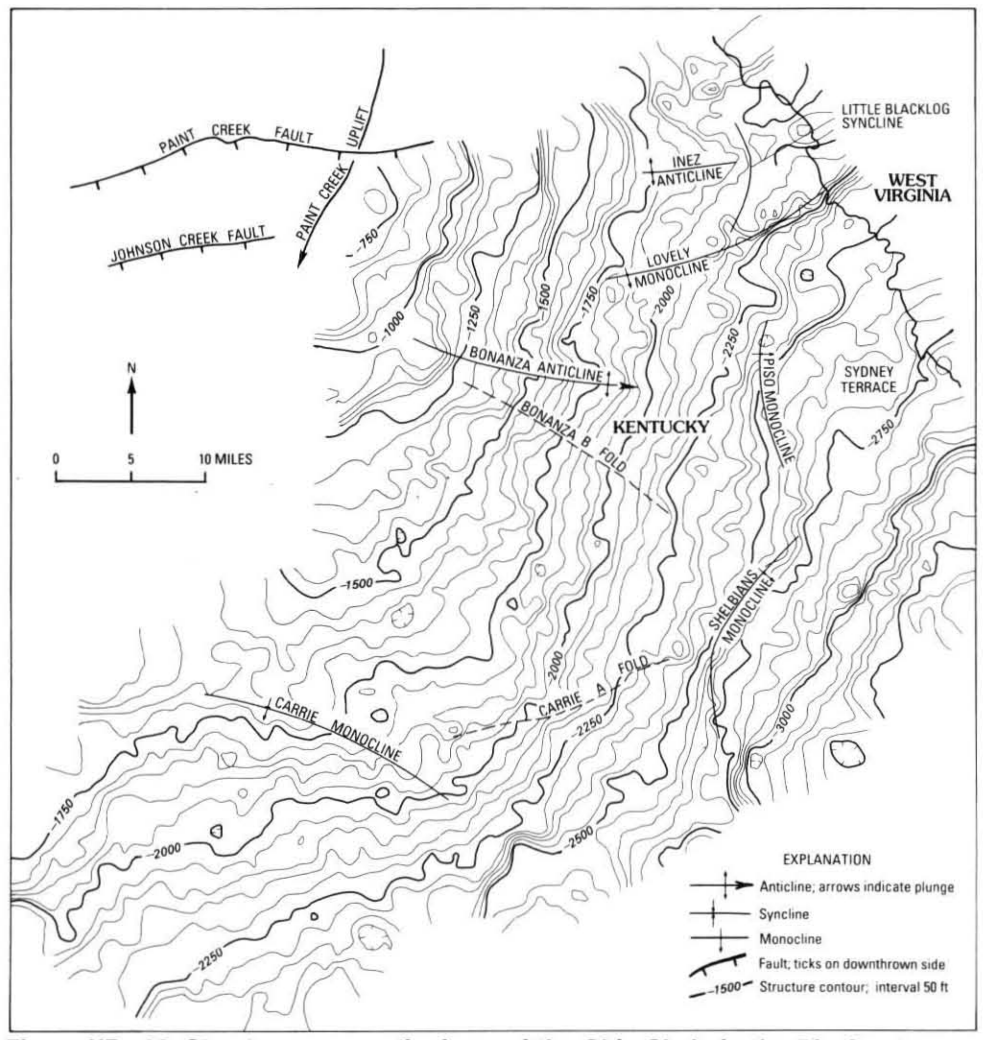


Figure UDs-26. Structure map on the base of the Ohio Shale in the Big Sandy area. From Shumaker (1993), based on data collected by Lee (1980).

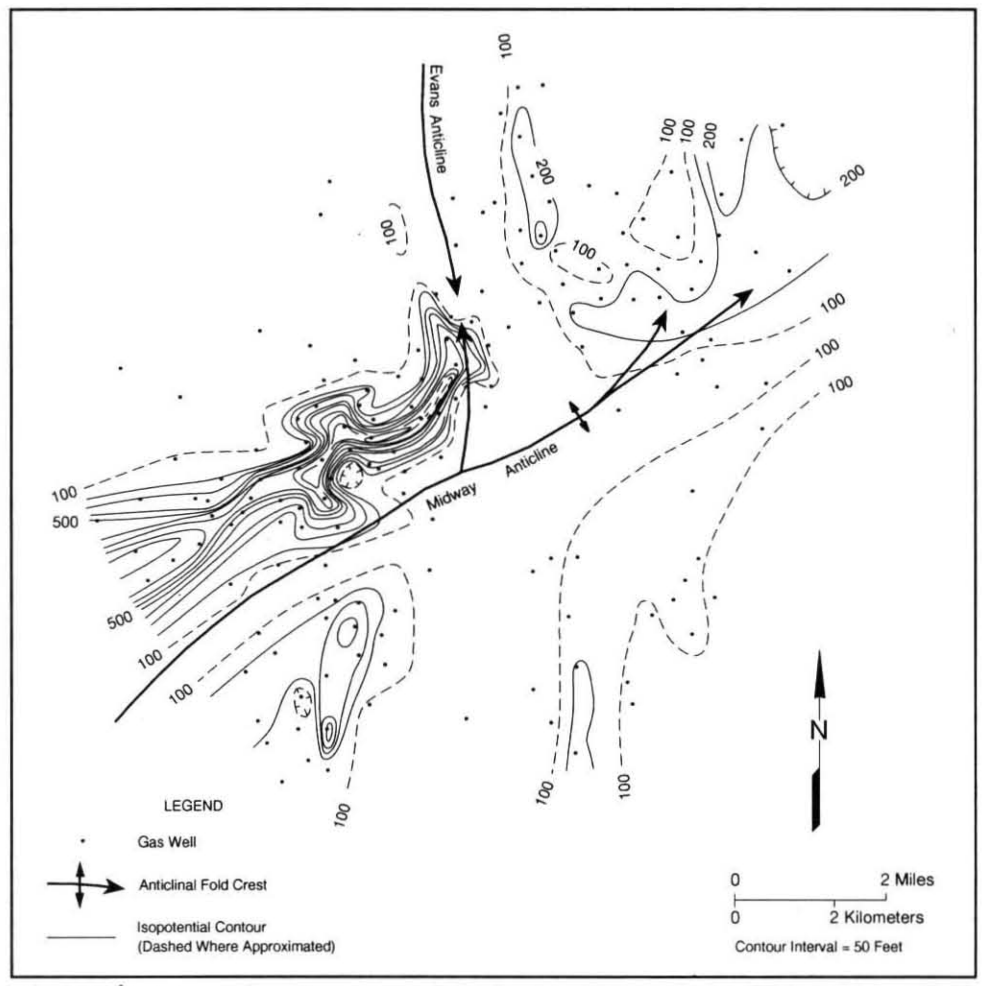


Figure UDs-27. Isopotential map of final open flows of the Midway-Extra field illustrating the distribution of productive wells relative to structural features. See Figure UDs-2 for location of Midway-Extra field. From Shumaker (1993) after modification from Schaefer (1979).

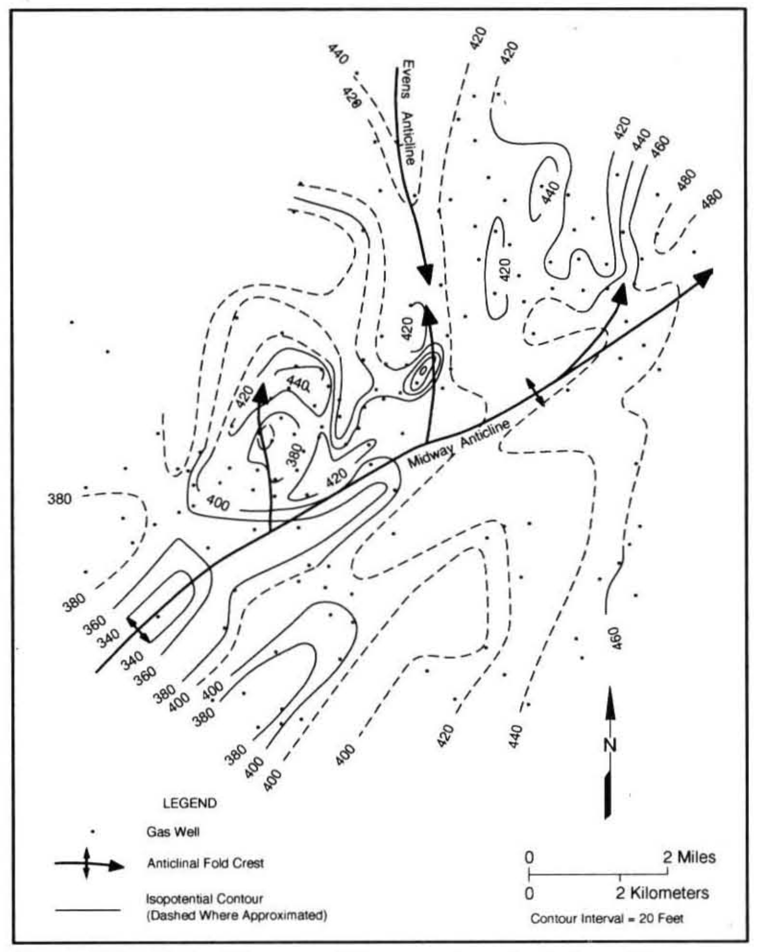


Figure UDs-28. Isolith map of the organic-rich shales of the lower part of the Huron Member of the Ohio Shale in the Midway-Extra field. See Figure UDs-2 for location of Midway-Extra field. From Shumaker (1993) after modification from Schaefer (1979).

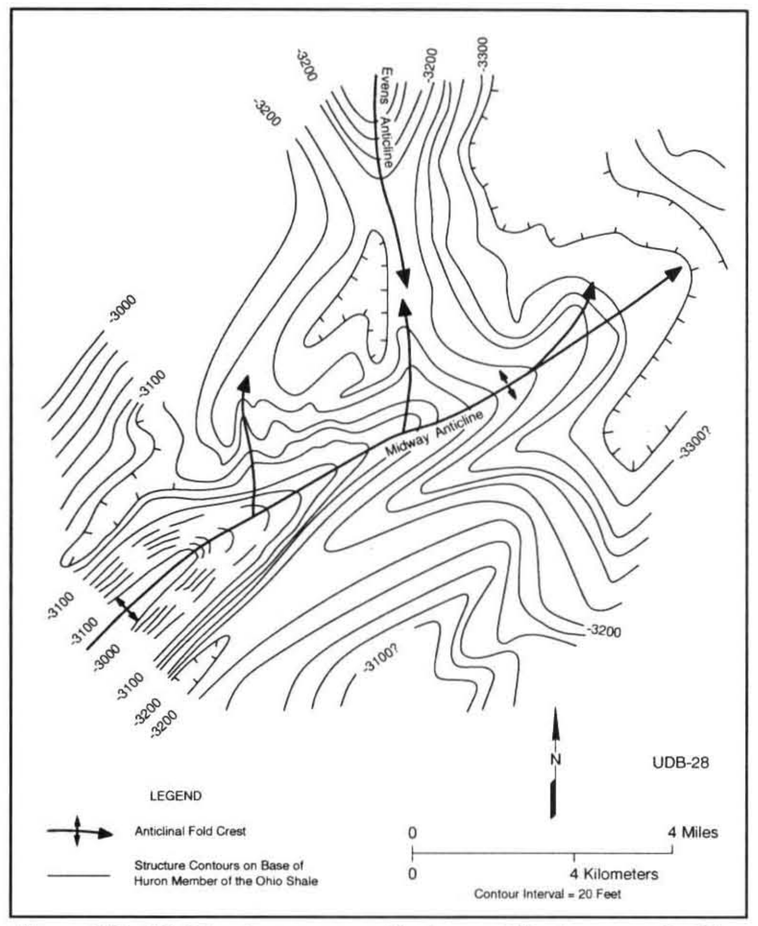


Figure UDs-29. Structure map on the base of the lower part of the Huron Member of the Ohio Shale in the Midway-Extra field. See Figure UDs-2 for location of Midway-Extra field. From Shumaker (1993) after modification from Schaefer (1979).

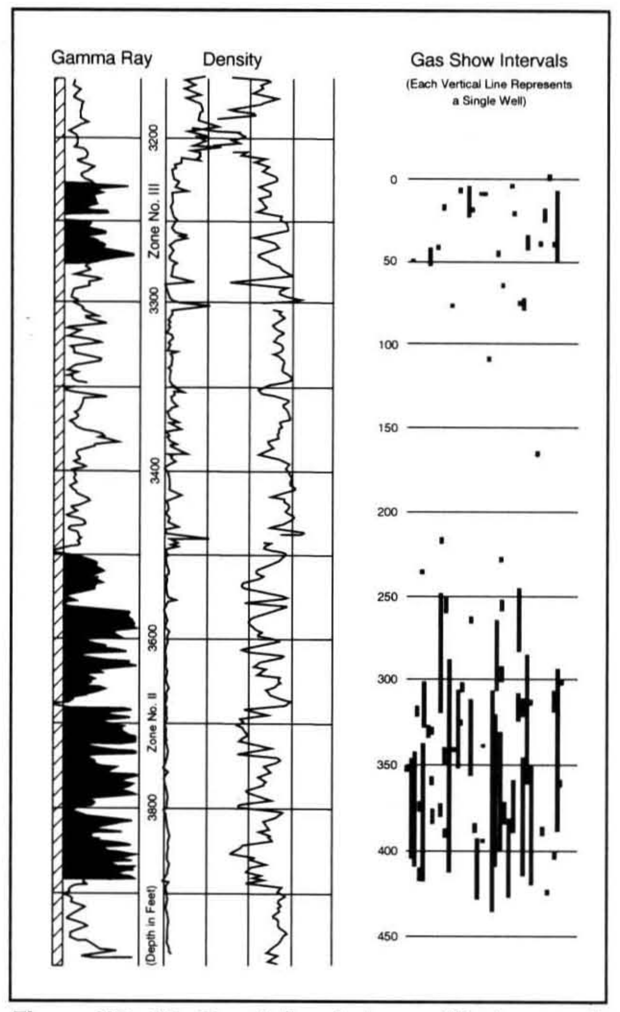


Figure UDs-30. Correlation between lithology and the location of gas shows in the upper (zone III) and lower (zone II) parts of the Huron Member of the Ohio Shale from 37 wells in the Cottageville field, Jackson and Mason counties, West Virginia. From Martin and Nuckols (1976).

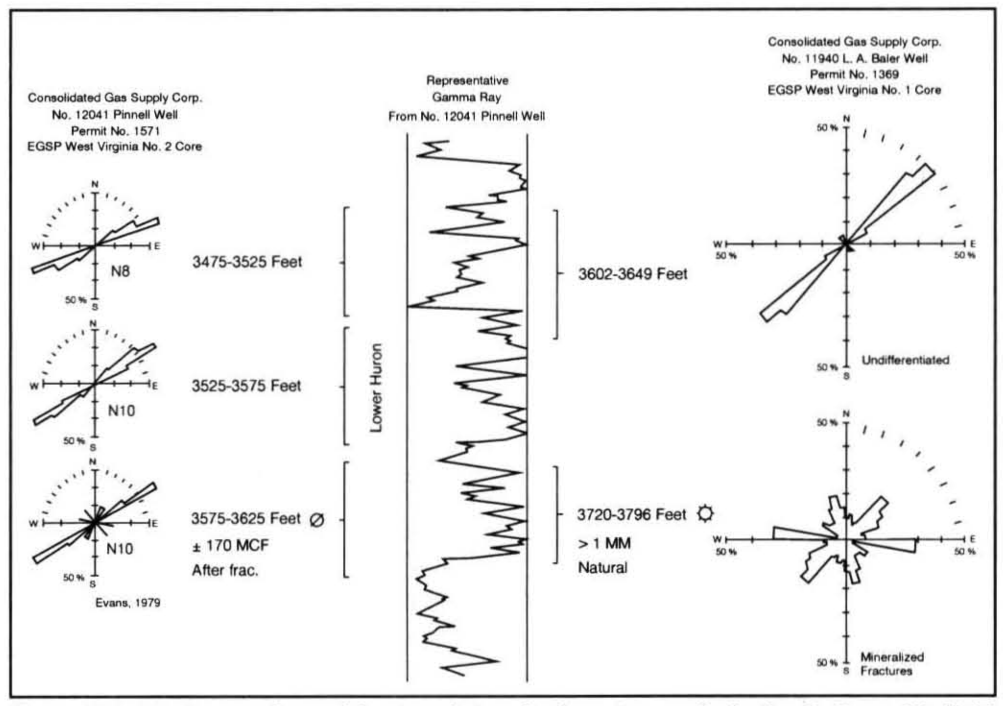


Figure UDs-31. Comparison of fracture intensity from two wells in the Cottageville field. The Consolidated Natural Gas Pinnel No. 12041 (Jackson (1371) well showed no natural production, only 171 Mcfg/d open flow after fracture, and first year's production of only 13 MMcfg. The Consolidated Natural Gas Baler No. 11940 (Jackson 11369) well was completed without stimulation, initially produced 250 Mcfg/d against 200 psig line pressure, and produced 90 MMcfg in the first year. Fracture orientation data are from Patchen and Larese (1976) from data supplied by Watts, US DOE.

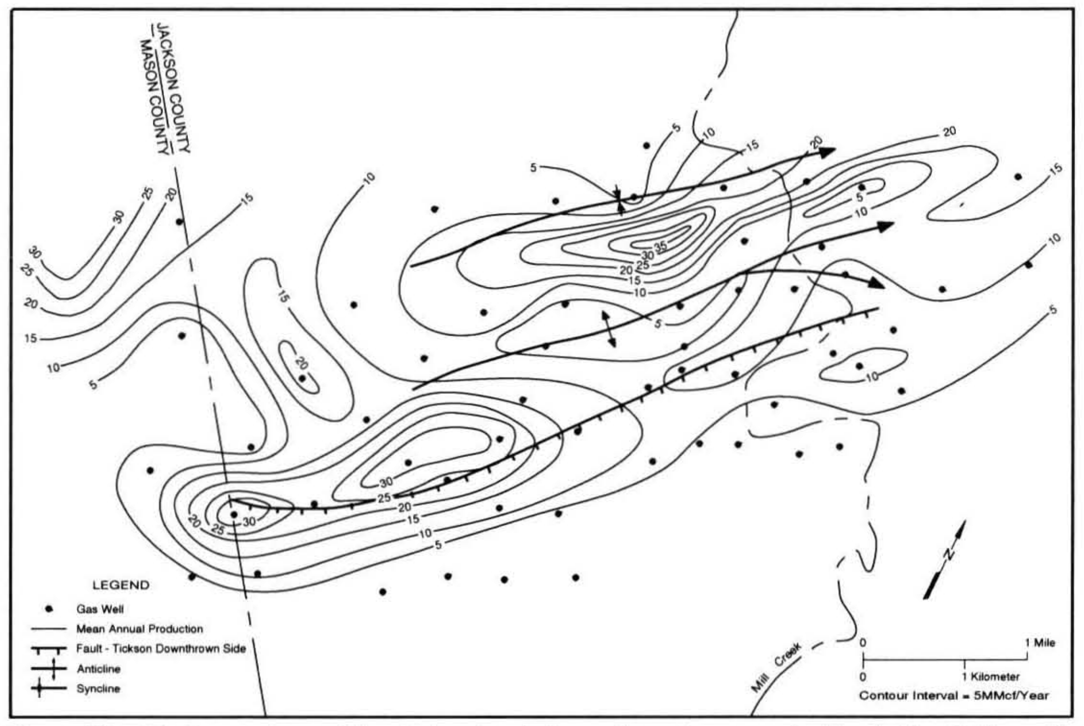


Figure UDs-32. Comparison of local structural elements and gas production in the Cottageville field. After Negus-deWys and Shumaker (1978). See Figure UDs-2 for location.

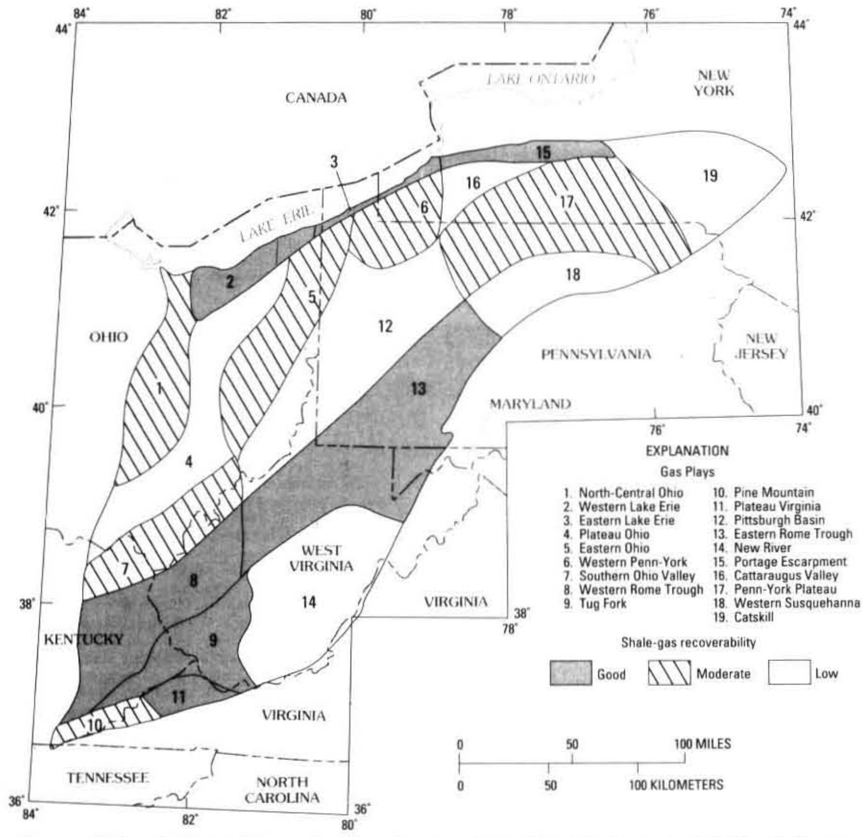


Figure UDs-33. Location of sub-plays within the Devonian black shale for which resource estimates were provided by Charpentier and others (1993).

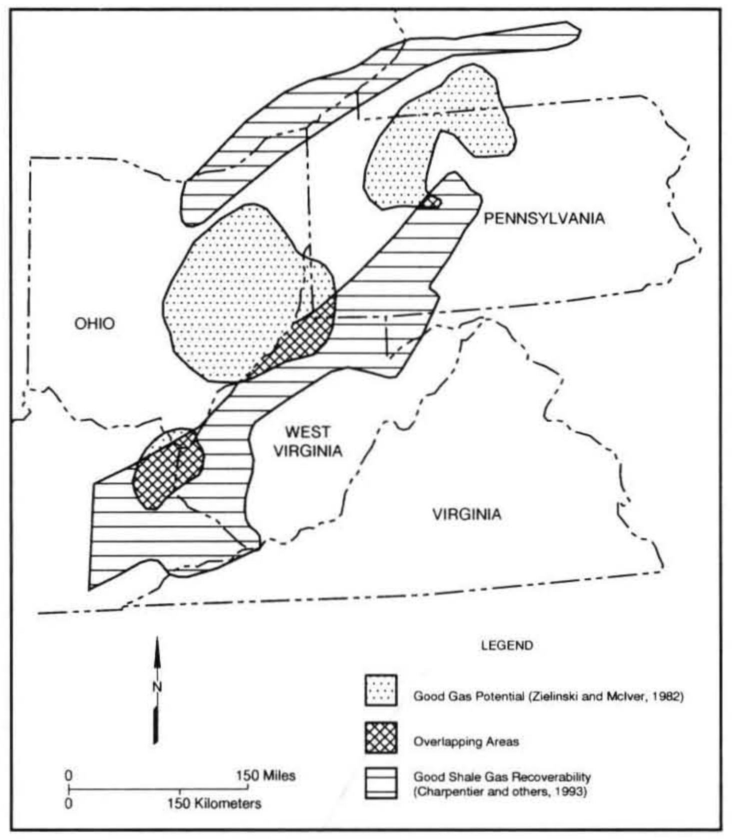


Figure UDs-34. Comparison of interpretations of Zielinski and McIver (1982) and Charpentier and others (1993) of the areas with good shale gas potential. The interpretation of Zielinski and McIver was based primarily on the gas content data derived from core analyses; the approach of Charpentier and others (1993) was based on assessment of not only the gas-in-place data but also the likelihood of natural fracturing.

Resources and Reserves

An enormous volume of gas is enclosed within the Upper Devonian shale sequence. Zielinski and McIver (1982) estimated 2,579 tcfg in-place in the Devonian shale sequence based on the results of off-gassing studies of 23 fresh cores obtained from pressure-retaining core barrels. Charpentier and others (1982; 1993) provided an alternative estimate based on a probabilistic Monte Carlo assessment of 19 separate Devonian shale plays (Figure UDs-33) that ranged 577 to 1,131 tcfg. Subsequent estimates for Kentucky (Kuuskraa and others, 1985), West Virginia (Kuuskraa and Wicks, 1984), and Ohio (Kuuskraa and Wicks, 1983) give gas-in-place values of 82 tcfg, 135 tcfg, and 390 tcfg, respectively, for a regional total of 607 tcfg. Of the West Virginia total, Kuuskraa and Wicks (1984) assign 25.3 tcfg in-place to the Huron and Rhinestreet and 67 tcfg in-place to the Marcellus Shale in deeper parts of the basin. Note that this estimate combines reservoirs that are split among this play and the Upper Devonian fractured black and gray shales and siltstones play (R. Milici, this atlas). The erratic distribution of fracture permeability and the low per-well recovery in areas of fracturing restricts recoverable reserves to a small fraction of the in-place values. Brown (1976) estimated the ultimate recovery in West Virginia to be 893 bcfg. Zielinski and McIver (1982) estimated that the recoverable resource for West Virginia, Kentucky, and Ohio ranges from 30 to 50 tcfg. Kuuskraa and others (1985) place technically recoverable reserves in Kentucky at 9 to 23 tcfg; Kuuskraa and Wicks (1983) give a range of 6 to 22.5 tcfg for Ohio; and Kuuskraa and Wicks (1984) estimate a range from 11 to 44 tcfg for West Virginia. The sum of these estimates is 26 to 89.5 tcfg.

Future Trends

Future development of the black shale resource will focus initially on expanding the area of production from the lower part of the Huron Member of the Ohio Shale. This extension will most likely occur to the north and south of the Big Sandy field, following the general trend of favorable reservoir thickness, organic carbon content, and thermal maturity. Success will depend on the ability to predict the presence and nature of natural fracture systems. Fracture detection methods will likely be based on detailed structural and isolith mapping of multiple intervals in an attempt to identify the effects of reactivated basement structures. However, direct means of measurement, including shear wave seismic, will continue to be tested. Although Shumaker (1993) asserted that a regional fracture system such as that existing at Big Sandy is not likely to be repeated elsewhere in the basin, successful gas shale exploration can be based on the discovery of isolated fields related to local structures. Furthermore, the vast amount of shale gas remaining, even in areas of profitable production, indicates that increased production can be obtained with improved drilling, completion, and reservoir stimulation technologies. Zielinski and McIver (1982) and Charpentier and others (1993) independently assessed the most favorable areas for future exploration in the black shale play (Figure UDs-34). The primary reason for the difference between the two interpretations is that the work of Charpentier and others (1993) is based on informed estimates of the likelihood of fracture permeability by region, whereas that of Zielinski and McIver (1982) focuses mainly on geochemical trends.

Exploration of the deeper, more thermally mature units within the center of the basin may not be economic in the near future unless the shale can be combined with other targets. These prospective units are thinner and deeper than the currently producing shale reservoirs, and may not be as intensely fractured. However, prospects for shale production are good. Analysis of a core of the Marcellus Shale in Monongalia County, West Virginia, revealed surprisingly high permeability to gas (5 to 50 md) and gas storage capacity (up to 26 Mcfg/cubic foot) (Randolph and Soeder, 1986) related to elevated formation pressure. Although it has been shown in the shallow shale fields that economic production of unfractured black shales cannot be established by stimulation alone, the possibility remains that technology to produce richer, deeper, pressurized shales in the absence of natural fractures may be feasible.

PLAY Dol: MIDDLE DEVONIAN ONONDAGA LIMESTONE REEF PLAY

by Arthur M. Van Tyne, Consulting Geologist

Location

Seven subsurface, gas-productive pinnacle reefs in the Onondaga Limestone have been found scattered across a wide area of southwestern New York and adjoining northwestern Pennsylvania (Figure Dol-1). They average a few hundred acres in areal extent, have maximum thickness of about 200 feet, and occupy a northeast-trending belt across New York and Pennsylvania. These subsurface reefs are similar to the nearly 30 smaller reefs that have been found along the Onondaga outcrop.

Production History

The discovery well for subsurface Onondaga reef gas production, although not recognized as such when the well was completed in 1933, was the J. Brooke Reed et. al. No. 1 Quinlan Oil located in Cattaraugus County, New York. The well was originally drilled beneath the Onondaga to explore the Oriskany Sandstone. A 106-foot section of Onondaga was encountered in an area where the normal thickness is 70 to 75 feet. A show of oil was reported in the Oriskany, and that zone was shot with 100 quarts of nitroglycerine with no positive results. Old records indicate that later, in January 1934, the well was flowing several thousand cubic feet of gas per day. The operator believed this gas was coming from the Oriskany. However, a temperature log, run when the well was reworked in 1957, showed that the gas was coming from the upper part of the Onondaga.

In early 1957, this well was reentered and logged by Eastern Royalties. They also fracture-treated the Onondaga, but the results were mixed. The well flowed at a rate of 3 MMcf/d briefly after treatment, but this soon decreased to a small flow that, however, remained steady. Later in 1957, the hole was drilled 65 feet deeper into the Helderberg but additional production was not found. Gas was produced from this well for use in various power plants on a surrounding oil lease at a rate said to be about 10 Mcf/d for more than 20 years.

In late 1977, Pennzoil drilled the No. E-2 Quinlan about 1,000 feet southwest of the original Quinlan reef well and encountered a flow of several million cubic feet of gas per day, with condensate, in the top of the Onondaga. That well confirmed the existence of an Onondaga reef at the Quinlan site. The field was named Quinlan Reef field (Table Dol-1; Figure Dol-2).

The first of the more recent subsurface Onondaga reef discoveries was made by the Wyckoff Development Company No. 1 Brewster in 1967. The well was also listed under the farm name of Cornell for the surface owner, not the mineral owner. The Brewster well is located in Steuben County, New York, and the gas field subsequently developed there became known as the Wyckoff field (Table Dol-1; Figure Dol-2). The well was drilled by cable tools as an Oriskany Sandstone exploratory test located on a seismic structural high. During the drilling of the well, a grayish-white, fossiliferous limestone with a show of gas was encountered at a depth of 4,661 feet, about 130 feet above the expected top of the Onondaga. It occurred in the dark gray and black Middle Devonian lower Hamilton shale section. The author identified this as mainly coralline debris and possibly Onondaga Limestone. A control head was installed, and when drilling had progressed to a little below 4,700 feet, the gas flow was gauged at 1 MMcf/d. The well was eventually drilled to a total depth of 4,814 feet into the top of the underlying Oriskany Sandstone. A large gas flow also occurred from the Oriskany.

Later in 1967, Sylvania drilled the No. 1 Banks about one-half mile west of the No. 1 Brewster. The Banks well penetrated 195 feet of Onondaga in apparently the thickest part of the reef. Large flows of gas occurred in both the Onondaga reef and the Oriskany Sandstone.

The Wyckoff discovery in 1967 touched off a major leasing and seismic exploration boom that was mainly centered in the area of Steuben County, New York. Shell Oil and Trend Exploration of Denver, Colorado, immediately began intensive well sample and geophysical log studies of the Onondaga in an attempt to understand the origin of the reefs. Later, Anderson Oil and Consolidated Gas also made extensive studies of the Onondaga.

The early well-sample studies showed an unusual thickness of white and light gray limestone in the Onondaga in a few scattered wells. An abnormal thickness of white limestone had been reported in some old well records, which was an indication that a reef might be nearby. Subsequent seismic work in those areas revealed the Adrian reef and the Stone Hill reef (Table Dol-1; Figure Dol-2).

In the mid to late 1970s, Pennzoil conducted an extensive program of seismic exploration work on its land holdings in southeastern Cattaraugus County, New York, and adjacent northern McKean County, Pennsylvania. Some of that work was in the vicinity of the old Quinlan reef discovery. This work was the basis for later drilling the Quinlan E-2 well in the heart of that reef. Pennzoil's early 1981 Flatstone reef discovery (Table Dol-1; Figure Dol-2), located 7.5 miles west-northwest of the Quinlan reef, was also a result of those seismic exploration studies.

The Thomas Corners reef in central Steuben County, discovered by Cabot in 1971 (Table Dol-1; Figure Dol-2), was drilled as a result of seismic work done by Trend Exploration. The Cyclone reef field in McKean County, Pennsylvania, was discovered by Amoco in early 1974 (Table Dol-1; Figure Dol-2) as a result of their earlier seismic exploration program.

The western group of three subsurface reefs (Table Dol-1; Figure Dol-2) produces condensate with the gas. The ratio of condensate to gas recovery from the Quinlan reef has ranged from nearly 50 barrels per MMcfg in the first stages of production to less than four barrels per MMcfg at present. The ratio has shown a steady decline over nearly 15 years of production. About 110,000 barrels of condensate have been produced from this reef. Flatstone reef started with a

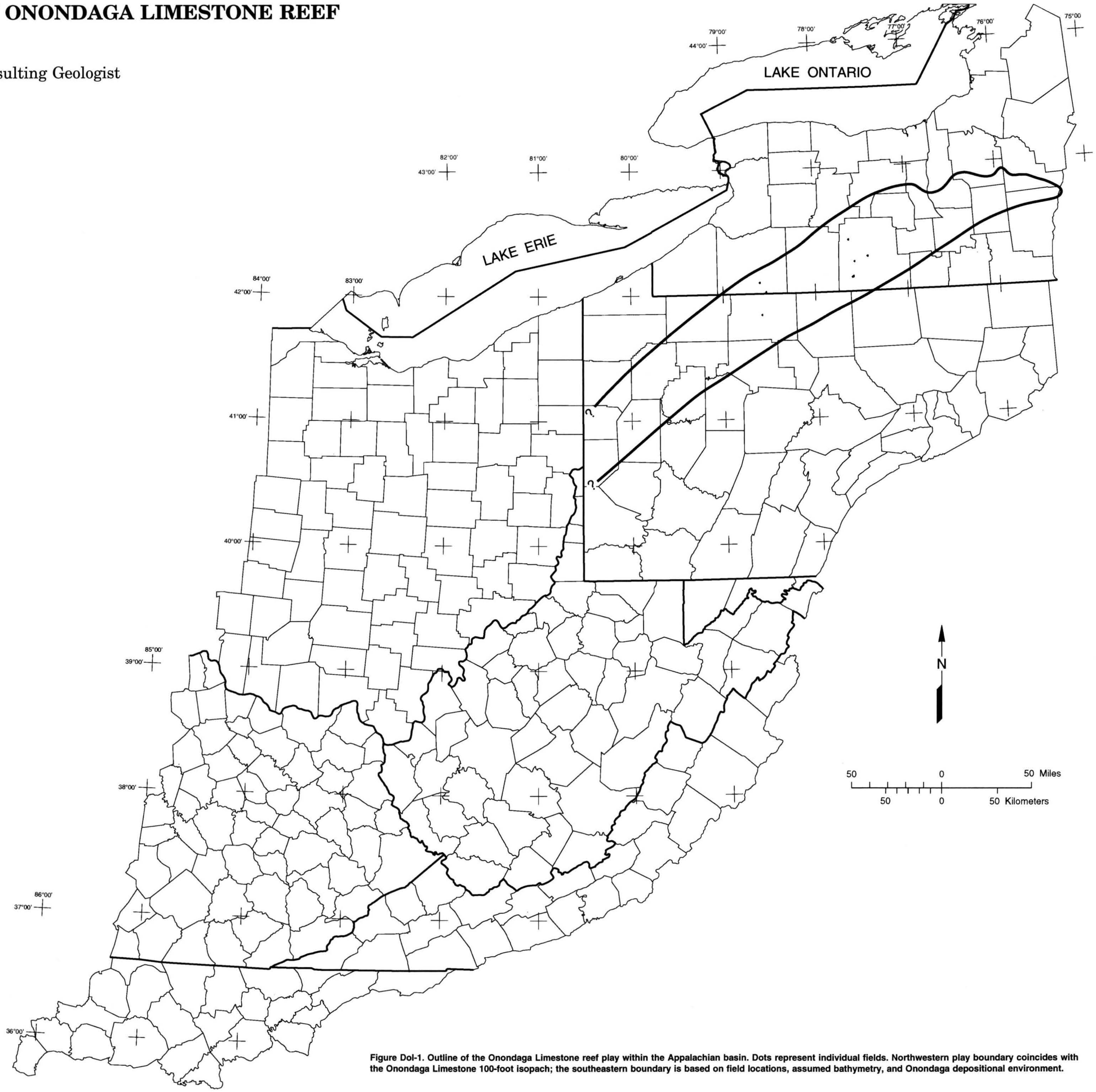


Figure Dol-1. Outline of the Onondaga Limestone reef play within the Appalachian basin. Dots represent individual fields. Northwestern play boundary coincides with the Onondaga Limestone 100-foot isopach; the southeastern boundary is based on field locations, assumed bathymetry, and Onondaga depositional environment.

PLAY Dol-1		Quinlan NY	Flatstone NY	Cyclone PA	Wyckoff NY	Adrian NY	Thomas Corners NY	Stone Hill NY
BASIC RESERVOIR DATA	POOL NUMBER							
	DISCOVERED	1933	1981	1974	1967	1971	1971	1974
	DEPTH TO TOP RESERVOIR	4,296	3,998	5,170	4,661	4,156	3,547	3,276
	AGE OF RESERVOIR	Middle Devonian	Middle Devonian	Middle Devonian	Middle Devonian	Middle Devonian	Middle Devonian	Middle Devonian
	FORMATION	Onondaga	Onondaga	Onondaga	Onondaga	Onondaga	Onondaga	Onondaga
	PRODUCING RESERVOIR	Onondaga Reef	Onondaga Reef	Onondaga Reef	Onondaga Reef	Onondaga Reef	Onondaga Reef	Onondaga Reef
	LITHOLOGY	Limestone	Limestone	Limestone	Limestone	Limestone	Limestone	Limestone
	TRAP TYPE	Reef	Reef	Reef	Reef	Reef	Reef	Reef
	DEPOSITIONAL ENVIRONMENT	carbonate ramp	carbonate ramp	carbonate ramp	carbonate ramp	carbonate ramp	carbonate ramp	carbonate ramp
	DISCOVERY WELL IP (Mcf)	7	21,000	200	1,000	10,000	10,000	
	DRIVE MECHANISM	gas cap	gas cap	gas cap	gas cap	gas cap	gas cap	gas cap
	NO. PRODUCING WELLS	2	1	2	3	2	2	1
	NO. ABANDONED WELLS	0	0	0	1	1	0	0
	AREA (acreage)	240	160	160	350	500	600	240
	OLDEST FORMATION PENETRATED	Helderberg	Onondaga	Queenston	Helderberg	Helderberg	Helderberg	Helderberg
	EXPECTED HETEROGENEITY DUE TO:	deposition diagenesis	deposition diagenesis	deposition diagenesis	deposition diagenesis	deposition diagenesis	deposition diagenesis	deposition diagenesis
RESERVOIR PARAMETERS	AVERAGE PAY THICKNESS (ft.)			34	50			
	AVERAGE COMPLETION THICKNESS (ft.)	28	58	86		80		26
	AVERAGE POROSITY--LOG (%)			6	7	8		
	MINIMUM POROSITY--LOG (%)		2			2		
	MAXIMUM POROSITY--LOG (%)		8					
	NO. DATA POINTS		1	1	2	1		
	POROSITY FEET							
	RESERVOIR TEMPERATURE (°F)	101	100	122	120	104	105	86
	INITIAL RESERVOIR PRESSURE (psi)	2,125	2,010	2,841	1,750	1,697	1,725	1,320
	PRODUCING INTERVAL DEPTHS (ft.)	4,200-4,324	4,000-4,058	5,184-5,270	4,500-4,700	4,164-4,244	3,550-3,718	3,284-3310
	PRESENT RESERVOIR PRESSURE (psi) / DATE							
FLUID & GAS PROPERTIES	Rw (Ωm)							
	GAS GRAVITY (g/cc)				0.58	0.6	0.5971	
	GAS SATURATION (%)				90	85	86	
	WATER SATURATION (%)				10	15	14	
	COMMINGLED	no	no	no	no	no	no	no
	ASSOCIATED OR NONASSOCIATED	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated
	Btu/scf			1,170	1,039			
VOLUMETRIC DATA	STATUS (producing, abandoned, storage)	producing	producing	producing	producing	storage	producing	producing
	ORIGINAL GAS IN PLACE (Mcf)				7,400,000			
	ORIGINAL GAS RESERVES (Mcf)							
	PRODUCTION YEARS	1933-1993	1983-1993	1974-1993	1972-1993	1972-1993	1975-1993	1981-1993
	REPORTED CUMULATIVE PRODUCTION (Mcf)	5,700,000	700,000	2,300,000	4,700,000	7,100,000	6,000,000	1,200,000
	NO. WELLS REPORTED							
	ESTIMATED CUMULATIVE PRODUCTION (Mcf)							
	REMAINING GAS IN PLACE (Mcf)/DATE				2,200,000/			
	REMAINING GAS RESERVES (Mcf)/DATE				500,000/			
	RECOVERY FACTOR (%)							
	INITIAL OPEN FLOW (Mcf/d)	250		200	1,000	10,000	10,000	
	FINAL OPEN FLOW (Mcf/d)	20,000	21,000	3,000	1,000	15,000	15,000	12,619

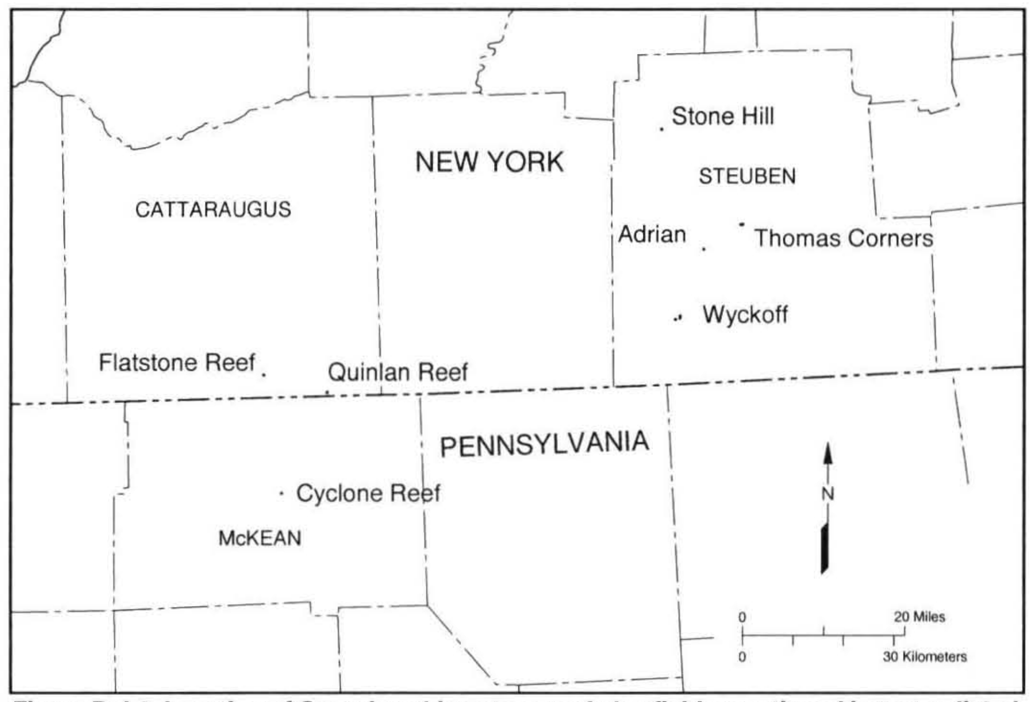


Figure Dol-2. Location of Onondaga Limestone reef play fields mentioned in text or listed in Table Dol-1.

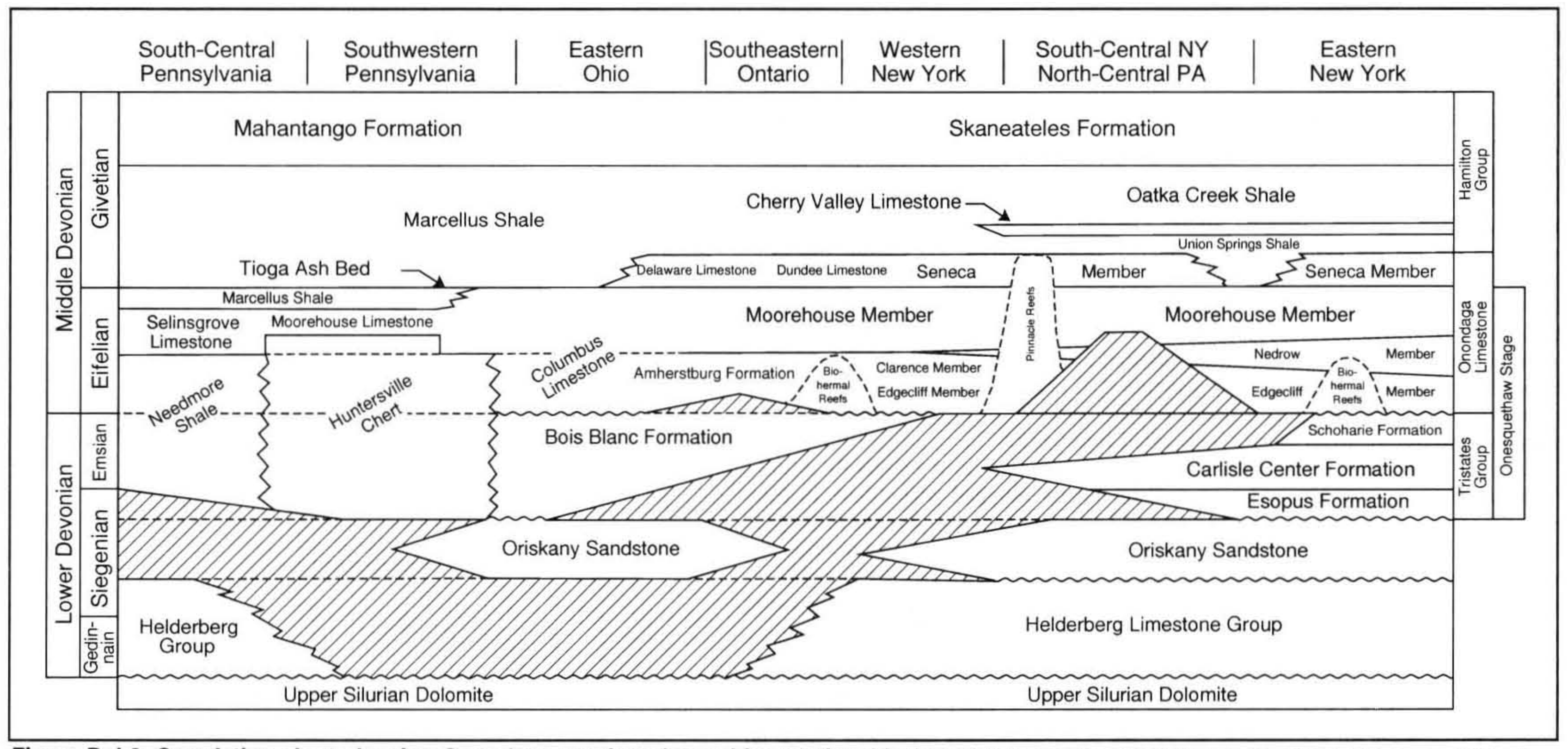


Figure Dol-3. Correlation chart showing Onondaga stratigraphy and its relationship to overlying and underlying units. From Cassa and Kissling (1982).

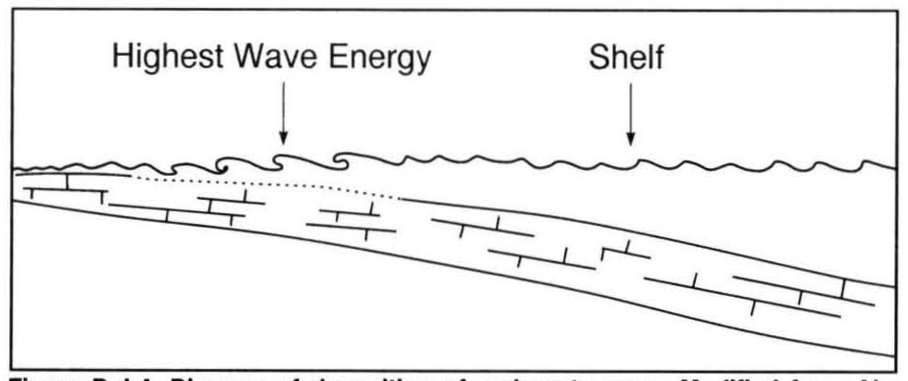


Figure Dol-4. Diagram of deposition of carbonate ramp. Modified from Ahr (1973) and Wilson (1975).

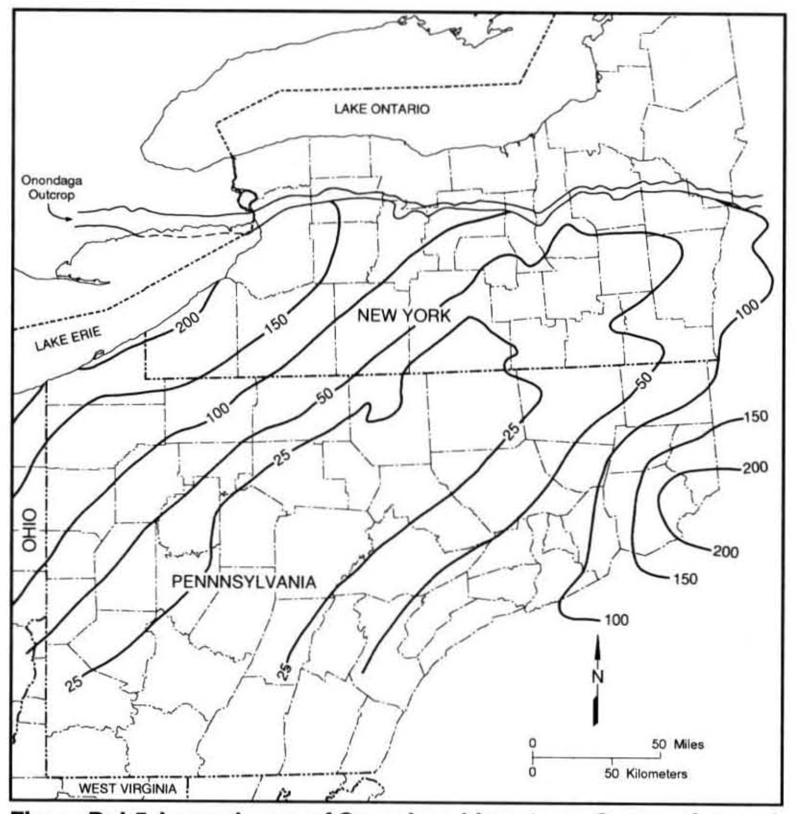


Figure Dol-5. Isopach map of Onondaga Limestone. Contour interval = 25 and 50 feet.

condensate/gas ratio of less than 10 barrels per MMcfg and has produced less than 4,000 barrels of condensate. Currently, it produces little or none. The Cyclone reef started with a condensate/gas ratio of five to eight barrels per MMcfg and has produced about 8,000 barrels of condensate.

The seven known subsurface Onondaga reefs have produced a total of 28 bcfg through 1992. At Wyckoff, there was also a little more than 4 bcfg produced from the Oriskany Sandstone. The largest producer is the Adrian field with 7.1 bcf; this field was not totally depleted when converted to storage in 1991. The smallest production, which is about 700 MMcf to date, is from the Flatstone field.

Stratigraphy

The Onondaga Limestone (Early Middle Devonian) was named by Conrad (1837) for exposures in Onondaga County in central New York. For many years, only generalized subdivisions of the Onondaga were suggested by various investigators. The first systematic study and subdivision of the formation into members was done by Oliver (1954; 1956b). He divided the Onondaga into an uppermost Seneca Member underlain in descending stratigraphic order by the Moorehouse, Nedrow, and basal Edgecliff members (Figure Dol-3). Later, Ozol (1963) and Rickard (1975) designated the Clarence Member in the lower Onondaga.

The Seneca Member, the uppermost member of the Onondaga, is a massive to occasionally shaley, dark gray limestone. The contact with the overlying Marcellus Middle Devonian Hamilton Group black shale is possibly an unconformity, but this is disputed by some researchers. The base of the member is marked by a Tioga volcanic ash bed (B of Rickard, 1984). In the subsurface of the Steuben County area in New York, the Onondaga is thinnest, and the Seneca is less than 10 feet thick. It wedges out to the south in northern Pennsylvania (Rickard, 1989).

The Moorehouse and Nedrow members, described and named from outcrops in central New York (Oliver, 1954; 1956b), are more difficult to distinguish individually in the subsurface by well cuttings and geophysical logs. Both are medium gray, fossiliferous and cherty limestones. In general, the Moorehouse is more brownish-gray and massive, whereas the Nedrow is a more shaley limestone.

The Clarence Member was named by Ozol (1963), who believed that it was the cherty equivalent of the Nedrow on outcrop in the far western part of New York. Rickard (1975), however, restricted the name to a separate cherty zone below the Nedrow and equivalent to the upper Edgecliff in western New York. In the subsurface of western New York, it is difficult to separate the Clarence from the Edgecliff. In gamma-ray log studies, Rickard (1989) combines the two units.

The productive reefs of this play are assigned to the Edgecliff Member, the basal member of the Onondaga. On outcrop, the Edgecliff is a light gray, coarsely crystalline, highly fossiliferous biostromal limestone. Light gray and whitish chert is common as is a soft, pale green shale. The Edgecliff usually contains solitary rugose and tabulate corals in profusion as well as some gastropods, fewer brachiopods, and rarer bryozoa and trilobites. These fossils are cemented in a groundmass which is sometimes a calcisiltite (Lindholm, 1969), sometimes consists of coarse, cemented clasts, and often is the soft, pale green shale. The outcrop Edgecliff can generally be classified as a packstone-grainstone. Drill cuttings of the Edgecliff are commonly a white or whitish-gray color. In western and central New York, a basal zone that varies from a few inches to several feet in thickness in the Edgecliff contains varying amounts of quartz sand grains reworked from the Oriskany Sandstone. This zone also contains scattered pellets and stains of dark green glauconite or illite.

In eastern New York, the Schoharie Formation unconformably underlies the basal Edgecliff Member of the Onondaga Limestone (Figure Dol-3). It wedges out by unconformity in east-central New York so that to the west the Onondaga overlies successively older rocks. In the area of Buffalo, New York, a tongue of the Early Devonian Bois Blanc Formation underlies the Onondaga.

Westward from New York, on the Niagara Peninsula of Ontario, Canada, the Seneca Member of the Onondaga is equivalent to the Dundee Limestone (Figure Dol-3). In the eastern part of the peninsula, the Tioga ash bed has been observed beneath the Dundee. The Moorehouse and Nedrow-Clarence members thin rapidly westward in Ontario and their equivalent units to the west are the Lucas and Amherstburg formations of the Detroit River Group (Figure Dol-3). The lower Amherstburg is correlative with the Edgecliff of New York.

In Ohio and northwestern Pennsylvania, the Seneca has been termed the Delaware, whereas the main body of the Onondaga of New York, beneath the Tioga, is the Columbus Limestone (Figure Dol-3).

The early Onondaga (Edgecliff) sea transgressed from the east and south upon an erosional surface resting upon the Springvale in east-central New York and the Bois Blanc in the west. According to Ettensohn (1985), Onondaga deposition took place during the fourth (last) stage of the first tectophase of the Acadian orogeny. This was during a time when tectonic activity to the east of the Appalachian foreland basin was temporarily at a minimum. The slow transgression of the warm Onondaga sea in a near equatorial setting provided a rich environment for the development of marine organisms.

The Edgecliff was deposited as a crinoidal and coralline limestone on a south-to-southeastward sloping ramp (Figure Dol-4). After the encroaching early Onondaga sea reached its maximum extent, shallower water depths in the north, more conducive to reef growth, graded to a deeper sea environment to the south. The Edgecliff, a biostromal limestone, displays wackestone, packstone, and grainstone facies to the north on the platform area in New York, but in the more southerly, deeper sea, basin environment becomes a mudstone, wackestone, or packstone. (Kissling and Polasek, 1982). In southern Pennsylvania, Maryland, eastern West Virginia, and western Virginia, this is the Needmore Shale.

The overlying Nedrow is a shaley limestone facies in central New York, but it is less argillaceous both to the east and west. In eastern New York, where more than 20 Edgecliff reefs have been found on the outcrop, cherty Nedrow Limestone is missing over the top of the reefs, but occurs around their flanks. The Moorehouse usually overlies the reefs (Oliver, 1956a; 1956b).

In Moorehouse time, the sedimentary environment returned to the clear water, less clastic conditions of Edgecliff time. The Moorehouse is still very fossiliferous but less so than the Edgecliff.

After several volcanic ash falls collectively termed Tioga, Onondaga Limestone deposition concluded with the Seneca Limestone Member. Immediately above the Tioga, the lower Seneca is very similar lithologically to the upper Moorehouse. The upper part, however, is darker gray, less fossiliferous and shaley. This signals the initiation of the heavy influx of Hamilton muds from the east, which was the beginning of the second tectophase of the Acadian Orogeny.

Onondaga reefs, both subsurface and surface, fall into two categories: those which extend above the local thickness of the Onondaga limestone; and those reefs and presumed reefs which are enclosed within a thicker Onondaga section.

Reefs presumably tend to begin forming on some higher portion of the sea floor somewhat above bottom carbonate muds. Some of the basal portions of known surface Onondaga reefs and cuttings samples through the basal part of subsurface reefs are rich in crinoid debris. This suggests that a crinoidal shoal was a particularly desirable substrate for the commencement of reef growth. Colonial and solitary rugose corals such as *Acinophyllum*, *Cylindrophyllum*, *Cystiphyllum*, and *Heliophyllum* followed and began to build up the mound. Various tabulates, such as *Cladopora*, *Emmonsia*, and *Favosites* also colonized the growing tract and perhaps acted as sediment baffles trapping broken coral and crinoid debris and also acted to build up the reef mound (Kissling and Coughlin, 1979). Lime mud filtered through the mass and filled cavities. Lesser numbers of brachiopods, gastropods, and bryozoa were part of the biota. The reef-mound nature of these structures is mainly due to the packing together of numerous rugose coral skeletons. They form a coral floatstone. Many of the surface reefs display flanking beds composed of reefal detritus, which dip away from the reef cores at angles of 10° or more (Oliver, 1956a).

Reefs developed along the northern edge of the early Onondaga sea. Their pattern appears random, although there seem to be shoals or banks, where several reefs have grown in proximity to one another. All outcropping reefs are thinner than those found so far in the subsurface.

Outcrop reefs appear to have formed in an arcuate belt in a shallow-sea environment south of the northern shoreline of the early Onondaga sea (Kissling, 1980). At some post-Nedrow time, a rapid deepening of the water could have drowned these reefs. Because of their low relief, they were readily covered by later Moorehouse deposits.

The southern subsurface reefs developed in an area which later became a downramp position toward the deeper part of the basinal sea as the sea prograded and deepened northward and westward. Consequently, rising sea level perhaps forced the reefs to grow higher toward the photic zone to accommodate the increasing water depth. Those southern reefs may have been overwhelmed by the continuation of the same rapid increase in water depth that drowned the outcrop reefs.

The subsurface reefs are overlapped by dark gray and black shales of the lower Hamilton. If those reefs continued to grow beyond Moorehouse time, their growth may have been terminated by the volcanic ash deposits of the Tioga ash falls.

The Edgecliff is thin (Van Tyne, 1972) and, according to Cassa and Kissling (1982), may be missing in an area including part of south-central New York but mainly in north-central Pennsylvania. For this to occur in a sedimentary unit that has shown such high organic productivity in other areas, even to the point of reef development, may appear unusual. However, it would seem to be a natural result of the depositional environment presented here. The area mentioned above is in the center of a large basin of carbonate deposition. Only minimal deposition took place because the area was sediment deprived. The Edgecliff may indeed be missing in limited areas, but this is believed to be due to local sea-floor scour.

The general area where subsurface reefs have been found may be part of a belt on the ramp south of which water depths eventually became too great to sustain the large variety of marine life seen further north in the Edgecliff biostrome. If this is true, Edgecliff reefs may not be present for any great distance to the south and southeast of the presently known subsurface reefs due to the excessive water depth that existed there during most of Edgecliff time.

The entire Onondaga section is also thin in the same area in which the

Edgecliff is thin (Figure Dol-5). However, the trend of thin Onondaga is to the southwest and extends well into southwest Pennsylvania. This thinning is also due to a lack of sediment.

Westward and northwestward, 25 miles from the Flatstone reef (Figure Dol-2), several presumed Onondaga reefs, which are buried within the total Onondaga section, have been accidentally discovered (Bastedo and Van Tyne, 1990). Sample cuttings from these wells are not available, so studies of the Onondaga lithology could not be made. The gamma-ray logs for some of these wells indicate the basal Onondaga section is less argillaceous than usual, but this part of the Onondaga section is normally a quite cherty and clean limestone in far western New York. These features have been called reefs mainly because gas flows (some of which are said to have been very large) were encountered in the lower Onondaga. The wells were being drilled for deeper Medina Sandstone gas production when the Onondaga gas was found. It is possible that these scattered occurrences could be Onondaga reefs, but the productive zones may simply be shelly biostromal deposits locally winnowed into banks.

In any event, gas production from these zones has been relatively small. Whatever porosity was present may well be mostly plugged with silica. In this area of western New York, in the vicinity of Lake Erie, several thousand deeper Medina wells have been drilled on 40-acre spacing or less, and fewer than 10 wells have reported significant shows of gas from the basal Onondaga zone. In wells where this gas was produced separately from Medina gas, the results have usually been disappointing. Gas production has ranged from a few million cubic feet to less than 40 MMcf in the few documented histories available. One well, said to be of this type, has produced about 30,000 barrels of oil and 25 MMcfg to date. However, that production may be related to a local faulted structure. Because these reefs do not extend above the local Onondaga sequence, there is no way to locate them except by random drilling. Consequently, it appears there is no viable exploration play for possible reefs that are hidden within the normal thickness of the Onondaga section.

Structure

The Onondaga Limestone in the play area has a regional southeast dip of 40 to 60 feet per mile towards the basin center. In the play area, the Onondaga is locally broken by northeast-trending thrust faults with displacements as much as several tens of feet. These faults, which have no surface expression, are associated with some minor folding. Reports to date do not specifically indicate that these structural features have any influence on reef formation or the recovery of gas from the Onondaga reef reservoirs.

Reservoir and Key Field Data

The reservoir in Onondaga reefs is inter-and intra-skeletal porosity within the body of the reef. The seal mainly consists of the surrounding and overlying black and gray, impervious shales of the Marcellus Shale and other overlying shales of the Middle Devonian Hamilton Group (Figure Dol-6). The basal portions of the known subsurface Edgecliff reefs are surrounded and sealed by onlapping and interfingering upper Onondaga limestones.

The source rock for the reef gas is believed to be the contiguous dark, richly organic Hamilton shales. These shales are often gassy when drilled through and sometimes have had shows of liquid condensate. The basal Marcellus Shale, which immediately overlies the Onondaga, is also productive of gas in several small fields in New York. As compaction of these shales took place, any gas present near the reefs could have migrated readily into the open spaces within the reef. Some gas may also have migrated upward into the Onondaga through fractures from the underlying Oriskany Sandstone.

In an attempt to determine if there was a difference between the Onondaga reef gas and Oriskany gas in the Wyckoff field, samples of each were taken in 1967. Analyses by the U.S. Bureau of Mines revealed an almost identical analysis for each sample. This would seem to indicate a similar source for both gases.

The subsurface reefs are free of water, but they have all produced condensate in varying amounts. Evidently, the reefs filled rapidly with gas that prevented water later expelled from the shales from entering the reef porosity in any substantial volume. The eastern subsurface reef group in Steuben County, New York, has produced only very small amounts of condensate. The only core taken in that group, the partial reef core from the Thomas Corners reef, contains considerable bitumen in pockets and cavities in its lower portion. In contrast, the subsurface reefs of the western group in Cattaraugus County, New York, and McKean County, Pennsylvania, have produced large volumes of condensate with the gas.

Drilling depths to the top of the reef zone in the seven subsurface reefs (Table Dol-1) range from 3,276 feet in the Stone Hill reef of Steuben County, New York, to 5,170 feet in the Cyclone reef in McKean County, Pennsylvania. The Cyclone reef is 25 to 30 miles downdip from the Stone Hill reef. The average depth to the top of the reef zone for all seven reefs is 4,141 feet. In some wells, gas shows were encountered in the top few feet of the reef with an increasing flow as more of the reef was drilled. In most wells, large flows of gas had occurred by the time the drill was about 10 to 15 feet into the reef.

The thickest reef zone so far encountered is 203 feet at Thomas Corners, whereas the thinnest is at Stone Hill where the reef is 115 feet thick. In two other wells, the greatest thickness of the reef is unknown because the wells were not drilled all the way through the reefal section.

At the Quinlan reef, the Pennzoil E-2 Quinlan well, which was reported to have been drilled at the crest of the reef as indicated by seismic log, only penetrated 38 feet of reef before the flow of gas was so great that drilling had to be stopped. The original Quinlan discovery well penetrated 106 feet of reef flank. At the Flatstone reef, the Pennzoil Flatstone Fee No. 1 penetrated 60 feet into the reef before drilling was stopped. By using the estimated subsea top of the Oriskany at each of these reefs and making a 5 to 10 foot allowance for the thickness of the unconformity zone, it is estimated that the thickness of each of these reefs is at least 150 feet. The average reef thickness for all seven reefs is 168 feet.

Rock pressure for the seven fields in the play range from a maximum of 2,841 psi bottom-hole pressure for the Cyclone reef in Pennsylvania to a minimum of 1,320 psi shut-in casing pressure for the Stone Hill reef in northern Steuben County, New York. The pressure differential might have been anticipated because these two reefs are the deepest and shallowest drilled in the play. The bottom-hole pressure for the Cyclone reef is the only such pressure on record. All the other pressures are top-hole shut-in casing pressures. In order to determine the pressure gradient for each field, 100 psi was added to the top-hole pressure for the six reefs where only the top-hole pressures are available. The author believes that this should give a near approximation to the actual bottom-hole pressure. This adjusted pressure value was divided by the deepest producing depth to obtain the gradient.

The three reefs in the western group—Quinlan, Flatstone, and Cyclone—have pressure gradients higher than the normal 0.43 lb/foot hydrostatic pressure gradient. All are overpressured. The gradients are about 0.5 lb/foot. The Cyclone reef has the maximum gradient at 0.53 lb/foot.

In the eastern group in Steuben County, New York, Wyckoff and Stone Hill reefs are underpressured; Adrian is slightly under or about even with hydrostatic; and Thomas Corners is a little above the hydrostatic pressure gradient.

Reef discovery wells had initial flows of gas from a few hundred thousand cubic feet of gas per day to 10 MMcf/d, which was recorded by the Cabot et al. No. 1 Sylvania at Thomas Corners. After acid treatment, final open flows ranged from about 2 MMcf/d to 15 MMcf/d, which was in Cabot's Sylvania well.

Little petrophysical data are available for these subsurface reefs. However, a core that accounted for about 70 percent of the total Onondaga reef thickness was taken at Thomas Corners. This core has been extensively examined and analyzed. The parameters found should generally apply to the other reefs.

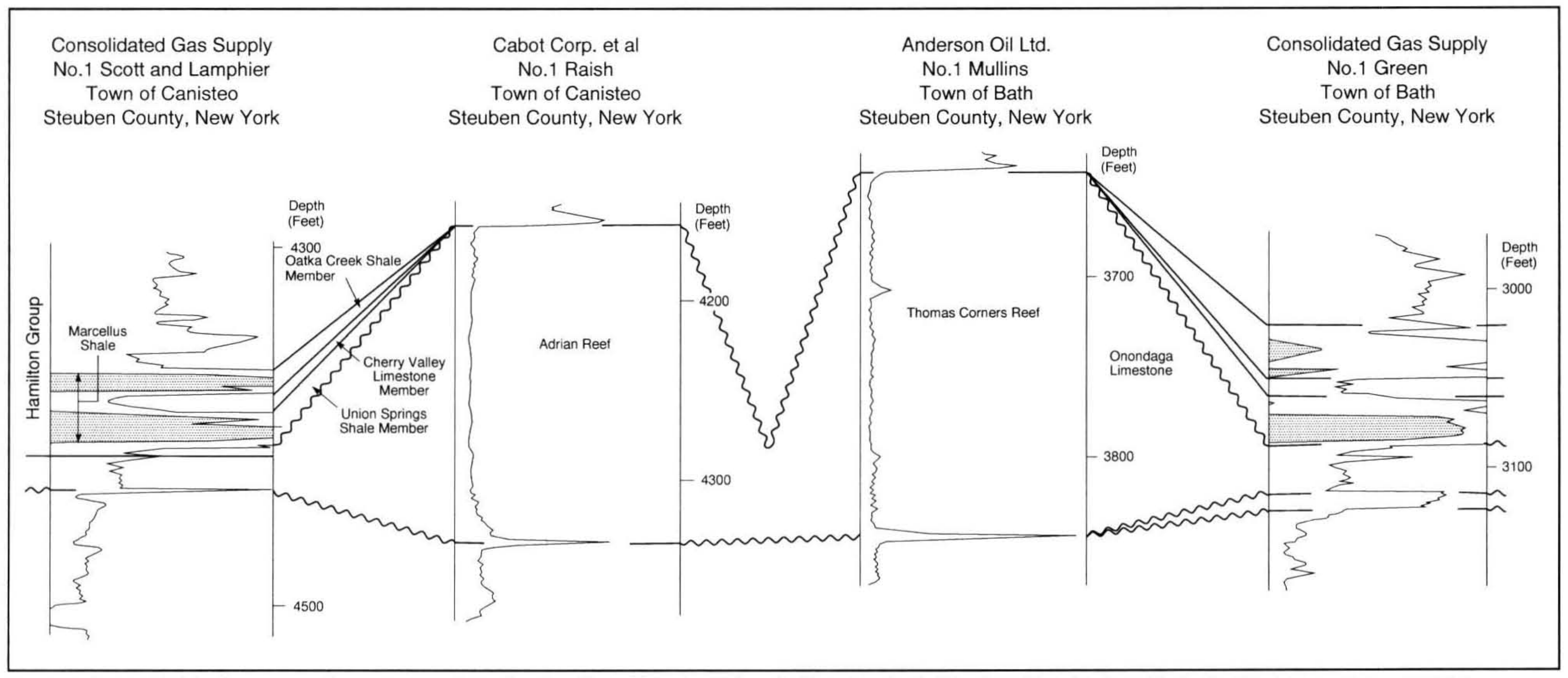


Figure Dol-6. Gamma-ray log cross section showing Onondaga in reef and off-reef wells in Steuben County, New York. Modified from Rickard (1989).

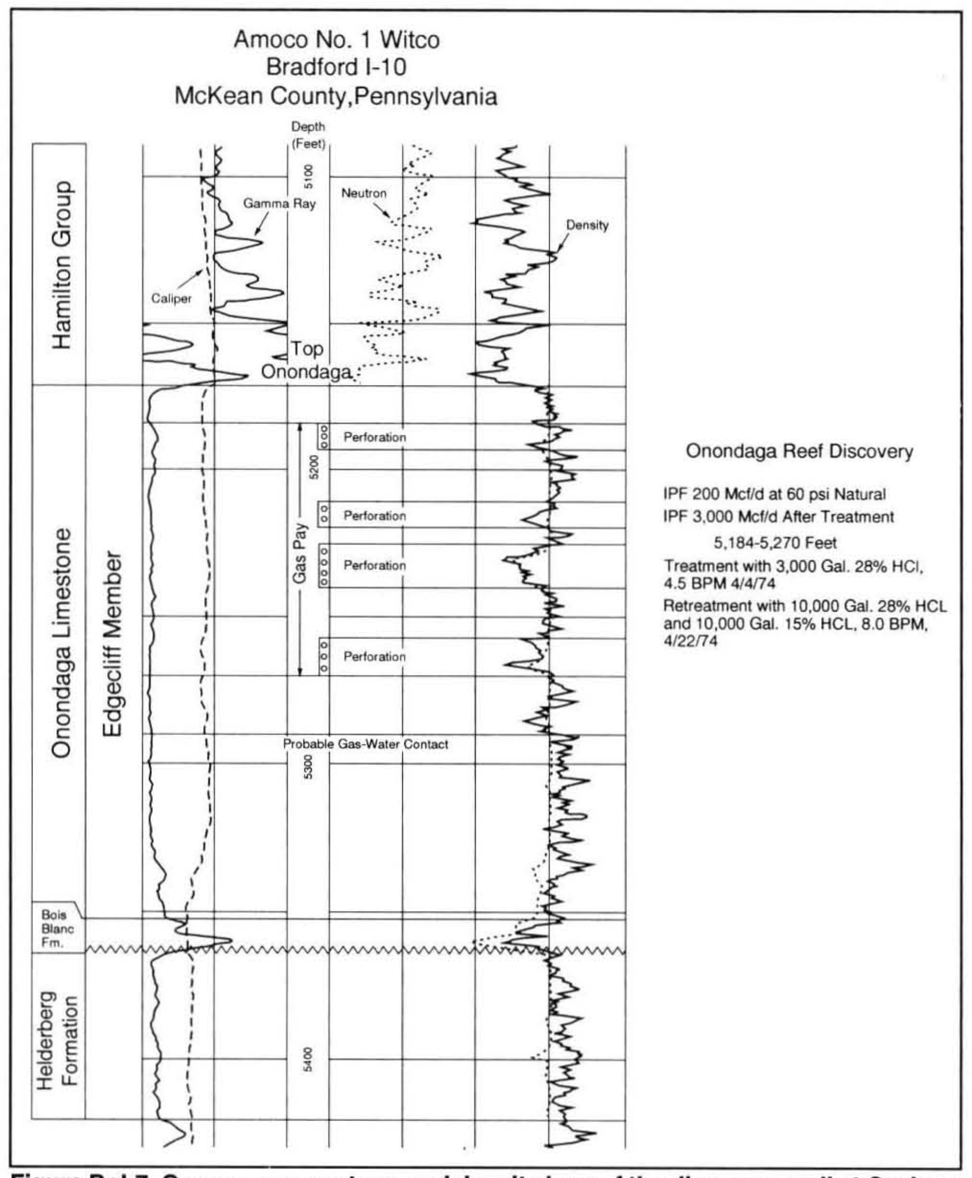


Figure Dol-7. Gamma-ray, neutron, and density logs of the discovery well at Cyclone pool indicating the stratigraphy, pay section, initial production, and treatment. From Lytle and others (1976).

Sample and core studies have shown that the carbonate in these reefs is essentially monomineralic calcite. Calcite twinning is common and can readily be seen in cuttings samples. This indicates that the reefs were stressed at some time, possibly during the late Paleozoic Alleghanian orogeny.

Analyses of plugs taken from the Thomas Corners core revealed porosities ranging from 11 percent in the upper part of the reef to cut-off values of 3 percent in the middle and lower part of the core (Table Dol-2). The depths where the 3 percent cut-off values were found correspond mainly to the lower half of the reef. Average porosity was 5.8 percent.

Permeabilities ranged from 608 md in the uppermost reef to 0.1 md in the lower part. In the lower half of the core, permeabilities ranged from 11 md to 0.1 md. The average permeability is 22.9 md. Of importance are some zones, usually only a few inches thick, in the upper part of the core that consist of masses of thin, stick-like coral branches interlocked like jackstraws and only partly cemented. Such zones will have cavernous porosity and great permeability. The porosity and permeability measurements from the Cabot et. al. No. 1 Sylvania Corp. core bear out reef drilling experiences. Large gas flows occurred in the uppermost portions, but little additional gas was encountered in the lower parts of the reefs.

Water was not encountered while drilling and so far none has been recovered during production. The core analysis shows water saturations from 4.2 to nearly 42 percent. Only eight of 55 samples had a water saturation greater than 20 percent, whereas 23 samples had a water saturation of 10 percent or less. There is no pattern to the water saturations. Higher and lower percentages are scattered throughout the core. The average water saturation is about 14 percent.

Reef porosity is primary inter-and intra-corallite. The voids are partly filled by calcite cement and bitumen. Calcite cement is common throughout the reef and was probably derived from pressure solution of carbonate grains and from stylolitic solution (Turner, 1977). Turner (1977) also found only a few percent of silica, in the form of chert, in the entire core. Evidently, little or no early marine cementation occurred in Thomas Corners reef because the calcite cementation is a late diagenetic feature in the reef.

A large amount of black, bituminous material is present in the middle to lower parts of the core. It occurs as inter- and intra-corallite fill and as filling of stylolitic seams. This hydrocarbon was introduced in a liquid state at a time when there was still a great deal of unfilled, primary porosity in the reef. Thermal alteration over time has converted this liquid hydrocarbon to pyrobitumen.

The completion technique used for the reef wells has been to set casing through the reef zone, perforate in the zones of best porosity, and acidize those zones. Because of the soluble monomineralic calcium carbonate in the reefs, this treatment works extremely well to stimulate the flow of gas. No additional stimulation appears necessary. The completion and geophysical logs for the Amoco No. 1 Witco well are typical for an Onondaga reef gas well (Figure Dol-7).

Resources and Reserves

Calculating the productive area of these reefs is risky, because in most reefs drilling has been minimal and detailed seismic studies have not been made. Because porosity in the lower portion of the reefs has been cemented or partly filled with pyrobitumens the exact extent of the upper porous zone is impossible to determine. Estimates of the productive area for each reef have been made, but these may be considerably in error. Based upon using these estimates for want of more precise data, a calculation of gas recovery per acre has been made. Because the reefs cover a small area, the recovery per acre is high, ranging from 4,375 Mcf/acre for the Flatstone reef to 23,750 Mcf/acre for the Quinlan reef. These are not final figures because six reefs are producing at present. The Adrian reef was shut-in for conversion to storage in 1991.

Production per well is also very high because only 10 producing wells have been drilled into the seven reefs of the play. Well production ranges from about 0.75 bcf for the presently producing well at Flatstone to more than 7 bcf for the well at Adrian.

Total remaining reserves for the six producing reefs are calculated to be about 4 bcfg. If the reefs are compartmented, there may be additional reserves still undrilled. The Anderson, Wyckoff Unit 8-1 well was drilled in 1974 as a quarter-mile-north offset to the Brewster discovery well. The Brewster began producing reef gas in 1972 after first producing from the Oriskany. It has produced about 1.5 bcf of reef gas and is still producing. The Unit 8-1 well has produced about 800 MMcf of reef gas and seemingly has not interfered with the Brewster production.

Table Dol-2. Permeability, porosity, and water saturation for core taken from the No. 1 Sylvania well at Thomas Corners, Steuben County, New York.

Sample Number	Depth (feet)	Maximum Permeability (md)	Percent Porosity	Percent Water
1	3,560	0.10	5.8	13.0
2	3,564	5.7	7.7	7.2
3	3,568	5.6	5.2	15.8
4	3,573	3.3	7.1	10.7
5	3,578	608.0	8.3	36.7
6	3,579	38.0	5.2	18.5
7	3,584	8.9	10.8	9.5
8a	3,585	272.0	5.5	12.1
8b	3,587	32.0	4.7	18.1
9	3,590	0.16	3.4	25.5
10	3,593	18.0	3.2	15.4
11	3,596	8.2	7.3	6.9
12	3,599	5.7	5.3	7.3
13	3,601	9.6	8.0	9.9
14	3,602	11.0	8.9	9.2
15	3,605	17.0	8.6	9.4
16	3,608	99.0	6.5	7.9
17	3,611	2.0	5.5	9.8
18	3,613	17.0	11.0	20.2
19	3,616	0.89	6.7	15.9
20	3,619	1.5	4.5	8.9
21	3,622	26.0	6.4	4.2
22	3,625	0.10	3.0	20.0
23	3,628	0.10	3.0	18.6
24	3,631	0.90	7.6	6.3
25	3,632	11.0	7.0	7.0
26	3,635	4.8	8.2	10.0
27	3,638	7.1	8.6	9.0
28	3,641	0.22	3.6	20.8
29	3,644	0.17	3.3	11.2
30	3,645	0.91	6.6	7.7
31	3,648	1.6	6.4	7.1
32	3,649	0.54	4.0	12.2
33	3,652	0.63	4.3	9.1
34	3,655	4.8	6.9	7.7
35	3,658	0.86	4.2	13.1
36	3,661	0.10	3.0	15.2
37	3,662	2.1	5.0	16.7
38	3,663	4.5	3.6	9.0
39	3,666	0.10	3.0	15.7
40	3,668	0.10	3.0	35.4
41	3,670	0.10	3.0	14.8
42	3,672	0.10	3.0	41.7
43	3,674	0.10	3.0	16.7
44	3,676	0.10	3.0	10.4
45	3,678	0.24	3.9	10.7
46	3,680	0.10	4.2	7.7
47	3,682	0.10	3.0	11.3
48	3,684	0.33	3.3	7.6
49	3,686	2.5	3.0	14.8
50	3,688	0.11	3.0	10.6
51	3,690	0.22	3.0	30.0
52	3,692	0.71	3.0	11.0
53	3,694	0.91	4.6	8.0
54	3,695	0.24	3.0	12.2

Future Trends

The Onondaga sea bathymetry seems to be a major limiting factor in the formation of the reefs. Where the shelf sea sloped southward into the deeper basin, it became deep early in Onondaga time and stayed deep. Such an environment would be unfavorable for reef development and growth. The boundary between the shallower water platform where reefs did grow and the deeper water, perhaps non-reef, basin is suggested to occur southeast of a line between the Cyclone reef and the Wyckoff reef (Figure Dol-2). These two reefs are farthest south along the shelf slope. The exact location of any such place can only be surmised. This south boundary of the play extends in a northeast-southwest direction from New York to northwestern Pennsylvania (Figure Dol-1).

Southeastward of this suggested line, the reef-generating Edgecliff Member exhibits a darker, finer-grained and more argillaceous facies as evidence of the westward-expanding apron of mud and silt from the Acadian highlands. The influx of argillaceous sediment would not have been favorable for the growth of corals.

Because the reefs are not detectable unless they project a good distance above the local thickness of the Onondaga, the author suggests that the east and west 100-foot Onondaga isopach contour should be the other limiting boundary for the Onondaga reef play (Figure Dol-1). This delimits a play area of more than 10,000 square miles in New York and Pennsylvania.

PLAY Dho: FRACTURED MIDDLE DEVONIAN HUNTERSVILLE CHERT AND LOWER DEVONIAN ORISKANY SANDSTONE

by Kathy J. Flaherty, Pennsylvania Bureau of Topographic and Geologic Survey

Location

The fractured Middle Devonian Huntersville Chert and Lower Devonian Oriskany Sandstone have produced significant quantities of natural gas from anticlinal structures within the Allegheny Plateau Physiographic Province of the Appalachian basin. Gas production extends from northern Clearfield County in Pennsylvania to Greenbrier County, West Virginia, along a northeast-southwest trend (Figure Dho-1). The proven area of this predominantly structural play occupies approximately 167,000 acres extending across parts of Maryland, Pennsylvania, and West Virginia. The actual play includes an estimated 11,800,000 acres: 4,400,000 acres in Pennsylvania, 250,000 acres in Maryland, and 7,150,000 acres in West Virginia.

Production History

The Huntersville Chert was first drilled and produced in Ligonier Township, Westmoreland County, Pennsylvania. Peoples Natural Gas Company spudded the No. 1 Booth and Flinn well in March 1919. Located on Chestnut Ridge, the well site was selected as a practical application of the anticlinal theory of gas accumulation in the deeper formations near an area of shallow gas production. Peoples Natural Gas was searching for "fresh supplies of fuel for its consumers after it had become evident that all present known gas-bearing sands were being depleted, as it was explained by John B. Tonkin, vice president and general manager of the Peoples Natural Gas Company" (Anonymous newspaper article, 1924). Thus, McCance pool of Lycippus field (Figure Dho-2) was discovered on March 3, 1920 with the completion of the No. 1 Booth and Flinn well having a natural open flow of 450 Mcf and a rock pressure estimated to be 3,600 psi. Peoples Natural Gas attempted to define the trend of this new discovery by spudding a second well in 1920, targeting the Huntersville and Oriskany. Although these formations were tight and dry, some commercial gas was found in a sandstone unit in the deeper Helderberg Group. Historical information is sketchy, but it seems the two wells produced for approximately six years before abandonment.

Summit field, in Fayette County, Pennsylvania (Figure Dho-2), was the first field to be drilled and developed in the combined Huntersville and Oriskany reservoir. By the time Summit field was discovered by W.E. Snee and New Penn Development Corporation's No. 1 Heyn well in 1937, the Oriskany Sandstone was already a major gas play in New York, Ohio, north-central Pennsylvania, and West Virginia. The No. 1 Heyn was an attempt to duplicate the success operators were realizing in developing the north-central Pennsylvania Oriskany gas fields. Drilling was completed April 23, 1937, with an initial open flow of 1,800 Mcf from 18 feet into the Huntersville Chert at 6,611 feet. Although many wells lacking initial flow were drilled and abandoned, within 10 years the fractured Huntersville/Oriskany reservoir was the target of numerous successful prospects drilled on anticlinal structures, and exploration had spread from south-central Pennsylvania to Maryland and West Virginia. As the reservoir became better understood and the hydraulic fracturing techniques of the mid 1950s were applied, operators realized that a well with little or no natural open flow, which previously would have been abandoned as a dry hole, could be stimulated into a well with high initial flow. These factors combined to make the play quite popular.

Total cumulative production since discovery in 1920 through 1993 from the Huntersville/Oriskany fractured reservoir play exceeds 650 bcf from about 60 fields in the Appalachian basin.

Stratigraphy

The producing formations of the play are the Lower and Middle Devonain Huntersville Chert and the Lower Devonian Oriskany Sandstone. The generalized stratigraphic chart in Figure Dho-3 illustrates regional relationships between the formations.

The regionally widespread Oriskany Sandstone overlies the Helderberg Group and is overlain by a sequence of laterally changing facies which, from east to west, consist of the Needmore Shale, the Huntersville Chert, the Bois Blanc Formation, and a portion of the overlying Onondaga Formation (Basan and others, 1980). Many Appalachian basin researchers have recognized the stratigraphic, geographic, and lateral facies changes in the lower part of the Middle Devonian (Patchen, 1968b; Inners, 1979; Basan and others, 1980; Cardwell, 1982b). Basan and others (1980) described three primary facies: eastern clastic facies, central basin chert facies, and western carbonate facies. The eastern clastic facies, represented by the Needmore Shale, has been characterized as "variously... dark, noncalcareous shale, calcareous silty shale, calcareous siltstone, argillaceous and silty or sandy limestone, and a subordinate amount of glauconitic or conglomeratic quartz sandstone" (Basan and others, 1980, p. 42). The lateral extent of the Huntersville Chert facies types is illustrated in Figure Dho-4. From Clearfield County, Pennsylvania, southward through Somerset County, Pennsylvania, western Maryland, and eastern and south-central West Virginia, these strata comprise the Needmore Shale (Figures Dho-2, Dho-4). The Needmore lies upon the Oriskany, and commonly includes grains of reworked Oriskany quartz sand and associated minerals (Basan and others, 1980). West of the eastern clastic facies, the central basin chert facies occupies the central part of the Appalachian basin from Forest and Elk counties, Pennsylvania, to Smyth County, Virginia (Figures Dho-2, Dho-4). In areas where the chert overlies the Oriskany Sandstone, the chert contains well-rounded

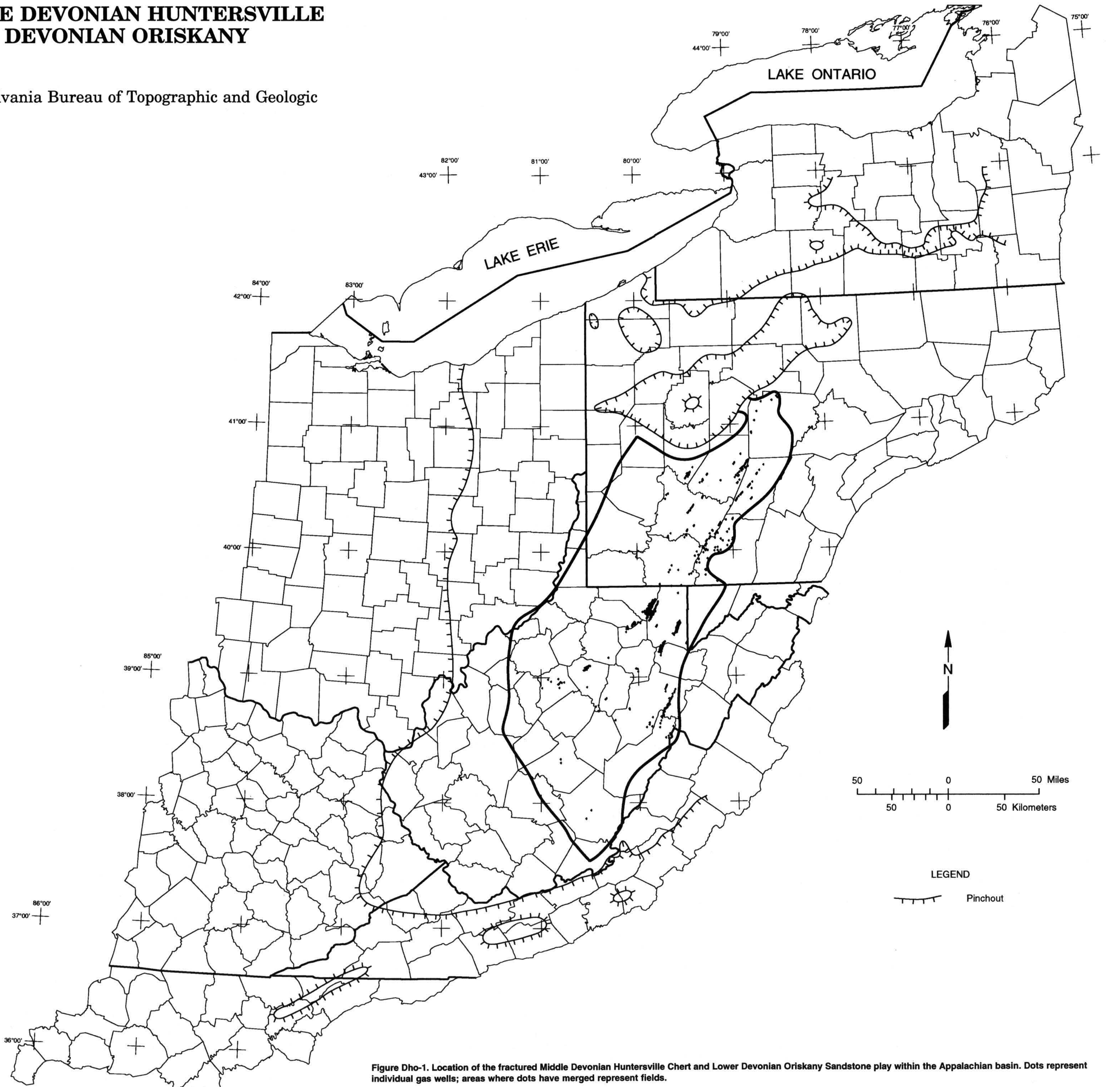


Figure Dho-1. Location of the fractured Middle Devonian Huntersville Chert and Lower Devonian Oriskany Sandstone play within the Appalachian basin. Dots represent individual gas wells; areas where dots have merged represent fields.

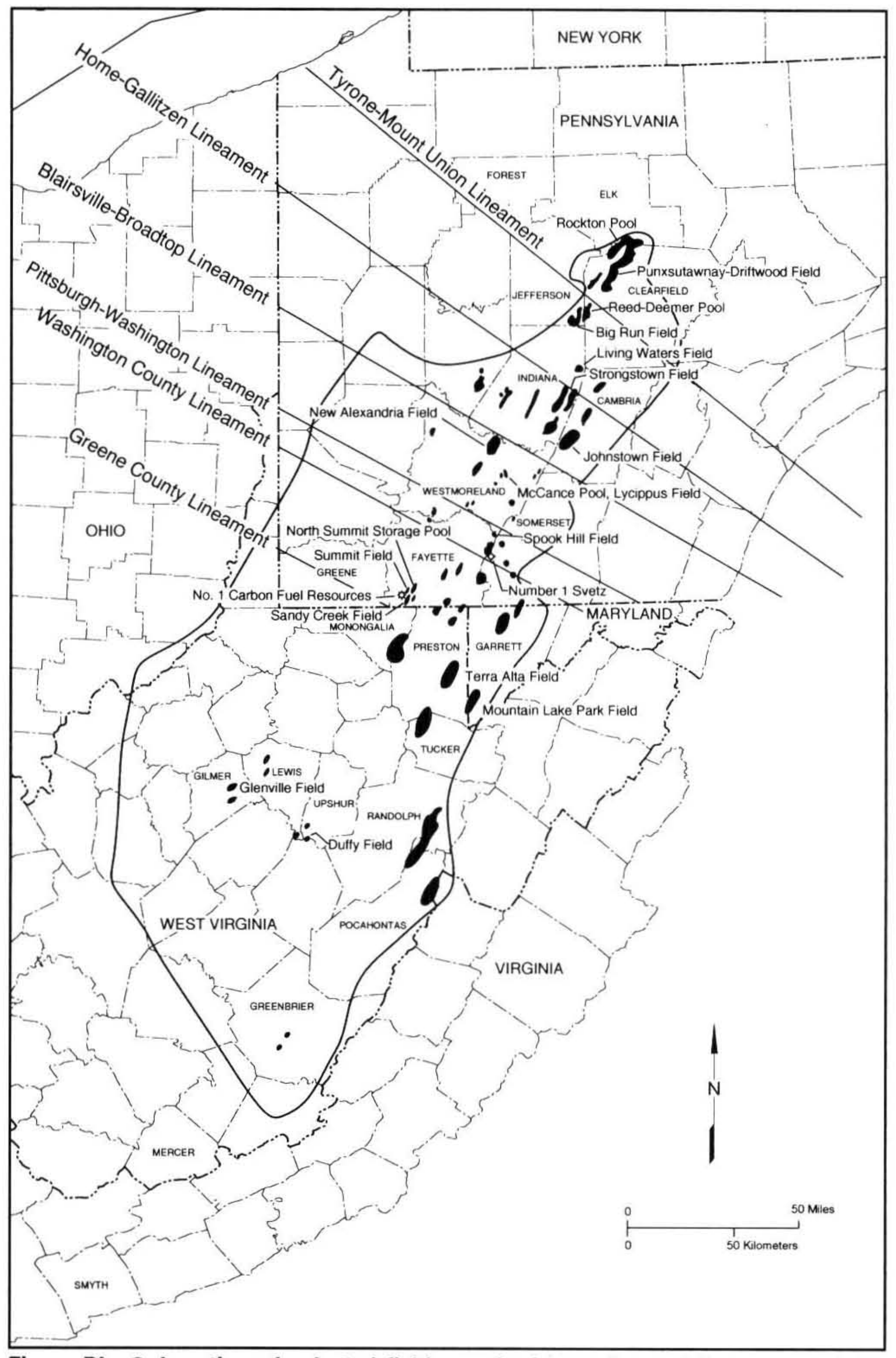


Figure Dho-2. Location of selected fields, pools, key wells, and lineaments of the Fractured Middle Devonian Huntersville Chert and Lower Devonian Oriskany Sandstone play.

quartz grains, thin argillaceous sandstone beds, phosphatic nodules, and glauconite as evidence of reworked Oriskany Sandstone (Basan and others, 1980). The stratigraphic cross section in Figure Dho-5 shows the lithologic variations of the central basin chert facies of the Huntersville. The western carbonate facies includes the combined Bois Blanc Formation and Onondaga Formation and overlie the tapering edge of the Oriskany Sandstone where the sandstone is present (Figure Dho-3). The Onondaga Formation grades upsection into the Marcellus Shale, but both are intermingled with a series of up to seven volcanic ash beds that are collectively known as the Tioga metabentonite (Way and others, 1986). The ash serves as an isochronous unit throughout the Appalachian basin.

The Huntersville Chert is typically microcrystalline, massive, and hard. It varies from translucent to opaque, and in color from white to dark brown and dark gray. Frequently, it includes small amounts of dolomite, quartz, glauconite, pyrite, calcite and trace fossils.

Some researchers favor a primary origin for the formation of the Huntersville Chert. Sherrard and Heald (1984) defended a biogenic primary origin; they cited the presence of large quantities of spicules from siliceous sponges preserved in the chert, and gradations from spicules to massive chert seen in thin sections suggesting that siliceous organisms were abundant but that their forms were destroyed during crystallization of the silica. Lack of feldspathic and pyroclastic material in the chert negates the possibility of contribution of significant quantities of silica through volcanic activity. Tropical to subtropical climate during Huntersville time favored terrestrial weathering of silicate minerals, probably the initial source of the silica utilized by the sponges (Sherrard and Heald, 1984). Harper (1989, p. 234) pointed out that the limits of the distribution of the chert "...and its northwestern equivalent, the Onondaga Limestone, is coincident with the [positions of the] Rome trough and the Tyrone-Mt. Union lineament." These structural features restricted the sea to the deeper portion of the basin, which created a nurturing environment for the growth of siliceous organisms (Figure Dho-4). Sherrard and Heald (1984) offered a possible sequence of events in the biogenic primary formation of the Huntersville Chert: weathering of silicate minerals; silica transported to chert basin; silica incorporated by sponges into amorphous biogenic silica; partial dissolution of amorphous biogenic silica to form siliceous colloidal solution; redistribution of silica as colloidal solution containing some undissolved biogenic silica; dehydration; crystallization (probable formation of contraction voids and fractures); formation of "opal-CT, a poorly ordered form of cristobalite and tridymite" (Sherrard and Heald, 1984, p. 41); dehydration; recrystallization (probable formation of contraction voids and fractures); and chalcedony and chert.

Basan and others (1980, p. 169-170) proposed an alternate theory for the origin of the Huntersville Chert: "1) deposition in a large, linear epicratonic (shelf) basin that was tectonically and topographically asymmetric with respect to its axis, such that the western limb sloped far more gradually than the eastern

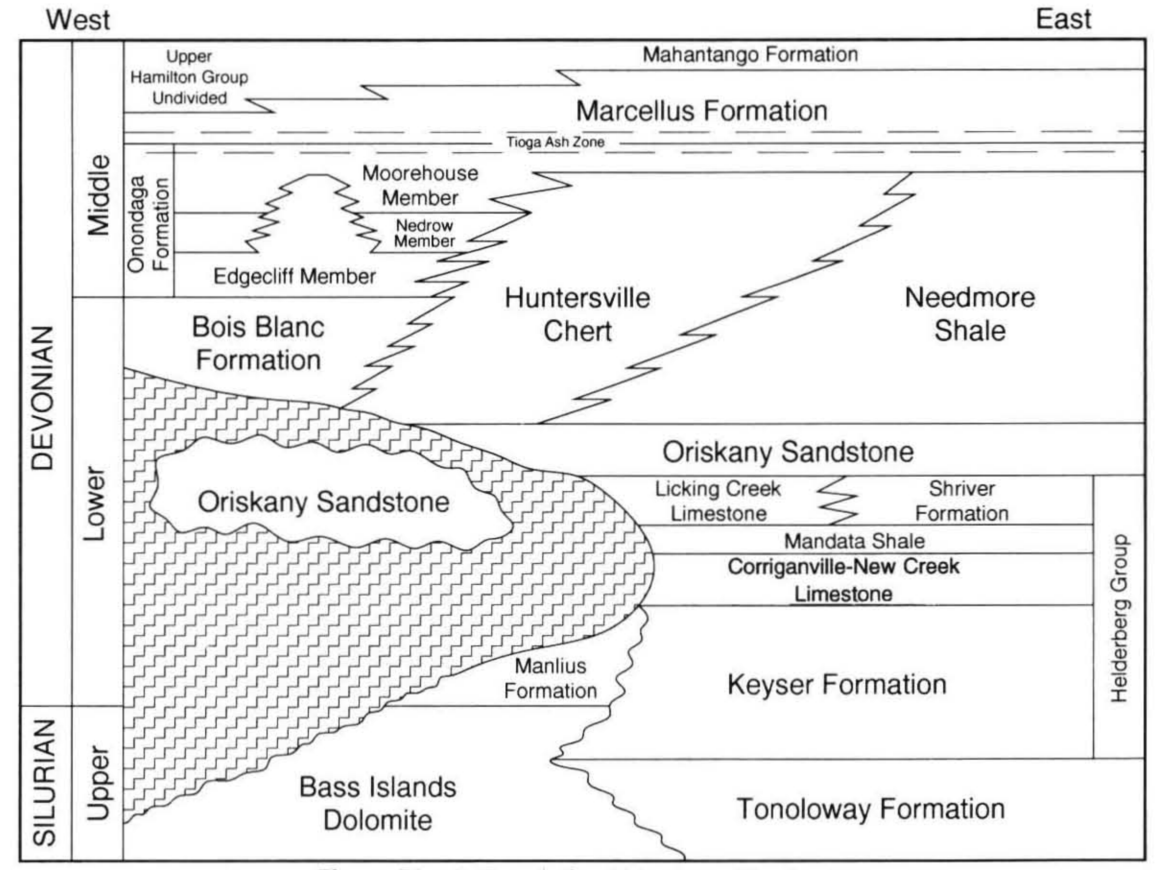


Figure Dho-3. Generalized stratigraphic chart.

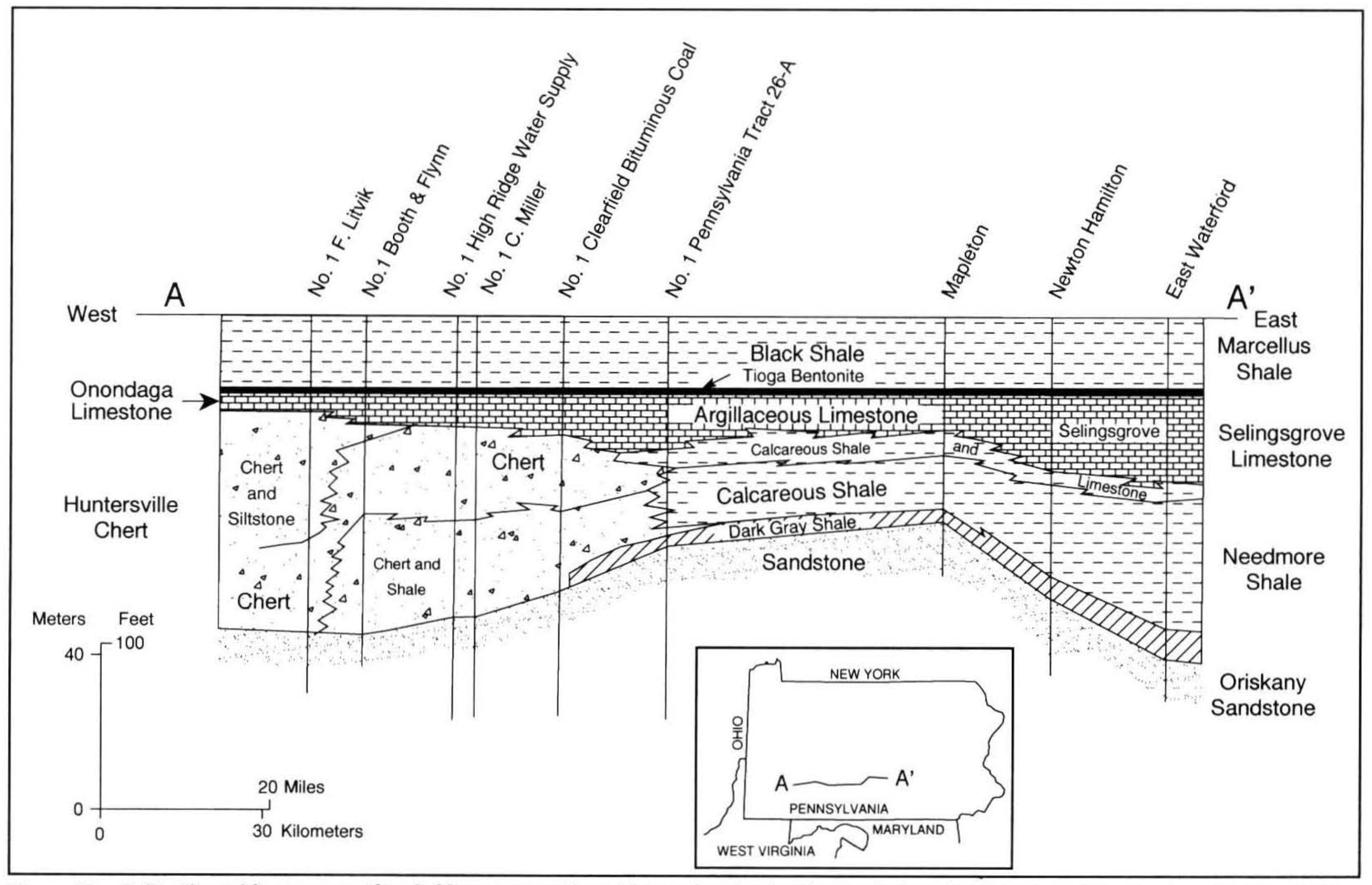


Figure Dho-5. Stratigraphic cross section A-A' across southern Pennsylvania showing variations in the facies of the Huntersville Chert. After Inners (1979).

limb; 2) progressive submergence and transgression westward with time, but with maximum depths established early along the basin axis, followed by progressive shoaling throughout the basin due to sedimentary fill exceeding the rate of subsidence and transgression; 3) progressive facies change westward from generally fine terrigenous clastics in the east, adjacent to its eastern source, to fine carbonate mud deposition (subsequently altered to chert), to skeletal-rich carbonate mud deposition along the shallower western limb of the basin."

Basan and others (1980, p. 173), stated that the Huntersville Chert is "a diagenetic replacement of large carbonate sediments, as indicated by the chert replacement of calcite skeletons, preservation of relict carbonate fabrics and limestone patches or lenses, and the complete gradation of solid chert to siliceous limestone, and in turn, to limestone with nodular chert in the Bois Blanc." Furthermore, Basan and others (1980) used the presence of chert beds and nodule zones within the Bois Blanc and Onondaga Limestone as further evidence of a replacement origin, stating that these units differ from the Huntersville Chert only in the degree of replacement.

Thickness of the Huntersville Chert (Figure Dho-6) varies from less than 100 feet in Elk and Forest counties in northwest Pennsylvania to more than 250 feet in Greene County in southwestern Pennsylvania and Monongalia County in northern West Virginia and in parts of Harrison, Doddridge, and Lewis counties, West Virginia. The chert facies thins southward to less than 100 feet in Mercer County, West Virginia.

Edmunds and Berg (1971, p. 124) described the Oriskany Sandstone as "a light gray, medium- to coarse-grained quartzose sandstone; it is usually cemented by calcite, but some silica cement occurs near the top" .

The Lower Devonian Oriskany Sandstone was deposited between normal wave base and storm wave base (Welsh, 1984) in the gas-productive Somerset County, Pennsylvania, area. The characteristics of the sandstone vary throughout the Appalachian basin, but in the area where the Huntersville and Oriskany are targeted for natural gas, Welsh (1984) identified four coarsening-upward marine shelf bar sequences based on his study of drill cores: interbar shelf (deeper, low energy shelf deposition); bar margin (bioclastic debris winnowed from central bar units by storm currents); central bar (transported and deposited by storm events); and tempestite (nearshore sands and fauna, deposited on the shelf by intense storm activity). Although an unconformity exists on top of the Oriskany Sandstone in many areas of the basin and is present in outcrop, Welsh (1984) did not find evidence of this in the cores he examined in the Somerset County area. This concurs with the findings of Dennison (1961) and Heyman (1977), who proposed continuous deposition through the Lower Devonian.

The Oriskany Sandstone varies from about 17 feet thick in the northern and westernmost reaches of this play to 241 feet thick in the southeastern fields, averaging 68 feet.

Structure

The Huntersville Chert/Oriskany Sandstone gas fields are located along faulted and offset anticlines in the Allegheny Plateau Province. The axes of these regional structural features trend northeast-southwest. The Allegheny Front lies to the southeast (Figure Dho-7). Structural deformation, which influences the gas fields, includes imbricate thrusts branching from a sole thrust, overturned beds, stacked thrust sheets, repeated key beds, high-angle reverse faults, and frequent oversteepening on one flank (Gwinn, 1964; Harper, 1989). A cross section of Mountain Lake Park field (Figure Dho-8a), Garrett County, Maryland, and Preston County, West Virginia, illustrates this type of structural deformation. Lyciippus field (Figure Dho-8b), Westmoreland County, Pennsylvania, is an

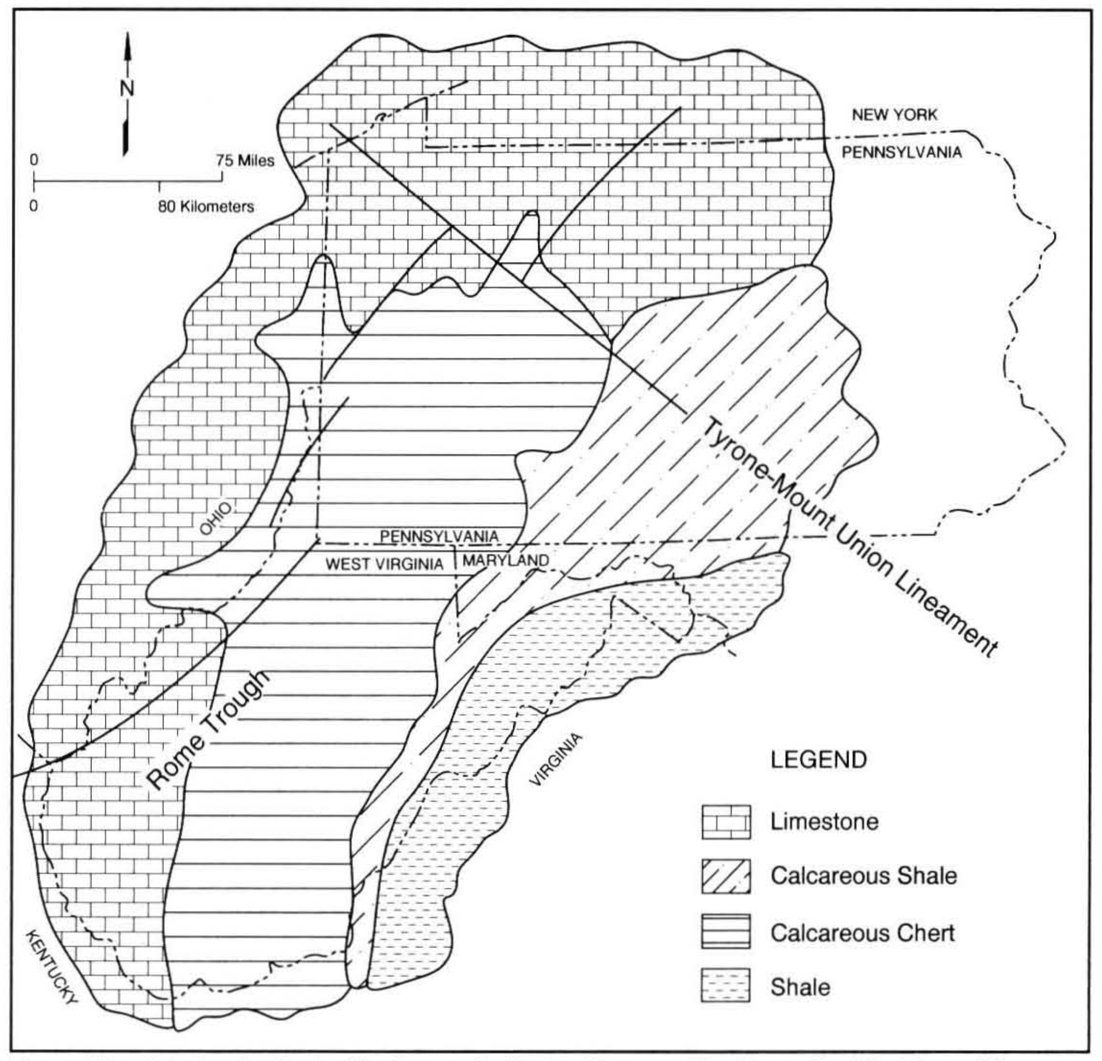


Figure Dho-4. Lateral extent of facies equivalent to Huntersville Chert. Modified from Oliver and others (1971) and Harper (1989).

example of a field characterized by a second type of structural deformation. At the Huntersville Chert/Oriskany Sandstone horizon on the anticline, the axis appears as a relatively down-faulted depression because of overthrusting limbs. The faults bounding the "depressed" zone are reverse faults, throw is greater on the northwest-dipping faults, anticlines are steeper on the southeast limbs, and vertical displacement of the Oriskany is up to 700 feet near the Allegheny Front, decreasing westward (Gwinn, 1964; Harper, 1989).

Further complicating the structure in the region are lineaments or cross-strike structural discontinuities (CSDs) that may correspond to wrench faults in the basement or within detached zones in the Paleozoic cover (Gwinn, 1964; Harper, 1989). The CSDs intersect and offset anticlines, provide fracturing and fluid migration paths, and they significantly affect the distribution and thickness of the Oriskany Sandstone in the northwestern corner of Pennsylvania as well as the Huntersville Chert north of the Tyrone-Mt. Union lineament (Figure Dho-4), where it is replaced by cherty limestone as previously mentioned (Harper, 1989). Some fields are terminated at their juncture with lineaments. Strongstown field in Indiana County, Pennsylvania, and New Alexandria field in Westmoreland County, Pennsylvania, terminate at the Home-Gallitzen and Blairsville-Broadtop lineaments, respectively (Figure Dho-2).

Reservoir

Fields producing from the Huntersville Chert and Oriskany Sandstone in this play are structurally controlled, and occur on isolated fault blocks with gas produced from a network of fractures. Summit field in Fayette County, Pennsylvania, and Terra Alta field in Preston County, West Virginia, are excellent examples. Some fields, however, have additional stratigraphic considerations. Fractured chert overlying porous Oriskany Sandstone, combined with the positive structural relief of an anticline, comprise the most favorable trap for natural gas. The Rockton pool in Punxsutawney-Driftwood field, Clearfield County, Pennsylvania (Figure Dho-2), is an example of a stratigraphic and structural trap.

In an extensive study of five cores from wells in the north-central West Virginia, central Pennsylvania, and western Maryland region, Sherrard and Heald (1984) obtained detailed information on the nature of porosity in the Huntersville Chert. They found that the fractures provide the best effective porosity, and are better developed in brittle pure chert, dying out in the more argillaceous chert. Sherrard and Heald (1984) also observed that spicules, spines, and vugs are more common in the more pure chert. They saw evidence of irregular fragments serving as props holding fractures open, fossils contributing to porosity due to void space resulting from hollow spines and spicules, silica contraction, and incomplete quartz filling. Sherrard and Heald used the presence of golden brown staining in the pores between fibers in the chalcedony to conclude that hydrocarbon had migrated through the chalcedony vugs and openings in fractures.

Sherrard and Heald (1984) noted salt crusts on cores taken through the chert and determined that the presence of the salts may indicate local variations in porosity. They observed solid salt crusts on the argillaceous zones, minor amounts of salt on the impure chert, and no salts present on the tight chert. Sherrard and Heald (1984) theorized that the cores contain connate water, and when the fresh core is left to dry, evaporation and capillary action in the more porous argillaceous and impure zones concentrates the salts on the surface of the core.

Extensive fracture networks allowed hydrocarbons generated in the overlying or adjacent organic-rich shales to migrate. The brittle fractured chert accumulated gas more readily than did the underlying sandstone, although the chert fractures probably functioned as a conduit between the source rocks and Oriskany Sandstone. Diecchio (1985) suggested that the less fractured sandstone was tighter and resisted gas accumulation, resulting in several fields that produce from Huntersville only with no contribution of gas from the Oriskany

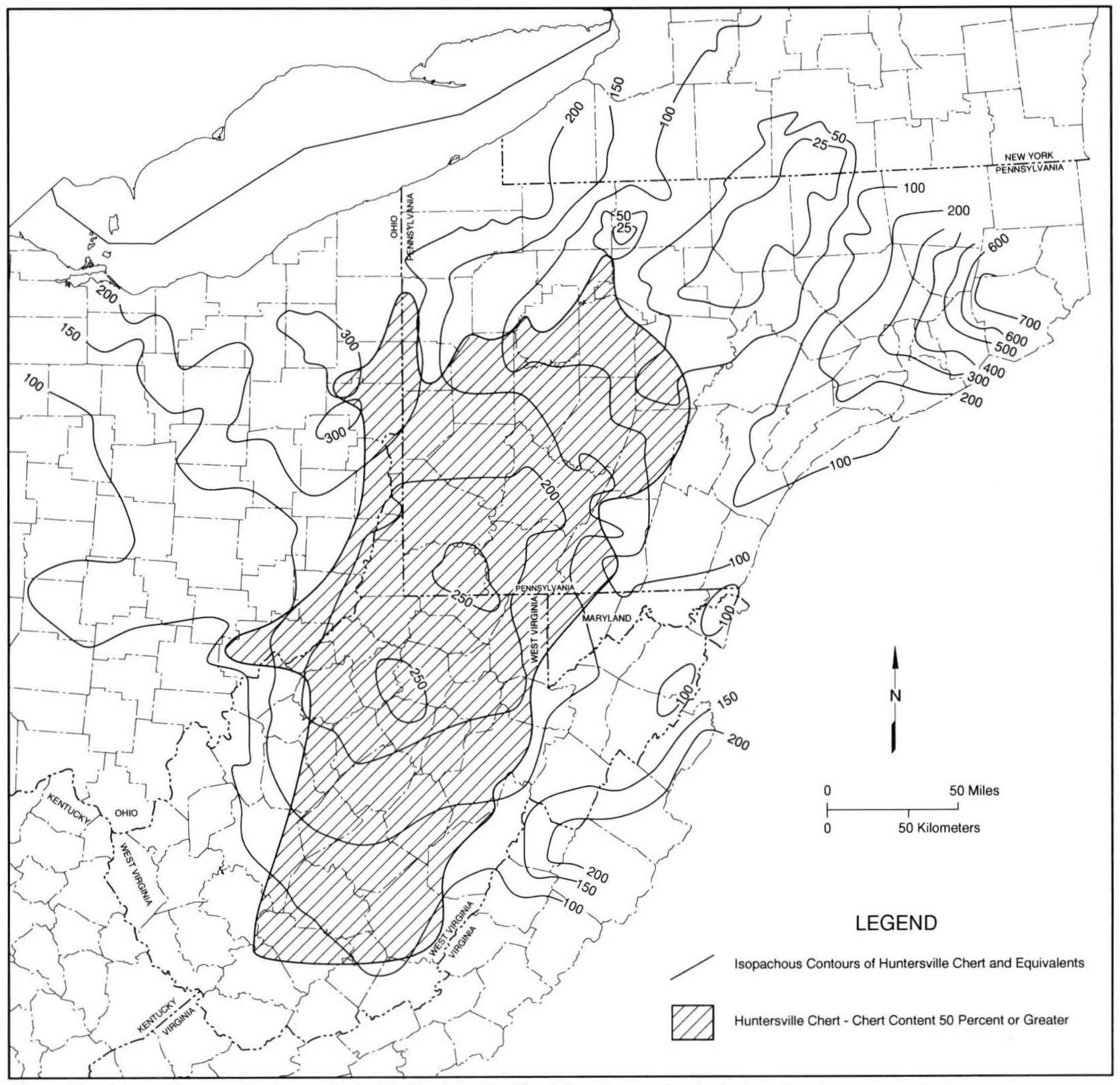


Figure Dho-6. Isopach map of facies equivalent to Huntersville Chert showing areal extent where the chert content is 50 percent or greater. Modified after Oliver and others (1971). Contour interval is variable.

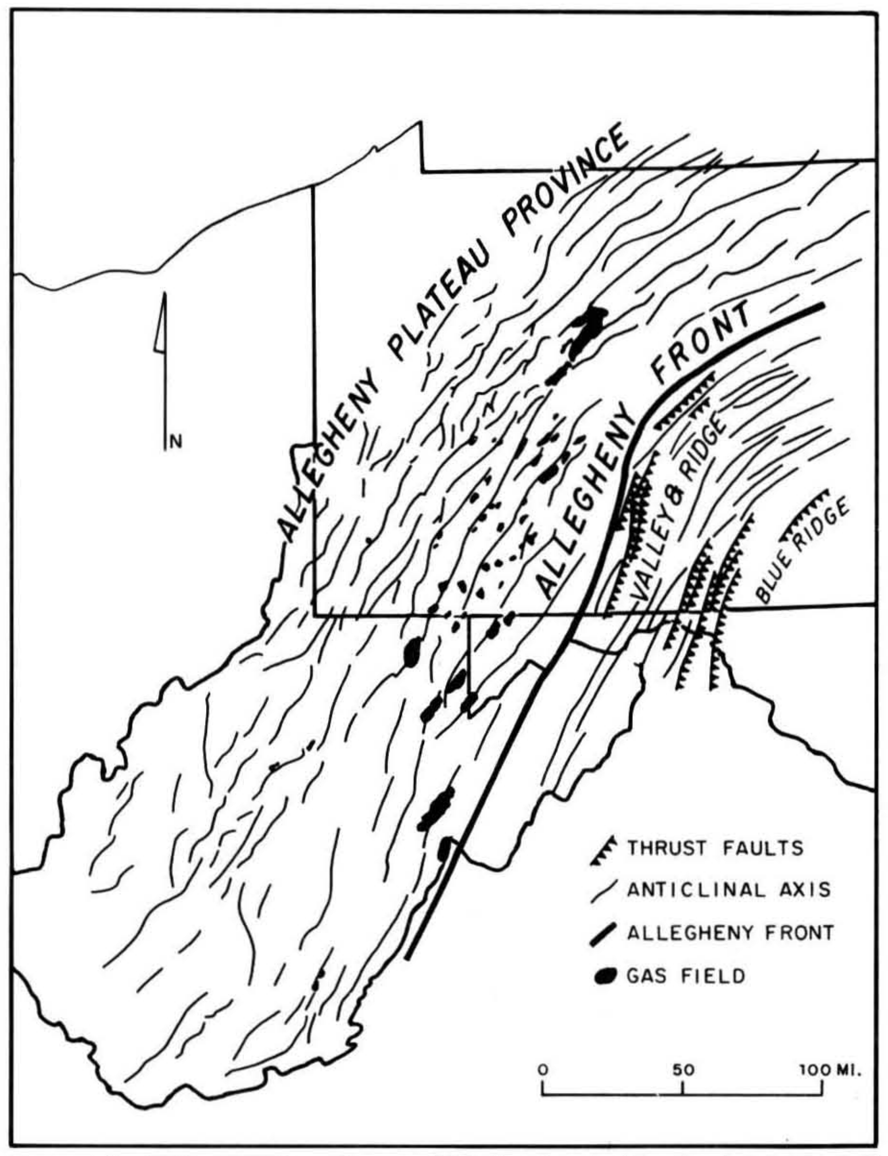


Figure Dho-7. Structural provinces within the Appalachian basin region and location of Huntersville Chert and Oriskany Sandstone gas fields.

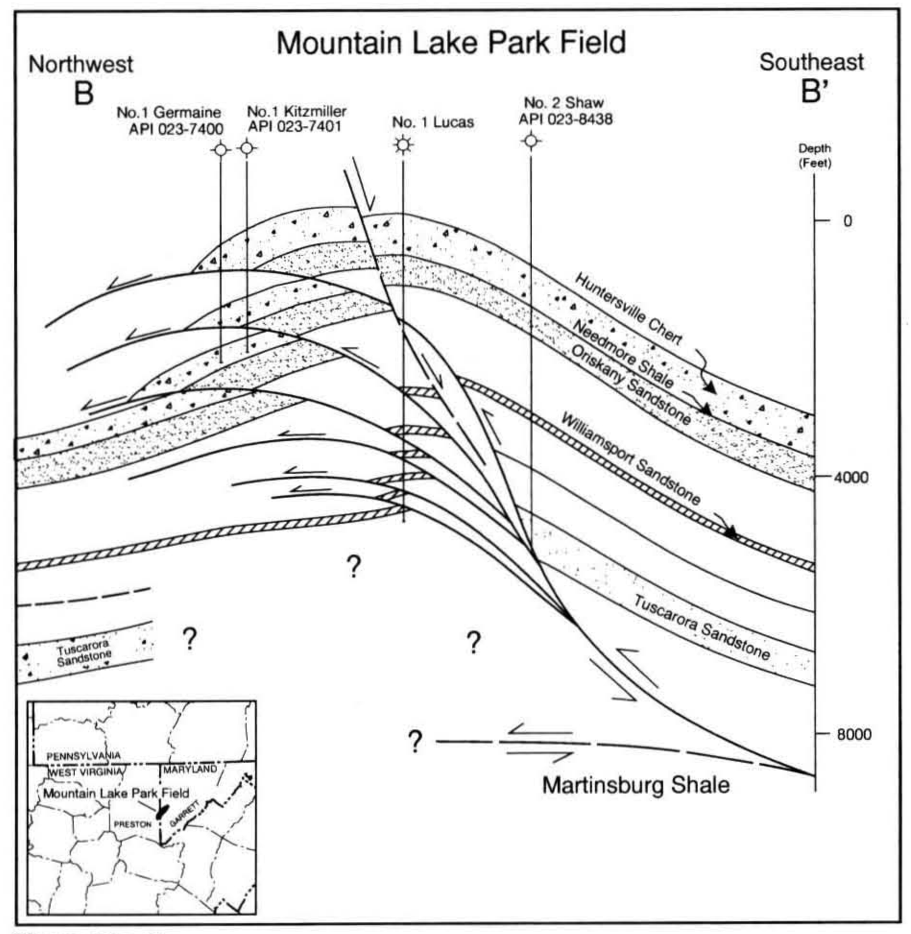


Figure Dho-8a.

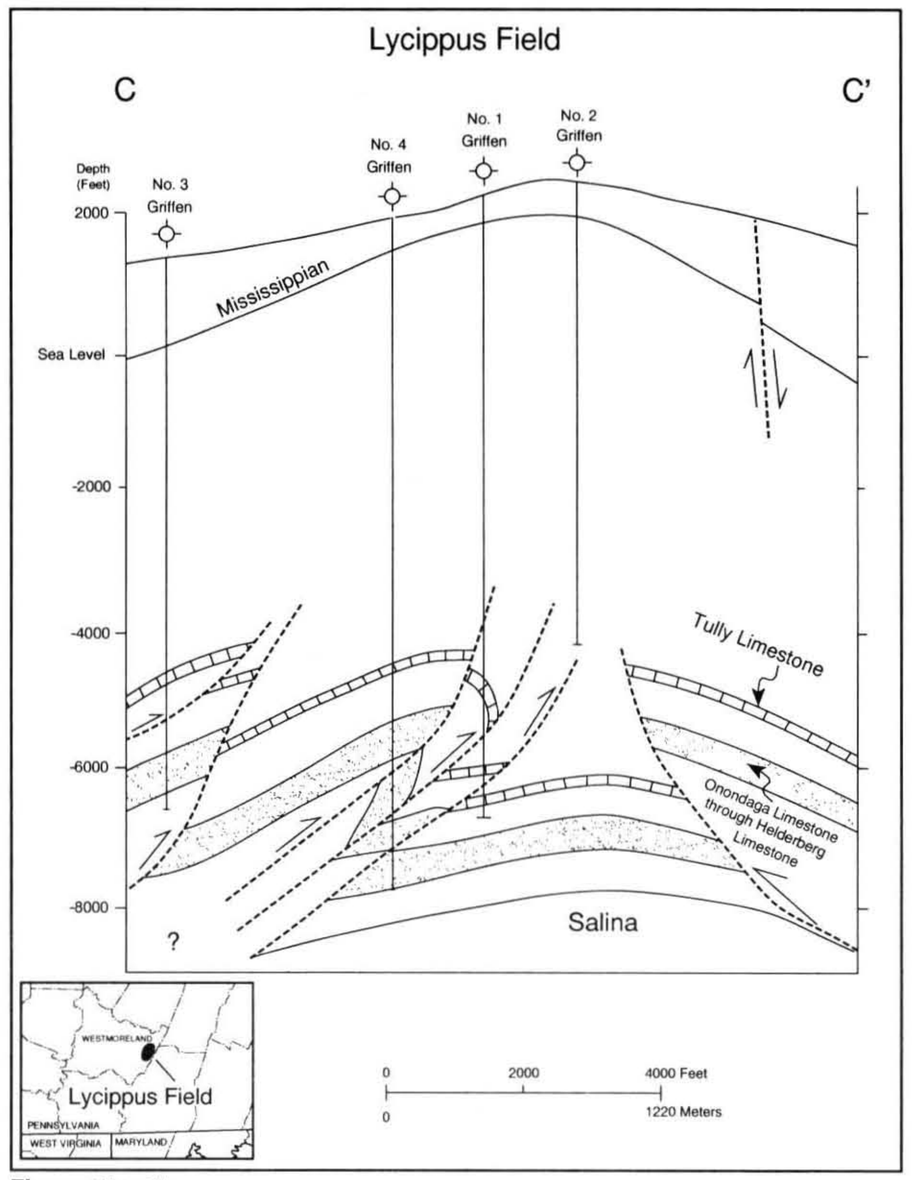


Figure Dho-8b.

Figure Dho-8. Imbricate thrust faulting in Huntersville/Oriskany play. From Gwinn (1964). Dho-8a. Cross section B-B' of Deer Park anticline, Mountain Lake Park field, Garrett County, Maryland. Dho-8b. Cross section C-C' of Chestnut Ridge anticline, Lycippus field, Westmoreland County, Pennsylvania.

(Lycippus field and Quebec Run pool in Sandy Creek field in Pennsylvania; Glenville and Duffy fields in West Virginia) (Figure Dho-2). Volume and pressure changes during the thermal cracking of oil to gas in the reservoir may also have influenced the relative distributions of gas in Huntersville and Oriskany reservoirs (Barker, 1990).

The top of the Huntersville Chert pay zone ranges from about 2,900 feet in Garrett County, Maryland, to 8,688 feet in Somerset County, Pennsylvania. Thickness of the pay zone is more difficult to determine with this play because of the communication within the fracture network characteristic of this reservoir. Well depth is likely to be determined in part by intersection of the well with the extensive fractures, which allow a significantly increased drainage area regardless of the amount of chert that was penetrated by the drill. In some fields, wells were acidized from the top of the chert to the total depth of the well, and in others, specific zones within the chert and Oriskany Sandstone were targeted for hydraulic fracture. Some wells were drilled through the chert; some were drilled through the Oriskany; and others just nicked the top of the chert. The thickness of the pay zone, therefore, varies from just a few feet to the entire thickness of the Huntersville and Oriskany sections, which measure up to 508 feet (probably due to fault-duplicated section) in Summit field, Fayette County, Pennsylvania. Average thickness is 155 feet for productive fields.

Initial rock pressures ranged from 200 to 4,310 psi and averaged 3,300 psi. The fields closer to the Allegheny Front have considerably lower rock pressure (Table Dho-1).

Initial open flows prior to any completion treatment ranged from no show of gas at all to 72,000 Mcf for one well in the Summit field. Three of the wells in the Rockton pool of Punxsutawney-Driftwood field had very high initial open flows of 45,000 Mcf, 60,000 Mcf, and 70,000 Mcf (Lytle and others, 1959). Average initial open flow for Huntersville Chert/Oriskany Sandstone wells was 1,938 Mcf. Many wells with significant natural open flows of gas were not treated, but of those that were, the average after treatment flow was 3,500 Mcf with a range of less than 50 Mcf to more than 41,000 Mcf.

Treatment and completion strategies have changed over time as better techniques evolved. The initial wells in the 1940s and 1950s were shot with nitroglycerine. In the middle 1950s through the 1960s, hydraulic fracturing was found to be much more effective with this reservoir. More recently, treatment with acid, sometimes combined with hydraulic fracturing, has become the most common method of completion.

Natural gas reserves are variable due to the variations in size, shape, orientation, and concentration of fractures of fractured fault block traps. Individual wells for which annual production is available indicate a range of total cumulative production from 234 MMcf to 10 bcf with an average near 400 MMcf over 20 to 35 years with various periods of shut-in. Figure Dho-9 illustrates an actual production decline curve.

A total organic carbon concentration of 0.5 to 1.0 weight percent is considered to have a fair generative potential for source rocks, and total organic carbon concentration exceeding 1.0 is good to very good (Hunt, 1979; Tissot and Welte, 1984). The Marcellus Shale is regarded an important source of hydrocarbons in the Appalachian basin in terms of organic richness, kerogen type, and sediment volume (Basan and others, 1980). The Needmore Shale should also be considered as a key hydrocarbon source. Results of a geochemical evaluation performed on the Amoco No. 1 Svetz well in Somerset County, Pennsylvania (Figure Dho-10), indicate the present average total organic carbon (TOC) for the Marcellus Shale to be 3.5 weight percent and the Needmore Shale is 2 weight percent. The original TOC was probably higher; both the Marcellus and Needmore are thermally overmature, and the hydrocarbon generative potential of these shales is diminished. Evidence of extreme maturity exists in the values for vitrinite reflectance (Ro), thermal alteration index (TAI), bitumen to TOC (Bit/TOC) ratio, and production indices calculated from kerogen pyrolysis data (Table Dho-2).

Prior to reaching overmaturation, the Marcellus and Needmore shales had considerable oil as well as gas potential. The organic matter contained in the shales is both marine and terrestrial; relative amounts of each depends on paleogeography and stratigraphic position. Generally, the organic matter is mixed (Type II), but nearly pure (70 to 80 percent) end members (Type I, Type III) occur in some samples (Basan and others, 1980; C.D. Laughrey, oral commun., 1993). Crossplots (Figure Dho-10) of stable carbon and hydrogen isotope ratios for gas samples from Huntersville Chert/Oriskany Sandstone reservoirs in Strongstown and Living Waters fields in Indiana County and Spook Hill field in Fayette County demonstrate that the gas is thermogenic associated gas (gas generated with the oil in the source rocks and/or gas formed from thermal cracking of oil in the reservoir).

There is a marked variation in the results of the analysis for the three fields. Spook Hill field gas is less thermally mature than gases in the other two fields. It was probably generated from marine organic matter within the oil window; the methane carbon isotope ratio of -46 percent and hydrogen isotope ratio of -241 percent are characteristic of gas cracked from Types I and II kerogens during peak oil generation (Schoell, 1983; Whiticar, 1994). Gases sampled from Living Waters and Strongstown fields are isotopically heavier. Methane carbon isotope ratio and hydrogen isotope ratio average -34.7 and -163.6 percent, respectively. These values are characteristic of gases associated with condensate that were generated from overmature Types I and II kerogens (Schoell, 1983; Whiticar, 1994).

The gases extracted and analyzed from wells in the Strongstown and Living Waters fields are distinctly different from Spook Hill field. Whereas methane is typically lighter (more negative) than ethane and propane from the same source, in the Strongstown field, for example, the methane is heavier. This isotopic reversal indicates that the gas is a mixture of very mature, dry, thermogenic gas and a less mature oil-associated gas. In Strongstown field, the ratio is 20 percent associated gas and 80 percent post-mature dry gas component. Laughrey (oral commun., 1994) proposed that while the associated gas was probably generated locally (Middle Devonian Marcellus and Upper Devonian Geneseo, Renwick, and Middlesex shales), the post-mature component migrated from some distant source. The location of Strongstown field, at the junction of fractures and the Home-Gallitzen lineament (Figure Dho-2) adds lateral and vertical migration pathways. As possible post-mature sources, Laughrey suggests: equivalent Devonian shale source rocks to the east which are more mature; deeper Ordovician source rocks well below the reservoir; a combination of eastern Devonian shales and deeper Ordovician source rocks; and hydrothermal and/or geothermal heavy methanes associated with deep crustal gases.

Description of Key Fields

North Summit storage pool: From the discovery of the Summit field (now called North Summit Storage pool in Summit field; see Figures Dho-2, Dho-11) in Fayette County, Pennsylvania, in 1937 until it was converted to storage in 1991, approximately 22 bcf was produced (Harper, 1987). W.E. Snee and New Penn Development Corporation drilled the discovery well in an attempt to imitate the north-central Pennsylvania Oriskany gas field successes. The No. 1 Leo F. Heyn well was completed on April 23, 1937, with an initial open flow of 1,800 Mcf from 18 feet into the Huntersville Chert at 6,611 feet. Twenty-one wells in the North Summit pool produced gas primarily from 40 to 70 feet into the fractured Huntersville Chert, which averages 6,713 feet deep and 197 feet thick, and the underlying Oriskany Sandstone, averaging 6,910 feet deep and 100 feet thick. A typical gamma-ray log for the wells in the Summit field is shown in Figure Dho-12. Original reservoir pressures in the Summit field were reported to be between 3,025 and 3,050 psi (Hickock and Moyer, 1940). Well records at the Pennsylvania Bureau of Topographic and Geologic Survey office indicate the average natural initial open flow was 2,752 Mcf and ranged from 132 Mcf to 11,700 Mcf. The Btu value of the gas is 1,018 with a specific gravity of 0.567 (Table Dho-3).

The North Summit pool is located on the crest of the Summit dome along the axis of the Chestnut Ridge anticline. A seismic line (Figure Dho-13) shows not only the reverse faults which are so typical of the anticlinal structures and domes of the Appalachian basin, but also the optimal positioning of wells in the North Summit pool with respect to structural features including the faults, isolated fault blocks, and closure between the blocks.

Mountain Lake Park field: The Mountain Lake Park field is located in Garrett County, Maryland, and extends southwestward into West Virginia. (Figures Dho-2, Dho-14) It is situated on the southern end of Deer Park anticline, and occupies approximately 3,400 acres. Gwinn (1964) called this region the Southeastern High Plateau Zone. Structural style in this area differs from that previously described. "The southeastern folds are steep on their northwest limbs like those in the Valley and Ridge...and many appear to lack northwest-flank reverse faults at the Oriskany level....[M]ode and style of subsurface deformation is similar to that along the Structural Front and in the Valley and Ridge province in general to the southeast, inasmuch as it is characterized by concentric folding at the surface and low-angle detachment thrusting at depth" (Gwinn, 1964, p. 824) (Figure Dho-8a). A northwest-southeast trending tear fault near the West Virginia-Maryland state line divides the field; gas wells in West Virginia are on the east flank of Deer Park anticline and are positioned south of the fault. The immediate vicinity surrounding the fault appears as a depression on the Huntersville structure (Figure Dho-14). The Maryland portion of the Mountain Lake Park field is on the east flank and north of the fault (Gwinn, 1964; Patchen, 1968b).

The first well drilled to the chert in Mountain Lake Park field was completed in 1948 by Columbian Carbon Company and tested 750 Mcf natural which blew down to 75 Mcf. The well quickly began to produce water and was plugged and abandoned, never having produced. The first successful well was the No. 1 Beachy, drilled and completed in 1949 by the Cumberland Oil and Gas Company. Initial reports indicated 380 Mcf after acidizing. After a second acid treatment, the well tested 432 Mcf at 1,600 psi. A year later, in 1950, the second successful well was drilled. This well, the Columbian Carbon No. 1 Welch, was completed with an open flow of 8,029 Mcf at a pressure of 1,610 psi after seven hours (Amsden, 1954). Within the next six months, there were 13 producing wells; by the end of 1953, the Mountain Lake Park field had produced 7.3 bcf from 42 wells (Amsden, 1954). Rapid overdevelopment of the field resulted in poor spacing and premature decline and abandonment of some wells. Amsden (1954) was stated that unitized spacing requirements would have yielded significantly improved, efficient, and economical production of the Mountain Lake Park field.

A typical gamma-ray log (Figure Dho-15) shows approximately 80 feet of Huntersville Chert and 80 feet of Oriskany Sandstone.

In 1954, the field was extended southwestward into Preston County, West

	TABLE Dho-1	Jacksonville PA	Johnstown PA	Living Waters PA	Lycippus PA	New Alexandria PA	Punxsutawney-Driftwood PA	Spook Hill PA	Strongstown PA	Summit PA	North Summit Storage Pool PA	Duffy WV	Terra Alta WV	Mountain Lake Park MD
BASIC RESERVOIR DATA	POOL NUMBER	353316	362634	8552	435403	5931	575168	13423	685071	688357	688357	204951	701821	489401
	DISCOVERED	1956	1957	1980	1920	1962	1955	1988	1954	1942	1936	1967	1945	1954
	DEPTH TO TOP RESERVOIR	7,510	7,591	8,180	7,446	7,637	7,282	8,196	8,075	7,095	6,593	6,740	5,294	3,634
	AGE OF RESERVOIR	Middle to Lower Devonian	Middle to Lower Devonian	Middle to Lower Devonian	Middle to Lower Devonian	Middle to Lower Devonian	Middle to Lower Devonian	Middle to Lower Devonian	Lower to Middle Devonian	Lower to Middle Devonian	Lower to Middle Devonian	Middle to Lower Devonian	Lower to Middle Devonian	Middle to Lower Devonian
	FORMATION	Huntersville/ Oriskany	Huntersville/ Oriskany	Huntersville/ Oriskany	Huntersville/ Oriskany	Huntersville/ Oriskany	Huntersville/ Oriskany	Huntersville/ Oriskany	Huntersville/ Oriskany	Huntersville/ Oriskany	Huntersville/ Oriskany	Huntersville/ Oriskany	Huntersville/ Oriskany	Huntersville/ Oriskany
	PRODUCING RESERVOIR	Huntersville/ Oriskany	Huntersville/ Oriskany	Huntersville/ Oriskany	Huntersville/ Oriskany	Huntersville/ Oriskany	Huntersville/ Oriskany	Huntersville/ Oriskany	Huntersville/ Oriskany	Huntersville/ Oriskany	Huntersville/ Oriskany	Huntersville/ Oriskany	Huntersville/ Oriskany	Huntersville/ Oriskany
	LITHOLOGY	chert/ sandstone	chert/ sandstone	chert/ sandstone	chert/ sandstone	chert/ sandstone	chert/ sandstone	chert/ sandstone	chert/ sandstone	chert/ sandstone	chert/ sandstone	chert/ sandstone	chert/ sandstone	chert/ sandstone
	TRAP TYPE	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure
	DEPOSITIONAL ENVIRONMENT	nearshore	nearshore	nearshore	nearshore	nearshore	nearshore	nearshore	nearshore	nearshore	nearshore	nearshore	nearshore	nearshore
	DISCOVERY WELL IP (Mcf)	179	6,501		400	6,000	515	0	480	1,784	1,900		4,355	70
	DRIVE MECHANISM	gas/water	gas/water	gas/water	gas/water	gas/water	gas/water	gas/water	gas/water	gas/water	gas/water	gas/water	gas/water	gas/water
	NO. PRODUCING WELLS	29	11	5	10	6	133	1	31	17	14	0	53	9
	NO. ABANDONED WELLS	6	5	0	9	3	64	1	1	1	0	3	3	> 53
	AREA (acreage)	2,713	2,218	533	1,292	710	26,691	160	7,307	770	1,081	1,920	6,400	3,400
	OLDEST FORMATION PENETRATED	Helderberg	Helderberg	Helderberg	Salina	Helderberg	Helderberg	Helderberg	Helderberg	Lockport	Tuscarora	McKenzie	Tuscarora	Tuscarora
	EXPECTED HETEROGENEITY DUE TO:	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure
RESERVOIR PARAMETERS	AVERAGE PAY THICKNESS (ft.)			110	129	180	82	131	167	301	297		54	
	AVERAGE COMPLETION THICKNESS (ft.)	164	129	40		180	82							148
	AVERAGE POROSITY--LOG (%)		7.29	8.88		8.21		5.45	6.97	2.79				
	MINIMUM POROSITY--LOG (%)		1.24	3.73		1.80		2.24	4.10	1.76				
	MAXIMUM POROSITY--LOG (%)		15.53	12.40		20.50		9.27	11.15	3.51				
	NO. DATA POINTS								2					
	POROSITY FEET													
	RESERVOIR TEMPERATURE (°F)		130	164	171	164		138	160	152				136
	INITIAL RESERVOIR PRESSURE (psi)	4,230	2,810	4,225	3,875	3,875	2,985	3,165	3,250	3,280	4,478	2,250	2,365	1,875
	PRODUCING INTERVAL DEPTHS (ft.)	7,510	7,591	8,180	7,446	7,637	7,276	8,196	8,076	7,095	6,713	6,740	5,294	3,634
	PRESENT RESERVOIR PRESSURE (psi) / DATE													
FLUID & GAS PROPERTIES	Rw (Ωm)	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035		0.035	0.035
	GAS GRAVITY (g/cc)	0.57					0.57				0.566			0.576
	GAS SATURATION (%)		66.3	69.5		69.5		48	58.32	54.2				
	WATER SATURATION (%)		33.7	30.5		30.5		52	41.68	45.8				
	COMMINGLED	no	no	no	no	no	no	no	no	no	no		no	no
	ASSOCIATED OR NONASSOCIATED	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated		nonassociated	nonassociated
	Btu/scf	1,026					1,023				1,018			1,003
VOLUMETRIC DATA	STATUS (producing, abandoned, storage)	producing	producing	producing	producing	producing	producing	producing	producing	producing	storage	abandoned	storage	producing
	ORIGINAL GAS IN PLACE (Mcf)		101,420,000	15,846,000	3,880	15,288,000		1,804,000	57,128,000	35,900,000	22,800,000			
	ORIGINAL GAS RESERVES (Mcf)												59,100,000	
	PRODUCTION YEARS	1956-1994	1957-1989	1980-1993	1924-1931& 1956-1992	1962-1992	1955-1992	1988-1992	1954-1992	1942-1992	1936-1986	1967-1973	1945-1959	1954-1992
	REPORTED CUMULATIVE PRODUCTION (Mcf)	30,923,555	34,868,452	2,411,196	6,167,077	12,744,721	133,204,405	84,000	28,455,613	23,079,925	21,975,214		47,010,000	17,726,869
	NO. WELLS REPORTED													
	ESTIMATED CUMULATIVE PRODUCTION (Mcf)											1,000,000		
	REMAINING GAS IN PLACE (Mcf)/DATE		66,552,000	13,435,000		2,543,000		1,720,000	28,673,000	13,309,000		1,000,000		
	REMAINING GAS RESERVES (Mcf)/DATE												12,090,000	
	RECOVERY FACTOR (%)		34	15		83		5	50	63				
	INITIAL OPEN FLOW (Mcf/d)	380	3,359		1,759	353	2,975	0	2,272	1,217	2,752		4,009	524
	FINAL OPEN FLOW (Mcf/d)	2,142	4,712	1,046	4,465	3,881	5,121	3,100	3,114	9,800		9,550	1,707	1,782

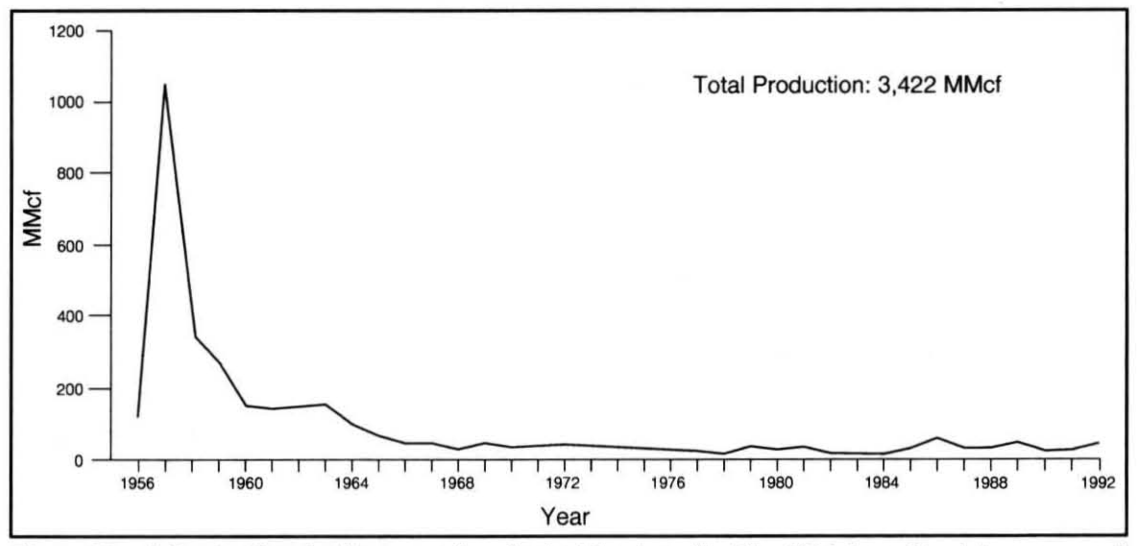


Figure Dho-9. Production decline curve for a typical Huntersville Chert/Oriskany Sandstone gas well in Jacksonville field, Indiana County, Pennsylvania.

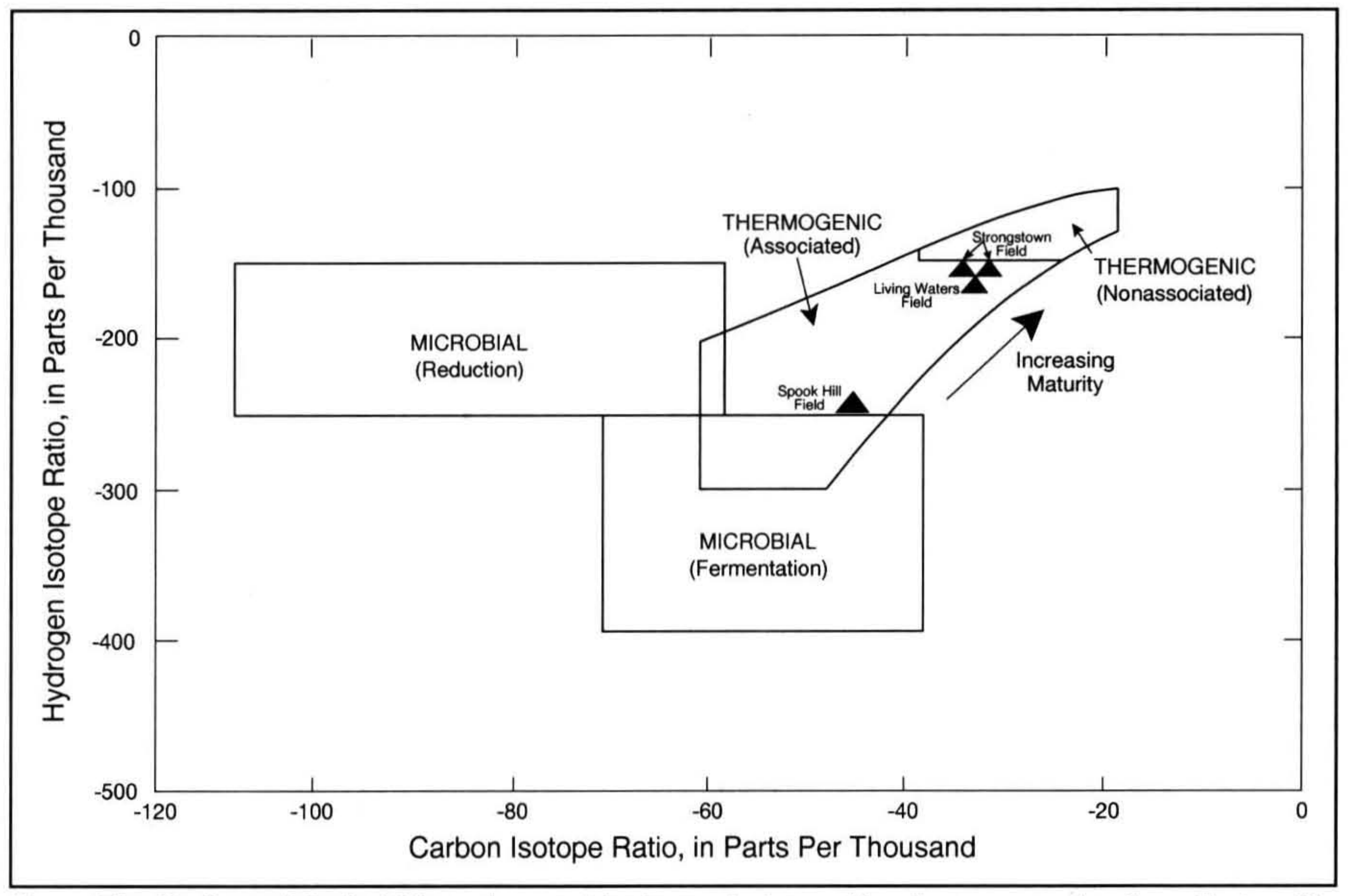


Figure Dho-10. Crossplot of stable carbon and hydrogen isotope ratios for gas samples from Huntersville Chert/Oriskany Sandstone reservoirs in Spook Hill field, Somerset County, Pennsylvania, and Living Waters and Strongstown fields, Indiana County, Pennsylvania. From Laughrey and Baldassare (1992).

Table Dho-2. Rock evaluation pyrolysis including information for the Marcellus Shale of the No. 1 Svetz well in Somerset County, Pennsylvania. After Peters and Moldowan (1993).

Maturation Level	PI	C	Ro%	TAI	Bit/TOC
Beginning Oil Window	0.1	435-445	0.6	1.5-2.6	0.05-0.1
Peak Oil Window	0.25	445-450	0.9	2.9-3	0.15-0.25
End Oil Window	0.4	470	1.4	> 3.2	< 0.1
Marcellus Shale No. 1 Svetz	0.63-0.69	332-339**	3.28	4.2	0.026

** The temperature measurement is invalid because the hydrocarbons from kerogen pyrolysis yields were too low. Thus the maximum generated hydrocarbons were at this low temperature and therefore invalid for these testing purposes.

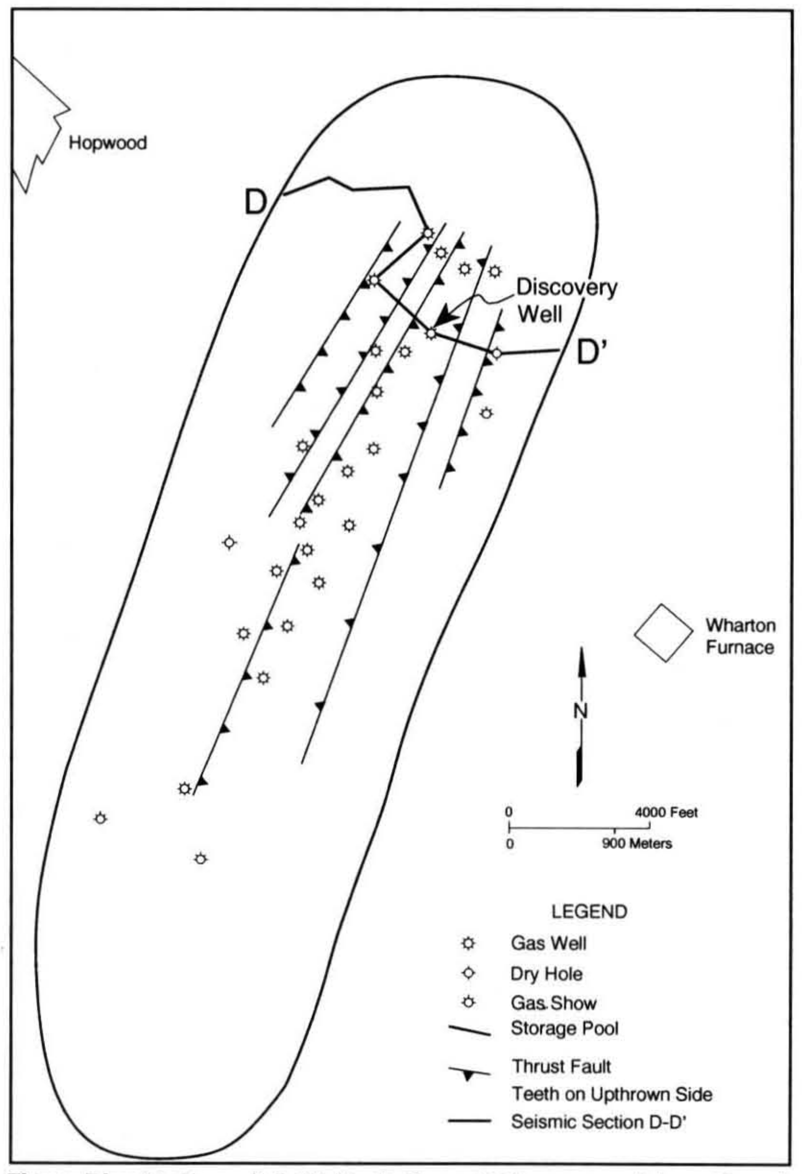


Figure Dho-11. Summit field, North Summit Storage pool. Location of seismic section D-D' (Figure Dho-13) is also shown.

Virginia, whereupon a total of five wells were drilled: two dry holes and three gas wells (Cardwell, 1982b). Initial open flows before treatment in Mountain Lake Park field ranged from no gas to 5,700 Mcf. After treatment, most commonly acidizing, open flows ranged from no gas and salt water to more than 12,000 Mcf. Although total production from the Maryland portion of the Mountain Lake Park field through 1992 was reportedly 15.8 bcf (K. Schwarz, Maryland Geological Survey, oral commun., 1993), many operators believe 20 bcf may be closer to actual production. An average Btu of 995 and gas gravity of 0.57 were measured (Table Dho-3). The seven wells remaining in production in the field are those highest on structure and in closest proximity to the tear fault near the southwestern end of the field.

Wells in West Virginia produced approximately 2 bcf through 1973 with an average Btu value of 1,015 and average gas gravity of 0.561 (Table Dho-3).

Terra Alta field: Snee and Eberly Drilling Company's No. 2 Sisler well, drilled in 1945, discovered Terra Alta field in Preston County, West Virginia (Figure Dho-2). Natural open flow from the Huntersville and Oriskany totaled 57 Mcf at 2,340 psi. After acidizing, the initial potential increased to 100 Mcf. The area had been tested in 1925 by Hope Natural Gas Company's No. 1 Gordon well, which, although targeting the Oriskany Sandstone, was abandoned before reaching the Oriskany. In 1944, the William E. Snee Company's No. 1 Sisler reached the Helderberg limestone with a show of 24 Mcf from the combined Huntersville Chert and Oriskany Sandstone. This well also was abandoned. Completion of the No. 3 Sisler well in 1946 by William E. Snee Company resulted in a natural open flow of 4.3 MMcf from the Huntersville Chert. According to Haught and McCord (1960), 40 of the 60 wells drilled in the field were productive, averaging 1.6 MMcf per well and ranging up to an initial production of 17 MMcf. Initial reservoir pressure was 2,365 psi, and the total depth of wells reached 5,100 to 6,250 feet. Cumulative production from Terra Alta was 47 bcf before conversion to storage in 1960.

Terra Alta field is located on the crest of the Briery Mountain anticline in Preston County, West Virginia. Although it is only about 8 miles west of Mountain Lake Park field, structurally Terra Alta more closely resembles Summit field, which is 25 miles north. The crest of the anticline is depressed and broken by reverse faults resulting in parallel isolated fault blocks with structural closure (Figure Dho-16).

The Huntersville chert as described from well cuttings in Terra Alta field is a brownish-gray to milky, translucent to nearly transparent, slightly calcareous chert containing sponge spicules, and occasional inclusions of highly silicified, phosphatic, glauconitic, silty, sandy or shaley chert. It ranges from 120 to 140 feet thick. The underlying Oriskany sandstone, which varies from 100 to 250 feet thick, is a fine- to coarse-grained, well-sorted, light to medium brownish-gray, highly calcareous, quartzitic, fossiliferous sandstone, containing thin, silty to sandy limestone interbeds. Figure Dho-17 is a typical gamma-ray log of a well in the Terra Alta field.

Punxsutawney-Driftwood and Big Run fields: The portions of the Punxsutawney-Driftwood field and Big Run field that produce gas from both the Huntersville Chert and Oriskany Sandstone occupy 26,691 acres in Clearfield County, Pennsylvania (Figure Dho-2). Punxsutawney-Driftwood and Big Run fields combine elements of stratigraphic and structural trapping mechanisms. Edmunds and Berg (1971) observed that the boundaries of these fields coincide with deep, high-angle reverse faults on the northwest flank of the Chestnut Ridge anticline, separating the fields into pools (Figure Dho-18). Vertical displacement on either side of these faults is approximately 200 feet (Roberts, 1960). Gas accumulation is affected by deep fractures as well as reservoir porosity and

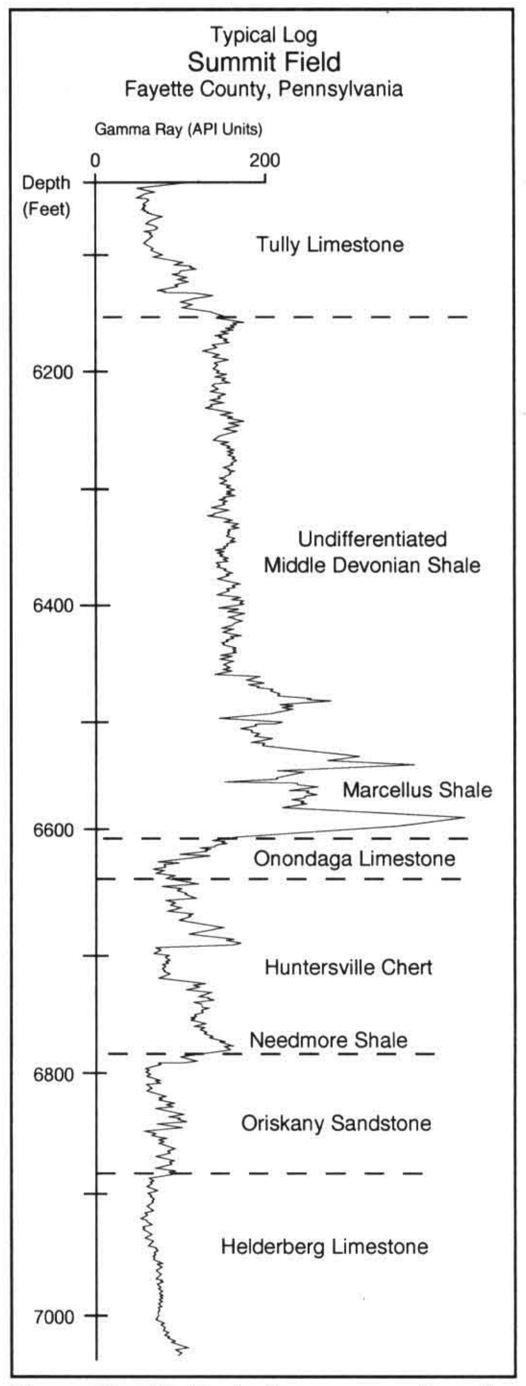


Figure Dho-12. Typical gamma-ray log of a well in Summit field, Fayette County, Pennsylvania.

Table Dho-3. Gas analysis figures. From Moore and Sigler (1987a).

Component	Summit Field		Mountain Lake Park Field					Punxsutawney-Driftwood Field	
	No. 1 Eutsey	No. 1 Barton	No. 1 Welch	No. 1 Miler	No. 1 Weeks	No. 2 Riley	No. 1 Burger	No. 1 Marshall	No. 1 Shaw
Methane	97.60	97.70	95.90	94.20	95.90	96.20	98.20	97.10	97.00
Ethane	1.50	1.50	1.10	1.00	0.10	1.00	1.00	2.00	2.20
Propane	0.10	0.10	0.10	0.10	0.10	0.00	0.10	0.10	0.10
N-Butane	0.00	0.00	0.10	0.00	0.10	0.00	0.00	0.00	0.00
Isobutane	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
N-Pentane	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Isopentane	0.00	0.00	0.10	0.00	0.00	0.00	0.00	0.00	0.00
Cyclopentane	0.00	0.00	trace	0.00	trace	0.00	0.00	0.00	0.00
Hexanes	0.00	0.00	0.00	0.00	0.10	0.00	0.00	0.00	0.00
Nitrogen	0.70	0.60	2.10	4.30	2.20	2.60	0.50	0.50	0.60
Oxygen	0.00	0.00	0.10	0.20	0.20	0.10	0.00	0.10	0.00
Argon	trace	0.00	trace	0.10	trace	0.00	0.00	trace	0.00
Hydrogen	0.00	0.00	0.10	0.10	0.10	trace	trace	0.00	0.00
Hydrogen Sulfide	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Carbon Dioxide	0.10	0.10	0.30	0.00	0.10	trace	0.00	0.20	0.10
Helium	0.02	0.01	0.07	0.08	0.08	0.08	0.10	0.02	0.02
Btu	1,018	1,019	1,003	975	985	992	1,015	1,022	1,025
Specific Gravity	0.57	0.57	0.58	0.58	0.57	0.57	0.56	0.57	0.57

permeability (Lytle and others, 1959). The Huntersville Chert averages 40 to 80 feet thick in the Punxsutawney-Driftwood field, and the Oriskany Sandstone is 10 to 20 feet in thickness (Berg and Glover, 1976), as shown on the gamma-ray log typical of wells in the area (Figure Dho-19).

The chert observed in this field is described as "brownish gray, slightly silty, usually non-calcareous, bedded chert with some dark siliceous shales in the lower part" (Edmunds and Berg, 1971, p. 124). The Oriskany is a "light gray, medium- to coarse-grained quartzose sandstone... cemented by calcite but some silica cement occurs near the top. Sufficient pore space has been retained to make the sandstone body an easily exploitable reservoir" (Edmunds and Berg, 1971, p. 124). Lytle and others (1959) observed that gas is not encountered until the Oriskany is penetrated, and the chert does not yield gas until both units have been stimulated.

F.C. Deemer was disappointed with the results of the No. 10 Irwin well he drilled in Bell Township, Clearfield County, Pennsylvania, while he was exploring for what would later be developed as Reed-Deemer pool in Big Run field. "[T]here was just a trace of the Oriskany Sand, and where the sand should have been was just limestone and shell life" (F.C. Deemer, written commun. to the Pennsylvania Bureau of Topographic and Geologic Survey, 1950). The well reached the Lower Devonian strata in November 1946. From that time until January 1949, the well was subjected to episodes of drilling deeper, shutting down, reaming, and was finally plugged back and shot twice with nitroglycerine to capitalize on the 13 gas shows they experienced while drilling through the lower portion of the Hamilton shales and Huntersville Chert. Unable to coax gas from the well, Deemer abandoned it but remained convinced that commercial quantities of gas existed in the area. He built a second location and spudded a new well 5,400 feet northwest of the No. 10, on the northwest flank of the Chestnut Ridge anticline. This well, the No. 13 Irwin, was completed in December 1953 and was the discovery well for the Deemer pool (now the Reed-Deemer pool in Big Run field). Seventy-two feet of Huntersville Chert and 6 feet of Oriskany Sandstone were penetrated. Only the top 2 feet of the Oriskany were fine- to medium-grained quartzose sandstone. The remaining 4 feet consisted of a fine- to coarse-grained, light gray to gray clastic limestone, sandy, containing occasional rounded and polished quartz grains and brachiopod shells. There was no show of gas during drilling, but after shooting, the well tested at 700 Mcf (Fettke, 1954) and experienced almost no decline in production for the first year the well was on line (Fettke and Lytle, 1956). Original reservoir pressure was 3,900 psi (Fettke and Lytle, 1956). The pool currently produces from 15 wells with nine holes abandoned. Average initial pressure was 3,182 psi and average initial open flow was 1,312 Mcf. Average depth to the top of the productive Huntersville-Oriskany interval is 7,452 feet. The Btu value of the gas is 1,023 with a specific gravity of 0.570 (Table Dho-3).

Guidance offered by unsuccessful tests on the eastern flank of the Chestnut Ridge anticline and the success of Deemer's No. 13 Irwin on the northwestern flank led to further drilling activity in the area. About 8 miles northeast of the Reed-Deemer pool, Rockton Drilling Company discovered the Rockton pool of the Punxsutawney-Driftwood field with the successful completion of the No. 1 Eva Moore well. The No. 1 Moore had an initial open flow of 515 Mcf after hydraulic

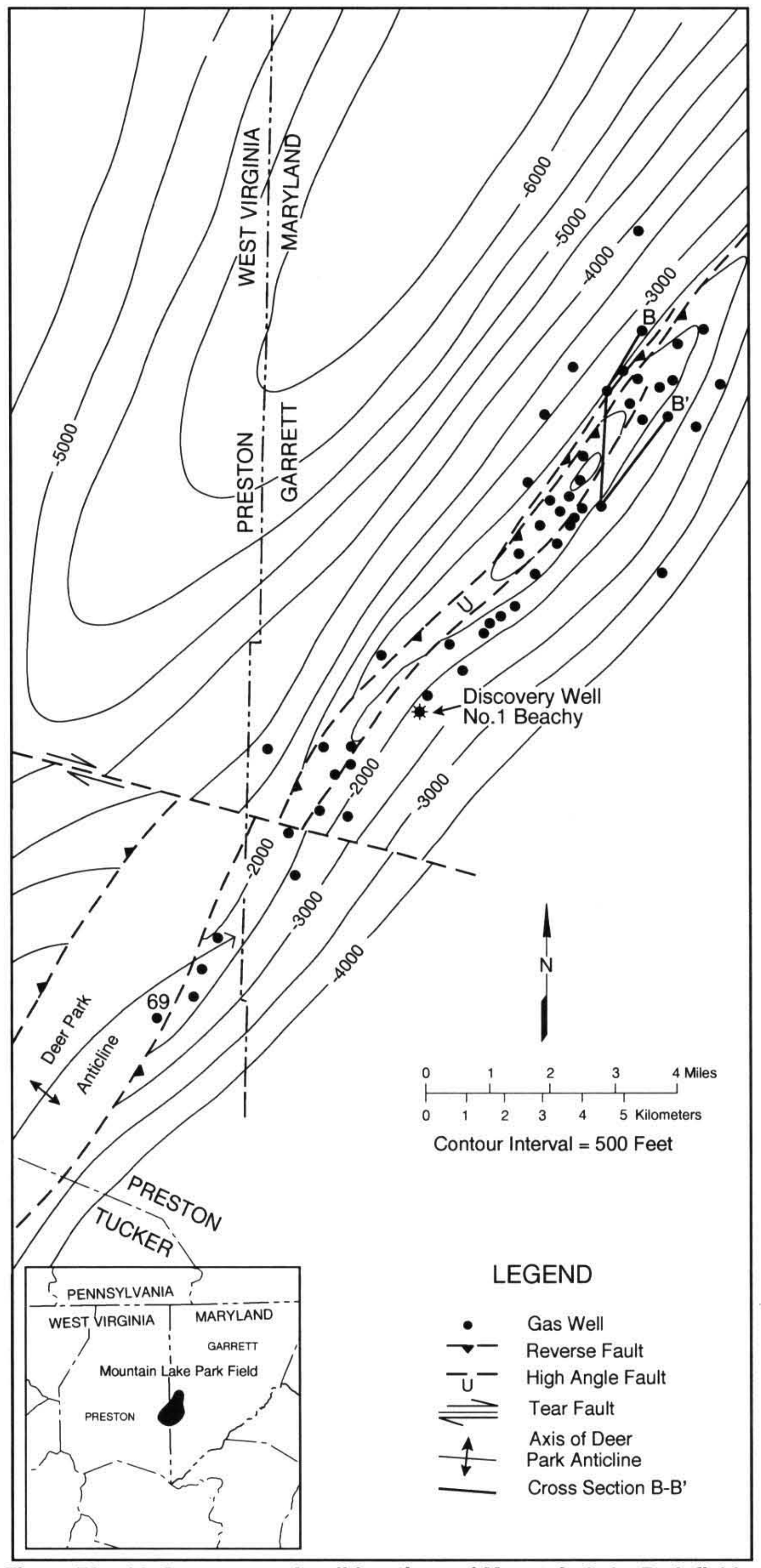


Figure Dho-14. Structure and well locations of Mountain Lake Park field, Garrett County, Maryland, and Preston County, West Virginia. From Gwinn (1964).

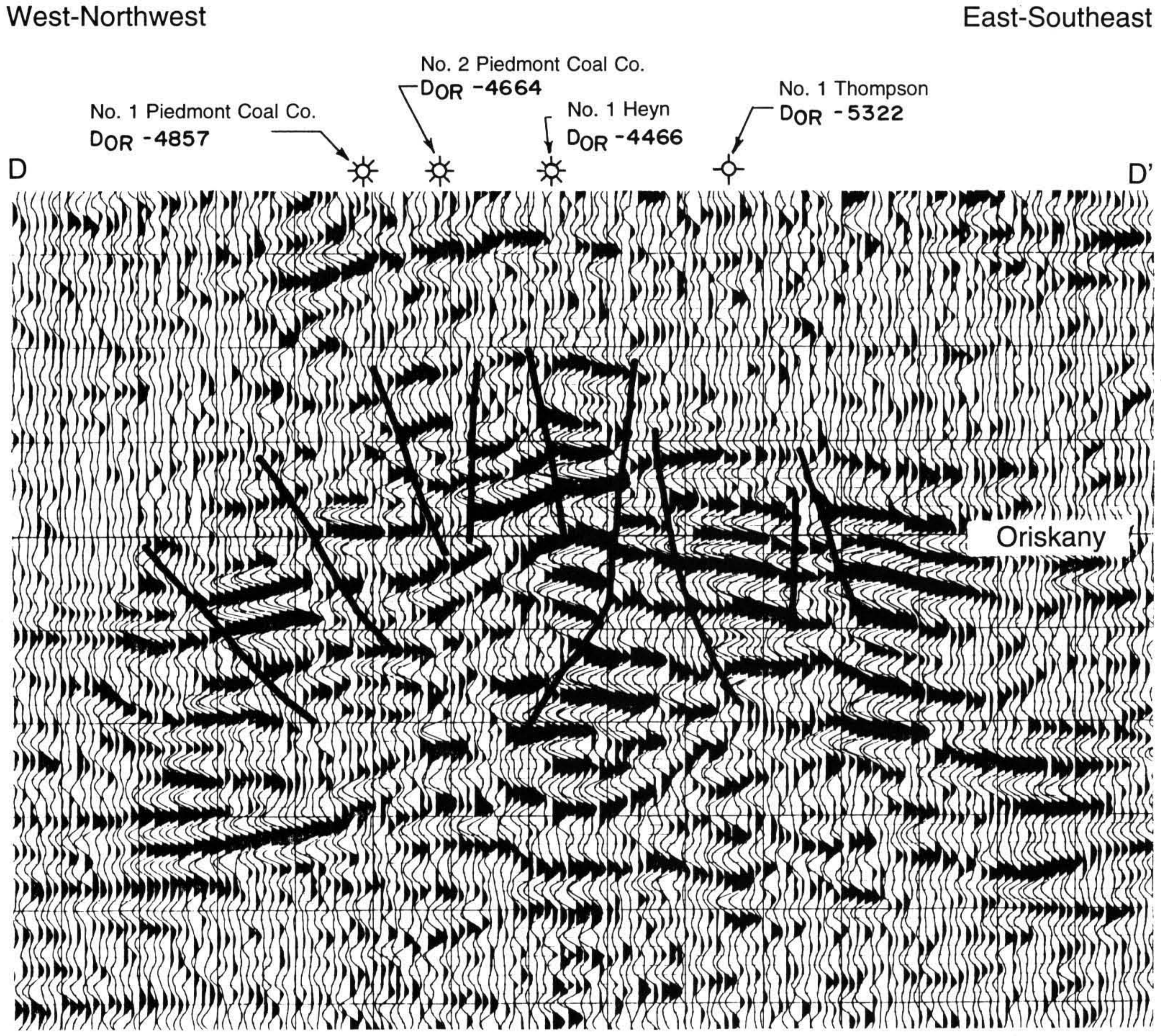


Figure Dho-13. Seismic line D-D' across the North Summit Storage pool, Fayette County, Pennsylvania. Line and interpretation courtesy of R. Beardsley and R. Campbell, Columbia Gas Transmission Corporation. See Figure Dho-11 for location.

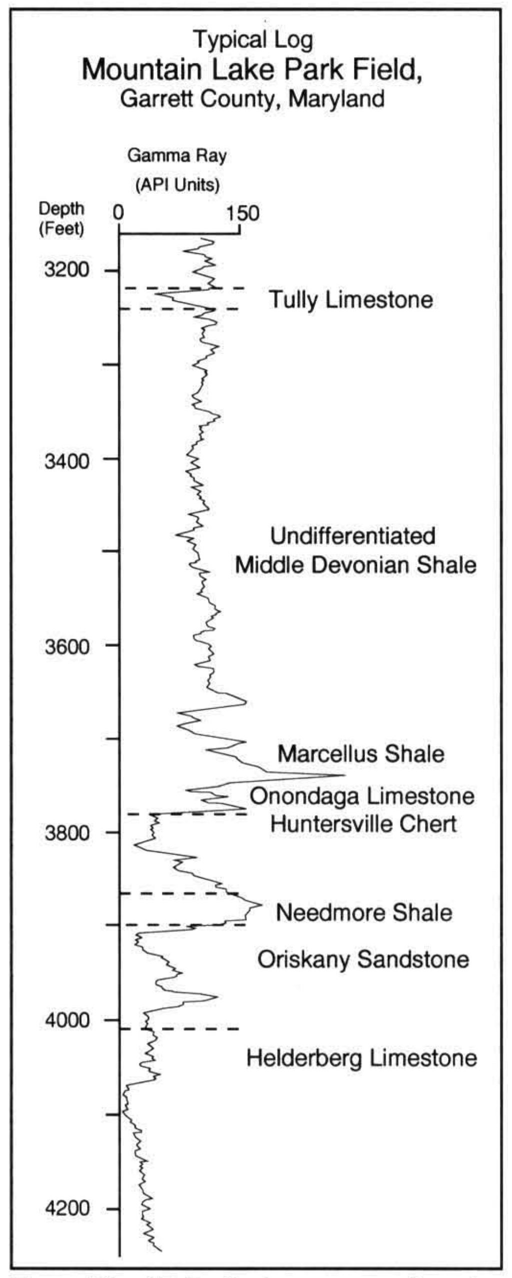


Figure Dho-15. Typical gamma-ray log of a well in Mountain Lake Park field, Garrett County, Maryland, and Preston County, West Virginia.

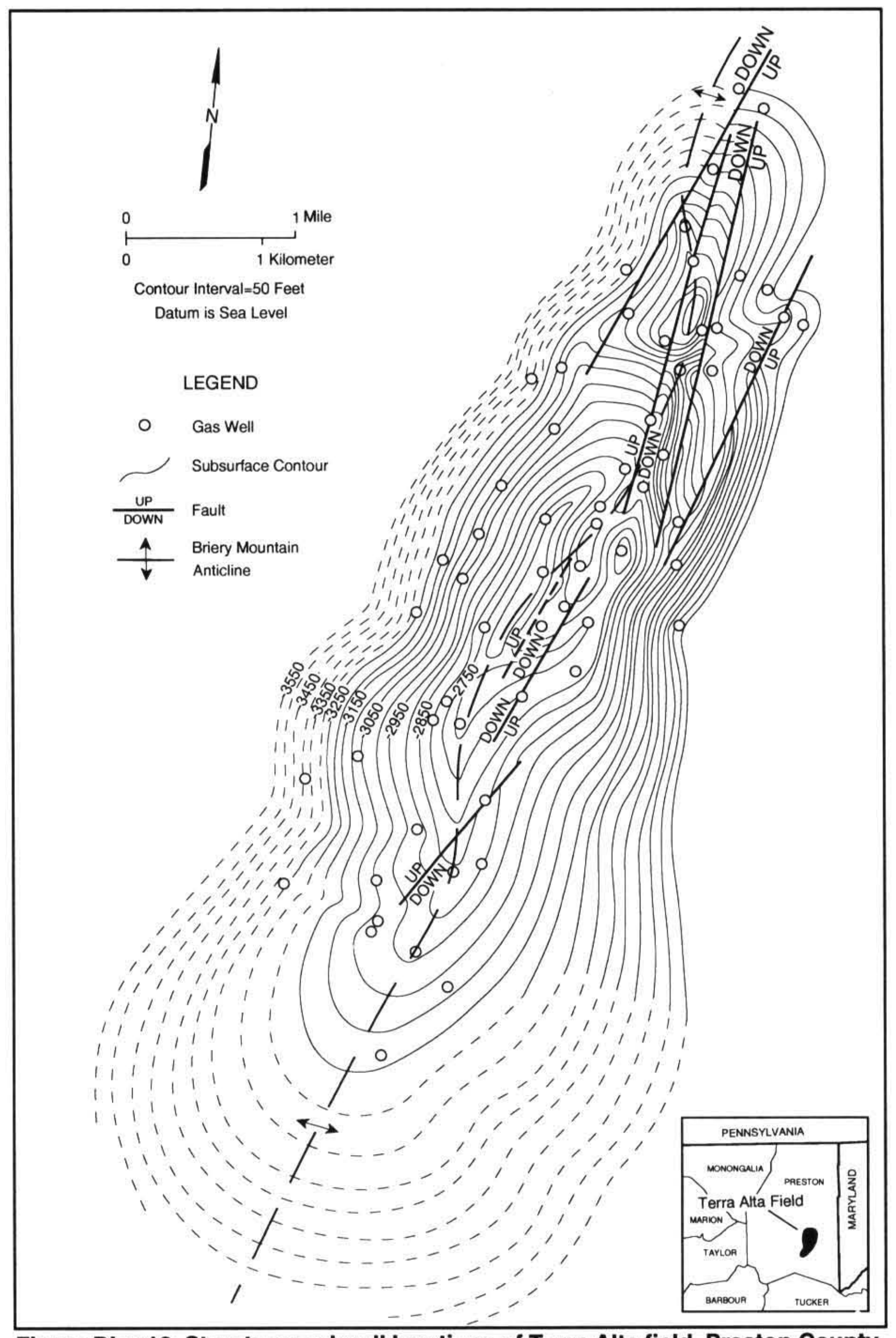


Figure Dho-16. Structure and well locations of Terra Alta field, Preston County, West Virginia. From Cardea (1959).

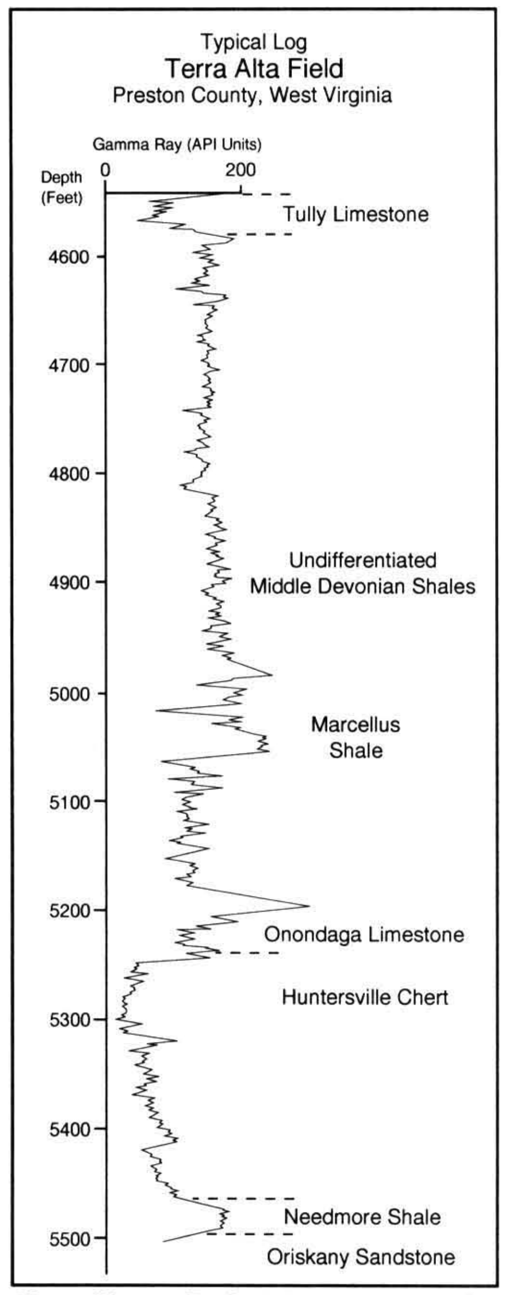


Figure Dho-17. Typical gamma-ray log of a well in Terra Alta field, Preston County, West Virginia.

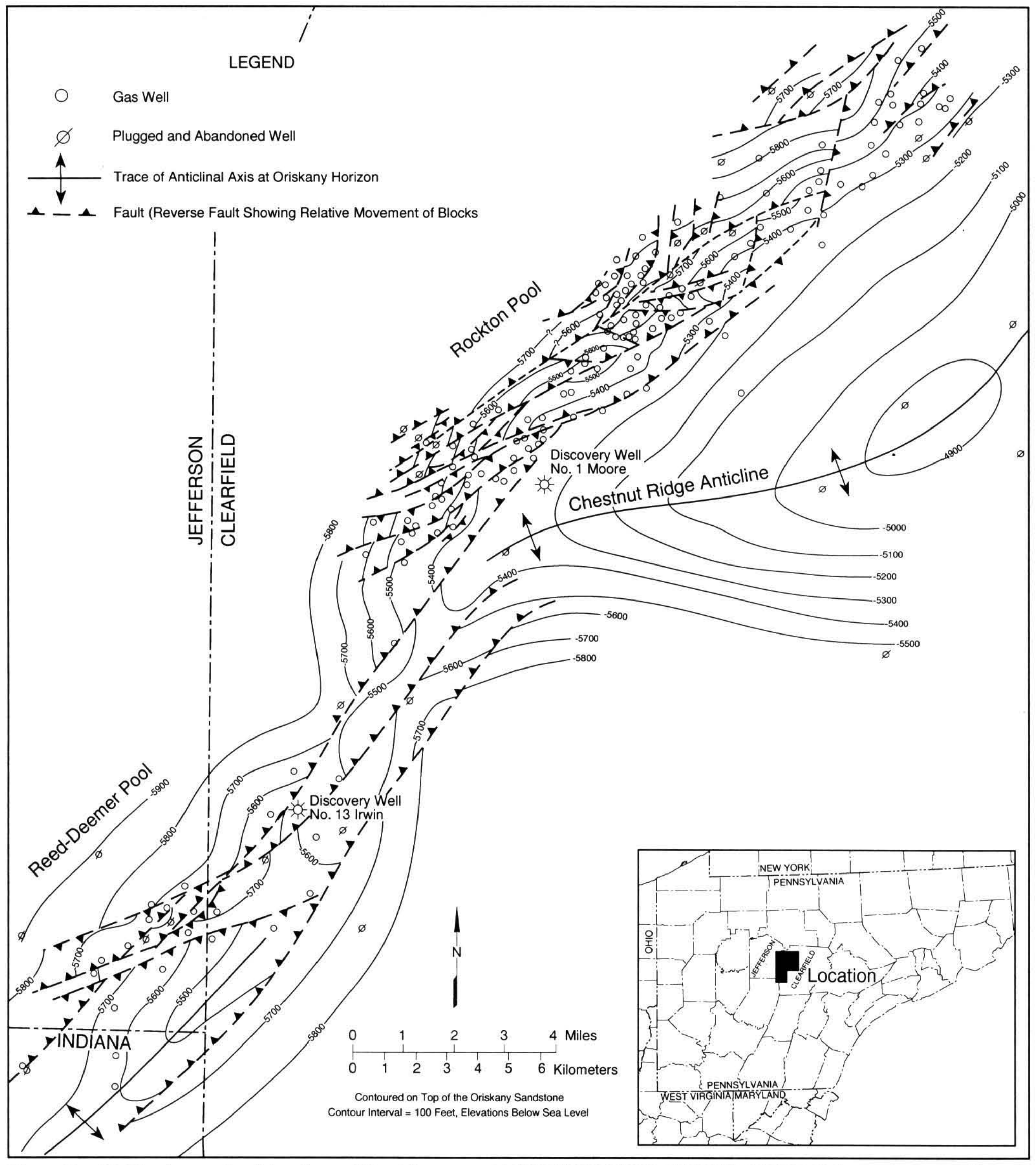


Figure Dho-18. Structure and well locations of Reed-Deemer pool of the Big Run field and the Rockton pool, Punxsutawney-Driftwood field, Clearfield and Jefferson counties, Pennsylvania. Modified from Cate in Lytle and others (1959).

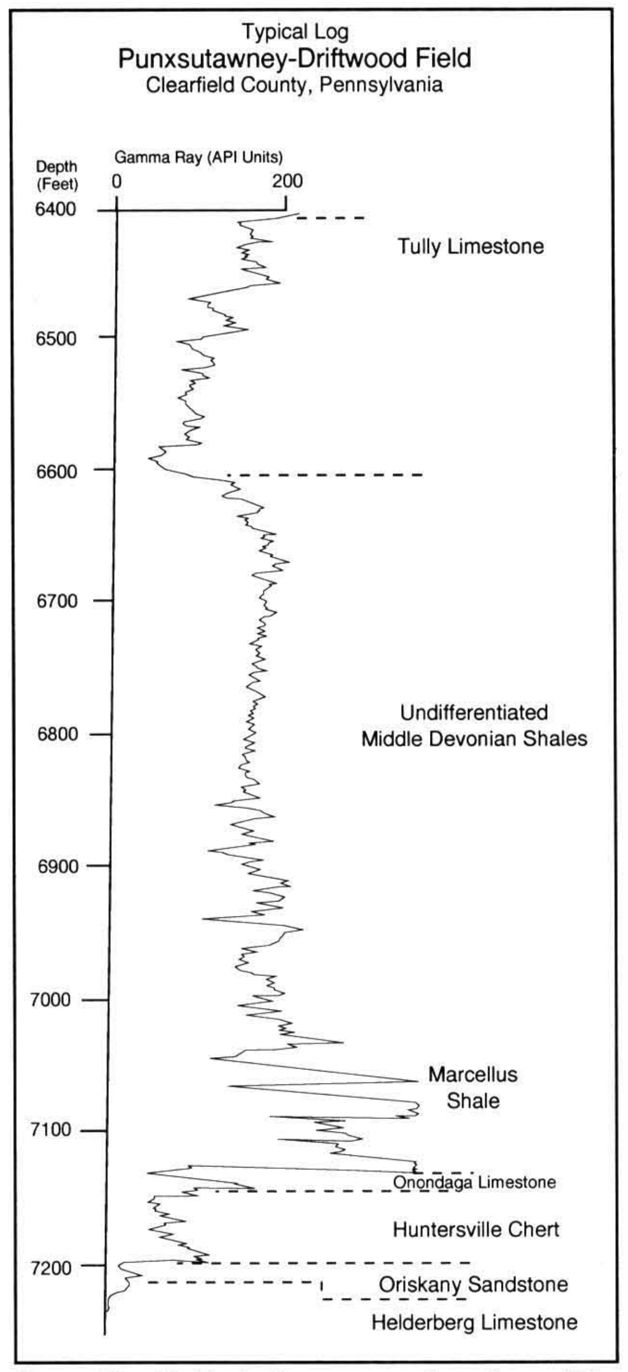


Figure Dho-19. Typical gamma-ray log of a well in Punxsutawney-Driftwood field, Clearfield County, Pennsylvania.

Table Dho-4. Average natural gas production per well per year.

Field	Location	Mcf
Roaring Run	Armstrong County, Pennsylvania	45,082
Carrolltown	Cambria County, Pennsylvania	27,464
Rager Mountain	Cambria County, Pennsylvania	35,567
Punxsutawney-Driftwood	Clearfield County, Pennsylvania	27,069
Penfield	Clearfield County, Pennsylvania	2,452
Ohiopyle	Fayette & Somerset Counties, Pennsylvania	16,002
Summit	Fayette County, Pennsylvania	27,153
North Summit	Fayette County, Pennsylvania	31,393
Spruell	Fayette County, Pennsylvania	54,763
Mill Run	Fayette County, Pennsylvania	17,765
Mt. Lake Park	Garrett County, Maryland & Preston County, West Virginia	18,660
Strongstown	Indiana & Cambria Counties, Pennsylvania	24,156
Jacksonville	Indiana County, Pennsylvania	28,061
Nolo	Indiana County, Pennsylvania	26,105
Living Waters	Indiana County, Pennsylvania	37,095
Cherry Hill	Indiana County, Pennsylvania	9,910
Murphy Creek	Lewis County, West Virginia	17,699
South Burns Chapel	Preston & Monongalia Counties, West Virginia	8,754
Etam	Preston & Tucker Counties, West Virginia	36,985
Terra Alta	Preston County, West Virginia	63,356
Concord	Preston County, West Virginia	35,714
Glady	Randolph & Pocahontas Counties, West Virginia	104,839
Boswell	Somerset County, Pennsylvania	47,348
Seven Springs	Westmoreland & Somerset Counties, Pennsylvania	47,451
New Alexandria	Westmoreland County, Pennsylvania	47,202
Johnstown	Westmoreland County, Pennsylvania	99,058
Crabtree	Westmoreland County, Pennsylvania	17,743
Jacobs Creek	Westmoreland County, Pennsylvania	38,261
Lycippus	Westmoreland County, Pennsylvania	66,392
Linn Run	Westmoreland County, Pennsylvania	28,868

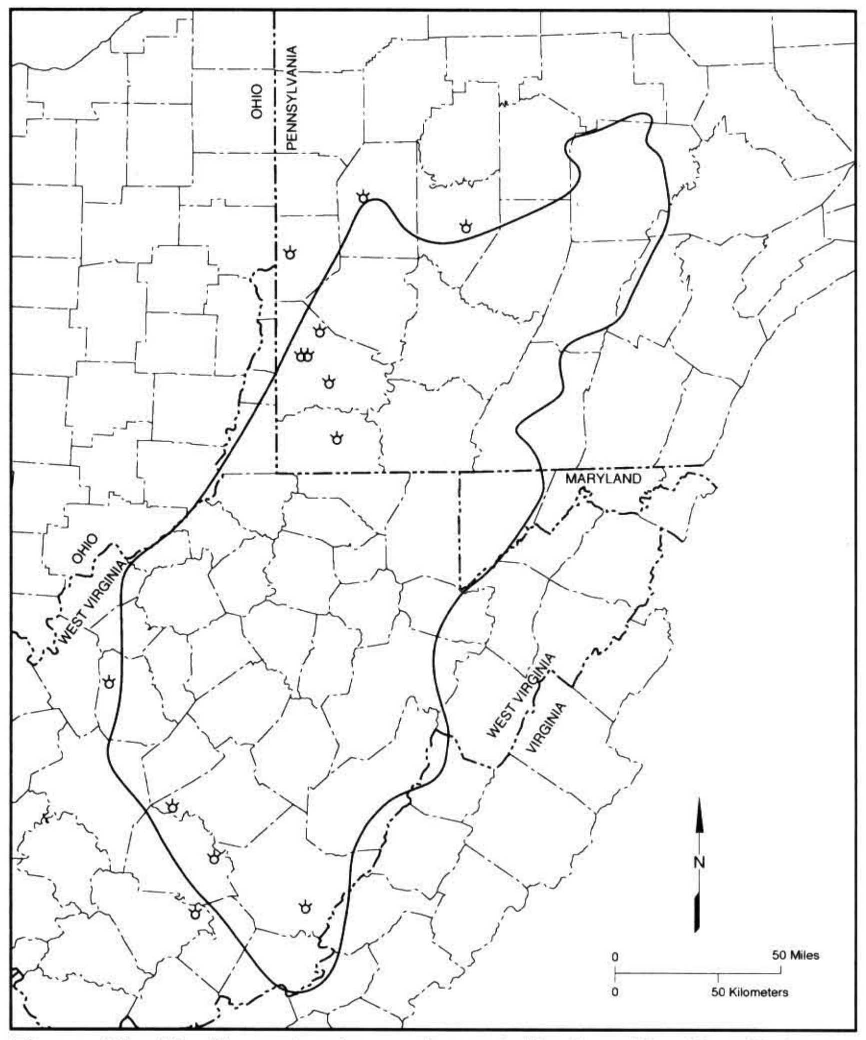


Figure Dho-20. Map showing outine of Huntersville Chert/Oriskany Sandstone play area with wells having gas shows.

fracturing and a rock pressure of 3,275 psi. By the end of 1955, there were four producing wells in the Rockton pool. During the next year, 22 wells were added to the pool, and an additional 65 were successfully completed in 1957. Rockton pool presently produces from 109 wells and contains 43 abandoned wells. The productive area of the pool comprises 21,458 acres.

Resources and Reserves

Main economic considerations of the Huntersville Chert and Oriskany sandstones play include the size of the drainage area, natural fracturing and hydraulic fracturing potential, structure, and stratigraphy. The size of the fault blocks from which the chert and sandstone produce gas are variable. Lateral extent of drainage area is difficult to determine without extensive seismic coverage to define block dimensions. Fracture systems characteristic of the Huntersville Chert reservoir may add a potentially significant multidimensional natural gas drainage channel, and are frequently influenced by the local stratigraphy. Keeping these factors in mind, the difficulty and inaccuracy of assigning a per-acre yield reserve figure becomes apparent. Therefore, average production per well per year for each field was calculated and results are listed in Table Dho-4. The figures are derived from actual reported gas production, divided by the number of years in production and the number of producing wells. This method is not without its own inaccuracies, for example, fluctuating gathering line pressure, shut-in periods, higher flush production in initial years, and number of wells actually producing. However, using the available data, the average Huntersville Chert/Oriskany Sandstone well has been in production 29.5 years, producing an average of 36,280 MMcf per year.

Briggs and Tatlock (1983) point out that once terrain, culture, and less optimal structural conditions are considered, only 3 percent of a given area will be productive from the Huntersville Chert/Oriskany Sandstone reservoir. Three percent of the total estimated play area of 11,800,000 acres equals 354,000 acres. Average spacing of producing wells in this play is 135 acres. Applying this 135-acre spacing scheme to the possible 354,000 drillable acres yields approximately 2,600 well locations. Optimistically assuming that each well will produce about 36 MMcf per year for about 30 years calculates to 2.8 tcf of recoverable resources. Since more than 650 bcf have already been produced, approximately 2.15 tcf might remain.

Future Trends

Searching for new production from a Huntersville Chert/Oriskany Sandstone reservoir involves pursuing small anticlinal upthrust fault blocks with structural closure. Fracture porosity is an essential ingredient, as proven by previous exploration. Deeper seated fractures may supply gas from deeper sources, and thereby recharge reservoirs. Isopach, structure mapping and sample study help to further define the target.

Well sites in this play are typically selected based on interpretations of seismic lines run over the surface in a prospective area. Wells such as the No. 1 Carbon Fuel Resources Unit in Fayette County, Pennsylvania (Figure Dho-2), drilled by R.E. Fox and Associates, Inc. in October 1993, show the results of optimal placement with respect to fractures, structure, and lithology. This well was located on the western flank of the Chestnut Ridge anticline, approximately 8,000 feet west of the South Summit pool of Summit field. Drilling through the Huntersville Chert/Oriskany Sandstone at 7,120 feet resulted in a natural open flow of 72 MMcf from gas-filled fractures intersected by the well bore. Similar small, isolated, untested fault blocks occur along the flanks of the anticlines in southwestern Pennsylvania, northern West Virginia, and western Maryland.

Aside from the more traditional defined structure prospects, less tested exploration possibilities exist along the edges of the present chert play. The northern and western edges of the play boundary, where the chert facies gradually alters to include limestone and more porous sediments, should be considered for gas potential. Shows of natural gas have been observed and recorded in the Huntersville Chert along the western edge of the play outline (Figure Dho-20). Drillers' records indicate that the lithology consists of chert and cherty limestone. Quantities of natural gas reported varied between ungauged shows of gas and 1 MMcfg/d from the combined chert and Oriskany sandstone after treatment.

Depleted fields and pools may be considered for gas storage purposes. The typical structurally closed, isolated blocks serve as good storage reservoirs. North Summit and Terra Alta fields have been successfully converted to underground gas storage.

PLAY Dos: LOWER DEVONIAN ORISKANY SANDSTONE STRUCTURAL PLAY

by John A. Harper, Pennsylvania Bureau of Topographic and Geologic Survey, and Douglas G. Patchen, West Virginia Geological and Economic Survey

Location

The Lower Devonian Oriskany Sandstone structural traps play consists of a large number of fields and pools occurring from central New York to northeastern West Virginia (Figures Dos-1, Dos-2). Most of the producing areas are situated on anticlines within 50 miles west of the Allegheny structural front, but some very important production has occurred in fields within the Wills Mountain anticlinorium and Broad Top synclinorium, the first two regional-scale structures east of the front.

Production History

The first well to produce from the Oriskany structural traps play, the Belmont Quadrangle Drilling Corporation No. 1 Pulver well in Tyrone Township, Schuyler County, New York, ushered in what was to become the most important phase of exploration and development in the Appalachian basin during the middle of the twentieth century. This well, which discovered the Wayne-Dundee field (Figure Dos-2), was completed in March 1930 with an open flow of 5,750 Mcfg/d from the Oriskany at 2,075 feet (Torrey, 1931). Subsequent drilling for Oriskany targets throughout the basin resulted in the discovery of four fields before the end of 1930 in areas as widely separated as Tioga County, Pennsylvania, and Kanawha County, West Virginia.

The discovery of Wayne-Dundee field resulted from mapping surface structures and projecting them within the subsurface. This utilization of the "anticlinal theory" led to numerous programs to map the surface structures of the Allegheny Plateau in New York, Pennsylvania, and West Virginia. Surface mapping, although still important in many aspects, eventually gave way in the 1950s to seismic survey data as the primary exploratory tool. Surface mapping could not be used effectively for comprehending the structural complexities involved in Oriskany gas accumulations throughout the Appalachian Plateau Province.

It soon became apparent in the central Appalachian Plateau Province that the overlying Huntersville Chert was as least as important a gas reservoir as the Oriskany. Thus, most of the Oriskany structural reservoirs in the central plateau have been assigned to the fractured Middle Devonian Huntersville Chert and Lower Devonian Oriskany Sandstone play (K. Flaherty, this atlas).

A combination of great geographic extent, diverse trap types, high production rates, and quick payouts (Owen, 1975) made the Oriskany structural play the most important exploratory and development play in the Appalachian basin between 1930 and 1960. During this period, thousands of Oriskany wells were drilled, establishing stratigraphic limits, sandstone thickness variations, and degrees of structural intensity. Industry produced hundreds of billions of cubic feet of gas from this single play. In Pennsylvania, where figures are readily available, more than 1,900 Oriskany and Huntersville wells had been drilled and had produced approximately 1 tcfg by 1960 (Kelley and others, 1970); production from 692 wells in the Oriskany structural traps play accounted for about 655 bcf of that total (Lytle and others, 1961). The largest initial open flow from the Oriskany in the basin, from the New York State Natural Gas Corp. No. 1 Finnefrock well in Leidy field, Clinton County, Pennsylvania, was gauged at 145,000 Mcfg/d when the well was drilled in 1951. Another well in Leidy field, the New York State Natural Gas No. 1 Pennsylvania Tract 45, caught fire with an initial open flow originally estimated at between 150,000 and 200,000 Mcfg/d. When the fire was extinguished, the well was gauged officially at 124,000 Mcfg/d.

Between 1960 and 1990, drilling of Oriskany (and Huntersville) wells decreased because of high costs and high risk, dwindling markets, and a ready supply of gas from shallower reservoirs. Despite this decrease, operators discovered almost as many producing fields and pools in the Lower Devonian Oriskany structural play between 1960 and 1990 as during the previous 30 years. Many of these later fields are very small by comparison with earlier ones. They typically consisted of fewer than 10 producing gas wells situated on one or more small fault blocks. Even the higher gas prices available to operators following passage of the Natural Gas Policy Act of 1978 could not stimulate significantly increased Oriskany drilling activity.

Stratigraphy

The Oriskany Sandstone structural play includes all quartzose sandstones reservoirs (Figure Dos-3) of Deerparkian (late Early Devonian) age. The "Oriskany" of drillers' terminology actually encompasses several distinct stratigraphic units in the Appalachian basin (Heyman, 1977), including: the "true" Oriskany Sandstone of New York, northwestern Pennsylvania, eastern Ohio, and Virginia and West Virginia; the Ridgeley Sandstone of Pennsylvania and Maryland, which may or may not be identical to the type Oriskany; the Palmerton Formation, a sandstone in eastern Pennsylvania that is equivalent to a portion of the basal Onondaga Limestone (Sevon, 1968); and the Springvale Sandstone, a basal sandstone member or sandy facies of the overlying Bois Blanc Formation in Ontario, northeastern Ohio, and northwestern Pennsylvania (Oliver, 1967). The Palmerton Formation has not yet been exploited as a gas play and, therefore, will not be discussed here. The Springvale Sandstone is an important gas reservoir in northeastern Ohio and northwestern Pennsylvania, especially in pockets where the underlying Oriskany is absent or water bearing. The Lower Devonian sandstones in this general area fall within the Lower Devonian Oriskany Sandstone updip permeability pinchout play (see S. Opritza, this atlas).

The name Oriskany Sandstone was first used by Vanuxem (1839) for outcrops of a pure, white, fossiliferous, quartz arenite on the hillsides above the town of Oriskany Falls, Oneida County, New York. The Oriskany often contains

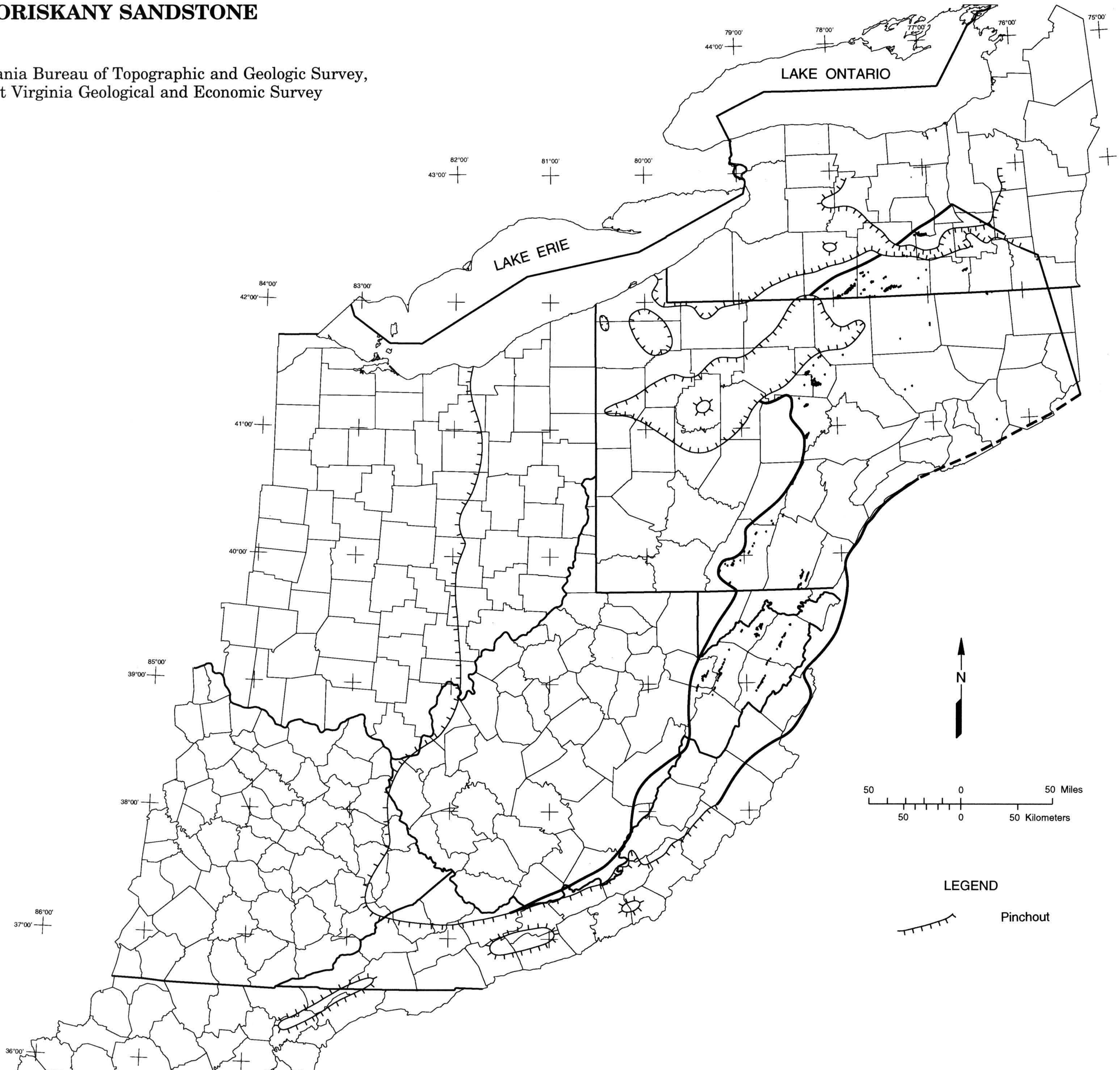


Figure Dos-1. Outline of the Lower Devonian Oriskany structural traps play within the Appalachian basin. Dots represent individual gas wells; areas where dots have merged represent fields.

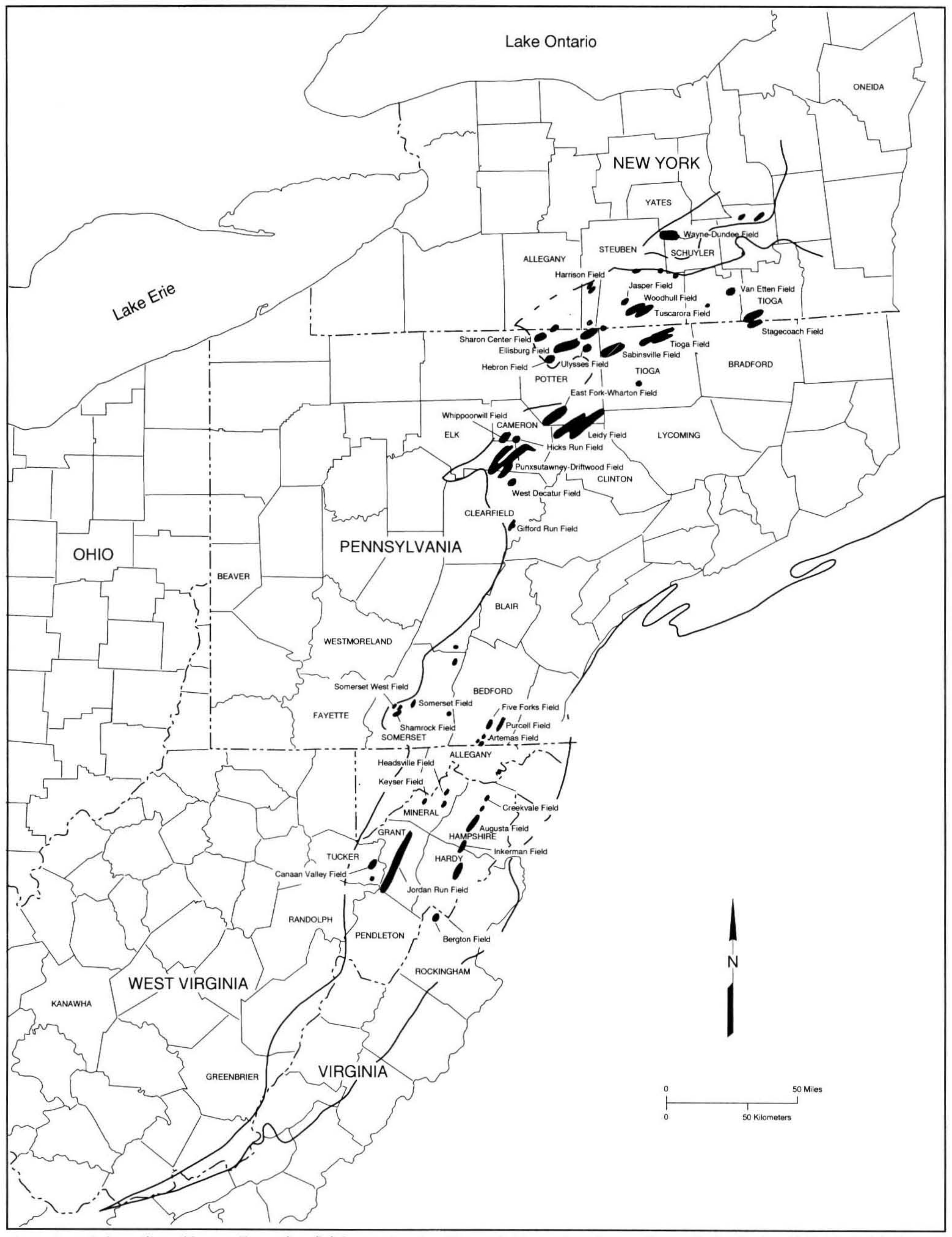


Figure Dos-2. Location of Lower Devonian Oriskany structural traps fields and pools mentioned in the text or listed in Table Dos-1.

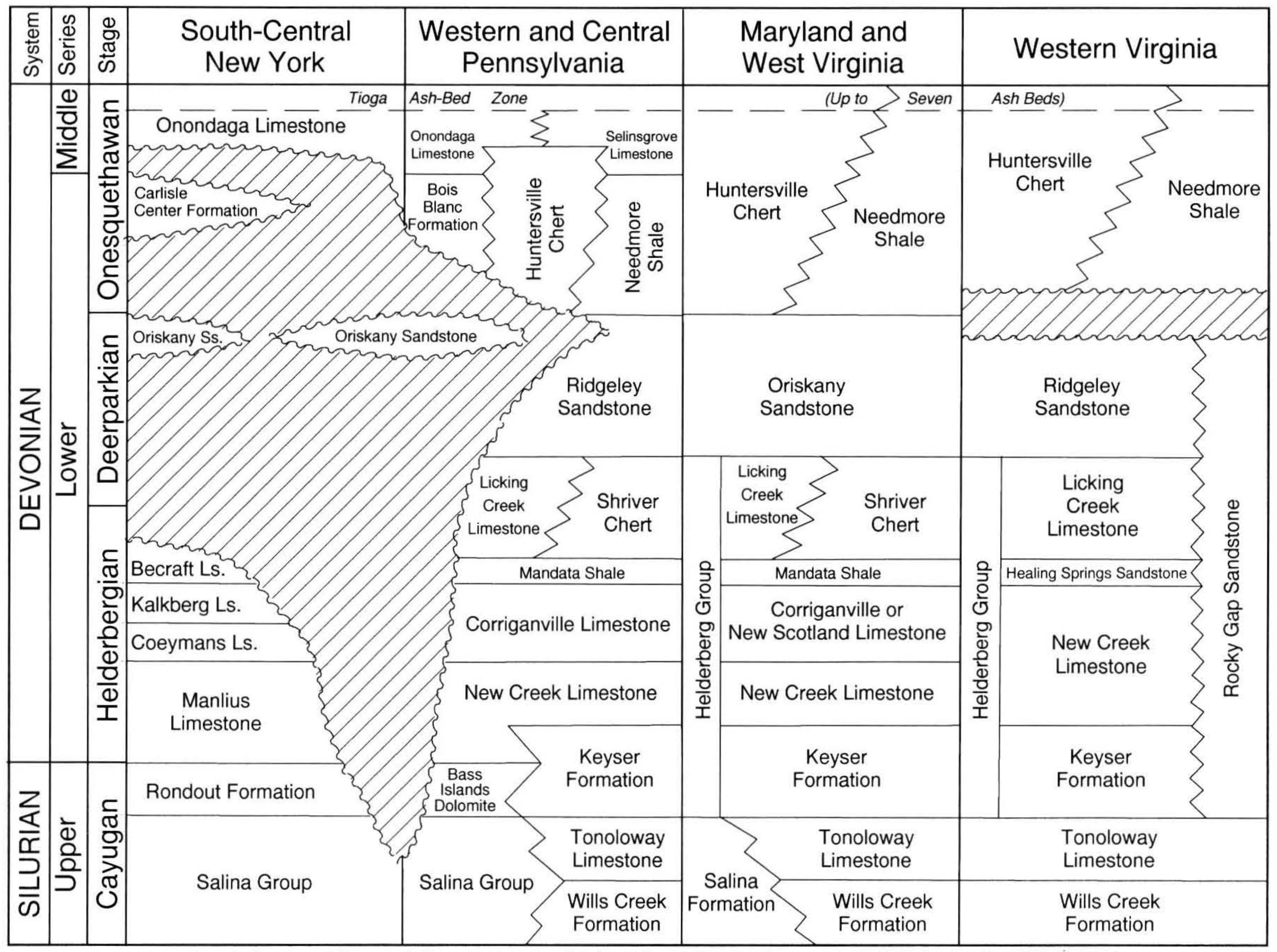


Figure Dos-3. Stratigraphic correlation chart of the Oriskany Sandstone and associated strata in the Appalachian basin.

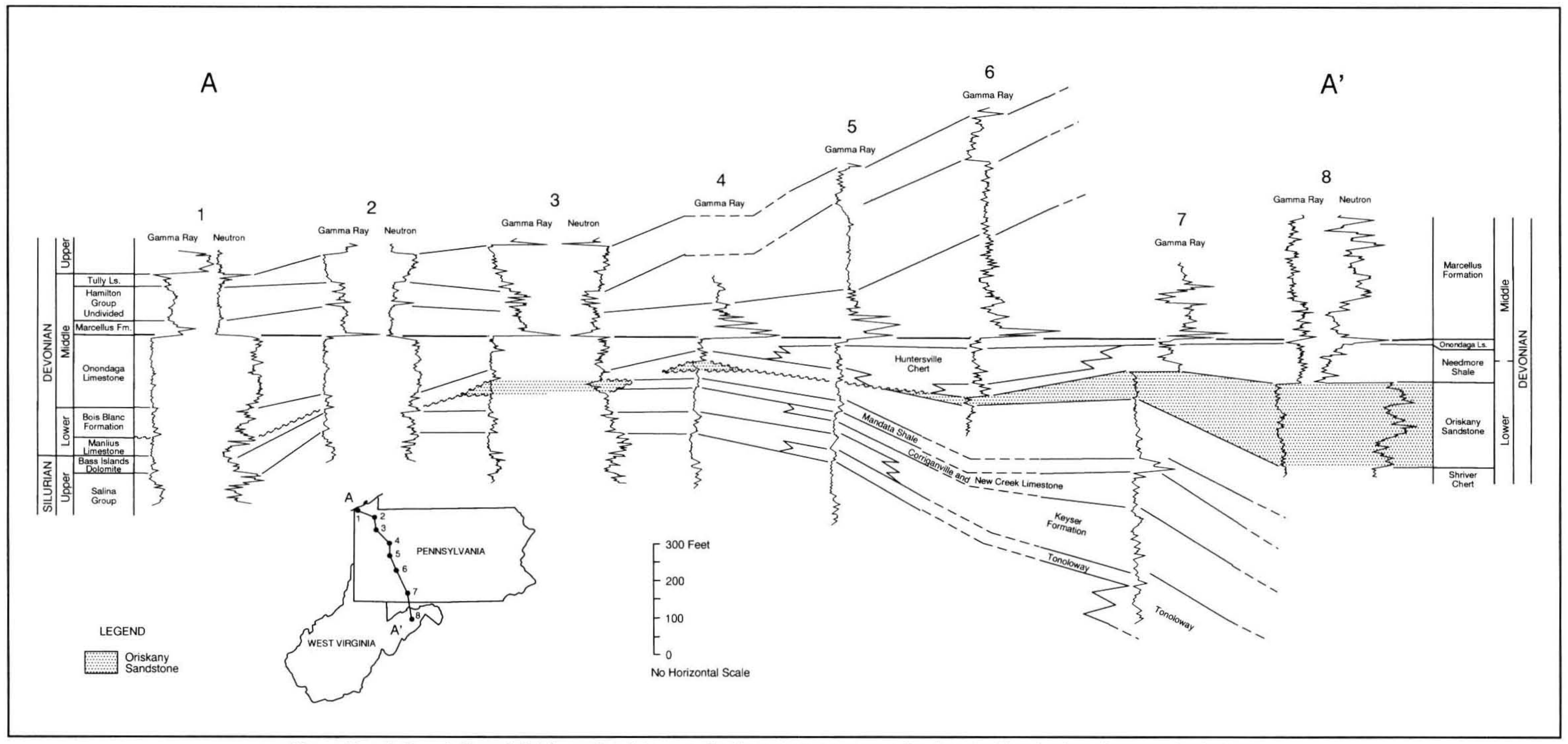


Figure Dos-4. Correlation of Oriskany Sandstone and adjacent strata across the Appalachian basin using geophysical logs.

an abundant, relatively robust faunal assemblage, and early stratigraphers relied on these fossils in correlating the Oriskany and other formations. Because the fauna of the Oriskany Sandstone was also found to exist in the underlying siliceous shales and cherts of Maryland, Pennsylvania, Virginia, and West Virginia, the Oriskany was elevated to group status. Swartz (1913) named the upper sandstone portion of the group Ridgeley, for exposures at Ridgeley, Mineral County, West Virginia; the lower portion was termed Shriver from Shriver Ridge near Cumberland, Maryland. The Shriver since has been relegated to the underlying strata of the Helderberg Group, but Ridgeley still is used in numerous places throughout the central Appalachians, and it is preferred in Maryland and central Pennsylvania. The stratigraphic relationship of the Oriskany Sandstone to other Lower Devonian formations within the Appalachian basin is shown in Figures Dos-3 and Dos-4.

Whether the typical Oriskany Sandstone and typical Ridgeley Sandstone are identical remains to be determined. Although it is clear that they are lithologically similar and biostratigraphically equivalent, differences in composition, reflecting sediment input from different provenances (Stow, 1938), and complexities in regional depositional and/or erosional architecture preclude the immediate recognition of these formations as being lithostratigraphically identical. For this report, the name Oriskany is used to avoid nomenclatural confusion, and because this is the name most often used in the oil and gas industry.

The Oriskany Sandstone is composed primarily of quartz arenite, but variations, primarily in the amount of carbonate cement, occur both laterally and vertically within the formation. In many areas, the formation contains so much carbonate, both as framework grains and as cement, that the rock is classified as an arenaceous limestone. In the northern part of the basin, in central New York and north-central Pennsylvania, the Oriskany commonly occurs as two lithofacies. The upper lithofacies has a slightly larger grain size and less carbonate cement than the lower (Finn, 1949). Throughout most of western and central Pennsylvania, clean quartz arenites predominate. In south-central Pennsylvania, and into Maryland, Virginia, and West Virginia, the rock varies greatly in texture and composition, ranging from extremely fine-grained arenaceous limestone to coarsely conglomeratic quartz arenite (Swartz, 1913; Cleaves, 1939; Woodward, 1943). In Somerset County, Pennsylvania, for example, the Oriskany includes as many as three vertically stacked, but horizontally discontinuous, sequences of quartz arenite separated by thick sequences of arenaceous and "argillaceous" limestone (Welsh, 1984) (Figure Dos-5). The conglomeratic element varies also, from conglomeratic sandstone to mere pebble beds, but it may occur as much as 50 percent of total formation composition.

The quartz arenites typically consist of well-rounded, well-sorted, medium-grained, mostly monocrystalline quartz (Basan and others, 1980; Foreman and Anderhalt, 1986), representing an average of 95 percent of the detrital fraction (Laughrey, 1995a). The limestones consist primarily of bioclastic calcarenites containing an average of 50 percent brachiopod valve fragments, echinoderm plates, ostracodes, bryozoan and coral debris, and trilobites plus micrite and carbonate cement. The quartz sand in these latter rocks typically is subangular and ranges in size from coarse silt to fine sand. Calcareous sandstones, a hybrid of detrital quartz and detrital carbonate, typically consist of fine- to very fine-grained quartz, feldspar and chert, fossil-shell debris, and calcite cement with varying amounts of argillaceous and organic materials (Laughrey, 1995a). Conglomerates consist of subangular to well-rounded, sometimes frosted, white quartz pebbles less than 0.5-inch in diameter (Cleaves, 1939; Woodward, 1943). Black chert pebbles, possibly derived from the underlying Helderberg carbonates or even some older source, are common in some areas. Undifferentiated clays and lithic grains comprising mostly mudstone clasts, dark-colored limestone, and chert constitute the remaining major components (Foreman and Anderhalt, 1986). Minor detrital components include feldspars, zircon, tourmaline, mica, rutile, leucoxene, opaque oxide minerals, and polycrystalline quartz derived from igneous or metamorphic rocks. Authigenic minerals include illite, chlorite, vermicular kaolinite, "glauconite" (actually, a group of greenish clay minerals of varying composition), sphalerite, and pyrite (Martens, 1939; Basan and others, 1980; Foreman and Anderhalt, 1986; Laughrey, 1995a).

The most common cements in the Oriskany Sandstone are silica and calcite with minor pyrite, dolomite, ankerite, "glauconite," and chalcedony (Basan and others, 1980). Silica cements occur mostly as syntaxial overgrowths on detrital quartz grains, or as chalcedony replacing carbonates. Carbonate cements include nonferroan and ferroan calcite, nonferroan and ferroan dolomite, and ankerite (Foreman and Anderhalt, 1986). Silica cements comprise up to 15 percent of the bulk mineralogy, whereas carbonate cements may account for fully 50 percent (Wood, 1960; Laughrey, 1995a). Authigenic clays occurring as pore-filling material, grain coats, and feldspar-alteration products make up less than 10 percent. Pyrite occurs as authigenic crystals, and "glauconite" represents micaceous aggregates that fill some void spaces (Laughrey, 1995a). The fabric of the Oriskany sandstone typically is grain supported, but in some examples where carbonate cement is well developed, the grains float in sparry calcite.

Foreman (1986; Foreman and Anderhalt, 1986) summarized the diagenetic history of the Oriskany from two cores in Fayette and Somerset counties, Pennsylvania. The early burial phase included the development of syntaxial quartz overgrowths and microcrystalline quartz, syntaxial calcite overgrowths, and minor pyrite cement. During maximum burial nonferroan sparry calcite developed, followed by nonferroan microcrystalline dolomite. Late-stage cement formation, which occurred during fracturing and uplift, included the development of megaquartz, chalcedony, both nonferroan and ferroan calcite, and both nonferroan and ferroan dolomite.

The Oriskany Sandstone represents a major change in deposition from the Late Silurian and earliest Devonian when predominant carbonate and evaporite sedimentation characterized the Appalachian basin. Marine transgressions and regressions slowly affected the basin at the beginning of the Devonian. Water depth variations occurred on a relatively small scale, however, resulting in minor clastic input and fluctuations between shallow and somewhat deeper water carbonate environments. The Early Devonian ended with a worldwide regression that resulted in erosion throughout much of North America (the Wallbridge discontinuity of Wheeler, 1963). Evidence for this discontinuity in the Appalachians exists as an unconformity between the Late Silurian/Early Devonian and Middle Devonian carbonate rock sequences at the basin margins. Wheeler (1963) posited the Oriskany was a basal sandstone deposited on a basin-wide unconformity. Heyman (1977) noted, however, that the Oriskany in a core from north-central Pennsylvania rested conformably on soft-sediment deformation features in the underlying Helderberg rocks. Bruner (1988) described the transitional nature between the Oriskany and Helderberg in a core from Greenbrier County, West Virginia. Both of these studies help to support the concept of Dennison and Head (1975) that deposition within the basin center probably continued, uninterrupted, from Late Ordovician through Early Mississippian. Erosion following Oriskany deposition might have been more extensive than pre-Oriskany erosion; there are large areas of the basin where the Oriskany is thin or absent, for example, the "Oriskany no sand area" in northwestern Pennsylvania (see the large hachured area in Figure Dos-1). It is likely, however, that such areas occur because of lack of deposition on positive paleotopography.

Most authors agree that the Oriskany represents deposition in a marine environment. Early workers, such as Swartz (1913), proposed a high-energy beachface environment for the Oriskany in the Valley and Ridge; this was supported later by fossil studies (Seilacher, 1968). Other authors have suggested near-shore, shallow water (Stow, 1938), tidal ridges and submarine dunes (Basan and others, 1980), shallow to deeper subtidal (Barrett and Isaacson, 1981), and marine shelf bar (Welsh, 1984; Bruner, 1988) environments. As Basan and others (1980) pointed out, even within a single outcrop or well location the Oriskany can represent either single or multiple depositional environments.

Although the character of the sand grains in the Oriskany indicate a mature, multicycled sediment, the specific origin of the Oriskany sand deposits remains unsettled. Many authors, such as Dennison (1961), suggested the Oriskany originated to the southeast and spread northwestward across the basin. Stow (1938), however, determined from petrologic studies of outcrop samples that only the Oriskany in the central Appalachians (northeastern Pennsylvania to southeastern West Virginia) was derived from older sedimentary deposits in the southeast. The Oriskany of New York was derived directly from crystalline rocks in the Adirondacks. Basan and others (1980) studied cores and outcrops throughout the basin and determined that the Oriskany is very different in numerous areas. They suggested three possible source areas for the Oriskany, including the Adirondacks, the emergent landmass on the southeastern margin of the basin, and an emergent landmass in east-central Pennsylvania or New Jersey. This latter provenance has been suggested because of the relative abundance in eastern Pennsylvania exposures of polycrystalline quartz derived originally from a metamorphic source.

Structure

The Lower Devonian Oriskany Sandstone structural traps play consists of several subplays that can be distinguished on the basis of structural type and the presence or absence of subsidiary stratigraphic trapping mechanisms. These subplays have been segregated geographically (Figure Dos-6). The easternmost, Valley and Ridge subplay, consisting of multiple, east-dipping thrust sheets (duplexes), is situated within the Wills Mountain anticlinorium and Broadtop synclinorium of the Valley and Ridge physiographic province in south-central Pennsylvania, west-central Maryland, eastern West Virginia, and northwestern Virginia (Figure Dos-6). To the west and north, in the Appalachian Plateau subplay, productive Oriskany fields occur as a result of complex structures originating through detachment in incompetent Silurian salt beds and, perhaps, Ordovician shales. The third subplay, a combination structure/pinchout subplay, occurs adjacent to the Oriskany pinchout in north-central Pennsylvania and south-central New York. This subplay consists primarily of Silurian salt-cored structural traps that have subsidiary control of production due to updip decrease in sandstone thickness toward the pinchout areas. Stratigraphic traps result from a combination of the sandstone wedging out between impermeable layers and updip loss of porosity enhancement. In all three subplays, extensive fracturing of the reservoir rocks, a common and important occurrence, enhances storage and deliverability of natural gas. Basilone (1984), in a study of the origin and implication of fluid inclusions from filled fractures in the Oriskany, determined that the fractures opened at great depth (22,000 feet in Somerset County, Pennsylvania) and remained open through a long episode of uplift.

Valley and Ridge subplay: The Wills Mountain anticlinorium and Broadtop synclinorium are large regional structures about 15 or 20 miles wide extending 250 miles or more from central Pennsylvania to southern Virginia in the western part of the Valley and Ridge Province (Jacobeen and Kanes, 1974; 1975) (Figure Dos-6). Surface structures in this area consist of numerous doubly plunging, possibly *en echelon*, folds commonly less than 10 miles long. Large-scale, low-angle thrust faults characterize this subplay, but some high-angle faults also have been identified by detailed mapping. In the subsurface, these structures are far more complex, however, consisting of a series of imbricate thrust sheets branching from a decollement typically based in the incompetent

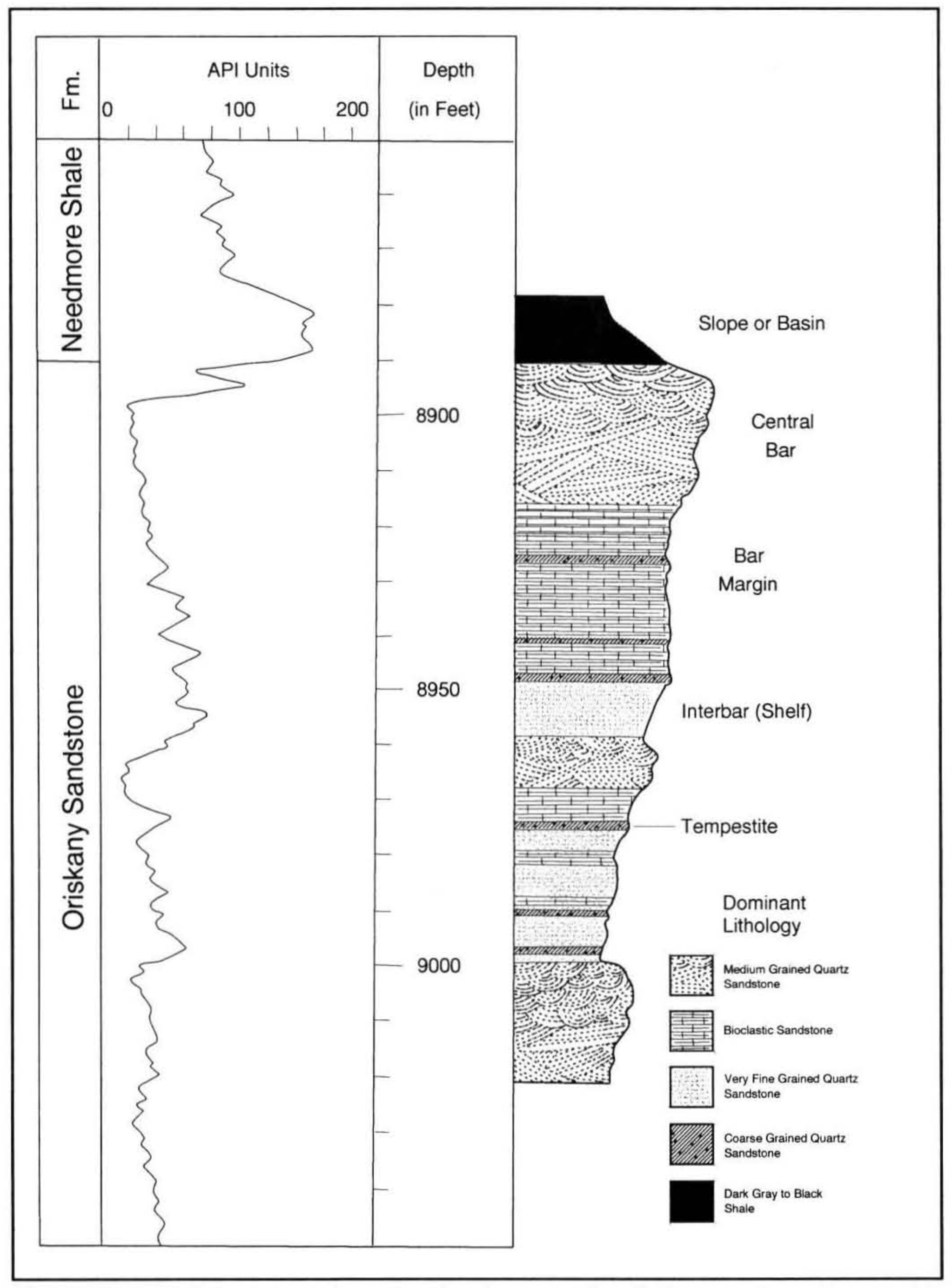


Figure Dos-5. Gamma-ray log, graphical core description, and environmental interpretation of the Lower Devonian Oriskany Sandstone in the Amoco Production Co. No. 1 Romesburg well. Modified from Welsh (1984).

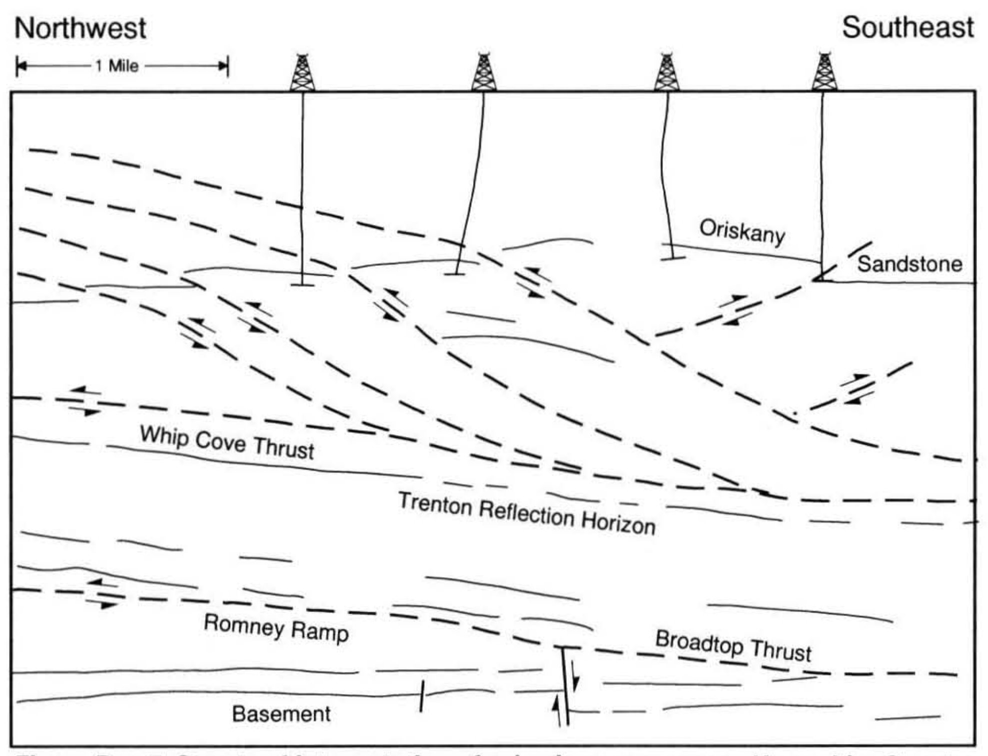


Figure Dos-7. Structural interpretation of seismic survey across Hampshire County, West Virginia. Modified from Jacobeen and Kanes (1975). Detachment within the Upper Ordovician shales created splay thrust faults within the overlying Lower Silurian through Devonian section.

shales of the Upper Ordovician Martinsburg Formation (Gwinn, 1964; Jacobeen and Kanes, 1974; 1975; Mitra, 1986; 1988) (Figure Dos-7).

The gas fields in this subplay are situated on thrust-faulted anticlines that generally parallel the regional structural grain (striking approximately 30°E). At the depth of the Oriskany Sandstone (about 4,500 feet in Bedford County, Pennsylvania, deepening to about 6,500 feet in Hardy County, West Virginia), the splay faults are considerably steeper than they are at the surface, about 60 degrees or more (Wagner *in* Lytle and others, 1966). Wells commonly intersect at least one thrust fault, and sometimes as many as six. Strata dip at moderate to steep angles, and early drilling in this play was difficult due to updip drift of the drill holes. According to Wagner (*in* Lytle and others, 1966), gas well drillers followed the lead of water well drillers who purposely moved their well locations an average of 500 to 700 feet downdip of the anticipated location at total depth in order to compensate for this drift of the bore hole (for example, the middle two

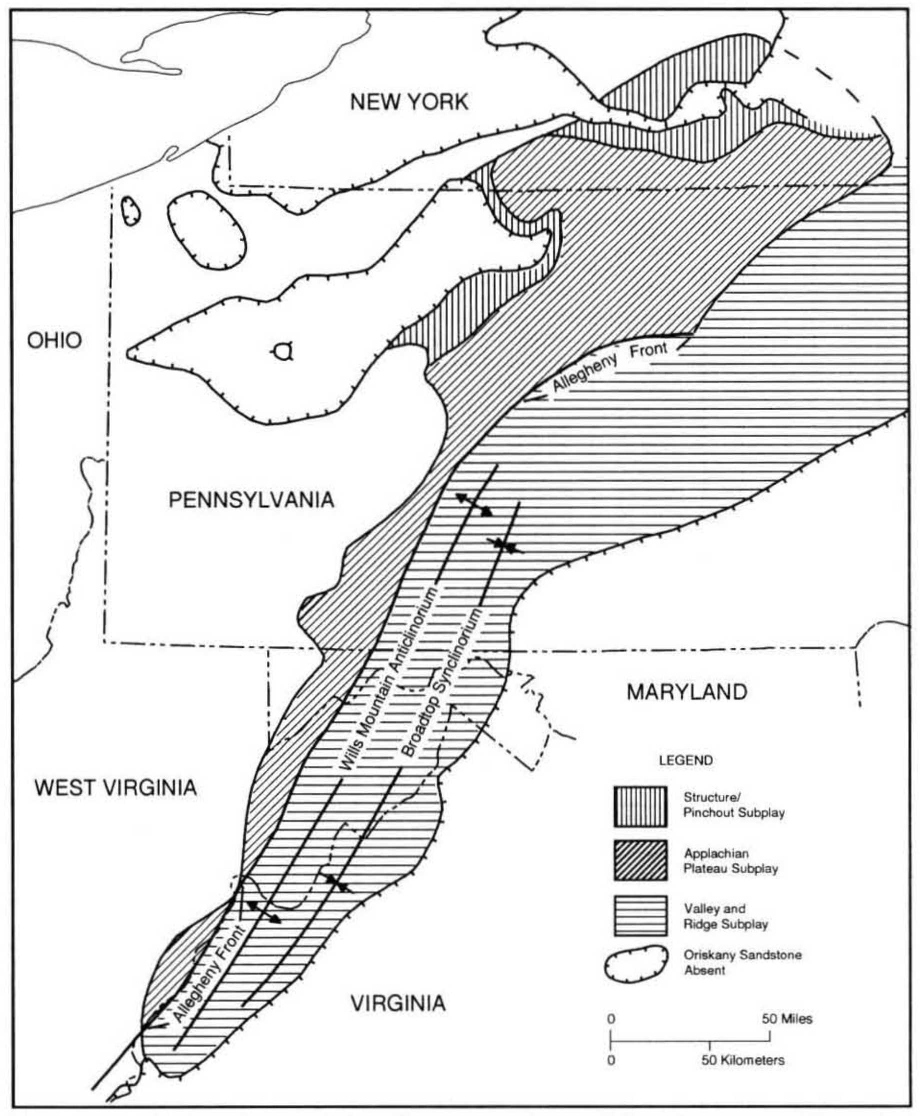


Figure Dos-6. Locations of the three subplays within the Lower Devonian Oriskany structural traps play.

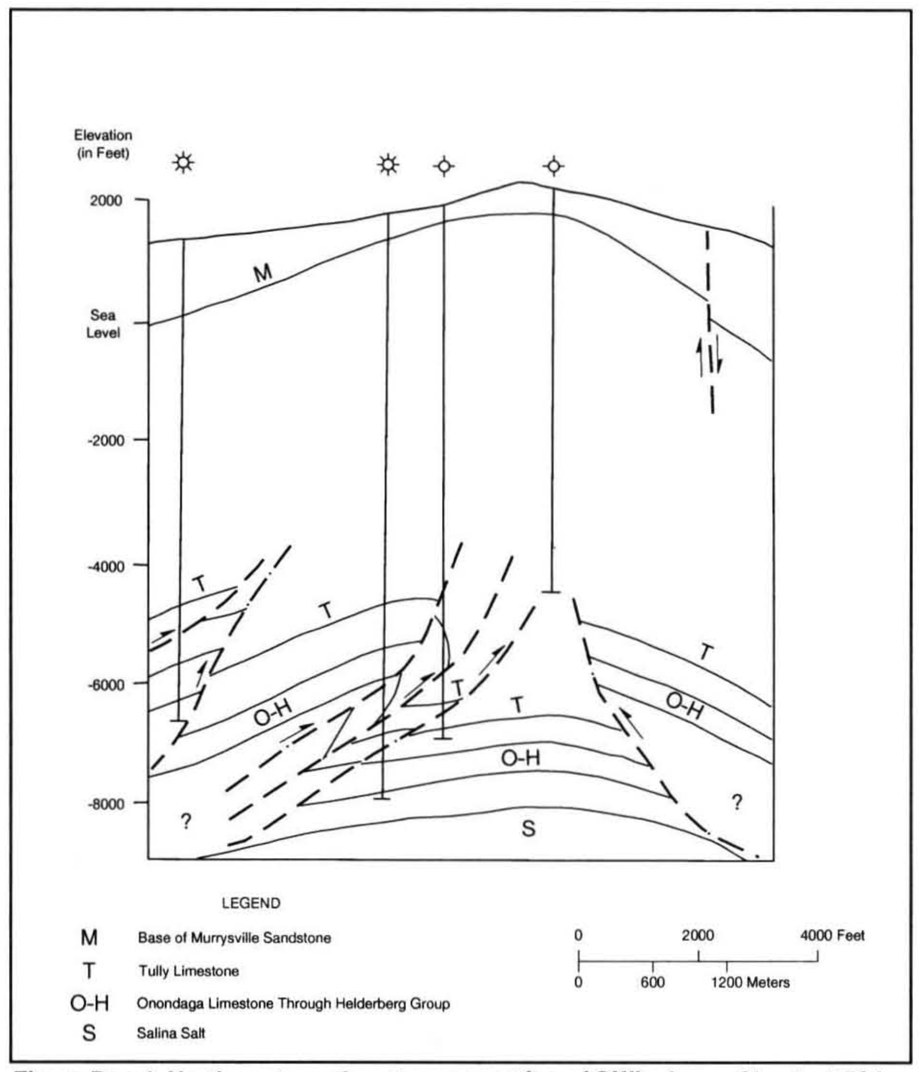


Figure Dos-8. Northwest-southeast cross section of Giffin dome, Chestnut Ridge anticline, in Westmoreland County, Pennsylvania. From Gwinn (1964). Imbricate sheets were thrust over the depressed core as a result of detachment in the Upper Silurian Salina salt beds.

wells in Figure Dos-7).

Appalachian Plateau subplay: Most of the Oriskany gas production in the Appalachian basin, including that associated with production from the overlying Huntersville Chert, results from structural traps associated with thrust faults generated by the flow of incompetent rocks within the Upper Silurian Salina Group and its correlatives, or within the Upper Ordovician Martinsburg Formation. Although plastic deformation of salt and shale was suspected early in the development of plateau fields (Fettke, 1933; Finn, 1949), it was not until the early 1960s that the concept and its mechanics were documented (Rodgers, 1963; Gwinn, 1964).

Plateau structures at the level of the Oriskany Sandstone typically consist of imbricate sheets thrust over seemingly depressed cores at or near the structural axes (Figure Dos-8). These anticlines commonly exhibit asymmetry resulting from one limb being steeper than the other. In most of the plateau structures, the southeastern limbs are shorter and steeper; however, the northwestern limbs are steeper and commonly overturned in structures nearer the Allegheny front (Gwinn, 1964). Flexure (subsidiary anticlines and homoclines) may be present on the thrust sheets as a result of drag. In Leidy field in Clinton and Potter counties, Pennsylvania, closure on these flexures ranges from less than 100 to more than 300 feet (Harper, 1990). In some portions of the anticlines, the southeastern splay faults may be absent, but these are atypical of the structures as a whole. Domes that are mappable at the surface typically indicate intensification of subsurface thrusting, whereas saddles represent the boundaries between adjacent thrust sheets, possibly offset along tear faults within the zone of deformation.

Structure/Pinchout subplay: This subplay is identical to the Appalachian Plateau subplay with the exception of subsidiary trapping due to regional pinchout and diagenetic changes in the sandstone in association with the pinchout areas of northwestern Pennsylvania and south-central New York (Figure Dos-6).

Oriskany thicknesses vary throughout the Appalachian Plateau, but adjacent to the pinchout areas the reservoir sandstone typically averages 30 feet thick (Finn, 1949; Abel and Heyman, 1981). The sandstone thins to 0 feet against the pinchout areas, forming a thin wedge of sandstone between relatively impermeable Lower and Middle Devonian carbonates and shales. Porosity enhancement in the upper few feet of the Oriskany, typically occurring as a result of late-stage dissolution of carbonate and silica cements, is very important in the more northwesterly Oriskany structural trap reservoirs (Figure Dos-2). In the structure/pinchout subplay, however, porosity decreases updip both in quality and distribution within the reservoir rock, until the effective porosity essentially is nil (Heyman, 1969). This effect is important even in fields where structural deformation is as important as, or less important than, stratigraphic pinchout.

Reservoir

Structural trapping mechanisms constitute the predominant controls of gas production from all fields within this play (Table Dos-1). The combination of structural flexure, creating subsidiary anticlines associated with drag on thrust sheets, and intense fracturing is very important throughout most of the area of the play. Structural intensity increases to the east and southeast; therefore, the development of important fracture porosity increases toward the eastern plateau and into the Valley and Ridge (Diecchio, 1985). In fact, fracturing and structural flexure appear to be the only trapping mechanisms in many, if not all, of the fields in the Valley and Ridge subplay (Young and Harnsberger, 1955; Patchen, 1968b).

Subsidiary stratigraphic trapping in the Oriskany results from both thinning of the sandstone toward the pinchout areas and development of intergranular porosity. In the areas adjacent to the pinchout areas, sandstone thickness typically decreases from 30 feet to 0 feet. By thinning to 0 feet against the pinchout areas, the Oriskany forms a wedge of sandstone sandwiched between relatively impermeable rocks above and below.

Intergranular porosity also plays a subsidiary but important role in gas entrapment in the Oriskany. The importance of local dissolution of carbonate and feldspar grains has been documented in the highly fractured Oriskany fields of Somerset County, Pennsylvania (Sanders, 1982), the salt-cored Oriskany structures present in north-central Pennsylvania (Harper, 1990), and in the Oriskany structural fields adjacent to the pinchout areas. Using cores, logs, and production data, Sanders (1982) determined that fracture porosity, although important in reservoir deliverability, provided little reservoir capacity and, therefore, was insufficient by itself in providing suitable economics.

Geochemical analyses of natural gases from the Oriskany Sandstone in western Pennsylvania indicate that, in general, these gases originated from Middle and Upper Devonian organic-rich shales (C. D. Laughrey, oral commun., 1993). The Middle Devonian Marcellus Formation probably constitutes the most important single sequence of source rocks in the Appalachian basin (Laughrey, 1995b). However, the Middle Devonian Needmore Shale, which lies immediately above the Oriskany in the eastern plateau and Valley and Ridge, probably contributed minor to moderate amounts of hydrocarbons to Oriskany reservoirs throughout the area. For example, total organic carbon (TOC) in the Marcellus Formation in the Amoco Production Co. No. 1 Svetz well in Somerset County, Pennsylvania, ranges from 1.5 to 3.4 percent, whereas TOC in the Needmore Shale ranges from 1.3 to 1.7 percent (Laughrey, 1995b). Figure Dos-9 shows the TOC measurements in Upper Devonian through Upper Silurian rocks from two wells in western Pennsylvania.

Although the source rocks lie stratigraphically above the Oriskany, it is likely that fluids migrated downsection through open fractures as well as updip from the deeper parts of the basin. Fracturing in the Appalachian Plateau and structure/pinchout subplays must have occurred soon after deposition of the Oriskany owing to early (probably Middle Devonian) movement of Salina evaporites (Piotrowski and Harper, 1979). Fracturing followed early-stage diagenetic events, providing conduits for fluid migration into the reservoir, and hydrocarbon emplacement within the Oriskany reservoirs preceded late-stage formation of quartz and ferroan calcite that filled the fractures, thereby trapping the fluids (Basilone, 1984).

The depth of the pay section in the Oriskany Sandstone structural play varies greatly throughout the area of the play. In this play, Oriskany reservoirs along the northern edge of the basin in New York average about 2,000 feet in depth. Drilling depth increases toward the south and southeast so that, in south-central New York and north-central Pennsylvania, the Oriskany commonly lies between 3,000 and 5,000 feet beneath the surface. In west-central Pennsylvania, the average depth is 6,750 feet. In the Valley and Ridge, Oriskany drilling depths average 5,565 feet in Hampshire County, West Virginia, and 5,200 feet in Bedford County, Pennsylvania. Depths may exceed 9,000 feet in central Somerset County, Pennsylvania, and Grant and Mineral counties, West Virginia.

The Oriskany Sandstone ranges from 0 feet at the various pinchout areas to more than 300 feet in northeastern West Virginia (Woodward, 1943). The formation averages about 100 feet thick throughout the basin. Figure Dos-10 shows the thickness of the Deerparkian Stage, which includes the Shriver Chert and equivalent carbonates as well as the Oriskany.

Many operators consider the Oriskany throughout the Appalachian basin to be an overpressured reservoir. Initial reservoir pressures in the Oriskany structural play vary greatly, ranging from 730 to 4,546 psi, averaging 2,549 psi. It is the pressure gradient (ratio of pressure to depth), rather than absolute

TABLE Dos-1		Jasper NY	Tuscarora NY	Van Etten NY	Wayne-Dundee NY	Woodhull NY	Artemas PA	East Fork-Wharton PA	Ellisburg PA	Five Forks PA
BASIC RESERVOIR DATA	POOL NUMBER	355393	722702	733131	752910	777445	26747	8117	220996	243009
	DISCOVERED	1939	1944	1962	1930	1937	1963	1933	1933	1962
	DEPTH TO TOP RESERVOIR	3,975	3,859	3,356	1,882	3,978	5,115	6,024	5,175	5,792
	AGE OF RESERVOIR	Early Devonian	Early Devonian	Early Devonian	Early Devonian	Early Devonian	Early Devonian	Early Devonian	Early Devonian	Early Devonian
	FORMATION	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany
	PRODUCING RESERVOIR	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany
	LITHOLOGY	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone
	TRAP TYPE	fracture/ structure	fracture/ structure	fracture/ structurefractur structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure
	DEPOSITIONAL ENVIRONMENT	nearshore	nearshore	nearshore	nearshore	nearshore	nearshore	nearshore	nearshore	nearshore
	DISCOVERY WELL IP (Mcf)		9,000	3,355	5,750	1,700	7,312	50	13,000	10,504
	DRIVE MECHANISM	gas/water	gas/water	gas/water	gas/water	gas/water	gas/water	gas/water	gas/water	gas/water
	NO. PRODUCING WELLS	5	6	3	136	19	6	40	47	9
	NO. ABANDONED WELLS	13	5	5	18	10	5	10	17	1
	AREA (acreage)	250	4,848	350	12,750	15,900	2,300	5,800	3,550	4,000
	OLDEST FORMATION PENETRATED	Oriskany	Oriskany	Oriskany	Medina	Oswego	Helderberg	Helderberg	Helderberg	Helderberg
	EXPECTED HETEROGENEITY DUE TO:	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure
RESERVOIR PARAMETERS	AVERAGE PAY THICKNESS (ft.)	30	11	48	14	17	58	13	11	89
	AVERAGE COMPLETION THICKNESS (ft.)	30	20	48						
	AVERAGE POROSITY--LOG (%)						7.02	7.24	9.87	7.72
	MINIMUM POROSITY--LOG (%)						0.49		1.09	2.91
	MAXIMUM POROSITY--LOG (%)						15.05		13.23	35.67
	NO. DATA POINTS						3		3	2
	POROSITY FEET									
	RESERVOIR TEMPERATURE (°F)						98	125	112	117
	INITIAL RESERVOIR PRESSURE (psi)	2,000	2,010	1,359	730	1,950	1,815	3,600	2,110	2,078
	PRODUCING INTERVAL DEPTHS (ft.)	3,861-4,165	3,608-4,159	3,194-3,479	1,543-2,201	3,602-4,229	4,768-5,574	5,372-6,514	4,891-5,667	5,530-6,689
	PRESENT RESERVOIR PRESSURE (psi) / DATE									
FLUID & GAS PROPERTIES	Rw (Ωm)	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035
	GAS GRAVITY (g/cc)			0.562	0.601		0.56	0.582		
	GAS SATURATION (%)						63		71.5	74.2
	WATER SATURATION (%)						37		28.5	25.8
	COMMINGLED	no	no	no	no	no	no	no	no	no
	ASSOCIATED OR NONASSOCIATED	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated
	Btu/scf			1,022	1,036		1,004	1,037		1,009
VOLUMETRIC DATA	STATUS (producing, abandoned, storage)	storage	storage	producing	storage	storage	storage	storage	storage	storage
	ORIGINAL GAS IN PLACE (Mcf)						29,550,000	43,970,000	96,500,000	113,088,000
	ORIGINAL GAS RESERVES (Mcf)				11,000,000			32,370,000	96,500,000	
	PRODUCTION YEARS	1939-1945	1944-1950	1962-1995	1930-1940		1963-1972	1933-1960	1933-1962	1962-1972
	REPORTED CUMULATIVE PRODUCTION (Mcf)	1,927,873					2,434,000	32,347,000	79,600,000	15,113,000
	NO. WELLS REPORTED									9
	ESTIMATED CUMULATIVE PRODUCTION (Mcf)									
	REMAINING GAS IN PLACE (Mcf)/DATE						27,116,000/ 1972	11,623,000/ 1960	16,900,000/ 1962	97,975,000/ 1972
	REMAINING GAS RESERVES (Mcf)/DATE								16,900,000/ 1962	
	RECOVERY FACTOR (%)						8	74	82	13
	INITIAL OPEN FLOW (Mcf/d)		6,427	242	2,849	8,389	8,373	2,399	18,039	6,822
	FINAL OPEN FLOW (Mcf/d)			2,012			4,848	2,052	95	2,162

TABLE Dos-1		Gifford Run PA	Harrison PA	Hebron PA	Hicks Run PA	Leidy PA	Punxsutawney-Driftwood PA	Purcell PA	Sabinsville PA	Shamrock PA	Sharon Center PA	Somerset PA	Somerset West PA
BASIC RESERVOIR DATA	POOL NUMBER	9604	307691	313512	6217	408747	575168	575199	623108	647475	648002	665277	665370
	DISCOVERED	1983	1934	1931	1956	1950	1951	1957	1935	1979	1938	1964	1978
	DEPTH TO TOP RESERVOIR	7,413	5,019	5,156	6,672	6,021	6537	4,790	4,504	8,823	4,850	8,750	8,830
	AGE OF RESERVOIR	Early Devonian	Early Devonian	Early Devonian	Early Devonian	Early Devonian	Early Devonian	Early Devonian	Early Devonian	Early Devonian	Early Devonian	Early Devonian	Early Devonian
	FORMATION	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany
	PRODUCING RESERVOIR	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany
	LITHOLOGY	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone
	TRAP TYPE	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure
	DEPOSITIONAL ENVIRONMENT	nearshore	nearshore	nearshore	nearshore	nearshore	nearshore	nearshore	nearshore	nearshore	nearshore	nearshore	nearshore
	DISCOVERY WELL IP (Mcf)	1,100	18,000	8,000	1,375	15,000	4,000	1,427	14,000	1,250	18,500	3,800	4,100
	DRIVE MECHANISM	gas/water	gas/water	gas/water	gas/water	gas/water	gas/water	gas/water	gas/water	gas/water	gas/water	gas/water	gas/water
	NO. PRODUCING WELLS	8	30	37	7	146	290	9	22	2	15	2	4
	NO. ABANDONED WELLS	4	9	11	5	86	86	5	3	1	15	2	1
	AREA (acreage)	970	8,200	4,000	1,250	24,120	27,700	1,700	6,800	250	1,333	200	285
	OLDEST FORMATION PENETRATED	Helderberg	Helderberg	Helderberg	Helderberg	Pleasant Hill	Helderberg	Tonoloway	Helderberg	Helderberg	Helderberg	Helderberg	Keyser
	EXPECTED HETEROGENEITY DUE TO:	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure
RESERVOIR PARAMETERS	AVERAGE PAY THICKNESS (ft.)	5	14	10	16	6	8	45	8	61	8	81	136
	AVERAGE COMPLETION THICKNESS (ft.)												
	AVERAGE POROSITY--LOG (%)	6.6	13.49			8.34	5.9	11.32	8	5.53	15.85	8.85	3.94
	MINIMUM POROSITY--LOG (%)	0.5				1.39		1.7	2	3.51	2	0.4	0.62
	MAXIMUM POROSITY--LOG (%)	20.1				>20.00		27.18	14	11.18	56.57	20	6.83
	NO. DATA POINTS	3	3			1		3	3	4	4	2	3
	POROSITY FEET												
	RESERVOIR TEMPERATURE (°F)	125	108			122	161	116	106	156	105	157	144
	INITIAL RESERVOIR PRESSURE (psi)	3,550	2,140	2,110	3,400	4,200	3,925	1,920	2,125	3,400	1,925	3,350	3,961
	PRODUCING INTERVAL DEPTHS (ft.)	7,212-7,526	4,701-5,241	4,871-5,659	6,193-6,815	5,587-6,501	5,790-7,184	4,595-5,082	4,153-5,195	8,712-9,030	4,633-5,126	8,744-8,850	8,676-9,208
	PRESENT RESERVOIR PRESSURE (psi) / DATE												
FLUID & GAS PROPERTIES	Rw (Ωm)	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035
	GAS GRAVITY (g/cc)	0.571		0.655		0.642	0.672						0.565
	GAS SATURATION (%)	59.5	71.3			80	61.4	83.3	80.3	91.1	86.3	55.4	84.6
	WATER SATURATION (%)	40.5	22.7			20	38.6	16.7	19.7	8.9	13.7	44.6	15.4
	COMMINGLED	no	no	no	no	no	no	no	no	no	no	no	no
	ASSOCIATED OR NONASSOCIATED	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated
	Btu/scf	1,030		1,103		1,127	1,023	1,067			1,041		1,015
VOLUMETRIC DATA	STATUS (producing, abandoned, storage)	producing	storage	storage	producing	storage	producing	abandoned	storage	producing	storage	abandoned	producing
	ORIGINAL GAS IN PLACE (Mcf)	7,475,000	69,451,000	49,510,000	4,931,000	180,000,000	258,807,000	37,026,000	36,311,000	24,029,000	12,839,000	6,641,000	13,047,000
	ORIGINAL GAS RESERVES (Mcf)		34,510,000	45,000,000		175,000,000	224,000,000		34,150,000		11,557,000		
	PRODUCTION YEARS	1983-1991	1934-1953	1931-1953	1956-1991	1950-1985	1951-1991	1957-1974	1935-1951	1979-1991	1938-1948	1965-1966	1978-1991
	REPORTED CUMULATIVE PRODUCTION (Mcf)	3,489,000	33,374,000	44,559,000	4,448,000	160,419,000	353,395,000	3,126,000	32,680,000	2,782,000	11,555,000	70,000	2,666,000
	NO. WELLS REPORTED	8	30	37	7	146	290	9	22		15	2	4
	ESTIMATED CUMULATIVE PRODUCTION (Mcf)												
	REMAINING GAS IN PLACE (Mcf)/DATE	4,327,000/ 1991	11,360,000/ 1953	4,951,000/ 1953	493,000/ 1991	19,581,000/ 1985	6,448,000/ 1991	33,900,000/ 1974	3,631,000/ 1951	21,248,000/ 1991	1,284,000/ 1948	6 ,571,000/ 1966	10,360,000/ 1991
	REMAINING GAS RESERVES (Mcf)/DATE			441,000/ 1953		14,581,000/ 1985			1,470,000/ 1951		2,000/ 1948		
	RECOVERY FACTOR (%)	4	48	90	90	89	137	8	90	12	90	1	20
	INITIAL OPEN FLOW (Mcf/d)	138	6,729	13,463	772	12,118	5,541	1,775	8,460	992	16,071	1,353	1,750
	FINAL OPEN FLOW (Mcf/d)	4,783	1,480		967	5,851	2,863	1,306		1,075		1,900	2,190

TABLE Dos-1		Tioga PA	Ulysses PA	West Decatur PA	Whippoorwill PA	Augusta WV	Canaan Valley WV	Creekvale WV	Headsville WV	Jordan Run WV	Keyser WV
BASIC RESERVOIR DATA	POOL NUMBER	709091	727022	184798	7368	47288475	47287475	47349475	47302475	47370475	47365475
	DISCOVERED	1930	1939	1973	1961	1953	1944	1964	1966	1982	1978
	DEPTH TO TOP RESERVOIR	3,960	5,177	8.07	6,679	5,417	8,208	5,401	2,056	8,500	8,530
	AGE OF RESERVOIR	Early Devonian	Early Devonian	Early Devonian	Early Devonian	Early Devonian	Early Devonian	Early Devonian	Early Devonian	Early Devonian	Early Devonian
	FORMATION	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany
	PRODUCING RESERVOIR	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany
	LITHOLOGY	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone
	TRAP TYPE	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure
	DEPOSITIONAL ENVIRONMENT	nearshore	nearshore	nearshore	nearshore	nearshore	nearshore	nearshore	nearshore	nearshore	nearshore
	DISCOVERY WELL IP (Mcf)	22,000	608	2,196	6,039	32	120	10		5,260	4,440
	DRIVE MECHANISM	gas/water	gas/water	gas/water	gas/water	gas/water	gas/water	gas/water	gas/water	gas/water	gas/water
	NO. PRODUCING WELLS	48	10	9	18	9	7	1	5	20	2
	NO. ABANDONED WELLS	26	10	3	5	0	5	1	2		
	AREA (acreage)	15,115	1,850	1,850	4,100	576	2,820	180	875	6,325	325
	OLDEST FORMATION PENETRATED	Helderberg	Salina	Helderberg	Helderberg	Tuscarora	Helderberg	Helderberg	Tuscarora	Keyser	Rose Hill
	EXPECTED HETEROGENEITY DUE TO:	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure	fracture/ structure
RESERVOIR PARAMETERS	AVERAGE PAY THICKNESS (ft.)	7	9	22	19		79			80	8
	AVERAGE COMPLETION THICKNESS (ft.)					37	101	105	106	84	29
	AVERAGE POROSITY--LOG (%)	10.01		8.68	5.26		5.75				15.6
	MINIMUM POROSITY--LOG (%)	2.48					5.36				8.93
	MAXIMUM POROSITY--LOG (%)	16.37					6.14				22.32
	NO. DATA POINTS	3		1	1		2				2
	POROSITY FEET										1.56
	RESERVOIR TEMPERATURE (°F)	106	110	140	135				86		
	INITIAL RESERVOIR PRESSURE (psi)	1,675	2,370	4,050	2,760	2,247	3,200	1,620	475	3,263	3,633
	PRODUCING INTERVAL DEPTHS (ft.)	3,210-4,307	4,935-5,345	7,991-8,182	7,418-6,861	4,808-6,582	7,950-8,756	5,156-5,506	1,125-3,010	7,724-9,902	8,500-8,610
	PRESENT RESERVOIR PRESSURE (psi) / DATE										
FLUID & GAS PROPERTIES	Rw (Ωm)	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035
	GAS GRAVITY (g/cc)			0.565			0.567			0.574	0.565
	GAS SATURATION (%)	75.2		78.9	64.6		78.95				89
	WATER SATURATION (%)	24.8		21.1	35.4		21.05				11
	COMMINGLED	no	no	no	no	no	no	no	no	no	no
	ASSOCIATED OR NONASSOCIATED	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated
	Btu/scf	1,259	1,024	1,019	1,023		1,010			1,024	1,020
VOLUMETRIC DATA	STATUS (producing, abandoned, storage)	storage	abandoned	producing	producing	storage	producing	storage	producing	producing	producing
	ORIGINAL GAS IN PLACE (Mcf)	41,348,000	5,336,000	28,972,000	18,907,000	6,000,000					
	ORIGINAL GAS RESERVES (Mcf)	39,700,000				5,400,000		4,000,000			
	PRODUCTION YEARS	1930-1940	1933-1988	1974-1991	1961-1991	1953-1971	1981-1993		1980-1993	1982-1993	1978-1992
	REPORTED CUMULATIVE PRODUCTION (Mcf)	37,213,000	4,766,000	3,584,000	16,618,000	1,000,000	12,090,400		98,200	18,000,000	2,049,000
	NO. WELLS REPORTED	48	10	9	18	9	9		6	20	2
	ESTIMATED CUMULATIVE PRODUCTION (Mcf)						13,836,600				
	REMAINING GAS IN PLACE (Mcf)/DATE	4,135,000/ 1940	534,000/ 1988	25,387,000/ 1991	2,289,000/ 1991						
	REMAINING GAS RESERVES (Mcf)/DATE	2,487,000/ 1940									
	RECOVERY FACTOR (%)	90	89	12	88	18					
	INITIAL OPEN FLOW (Mcf/d)	15,174	322	496	1,142	2,365	1,287	6	2,264	1,161	13,180
	FINAL OPEN FLOW (Mcf/d)		233	1,044	6,903	3,602	1,275	92	165	3,653	48,938

pressure, however, that determines whether a reservoir is underpressured, overpressured, or normal. A pressure-depth ratio of 0.44 psi per foot of depth is generally considered to be the normal fluid pressure gradient. Russell (1972) considered ratios between 0.4 and 0.6 as normal. Figure Dos-11 shows pressure-depth ratios for 68 Oriskany fields and pools in the Appalachian basin. These ratios range from 0.228 to 0.742, averaging 0.441, which is essentially the normal hydrostatic pressure gradient. Russell (1972) suggested that, on average, the Oriskany is not an overpressured reservoir, and that overpressuring is more common in areas of intense deformation. Data collected for this study, however, indicate that the more highly deformed areas, such as south-central Pennsylvania and eastern West Virginia, tend to have abnormally underpressured reservoirs (Figure Dos-11). Pressure-depth ratios for 19 fields in this area range from 0.257 to 0.500 with an average of 0.393. Only 16 percent of the fields had ratios exceeding 0.441, and none exceeded 0.6. In contrast, pressure-depth ratios for 49 Oriskany fields and pools in the less deformed areas of western Pennsylvania and south-central New York range from 0.228 to 0.742, averaging 0.459. Fifty-five percent of these fields had ratios exceeding 0.441, whereas 12 percent had ratios exceeding 0.6. These data indicate, as Russell (1972) suggested, that the Oriskany typically is not overpressured. The relationship of degree of deformation to pressure gradient is not readily apparent but might be due, at least in part, to the ability of the reservoir to maintain fluids following intense fracturing.

Initial open flows in wells in the northern fields, where porosity enhancement occurred through dissolution of carbonate cements, were often high, particularly in those fields close to the pinchout areas (within the structure/pinchout subplay). The largest recorded open flow was 145,000 Mcfg/d from the New York State Natural Gas No. 1 Finnefrock in Leidy field, Clinton County, Pennsylvania. Although the average initial open flow of wells in south-central New York and north-central Pennsylvania was 9,600 Mcfg/d, averages per field ranged from as little as 322 Mcfg/d in fields such as Ulysses field in Potter County, Pennsylvania, to as much as 18,039 Mcfg/d in Ellisburg field in Tioga County, Pennsylvania. Farther south, where porosity enhancement relies almost exclusively on fracturing, initial open flows commonly are lower. A few wells had reported natural open flows large enough not to require acidization or hydraulic fracturing.

Although most of the wells drilled in south-central New York and north-central Pennsylvania produced naturally, a few wells had to be stimulated. This was especially true in the more marginal areas of the fields. Stimulation is far more common, however, in south-central Pennsylvania and eastern West Virginia where the lack of effective porosity in the sandstone requires enhancement by acidization or hydraulic fracturing. Even with treatment, final open flows (FOF) in this area average only 6,800 Mcfg/d, with individual field averages ranging from a low of 92 Mcfg/d for Creekvale field in Hampshire County, West Virginia, to a high of 48,938 Mcfg/d for Keyser field in Mineral County, West Virginia (Table Dos-1).

Oriskany Sandstone reservoirs vary widely in both porosity and permeability, depending on mineralogy, diagenesis, and amount of fracturing. Intergranular porosity is a hybrid of reduced primary porosity and secondary (dissolution and fracture) porosity (Laughrey, 1995a). Secondary porosity due to dissolution of carbonate cements in the quartz arenites may produce 20 percent or more porosity, whereas in the arenaceous limestones porosity is minimal, generally less than five percent (Basan and others, 1980). In general, porosity averages less than 10 percent. In south-central New York and north-central Pennsylvania where the fields lie within the zone of enhanced porosity development, the Oriskany averages nine percent (Fettke, 1931; Gaddess, 1931; Finn, 1949). In south-central Pennsylvania, the Oriskany has intergranular porosities of less than four percent. In Maryland, Virginia, and West Virginia, porosities range up to 15 percent because of secondary dissolution of cement, as indicated by petrographic studies of well cuttings. Basan and others (1980) indicated that porosities determined by petrographic examination tend to be higher than log-derived porosities.

Fracture porosity, where it is developed, aids in storage within the Oriskany. Fracture density is greater in quartz arenites than in the arenaceous limestones because of the greater ductility of the latter. For example, Welsh (1984) noted that fractures were common in quartz arenites in cores taken from wells in Somerset County, Pennsylvania, whereas they were relatively uncommon in the more calcareous zones. However, the timing of fracturing also is important. Early fractures generally healed during diagenesis whereas late-stage fractures commonly remain open. In an Oriskany well in Beaver County, Pennsylvania

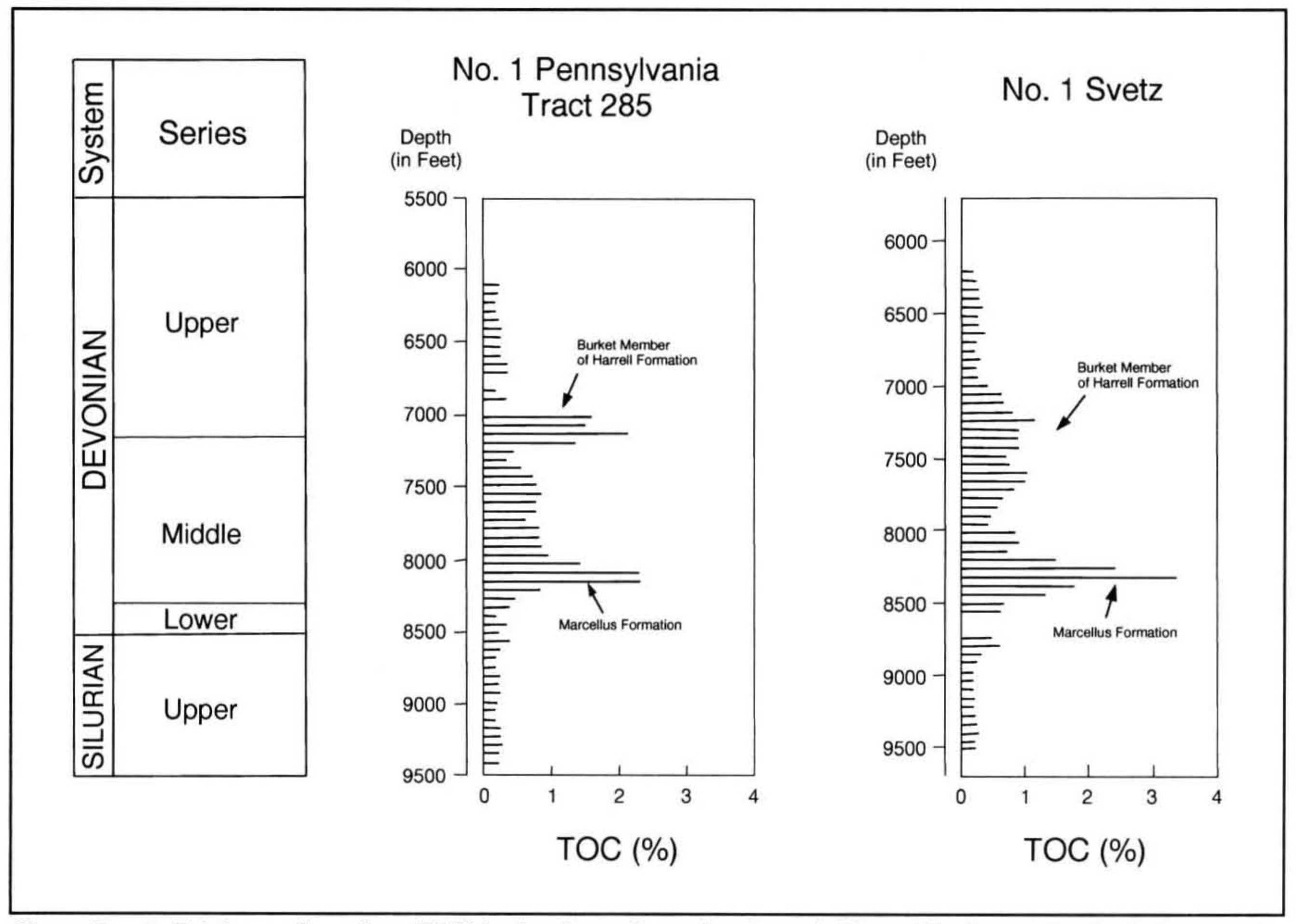


Figure Dos-9. Total organic carbon (TOC) in the Upper Devonian through Upper Silurian strata of the Texaco No. 1 PA Tract 285 well in Clinton County, Pennsylvania, and the Amoco No. 1 Svetz well in Somerset County, Pennsylvania. Data used to construct the histograms is from Laughrey (1995b).

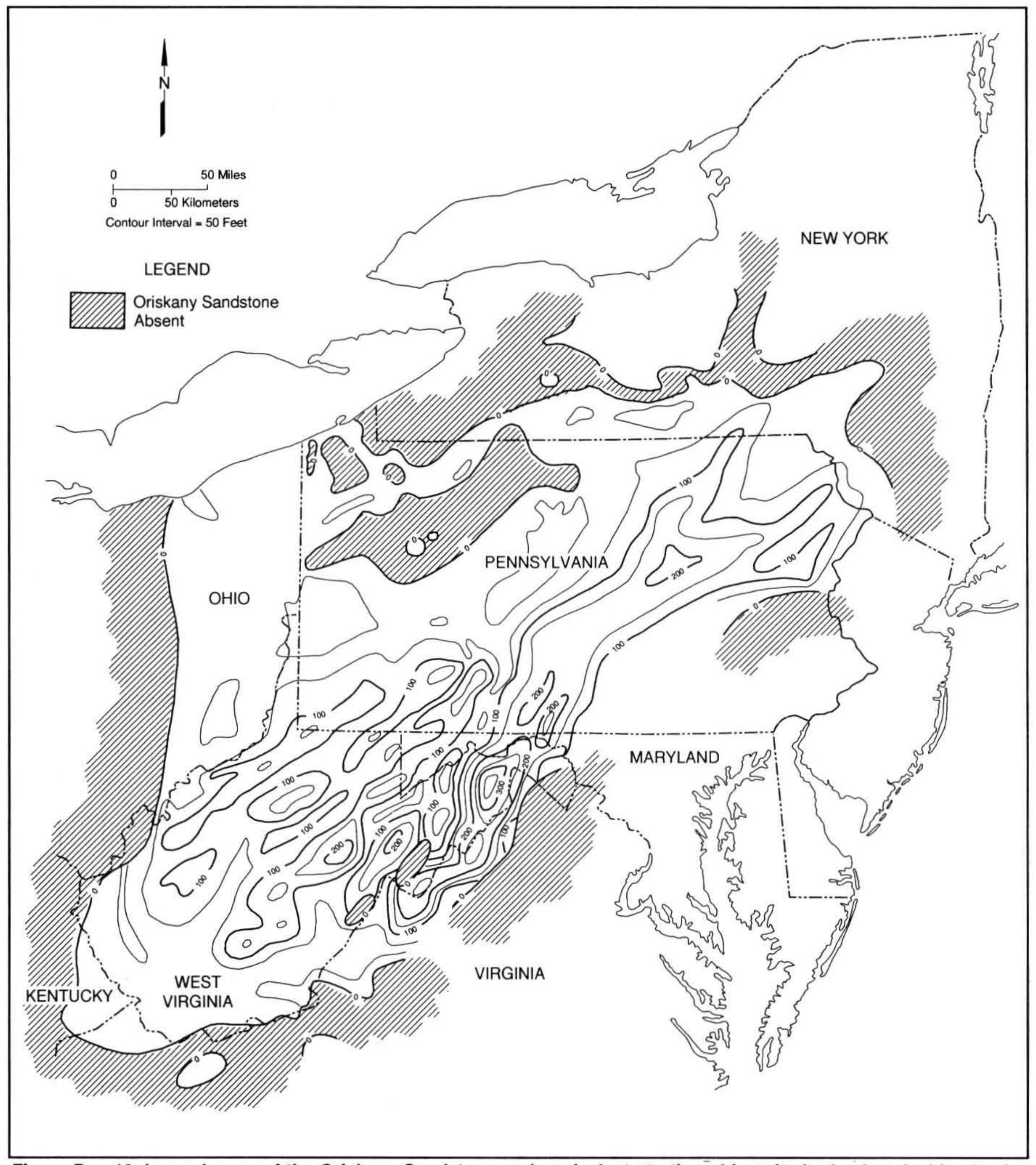


Figure Dos-10. Isopach map of the Oriskany Sandstone and equivalent stratigraphic units in the Appalachian basin. Modified from Basan and others (1980).

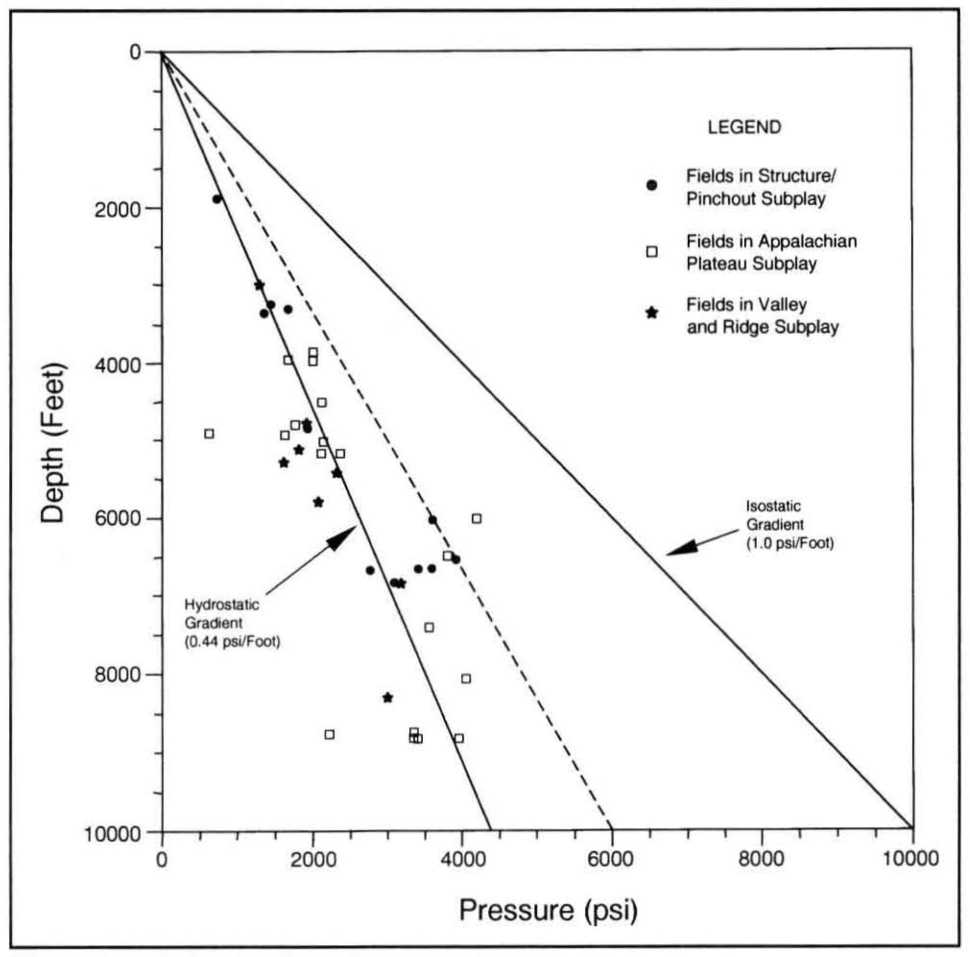


Figure Dos-11. Graph of original reservoir pressures versus drilling depth for 68 Oriskany fields and pools in New York, Pennsylvania, and West Virginia. The dashed line represents a ratio of 0.6.

Table Dos-2. Core test analyses for two wells in Pennsylvania.

County	Depth (feet)	Porosity (percent)	Vertical Permeability (md)	Horizontal Permeability (md)	Grain Density
Beaver	5,383	3.3	<0.10	<0.10	2.69
Beaver	5,384	2.9	<0.10	<0.10	
Beaver	5,387	6.6	5.43	29.6	
Beaver	5,388	7.0	2.31	4.95	
Beaver	5,404	7.9	4.83	8.35	2.67
Beaver	5,418	4.4	1.67	<0.10	2.67
Bedford	6,833	2.6	<0.10	<0.10	2.67
Bedford	6,835	3.8	<0.10	<0.10	2.66
Bedford	6,837	3.7	<0.10	<0.10	
Bedford	6,840	3.1	<0.10	<0.10	2.66

(Table Dos-2), porosities increase downward owing to increased fracturing. In a Bedford County, Pennsylvania well (Table Dos-2), porosities remain low throughout the sampling interval.

Permeabilities in the Oriskany Sandstone range from less than 0.1 to almost 30 md (Laughrey, 1995a). Higher permeabilities occur in rocks that are highly fractured, or where carbonate dissolution has occurred. Low permeabilities occur where carbonate dissolution has been minimal at best, or where fractures have been healed by secondary mineralization. In a Beaver County, Pennsylvania, well (Table Dos-2), vertical permeability exceeds horizontal permeability only in the deepest sample; if vertical fracturing exists in this well, it probably occurs at this depth. Permeabilities in a well in Bedford County, Pennsylvania, are consistently low, as are the porosities, suggesting that carbonate dissolution is nonexistent.

Completion strategies have necessarily varied over the decades as the more productive areas became depleted. Early discoveries commonly were completed naturally with very high initial open flows. As continued drilling placed limits on the best producing areas, operators began shooting wells with nitroglycerine torpedoes in order to increase flows. Hydraulic fracturing became the preferred practice in the late 1950s. Modern wells typically are cased through the pay zone and the casing is perforated before the treatment is applied. A typical hydraulic fracture of the Oriskany Sandstone in a well in Somerset County, Pennsylvania, consists of several thousand to tens of thousands of gallons of fluid (typically a gel) and as much as 110,000 pounds of sand injected at 20 barrels per minute. In addition, the carbonate fraction typical of Oriskany lithology makes the formation highly susceptible to acidization. A typical acidized well in Somerset County, Pennsylvania uses several thousand gallons of 15 percent HCl injected at between 0.5 and 10 barrels per minute through perforations in the casing.

Description of Key Fields

The following key fields were chosen to illustrate the three subplays of the Oriskany Sandstone structural traps play.

Jordan Run and Keyser fields: Jordan Run and Keyser fields in Grant, Mineral, and Pendleton counties, West Virginia (Figure Dos-12; Table Dos-1), examples of fields in the Valley and Ridge subplay, are situated close to each other on separate sets of fault blocks in the Wills Mountain anticlinorium. They fall within a structural fairway that Columbia Natural Resources has termed the "frontal zone." This zone occurs between two major surface features: the Allegheny Front to the west and the axis of the Wills Mountain anticline to the east. The first wells in this area discovered some rather spectacular, previously unknown, structures.

Jordan Run and Keyser fields produce primarily from the structurally deformed Oriskany Sandstone (Figures Dos-13, Dos-14, Dos-15, Dos-16; Table Dos-3), although some commingled production occurs from the carbonate rocks of the underlying Helderberg in Jordan Run field. The Oriskany Sandstone pay section averages 29 feet in Keyser field and 81 feet in Jordan Run field. The Oriskany reservoir in Keyser field consists of what appears to be a reworked storm deposit directly beneath the overlying Needmore Shale (R. Drabish, Columbia Natural Resources, written commun., 1994). In contrast, the reservoir in Jordan Run field consists of a sandy zone about 100 feet below the top of the Oriskany Sandstone that drillers call the "second bench," separated from the upper bench of Oriskany by calcareous sandstones and limestone. This is similar to the Oriskany in Somerset County, Pennsylvania, where, according to Welsh (1984), the formation includes numerous vertically stacked sequences of quartz arenite separated by thick sequences of arenaceous and "argillaceous" limestone (Figure Dos-5). The "second bench" consists of varying lithofacies representing different environments of deposition ranging from the crests of a set of barrier bars to the shore face.

Both areas are complicated by substantial deformation, including multiple thrust sheets and recumbent folds (Figure Dos-16). In addition, certain Lower Devonian and Upper Silurian formations are repeated within the largest recumbent fold on the right side of Figure Dos-14 indicating the possible existence of a thrust fault that preceded folding.

Keyser field, located in northwestern Mineral County, West Virginia (Figure Dos-12), was discovered by Columbia Natural Resoures in 1978 upon completion of the No. 1 Mastellar Coal Co. well. The well had a natural open flow of 4,400 Mcfg/d and, after acidizing, a final open flow of 9,728 Mcfg/d. The second well in the field, the Columbia Natural Resources No. 2 Mastellar Coal Co. well completed in 1979, had a final open flow after acidizing of 88,148 Mcfg/d. This well is credited with touching off a flurry of exploratory activity throughout the Eastern Overthrust Belt in the 1980s. Keyser field contains only these two commercially producing wells. Six dry holes (Figure Dos-12) were drilled as unsuccessful attempts to extend Keyser field production. The two successful wells produced approximately 2 bcfg by the end of 1994.

Jordan Run field is situated in western Grant County and northwestern Pendleton County just to the east of the Allegheny Front and about 13 miles southeast of Keyser field (Figure Dos-12). Jordan Run field contains 20 commercially producing wells. Seven dry holes (or wells with only shows of gas) helped to define the field. The discovery well, the Columbia Natural Resources No. 1 USA well completed in 1982, had a natural open flow of 5,260 Mcfg/d. The well was acidized, but received no other treatment; the final open flow was gauged at 4,708 Mcfg/d. The natural open flow of the Jordan Run wells averaged 1,161 Mcfg/d and the final open flow averaged 3,653 Mcfg/d. As of the end of 1994, the field had produced an estimated 18 to 20 bcfg from the Oriskany Sandstone.

Oriskany gas in Jordan Run and Keyser fields is dry, generally containing greater than 96 percent methane and less than two percent ethane (other hydrocarbons are negligible) (Table Dos-4).

Leidy field: Leidy field (Figure Dos-2; Table Dos-1), an excellent example of a field in the Appalachian Plateau subplay, is located in the Allegheny High Plateau Section of the Appalachian Plateau physiographic province. It lies in parts of five townships in Clinton and Potter counties, Pennsylvania, and consists of six pools, one in the Upper Devonian Lock Haven Formation and five in the Oriskany Sandstone (Figures Dos-17, Dos-18). The pools occur on both flanks of the faulted Wellsboro anticline, a structure trending northeast-southwest for about 95 miles through north-central Pennsylvania. At Leidy, a dome with several hundred feet of closure exists within the shallow subsurface structural configuration of the anticline (Figure Dos-17).

The first Oriskany production in Leidy field was obtained in 1950 by the Leidy Prospecting Company No. 1 Calhoun well on the flank of the Wellsboro anticline near Leidy, Clinton County. The well blew out with a flow estimated at 15,000 Mcfg/d, almost destroying the rig in the process. The total depth of the well was 5,659 feet, and when the well was brought under control, it had a gauged rock pressure of 4,200 psi.

Between 1950 and 1960, approximately 300 wells were drilled along the Wellsboro anticline in the vicinity of Leidy. All of the early drilling was done with cable-tool rigs. This drilling activity discovered five fault-block pools in the Oriskany Sandstone (Figure Dos-18). Tamarack pool, situated on the southeastern flank of the anticline, was discovered February 25, 1952, with the successful completion of the McGuire et al. No. 1 Jents well. This well had an open flow of 60,000 Mcfg/d and a shut-in well-head pressure of 600 psi after only two hours. Downs pool was discovered May 18, 1954, in the Downs Oil and Gas Co. No. 1 Downs well on the southeastern flank of the structure southwest of Tamarack. The discovery well had a reported open flow of 6,048 Mcfg/d and a shut-in well-head pressure of 1,706 psi in 19 hours. Greenlick pool, on the southeastern flank, was discovered January 25, 1955, with the completion of the New York State Natural Gas No. 7 Pennsylvania Tract 16 well in Stewardson Township, Potter County. This well had an open flow of 35,500 Mcfg/d and a shut-in well-head pressure of 4,240 psi in 39 hours. The final pool in the field, Ole Bull, was discovered on January 9, 1959, when the Phillips Petroleum No. 1 Pennsylvania Tract 81 well was completed with an open flow of 983 Mcfg/d at a shut-in well-head pressure of 4,427 psi in 24 hours. Ole Bull pool, situated on the northwestern flank of the anticline northeast of Leidy pool, is the only pool not currently used for storage.

Early drilling was haphazard; there was no attempt at spacing or conservation. Tamarack pool, for example, consisted of 29 wells with an average of 7.5 acres per well. Later drilling was more consistent with established drilling and production practices. Greenlick pool, for example, contained 40 producing Oriskany wells, each with an average spacing of 40 acres.

Most of the Oriskany pools in Leidy field produced huge quantities of gas, but they were relatively short-lived. Leidy pool produced approximately 94 bcf before being converted to storage in 1959. Greenlick pool was converted to storage in 1961 after producing about 50 bcf, and Tamarack and Downs were

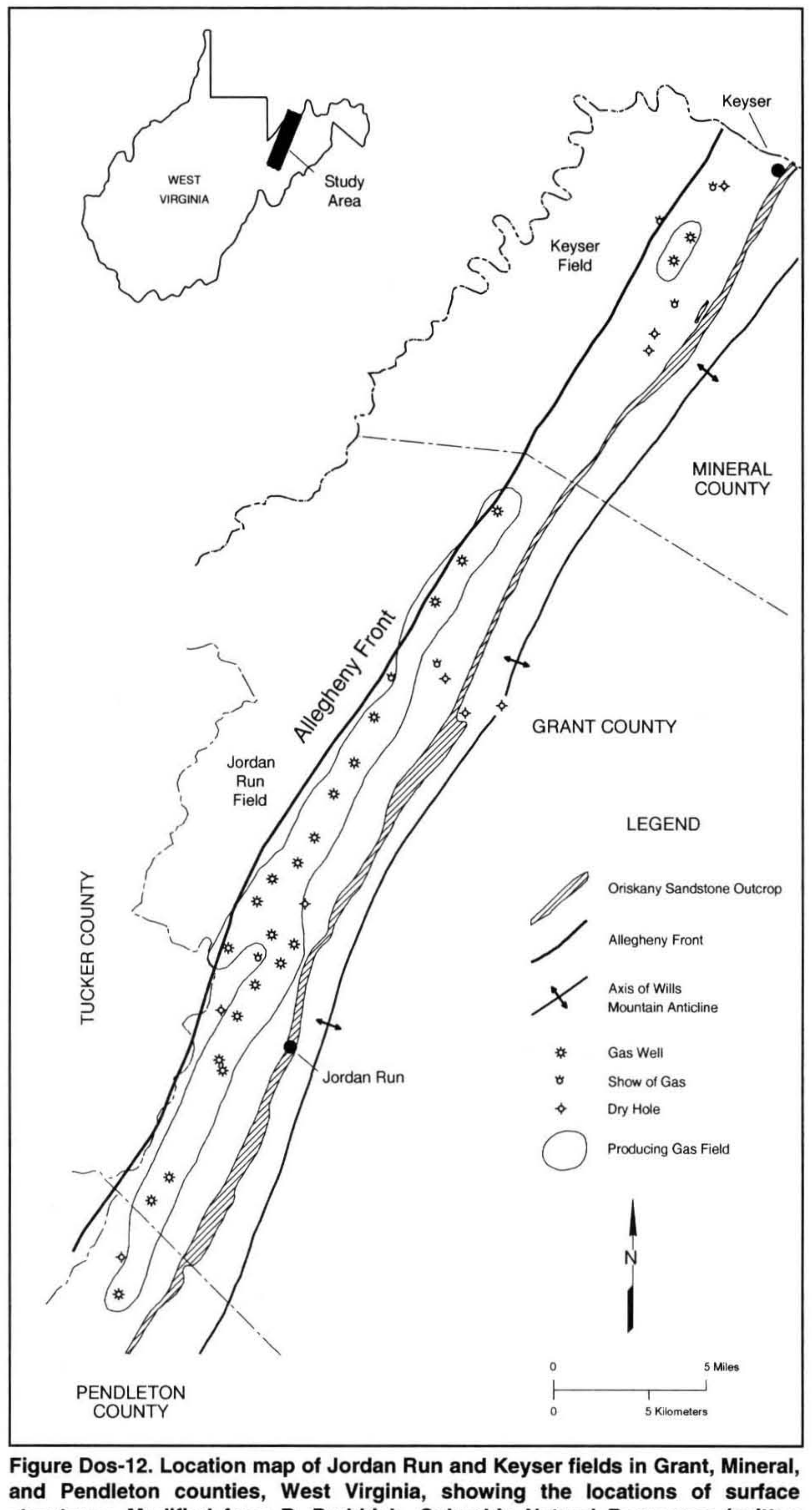


Figure Dos-12. Location map of Jordan Run and Keyser fields in Grant, Mineral, and Pendleton counties, West Virginia, showing the locations of surface structures. Modified from R. Drabbish, Columbia Natural Resources (written commun., 1994).

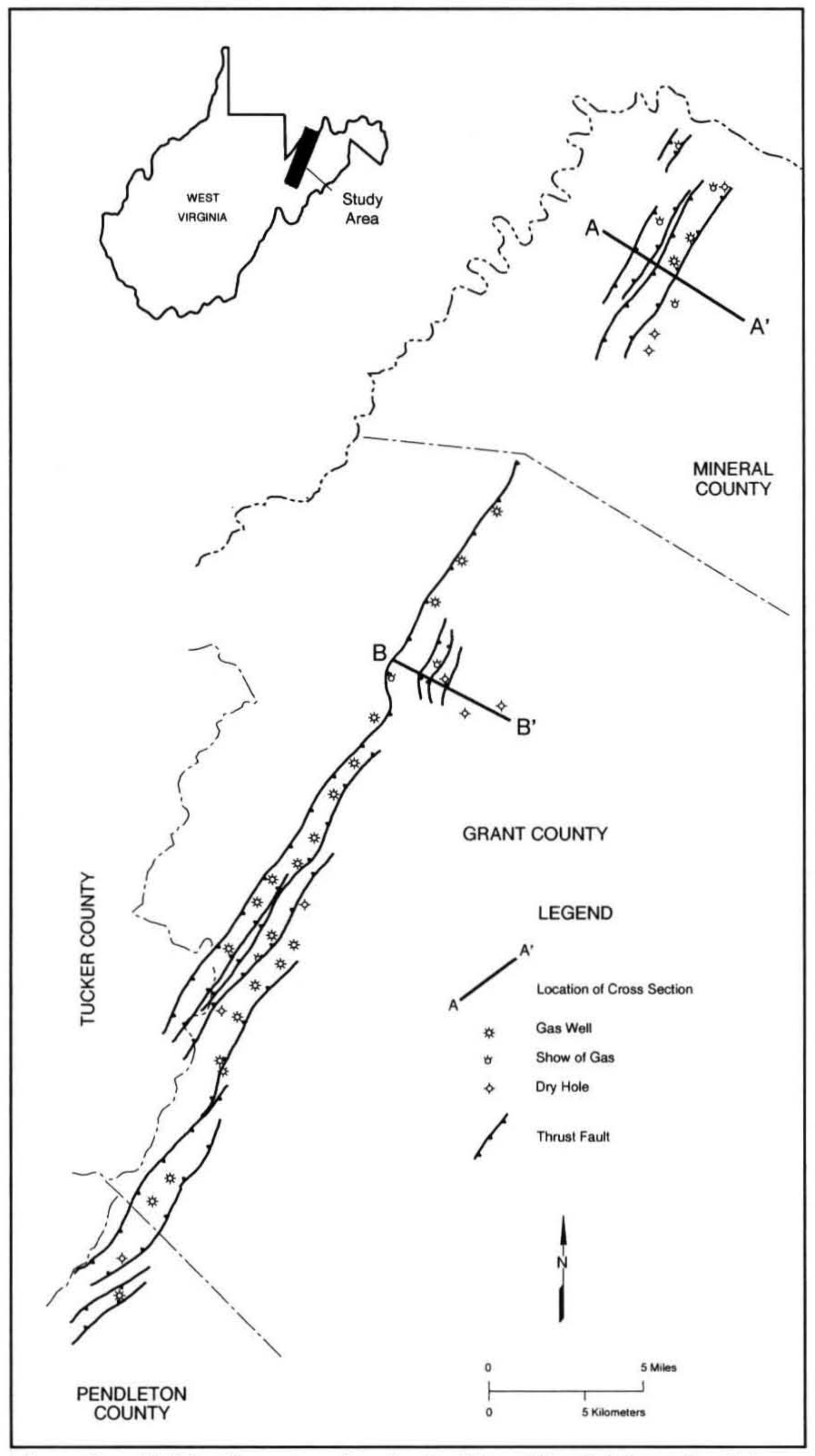


Figure Dos-13. Structure map showing faulting of the Oriskany Sandstone, Jordan Run and Keyser fields, West Virginia. Modified from R. Drabbish, Columbia Natural Resources (written commun., 1994).

consolidated and converted to storage in 1971 after producing a combined 11.4 bcf. Ole Bull was the last pool reported to be producing; Harper (1986) reported an annual production of approximately 2,500 Mcf for 1985.

Oriskany structure in Leidy field is illustrated in Figures Dos-19 and Dos-20. Because of the lack of nonproprietary seismic information across the field, the structure map and cross sections are based solely on well data and surface mapping. The structure consists of a salt-cored anticline with overthrusted limbs at the level of the Oriskany Sandstone, but becomes a simple asymmetrical fold at the surface (Figure Dos-21). Surface structural relief is generally on the order of 500 to 800 feet, whereas structural offset at depth may be more than 1,500 feet. Complexity of faulting in the Oriskany increases from the northeast to the southwest (Figures Dos-19 and Dos-20). The exact number and distribution of faults is not known for certain, but they have created a set of independently producing pools situated on separate blocks. Except for the anomalous Downs pool, which is situated on an upthrown block between opposing thrusts near the core of the anticline, all of the Oriskany gas production occurs in fault-produced flexures on the anticlinal flanks. All of these flank pools are structurally high relative to the low axial zone of the anticline.

Traps in the Oriskany exist where flexure occurs on the thrust-faulted limbs. In some areas flexure constitutes secondary anticlines with closure of less than 100 to more than 300 feet; other flexures create homoclines terminating at the faults. The upper seal of these reservoirs is the relatively impermeable Needmore Shale. Diagenetic effects on the structural traps consist of porosity enhancement/degradation contacts. The upper few feet of the Oriskany typically consists of friable sandstone, and this is commonly the zone from which the best gas production comes. About 4 feet below the top of the formation in these wells, the sandstone becomes very calcareous, and the typically rounded, frosted sand grains show signs of quartz overgrowths.

Greater sandstone thickness values in Leidy field (Figure Dos-22) result from structural, rather than stratigraphic, thickening. Although the Oriskany averages 33 feet in gross thickness in Leidy field, the best pay zone is considerably thinner and is generally limited to the higher porosity zones in the upper third to half of the formation (Ebright and Ingham, 1951) (Figure Dos-23). Modern stimulation technology has helped increase the pay zone thickness, so that now most of the formation will produce some gas. Porosity in a typical well in Leidy field ranges from 1.4 percent to 7.8 percent (Figure Dos-23), and enhanced porosity occurs in association with unhealed fractures. Although higher porosities generally mean better gas recovery, they have their disadvantages as well in the Oriskany—producible water saturations commonly are higher. Water saturation in Leidy field ranges from near 0 percent in low-porosity, low-permeability zones to more

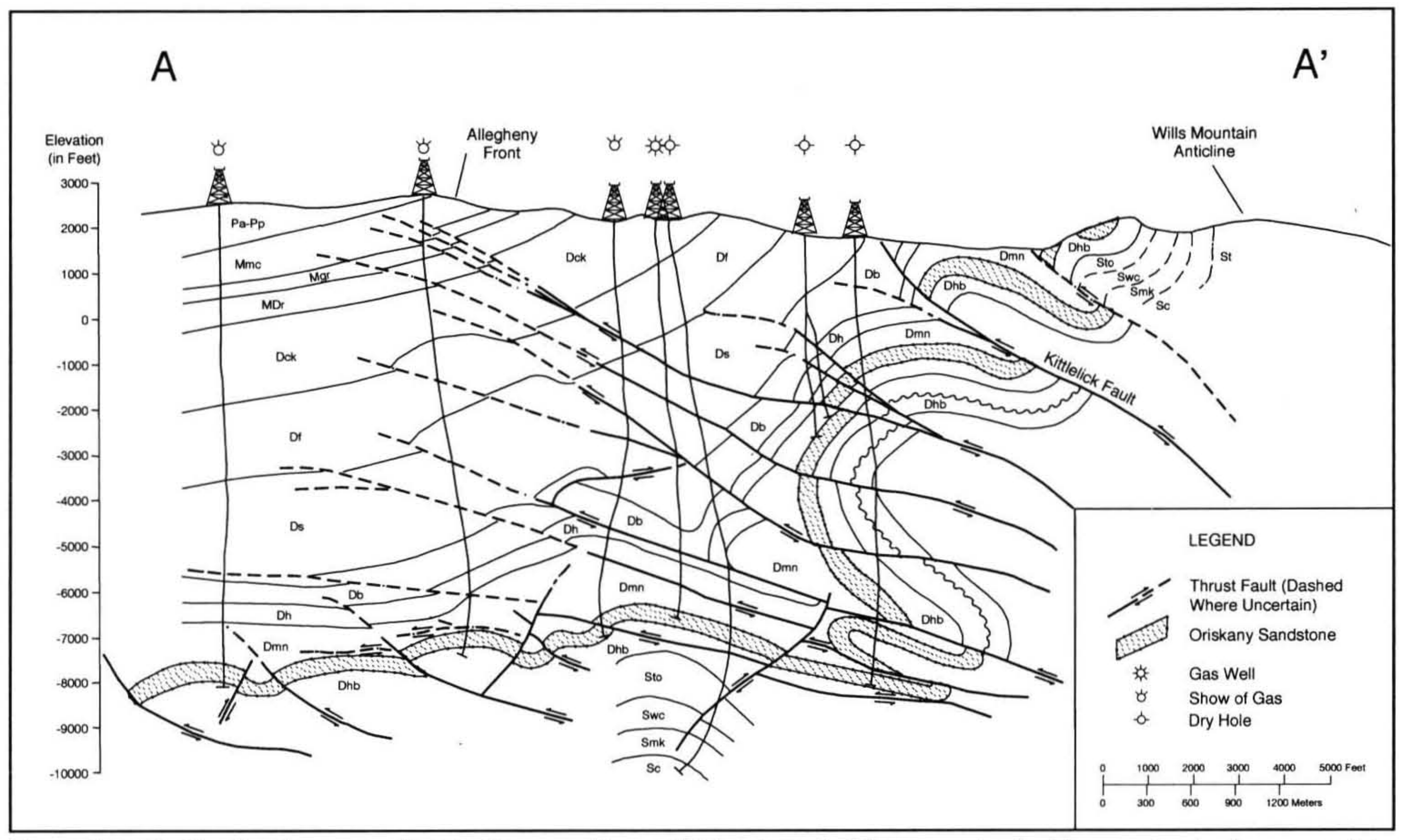


Figure Dos-14. Structural cross section A-A' across Keyser field, interpreted from geophysical logs and seismic survey data. Modified from R. Drabbish, Columbia Natural Resources (written commun., 1994). See Figure Dos-13 for location of cross section; see Table Dos-3 for list of formation abbreviations.

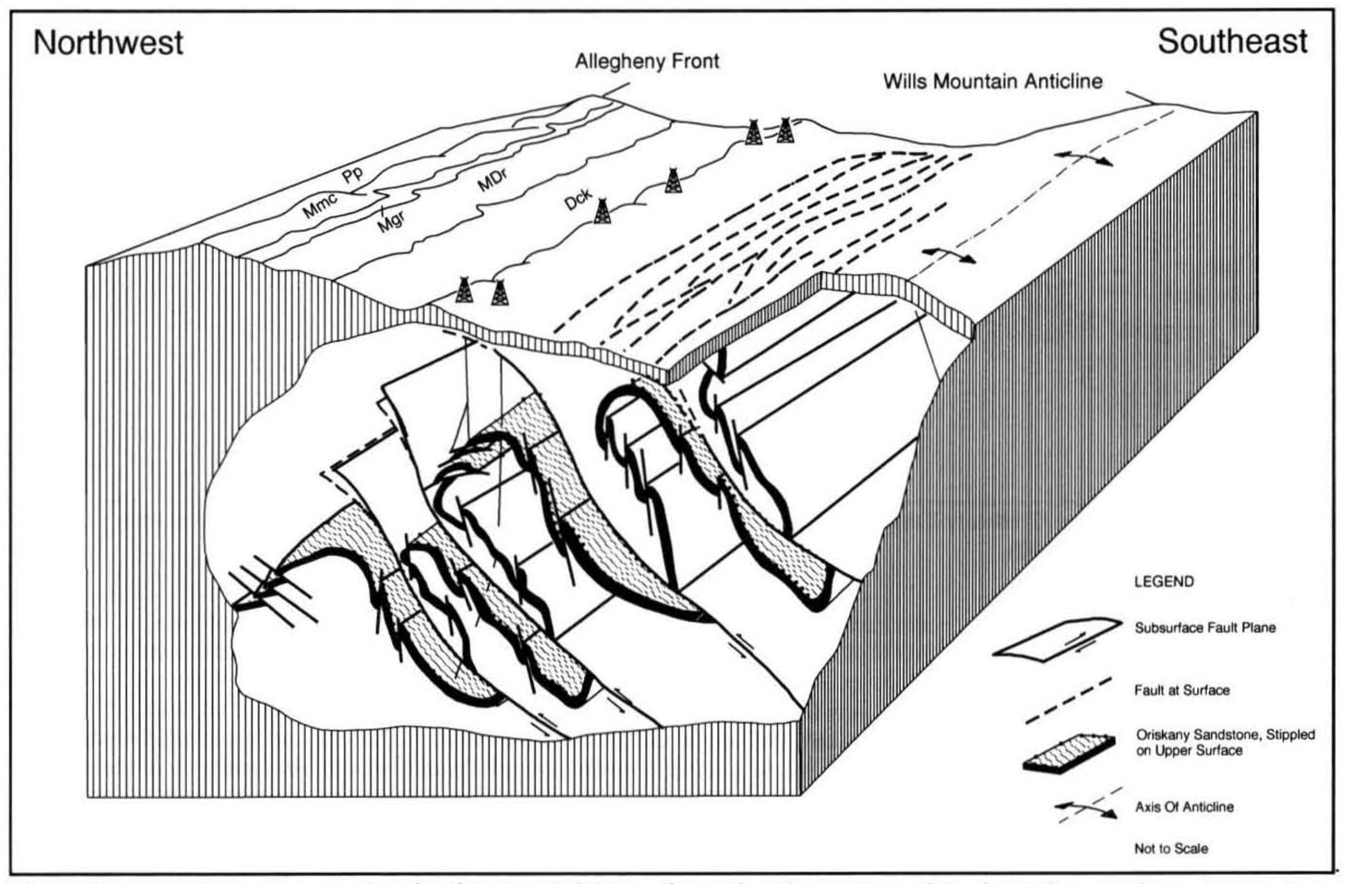


Figure Dos-16. Block diagram showing interpreted three-dimensional structure of the frontal zone where Jordan Run and Keyser fields are located. Cutaway section aids in visually identifying separate thrust sheets and large-scale recumbent folds. Modified from R. Drabbish, Columbia Natural Resources (written commun., 1994). See Table Dos-3 for list of formation abbreviations.

Table Dos-3. List of formation abbreviations used in Figures Dos-14, Dos-15, and Dos-16.

Abbreviation	Geologic Unit	Age
Pa-Pp	Allegheny & Pottsville Formations	Pennsylvanian
Mmc	Mauch Chunk Formation	Mississippian
Mgr	Greenbrier Formation	Mississippian
MDr	Rockwell Formation	Mississippian & Devonian
Dck	Catskill Formation	Devonian
Df	Foreknobs Formation	Devonian
Ds	Scherr Formation	Devonian
Db	Brallier Formation	Devonian
Dh	Harrell Formation	Devonian
Dmn	Hamilton Group to Needmore Shale	Devonian
Dhb	Helderberg Group	Devonian
Sto	Tonoloway Formation	Silurian
Swc	Wills Creek Formation	Silurian
Smk	McKenzie Formation	Silurian
Sc	Clinton Group	Silurian
St	Tuscarora Sandstone	Silurian
Ojo	Juniata & Oswego Formations	Ordovician
Om	Martinsburg Formation	Ordovician
Otb	Trenton & Black River Limestone	Ordovician
Ob	Beekmantown Formation	Ordovician

Table Dos-4. Analyses of gas from Oriskany Sandstone in the Columbia Natural Resources No. 1 Weimer well in Jordan Run field, Grant County, West Virginia (from Moore and Sigler, 1987b, sample number 18242).

Component	Mole Percent
Methane	96.8
Ethane	1.4
Propane	0.2
N-Butane	0.0
Isobutane	0.2
N-Pentane	0.0
Isopentane	0.0
Cyclopentane	0.2
Hexanes plus	0.3
Nitrogen	0.6
Oxygen	Trace
Argon	0.0
Hydrogen	0.2
Hydrogen sulfide	0.0
Carbon dioxide	0.2
Helium	0.04
Btu value	1,041
Specific gravity	0.581

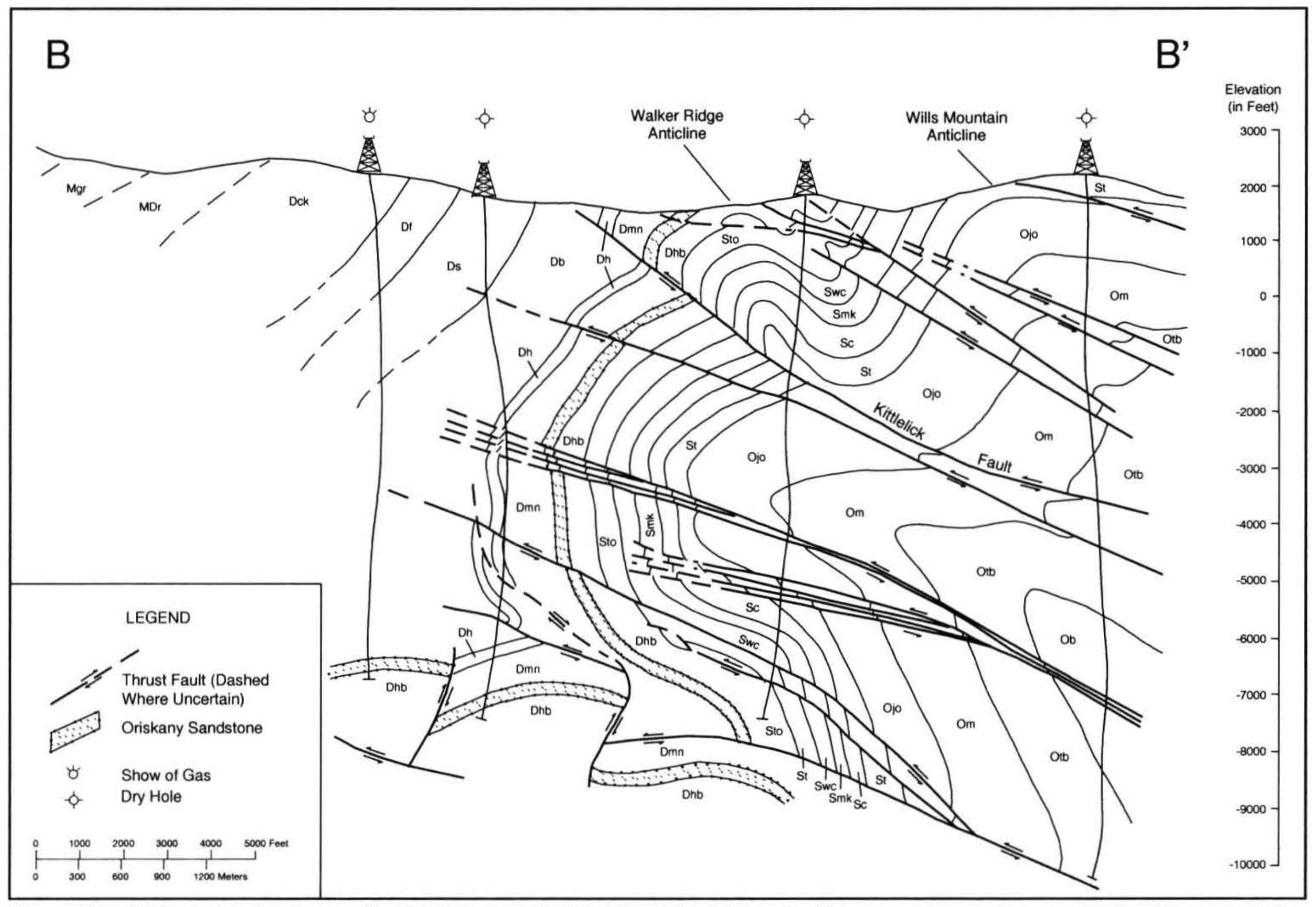


Figure Dos-15. Structural cross section B-B' across Jordan Run field, interpreted from geophysical logs and seismic survey data. Modified from R. Drabbish, Columbia Natural Resources (written commun., 1994). See Figure Dos-13 for location of cross section; see Table Dos-3 for list of formation abbreviations.

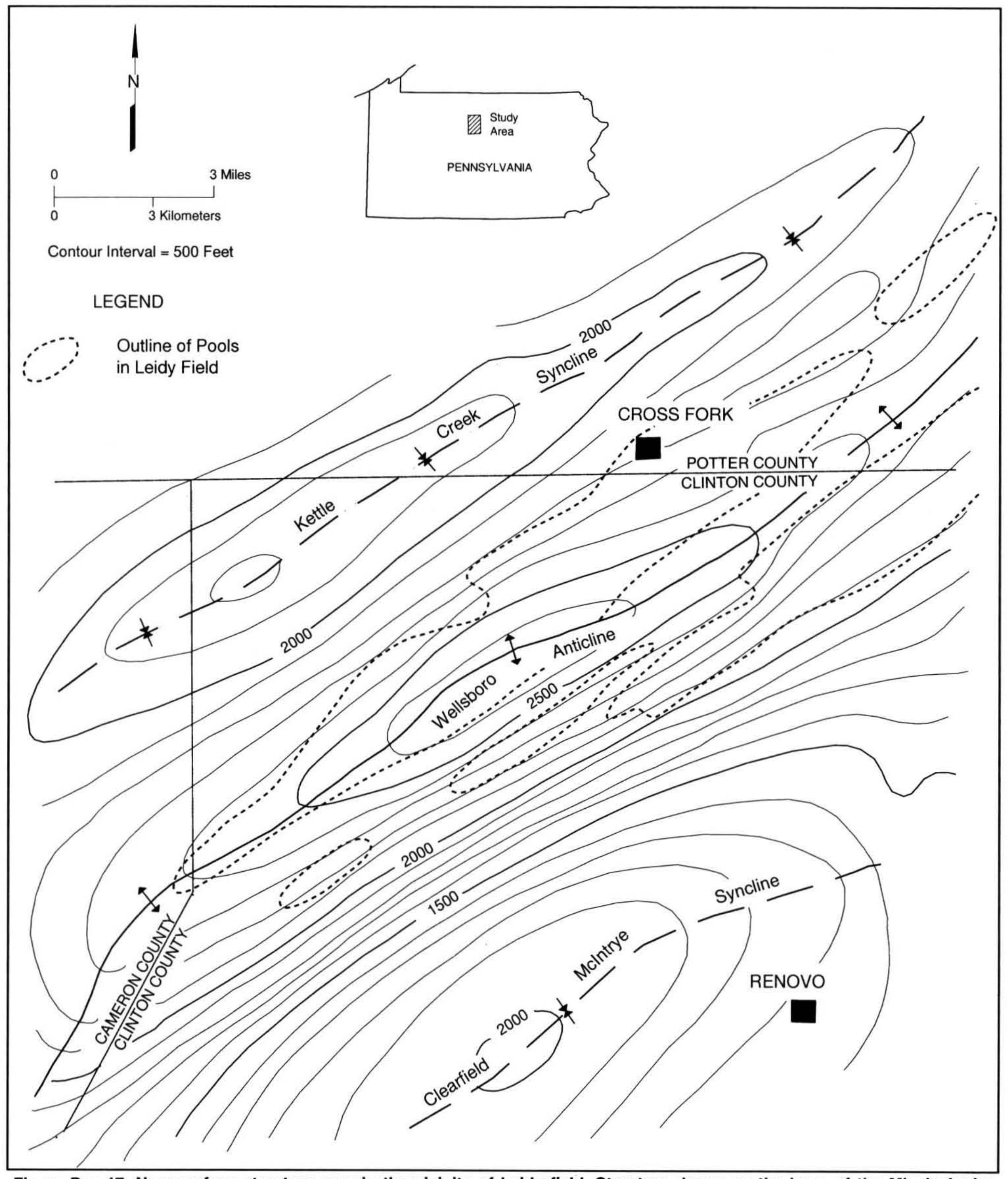


Figure Dos-17. Near-surface structure map in the vicinity of Leidy field. Structure drawn on the base of the Mississippian Burgoon Sandstone. Modified from Ebright and Ingham (1951).

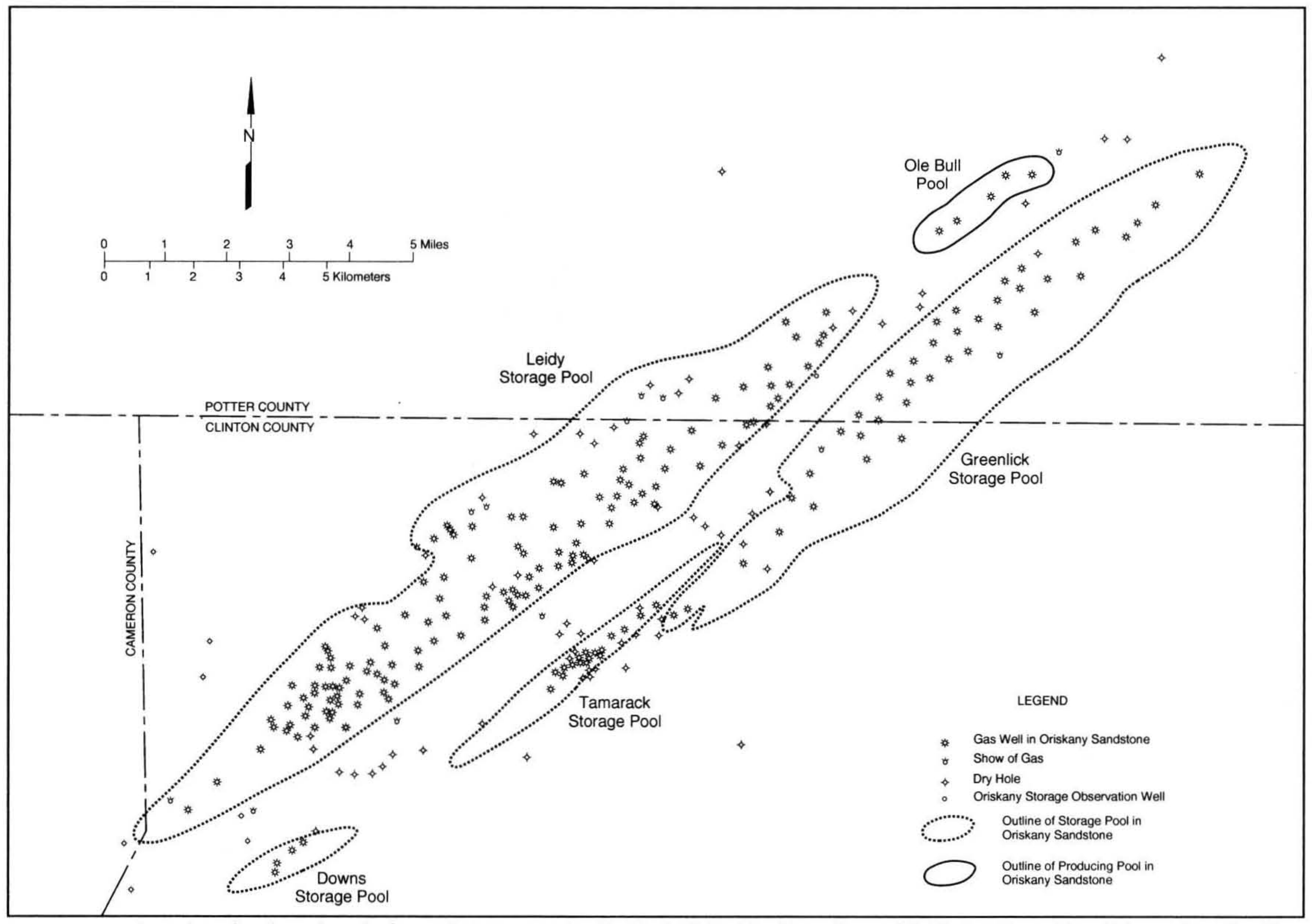


Figure Dos-18. Location of wells and producing and storage pools of Leidy field. Modified from Harper (1990). See Figure Dos-17 for regional location.

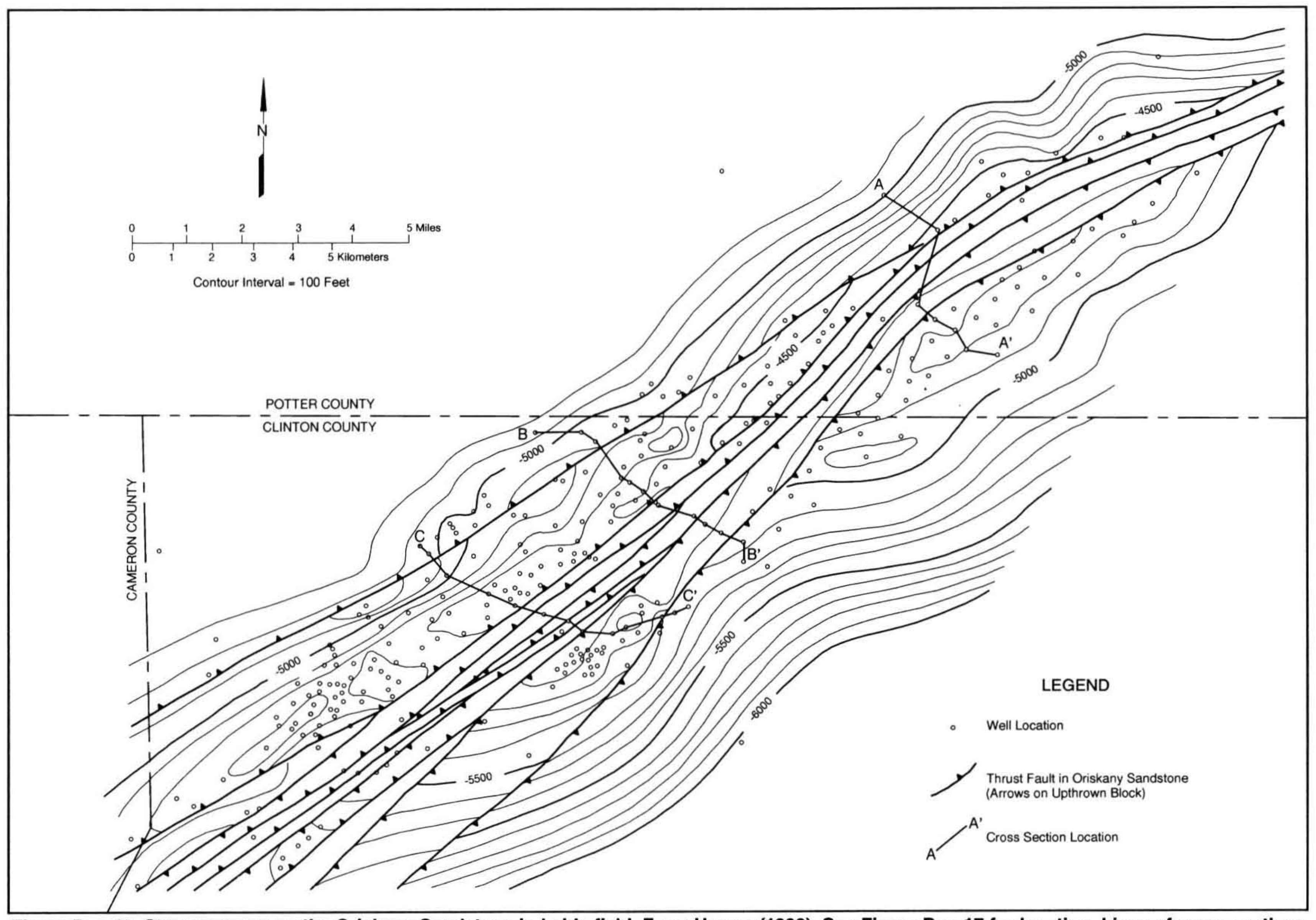


Figure Dos-19. Structure map on the Oriskany Sandstone in Leidy field. From Harper (1990). See Figure Dos-17 for location. Lines of cross sections A-A', B-B', and C-C' (Figure Dos-20) are shown.

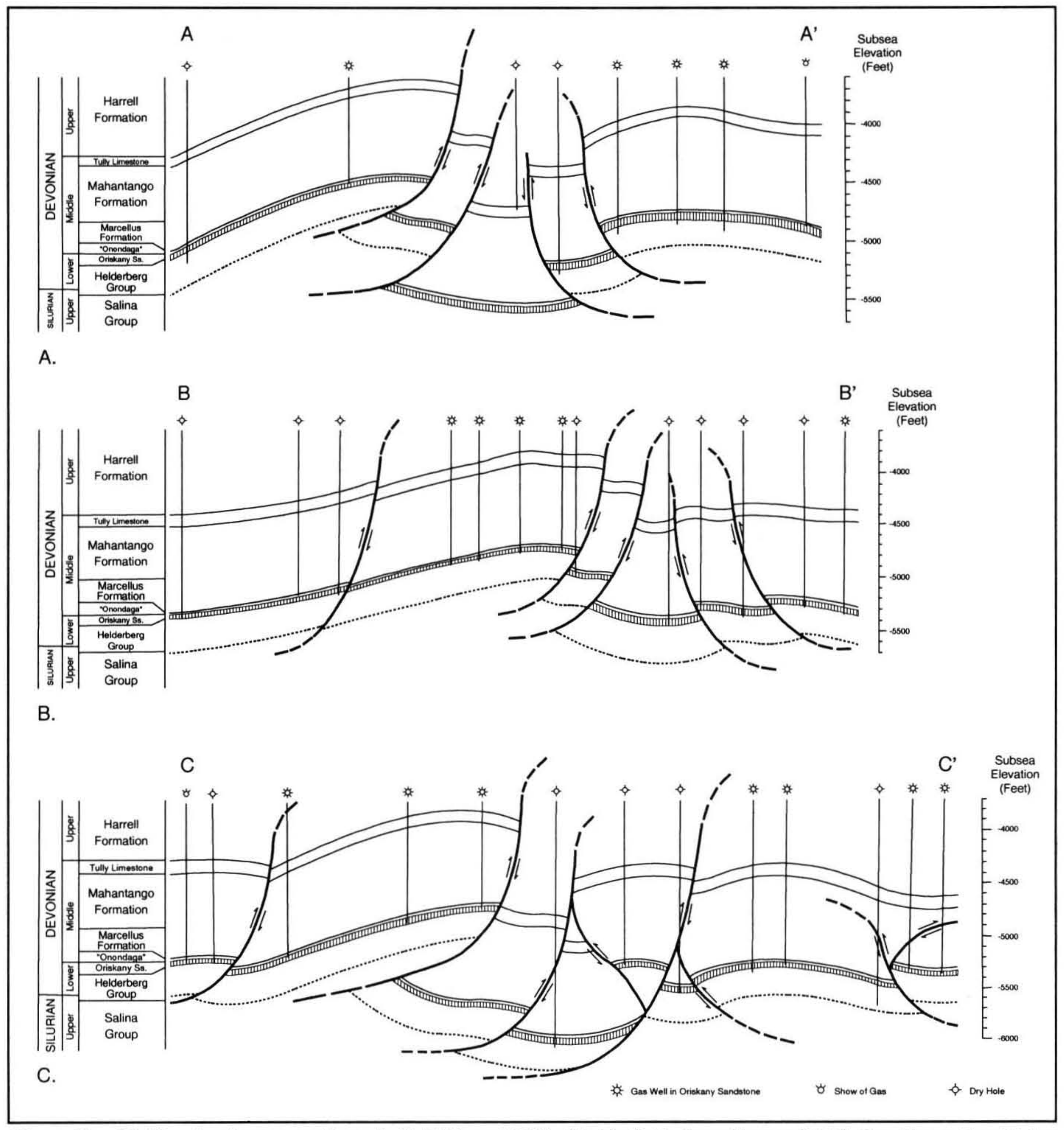


Figure Dos-20. Structural cross sections A-A', B-B', and C-C' of Leidy field. From Harper (1990). See Figure Dos-19 for location of cross sections. "Onondaga" refers to the combined Selinsgrove Limestone and Needmore Shale interval.

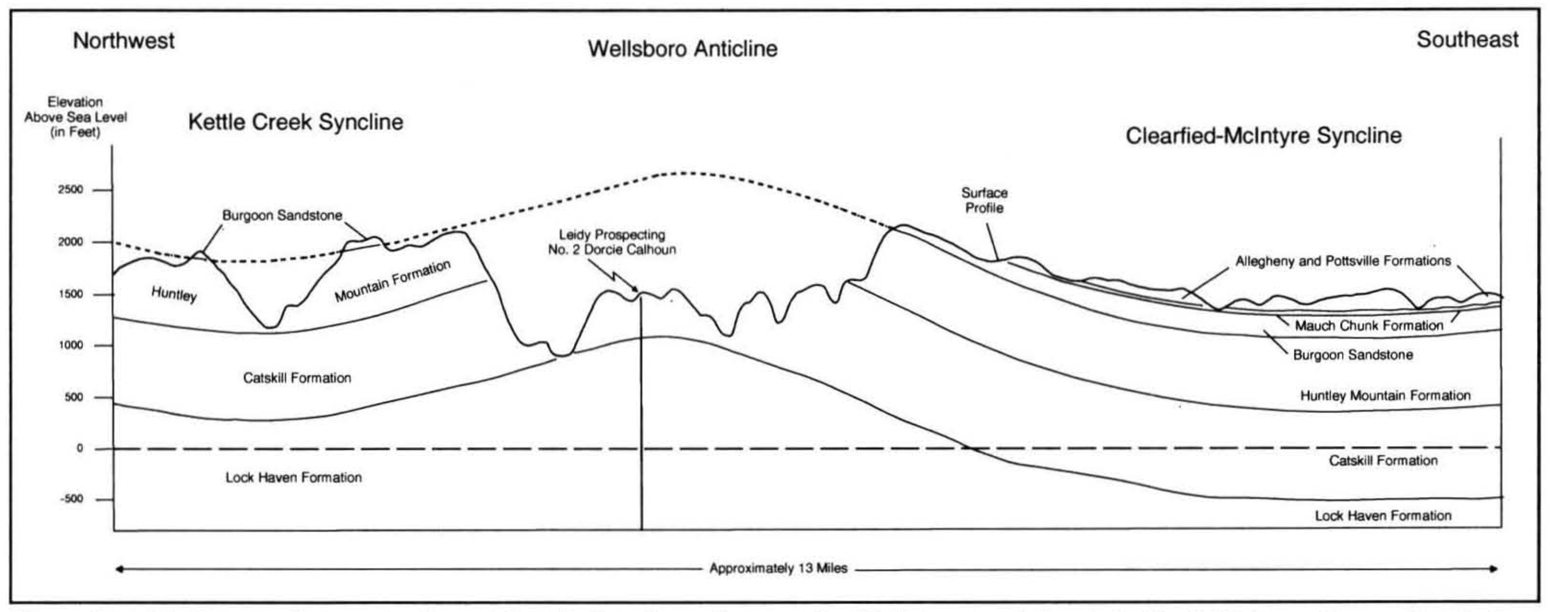


Figure Dos-21. Structural cross section of the shallow formations on the Wellsboro anticline in Leidy field. From Harper (1990). See Figure Dos-2 for location of Leidy field.

than 30 percent in the highest-porosity zone near the top of the formation (Figure Dos-23). A typical log suite (Figure Dos-24), however, indicates water saturations are higher in the lower porosity zones, but this is due to irreducible water in the formation which was not recorded during core analyses. Permeabilities (to air) in the Oriskany range from less than 0.1 md to greater than 40 md, with lower permeabilities in tightly cemented zones and higher permeabilities in fractured or high porosity zones. A typical well in Leidy field has permeabilities ranging from 0.03 md to 13.03 md (Figure Dos-23).

Shut-in well-head pressures in the Oriskany Sandstone in Leidy field initially ranged from 2,660 to 4,200 psi, and were considered to be anomalously high for the depth of the reservoir, about 5,600 feet (Ebright and Ingham, 1951). Subsequent drilling and production decreased these pressures significantly. Figure Dos-25 illustrates the decrease in pressure decline in Ole Bull pool, and Figure Dos-26 shows the production decline in the pool. Production rose sharply in early 1961 with the successful completion of the Phillips Petroleum Co. No. 6 Pennsylvania Tract 81 well on December 30, 1960. This well had an after-treatment open flow of 7,770 Mcfg/d and an initial shut-in well-head pressure of 3,235 psi in seven days. Combined with the other four wells in the pool, production reached a peak of 233,578 Mcf in January, 1961. Annual production in the pool in 1961 amounted to 1.8 bcf.

Oriskany natural gas is primarily dry gas, composed of greater than 95 percent methane (Table Dos-5). Heavier hydrocarbons and non-hydrocarbon gases are typically very minor constituents. Oil does not occur in the Oriskany structural traps play in Pennsylvania.

Wayne-Dundee field: Wayne-Dundee field (Figure Dos-2; Table Dos-1) represents the structure/pinchout subplay. It is situated on a domal structure near the intersection of Schuyler, Yates, and Steuben counties in central New York (Figure Dos-27). The field was drilled on the basis of surface structure in the Upper Devonian Naples Group where a dome occurs in the eastern part. This dome also appears within the Upper Devonian Rhinestreet Formation (Figure Dos-27). At the level of the Oriskany Sandstone, however, the structure consists of two domal flexures separated by a low saddle (Figures Dos-28, Dos-29). This saddle acts as a primary trapping mechanism by creating two supposedly noncommunicating pools within the one field. Subsidiary trapping occurs within the saddle where porosity, probably related to dissolution of carbonate cement, decreases away from the domal crests. It is possible that one or more faults cut this structure, particularly at the saddle. The vertical offset would be only a few feet, but might be enough to act as a permeability barrier between the domes. The westernmost flexure disappears stratigraphically upward (Figure Dos-27, Dos-28) owing in part to an eastward thinning of the Upper and Middle Devonian shale formations on the relatively steep west end of the dome (Bradley and Pepper, 1938).

The discovery well, the Belmont Quadrangle Drilling Corporation No. 1 Pulver, penetrated the top of the Oriskany Sandstone at 2,075 feet and flowed 5,750 Mcfg/d with a rock pressure of 730 psi when it was drilled in 1930. This well is situated on the eastern, or Dundee, portion of the structure. During the next year, 15 wells were completed with an average flow of 6,000 Mcfg/d. It was only after the Dundee area had been sufficiently explored that the Wayne portion of the field was drilled. The first major well in this area, the Tyrone Oil and Gas No. 1 Bigelow drilled in the village of Wayne, Steuben County, reached the Oriskany at 1,747 feet in 1931 and flowed 10,000 Mcfg/d. Overdevelopment of the pool resulted in subsequent wells commonly having open flows of less than 3,500 Mcfg/d (Newland and Hartnagel, 1932). Of 111 wells drilled in the field between March 1930 and December 1931, 93 were productive with open flows averaging 3,900 Mcfg/d, and 18 were dry.

Oriskany gas in Wayne-Dundee field consists mostly of methane with smaller but significant percentages of heavier hydrocarbons (Table Dos-6). The gas contains an abnormally high percentage of nitrogen and other non-hydrocarbon gases. In the Dundee flexure, the gas typically is rich in hydrogen sulfide, whereas in the Wayne portion of the field the gas is "sweet." According to Owen (1975), D.M. Ellington speculated that the heavier hydrogen sulfide collected on the lower eastern side of the field by gravitational separation.

Early reserve estimates for gas in the Wayne-Dundee field ranged from 16.9 to 17.3 bcf, with between 4 and 5 bcf estimated for the Wayne portion and 12 to 13 bcf estimated for Dundee (Newland and Hartnagel, 1932). Revised reserve estimates by Columbia Gas Transmission Corporation and New York State Natural Gas, however, placed the total field capacity at 11 bcf (A. Van Tyne, written commun., 1994).

Resources and Reserves

Original natural gas resources within the discovered fields of the Oriskany structural traps play were substantial, exceeding an estimated 1.2 tcf in Pennsylvania alone (65 percent, or 786 bcf, has been produced to date). That figure might be low, however, because determining original-gas-in-place figures for many Oriskany fields is difficult; 32 percent of these fields ultimately produced more gas than can be calculated based on bulk reservoir volume, porosity, water saturation, initial pressure, and temperature. For example, Hebron field in Potter County, Pennsylvania, produced 45 bcf prior to conversion to gas storage in 1953, yet based on available reservoir parameters, this field had

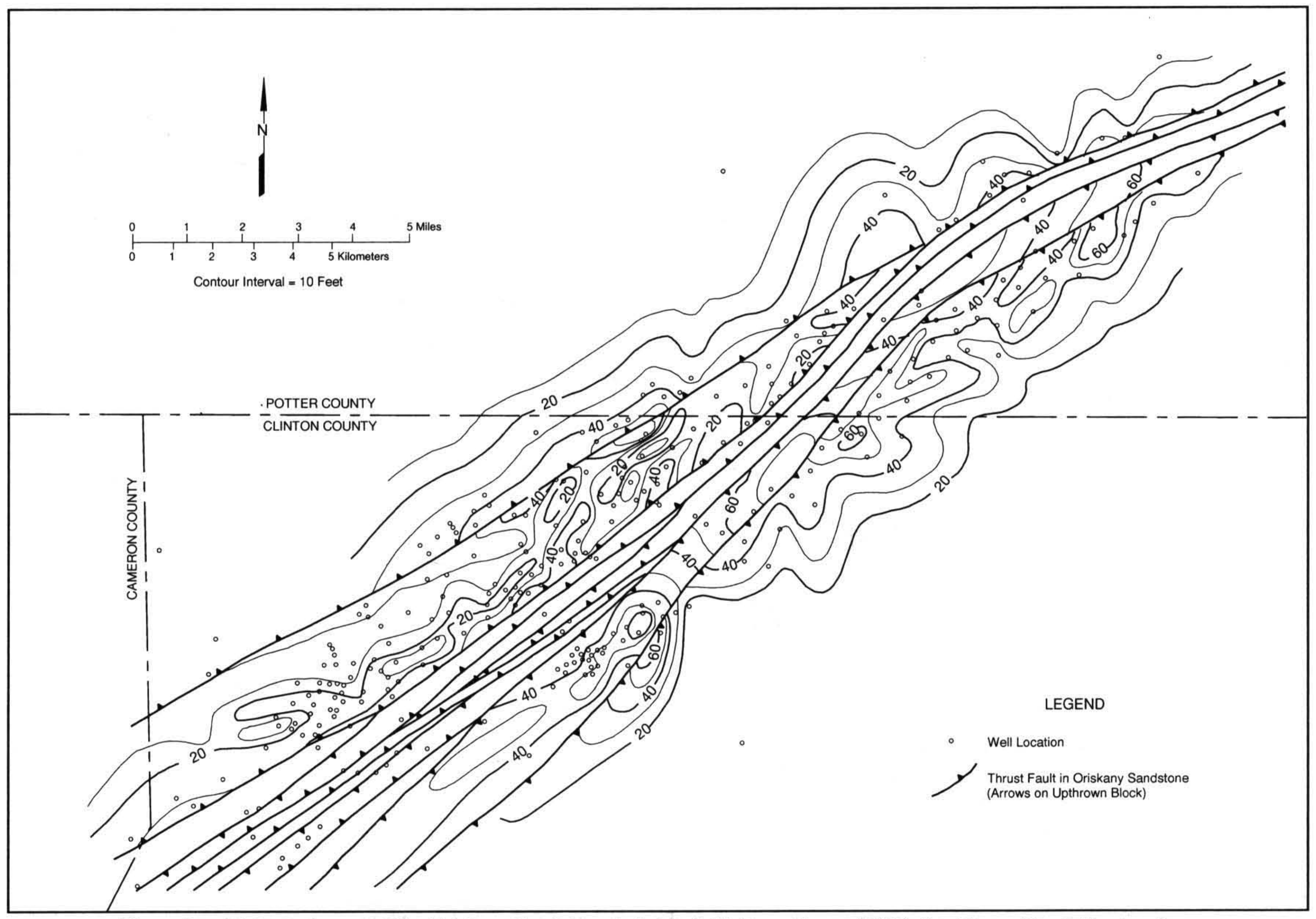


Figure Dos-22. Isopach map of the Oriskany Sandstone in Leidy field. From Harper (1990). See Figure Dos-17 for location.

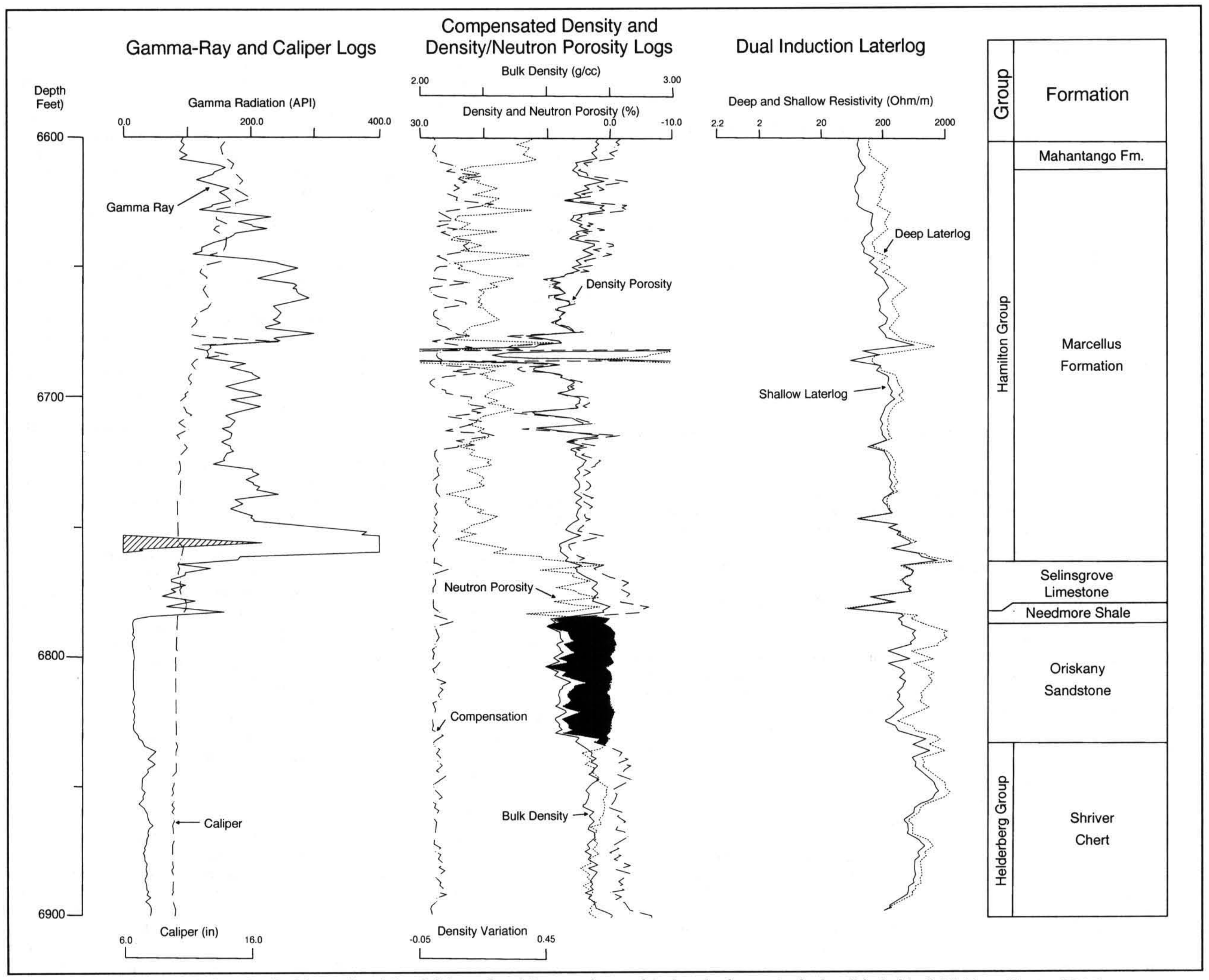


Figure Dos-24. Geophysical log suite of the Oriskany Sandstone and associated rocks from a typical well in Leidy field. From Harper (1990).

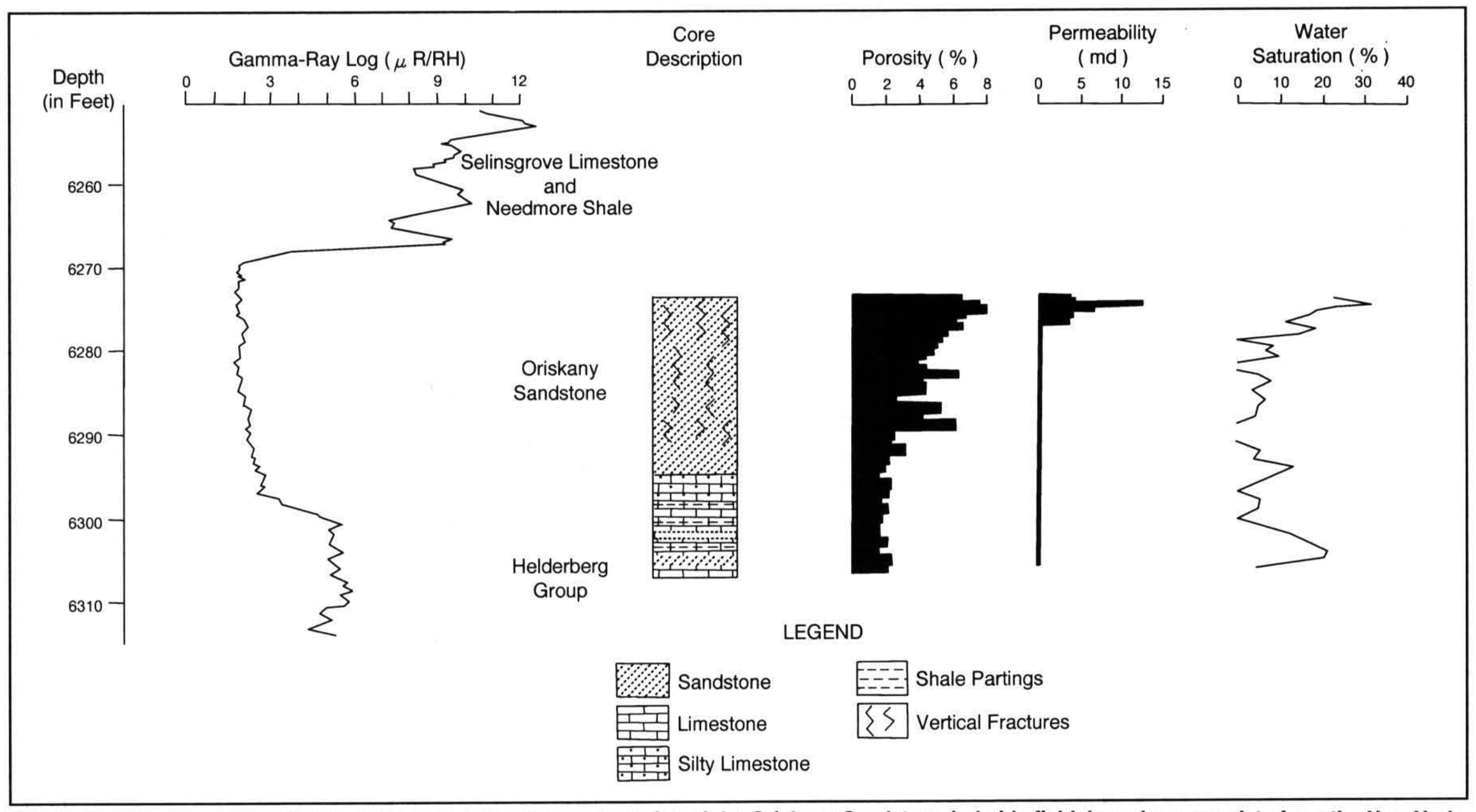
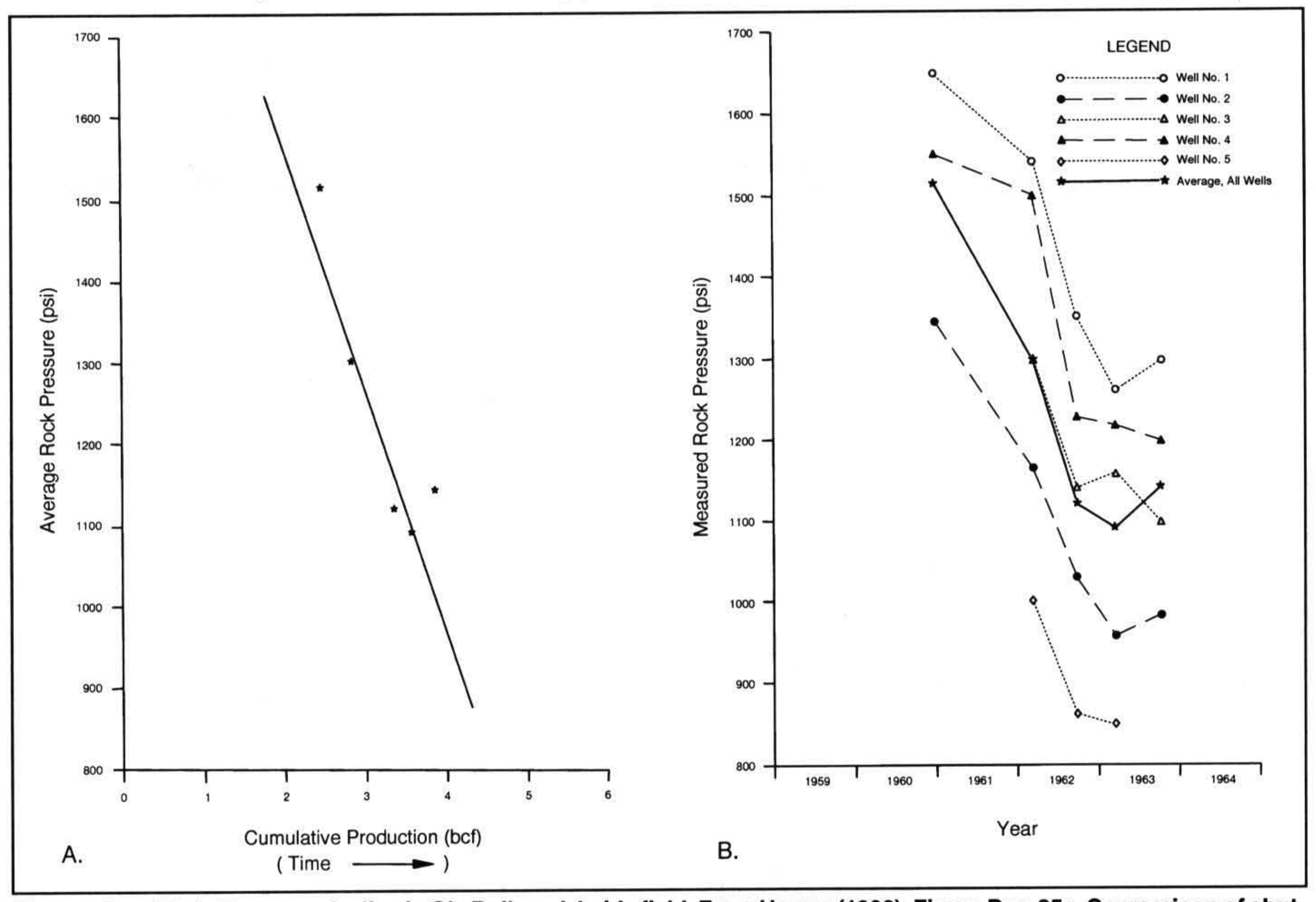


Figure Dos-23. Correlation of geological and petrophysical properties of the Oriskany Sandstone in Leidy field, based on core data from the New York State Natural Gas No. 6 Pennsylvania Tract 81 well in Leidy pool. From Harper (1990).



Figures Dos-25a-b. Pressure decline in Ole Bull pool, Leidy field. From Harper (1990). Figure Dos-25a. Comparison of shut-in well-head pressure decline with cumulative production. The straight line is the predicted decline curve. Figure Dos-25b. Comparisons of shut-in well-head pressure decline in five producing wells over the first three years of production.

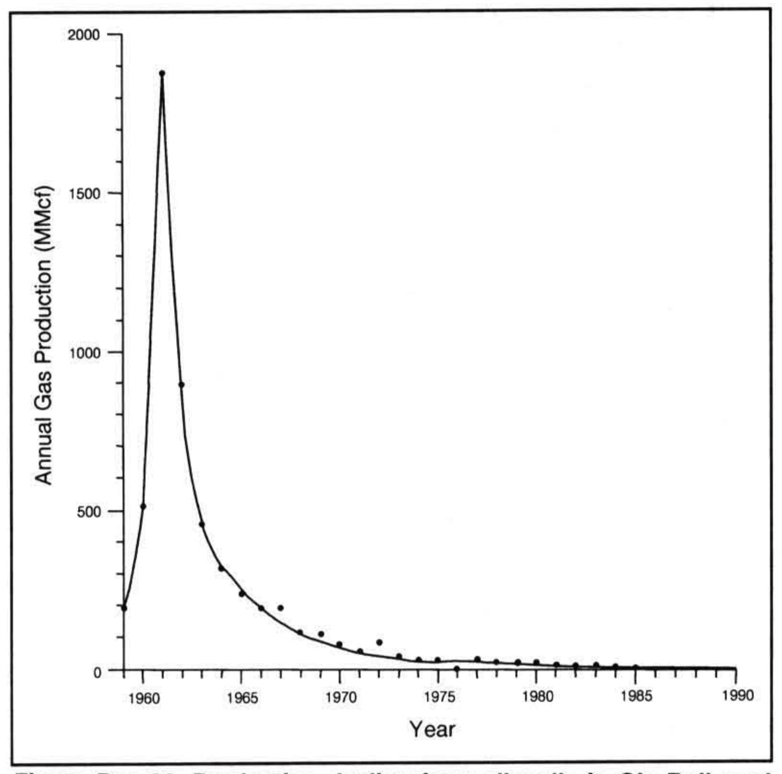


Figure Dos-26. Production decline from all wells in Ole Bull pool. From Harper (1990).

Table Dos-5. Analysis of gas from Oriskany Sandstone in the Minter Associates No. 1 Logue well, East Fork-Wharton field, Potter County, Pennsylvania (from Moore and Sigler, 1987a, sample number 10316).

Component	Mole Percent
Methane	95.5
Ethane	2.9
Propane	0.5
N-Butane	0.1
Isobutane	Trace
N-Pentane	0.1
Isopentane	Trace
Cyclopentane	Trace
Hexanes plus	0.1
Nitrogen	0.5
Oxygen	Trace
Argon	Trace
Hydrogen	0.0
Hydrogen sulfide	0.0
Carbon dioxide	0.2
Helium	0.01
Btu value	1,045
Specific gravity	0.583

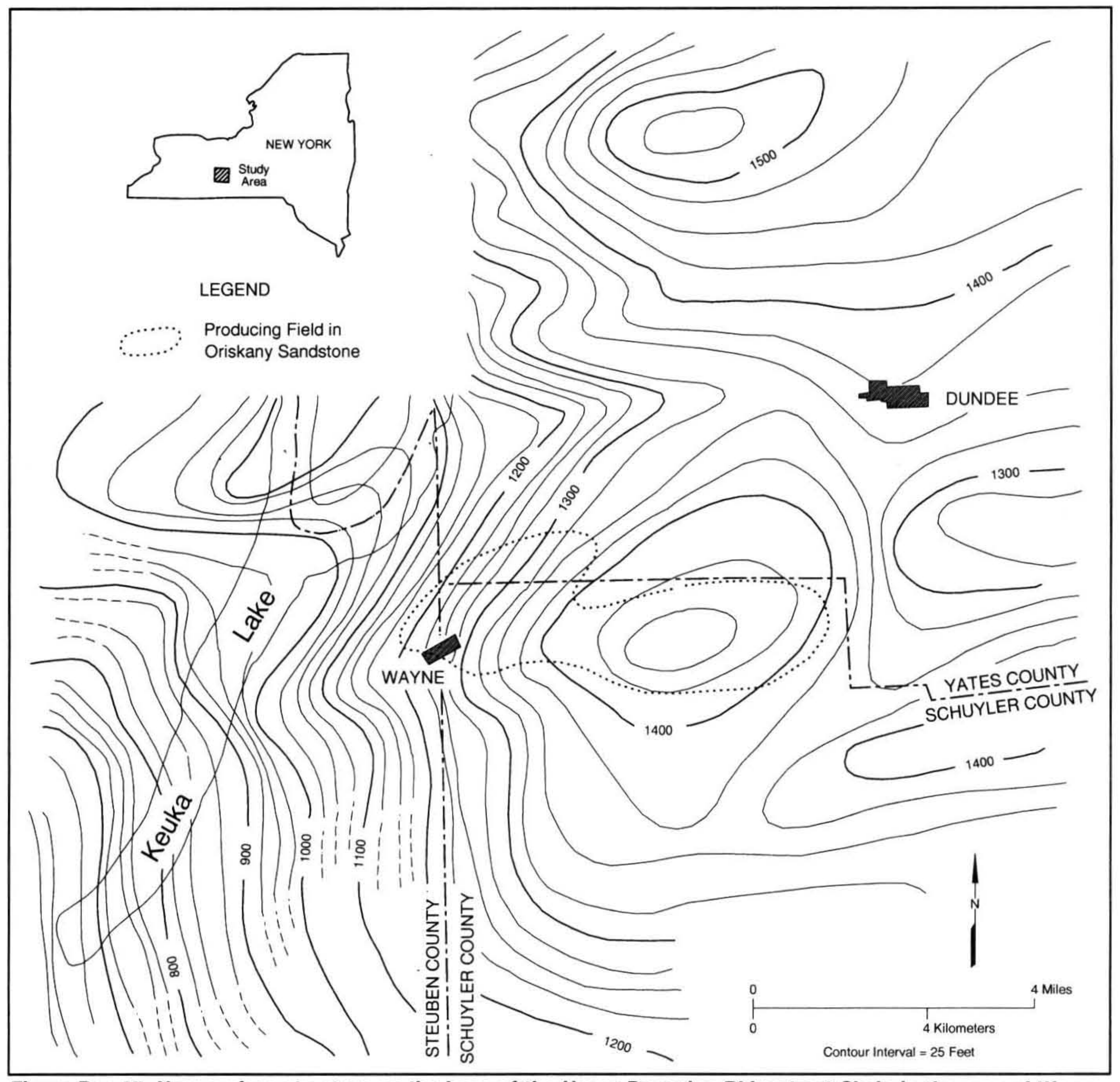


Figure Dos-27. Near-surface structure on the base of the Upper Devonian Rhinestreet Shale in the area of Wayne-Dundee field, Schuyler, Yates, and Steuben counties, New York. Dotted line indicates the outline of Wayne-Dundee field. Modified from Bradley and Pepper (1938).

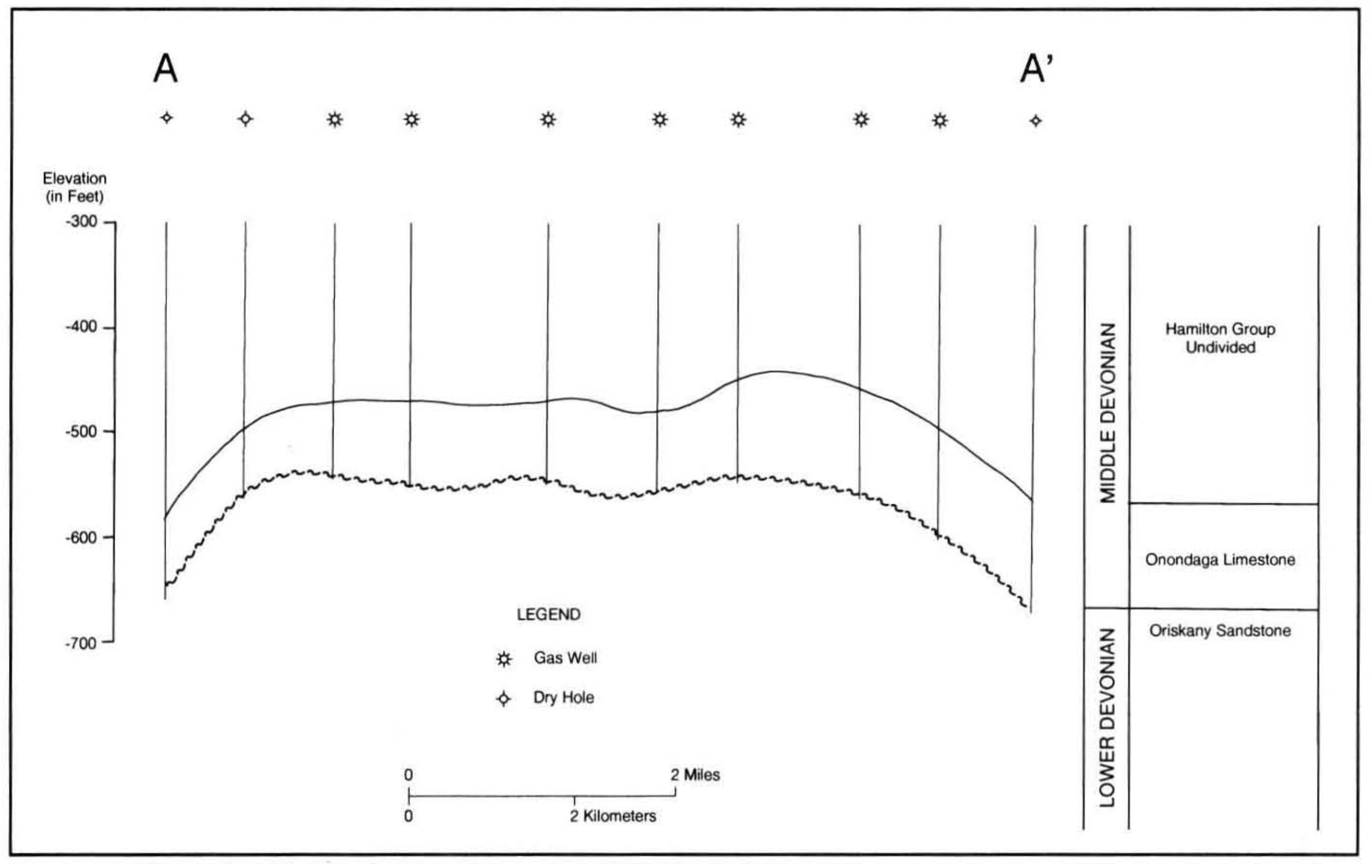


Figure Dos-29. Structural cross section of Wayne-Dundee field. See Figure Dos-28 for location.

Table Dos-6. Analyses of gases from Oriskany Sandstone in the Belmont Quadrangle Drilling No. 1 Pulver and No. 1 Lent wells, Wayne-Dundee field, Schuyler County, New York (from Moore and Sigler, 1987a, sample numbers 2374 and 2431).

Component	Mole Percent	
	No. 1 Pulver	No. 1 Lent
Methane	90.8	95.0
Ethane	6.5	2.1
Nitrogen	1.7	2.5
Oxygen	0.6	0.3
Carbon dioxide	0.4	0.1
Helium	0.04	0.05
Btu value	1,036	1,000
Specific gravity	0.601	0.578

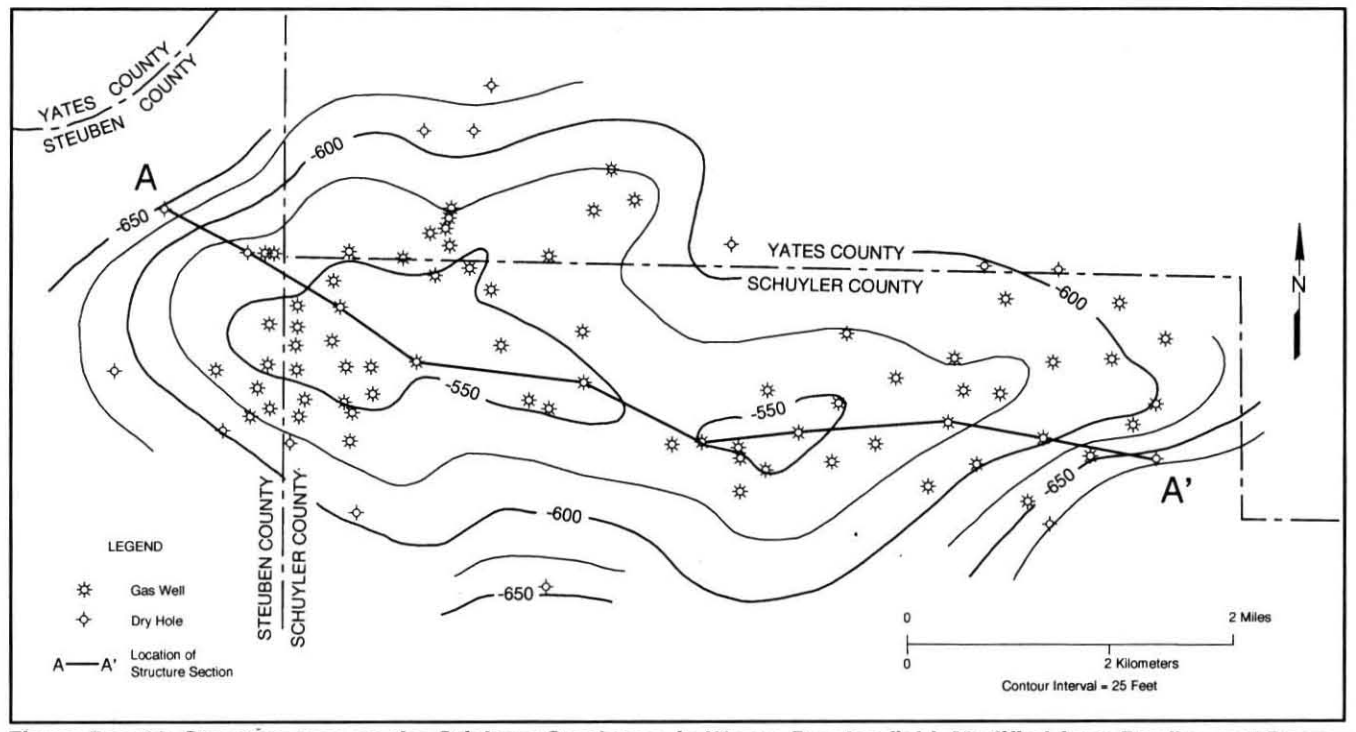


Figure Dos-28. Structure map on the Oriskany Sandstone in Wayne-Dundee field. Modified from Bradley and Pepper (1938). See Figure Dos-27 for location. Line of structural cross section A-A' (Figure Dos-29) is shown.

only 22 bcf original-gas-in-place. This situation, which seems to be relatively common to Oriskany and Huntersville reservoirs in the basin, has not been resolved satisfactorily. It is possible that open fractures account for more reservoir volume and porosity than can be determined from log analysis, or that the amount of acreage drained by Oriskany wells is grossly underestimated. Another possibility is that the reservoirs continue to be recharged while the field is being produced (C.D. Laughrey, oral commun., 1994). Regardless of the cause, this situation will likely continue during future exploration and development. More reasonable volumetric estimates can be made on old, depleted, or nearly depleted fields by assuming a 90 percent recovery rate. Using this approach, Hebron field had about 50 bcf original-gas-in-place.

Because the Oriskany structural traps play relies so heavily on the presence of anticlinal structures for gas entrapment and productivity, the total amount of acreage available for future drilling is necessarily limited. The total potential area of the play encompasses approximately 20.5 million acres in New York, Pennsylvania, Maryland, West Virginia, and Virginia. Of that total, only about 1.3 percent (267,000 acres) has been developed for gas production. Geomega, Inc. (1983), in preparing estimates of undiscovered recoverable resources of natural gas in Pennsylvania, determined that 1.6 percent of the total acreage ultimately would be shown to be productive, with an additional three percent categorized as possible to speculative. Extrapolating this concept to the whole region of the play yields 370,000 acres probable and 615,000 acres possible, totalling 965,000 acres having the potential to produce gas from the Oriskany structural traps play.

Geomega, Inc. (1983) assigned an average yield of 5,000 Mcf per acre for probable acreage and 3,000 Mcf per acre for possible acreage. Using these numbers for the entire play yields the following: 1.7 tcf has already been proved, 1.7 tcf probably will be discovered, and 1.8 tcf possibly will be discovered. Therefore, the total amount of gas yet to be discovered from the Oriskany structural traps play could be as much as 3.5 tcf.

Future Trends

Future Oriskany discoveries in the deformed areas of the Appalachian basin probably will consist mostly of very small fields and pools, generally consisting of fewer than 10 wells. Although the potential exists for discovery of new Oriskany fields and pools in all three subplays, the Valley and Ridge and Appalachian Plateau subplays have the most unexplored territory.

Many anticlines in the eastern West Virginia, north-central Pennsylvania, and south-central New York portions of the Appalachian Plateaus Province remain either untested or insufficiently tested to be ruled out as potential target areas. The 1986 discovery of Stagecoach field in Tioga County, New York,and its 1992 extension into Bradford County, Pennsylvania (Figure Dos-2), demonstrates that there still are fields and pools to be found in distal areas. In addition, industry needs to reevaluate structures that were abandoned after only a few unsuccessful test wells were drilled. Low-porosity, low-permeability sandstones often contain great quantities of natural gas locked within micropores. These sandstones, which might have been considered at best marginal reservoirs in the past, have the potential to produce commercially with the development of new stimulation techniques. Higher prices and close proximity to pipelines supplying northeastern markets would also make many of these previously marginal reservoirs more acceptable.

The intensely deformed rocks of the Valley and Ridge Province have only received cursory attention, yet there are more than ten Oriskany fields stretching from Bedford County, Pennsylvania, to Rockingham County, Virginia. Although most of these had reserves of less than 5 bcf, several of them, such as Five Forks in Pennsylvania and Lost River in West Virginia (Figure Dos-2), produced 10 to 15 bcfg before being converted to storage. Continued exploration utilizing modern geophysics should help to expand the known limits of Valley and Ridge production potential.

PLAY Doc: THE LOWER DEVONIAN ORISKANY SANDSTONE COMBINATION TRAPS PLAY

by Douglas G. Patchen, West Virginia Geological and Economic Survey, and
John A. Harper, Pennsylvania Bureau of Topographic and Geologic Survey

Location

The Oriskany Sandstone combination traps play occupies a 25- to 50-mile-wide zone that extends from southwestern New York through northwestern Pennsylvania and eastern Ohio into western West Virginia (Figure Doc-1). The play is flanked on the west by the Oriskany pinchout play (see S. Opritza, Lower Devonian Oriskany Sandstone updip permeability pinchout play, this atlas), and on the east by the fractured Huntersville Chert-Oriskany Sandstone play (see K. Flaherty, Fractured Middle Devonian Huntersville Chert and Lower Devonian Oriskany Sandstone play, this atlas). Twenty-four named fields are included in the play, as well as a few small, unnamed areas of gas production and some isolated Oriskany wells. Fields in this play produce from combination stratigraphic-structural traps, whereas Oriskany fields to the west are associated with the pinchout of the Oriskany Sandstone. Fields to the east produce gas from fractured reservoirs in both the Oriskany Sandstone and the overlying Huntersville Chert on larger structural features.

The western edge of the Oriskany Sandstone combination traps play is defined by the westernmost extent of small structures that have created stratigraphic-structural traps in the Oriskany. The eastern boundary of the play is defined by a line that marks the westward limit of detached folds at the Oriskany level.

Production History

The earliest gas production from the Oriskany Sandstone in fields belonging to the combination traps play occurred in 1930 when the Campbell Creek-Malden field was discovered in Kanawha County, West Virginia. During the next seven years, seven additional fields were discovered: Allen (1932) in Allegany County, New York; Elk-Poca (1933) in Kanawha and Jackson counties, West Virginia; Big Chimney (1934) in Kanawha County, West Virginia; Blackhawk (1935) in Beaver County, Pennsylvania; Wellsville (1935) in Columbiana County, Ohio; Howard (1936) in Steuben County, New York; and Hernshaw-Bull Creek (1937) in Kanawha County, West Virginia (Figure Doc-2). The remaining 16 named fields in the Oriskany Sandstone combination traps play were discovered between 1944 and 1972. Significant fields discovered during this interval of time include Blue Creek (1944) in West Virginia, Allegany State Park (1955) in New York, and Elk Run (1965) in Pennsylvania. Cumulative production figures are available for just six of the 24 fields in the play. Gas production from these six fields has exceeded 1.12 tcf, of which nearly 1 tcf was from the giant Elk-Poca field. The estimated production from all 24 fields is approximately 1.3 tcf.

Stratigraphy

The productive interval for each of the 24 fields in this play is in the Lower Devonian Oriskany Sandstone, or in another sandstone at the approximate stratigraphic position of the Oriskany Sandstone as first used in Oneida County, New York. In its type section, the Oriskany Sandstone is a white, fossiliferous quartz arenite that is separated from the underlying Helderberg Limestone and the overlying Onondaga Limestone by unconformities. Use of the name Oriskany Sandstone has been extended throughout the basin, although the presence of the unconformities above and below the Oriskany suggests several erosion events that resulted in deposition of local sandstones (Figure Doc-3) in the approximate stratigraphic position of the Oriskany. These local sandstones include the Sylvania in Ohio, the Springvale in New York, and the Ridgeley in Pennsylvania. As used in this play description, the name Oriskany Sandstone could apply to any of these sandstones as well as to a sandstone that is continuous with the true Oriskany of New York.

As defined, within the geographic limits of this play the Oriskany Sandstone is a white, fossiliferous quartz arenite that occurs between two gray, cherty limestone units: the overlying Middle Devonian Huntersville Chert and Onondaga Limestone and the underlying Lower Devonian Helderberg Limestone (Figures Doc-3, Doc-4). Overlying rocks vary in lithology from limestone in the north and west to chert in the eastern portion of the play trend (Figure Doc-5). The limestone facies is the Onondaga Limestone, and the chert facies is the Huntersville Chert. The Huntersville is present above the Oriskany east of the play boundary, but is not present above the Oriskany in most of the combination traps play area. The chert is productive to the east in the fractured Huntersville-Oriskany play trend.

The Oriskany thins from east to west across the basin, from a maximum of 350 feet in western Maryland to 0 feet at the eroded edge of the unit in Ohio, Kentucky, West Virginia, southwestern Virginia, and New York (Figure Doc-6). In addition, several areas of no sandstone occur within the sheet of Oriskany Sandstone in Ohio, Pennsylvania, and New York. Some traps in the play occur where the sandstone pinches out across low-amplitude structural highs that plunge toward the pinchout. Other traps were created where thinning of the sandstone removed the upper, porous pay section, creating an updip pinchout of permeability in combination with a structural feature. Within some of the larger fields, variations in sandstone thickness due to depositional processes have created areas of thicker sandstone that often overlie structural highs, yielding higher gas production from wells drilled in those areas.

Four facies have been recognized in the Oriskany in cores from West Virginia gas wells (Bruner, 1991). Facies 1, a mixed carbonate-clastic shelf facies, occurs at the base of the Oriskany and represents deposition in quiet water below fair weather wave base. Facies 2, a submarine sand ridge facies, is characterized by trough cross-bedded sandstones, and represents deposition in a high energy

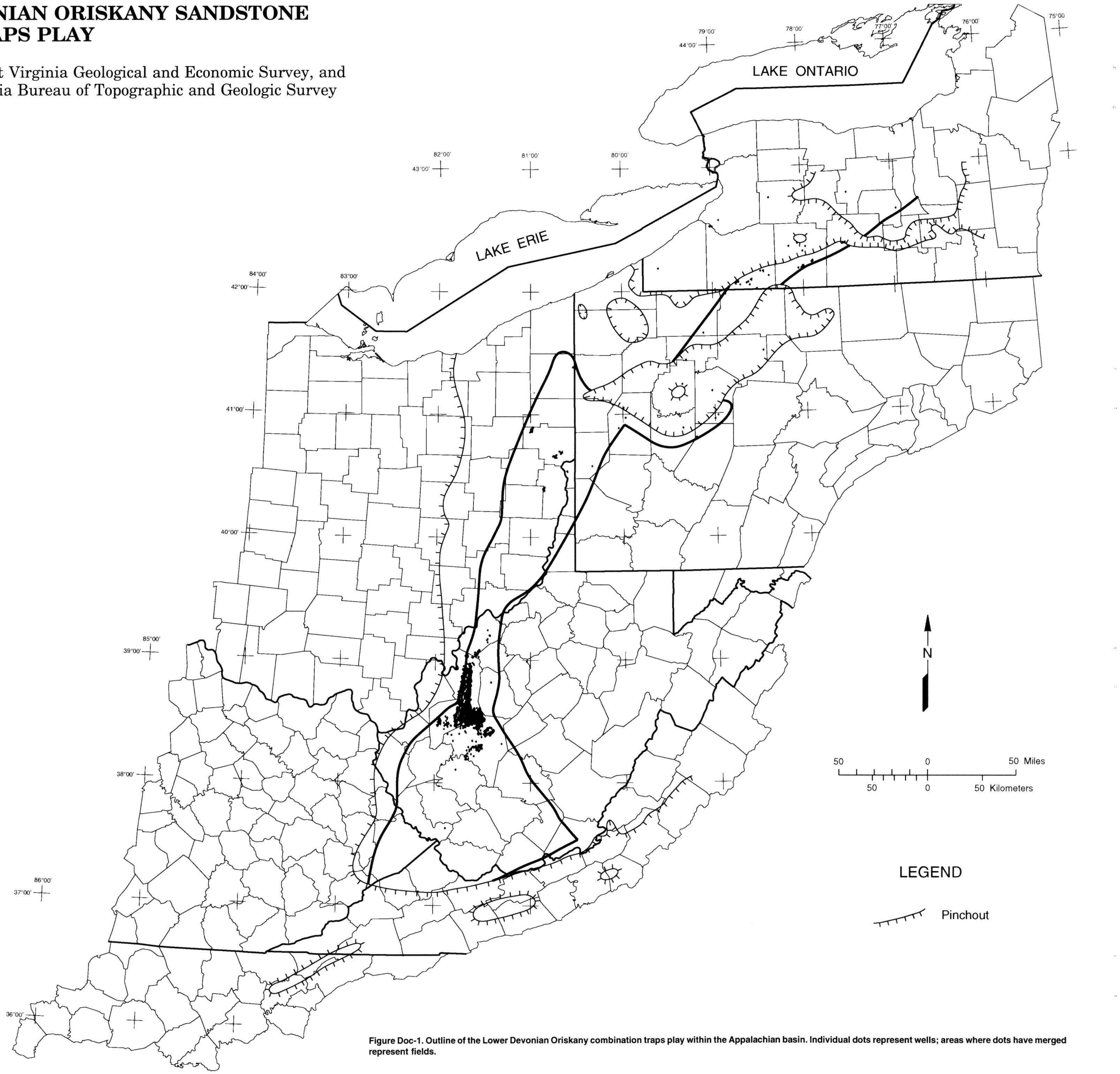


Figure Doc-1. Outline of the Lower Devonian Oriskany combination traps play within the Appalachian basin. Individual dots represent wells; areas where dots have merged represent fields.

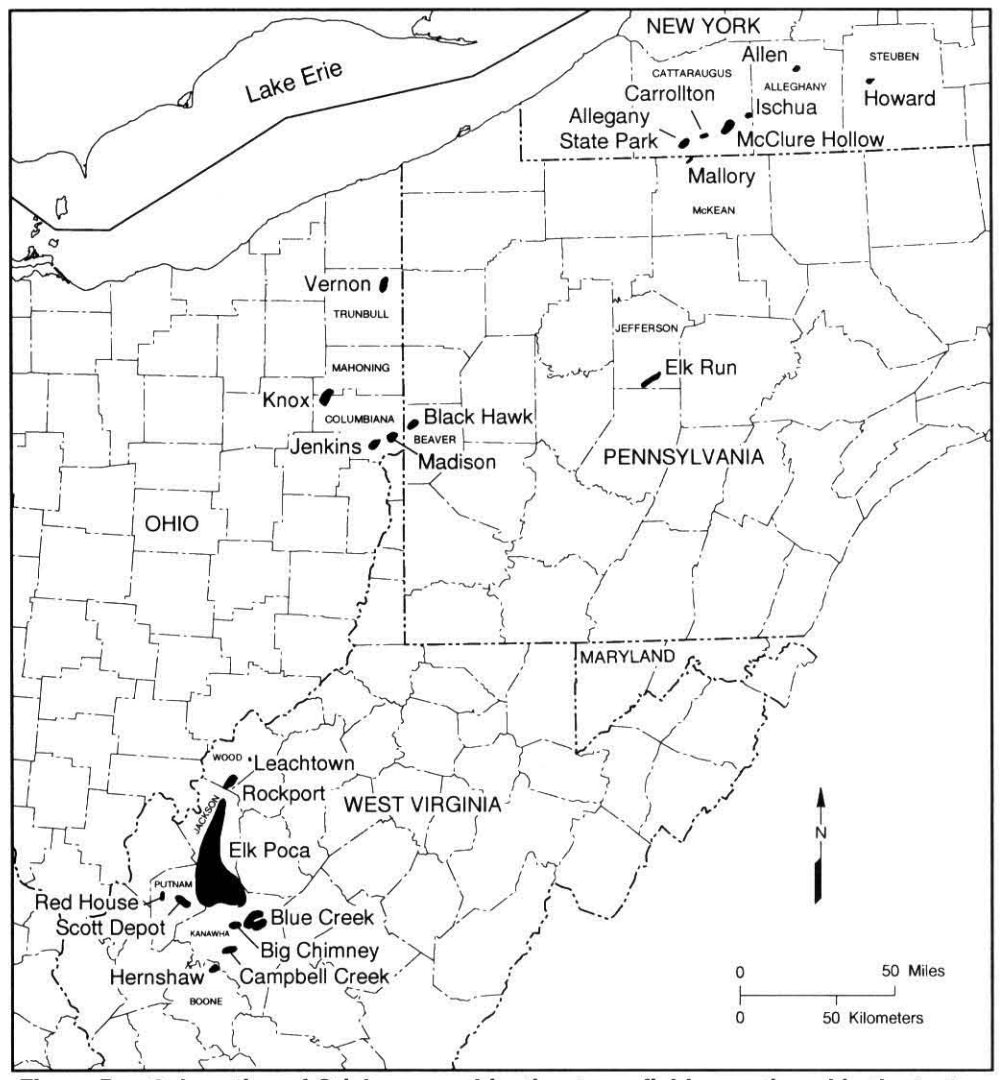


Figure Doc-2. Location of Oriskany combination traps fields mentioned in the text or in Table Doc-1.

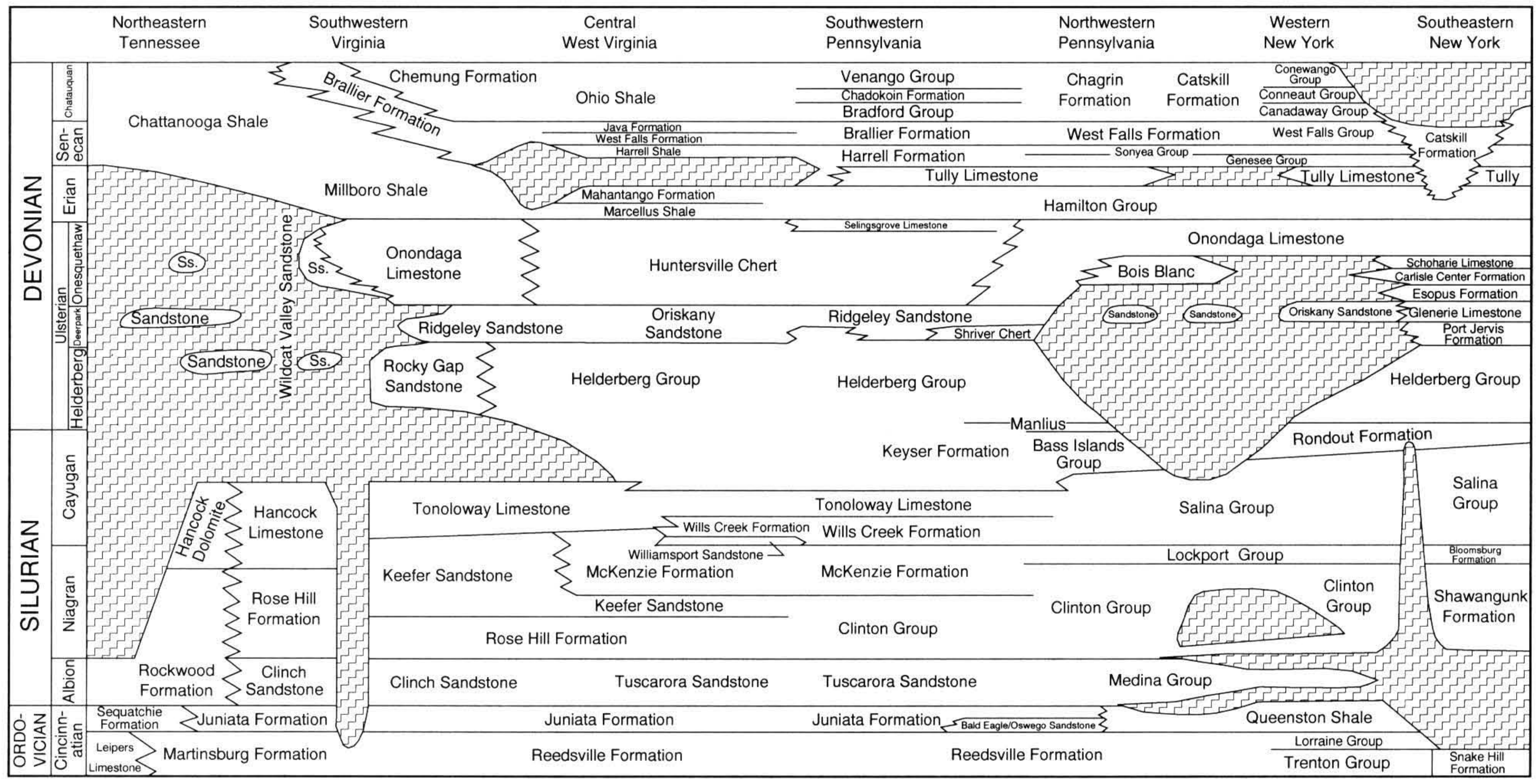
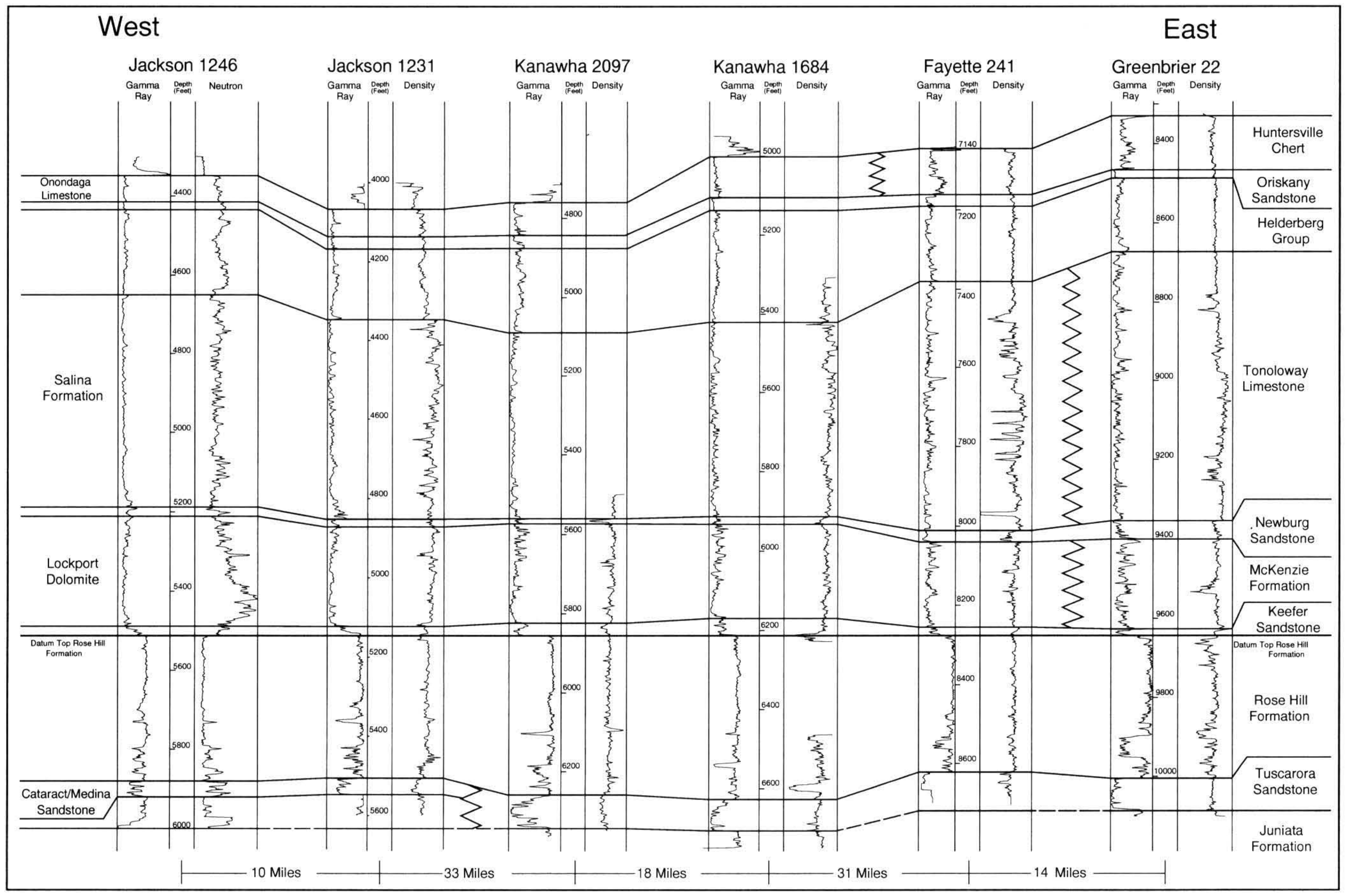


Figure Doc-3. Correlation chart (modified from Diecchio, 1985) illustrating the stratigraphic position of the Oriskany and Ridgeley sandstones, the location of unconformities, and other sandstones in the approximate stratigraphic position of the Oriskany.



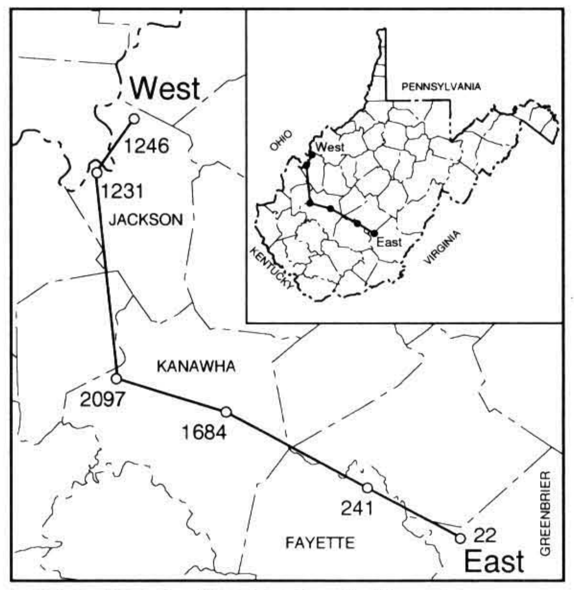


Figure Doc-4. West-east stratigraphic cross section based on gamma-ray logs from wells in southern West Virginia illustrating the stratigraphic position of the Oriskany Sandstone.

environment that was affected by waves and currents. Facies 3, a fair weather shallow shelf facies, is characterized by wavy, discontinuous, argillaceous, and organic laminae disrupted by burrows and a diverse normal marine fauna. Rocks in this facies were deposited during normal fair weather conditions at depths between fair weather and storm wave base. Facies 4, a storm deposit or tempestite facies, consists of an erosional base succeeded by coarse-grained to pebbly quartz and skeletal fragments overlain by laminated, finer-grained sandstones. It records storm events that interrupt normal fair weather sedimentation.

The vertical distribution of these facies reflects an overall regressive pattern of Oriskany sedimentation (Bruner, 1991). The distribution of facies also records lateral changes in depositional environments. In general, the Oriskany is more quartzose in eastern areas and storm deposits are thicker and contain coarser grains. Farther west, in the area of the combination traps play, storm deposits are present but are thinner, reflecting deposition in distal portions of the Oriskany seaway (Bruner, 1991).

Structure

Throughout most of the basin where the Oriskany is productive, structural deformation is a significant factor in controlling the occurrence of natural gas. These productive areas span four structural provinces, each of which decreases in structural complexity from east to west (Figure Doc-7). Fields in the Oriskany Sandstone combination traps play are located in the two areas with the least structural deformation: the low-amplitude fold province and the western basin province (Diecchio, 1985). In these areas, intergranular porosity in the Oriskany is assumed to be more dominant than fracture porosity (Diecchio, 1985). Fracture porosity does occur in some fields such as the Elk Run pool in Jefferson County, Pennsylvania (Heyman, 1969), but it is considered to be subsidiary to intergranular porosity in those fields.

As its name implies, the low-amplitude fold province is a low upland in which surface and subsurface folds are prominent, although of less amplitude and fewer in number than in the high-amplitude fold province to the east (Figure Doc-7). The Elk Run pool in Pennsylvania is present on the east flank of a structural high near the eastern edge of the low amplitude fold province, between the western edge of the high amplitude fold province and the area of no Oriskany (Figure Doc-8). Allegany State Park field in New York is located on the western edge of the low amplitude fold province, in a narrow area between two no-sandstone areas. The western boundary of the low-amplitude fold province coincides with the approximate western limit of Alleghanian thrusting (Bayer, 1983).

The area west of the limit of detachment and prominent folding is referred to as the western basin (Figure Doc-7). Although folds in this area are few in number and low in relief, several prominent folds are present; two of these, the Milliken anticline and the Sissonville high, are responsible for gas accumulation in the giant Elk-Poca field in Kanawha County, West Virginia (Figure Doc-9). Smaller Oriskany fields occur in the western basin where more subtle anticlinal features, developed on the down-to-the-east regional structural dip, are combined with westward updip pinchout of permeability.

Reservoir

As the name of the play indicates, all fields within this play are classified as combination stratigraphic-structural traps. In the northern part of the play in New York and Pennsylvania, traps are developed on low-amplitude anticlines that subparallel the erosional edge of the sandstone. In some cases, the sandstone pinchout occurs on anticlinal flanks parallel to the axis of the structure, whereas in others the pinchout crosses the axis where the anticline strikes into the pinchout. The combination of porosity enhancement and structural highs traps the gas that has accumulated in these fields.

Farther south, in West Virginia, traps are developed parallel to, but set back from, the erosional edge of the sandstone. In these areas, pay sections near the top of the sandstone are eliminated before the entire sandstone pinches out updip to the west. Structure is important, however, as most of the fields are located on small, low-amplitude structural highs that were the targets of drillers.

Two intervals of thick, black shale rich in organic matter are present above the Oriskany throughout most of the play area: the Rhinestreet Shale Member of the West Falls Formation and the Huron Shale Member of the Ohio Shale. In addition, older, thinner black shales—the Marcellus Shale, Geneseo Shale Member of the Genesee Formation, and the Middlesex Shale Member of the Sonyea Formation—occur above the Oriskany along the eastern edge of the play. The interval that contains these black shales and interbedded gray shales thickens eastward from less than 1,000 feet on the west to several thousand feet in the center of the basin. This eastward thickening placed black shale source beds in the basin center at the same or lower elevation as Oriskany reservoir rocks to the west. This allowed horizontal migration of gas from the black shales into Oriskany fields in this play.

The reservoir rock in each of the fields in this play is the white, fine-grained, texturally mature Oriskany Sandstone. The dominant intergranular porosity in the Oriskany Sandstone reservoirs in this play may be related to the close proximity of the reservoirs to the Oriskany pinchout. Erosion responsible for removing the Oriskany Sandstone around the western side of the basin and in the no-sandstone areas was accompanied by leaching that produced higher intergranular porosity near the Oriskany Sandstone pinchouts. Eastward (basinward) intergranular cement commonly increases so that large areas of the low-amplitude fold province have no commercial production in the less porous and permeable Oriskany Sandstone.

Throughout the play area, the Oriskany is a white to light gray, fine- to medium-grained, subround to rounded, calcareous sandstone. Quartz is the main cement in the upper pay zone, whereas the abundance of calcite cement increases downward as porosity decreases. The upper contact with the overlying Huntersville Chert is usually sharp in samples and on gamma-ray and density logs, although in some areas a siltstone or poorly developed cherty sandstone is present in the basal Huntersville.

The lower contact of the Oriskany with the underlying Helderberg Limestone is gradational and has been placed at different stratigraphic positions by different geologists. In much of the Elk-Poca field, two sandstones are present: an upper, porous sandstone and a lower, tighter sandstone, separated by a thin limestone (Figure Doc-10). The upper sandstone is more variable in thickness, less

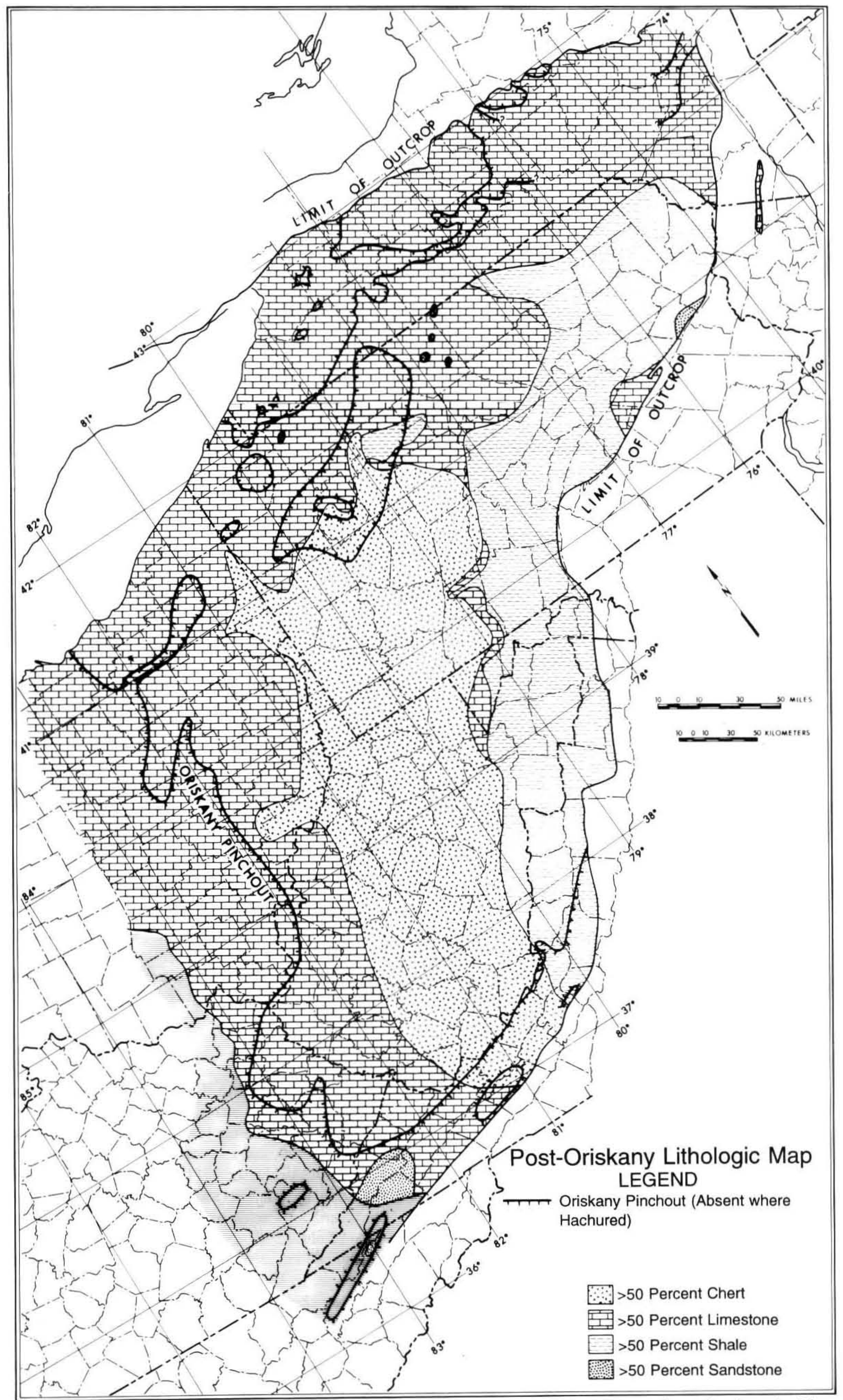


Figure Doc-5. Lithologic map of units that overlie the Oriskany Sandstone throughout the Appalachian basin. From Diecchio and others (1984).

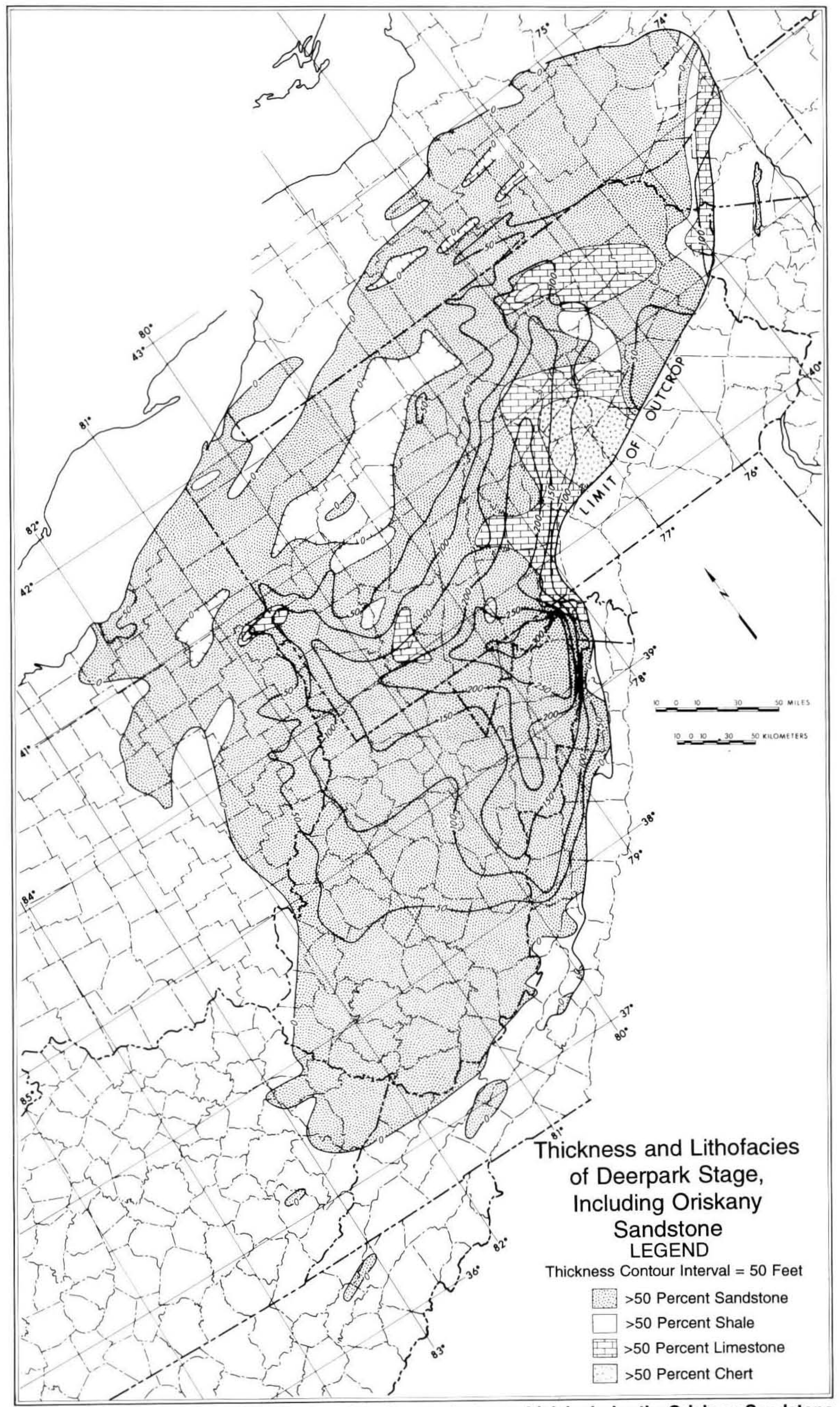


Figure Doc-6. Thickness and lithofacies of the Deerpark stage which includes the Oriskany Sandstone throughout the Appalachian basin. From Diecchio and others (1984).

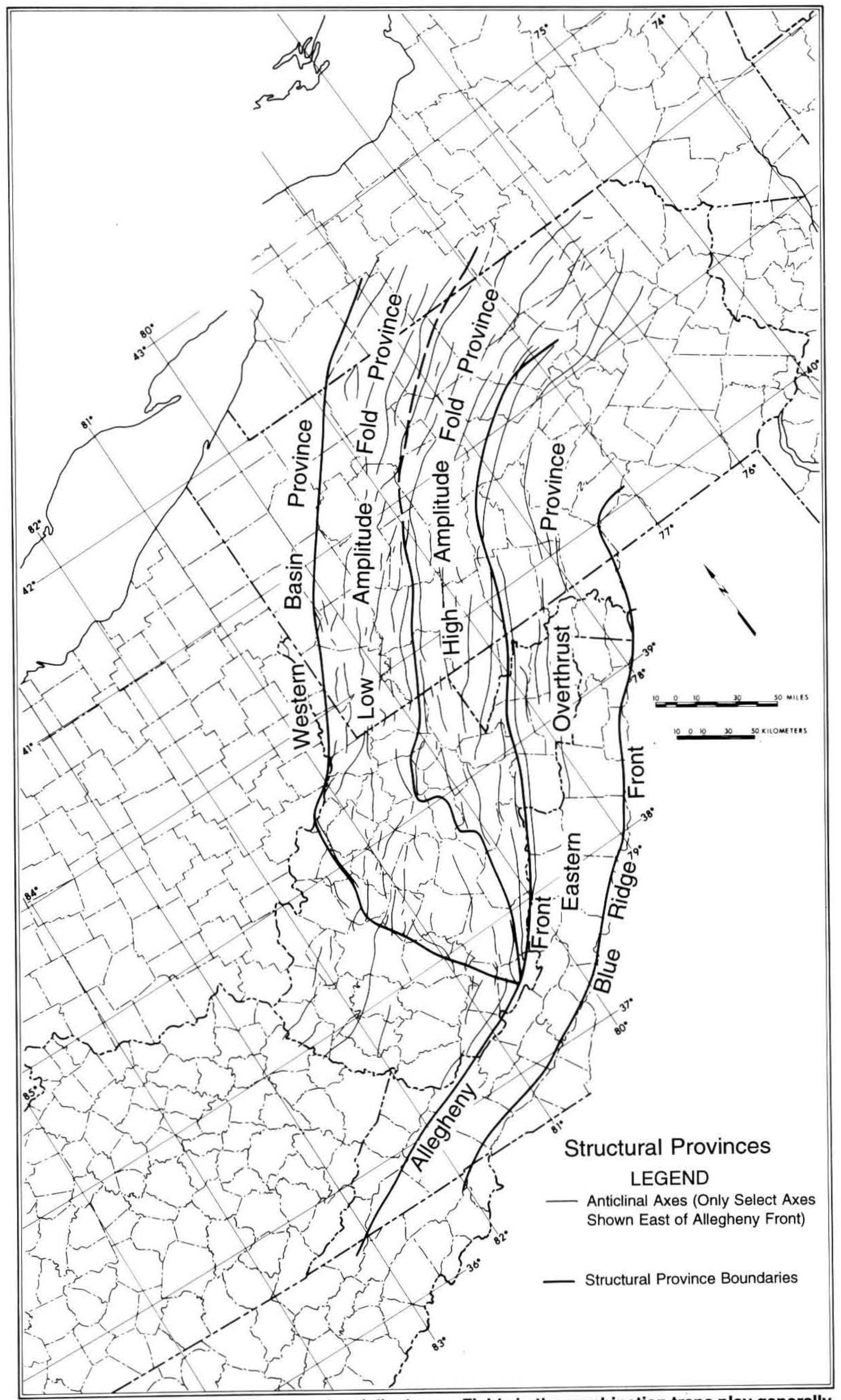


Figure Doc-7. Structural provinces and anticlinal axes. Fields in the combination traps play generally are west of the low amplitude fold province. Modified from Diecchio and others (1984).

calcareous, coarser grained, and more mature. Both porosity and permeability are higher in this upper sandstone than in the lower sandstone; consequently, many geologists placed the base of the Oriskany below it at the top of the thin limestone. Other geologists, however, defined the Oriskany as a sandstone interval between two cherty limestone formations (Onondaga and Helderberg), and placed the lower contact below the lower sandstone. Thus, the first definition is based on reservoir quality, whereas the second definition is based on lithology.

The gas reservoir within the Oriskany is developed in the upper part of the sandstone where incomplete cementation by quartz and carbonate has resulted in higher porosity and permeability. Areas of thinner sandstone to the west lack this porous zone, but have been completed using modern stimulation techniques. Within the pay zone, individual pores are most commonly surrounded by euhedral, often prismatic quartz overgrowths (Bruner, 1991). More than half of the pores observed in thin section were of this type. The euhedral shape of the overgrowths indicates that voids were present at the time of quartz growth.

Local secondary porosity in the Oriskany Sandstone consists of two types: intragranular secondary pores and framework grain dissolution pores (Bruner, 1991). The most common intragranular pores are caused by eroded channels within quartz grains. Partial to complete dissolution of feldspar grains typically created the framework grain dissolution pores. Combination pores, primary pores enhanced by secondary processes, also contribute a significant amount of porosity to the Oriskany.

Depths to the Oriskany in fields within this play range from 3,200 feet in Vernon field in Ohio to 7,100 feet in Elk Run pool in Pennsylvania. In general, depths range from less than 4,000 feet to 4,700 in New York and Ohio, and from 4,500 to 5,200 feet in West Virginia at the southern end of the play.

Because most of the fields within this play are near the erosional limit of the Oriskany, the thickness of the Oriskany within them is less than 50 feet. The portion of the Oriskany that is completed in these fields ranges from 8 to 25 feet, although the true pay section, as determined from density and porosity logs, ranges from 6 to 20 feet (Table Doc-1).

Reservoir pressure within fields in this play varies with depth. Most fields appear to be of normal pressure, with initial pressures ranging from 1,200 to 3,900 psi. Initial open flows range from less than 100 Mcf/d in Scott Depot field to more than 11,000 Mcf/d in Rockport field. Final open flows following stimulation range from 150 Mcf/d in Red House field to 8,265 Mcf/d in Elk Run pool. In many of the older fields, the better wells were completed as natural producers and only the poorest wells were stimulated. Thus, in some fields the average initial open flow is higher than the average final open flow after stimulation.

Heterogeneity in reservoirs within this play is due to diagenetic and depositional features. Diagenetic heterogeneity is due to variations in the type and amount of cements, and the ratio of primary to secondary porosity. Heterogeneity due to deposition is reflected in variations in sandstone thickness in fields such as Elk-Poca.

Many of the fields within this play are known to have a salt water drive (Table Doc-1). Other fields also may have a water drive, or are driven by gas expansion as the wells are produced and pressure declines.

The nature of the decline in production from most of these fields is unknown due to the scarcity of individual well production histories. Production declined rapidly in Elk-Poca field, and the decline is typical for reservoirs with average porosity but high permeability.

Description of Key Fields

Elk-Poca field: The giant Elk-Poca gas field is located in Kanawha, Jackson, and Putnam counties, West Virginia, west of the low amplitude fold province (Figures Doc-2, Doc-7). Although low amplitude anticlinal features controlled early drilling trends and production, full field development was controlled by thickness trends within the Oriskany and the loss of permeability updip to the west.

The field was discovered in 1933 when a shallow well, the No. 2 P.H. Frankenberger (West Virginia permit number Kanawha 204) (Figure Doc-11), located near the southern end of the Milliken anticline was deepened to the Oriskany by N. N. Grosscup and others. Gas was noted during drilling in a thin, 4-foot-thick zone near the top of the Oriskany Sandstone. After the entire 18-foot-thick Oriskany interval open to the well bore was stimulated with explosives, a gas flow of 134 Mcf/d was tested. Two nearby wells (Kanawha 111 and 116) (Figure Doc-11) also were deepened to the Oriskany, but neither tested more than 150 Mcf/d after stimulation. However, one year after the discovery well was completed, Grosscup and others completed a 200-barrel-per-day oil well on the W.L. Burdette farm, in what is now the Big Chimney field. That oil discovery renewed interest in drilling Oriskany wells on the Milliken anticline. Although this was the only Oriskany well that produced much oil, it provided the stimulus for the rapid development of acreage farther north along the crest of the Milliken anticline.

Following completion of the discovery well, nine additional wells were drilled within three years, resulting in eight gas wells, some of which tested gas flows in the 1,000 Mcf/d to 5,000 Mcf/d range. These early wells usually did not penetrate the entire Oriskany Sandstone. Large gas flows commonly terminated drilling in the first 10 to 15 feet of Oriskany. Drilling of other wells ceased when a thin limestone was encountered below the upper, porous Oriskany (Figures Doc-10, Doc-12). This limestone usually was only 8 to 10 feet thick, and was underlain by another 20 to 25 feet of sandstone. Thus, it became common practice early in the 1940s to re-enter a well that had been producing for two or three years to deepen it to the lower sandstone (Figure Doc-13). This practice resulted in the discovery of additional pay zones in both the upper and lower parts of the Oriskany Sandstone.

Prior to 1940, most of the Oriskany wells completed in this field were in the southern part of the field in Elk and Poca districts (hence the name Elk-Poca), Kanawha County (Figure Doc-13). However, three important wildcat wells were completed in Jackson County in 1938 and 1939. One well (Jackson 25) defined the updip edge of the Jackson County portion of the field (Figure Doc-11); another well (Jackson 47) discovered a trend of thicker sandstone in the middle of the field; and the third (Jackson 43) defined the northern edge of the field. Discovery of gas in the Oriskany this far north of the Milliken anticline led to rapid development of the giant field during the next few years.

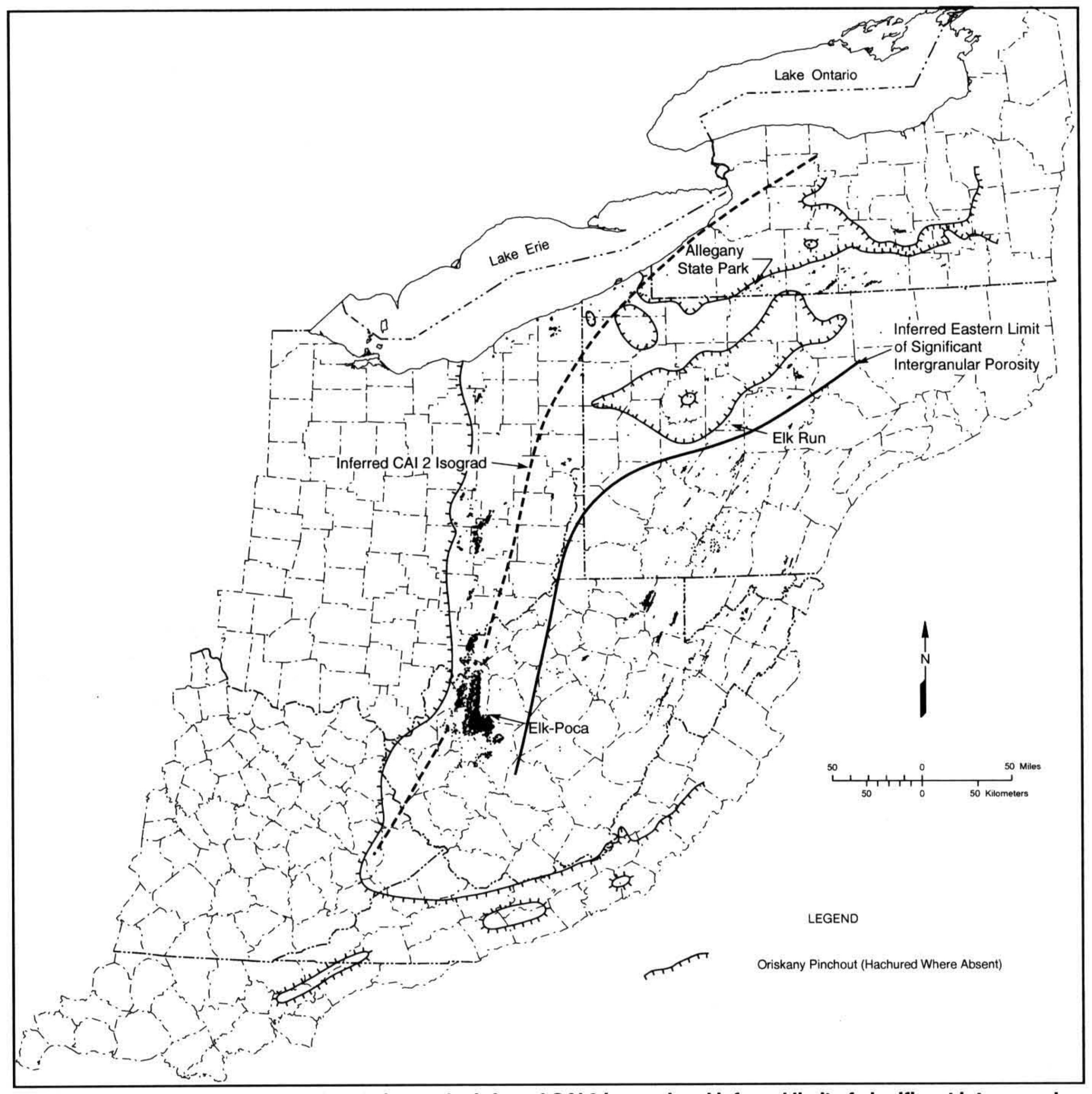


Figure Doc-8. Oriskany gas fields in relation to the inferred CAI 2 isograd and inferred limit of significant intergranular porosity. Locations of Elk-Poca and Allegany State Park fields and Elk Run pool are shown. From Diecchio (1985).

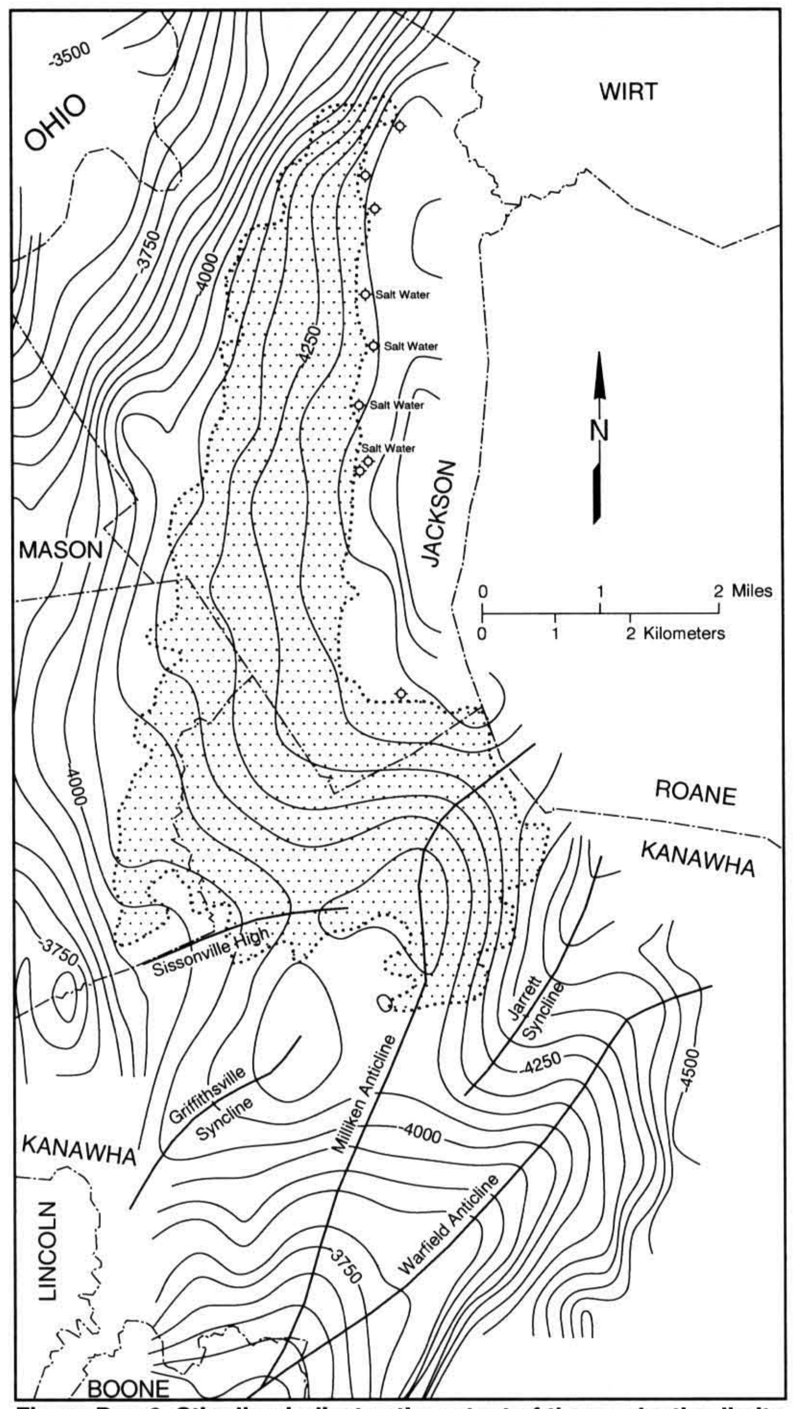


Figure Doc-9. Stippling indicates the extent of the productive limits of the Elk-Poca field, West Virginia. The structural control on gas production is due to the Milliken anticline and the Sissonville high. Contour interval = 50 feet. From Patchen and others (1992). See Figure Doc-2 for location.

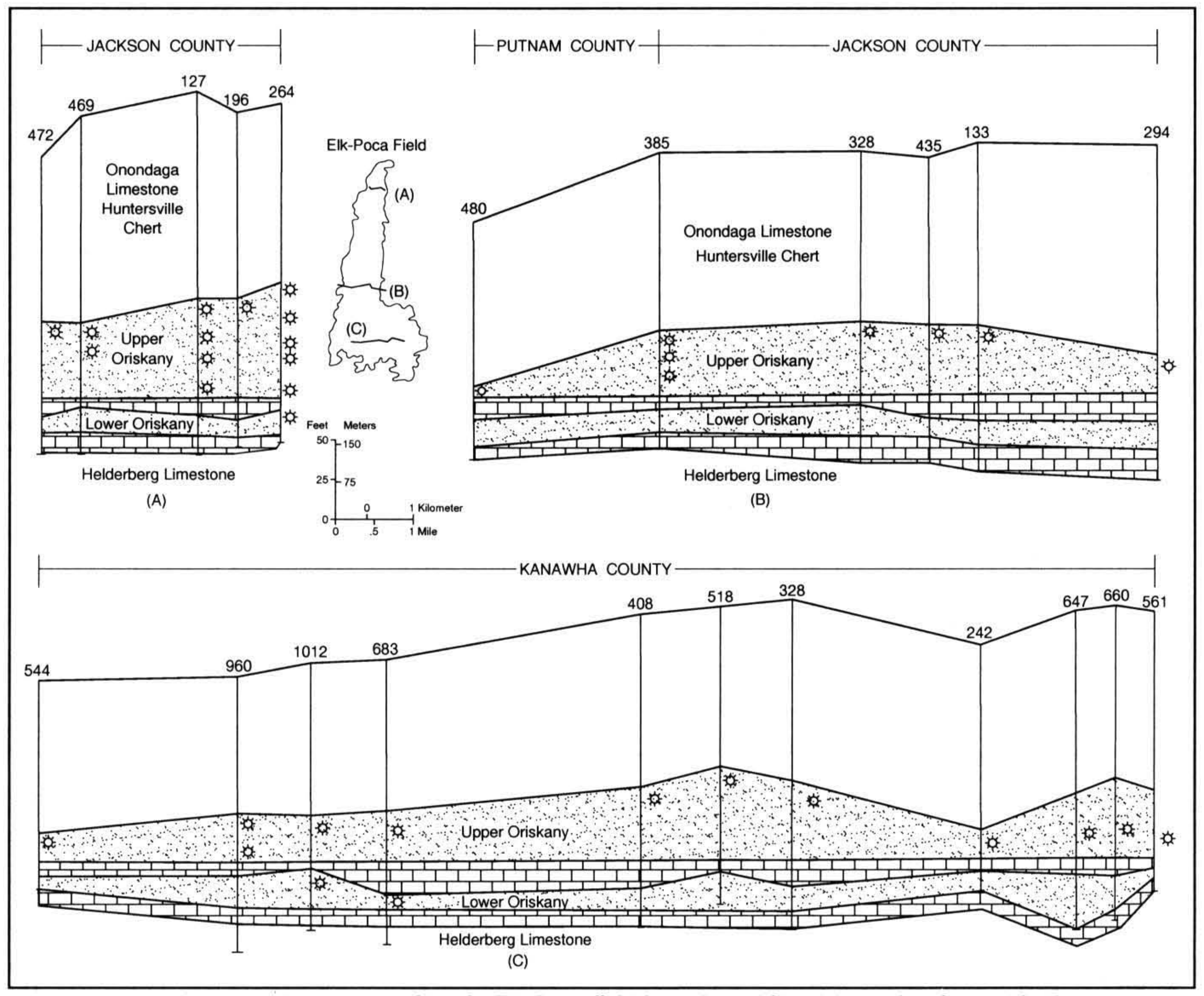


Figure Doc-10. Stratigraphic cross sections in Elk-Poca field based on drillers' logs showing a thin limestone that separates the Oriskany into an upper, porous sandstone and a lower, more calcareous and less porous sandstone. From Patchen and others (1992). Well designations are West Virginia permit numbers.

From 1940 to 1944, most of the productive acreage was defined (Figure Doc-13). Initially, wells were drilled west of the Milliken anticline, along the Sissonville high (Figure Doc-9), and then northward, following thickness trends (Figure Doc-14) in the Oriskany. Thus, the initial structural play soon became a stratigraphic play as drillers traced thickness trends northward keeping west of the downdip gas-salt water contact that defined the eastern edge of the field (Figure Doc-9).

By the end of World War II, not only had the entire productive trend of the field been defined, but most of the infield acreage had been drilled and many of the original producing wells had been abandoned. Thus, later drilling moved westward (updip) into areas of thinner, tighter sandstone closer to the pinchout of the Oriskany Sandstone, resulting in development of small areas in Jackson and Putnam counties (Figure Doc-13). Stimulation by hydraulic fracturing that began in the 1950s aided in the later development of these areas of tighter sandstone.

The Oriskany ranges in thickness from less than 30 feet on the western edge of the field to as much as 70 feet on the eastern edge of the field (Figure Doc-14). In addition to the overall east-to-west thinning, individual thickness trends in the Oriskany are oriented north-south within the field. One of these thickness trends correlates closely with the crest of the Milliken anticline, an area with better than average gas wells, whereas another thickness trend crosses the Sissonville high subparallel to the axis of the Milliken Anticline (compare Figures Doc-9 and Doc-14). One interpretation of these trends is that the clean, mature quartz sand in the upper sandstone of the Oriskany was deposited as a series of offshore bars in a high energy, shallow marine environment.

Variations in cement and porosity have played a significant role in creating the reservoir in Elk-Poca field (Bruner, 1991). Unconformities may be present above and below the Oriskany. Solution associated with the unconformities may account for some of the secondary porosity observed in the carbonate fraction of the Oriskany Sandstone. However, because most of the porosity in the Oriskany is in the quartzose facies, where porosity has been preserved by incomplete cementation and enhanced by secondary pores, the effect of local unconformities on the overall porosity of the Oriskany Sandstone does not appear to be significant.

Porosity measured on samples of Oriskany blown out of the hole either by high gas flows or during shooting is relatively low but consistent, averaging 8 percent. Permeability measurements on these samples average 27.5 md (Headlee and Joseph, 1945), and correlate with natural open flows (Figure Doc-15). Because of these factors, gas wells in the Elk-Poca field are characterized by high flow rates followed by a rapid decline in production (Headlee and Joseph, 1945). Gas in less permeable sections above and below the main pay zone may eventually flow into the main reservoir, enhancing ultimate production.

Of the nearly 1,200 wells in this field, approximately 1,100 were successful completions. The average well spacing on the 165,000 acre field is 150 acres per well. Average well depth was 4,900 feet, with a range of 4,600 to 5,300 feet. The thickness of the Oriskany ranges from 30 to 80 feet, and averages 40 feet, whereas net pay thickness ranges from 10 to 20 feet in most wells, averaging 14 feet (Table Doc-1).

During the first 40 years of production from this field, the 1,100 gas wells produced nearly 1 tcfg. Yield per acre-foot was approximately 416 Mcf. Some production still occurs from isolated wells, but most of the wells in this field have either been abandoned or converted to storage. Two productive trends within the field are aligned north-south (Figure Doc-16): a western updip trend, and an eastern downdip trend. Of these, the eastern downdip trend was more productive. This downdip trend correlates with areas of thicker sandstone (compare Figures Doc-14 and Doc-16). Natural IPs (Figure Doc-17) ranged from less than 50 Mcf/d to more than 20,000 Mcf/d. Areas of high IPs correlate with areas of greater sandstone thickness on the isopach map (compare Figures Doc-14 and Doc-17). The isopotential map for wells that were stimulated by shooting or fracturing (Figure Doc-18) indicates a moderately good correlation between natural and post-stimulation open flows (compare Figures Doc-17 and Doc-18).

A production decline curve for a representative set of wells (Figure Doc-19a) indicates that a large volume was produced during the first year followed by a rapid four-year volume decline. Rock pressure (Figure Doc-19b) shows a similar drop over the same period of time. As the rock pressure dropped, the rate of production decreased. Pressure leveled off at about 100 psi after the first seven years (Figure Doc-19c). Thus, deliverability of the wells was high, but reserves were low. Average gas recovery per acre was 6 MMcf in areas with 8 percent porosity, but perhaps only 2 MMcf in areas with only 6 percent porosity.

The relationship between open flows and cumulative production is shown in Figure Doc-19d. Although there is some scatter in the data, a direct relationship can be observed. Maps of five-year and ultimate production show a strong correlation with initial open flow maps and sandstone thickness trends. Six separate areas where cumulative production ranged from 1 to 2.5 bcf per well correlate with areas of thick (40 to 70 feet) sandstone (compare Figures Doc-14 and Doc-16). Two of these areas of high ultimate production also correlate with two structural features, the Sissonville high and the Milliken anticline.

Within the Oriskany reservoir in Elk-Poca field, the main difference between the more permeable and the tighter beds is the amount of carbonate cement present. The gas reservoir is located in the upper part of the Oriskany because the amount of both carbonate cement and interbedded carbonates increases downward. Updip to the west, post-Oriskany erosion appears to have removed these upper reservoir rocks, leaving stratigraphically lower, tighter rocks at the top of the formation (Figure Doc-20).

Following deposition of the Oriskany Sandstone and the overlying Huntersville Chert-Onondaga Limestone section, a long period of deposition of fine clastic sediments occurred, during which several intervals of black shale rich in organic matter accumulated. These black shales, particularly the Marcellus Shale, Rhinestreet Shale Member of the West Falls Formation, and Huron Member of the Ohio Shale, are considered to be the source beds for the gas that migrated into the Oriskany Sandstone reservoir in Elk-Poca field. Because this Devonian shale interval thickens from west to east above the field and beyond it to the east, the Oriskany in the eastern edge of the field was depressed to the same structural level as these black shales (Figure Doc-21), allowing gas generated in the shale to migrate horizontally into the Oriskany reservoir. The mean average vitrinite reflectance value in the Devonian shale (Tetra Tech, 1979) is 1.0 over the field and increases eastward, adequate for the generation of gas. Gas in the Oriskany in this field has a heating value in excess of 1,142 Btu (Table Doc-2).

Elk Run pool: The Elk Run pool in the Frostburg field produces gas from an Oriskany Sandstone reservoir in Jefferson County, Pennsylvania (Figure Doc-2), along the southeast side of a large area where the Oriskany Sandstone was reported by Fettke (1935) to be absent in the subsurface. Frostburg field was developed originally as a shallow gas field within the Upper Devonian beginning in the late 1800s. The Elk Run pool was discovered in 1965 when Consolidated Gas Supply Corp. drilled the No. 2 Rochester and Pittsburgh Coal well on the east flank of the Sabinsville anticline. The well was drilled to the Lower Devonian Helderberg Group at 7,198 feet, and was completed in the Oriskany with a natural open flow of 2,214 Mcf/d and 199-hour shut-in pressure of 3,960 psi (Heyman, 1969). Following this discovery, a successful step-out well was drilled southwest of the discovery well along the flank of the Sabinsville anticline. Subsequent development occurred between and around these two wells. The last well was drilled in the pool in 1968. Of the 53 wells drilled along the trend, 48 produced gas from the Oriskany Sandstone. All of the wells were drilled with air rotary rigs, and all but one were completed open hole. Although most wells produced naturally, 18 wells had to be stimulated with a hydraulic fracture treatment. The largest reported natural open flow was 13,385 Mcf/d, whereas the largest reported open flow after treatment was 20,731 Mcf/d.

The trapping mechanism in Elk Run pool is a combination of a relatively gentle southeast-dipping anticlinal flank and stratigraphic and diagenetic effects that occur along a northwestward pinchout of the Oriskany Sandstone reservoir rock (Diecchio, 1985). At the surface, Elk Run pool occurs along a relatively undeformed southeast dipping flank of the Sabinsville anticline and the adjoining Punxsutawney-Caledonia syncline (Figure Doc-22). At the level of the Oriskany Sandstone, however, the anticlinal flank is contorted by localized southeast-plunging anticlinal noses. The southwest end of the pool is defined by a southwest-plunging anticlinal nose with as much as 250 feet of relief, whereas a northeast-southwest trending fault with 350 feet of down-to-the-southeast throw defines the northeastern limit of the pool (Figures Doc-23, Doc-24). The Oriskany decreases in thickness from a maximum of 25 feet at the southeastern margin of the pool to 0 feet where the sandstone pinches out at the edge of the no-sandstone area on the northwest (Figures Doc-25, Doc-26). The average sandstone thickness is 19 feet. Heyman (1969) described the Oriskany in Elk Run pool as a very fine- to sporadically coarse-grained, calcareous, poorly sorted, quartzose sandstone composed mainly of sub-rounded, frosted grains. Porosity occurs in the upper two-thirds of the sandstone but is limited at the top of the unit by a 1-to-2-foot-thick cap of hard, impermeable sandstone.

The pay zone occurs within the porous zone where porosity exceeds 6 percent. The updip limit of this zone, about one mile downdip from the edge of the no-sandstone area, defines the northwestern margin of the pool. A gas-water contact present along the southeastern edge of the field at the approximate subsea elevation of -5,940 feet forms the southeastern margin of the reservoir (Heyman, 1969) (Figure Doc-23). The pay thickness in Elk Run pool ranges from 4 to 19 feet (Figure Doc-27) with a calculated average of about 9 feet (Heyman, 1969).

Porosity is largely intergranular, ranging from less than 1.5 to 21 percent with an average of 7.75 percent (Figure Doc-28). Based on the behavior of shut-in pressures and natural open-flow distributions, Heyman (1969) suggested the existence of a limited fracture network in the Oriskany that may have enhanced the overall quality of the reservoir. Initial shut-in pressures between widely separated wells relate directly to completion date (Figure Doc-29), indicating fracture communication between wells. This proposed fracture network may be partially substantiated by sonic amplitude data from one well. Similar data occur in other Oriskany fields along the no-sandstone area to the northeast.

Initial open flows in wells completed naturally ranged from 1,400 to 13,385 Mcf/d, averaging 4,721 Mcf/d. In stimulated wells, initial open flows ranged from 186 to 3,970 Mcf/d, averaging 2,080 Mcf/d, whereas after treatment open flows ranged from 1,810 to 20,731 Mcf/d, averaging 8,266 Mcf/d per well. The initial pressure in the field ranged from 2,282 to 4,200 psi, with an average of 2,920 psi at an average producing depth of 7,258 feet to the bottom of the pay. This yields an average pressure gradient of 0.40 psi per foot. Two breaks in the slope of the curve plotted in Figure Doc-29 indicate abrupt pressure changes probably due to the first intensive development phase of the pool and subsequent large-scale gas withdrawals (Heyman, 1969).

Elk Run pool encompasses 4,000 acres, and producing wells are spaced an average of one well per 83 acres. Approximately 50 bcfg were produced from this pool between 1965 and 1992 (Figure Doc-30), averaging 1.04 bcf per well. Early in the development of the field, the original producible gas in place was estimated to be 46,670,000 Mcf with a recovery factor of 276.2 Mcf per acre-foot (Lytle and others, 1968). Heyman (1969) later revised the recovery factor to 809.7 Mcf per acre-foot. However, the 50,135,021 Mcfg have been produced from a thin 9-foot zone that covers 4,000 acres (36,000 acre-feet), yielding a recovery factor of 1,392 Mcf per acre-foot.

Natural gas in Elk Run pool is primarily dry gas, composed of greater than 97 percent methane (Table Doc-3). The minor amounts of heavier hydrocarbons and non-hydrocarbon gases in this pool are typical of Oriskany gas throughout the central and eastern Appalachian Plateau Province. Oil has not been reported from the Oriskany Sandstone in this pool.

Allegany State Park field: The first hydrocarbon production in the area now known as Allegany State Park in southern Cattaraugus County, New York (Figure Doc-31), occurred in the 1870s when oil was discovered in commercial quantities in an Upper Devonian sandstone. Natural gas was discovered in 1891 from a separate Upper Devonian sandstone reservoir (Brewer, 1933), but very few wells were drilled to deeper formations until the 1950s. Four early wells, drilled west and north of the shallow producing areas, penetrated the Lower Silurian Medina Group without encountering the Oriskany Sandstone.

It was not until 1955 that the Oriskany was found to exist within the area of the park when Allegany State Park field was discovered with the successful completion of the Felmont Oil Corp. No. 1 Lena Lockwood well (Figure Doc-31). The well penetrated the top of the Oriskany Sandstone at a depth of 3,754 feet below the surface and was drilled only one additional foot into the formation. The initial open flow was 8,400 Mcf/d with some distillate, but the flow decreased to

TABLE Doc-1

	Rockport WV	Red House WV	Scott Depot WV	Allegany State Park NY	Carrollton NY	Ischua NY	Elk Run PA	McClure Hollow NY	Campbell Creek WV
BASIC RESERVOIR DATA									
POOL NUMBER	47279475	47191475	47212475						47214475
DISCOVERED	1948	1954	1955	1955	1957	1957	1965	1965	1935
DEPTH TO TOP RESERVOIR	5,124	4,503	4,525	4,000	3,480	3,800	7,100	3,600	4,822
AGE OF RESERVOIR	Early Devonian	Early Devonian	Early Devonian	Early Devonian	Early Devonian	Early Devonian	Early Devonian	Early Devonian	Early Devonian
FORMATION	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany
PRODUCING RESERVOIR	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany
LITHOLOGY	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone
TRAP TYPE	stratigraphic structural	stratigraphic structural	stratigraphic structural	stratigraphic structural	stratigraphic structural	stratigraphic structural	stratigraphic structural	stratigraphic structural	stratigraphic structural
DEPOSITIONAL ENVIRONMENT	shallow shelf	shallow shelf	shallow shelf	shallow shelf	shallow shelf	shallow shelf	shallow shelf	shallow shelf	shallow shelf
DISCOVERY WELL IP (Mcf)	12,026	103	73	8,400	9,000	2,700	2,214	375	168
DRIVE MECHANISM	salt water	water	water	gas cap	gas cap	gas cap		gas cap	water
NO. PRODUCING WELLS	27	17	19	13	1	1	48	3	28
NO. ABANDONED WELLS	6	3	1	0	1	1	3	3	22
AREA (acreage)	3,531	6,800	4,440	2,200	80	80	2,318	250	8,400
OLDEST FORMATION PENETRATED	Juniata	Tuscarora	McKenzie	Helderberg	Helderberg	Helderberg	Helderberg	Helderberg	Juniata
EXPECTED HETEROGENEITY DUE TO:									
RESERVOIR PARAMETERS									
AVERAGE PAY THICKNESS (ft.)		6	6	5	5	12	20	5	
AVERAGE COMPLETION THICKNESS (ft.)	19	10	10	20	5	12		10	15
AVERAGE POROSITY–LOG (%)			4.29						
MINIMUM POROSITY–LOG (%)			4.29						
MAXIMUM POROSITY–LOG (%)			4.29						
NO. DATA POINTS			1.00						
POROSITY FEET									
RESERVOIR TEMPERATURE (°F)	122		102						
INITIAL RESERVOIR PRESSURE (psi)	1,925	1,500	1,735	1,900	1,930	1,750	3,960	1,825	1,400
PRODUCING INTERVAL DEPTHS (ft.)	4,800-5,525	4,350-4,750	4,400-4,750	3,700-4,350	3,480-3,485	3,824-3,836		3,600-3,900	4,450-5,200
PRESENT RESERVOIR PRESSURE (psi) / DATE									
FLUID & GAS PROPERTIES									
Rw(Ωm)	0.05	0.05	0.05						0.05
GAS GRAVITY (g/cc)	0.671								
GAS SATURATION (%)			57						
WATER SATURATION (%)			43						
COMMINGLED	no	no	yes						no
ASSOCIATED OR NONASSOCIATED	associated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated			nonassociated
Btu/scf	1,157			1,180					
VOLUMETRIC DATA									
STATUS (producing, abandoned, storage)	storage	producing/ abandoned	producing	storage	abandoned	abandoned			producing/ abandoned
ORIGINAL GAS IN PLACE (Mcf)	12,000,000								31,000,000
ORIGINAL GAS RESERVES (Mcf)	10,960,000			20,400,000					27,750,000
PRODUCTION YEARS	1948-1993	1981-1993	1981-1993	1956-1970	1957-1960	1957-1963	1965-1992		1935-1993
REPORTED CUMULATIVE PRODUCTION (Mcf)	1,260,000	1,136,900	150,400						6,035,300
NO. WELLS REPORTED	7	12	7						22
ESTIMATED CUMULATIVE PRODUCTION (Mcf)	10,400,000	4,525,000	1,550,000	14,000,000		200,000	50,135,021	135,000	24,750,000
REMAINING GAS IN PLACE (Mcf)/DATE	1,600,000/ 1973								6,250,000/
REMAINING GAS RESERVES (Mcf)/DATE	560,000/ 1973								3,000,000/ 1973
RECOVERY FACTOR (%)	90								90
INITIAL OPEN FLOW (Mcfd)	11,043	131	87		9,000	2,700	3,702	879	630
FINAL OPEN FLOW (Mcfd)	1,990	153	315	3,643		50	8,265		1,192

	Allen NY	Elk-Poca WV	Big Chimney WV	Blackhawk PA	Wellsville OH	Hernshaw WV	Blue Creek WV	Vernon OH	Howard NY	Mallory PA	Leachtown WV
BASIC RESERVOIR DATA											
POOL NUMBER		47192475	472215475			47238475	47217475				47345475
DISCOVERED	1932	1933	1934	1935	1935	1937	1944	1947	1936	1960	1971
DEPTH TO TOP RESERVOIR	3,000	5,034	4,950	4,660	4,300	4,565	5,237	3,200	3,550		5,035
AGE OF RESERVOIR	Early Devonian	Early Devonian	Early Devonian	Early Devonian	Early Devonian	Early Devonian	Early Devonian	Early Devonian			Early Devonian
FORMATION	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany			Oriskany
PRODUCING RESERVOIR	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany			Oriskany
LITHOLOGY	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone			sandstone
TRAP TYPE	stratigraphic structural	stratigraphic structural	stratigraphic structural	stratigraphic structural	stratigraphic structural	stratigraphic structural	stratigraphic structural	stratigraphic structural			shallow shelf
DEPOSITIONAL ENVIRONMENT	shallow shelf	shallow shelf	shallow shelf	shallow shelf	shallow shelf	shallow shelf	shallow shelf	shallow shelf			
DISCOVERY WELL IP (Mcf)	200	134	17	787	25	300		show	30		4,000
DRIVE MECHANISM	gas cap	salt water	salt water	salt water		gas expansion	water		gas cap		water
NO. PRODUCING WELLS	7	200	2	5		7	73		10		1
NO. ABANDONED WELLS	7	900	10	4	11	5	4	4	9		2
AREA (acreage)	600	165,000	1,400	580	960	3,100	6,622	100	1,200		400
OLDEST FORMATION PENETRATED	Queenston	Juniata	Williamsport	Queenston	Rose Run	McKenzie	Juniata	Queenston	Helderberg		McKenzie
EXPECTED HETEROGENEITY DUE TO:	deposition								deposition		
RESERVOIR PARAMETERS											
AVERAGE PAY THICKNESS (ft.)	8	14						8	9		
AVERAGE COMPLETION THICKNESS (ft.)	8	24	25	8	22	19	23		5		15
AVERAGE POROSITY–LOG (%)		8.7			7						
MINIMUM POROSITY–LOG (%)		4.47									
MAXIMUM POROSITY–LOG (%)		15.18			12						
NO. DATA POINTS		8			2						
POROSITY FEET		1.22									
RESERVOIR TEMPERATURE (°F)		108		131	103		131	93			
INITIAL RESERVOIR PRESSURE (psi)	1,475	2,500	1,450	1,870	1,330	1,250	1,850		1,470		1,700
PRODUCING INTERVAL DEPTHS (ft.)	2,900-3,300	4,480-5,450	4,775-5,200			4,375-4,825	4,950-5,600		3,400-3,600		5,035-5,050
PRESENT RESERVOIR PRESSURE (psi) / DATE		280/ 1973		2,000/ 1983							
FLUID & GAS PROPERTIES											
Rw(Ωm)		0.05	0.05		0.35	0.05					0.05
GAS GRAVITY (g/cc)		0.658									
GAS SATURATION (%)											
WATER SATURATION (%)											
COMMINGLED		no	no	no	no	yes	no				yes
ASSOCIATED OR NONASSOCIATED	nonassociated	nonassociated	associated	associated	nonassociated	associated	nonassociated		nonassociated		nonassociated
Btu/scf		1,135					1,164				
VOLUMETRIC DATA											
STATUS (producing, abandoned, storage)	abandoned	storage	abandoned		abandoned	producing	storage	abandoned	producing		abandoned
ORIGINAL GAS IN PLACE (Mcf)		1,150,000,000		3,102,000		5,000,000	86,000,000				1,750,000
ORIGINAL GAS RESERVES (Mcf)		1,054,000,000		2,300,000		4,500,000	78,400,000				1,500,000
PRODUCTION YEARS	1940-1944	1937-1993	1937-1938	1935-1960		1930-1993	1945-1993		1942-1968		1971-
REPORTED CUMULATIVE PRODUCTION (Mcf)		34,402,406	88,500			1,659,247	27,473,518				
NO. WELLS REPORTED		210	1			4	28				
ESTIMATED CUMULATIVE PRODUCTION (Mcf)	250,000	962,207,000		3,000,000		2,100,000	66,550,000	320,000	1,500,000		500,000
REMAINING GAS IN PLACE (Mcf)/DATE		187,793,000		102,000/ 1960		2,900,000/ 1973	19,450,000/ 1973				1,250,000
REMAINING GAS RESERVES (Mcf)/DATE		91,793,000/ 1973				2,400,000/ 1973	11,850,000/ 1973				1,000,000/ 1973
RECOVERY FACTOR (%)		90				90	90				90
INITIAL OPEN FLOW (Mcfd)	1,000	5,134	2,250	2,897		200	6,096		1,000		
FINAL OPEN FLOW (Mcfd)	50	3,194	650			225	2,079		40		4,000

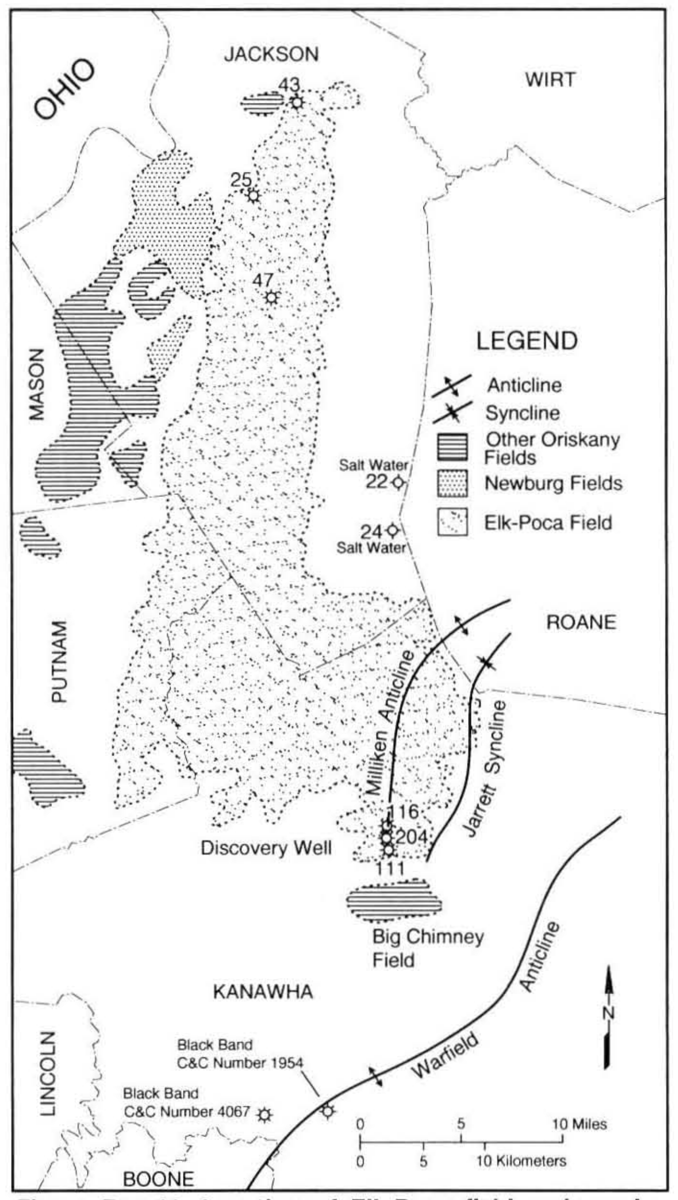


Figure Doc-11. Location of Elk-Poca field and nearby fields in Jackson, Kanawha, Mason, and Putnam counties, West Virginia. The discovery well for Elk-Poca (Kanawha 204) and other key wildcat wells also are shown. Structural axes based on surface mapping, not the top of the Oriskany Sandstone. From Patchen and others (1992).

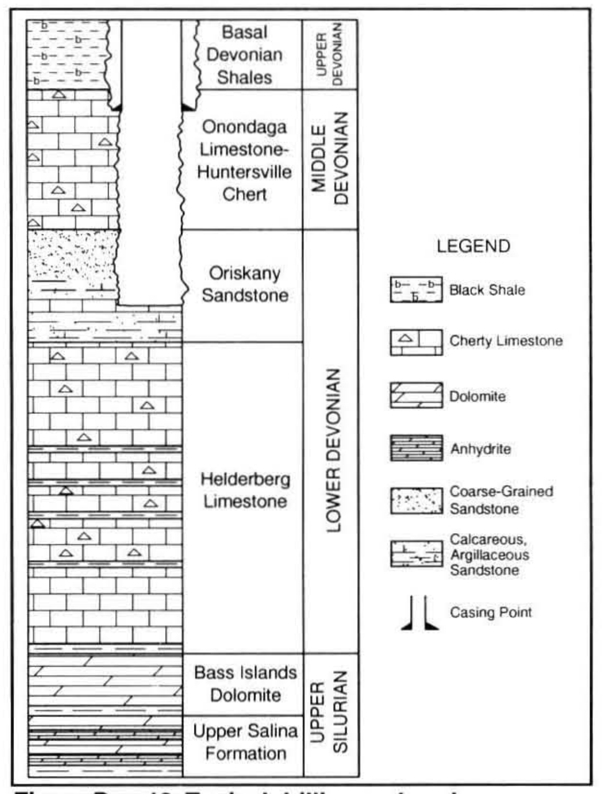


Figure Doc-12. Typical drilling and casing program in Oriskany wells drilled in Elk-Poca field. Casing was set in the Onondaga/Huntersville and drilling stopped when a thin limestone was encountered below the upper, porous sandstone. From Patchen and others (1992).

4,100 Mcf/d; the initial rock pressure was gauged at 1,900 psi. Felmont eventually abandoned the well in 1959 due to salt water invasion (Kreidler, 1963).

Felmont Oil Corp. drilled Allegany State Park field in two phases: the first phase extended from late 1955 until mid-1957, and the second phase occurred in the mid-1960s. Cable tools were used during the early phase, and the operator typically shot the wells with nitroglycerine. As the primary operator in the field, Felmont used the best available engineering practices from the beginning to develop the field, including drilling on a 250-acre spacing (Harding, 1966). Late-phase drilling was by rotary rig on much smaller spacing, and almost all wells flowed naturally. By 1966, there were 11 wells in the field that had initial open flows in the Oriskany ranging from 750 to 7,000 Mcf/d, averaging 3,643 Mcf/d. Initial rock pressures ranged from 1,730 to 1,920 psi, averaging 1,719 psi. The average pressure gradient is about .46 psi per foot. Ten wells in the field were converted to gas storage in 1970.

Allegany State Park field results from a combination of structural terracing and proximity to the Oriskany pinchout area in western New York (Figures Doc-31, Doc-32). The regional dip in this area is to the southeast, and the terrace at the northeast and southwest edges of the field strikes into the pinchout. There is no evidence of faulting in the field, but minor faulting occurs about 3 miles southeast of the field (Harding, 1966) (Figure Doc-32). Proximity to the pinchout affects the reservoir in two ways. The sandstone decreases in thickness from about 30 feet to about 4 feet in a northerly direction with no production along the pinchout where less than 4 feet of sandstone are present. Thus, the amount of porous and permeable sandstone decreases updip. Downdip along the southeastern edge of the field, a positive salt water drive occurs within the Oriskany that produces a definite gas-water contact zone (Harding, 1966) (Figure Doc-31). The average thickness of the pay zone reportedly is 25 feet (Underground Storage Committee, 1983). However, this is a storage figure that probably uses the average thickness of the sandstone. Gas flow in most wells began almost immediately after the sandstone was penetrated.

In an attempt to avoid salt water invasion for as long as possible, Felmont maintained high pressures in the wells, and produced them regularly for only six months out of the year (Harding, 1966). Original reserves have been calculated at 20.4 bcf for this field. Based on an area of 3,140 acres and an estimated 5 feet of pay section, the recovery factor for Allegany State Park field is 1,299 Mcfg per acre-foot.

Harding (1966) estimated that, for every 100 psi in pressure decline, the field produced 1 bcfg. By 1963, the bottom hole pressure had dropped from 1,900 psi to 1,265 psi, or 6.35 bcfg plus about 30,000 barrels of condensate. Undoubtedly, the completion and production of five new wells in the mid-1960s helped decrease bottom-hole pressures below the field-abandonment limit, and the field was converted to gas storage.

Natural gas in Allegany State Park field is wet, containing relatively high percentages of ethane, propane, and other heavier hydrocarbons (Table Doc-4). Btu values exceed 1,100. This composition appears to be typical of Oriskany gas in western New York. For example, McClure Hollow, a field about 15 miles northeast of Allegany State Park field (Figure Doc-2), contains 82.9 percent methane, 10.6 percent ethane, 3.7 percent propane, and has a Btu value of 1,196. Jenden and others (1993) considered Oriskany gas to fall into their Group I (wet thermogenic gas), which is characterized by wetness greater than 14 percent, methane carbon isotope ratio δ13C less than -43 o/oo, and methane hydrogen isotope ratio δD less than -210 o/oo. Such gases are typical of Devonian and uppermost Silurian hydrocarbons from areas exhibiting conodont alteration index

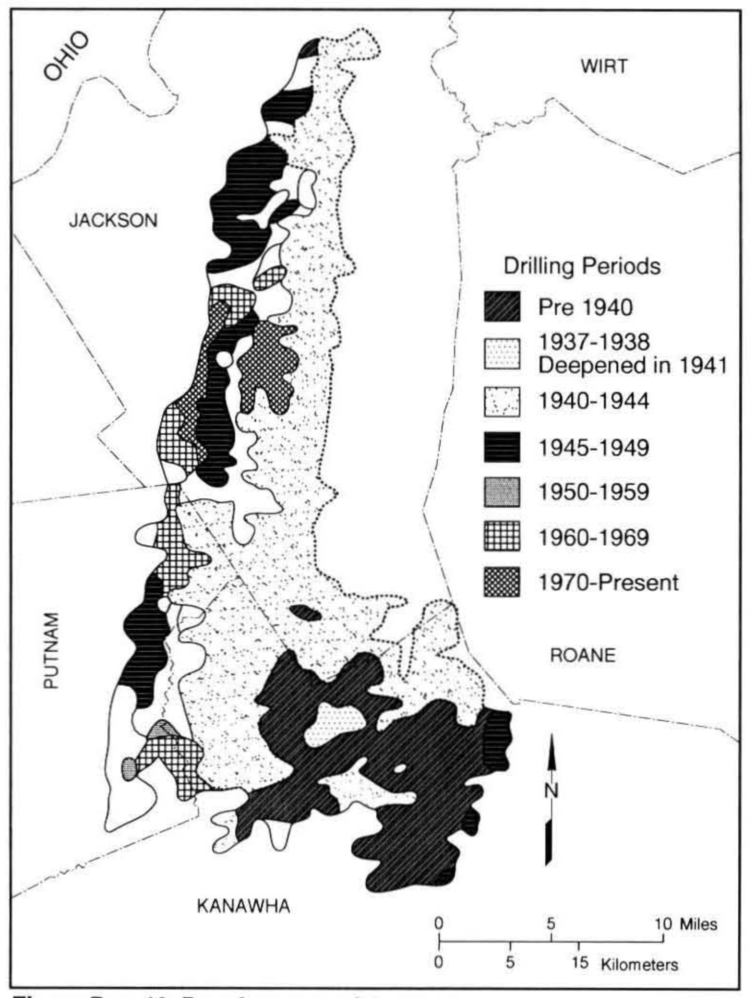


Figure Doc-13. Development of the Elk-Poca field from the 1930s to the 1970s. Early drilling was on structural highs, followed by drilling of a north-south trend that followed thick areas in the sandstone. From Patchen and others (1992).

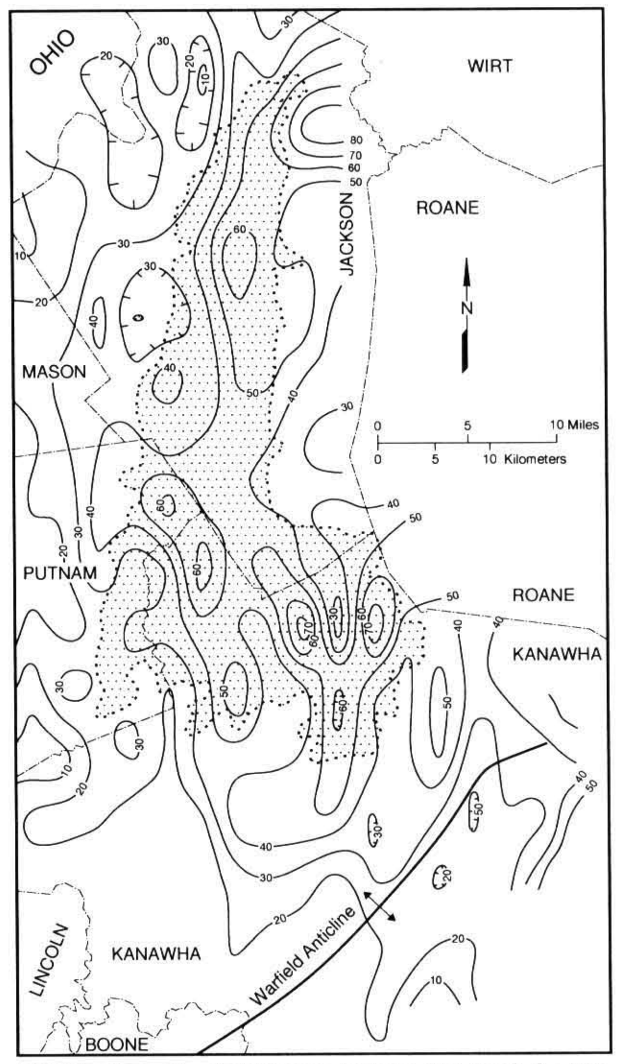


Figure Doc-14. Thickness trends (in feet) in the Oriskany Sandstone in Elk-Poca field (stippled area) and adjacent areas. Contour interval = 10 feet. From Patchen and others (1992). See Figure Doc-2 for location.

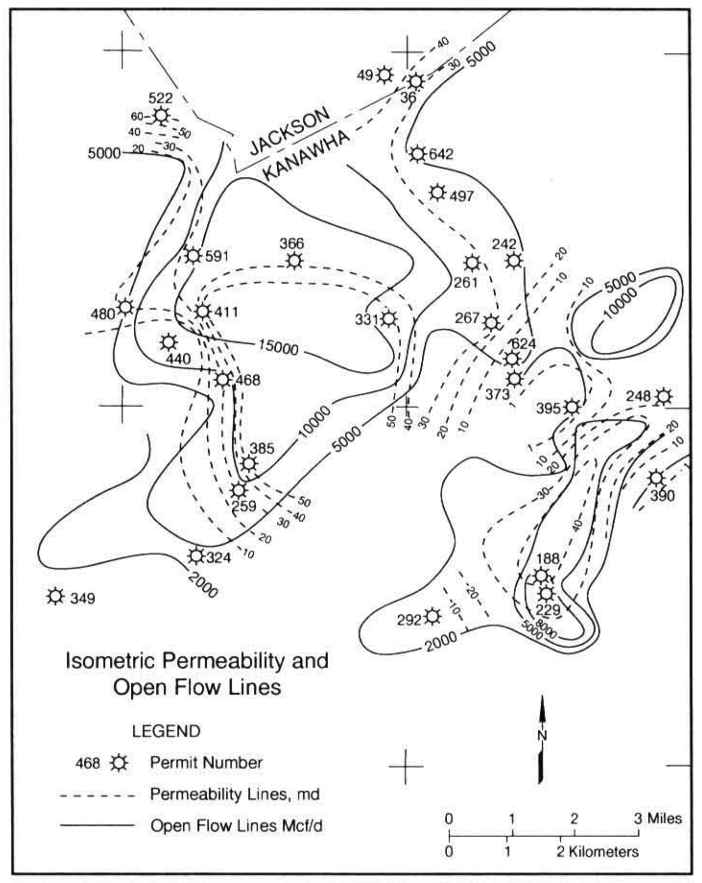


Figure Doc-15. Correlation of permeability and initial open flows in the eastern portion of Elk-Poca field. Control wells shown are those from which rock samples were collected; additional wells were used to contour open flows. From Headlee and Joseph (1945). See Figure Doc-2 for location.

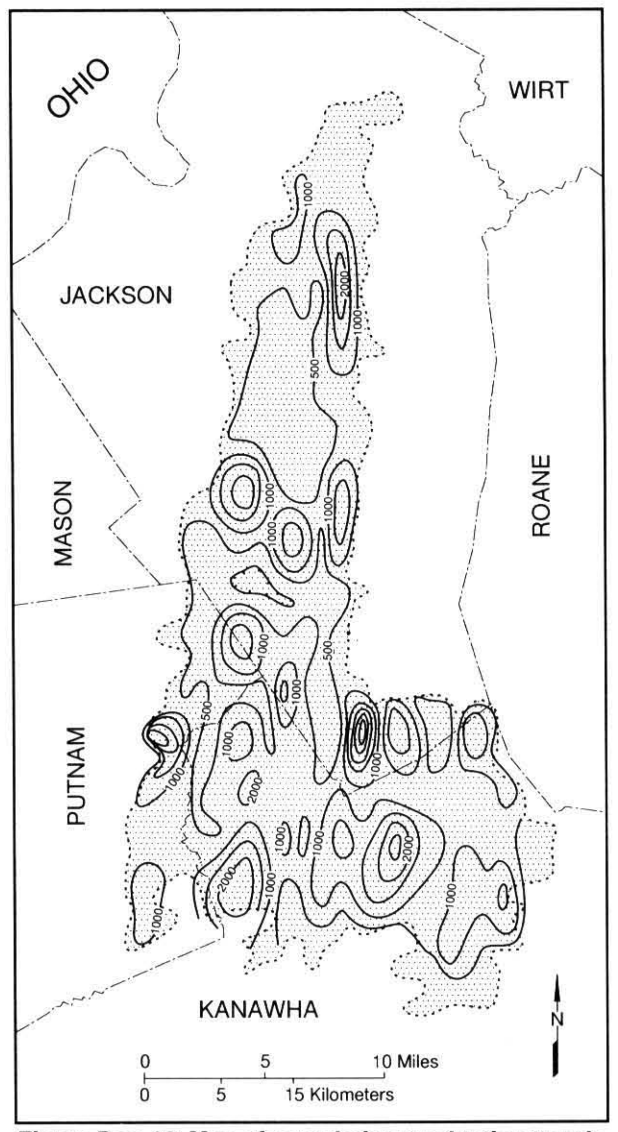


Figure Doc-16. Map of cumulative production trends in Elk-Poca field. Dry holes were not used in the contouring program. Contour interval = 500 MMcf. From Patchen and others (1992). See Figure Doc-2 for location.

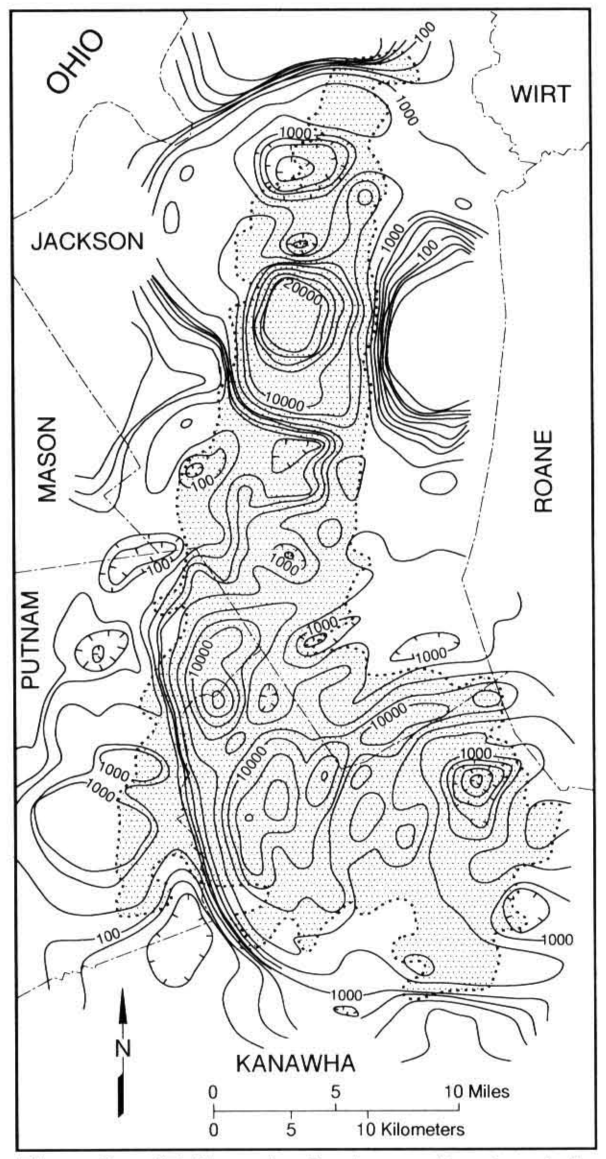


Figure Doc-17. Map of natural open flow trends in Elk-Poca field and adjacent areas. Contoured values are in Mcf/d; contour interval varies. From Patchen and others (1992). See Figure Doc-2 for location.

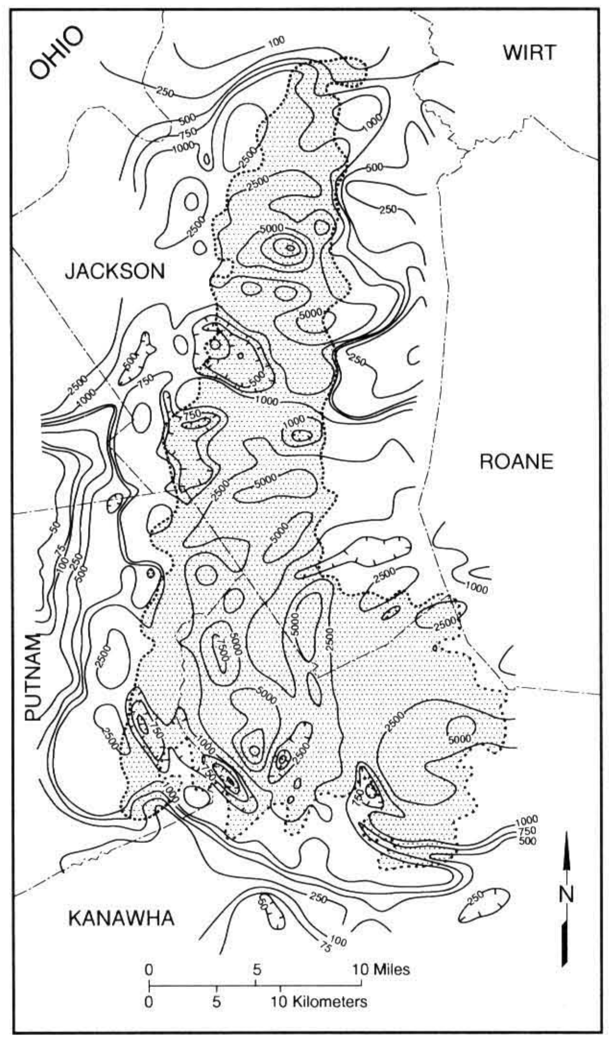
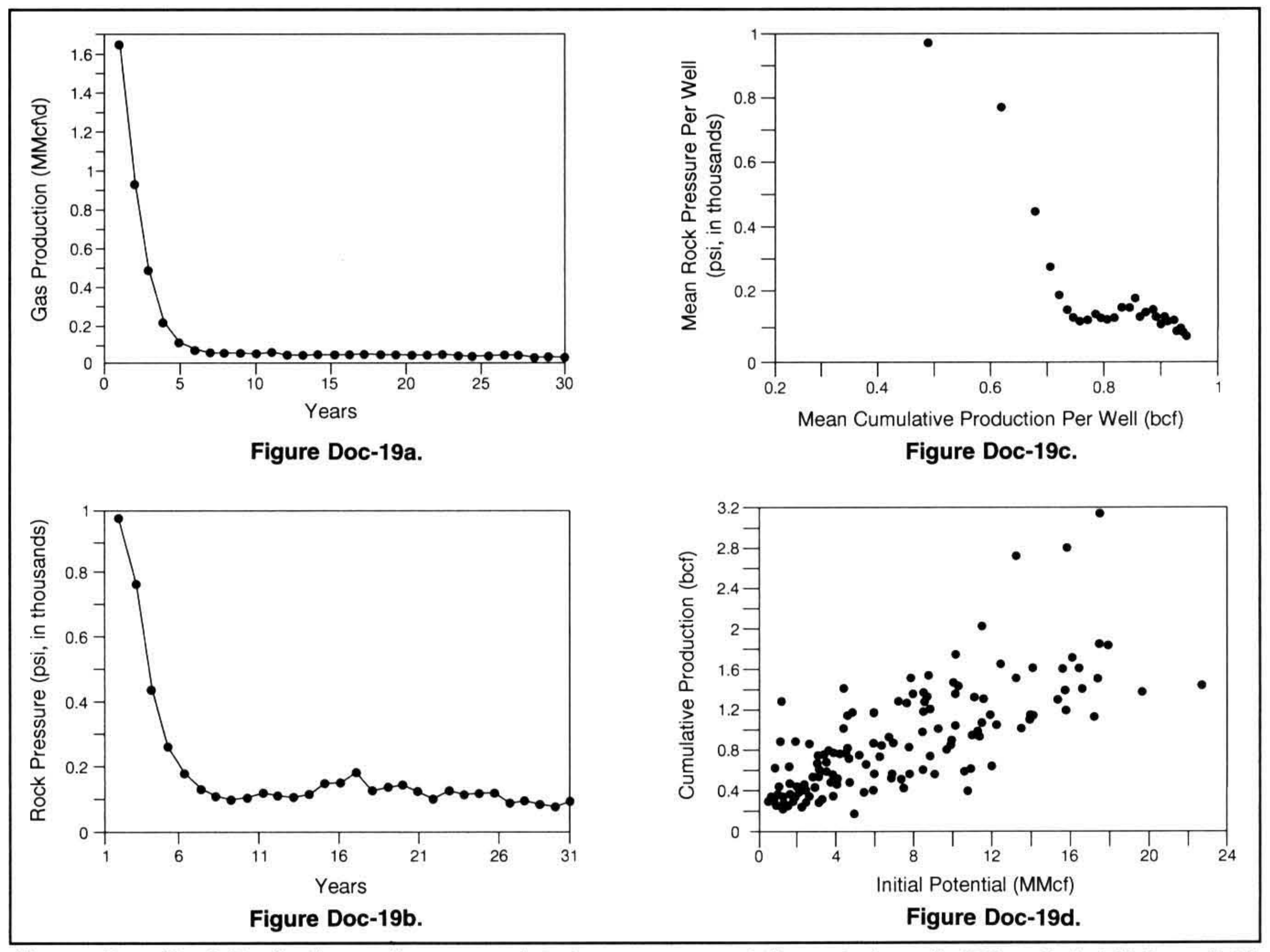


Figure Doc-18. Map of open flows of gas following stimulation of wells in Elk-Poca field and adjacent areas. Only those wells with low natural open flows were stimulated. Therefore, final open flows on this map appear to be lower than the natural open flows contoured in Figure Doc-17. High open flow areas on both maps are in the same locations. Contoured values are in Mcf/d; contour interval varies. From Patchen and others (1992). See Figure Doc-2 for location.



Figures Doc-19a-d. Production and pressure data from a representative set of nearly 200 wells in Elk-Poca field. Figure Doc-19a. Production decline curve, plotting mean production per day versus years of production. Figure Doc-19b. Rock pressure decline curve, plotting mean rock pressure per year versus years of production. Figure Doc-19c. Decline in mean rock pressure per year versus mean annual cumulative production, calculated for 27 years. Figure Doc-19d. Relationship between initial potential and cumulative production. From Patchen and others (1992).

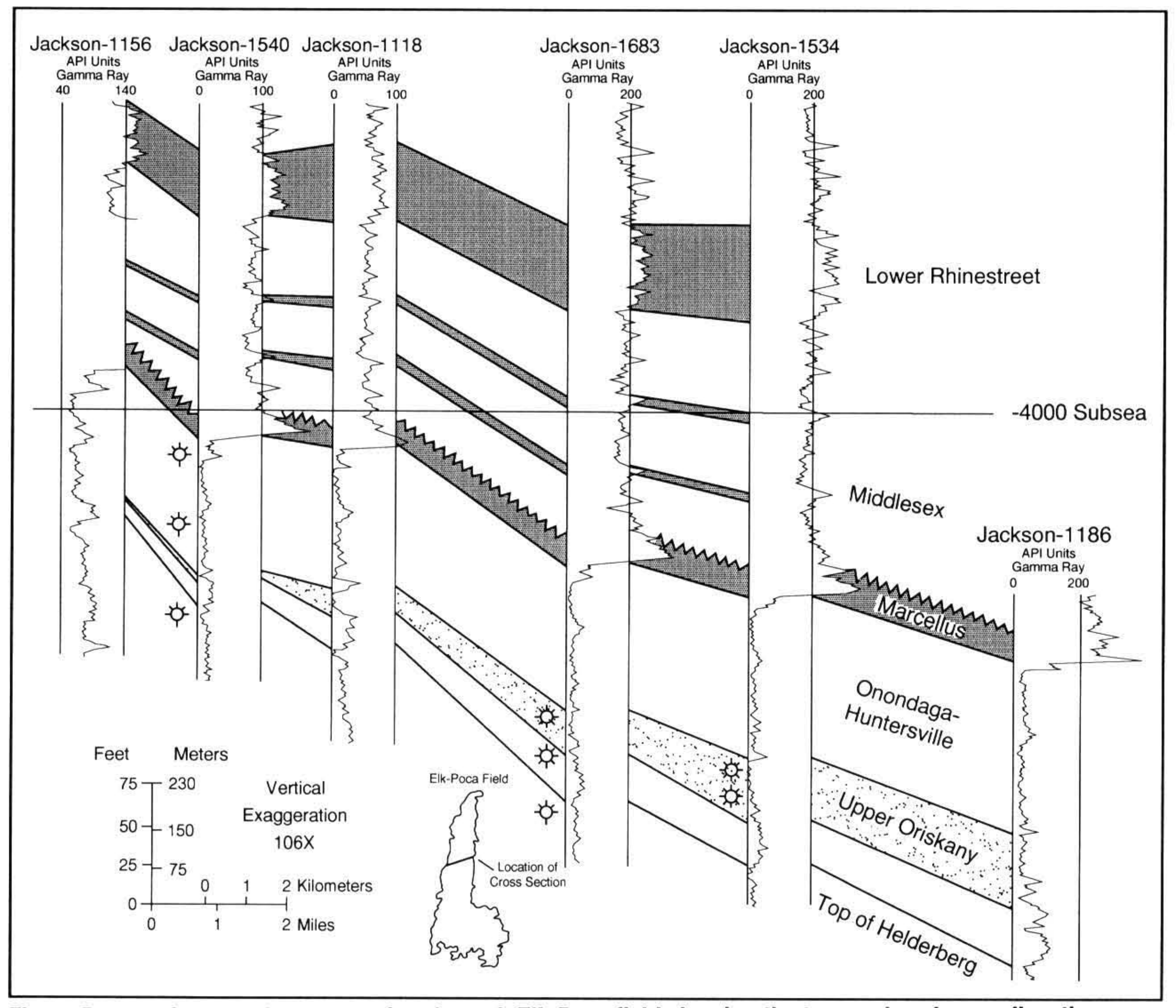


Figure Doc-20. Structural cross section through Elk-Poca field showing the trap and seal, as well as the upper Oriskany reservoir and several black shale source beds in younger units. From Patchen and others (1992).

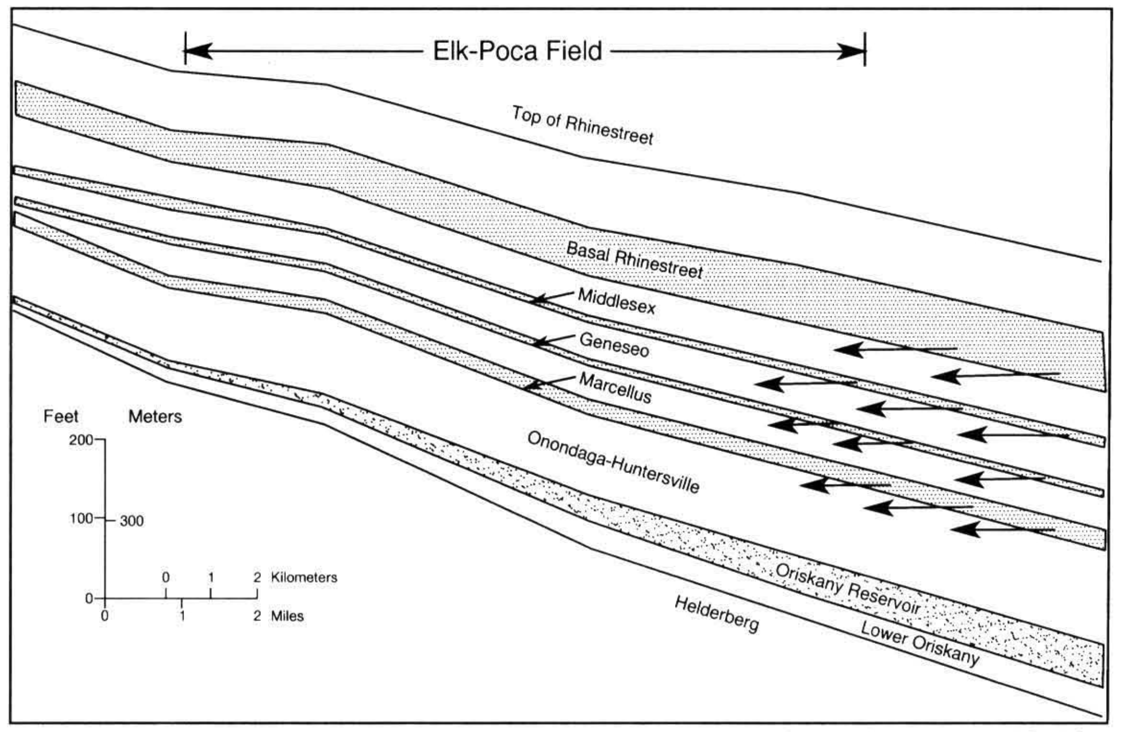


Figure Doc-21. Adjusted stratigraphic cross section assuming a flat surface on the Big Lime (Greenbrier Limestone) following deposition of that unit. Increased thickness of the Devonian shale section from west to east would place black shales rich in organic matter at the same structural elevation as the Oriskany reservoir in Elk-Poca field. Lateral migration of gas from black shale source beds to the Oriskany is illustrated by horizontal arrows. From Patchen and others (1992).

Table Doc-2. Analysis of gas from Oriskany Sandstone in the Ashland Oil & Refining Co. No. 1 R.D. Hutchison well in Elk-Poca field, Jackson County, West Virginia. From Moore and Sigler (1987a).

COMPONENT	MOLE PERCENT
Methane	85.1
Ethane	7.8
Propane	2.4
N-Butane	0.8
Isobutane	0.3
N-Pentane	0.3
Isopentane	0.2
Cyclopentane	0.1
Hexanes Plus	0.3
Nitrogen	2.3
Oxygen	0.2
Argon	0.2
Hydrogen	0
Hydrogen Sulfide	0
Carbon Dioxide	0.1
Helium	0.06
Btu Value	1,142
Specific Gravity	0.664

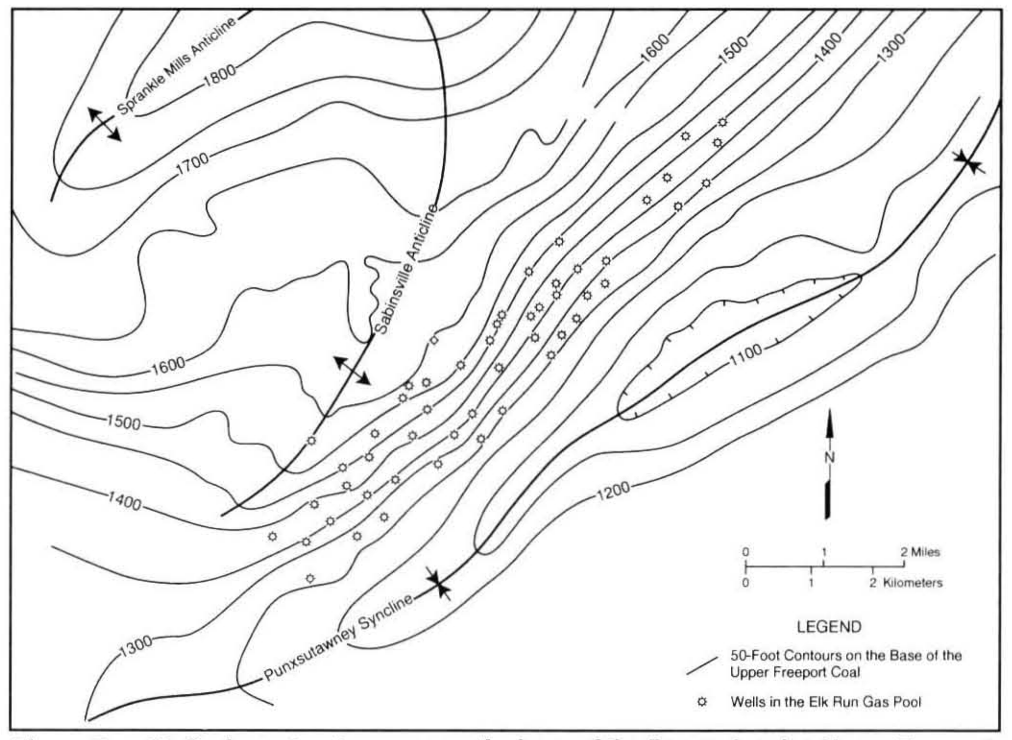


Figure Doc-22. Surface structure map on the base of the Pennsylvanian Upper Freeport coal in the vicinity of Elk Run pool. Modified from Heyman (1969). See Figure Doc-2 for location.

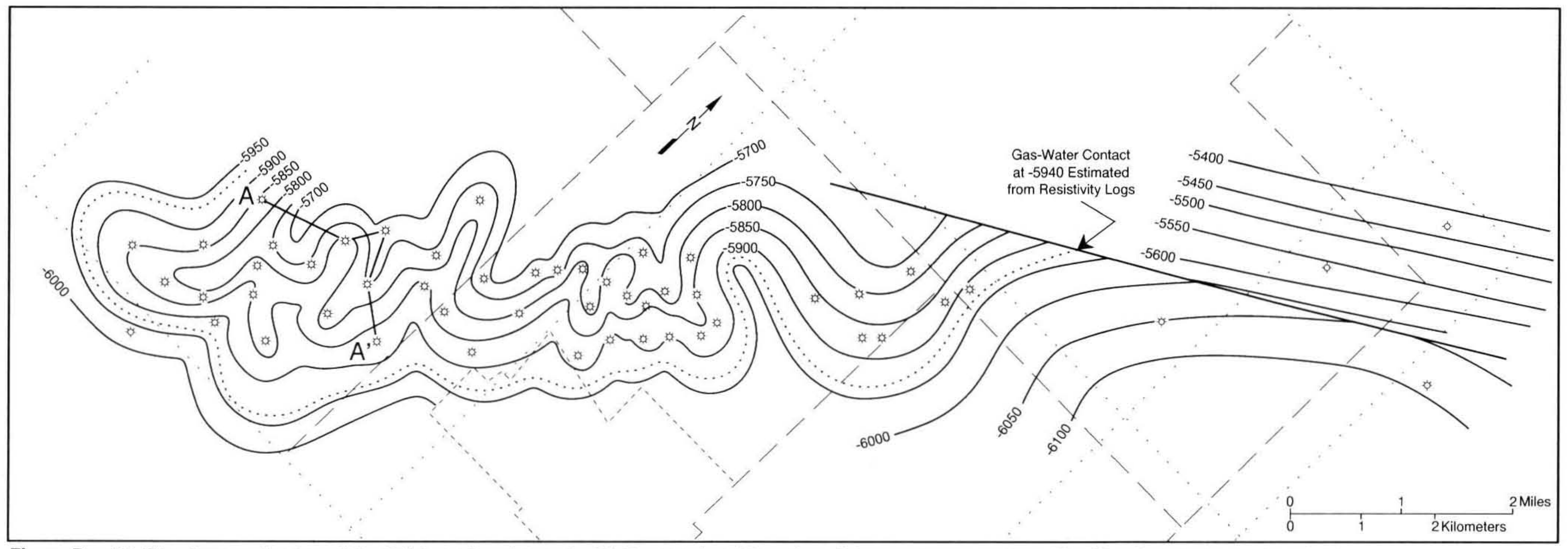


Figure Doc-23. Structure on the top of the Oriskany Sandstone in Elk Run pool and location of the gas-water contact. Modified from Heyman (1969). Line of cross section A-A' (Figure Doc-24) is also shown. Contour interval = 50 feet. See Figure Doc-2 for location.

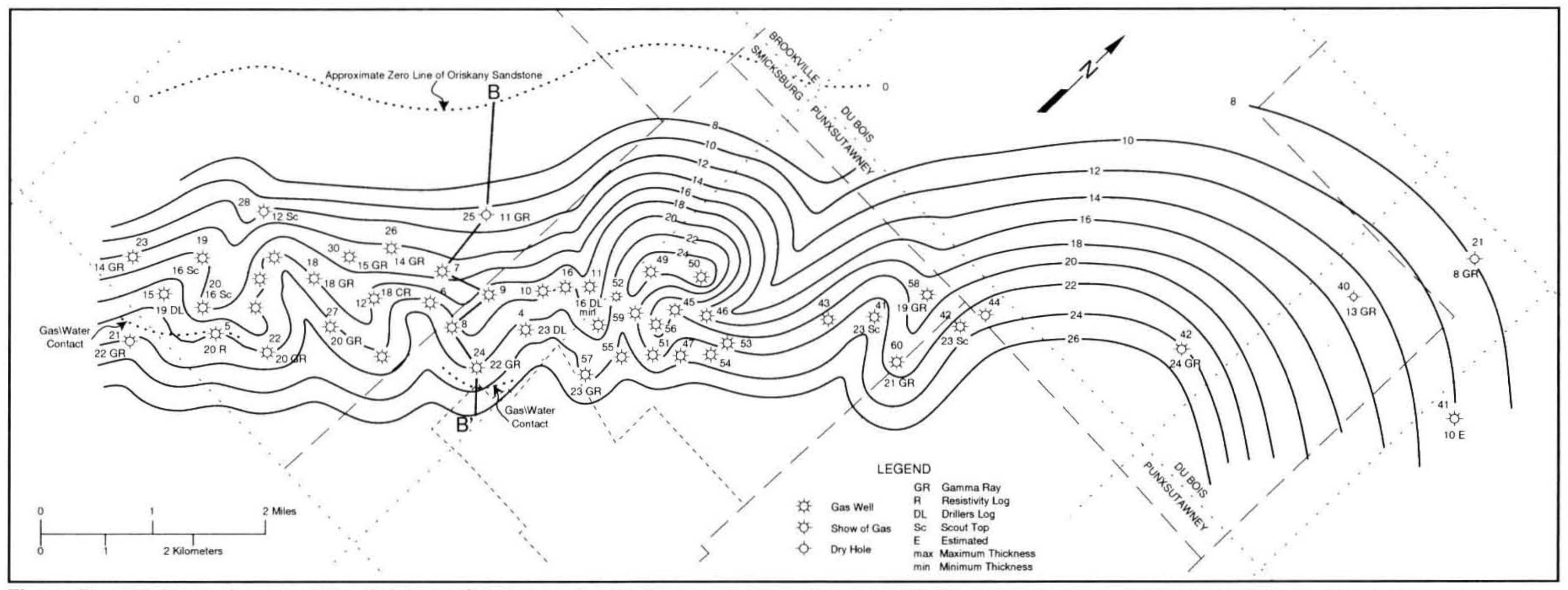


Figure Doc-25. Isopach map of the Oriskany Sandstone in Elk Run pool. From Heyman (1969). Line of cross section B-B' (Figure Doc-26) is also shown. Contour interval = 2 feet. See Figure Doc-2 for location.

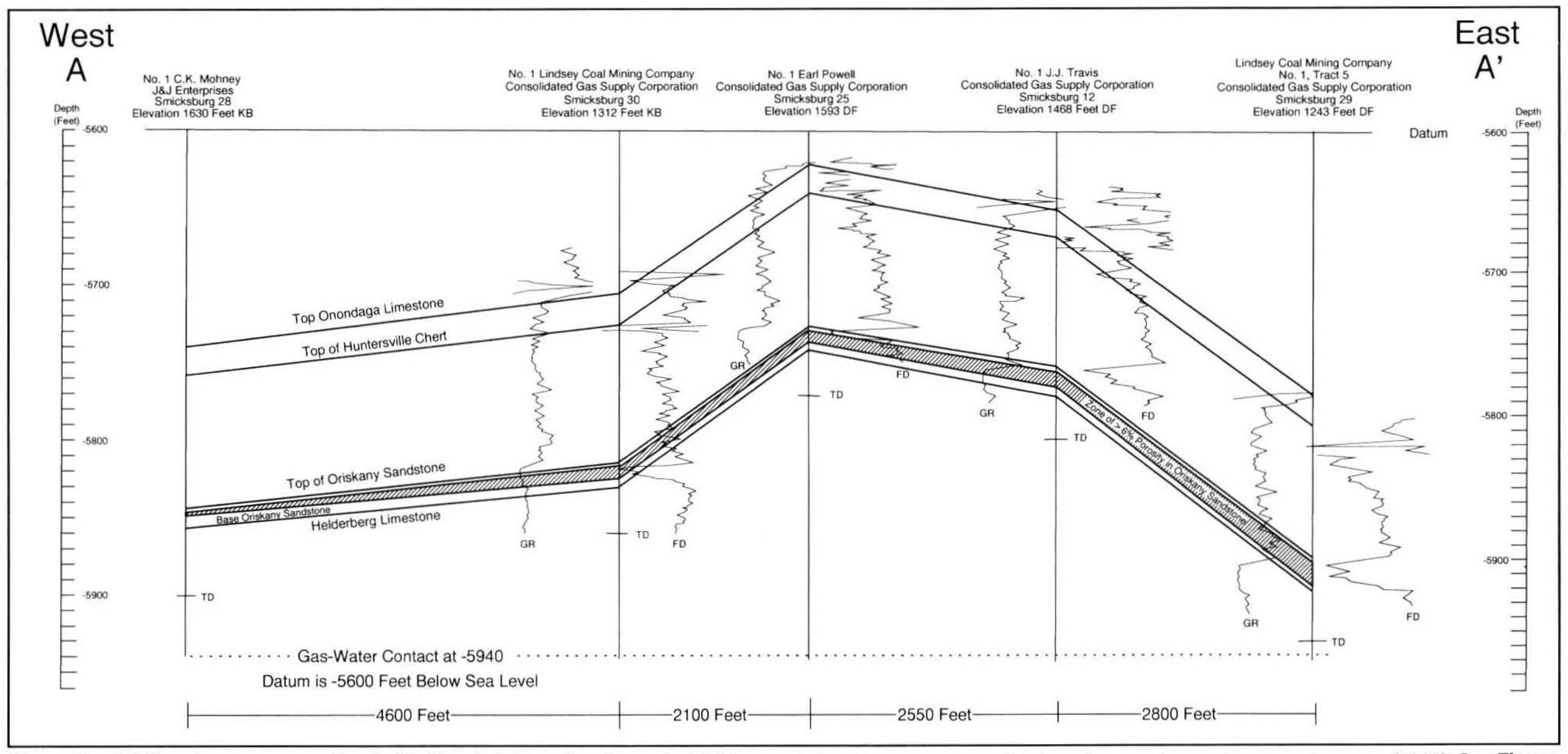


Figure Doc-24. Structural cross section A-A' of the Oriskany Sandstone in Elk Run pool showing zone of greater than 6 percent porosity. From Heyman (1969). See Figure Doc-23 for location of cross section.

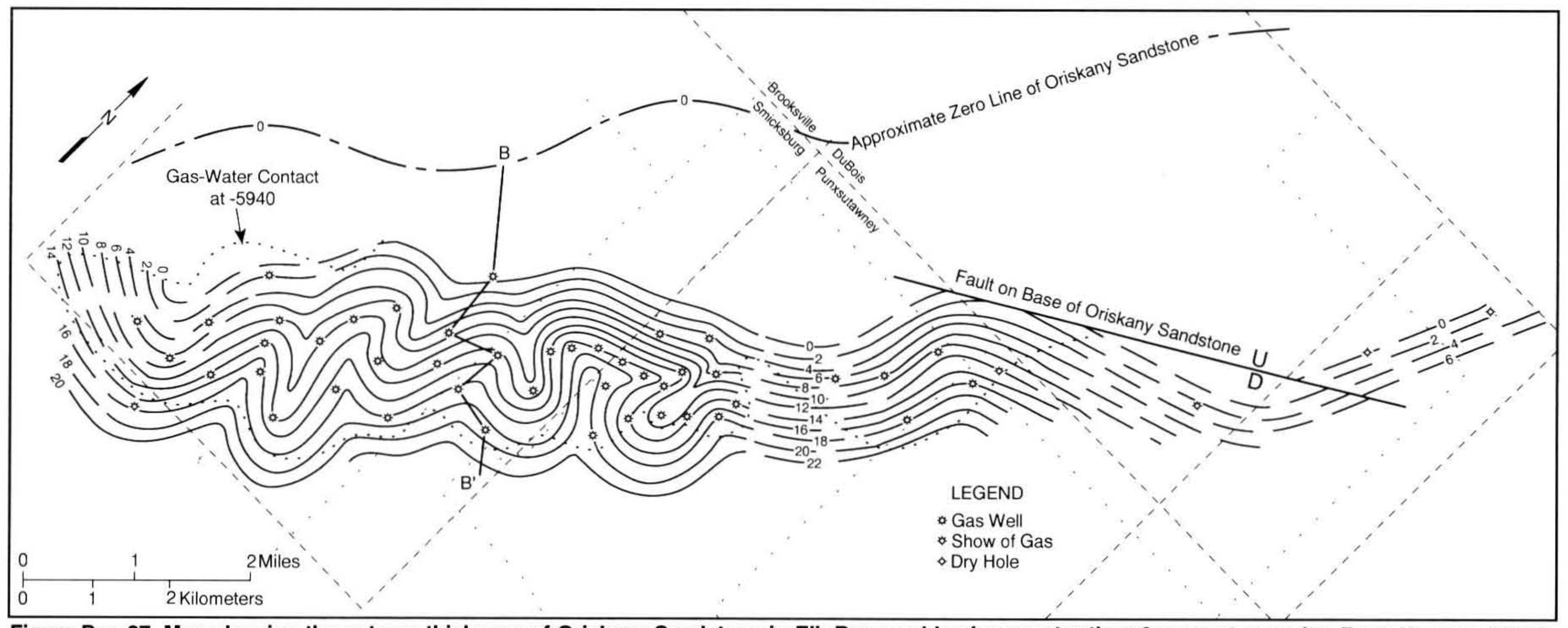


Figure Doc-27. Map showing the net pay thickness of Oriskany Sandstone in Elk Run pool having greater than 6 percent porosity. From Heyman (1969). Contour interval = 2 feet. See Figure Doc-2 for location.

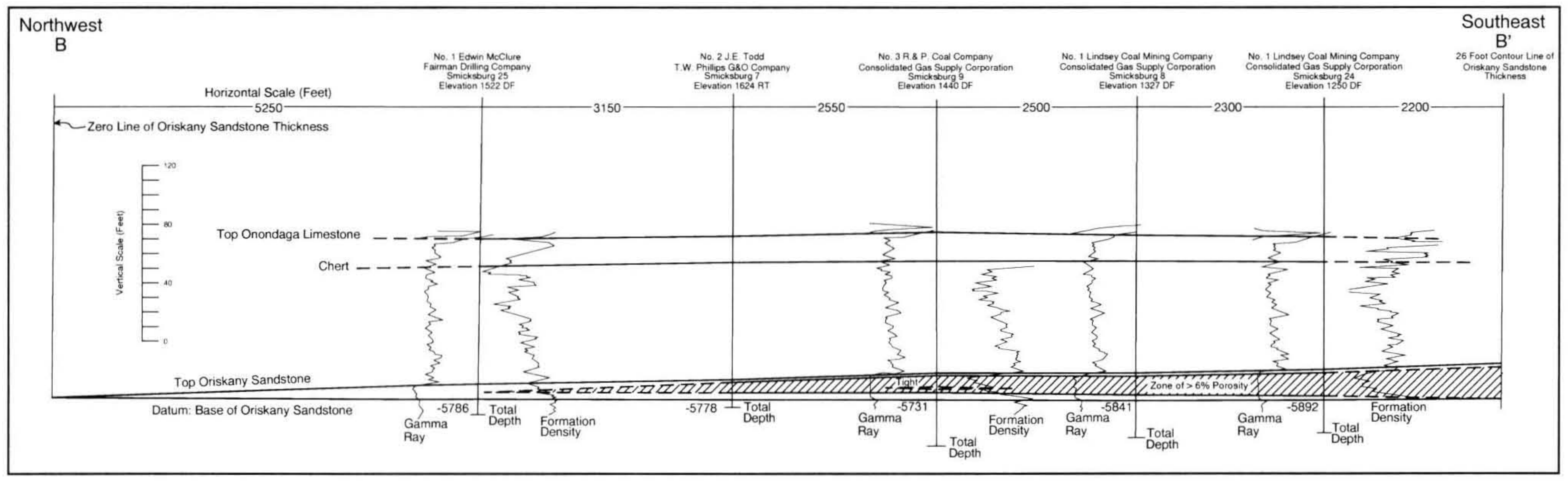


Figure Doc-26. Stratigraphic cross section B-B' of the Oriskany Sandstone in Elk Run pool, showing stratigraphic pinchout and zone of greater than 6 percent porosity. From Heyman (1969). See Figure Doc-25 for location of cross section.

(CAI) values equal to or slightly less than 2, which suggests local sources in the Middle and Upper Devonian black shales.

Resources and Reserves

Remaining gas resources in Oriskany Sandstone reservoirs in this combination traps play can be subdivided into proved reserves associated with producing wells, probable resources associated with existing gas fields, and undiscovered possible resources in undrilled or unproductive areas of the play.

Because most wells and fields producing from the Oriskany in this play are mature or old in age—indeed, many either have been abandoned or converted to storage—proved reserves and probable resources are small compared to that amount of gas already produced. Consequently, no attempt was made to subdivide these two categories of remaining gas. Instead, estimates of remaining gas were made for each field based on average values for Oriskany production and reserves for certain representative fields, and these data were then applied to all fields.

In West Virginia, data for original reserves, cumulative production, and remaining reserves are available for five fields in Kanawha, Jackson, and Wood counties. In addition to the volumetric data, the number of producing wells and

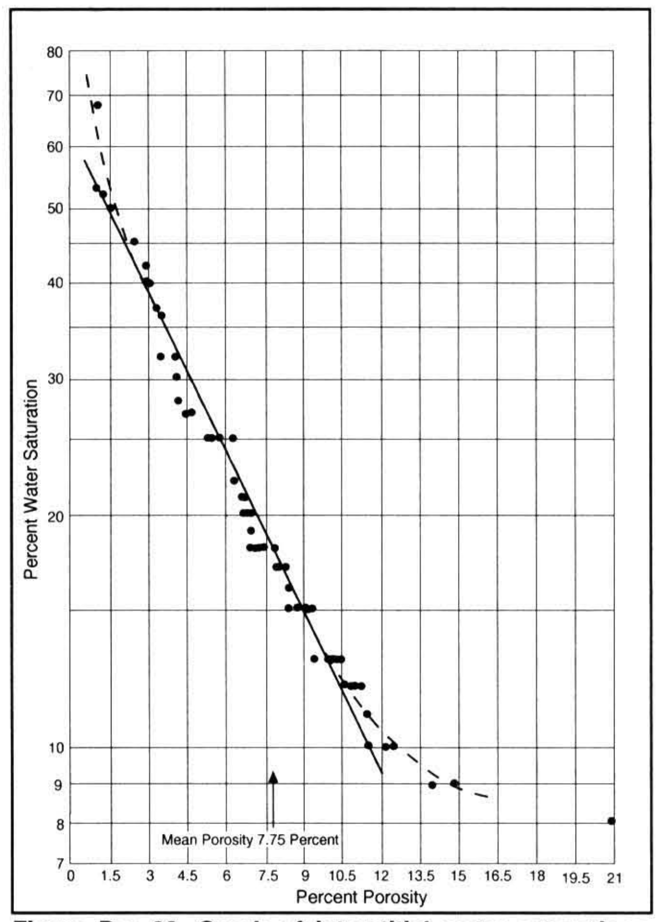


Figure Doc-28. Graph of interstitial water saturations plotted against interstitial porosity in the Oriskany Sandstone in Elk Run pool. Values were calculated at 2-foot intervals from formation density and induction logs. Modified from Heyman (1969).

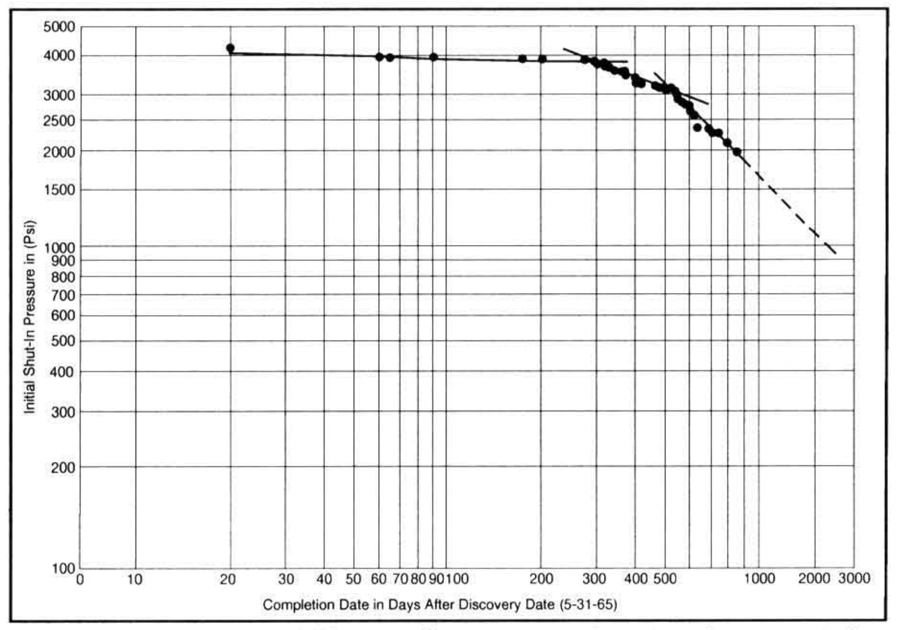


Figure Doc-29. Graph of initial shut-in pressures plotted against completion date for wells in Elk Run pool. Modified from Heyman (1969). Data arranged by forced-fit technique of Havlena (1967). Arrows indicate approximate points of change in rate of pressure decline.

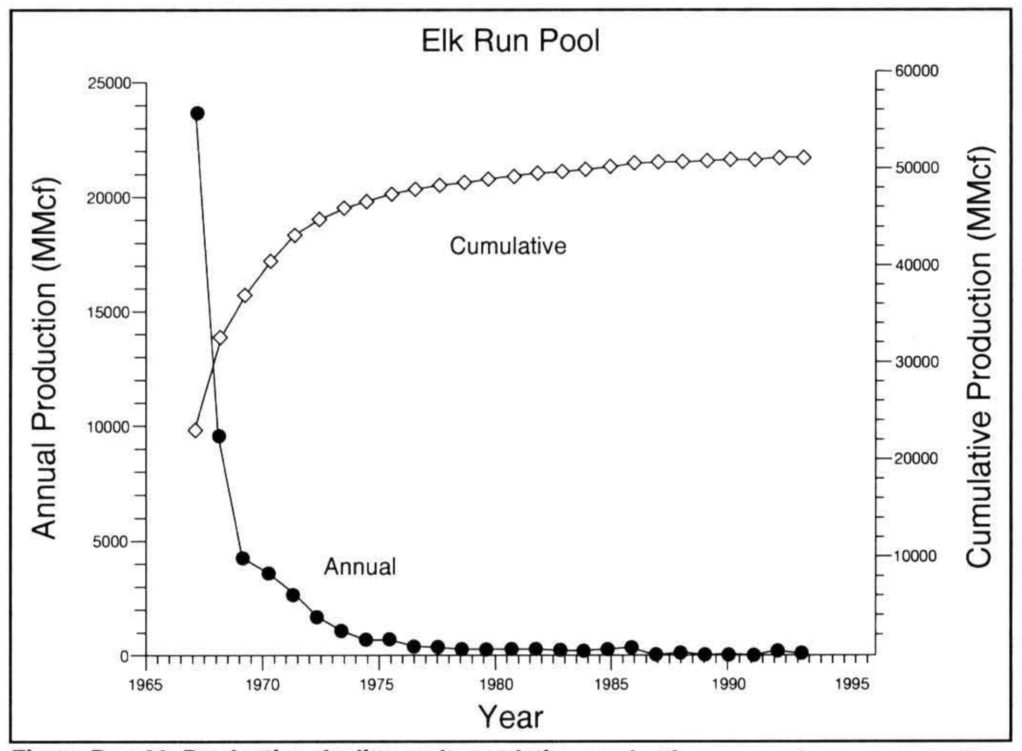


Figure Doc-30. Production decline and cumulative production curves for gas production in Elk Run pool.

Table Doc-3. Analysis of gas from Oriskany Sandstone in the Consolidated Gas Supply Corp. No. 4 R & P Coal Co. well in Elk Run pool, Jefferson County, Pennsylvania. From Moore and Sigler (1987a).

COMPONENT	MOLE PERCENT
Methane	97.1
Ethane	2.1
Propane	0
N-Butane	0
Isobutane	0
N-Pentane	0
Isopentane	0
Cyclopentane	0
Hexanes Plus	0
Nitrogen	0.6
Oxygen	0
Argon	0
Hydrogen	0
Hydrogen Sulfide	0
Carbon Dioxide	0.2
Helium	0.02
Btu Value	1,173
Specific Gravity	0.569

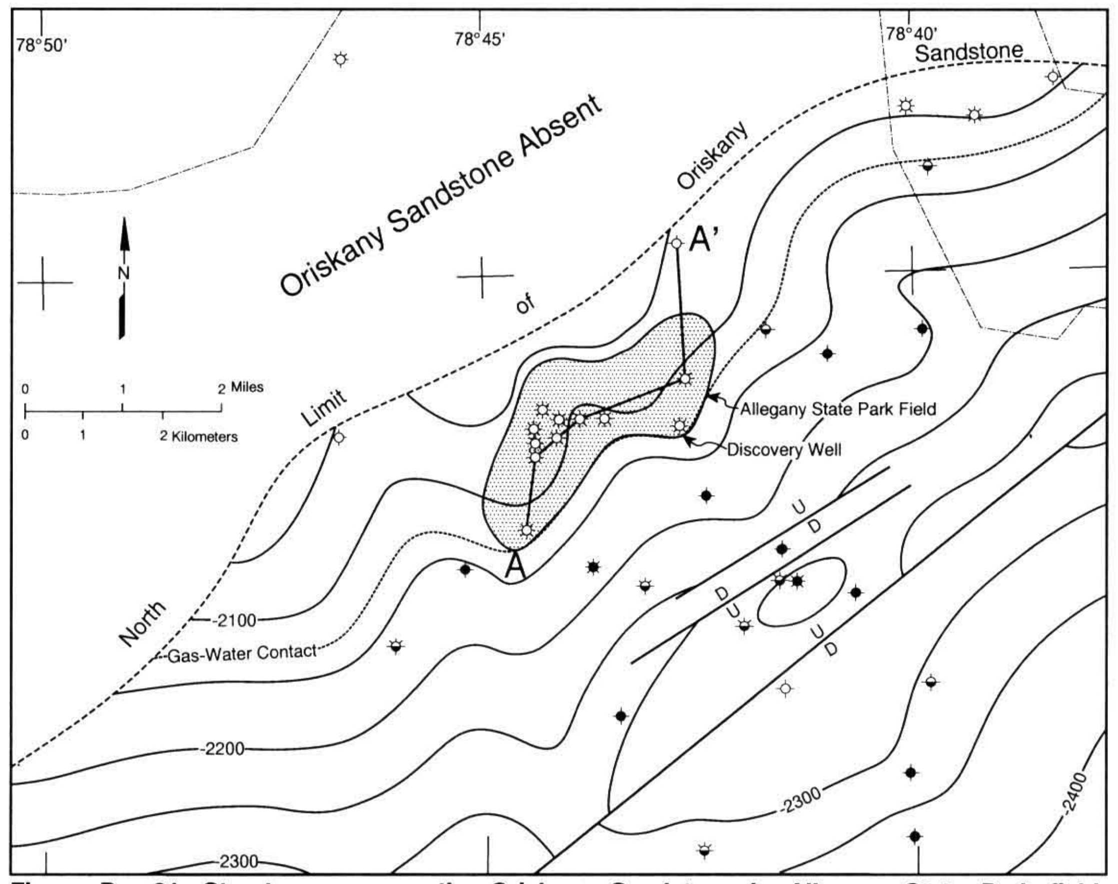


Figure Doc-31. Structure map on the Oriskany Sandstone in Allegany State Park field, Cattaraugus County, New York, and vicinity. Modified from Harding (1966) using data from Kreidler and others (1972). Contour interval = 50 feet. See Figure Doc-2 for location.

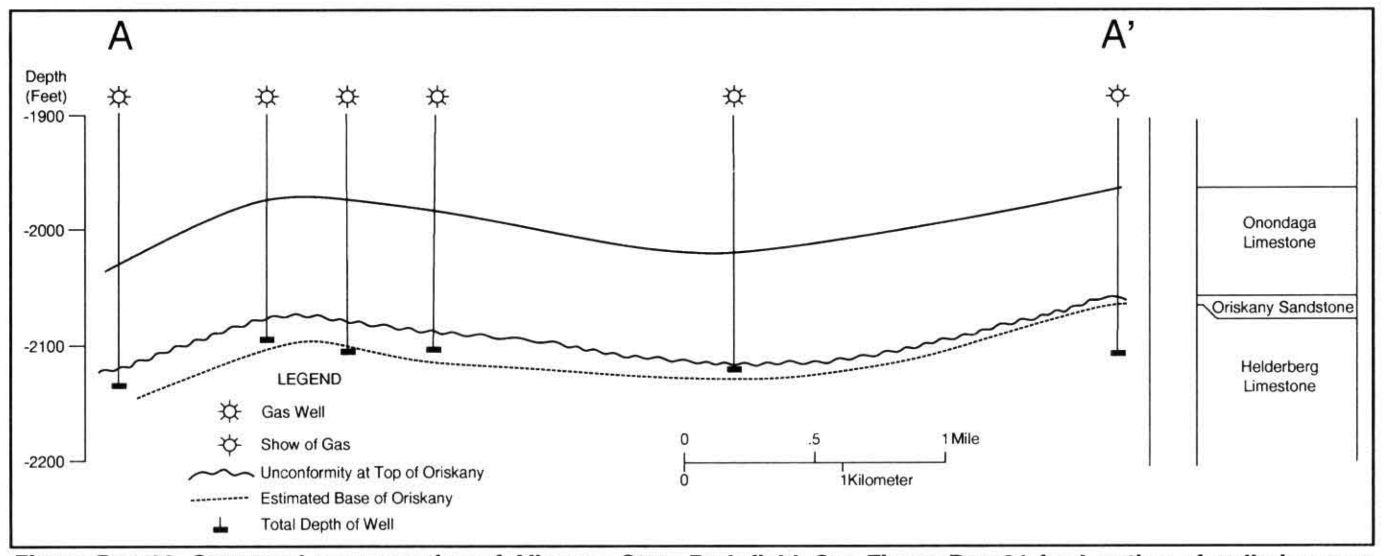


Figure Doc-32. Structural cross section of Allegany State Park field. See Figure Doc-31 for location of wells in cross section.

Table Doc-4. Analysis of gas from Oriskany Sandstone in the Felmont Oil Corp. No. 5 Lena Lockwood well, Allegany State Park field, Cattaraugus County, New York. From Moore and Sigler (1987a).

COMPONENT	MOLE PERCENT
Methane	84.1
Ethane	10.2
Propane	2.9
N-Butane	0.7
Isobutane	0.5
N-Pentane	0.2
Isopentane	0.1
Cyclopentane	Trace
Hexanes Plus	0.2
Nitrogen	1
Oxygen	0
Argon	Trace
Hydrogen	0
Hydrogen Sulfide	0
Carbon Dioxide	0.1
Helium	0.04
Btu Value	1,173
Specific Gravity	0.668

the size of the fields, in acres, also are known. For fields that had been drilled on a fairly regular spacing, produced and then abandoned or converted to storage, average values for production per acre and production per well were calculated by combining the data for all fields. The goal was to obtain production values that would be representative for the entire play. The Mcf/acre value multiplied by the area (in acres) in a given field would yield an estimate of the gas that could be recovered from a field that size once it was fully developed. The average Mcf/well value multiplied by the number of wells that had been drilled and produced would yield an estimate of cumulative production from the portion of the field that had been developed. The difference between the two values represents the remaining gas resource. The average values used in the calculations were 6,313 Mcf/acre and 930,643 Mcf/well.

The same technique was used for fields in New York, Ohio, and Pennsylvania: values for Mcf/acre and Mcf/well were calculated from data in representative fields and then applied to other fields for which volumetric data were not available. The result was a set of numbers representing either actual or estimated production for each field in the play, and a value for remaining gas in each field. The total estimated production for these fields was 1.3 tcf. Remaining proved reserves and probable resources associated with producing and storage fields were estimated at 168 bcf, a number that includes native gas left in a field when it was converted to storage. Combining the estimates for production (1.3 tcf) and remaining gas (.17 tcf) yields a value of 1.47 tcf proved reserves and probable resources in the fields. The estimated production volume represents 88.5 percent of the estimated 1.47 tcf original proved reserves and probable resources within gas fields in this play.

Approximately 10,800,000 acres in Kentucky, New York, Ohio, Pennsylvania, Virginia, and West Virginia are within the boundary of this play. If only one percent of this acreage contains undiscovered producible gas (possible resources), and each acre yields only 1,500 Mcf, then a conservative estimate of possible gas resources would be 162 bcf. If two percent of the acreage contains undiscovered producible gas, and each acre yields 3,000 Mcf, then a more optimistic estimate of possible gas resources would be 648 bcf. Thus, total gas resources for this play, including remaining proved reserves and probable and possible resources, may range from 330 (168 + 162) to 816 (168 + 648) bcf, still less than the 1.3 tcf already estimated to have been produced.

Due to the high drilling density in the play area, it is safe to assume that new fields will be small, in the 6 to 10 bcf range, so it can be estimated that between 16 and 27 fields will have to be discovered to find 162 bcf. Using these same assumptions, between 65 and 108 fields would have to be discovered to find 648 bcf. Given the fact that 65 years of drilling have resulted in the discovery of only 24 fields, the conservative estimate is perhaps the more realistic. However, it should be pointed out that in West Virginia alone, in addition to the nine named fields that have been developed in this play, gas has been discovered in the Oriskany in 14 deeper pool tests drilled in fields with shallow production. Confirmation wells have been drilled in five of the fields, bringing the total number of discovery wells (deeper pool tests and extensions) to 19, of which only three have been abandoned. Thus, these numerous though scattered successes suggest that a focused Oriskany program could result in the discovery and development of 16 to 27 fields that could contain the conservative estimate of 162 bcf.

Future Trends

Future exploration probably will concentrate on drilling small structures near the Oriskany pinchout where sandstone with enhanced porosity is thought to have been preserved, and in drilling similar structures in the eastern part of the play area in New York, Ohio, and West Virginia where variations in sandstone thickness may occur. In the shallower part of the play area, along the western pinchout of the Oriskany and along all borders of the no-sandstone areas within the play boundary, small, undrilled structural highs may be present where an appropriate amount of sandstone is assumed to be preserved. Thus, additional combination stratigraphic-structural fields may be found along, but set back from, the pinchout of the Oriskany Sandstone, similar to conditions that created Elk Run Pool. In other areas, variations in sandstone thickness in combination with minor structural highs, similar to Elk-Poca field, may be encountered.

Although most of the large structures at the Onondaga or Oriskany level have been tested in this play, numerous smaller structures, especially in the deeper portion of the play, have yet to be tested adequately. Thus, future drilling will concentrate on small structures mapped using subsurface well control and seismic data. Once the fields are discovered, additional stratigraphic controls will become obvious, if they are present.

PLAY Dop: LOWER DEVONIAN ORISKANY SANDSTONE UPDIP PERMEABILITY PINCHOUT

by Steven T. Opritza, Ohio Division of Oil and Gas

Location

Oriskany Sandstone gas production associated with an updip loss of permeability occurs in scattered pools located near the western and northern margins of the Appalachian basin (Figure Dop-1). The majority of the gas has been produced from wells within a narrow linear trend that extends along depositional strike from Jackson County, West Virginia, northward to Ashtabula County, Ohio. Lesser amounts have been produced from several small fields from northwestern Pennsylvania (Figure Dop-2). Beyond this trend, the reservoir is absent due to erosion or nondeposition; toward the basin, the formation is typically water saturated unless influenced by local structure. The Oriskany Sandstone is commonly known to drillers as the First Water of the Big Lime sequence in Ohio due to the common occurrence of brine in the formation.

Production History

The first commercial gas well to produce from the Oriskany Sandstone in the Appalachian basin was drilled in early 1900 in Austinburg Township, Ashtabula County, Ohio. The well flowed a large volume of gas from a depth of 1,989 feet and was an updip offset to an oil well drilled several months earlier near the town of Jefferson (Myers, 1937). This discovery led to local development of the Jefferson gas sand, as it was known to the drillers. By 1929, nine small fields had been discovered in Ashtabula and Lake counties. Cumulative production figures are unavailable for these fields, but it is known that the wells were relatively short lived due to salt-water encroachment (Hermann, 1983).

In 1922, the Ohio Fuel Supply Company No. 1 Miller well was drilled as a deeper pool wildcat near the town of Cambridge, Ohio, in Guernsey County (Figure Dop-2). Located on the crest of the Cambridge arch in an existing Berea Sandstone pool, the Miller well struck gas at 3,470 feet in a hard, white sandstone 125 feet below the top of the Onondaga Limestone. This discovery well, which flowed 8 MMcfg/d, was soon offset by five additional wells, all of which yielded large volumes of gas from the same sandstone reservoir that local drillers called the Cambridge gas sand or Niagara lime sand (Lockett, 1937). Drilling was extended to the north as productive limits were defined to the east and west. By the early 1930s, nearly 300 wells had been drilled in the Cambridge area. During the peak year of 1926, the daily average production was 190 MMcfg (Hall, 1952). Much of this gas supplied the local glass and brick industries, and the area became renowned for its quality glassware.

In the course of drilling "Newburg" wells in the late 1930s near Mayfield village in Cuyahoga County, Ohio, gas was discovered in the Oriskany. By 1941, the Mayfield Oriskany field was under development. Based upon closure mapped on the Onondaga surface, Rothrock (1949) considered this field a structural trap; however, the Mayfield pool is within the pinchout trend. Only six wells actually were produced from the Oriskany as further drilling was restricted in the area during this time. Between 1942 and 1948, these six wells each produced an average of 412 MMcfg.

South of Mayfield in Summit County, the Wiser Oil Company discovered gas and oil in the Oriskany in Richfield Township. Between 1941 and the late 1950s, 58 wells were drilled, which defined the productive limits of the Bath-Richfield gas field. Cumulative gas production for this field has exceeded 5 bcfg.

In Erie County, Pennsylvania, Oriskany gas was discovered in 1946 on the Mead farm. This well was successfully completed and led to the drilling of more than 60 producing wells in the area. These wells produced an average of 73 MMcfg each during their productive life. Similar to the fields in northeast Ohio, the Meade field did not sustain production for long, and the field was converted to gas storage in 1959 (Harper, 1982).

In 1951, B.H. Putnam drilled the No. 1 Wilson well (Athens 1027) to a total depth of 4,231 feet. The well flowed 360 Mcfg/d from the Oriskany at 4,150 feet, but the hole was lost after shooting. An offset well was drilled 200 feet away and was successfully completed, flowing 6 MMcfg/d. These tests led to the development of the Putnam (Belpre-Troy) field in eastern Athens and Meigs counties and Belpre Township, Washington County. By 1955, 24 wells had been drilled in the field and Putnam had extended the play into West Virginia with the discoveries of the Neptune and New England fields in Jackson and Wood counties. Similar to other Oriskany pinchout fields, most of these wells "watered out" within a relatively short time and were either plugged back or abandoned altogether (W. Putnam, oral commun., 1993).

Throughout the 1950s and 1960s, several small gas fields of 15 wells or less were discovered near the updip limit of Oriskany Sandstone deposition in Pennsylvania and West Virginia.

While drilling a "Clinton" sandstone test in 1970 in eastern Morgan County, Ohio, a strong flow of Oriskany gas was encountered in the Texaco Inc. No. 1 Stout well (Morgan 1173). After treatment, the Oriskany flowed 1,696 Mcfg/d, and the Stout well became the discovery well for the Hackney field. A total of 21 wells were drilled and have produced more than 5 bcfg to date.

In West Virginia, Oriskany drilling continued in Jackson and Wood counties where the Ravenswood, Rock Castle, and Washington Bottom fields were developed in the 1970s as extensions of the earlier discoveries by Putnam and others. The Washington Bottom field in Wood County was a self-help effort by the DuPont Corporation to supply gas for its chemical production facility on the Ohio River.

In 1973, Oriskany gas was again discovered incidental to "Clinton" drilling in Lafayette Township, Coshocton County. In the West Lafayette field, 25 wells were drilled and dually completed in the Oriskany and "Clinton". Cumulative

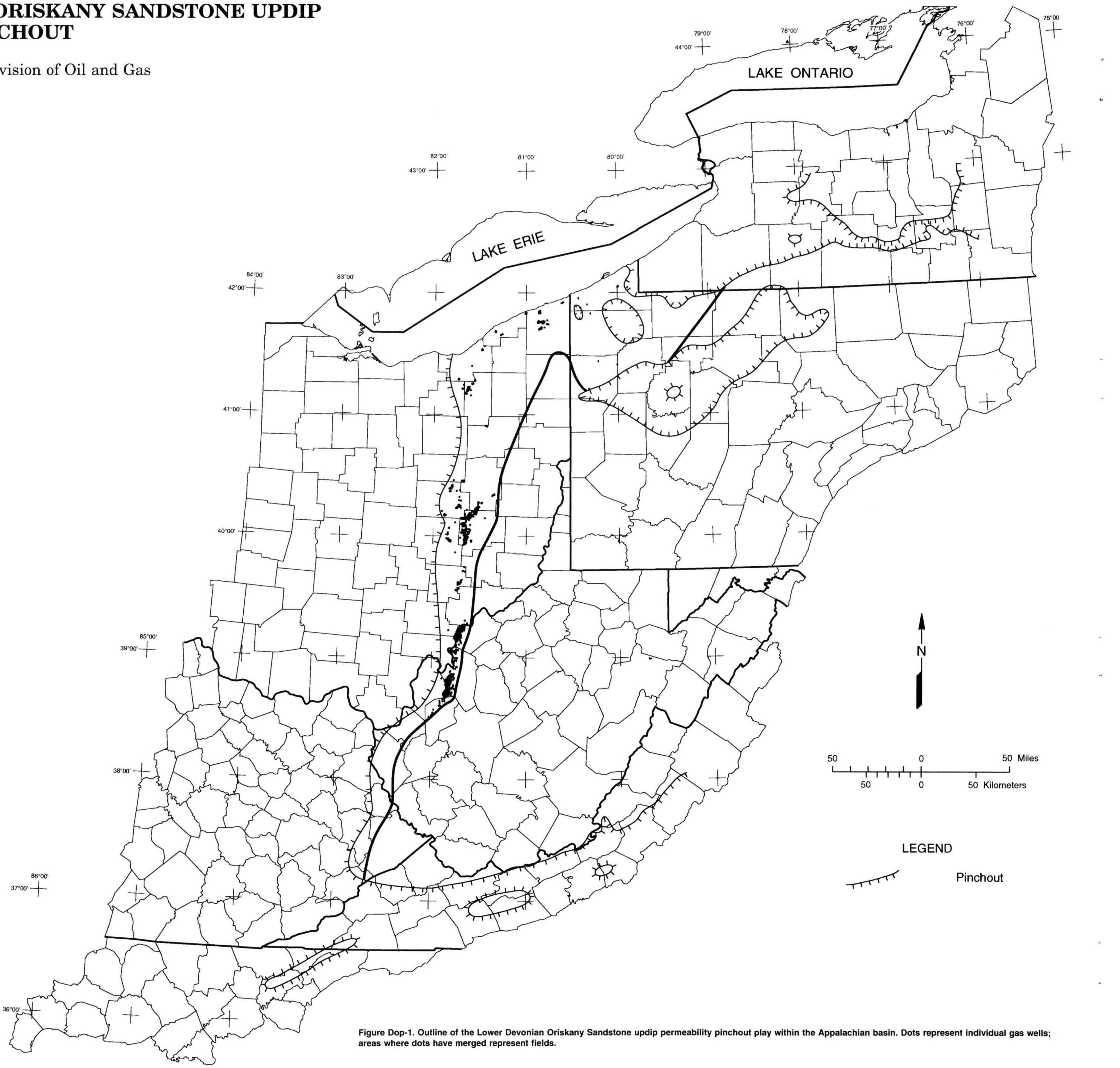


Figure Dop-1. Outline of the Lower Devonian Oriskany Sandstone updip permeability pinchout play within the Appalachian basin. Dots represent individual gas wells; areas where dots have merged represent fields.

production for the field is about 2.5 bcfg. Ten miles to the northwest, in Mill Creek Township, a smaller Oriskany pool was discovered in 1973. Thirteen wells produce gas and oil from the Oriskany.

In Lake County, Ohio, Viking Resources No. 1 Vernick-Wright hit gas at 1,580 feet in the Oriskany while drilling a "Clinton" well. This well was the discovery for the Geneva-Madison field, which has produced nearly 2 bcfg since 1982.

Table Dop-1 shows cumulative gas production for selected Oriskany Sandstone pinchout fields in the Appalachian basin. In general, the wells in this play have high initial open flow gas volumes. The reservoirs have high initial pressures and a gas-water contact. Overproducing the reservoir in the early stages of the well's life tends to hasten water encroachment and leads to premature abandonment. Based on available data, the average Oriskany well drilled within the pinchout trend is estimated to produce a cumulative total of 113 MMcfg during its productive life, which averages eight years. Estimated cumulative production for the play is 82 bcf.

Stratigraphy

The Oriskany Sandstone is Early Devonian in age and was named by Vanuxem for the white, fossiliferous sandstone exposed at Oriskany Falls, New York (Hermann, 1983). Use of the term Oriskany did not gain acceptance in Ohio until 1930 when it was recognized that the Cambridge gas sand, the Austinburg, the Jefferson gas sand, and the Niagara lime sands of the Ohio drillers were the stratigraphic equivalents of the Oriskany, which was being concurrently developed in Pennsylvania and New York.

The Oriskany does not crop out anywhere within the pinchout trend. In the subsurface, the reservoir is 100 to 300 feet below the Devonian shales. It is overlain by either the Bois Blanc Formation or the Onondaga Limestone if the Bois Blanc is absent (Figure Dop-3). This contact is unconformable and has caused considerable confusion as to whether certain fields in northeast Ohio and northwestern Pennsylvania are true Oriskany reservoirs or are reworked younger sandstones of Bois Blanc or Onondaga age. Abel and Heyman (1981) considered the reservoir in the Erie County, Pennsylvania, fields to be a basal Onondaga sandstone. Hermann (1983) posited that the Cuyahoga and Summit County fields produced from a sandy facies of the Bois Blanc. He also mapped the Oriskany as absent from most of Portage, Summit, and Trumbull counties, Ohio. Near the distal edge of deposition, it is impossible to distinguish Oriskany from other slightly younger Devonian sandstones on the basis of well logs or cuttings alone. In 1991, a core test by Summit Energy in Norton Township, Summit County indicated 5 feet of fine-grained, light gray fossiliferous sandstone 244 feet below the top of the Onondaga Limestone, which was described as Oriskany Sandstone. Consequently, the fields in northern Summit County are included in this report and the western edge of the pinchout as mapped by Hermann (1983) has been revised. West of this pinchout, limited gas production occurs from northeastern Kentucky to north-central Ohio from local sandstone reservoirs known variously as Hillsboro, Sylvania, or Springvale. Some of these may be outliers of true Oriskany Sandstone, while others appear to be those younger Devonian sandstones that are roughly in the same stratigraphic position as the Oriskany. More detailed stratigraphic work including faunal studies needs to be done to resolve this correlation problem. Underlying the Oriskany is either the Devonian Helderberg Limestone or the Silurian Bass Islands Dolomite (Figure Dop-4). This contact is also recognized as unconformable (Reeve, 1983).

Lithologically, the Oriskany is a well-sorted, relatively pure quartzose sandstone ranging in color from white to light gray and gray-brown. Grain size varies from fine to medium-coarse, and the grains tend to be subangular to subrounded. Calcium carbonate is the principal cementing agent. Brachiopod shell fragments are common throughout the Oriskany, indicating a high-energy nearshore marine environment of deposition (Hermann, 1983).

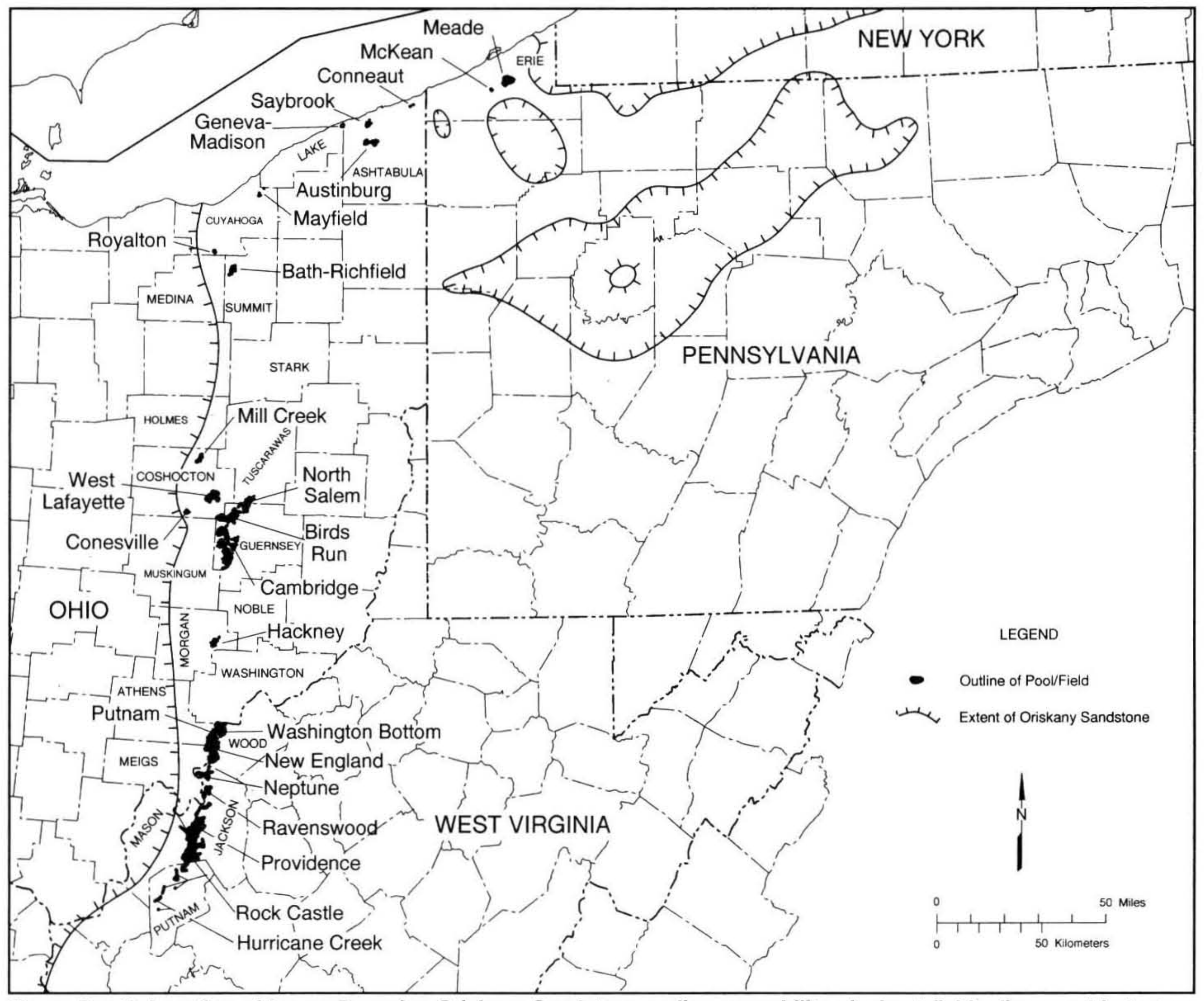


Figure Dop-2. Location of Lower Devonian Oriskany Sandstone updip permeability pinchout fields discussed in text or listed in Table Dop-1. Modified from Diecchio and others (1984).

Structure

The trend of the Oriskany Sandstone pinchout play is at the western and northern margins of the Appalachian Plateau structural province (Figure Dop-5). Although this play is by definition a stratigraphic play, it has been suggested that local folding or faulting has influenced production in several fields within the pinchout trend (Rothrock, 1949; Coogan and Reeve, 1985). Lockett (1937) and Rothrock (1949) established that there is a definite gas-water contact in the reservoir and that commercial gas would be found only in those wells completed above the water level. The actual structural effect on production of wells drilled within the pinchout trend is subtle and of local importance only. A little relief on the Oriskany is present in the area of the Cambridge arch in southeastern Ohio (Figure Dop-6).

Reservoir

Hydrocarbons that accumulated in the Oriskany may have originated in the west-central Appalachian basin and migrated updip to the western margin of the reservoir where entrapment occurred against the impermeable carbonates of the Onondaga. The organic-rich black Devonian shales are the most likely source rocks for the Oriskany hydrocarbons (de Witt, 1993).

TABLE Dop-1		Austinburg OH	Bath-Richfield OH	Cambridge OH	Birds Run OH	North Salem OH	Conesville OH	West Lafayette OH	Hackney OH	Royalton OH	Meade PA
BASIC RESERVOIR DATA	POOL NUMBER	317	352	132	139	159	137	160	949	350	
	DISCOVERED	1899	1941	1922	1925	1926	1929	1973	1970	1954	1946
	DEPTH TO TOP RESERVOIR	1,990	2,000	3,300	3,225	3,550	2,700	2,920	3,580	1,790	2,360
	AGE OF RESERVOIR	Lower Devonian	Lower Devonian	Lower Devonian	Lower Devonian	Lower Devonian	Lower Devonian	Lower Devonian	Lower Devonian	Lower Devonian	Lower Devonian
	FORMATION	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany
	PRODUCING RESERVOIR	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany	Oriskany
	LITHOLOGY	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone
	TRAP TYPE	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic
	DEPOSITIONAL ENVIRONMENT	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine
	DISCOVERY WELL IP (Mcf)	8,000	260	8,000	151	885	685	698	1,686	958	420
	DRIVE MECHANISM	water	gas cap	water	water	water	gas cap	gas cap	gas cap	gas cap	water
	NO. PRODUCING WELLS	0	0	0	0	0	0	13	21	0	67
	NO. ABANDONED WELLS	85	58	145	84	75	8	12	6	11	38
	AREA (acreage)	1,187	704	3,083	1,270	758	160		480		1,540
	OLDEST FORMATION PENETRATED	Mt. Simon	Knox	Precambrian	Rose Run	Knox	Oriskany	Knox	Knox	Queenston	Gatesburg
	EXPECTED HETEROGENEITY DUE TO:	deposition	deposition	deposition	deposition	deposition	deposition	deposition	deposition	deposition	deposition
RESERVOIR PARAMETERS	AVERAGE PAY THICKNESS (ft.)	16	58	9	13	6	8	8	10	50	11
	AVERAGE COMPLETION THICKNESS (ft.)	2	50	2 - 3	13	6	8	8	10		8
	AVERAGE POROSITY–LOG (%)	12	9	5	9	8	7	8	11		5
	MINIMUM POROSITY–LOG (%)	4	5	2	5	6	4	4	7		2
	MAXIMUM POROSITY–LOG (%)	16	12.5	14	13	11	9	12	19		10
	NO. DATA POINTS	3	2	4	2	3	1	3	2		1
	POROSITY FEET	94	167	48	19	68		75	93		77
	RESERVOIR TEMPERATURE (°F)	80	81	93	92	95	87	89	96	78	84
	INITIAL RESERVOIR PRESSURE (psi)	800	700	1,260	1,200	1,010	1,135	837	1,000	680	825
	PRODUCING INTERVAL DEPTHS (ft.)	1,800-2,000	1,900-2,200	3,200-3,400	3,100-3,300	3,400-3,600	2,600-2,800	2,800-3,000	3,500-3,700	1,700-1,900	2,200-2,500
	PRESENT RESERVOIR PRESSURE (psi) / DATE			100				150	65		
FLUID & GAS PROPERTIES	Rw (Ωm)	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.035		
	GAS GRAVITY (g/cc)										
	GAS SATURATION (%)	50	60			43			64		49
	WATER SATURATION (%)	50	30			40		28	28		51
	COMMINGLED	no	no	no	no	no	no	yes	yes	yes	no
	ASSOCIATED OR NONASSOCIATED	nonassociated	associated	associated	nonassociated	associated	nonassociated	associated	nonassociated	nonassociated	nonassociated
	Btu/scf		1,100	1,194	1,100						
VOLUMETRIC DATA	STATUS (producing, abandoned, storage)	abandoned	abandoned	abandoned	storage	abandoned	abandoned	producing	producing	abandoned	storage
	ORIGINAL GAS IN PLACE (Mcf)	3,740,200	9,678,000	22,135,556		8,213,343	1,257,181	1,744,913	5,782,776	2,439,583	5,430,000
	ORIGINAL GAS RESERVES (Mcf)	3,366,100	4,839,000	19,922,000		7,392,009	1,131,463	1,570,422	5,204,500	2,195,625	4,887,000
	PRODUCTION YEARS	1899-1930	1953-1971	1926-1964	1926-1964	1930-1966	1930-1965	1975-	1971-	1954-1972	1946-1959
	REPORTED CUMULATIVE PRODUCTION (Mcf)		4,839,000	19,922,000	7,953,900	7,392,009	1,131,463	1,570,422	5,204,499	2,342,000	4,887,000
	NO. WELLS REPORTED										
	ESTIMATED CUMULATIVE PRODUCTION (Mcf)	3,366,100	4,839,000	19,922,000	7,953,900	7,392,009	1,131,463		5,204,499		4,887,000
	REMAINING GAS IN PLACE (Mcf)/DATE	374,100	4,839,000	2,213,556		821,334	125,718		578,277	243,958	543,000
	REMAINING GAS RESERVES (Mcf)/DATE	0	0	0		0	0			0	0
	RECOVERY FACTOR (%)	90	50	90		90	90	90	90	90	90
	INITIAL OPEN FLOW (Mcf/d)	2,521	250	1,822	636	513	824		1,696	637	6,575
	FINAL OPEN FLOW (Mcf/d)	250	460	2,632	534	666	245	758	534	966	4,024

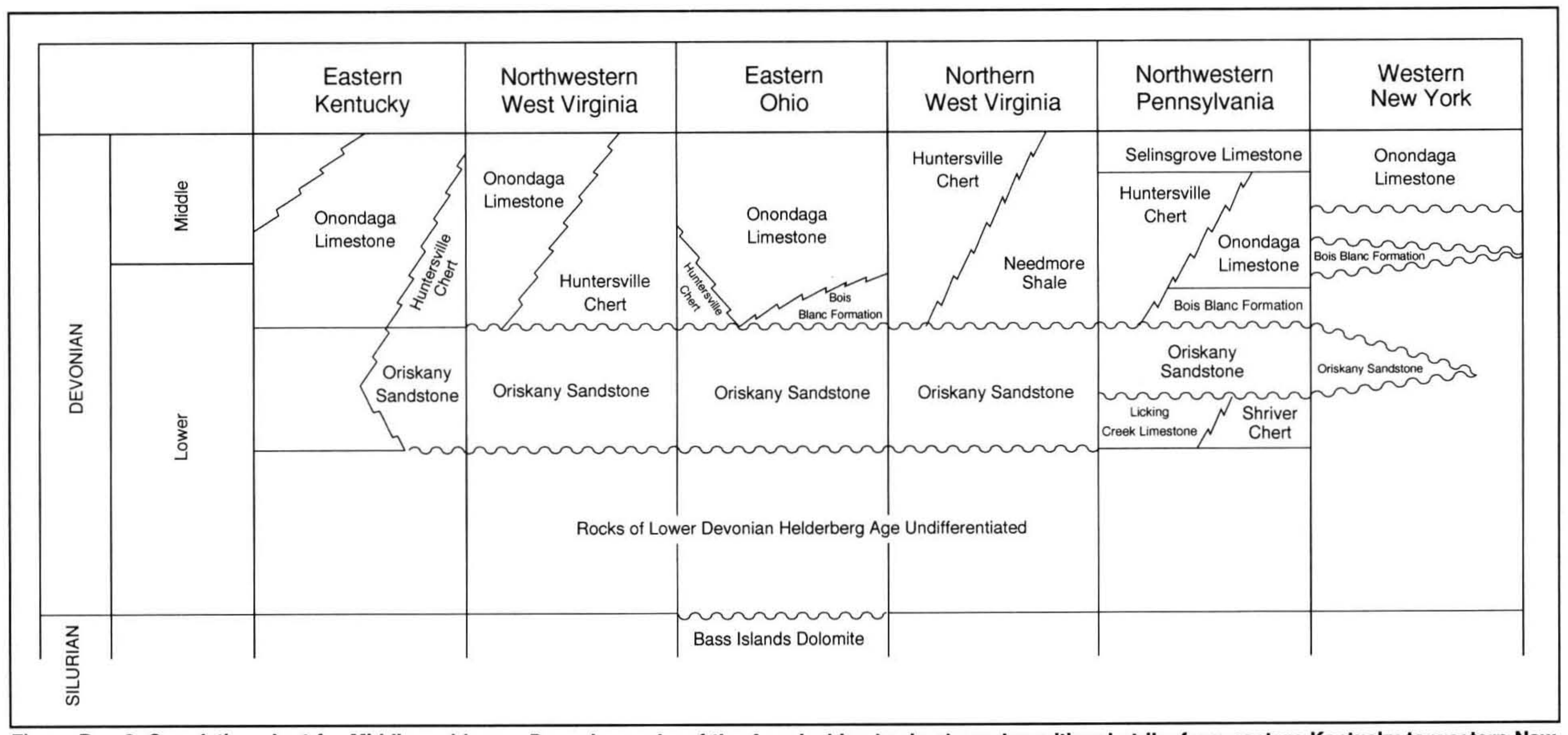


Figure Dop-3. Correlation chart for Middle and Lower Devonian rocks of the Appalachian basin along depositional strike from eastern Kentucky to western New York. Modified from Patchen and others (1985a).

Depth to the Oriskany ranges from about 4,900 feet in the Rock Castle field of Jackson County, West Virginia, to less than 1,600 feet in the fields of Ashtabula County, Ohio. Average depth for the play is 3,500 feet.

Thickness of the reservoir averages 10 to 20 feet in most of the productive trend and reaches a maximum of about 60 feet. Porosity is primarily intergranular and ranges from 2 to 19 percent. Average porosity is 7 percent. Permeability data is scarce for the Oriskany, but it is believed to be high (de Witt, 1993). In the Diamond Alkali No. 201 DAC well (Lake 19), a whole core analysis of the Oriskany section indicated a permeability range from 0.01 to 365 md.

Along the trend, reservoir pressures commonly ranged from 700 to 1,100 psi. Pressure rapidly decreased with time in individual wells and in the fields as development expanded. In the fully developed fields that are still active, reservoir pressure is 100 psi or less.

A type log (Figure Dop-7) from the Carless Resources No. 1 Combs well (Guernsey 3471) illustrates the log response of reservoir quality Oriskany Sandstone. This well is an offset to the Tipka-Bartlo No. 1 Orr (Guernsey 2459) that "blew out" in the Oriskany and was gauged at 20 MMcfg/d. Open flows of the earlier wells more commonly ranged from 1 to 2 MMcfg/d prior to stimulation. Post-stimulation flows as high as 14 MMcfg/d were recorded. In most cases, production declined rapidly after the flush period; 50 percent of the total recoverable volume commonly was produced in the first year of the life of the well (Figure Dop-8).

Early completion techniques consisted of shooting the wells with 30 quarts or more of nitroglycerin. Wells drilled since the 1950s have been stimulated by various methods of hydrofracturing or acidizing. The most successful wells are those that are treated in the uppermost section of the reservoir above the water contact.

Description of Key Fields

Cambridge field: The Cambridge field of Guernsey County, Ohio, was discovered in 1922 and is the largest and most significant of the Oriskany pinchout fields. Although located on the Cambridge arch, this field is not structurally controlled at the Oriskany level. Thickness of the reservoir ranges up to 20 feet with porosity as high as 14 percent. Based on pressure decline at the wellhead, communication between wells more than a half mile apart suggests a high degree of permeability in the reservoir. A rapid decline in production and brine encroachment are characteristic of wells drilled in this field. A downdip gas-water contact was determined at 2,600 feet below sea level (Lockett, 1937).

Wells drilled below this depth invariably produced brine. Immediately updip from this contact, approximately 80 oil wells were drilled and produced from 3 to 200 bbl/d (Hall, 1952).

A total of 145 wells were drilled and produced nearly 20 bcfg from this field, which was largely developed by 1930. Average cumulative production per well is estimated at 137 MMcf. Occasionally, a well drilled for "Clinton" production will yield a show of gas in the Oriskany, but for the most part, the field is pressure depleted and most of the wells have been plugged.

North Salem field: As a result of the success of the Cambridge field, drilling expanded to northern Guernsey County and, in 1926, gas was discovered in the Oriskany near the village of North Salem. By the early 1930s, the North Salem field had approximately 75 producing oil and gas wells, and the field had been extended into southern Tuscarawas County. Like the Cambridge field, these wells rapidly declined and most were plugged within seven years. Producing wells averaged 98 MMcfg during their productive lifetime. The field is now abandoned.

Conesville field: The Conesville field was discovered in 1929 in Franklin Township, Coshocton County, Ohio, near the village of Conesville. The discovery well, Ohio Fuel Gas No. 1 Corry (Coshocton 64A-1), gauged 625 Mcfg/d from a depth of 2,575 feet. By 1936, 10 wells had been drilled, of which eight were productive. The Oriskany averaged only 8 feet in thickness and porosity ranged up to 10 percent. When the field was abandoned in 1965, 1,131 MMcfg had been produced from the original eight wells, averaging 141 MMcf per well. Although small, the Conesville field is considered significant because no extensional development wells were drilled in the area. Consequently, there may be future Oriskany potential in this field.

Meade field: The Meade field (Figure Dop-9) was discovered in 1946 with the completion of the Appalachian Development Corp. No. 1 Merle K. Meade well (Erie A-32) in Summit Township, Erie County, Pennsylvania. This well flowed 420 Mcfg/d from the Oriskany between 2,281 to 2,291 feet. Rock pressure was 825 psi. Between 1946 and 1958, 105 wells were drilled, and 67 were successfully completed. The productive wells totaled nearly 5 bcfg during the life of the field for an average of 73 MMcf per well. The Meade field is significant because it is the largest of the Oriskany pinchout fields outside of Ohio. In 1959, the field was converted to gas storage.

Bath-Richfield field: In 1941, gas was found in the Oriskany at 2,040 feet in the Wiser Oil Co. No. 2 Bachan well (Summit 126) near Richfield in Summit County, Ohio. The well had 40 feet of reservoir sandstone and gauged 260 Mcfg/d after shooting. Subsequent drilling extended the play south into Bath Township and by the mid-1950s, 58 wells were producing in the field. Most of the wells produced oil with the gas. Thickness of the reservoir ranged from 10 to 60 feet with an average porosity of 9 percent. Initial rock pressure was 600 to 700 psi. Between 1953 and 1971, the field produced an estimated 5 bcfg plus an unknown amount of oil. Only a few wells are still active supplying domestic gas. In 1987, two wells were drilled to test the Oriskany. The reservoir was pressure depleted and the wells were abandoned.

Putnam field: The Belpre-Troy field in Athens, Meigs and Washington counties, Ohio, was discovered in 1951 in Troy Township, Athens County and was subsequently renamed Putnam field for the driller who developed it, B.H. Putnam. Putnam drilled a total of 24 wells in the early 1950s, most of which were located near the Ohio River in western Washington County. The Oriskany was found from 85 to 100 feet below the top of the Onondaga at an average depth of 4,100 feet. Porosity ranges from 4 to 12 percent. Post-stimulation open flows averaged 1,600 Mcfg/d. Typically, brine production overtook the gas within a few

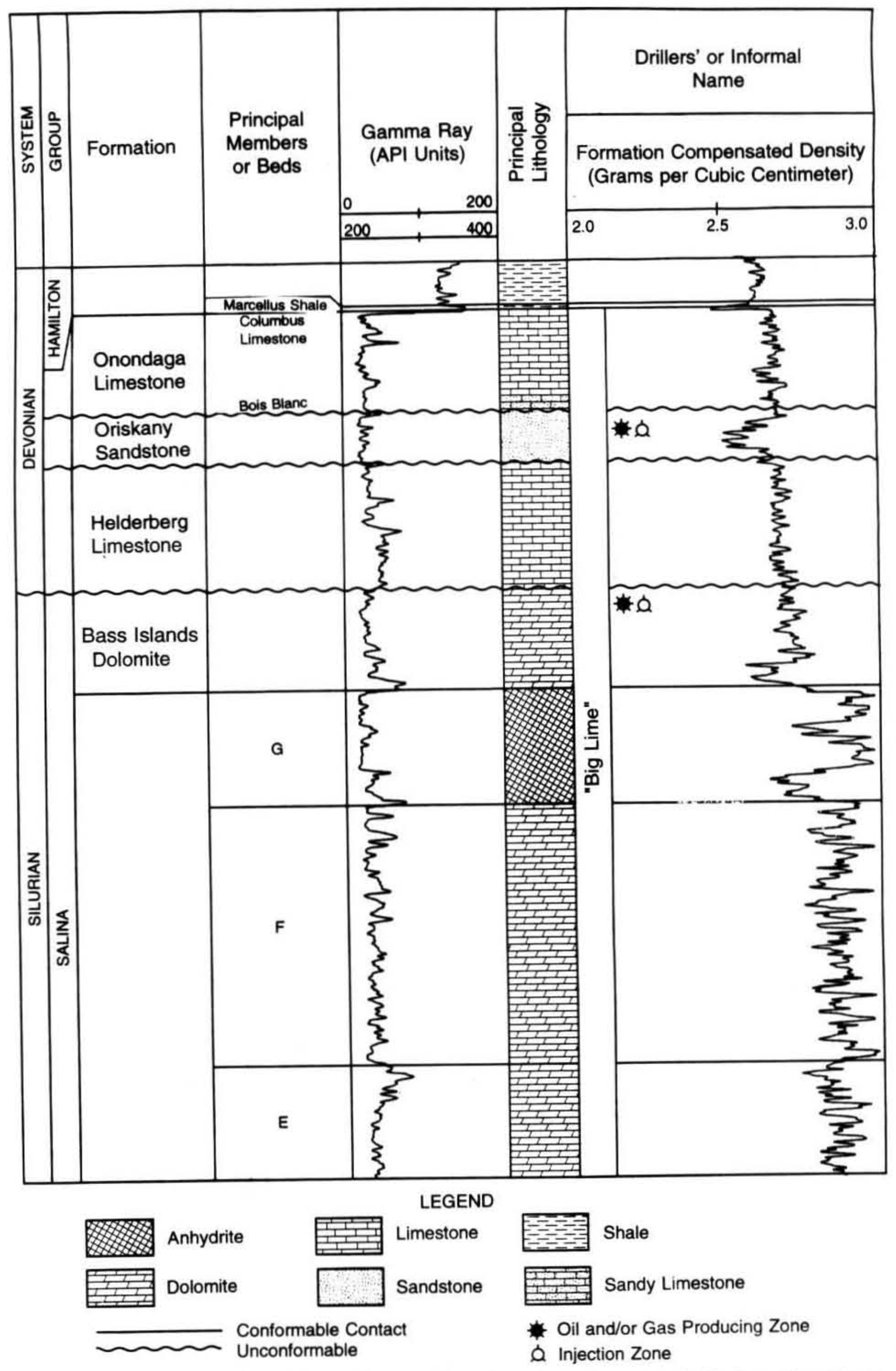


Figure Dop-4. Stratigraphic column of rocks with characteristic log signature showing Lower Devonian-Upper Silurian sequence from the Benatty Corporation No. 95 Ohio Power well (Noble 3357) in Jackson Township, Noble County, Ohio.

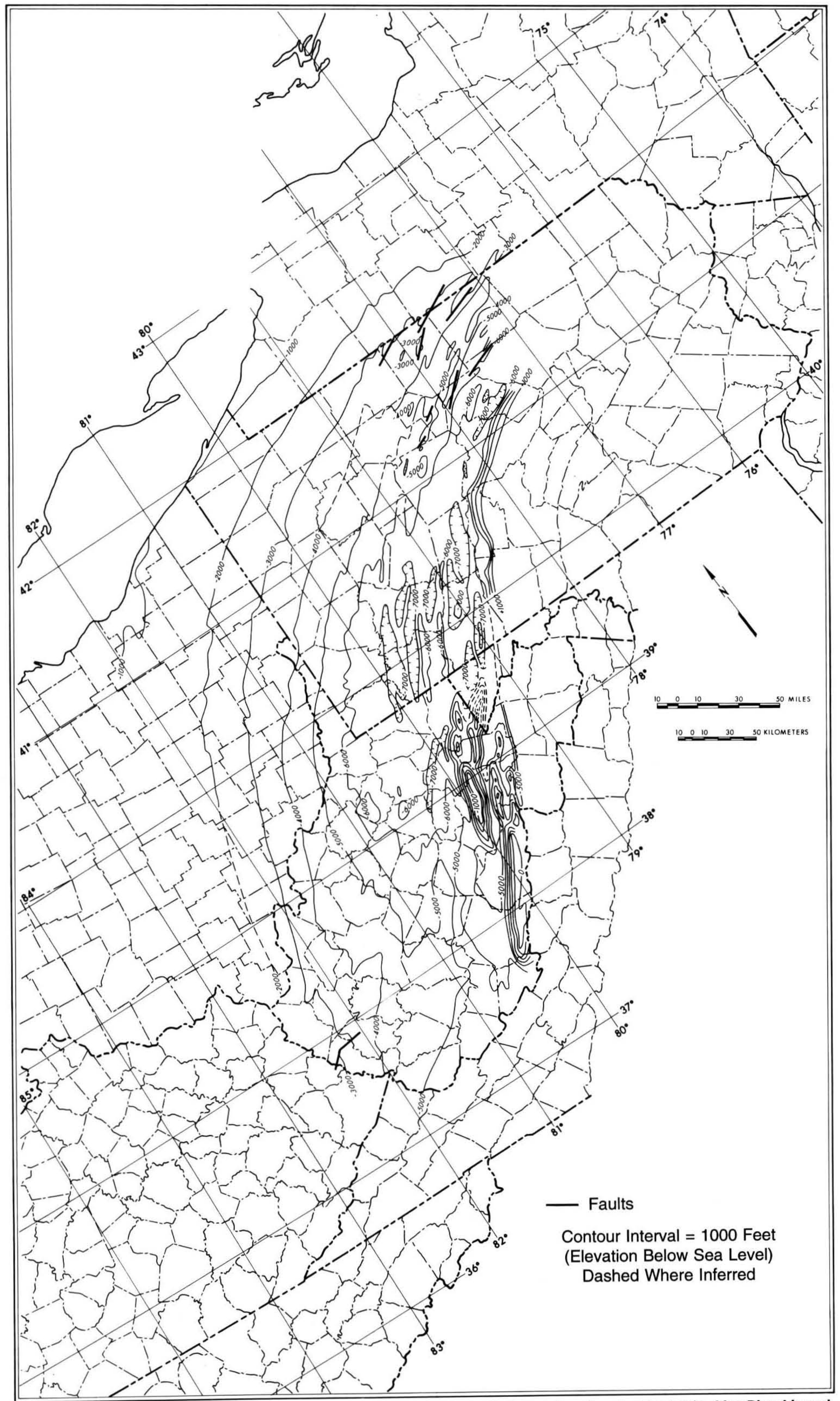


Figure Dop-5. Structural contours drawn on top of the Oriskany Sandstone in the western Appalachian basin. After Diecchio and others (1984).

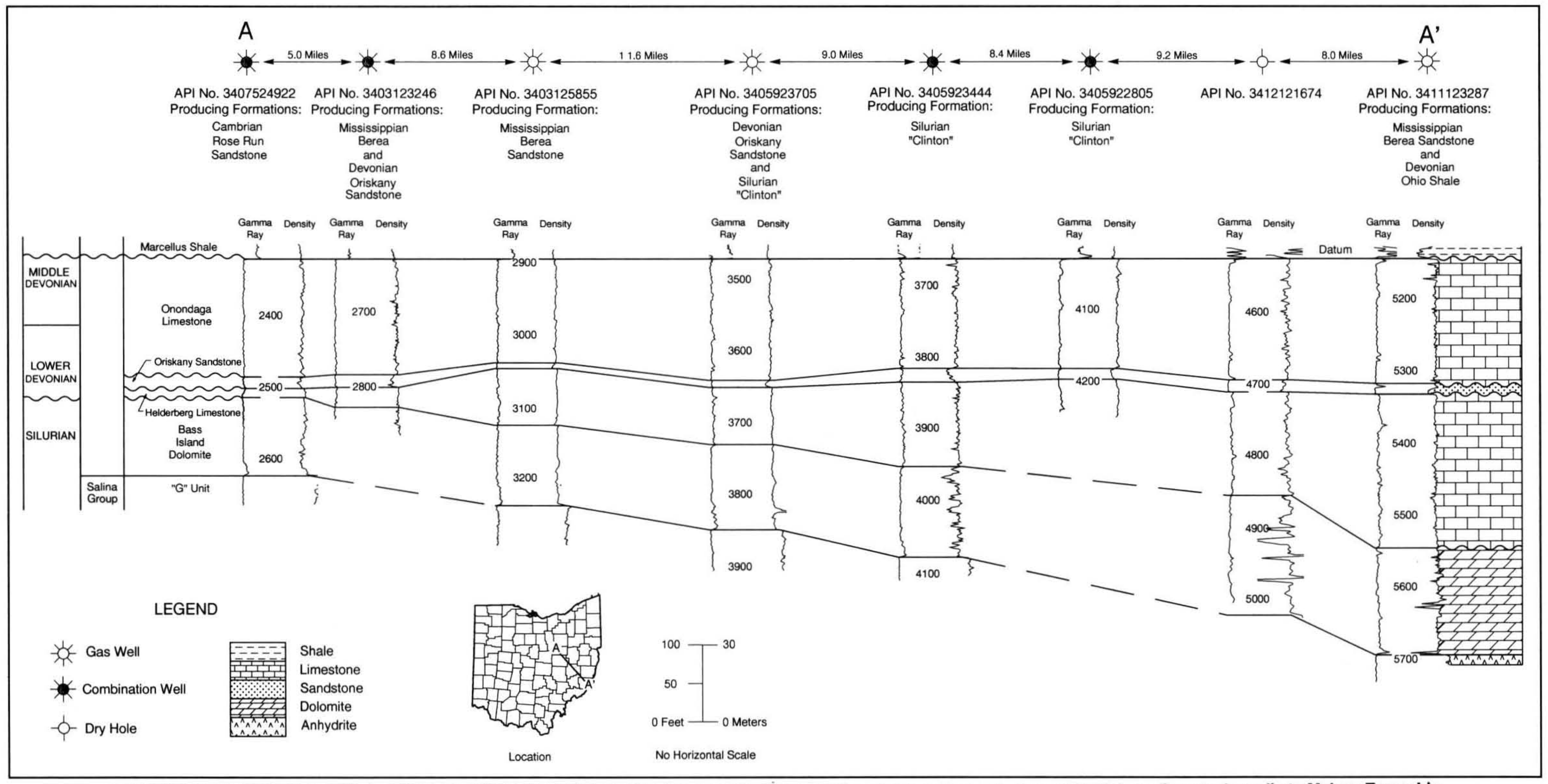


Figure Dop-6. Cross section A-A' showing Lower Devonian Oriskany Sandstone and adjacent rock units from Mechanic Township, Holmes County downdip to Malaga Township, Monroe County in southeastern Ohio.

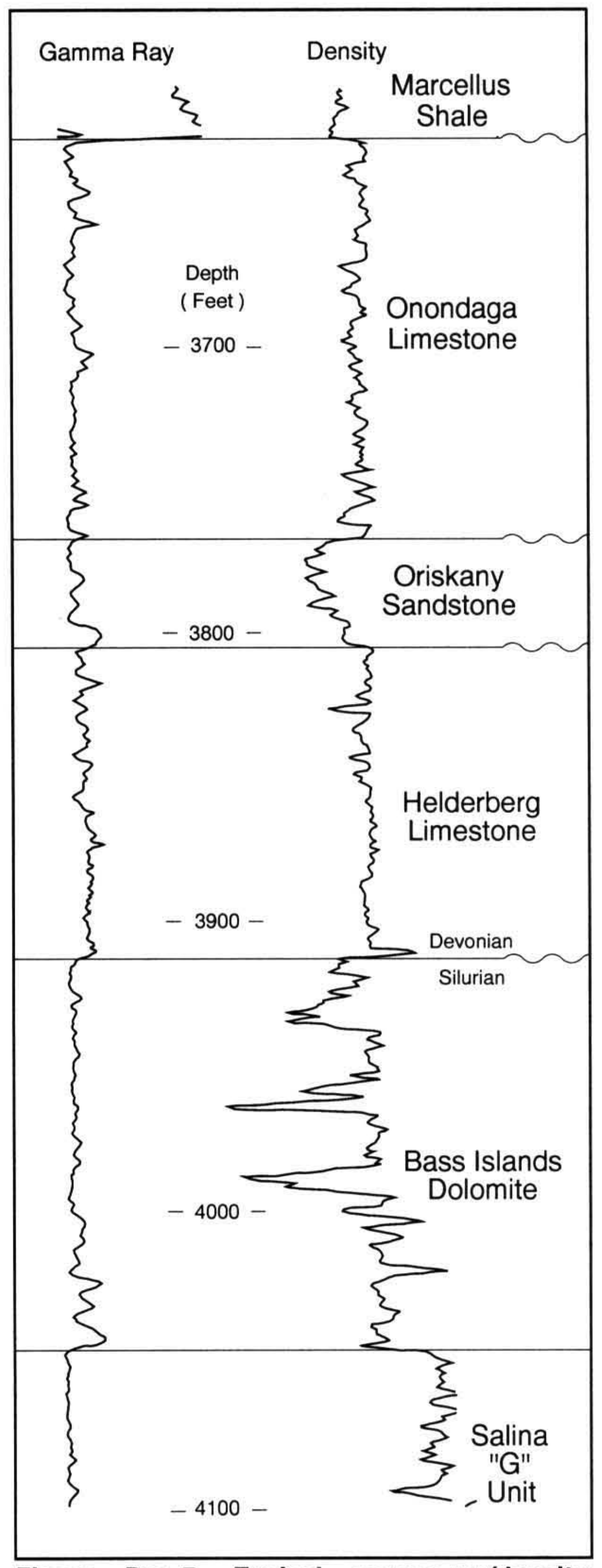


Figure Dop-7. Typical gamma-ray/density geophysical log curves showing Oriskany Sandstone and adjacent units in the Carless Resources, Inc. No. 1 J. Combs well (Guernsey 3471) in Monroe Township, Guernsey County, Ohio.

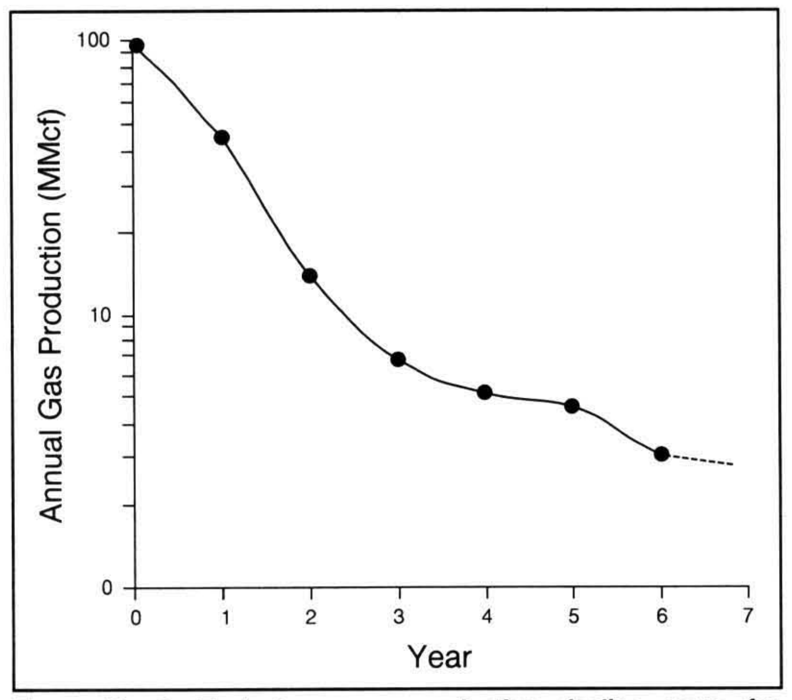


Figure Dop-8. Typical average production decline curve for Oriskany Sandstone wells in the Cambridge field, Guernsey County, Ohio.

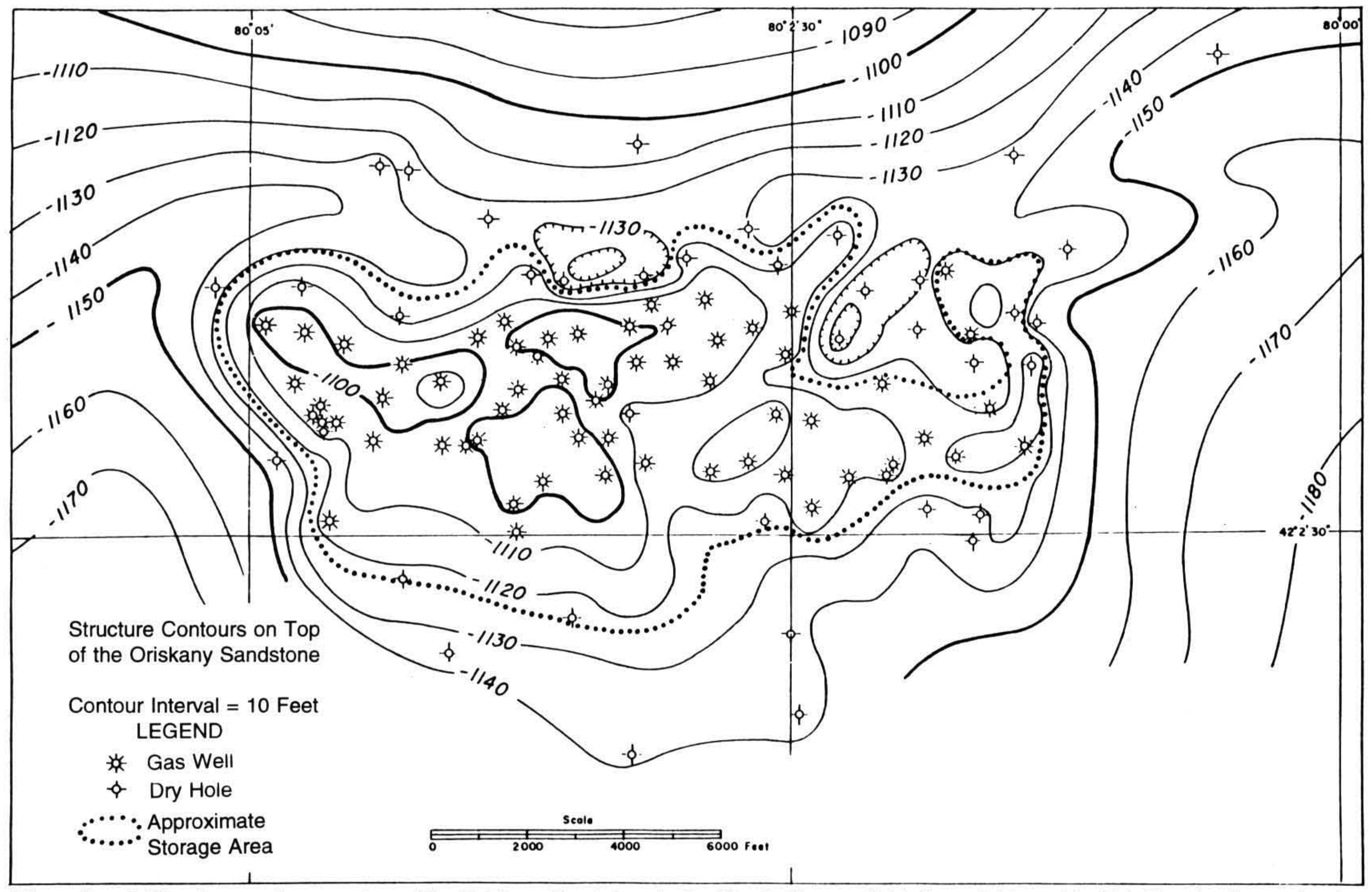


Figure Dop-9. Structure contours on top of the Oriskany Sandstone in the Meade Storage field, Summit Township, Erie County, Pennsylvania. After Lytle and others (1963).

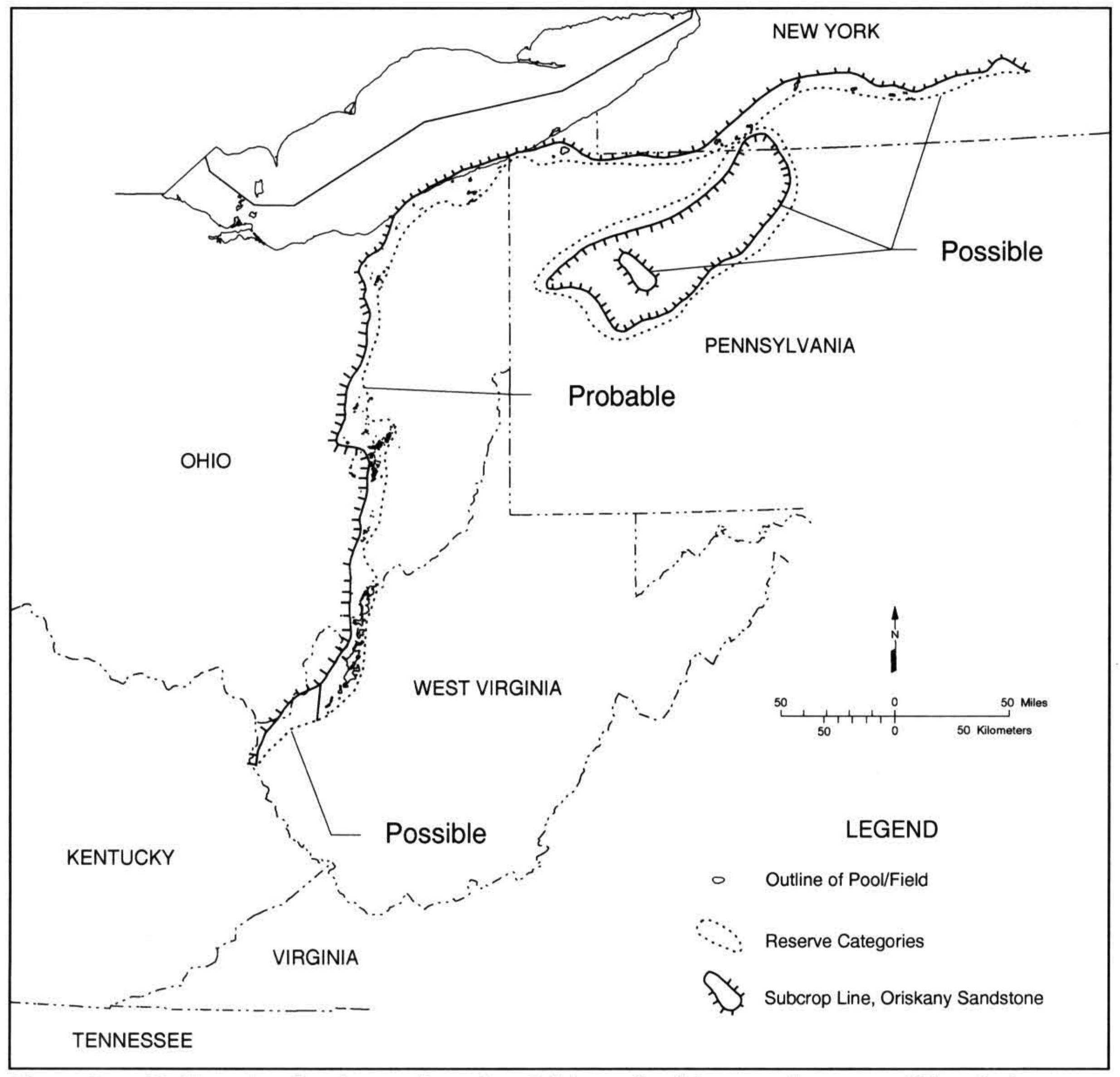


Figure Dop-10. Map showing Lower Devonian Oriskany Sandstone updip permeability pinchout gas fields/pools with outlines of probable and possible reservoir trends in the Appalachian basin.

Table Dop-2. Estimated proven gas resources for the Oriskany Sandstone reservoir in the Appalachian basin.

Lithology	Number of Wells	Estimated Cumulative Production Per Well	Recovery Factor	Total Estimated Drainage Area for all Wells	Original Gas-In-Place	Original Gas Reserves	Average Life of Well
Sandstone	652	113 MMcfg	90%	19,560 acres	82 bcf	74 bcf	5-10 years

Table Dop-3. Estimated undiscovered probable and possible gas resources for the Oriskany Sandstone pinchout play in the Appalachian basin.

Trend Type	Gross Area in Acres	Estimated Net Productive Area in Acres	Estimated Gas Recovery Per Acre	Estimated Recoverable Gas Reserves	Probability of Recovery
Probable	2,176,000	20,000	3,780 Mcf	76 bcf	80%
Possible	1,238,309	11,400	5,000 Mcf	57 bcf	20%

years, and the wells were either plugged back for Berea production or abandoned altogether. The Putnam field is significant because there has been a renewed interest in Oriskany development there since late 1993.

New England field: The New England field in Wood County, West Virginia, was discovered in 1952 when B.H. Putnam drilled the No. 1 Wigal well (Wood 375) in West Virginia as a southern extension of his Ohio field. This discovery flowed 4.7 MMcfg/d after fracturing and led to the drilling of 26 producing wells and eight dry holes between 1952 and 1956 (Cardwell, 1982b). The New England field was the first of the true Oriskany pinchout fields in West Virginia with reservoir characteristics much like those in the Putnam field in Ohio. Cardwell (1982b) estimated total cumulative production for the New England field at 6 bcfg.

Hackney field: The 1970 discovery of gas in the Oriskany by Texaco (Morgan 1173) led to the development of the Hackney field in eastern Morgan County, Ohio, which has produced more than 5 bcfg. The better-producing wells have well-developed sandstone reservoirs with porosity as high as 19 percent. Unlike most of the other Oriskany pinchout fields along the trend, high water saturation in the reservoir is not a problem in the Hackney field and well longevity is increased. Texaco's No. 1 Murray-Gannon well (Morgan 1184) still averages 120 Mcfg/d after 23 years of production. This well has produced about 1.5 bcf during its lifetime.

Resources and Reserves

The 10 fields shown in Table Dop-1 were selected as representative of the productive Oriskany Sandstone fields along the pinchout trend. Eight of these fields had sufficient production histories available to allow estimates of original gas in place and remaining recoverable reserves. Production data were not available for the Austinburg and Putnam fields. Reserves for those fields were calculated by the volumetric reserve method.

A total of 652 wells was used to determine the initial and remaining reserves for these 10 fields. Original gas-in-place was found to be 82.1 bcf. In the non-associated fields, a recovery factor of 90 percent was used. This percentage was reduced to 50 percent for the fields that produced significant quantities of oil with the gas. The average cumulative recovery per well for all 10 fields in Table Dop-1 was determined to be 113,344 Mcfg. Proven resources are shown in Table Dop-2 for these fields.

Figure Dop-10 illustrates the areas within the trend in which probable and possible gas resources may be discovered. The area of probable recoverable resources encompasses 2,176,000 acres and is entirely within the proven productive trend of the Oriskany pinchout play. Possible resources may be discovered as northern and southern extensions of the proven trend and immediately adjacent to the "no-sand" area in west-central Pennsylvania where stratigraphic pinchout of the Oriskany might be expected. A total of 1,238,309 acres is within the areas designated for possible resources. Due to the geographic limitation inherent to this play, no deep-basin area of speculative resources is indicated on the map. Table Dop-3 shows the estimated resources for the probable and possible resources trends in the basin.

Future Trends

Limited potential exists for gas production in wells that have been drilled for "Clinton" sandstone production but have not yet treated the Oriskany. In August 1992, a "Clinton" well, Carter-Jones No. 2 Parrish (Noble 1742), was plugged back and acidized in the Oriskany. Cumulative production figures for the next eight months show this well produced 93 MMcfg (A. Janssens, oral commun., 1993). There may be hundreds of other "Clinton" wells within the probable Oriskany trend which have similar plug-back potential. Reserve estimations for these are included in Table Dop-3.

Occasionally, strong flows of gas are encountered in the Oriskany during the drilling of "Clinton" or other deeper formations. These incidental discoveries have led to the development of small pools in Lake and Guernsey counties in the 1980s. In most cases, these wells rapidly deplete and are either deepened to the original target or are abandoned.

Potential exists for drilling in Lake Erie if environmental and economic conditions can be satisfied. The shoreline from Cleveland to Erie County, Pennsylvania, would fall within the trend of probable reserves. These reserves are included in Table Dop-3.

In late 1993, five new Oriskany wells were drilled and completed in the Putnam field. Reported initial daily production from these wells ranges from 75 Mcf to 250 Mcf. In 1994, eight more new permits were issued for this area, and six of these were successfully completed in the Oriskany. If production is sustained in these new wells, it is conceivable that an ongoing developmental drilling play will extend this field and possibly carry over into West Virginia.

The current operators of the wells in the Hackney field report that conversion of the field to gas storage may be feasible at some point in the future. The Oriskany reservoir has excellent storage properties because of its relatively uniform thickness and porosity. There are two Oriskany pinchout fields in the Appalachian basin that have been successfully converted to gas storage (Table Dop-1).

PLAY Sbi: UPPER SILURIAN BASS ISLANDS TREND

by Arthur M. Van Tyne, Consulting Geologist

Location

Gas and oil production from the Bass Islands play occurs from zones of extensive fracturing and thrust faulting within units ranging in age from late Silurian to early Middle Devonian along a structural trend that extends for approximately 84 miles from southwestern New York into northwestern Pennsylvania south of Lake Erie (Figure Sbi-1). Production occurs from the Bertie Dolomite; the Bass Islands Dolomite and its New York equivalent, the Akron Dolomite; the Bois Blanc Limestone; the Onondaga Limestone; and the Marcellus Shale. In New York, the play trends in a northeast-southwest direction for 68 miles but changes to a more east-west direction for 16 miles in Pennsylvania. Extensive production has been found in the more southerly portion of the play in Chautauqua County, New York, but only scattered production in its northern reaches. In Erie County, Pennsylvania, production also is scattered and less extensive (Figure Sbi-2a). This structural trend marks the northwestern limit of Appalachian type thrust fault and fold tectonics.

Production History

The discovery well for this trend was the No.1 Kelley, which was completed on January 10, 1888 as the discovery well of the Zoar field (Figure Sbi-2a). Bishop (1895) presented a minimal record for the well but did not mention the operator.

The Zoar gas field (Figure Sbi-2a; Table Sbi-1), used since 1916 for gas storage, is located near the northeastern end of this trend. Early wells at Zoar encountered large flows of gas (one estimated at 25,000 to 30,000 Mcf/d) and shows of oil in the same rocks later found productive farther to the southwest in the heart of the trend. Because of a lack of detailed well data, there was no evidence that Zoar might be a complex structural feature. Bishop (1895) suggested that the gas was contained in vugs or cavities in the Akron. However, such large gas flows and the shows of oil are more indicative of the fracture production found in the Bass Islands play.

While mapping the structure of the northern part of the play area, it was found from study of a gamma-ray log of the No. 1 Darling well drilled by the New York State Natural Gas Company in the Zoar storage field (Figure Sbi-2a) that the well had cut a substantial thrust fault zone in the productive section. This was evidence that the structural trend extended farther to the northeast into southern Erie County, New York.

In 1932, a well drilled on the Randall farm, south of Chautauqua Lake and 1 mile northwest of the edge of this trend in one of its main producing areas (Figure Sbi-2b), encountered a show of oil in the black Marcellus Shale. This is the closest well to this play that had a show of hydrocarbons in a zone later found to be productive in the trend.

In late 1963, a Pennzoil subsidiary, Wolfs Head Oil Refining, drilled the No. 1 Harrington well in central Chautauqua County (Figure Sbi-2b). This was a deep test that ended in the Late Cambrian Potsdam Sandstone. The well encountered some oil in what was termed the "Bass Island (sic) zone," and the zone also was found to be thickened by thrust faulting. The section was fracture-treated, and during a two-week test, the well produced a small amount of gas, about 100 barrels of oil, and a large volume of salt water. Although Pennzoil decided not to complete the well because oil prices were low at that time, the well is within the area of this play and may be termed the present-day discovery well of the Bass Islands play trend. It is also the discovery well of the Ellery pool in the trend.

No further drilling developments took place in the area of the play until the mid to late 1970s. It was at this time that a drilling boom occurred as a result of operators looking for tight sandstone gas production from the deeper Medina Sandstone. Both Chautauqua County, New York, and Erie County, Pennsylvania, became the sites of extensive Medina gas well drilling. In 1975 and 1976, a large number of Medina Sandstone wells were drilled by Resource Exploration, Inc., in an area about 4 miles southwest of Chautauqua Lake in what was later found to be the more southerly part of the Bass Islands play trend in New York. An unknown number of those wells encountered flows of gas and oil when they penetrated the Bass Islands or adjacent units. Drillers, however, considered this only a nuisance and cased off the zones so that they could continue drilling to the deeper Medina Sandstone gas pay. Few, if any, of those shows were ever officially reported. It was through the use of the gamma-ray logs for those wells during a U.S. Department of Energy-sponsored study of Devonian black shales that the structural basis for this play trend was first revealed (Van Tyne and others, 1980).

In February 1981, Envirogas, Inc., encountered a large flow of oil, reportedly 200 barrels of oil per day, and some gas from the Bass Islands section in the No. 8 Wassink well just west of the village of Clymer in southwestern Chautauqua County, New York (Figure Sbi-2b). This well has been considered to be the discovery well of the Bass Islands trend and its associated production. It is actually only the discovery well of the Clymer pool, but it spurred a high level of drilling activity looking for similar production in the trend. Most of this was guided by maps of the trend by Van Tyne and others (1980) published as part of the U.S. Department of Energy-financed Eastern Gas Shales Project. A portion of one of those maps showing the bounding thrust faults of the Bass Islands trend is shown in Figure Sbi-3. The trend and the configuration as defined by the bounding thrust faults is still essentially the same as originally depicted (Figure Sbi-3). Almost all of the drilling for Bass Islands objectives has taken place within the confines of the trend as shown in Figure Sbi-3.

Because Bass Islands type production has been found in an area where established Medina tight sandstone gas production lies 800 to 1,000 feet deeper, only a small number of wells have been drilled solely for the shallower production. When shallower Bass Islands production was discovered, often by

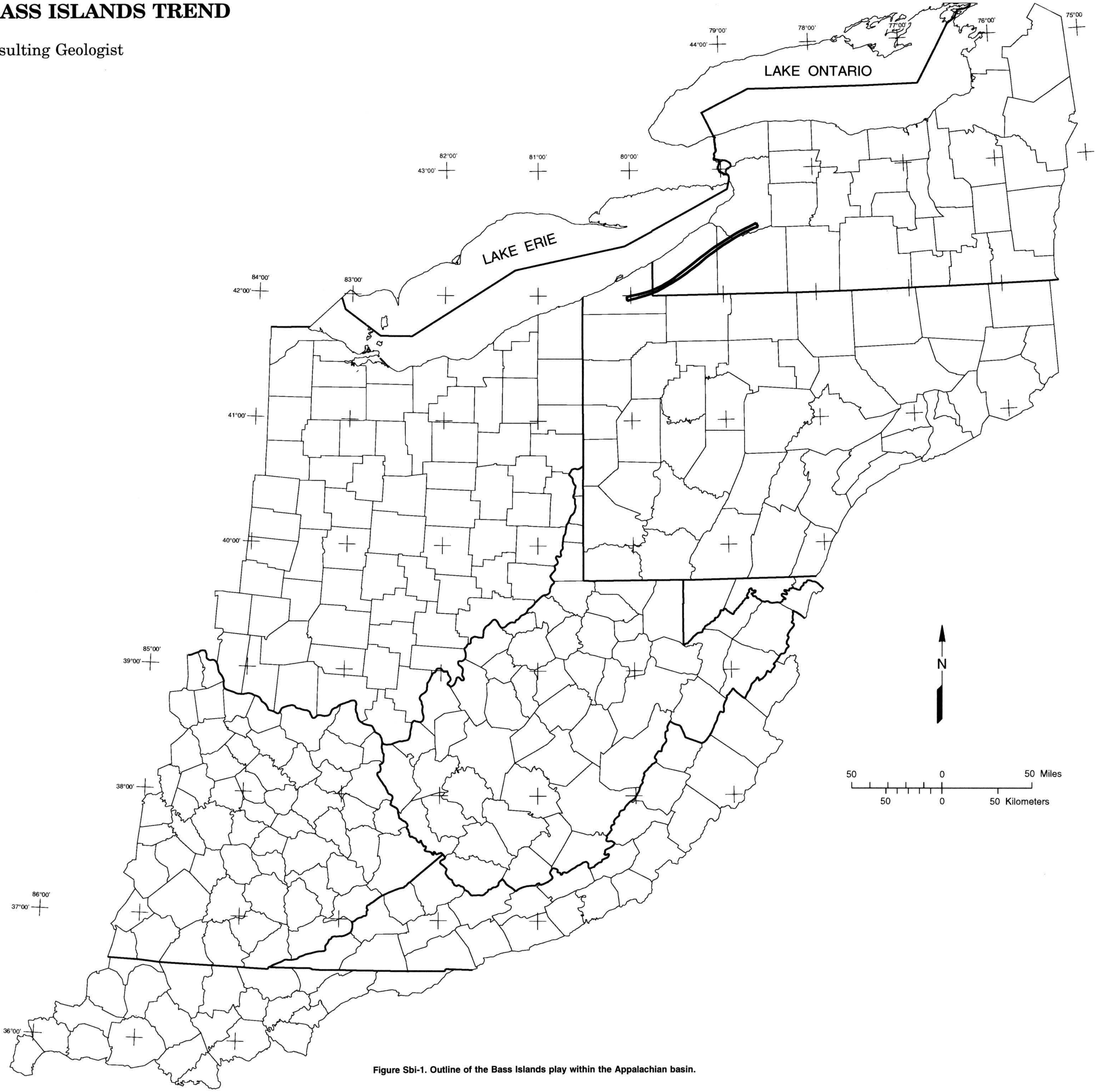


Figure Sbi-1. Outline of the Bass Islands play within the Appalachian basin.

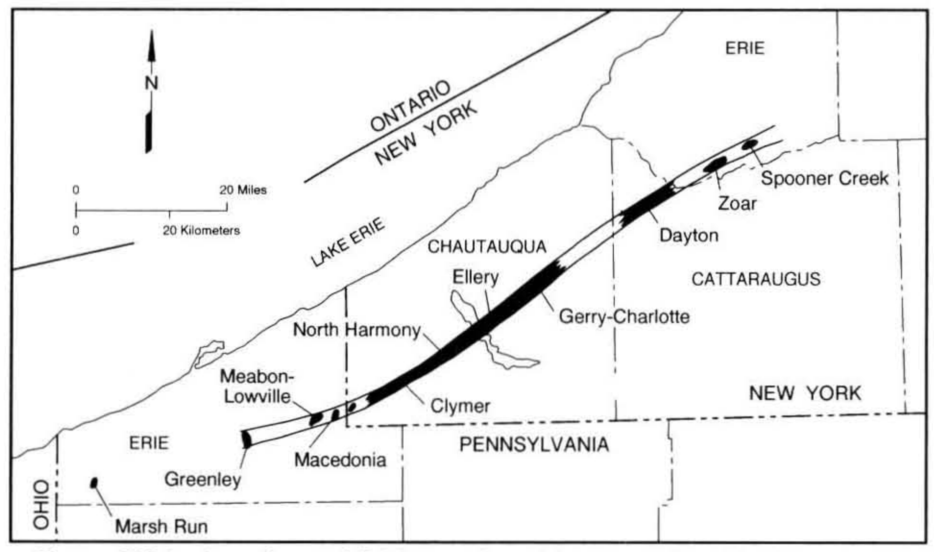


Figure Sbi-2a. Locations of fields mentioned in text or listed in Table Sbi-1.

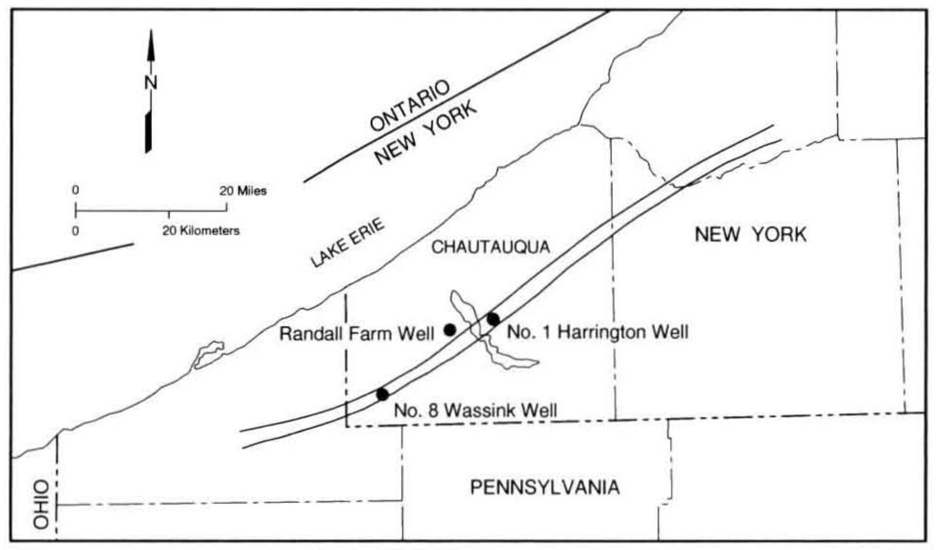


Figure Sbi-2b. Locations of key wells mentioned in text.

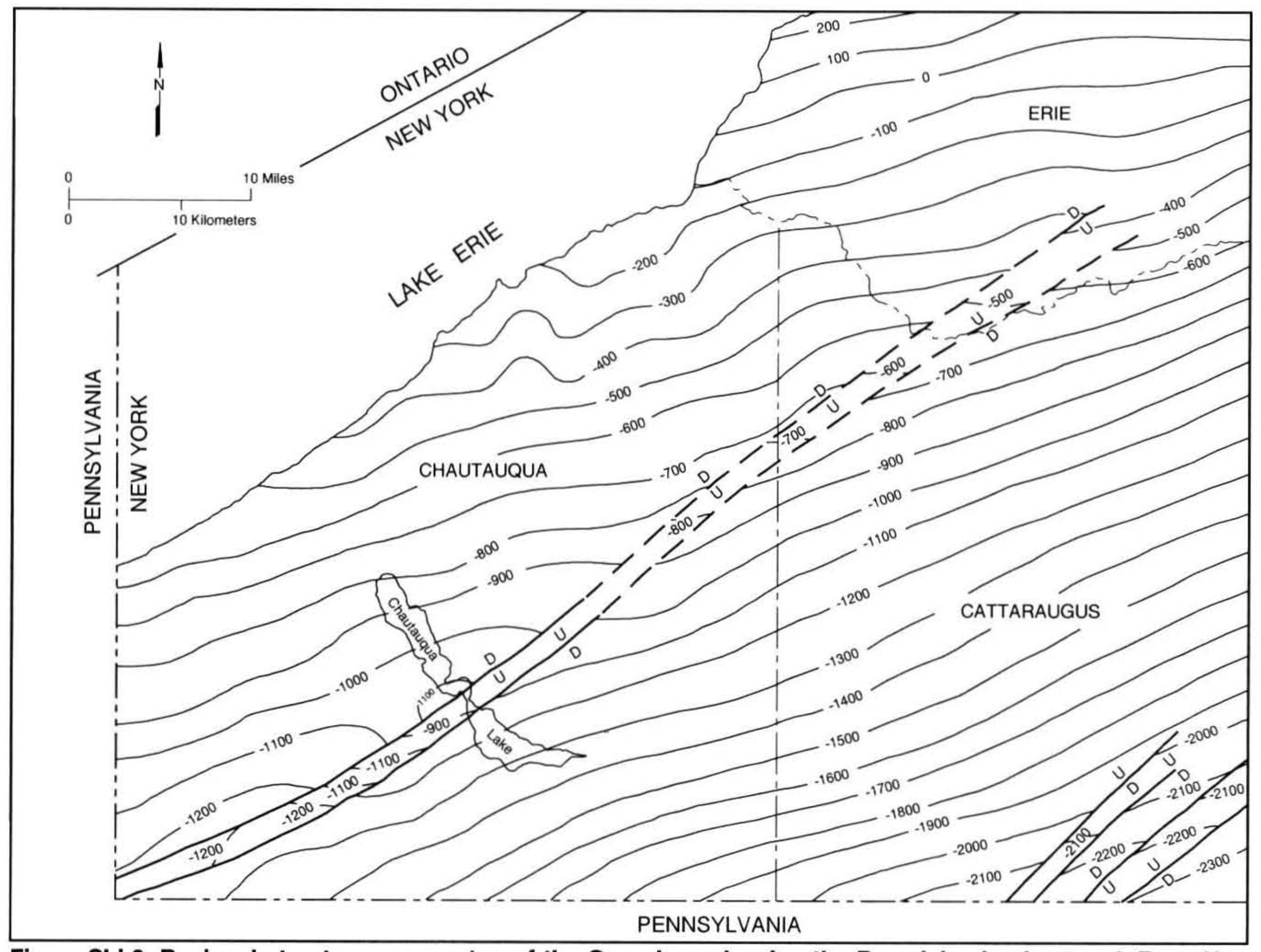


Figure Sbi-3. Regional structure map on top of the Onondaga showing the Bass Islands play trend. From Van Tyne and others (1980). Contour interval = 100 feet.

TABLE Sbi-1		Zoar NY	Ellery NY	Clymer NY	Gerry-Charlotte NY	North Harmony NY	Dayton NY	Spooner Creek NY	Greenley PA	Macedonia PA	Meabon-Lowville PA
BASIC RESERVOIR DATA	POOL NUMBER	792603	10721	7308	270533	9882	183100				
	DISCOVERED	1888	1963	1981	1981	1982	1982	1988	1983	1984	1986
	DEPTH TO TOP RESERVOIR	1,700	2,800	2,950	2,750	2,850	1,900	2,100	2,650	2,550	2,650
	AGE OF RESERVOIR	Late Silurian-Early Mid-Devonian	Late Silurian-Early Mid-Devonian	Late Silurian-Early Mid-Devonian	Late Silurian-Early Mid-Devonian	Late Silurian-Early Mid-Devonian	Early Mid-Devonian	Early Mid-Devonian	Late Silurian-Early Mid-Devonian	Late Silurian-Early Mid-Devonian	Late Silurian-Early Mid-Devonian
	FORMATION	Onondaga, Bois Blanc, Akron, Bertie	Onondaga, Bois Blanc, Akron, Bertie	Onondaga, Bois Blanc, Akron, Bertie	Onondaga, Bois Blanc, Akron, Bertie	Onondaga, Bois Blanc, Akron, Bertie	Onondaga	Onondaga	Onondaga, Bois Blanc, Akron, Bertie	Onondaga, Bois Blanc, Akron, Bertie	Onondaga, Bois Blanc, Akron, Bertie
	PRODUCING RESERVOIR	Onondaga, Bois Blanc, Akron, Bertie	Onondaga, Bois Blanc, Akron, Bertie	Onondaga, Bois Blanc, Akron, Bertie	Onondaga, Bois Blanc, Akron, Bertie	Onondaga, Bois Blanc, Akron, Bertie	Onondaga	Onondaga	Onondaga, Bois Blanc, Akron, Bertie	Onondaga, Bois Blanc, Akron, Bertie	Onondaga, Bois Blanc, Akron, Bertie
	LITHOLOGY	limestone, dolomite	limestone, dolomite	limestone, dolomite	limestone, dolomite	limestone, dolomite	limestone	limestone	limestone, dolomite	limestone, dolomite	limestone, dolomite
	TRAP TYPE	faulted anticline	faulted anticline	faulted anticline	faulted anticline	faulted anticline	faulted anticline	faulted anticline	faulted anticline	faulted anticline	faulted anticline
	DEPOSITIONAL ENVIRONMENT	shallow water carbonate	shallow water carbonate	shallow water carbonate	shallow water carbonate	shallow water carbonate	shallow water carbonate	shallow water carbonate	shallow water carbonate	shallow water carbonate	shallow water carbonate
	DISCOVERY WELL IP (Mcf)		show gas	show gas	500	100	25	700	4,100	6,750	300
	DRIVE MECHANISM	gas cap, dissolved gas	gas cap, dissolved gas	gas cap, dissolved gas	gas cap, dissolved gas	gas cap, dissolved gas	gas cap, dissolved gas	gas cap, dissolved gas	gas cap, dissolved gas	gas cap, dissolved gas	gas cap, dissolved gas
	NO. PRODUCING WELLS	10	19	15	34	25	5	3	14	2	14
	NO. ABANDONED WELLS										
	AREA (acreage)	960	1,600	1,200	2,450	2,400	400	200	700	150	750
	OLDEST FORMATION PENETRATED	Theresa	Potsdam	Queenston	Queenston	Theresa	Queenston	Queenston	Queenston	Queenston	Queenston
	EXPECTED HETEROGENEITY DUE TO:	deposition, diagenesis	deposition, diagenesis	deposition, diagenesis	deposition, diagenesis	deposition, diagenesis	deposition, diagenesis	deposition, diagenesis	deposition, diagenesis	deposition, diagenesis	deposition, diagenesis
RESERVOIR PARAMETERS	AVERAGE PAY THICKNESS (ft.)	30	100	100	100	100	75	50	60	80	70
	AVERAGE COMPLETION THICKNESS (ft.)	30	25	25	25	25	20	20	30	65	20
	AVERAGE POROSITY–LOG (%)								10		
	MINIMUM POROSITY–LOG (%)								2		
	MAXIMUM POROSITY–LOG (%)								15		
	NO. DATA POINTS								2		
	POROSITY FEET										
	RESERVOIR TEMPERATURE (°F)	85	86	86	87	87			82	81	84
	INITIAL RESERVOIR PRESSURE (psi)	600	1,243	980	1,056	1,001	723	600	925	910	1,000
	PRODUCING INTERVAL DEPTHS (ft.)	1,550-2,000	2,500-2,900	2,800-3,000	2,500-2,900	2,350-3,000	1,700-2,700	1,950-2,150	2,500-2,700	2,450-2,850	2,500-2,750
	PRESENT RESERVOIR PRESSURE (psi) / DATE										
FLUID & GAS PROPERTIES	R_w (Ωm)										
	GAS GRAVITY (g/cc)										
	GAS SATURATION (%)										
	WATER SATURATION (%)										
	COMMINGLED										
	ASSOCIATED OR NONASSOCIATED	nonassociated	both	both	both	both	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated
	Btu/scf										
VOLUMETRIC DATA	STATUS (producing, abandoned, storage)	storage	producing	producing	producing	producing	producing	producing	producing	producing	producing
	ORIGINAL GAS IN PLACE (Mcf)										
	ORIGINAL GAS RESERVES (Mcf)										
	PRODUCTION YEARS	1888-1916	1982-1993	1981-1993	1981-1993	1982-1993	1982-1993	1988-1993	1983-1993	1984-1993	1986-1993
	REPORTED CUMULATIVE PRODUCTION (Mcf)										
	NO. WELLS REPORTED										
	ESTIMATED CUMULATIVE PRODUCTION (Mcf)	2,200,000	1,537,522	512,670	5,725,630	2,639,010	683,272	360,262	877,000	716,000	377,000
	REMAINING GAS IN PLACE (Mcf)/DATE										
	REMAINING GAS RESERVES (Mcf)/DATE										
	RECOVERY FACTOR (%)										
	INITIAL OPEN FLOW (Mcf/d)										
	FINAL OPEN FLOW (Mcf/d)										

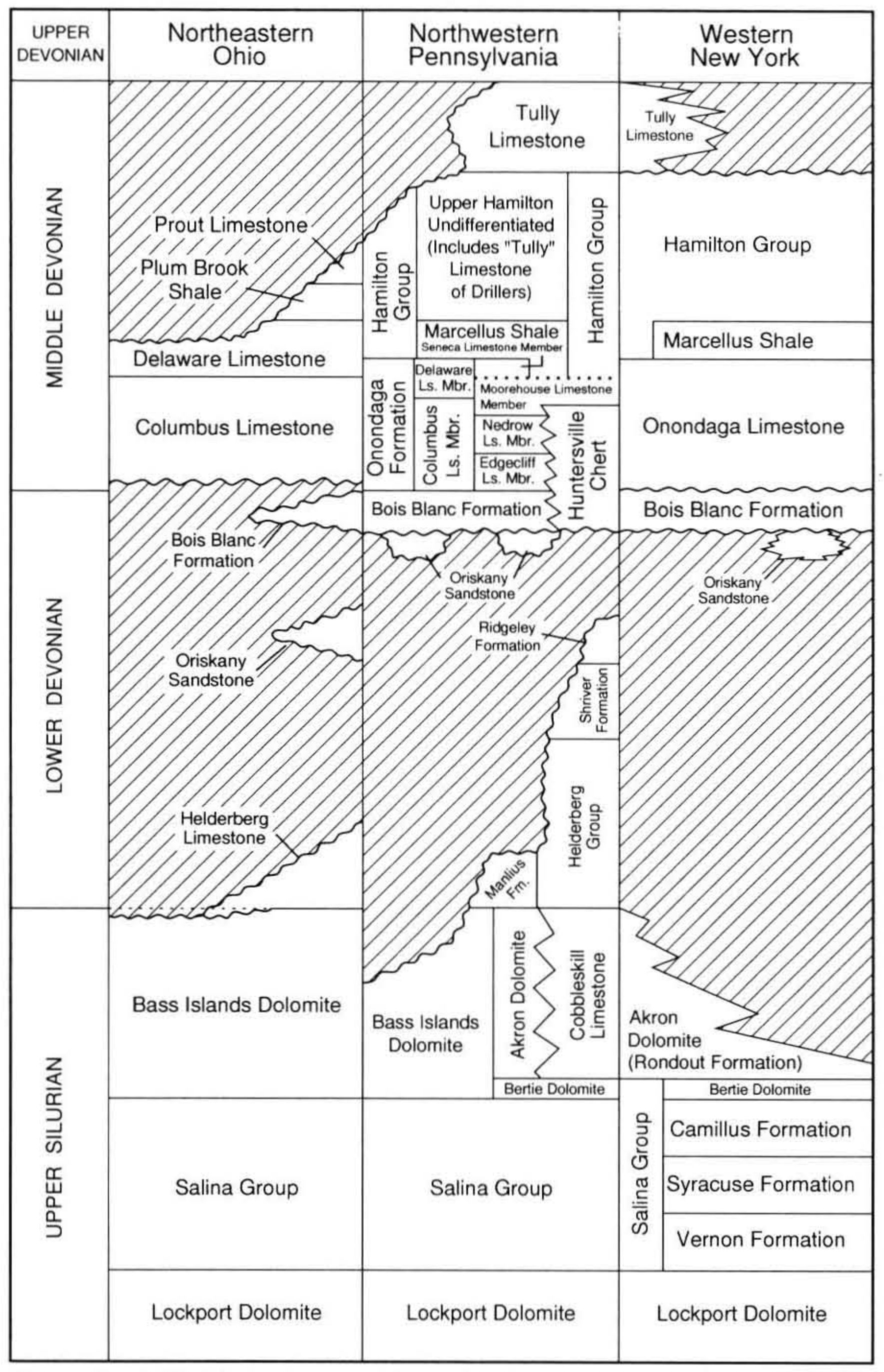


Figure Sbi-4. Stratigraphic correlation chart for the Bass Islands play trend. Modified from Patchen and others (1985a).

chance while drilling for deeper Medina gas, additional tests were drilled in that immediate area. If the shallow targets were nonproductive, the wells were drilled deeper to the Medina Sandstone if the Medina spacing was adequate.

Many, if not most, successful Bass Islands zone wells have been located by detailed geology and/or seismic studies. Probably fewer than 50 specifically designated Bass Islands tests have been dry and abandoned. However, if one takes into account all of the wells that were drilled with expectations of production in the Bass Islands trend, then the success ratio is estimated at 0.25.

Some 111 productive wells have been drilled in the New York portion of the trend, while in the Pennsylvania portion there are 30 such producers. Several additional wells in Pennsylvania that found production in this same stratigraphic zone are scattered at some distance from the established play trend.

Total play gas production (partly estimated) through 1993 is 15.6 bcf. This includes 2.2 bcf produced from the Zoar field from 1888 to 1916. Oil production from wells in the trend (partly estimated) is 1,785,567 barrels through 1993. Pennsylvania wells have produced 2.5 percent of that total amount of oil.

Stratigraphy

Early wells drilled in this play often found gas and oil in a zone below the early Middle Devonian Onondaga Limestone. Drillers and operators involved in that early drilling activity in this trend applied the Ohio name, Bass Islands (Late Silurian), to what they considered to be the main zone of production because they were familiar with Ohio nomenclature for the section below the Onondaga. The New York equivalent of the Bass Islands Dolomite is the Akron Dolomite (Figure Sbi-4).

Later drilling encountered production in several other zones such as the Marcellus Shale, Onondaga Limestone, Bois Blanc Formation, and Bertie Dolomite. These are both above and below the Bass Islands/Akron section (Figure Sbi-4).

The uppermost production found along the trend in New York is from the lowermost Hamilton Group black Marcellus Shale of Middle Devonian age. Only small production has been obtained from this section in areas where a well has cut a fault within the shale.

The Onondaga Limestone has been the source of prolific production where fractured by faulting. Westward, in northeastern Ohio, its equivalents are the Delaware and Columbus limestones.

The Bois Blanc Formation underlies the Onondaga. In the area of this play, it is a pale to dark yellowish-brown, fine crystalline limestone. The limestone is highly siliceous and contains zones of milky chert and scattered glauconite. Like the other units, it becomes a reservoir when fractured.

The Akron (Bass Islands) is a dark yellowish-brown to medium brown dolomitic limestone and dolostone that is fine crystalline and highly siliceous. It often has shows of gas or oil.

The Bertie Dolomite is a medium brown and yellowish-gray dolostone and dolomitic limestone. It is highly crystalline and siliceous and contains scattered glauconite.

Structure

The feature that forms this play trend is a low-relief, highly thrust-faulted anticline. For much of its length, it is about 1.5 miles wide. The bounding thrust faults of the trend are shown as the play outline in Figures Sbi-1, Sbi-2a, Sbi-2b, and Sbi-3. The structure consists of a series of linear, en-echelon thrust faults that form an anticline consisting of a complex of horst and graben blocks. The feature is a decollement structure with faults emanating from a glide plane in the Vernon "B" salt of the Salina Group. Little or no structure occurs from that zone down to the Upper Ordovician Queenston Shale where Medina Sandstone wells reach their total depth. It is located along part of the local western limit of the Vernon "B" salt zone (Figure Sbi-5). Evidently, the salt was severely deformed by plastic flow against the rock buttress to the west, and complex thrusting was the result.

This structure is similar to other linear, arcuate structures located 30 miles and more to the southeast that were formed during the late Paleozoic Alleghanian deformation. Those structures are generally larger, having been closer to the southeastern source of the compressive forces that caused them to be formed. The Chautauqua structure, the Bass Islands trend, is the farthest northwestern-such feature found so far.

Detailed structure mapping indicates that the reservoirs in this trend are related to structure and not stratigraphy. Fracturing of the entire brittle rock section between the overlying, more plastic Hamilton shales and the underlying Salina shales and evaporites has provided an excellent reservoir. The stratigraphic name Bass Islands is, therefore, inappropriate for this structural trend. Perhaps the geographic name of Chautauqua anticline or Chautauqua structural trend would have been a better name for this feature.

The thrust faults that have formed the structure apparently originate as splays from a flat-lying glide plane in the Vernon "B" zone and break upwards at a steep angle. Beinkafner (1983) indicated that splay faults from the salt decollement zone are inclined at 50 to 55° (Figure Sbi-6). However, there is some evidence that, where they break through the brittle dolomites and limestones that act as reservoirs, the faults are very steep and may be nearly vertical. As they pass above this into the Hamilton shales, some flatten out into bedding-plane thrusts and die out (Figure Sbi-7).

As the rocks were deformed, additional shallow thrust faulting, which was not rooted in the lower Salina but splayed off larger thrusts, also occurred. This has resulted in a large number of faults within the fairly narrow trend. Detailed subsurface mapping has revealed 10 to 15 discernible fault traces at some places in the trend. Perhaps more, too small to be mapped, are also present.

This feature has been traced from southern Erie County, New York, southwesterly through central Chautauqua County and west-southwesterly into central Erie County, Pennsylvania. Westward from there, the structure is less distinct and may die out. Although the one-well Marsh Run pool in southwestern Erie County, Pennsylvania (Figure Sbi-2a), produces from the Bass Islands, it is located in Conneaut Township in far western Erie County, Pennsylvania. This is 20 miles southwest of the last known Bass Islands trend production. There is no good evidence available for extending the Bass Islands play trend to include the Marsh Run pool. There is also no evidence that the trend extends farther west into Ohio (M. Baranoski, oral commun., 1994).

Three other one-well pools that found small hydrocarbon production from the Marcellus, Onondaga, and Bass Islands sections have been discovered from 1982 to 1985 outside the play trend in Erie County, Pennsylvania. The pools are located within 3 to 5 miles north and south of the present southwestern end of the trend. These wells apparently have encountered limited areas where structural movement related to the formation of the trend caused similar reservoirs to be developed.

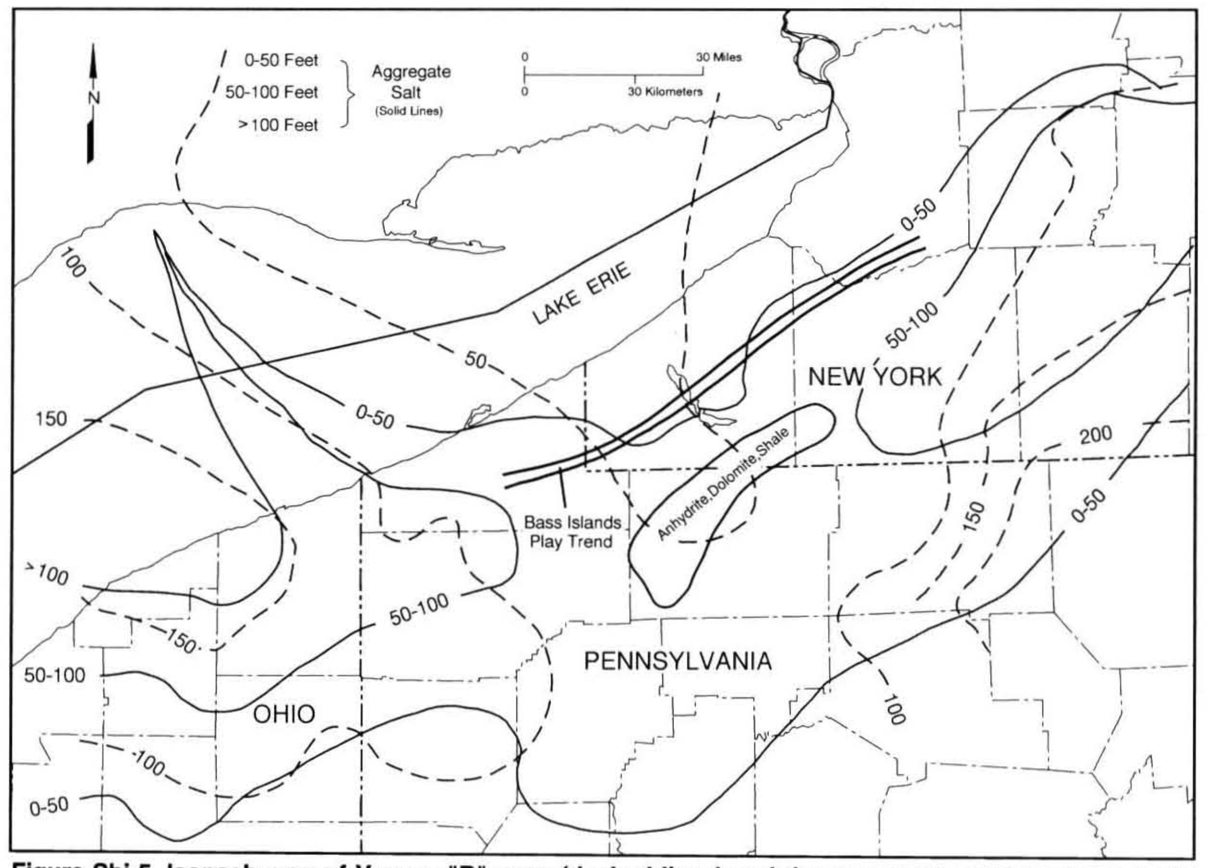


Figure Sbi-5. Isopach map of Vernon "B" zone (dashed lines) and the aggregate amount of salt (solid lines) showing salt wedgeout in the area of the Bass Islands play trend. Modified from Rickard (1969).

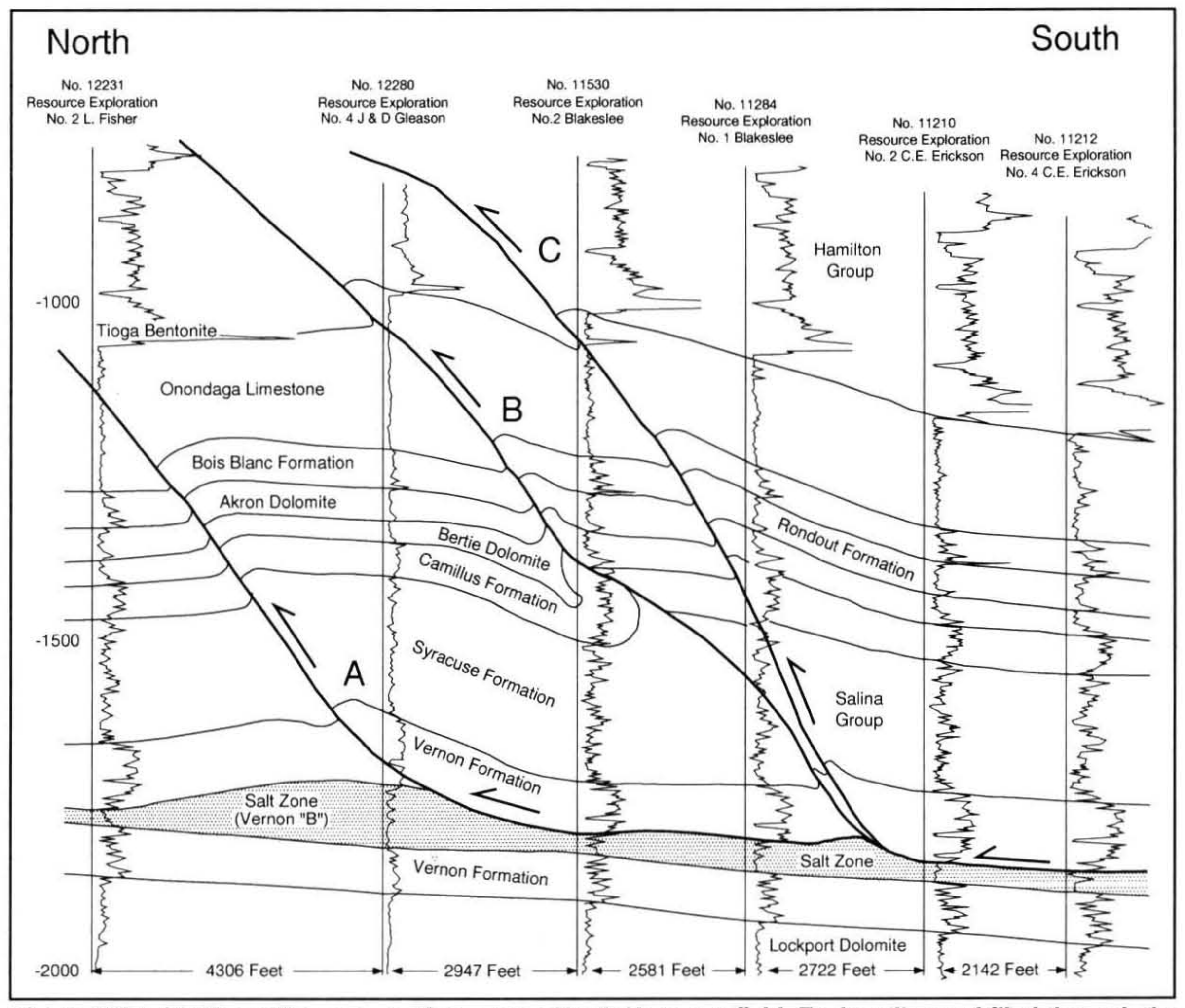
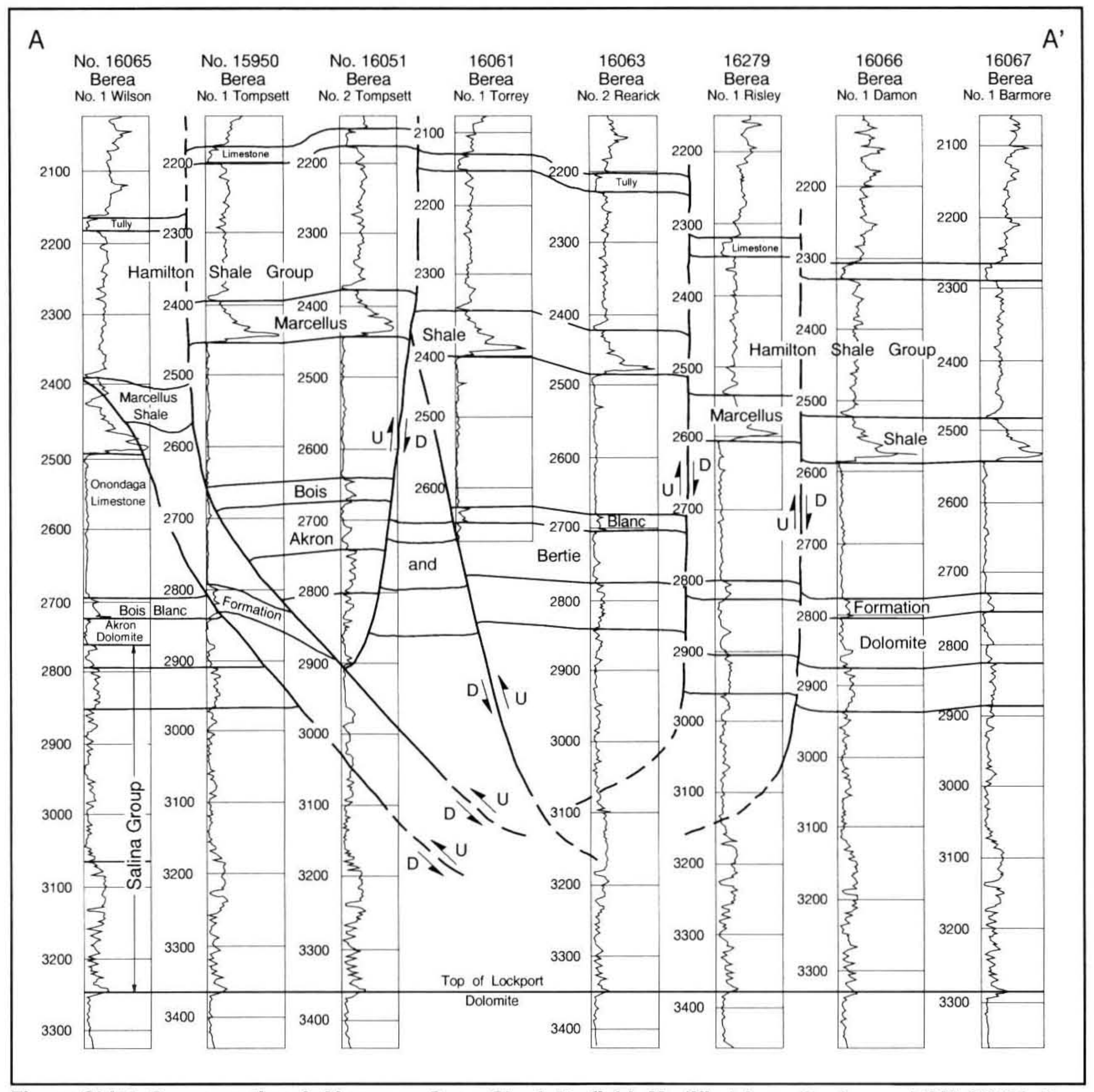


Figure Sbi-6. North-south cross section across North Harmony field. Each well was drilled through the Bass Islands Dolomite and produces from the Medina Sandstone. From Beinkafner (1983). See location map for location of cross section.



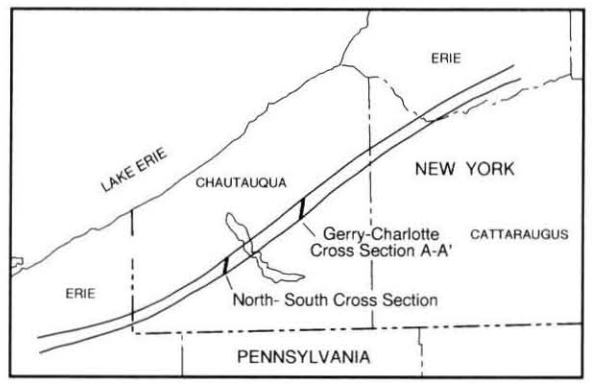


Figure Sbi-7. Cross section A-A' across Gerry-Charlotte field. Modified from Copley and Gill (1983). See locator map for location of cross section. No horizontal scale. Vertical scale in feet.

Table Sbi-2. Analysis of gas from the Akron zone in Gerry-Charlotte field. From Copley and Gill (1983).

Natural Gas Constituents Akron Dolomite	
Component	**Separator Gas Mol Percent**
Hydrogen Sulfide	0.00
Carbon Dioxide	Trace
Nitrogen	1.60
Methane	80.37
Ethane	11.27
Propane	4.39
iso-Butane	0.46
n-Butane	1.16
iso-Pentane	0.23
N-Pentane	0.25
Hexanes	0.15
Heptanes plus	0.12
	100.00

Calcualted Gas Gravity — 0.698
Calcualted Gross Heating Value — 1,204 Btu/cu. ft.
Dry Gas @ 14.65 psia and 60° F.

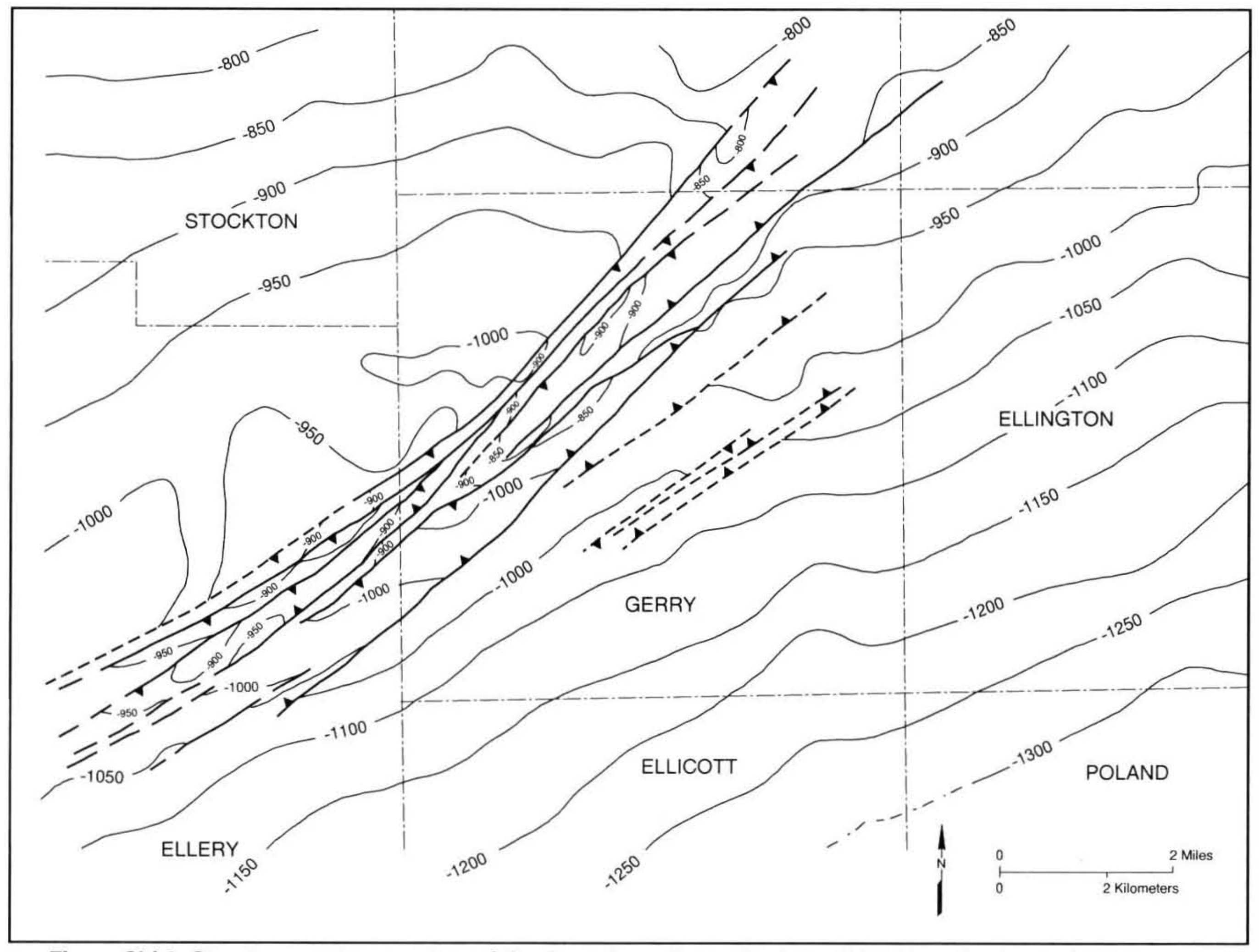


Figure Sbi-8. Structure contours on top of the Onondaga, Gerry-Charlotte field. From Copley and Gill (1983).

Reservoir

The reservoirs in this play are fractured limestones, dolomites, and shales within the structural trend. The traps are closures, with fractures, against faults; fractured high areas on the upthrown blocks of faults; fractured drag folds on upthrown blocks; and isolated fracture pods along the fault trends. Areas within the trend that are without fracturing may have shows but are nonproductive. Sometimes, it has been possible to fracture-treat a well in such an area and break through to an area of fracturing to obtain production. In one case, a well encountered a show of gas and oil with salt water in the lower Onondaga. The operator decided to pump the well to see if the amount of oil it was making could be economic. After several weeks of pumping, the salt-water flow declined and the oil increased until the well was flowing several hundred barrels of oil per day. The well became one of the better "Bass Islands" type of producer.

The New York State Division of Mineral Resources has delineated 43 separate pools within the play trend in New York. In Pennsylvania, there are four pools in the play trend.

The source of the hydrocarbons in this play is believed to be the Akron Dolomite and possibly Upper Salina shales and dolomites of Late Silurian age. According to Columbia Gas, samples from the Akron (Beardsley, oral commun., 1984) and the underlying Bertie Dolomite and Camillus Formation were tested and found to have had the capacity for being potential source beds. Jenden and others (1993) also suggested a possible Devonian black shale source (Marcellus?) as well as an Upper Silurian source for gas and oil in this trend. Hydrocarbons generated in these source beds have migrated upwards and laterally into traps along the extensive fracture systems. Because of the linear nature of the main faults, communication between wells as far as 2 miles apart has been noted.

According to Copley and Gill (1983), initial bottom-hole pressures for wells in their study ranged from 600 to 950 psi at depths of 1,900 to 3,000 feet. The average depth to production in the trend is about 2,500 feet. In 1988, the New York State Division of Mineral Resources released general pressure data from a mandatory shut-in period in 1987 for "Bass Islands" wells. These data show that the highest recorded pressures in the trend ranged from 773 to 1,243 psi. In Pennsylvania, original pressures (believed to be top-hole pressures) have ranged from 600 to 1,000 psi. Most have been in the range of 800 to 1,000 psi. They tend to average about 100 psi lower than those in New York. The reservoirs in this play trend are indicated to be either at hydrostatic pressure for the depths involved or slightly underpressured.

Until late 1982, as exploratory drilling progressed, wells in this play sometimes encountered unexpectedly high flows of gas and oil. This resulted in several blowouts and fires that caused concern among local officials and landowners. In the following months, the state regulatory agency instituted new rules for drilling and completing "Bass Islands" type wells, and the blowout problem was resolved.

The thickness of the pay section varies considerably, depending upon the amount of fracturing present. The total thickness of the rock section where production has occurred is about 350 feet.

In New York, initial open flows as high as 60,000 Mcf/d and 2,400 barrels of oil per day have been reported. Such high flows are typical of highly permeable, fractured reservoirs. These flows also showed a rapid decline as the wells were produced. Initial open flows in Pennsylvania have ranged from 250 Mcf/d to a reported 27,000 Mcf/d. In the Pennsylvania section of the trend, only a few of the wells have been oil producers, but initial oil flows of up to 100 barrels of oil per day have been recorded.

The produced gas is primarily methane with associated high fractionates. This accounts for the high Btu content of the gas. It usually has a heating value of about 1,200 Btu/cf. An analysis of the gas from a well in the northern section of the New York trend is shown in Table Sbi-2. The oil is a high gravity (46°) paraffin base crude. The paraffin content ranges from 6 to 30 percent (Coleman, 1986), and in some cases the oil forms a paraffin mush at room temperature. Paraffin has caused a considerable production problem and must regularly be scraped or dissolved from the wells and production equipment.

Description of Key Field

Gerry-Charlotte field: The general structure of all fields in this play is similar. This field was chosen as representative of the type of production that occurs in this play because of the availability of data through a published report by Copley and Gill (1983).

The Gerry-Charlotte field, located in central Chautauqua County, New York (Figure Sbi-2a), was discovered in June 1981 by Berea Oil and Gas Corporation's No. 1 Torrey well. The well had a blow-out at a depth of 2,663 feet in the Akron and caught fire but was eventually completed as an oil and gas producer. The field has produced 772,000 barrels of oil and 5.7 bcfg through 1993. This production has come from 16 oil wells and 18 gas wells at an average depth of 2,700 feet. The New York State Division of Mineral Resources has delineated 13 pools in this field based upon pressure test data. The average spacing is 72 acres per well.

Core studies of the Akron made by Berea gave a matrix porosity of less than 5 percent and permeability of less than 0.1 md (Copley and Gill, 1983). Copley and Gill (1983) concluded that the reservoir in this field is probably totally due to extensive fracturing along linear thrust fault trends.

A structure contour map on the top of the Onondaga Limestone (Figure Sbi-8) as interpreted by Copley and Gill (1983) shows the linear nature of this field. It also displays the numerous thrust faults so typical of this play trend and the numerous trapping structures along those faults. Their interpretation of how the numerous faults interact in the subsurface (Figure Sbi-7) is typical for this play.

Wells are drilled with air. When producing zones are drilled, New York State Division of Mineral Resources rules require that kill fluid, mud materials, and mud pumping capability be on-site. The use of a blow-out preventer and daylight drilling through the producing zones is also mandated. For completion, 4.5-inch production casing and 2.37-inch tubing are run and parrafin control is commenced, usually with solvents. Most wells produce little or no salt water at first, but some have produced 50 barrels or more per day. In most cases, the wells flow naturally and don't require stimulation. However, some of the smaller natural producers have been stimulated with hydrochloric acid with good results.

Resources and Reserves

Production data from all fields in this play and reservoir data from the Gerry-Charlotte field were used in estimating the potential gas reserves in this trend. Of the approximately 80,000 acres in the play trend, about 20 percent, or 16,000 acres, has not been adequately tested. Of the remaining 64,000 acres, which have been tested, about 17 percent is productive. If this same percentage of success holds for the 16,000 acres which are poorly tested, then 2,700 acres could be productive. Using the 72-acre well spacing from the Gerry-Charlotte field, this would require 38 gas wells for proper drainage.

As far as can be determined, of the 141 productive wells in this play trend, about 90 have been mainly or solely gas producers. Each well would then have produced about 175 MMcf of the 15.6 bcf total gas production. Applying this per-well production figure to the 38 possible new wells gives a potential gas resource of 6.65 bcf. Much of this gas could be found in the Pennsylvania portion of the trend where a large amount of the untested acreage is located.

In addition, it is estimated that, with more detailed geology and seismic studies, another 20 successful gas wells could be drilled in the known field areas. Those wells would add 3.5 bcf of gas resources. This gives a total potential new gas resource of 10.15 bcf for the play trend. The current recoverable gas reserves are estimated at 1.5 bcf in the play trend.

Future Trends

There is probably only a small chance of extending this play at either end of the Bass Islands trend. Seismic studies might reveal some addition to the southwestern end of the play in Erie County, Pennsylvania. However, there may be a better possibility for extending the trend to the northeast in Erie County, New York. Such extensions to the structure could yield additional productive areas.

The bounding faults of this play are quite well defined. Most production is confined to the established trend, although small, outlying areas of similar production have been found in both New York and Pennsylvania. Additional areas might be found fortuitously by seismic work or while drilling for deeper production. However, there does not seem to be a pattern to this production and no systematic technique can be suggested to search for it.

Portions of the play trend that have not been drilled or that have been nonproductive so far need a more careful search for possible traps utilizing the latest seismic techniques and more detailed subsurface geological studies. Because of the complex nature of this feature, areas that have been productive may still hide undrilled traps. The exact relationship between hydrocarbon and brine production and structure in this play is still poorly known and less understood. This play could benefit greatly from the use of 3-D seismic studies and horizontal drilling. That seismic technique, although expensive, could point the way to additional traps, and horizontal wells could test possible traps on several faults with one hole.

PLAY DSu: LOWER DEVONIAN-UPPER SILURIAN UNCONFORMITY PLAY

by Joseph F. Meglen, Peoples Public Gas Company, and Martin C. Noger, Kentucky Geological Survey

Location

The Lower Devonian-Upper Silurian unconformity play includes carbonate and sandy carbonate reservoirs, commonly referred to as the Corniferous, which occur below the major regional unconformity that is overlain by the Upper Devonian organic-rich Chattanooga and Ohio Shale. The play area is dependent upon the extent of the regional unconformity and is largely in eastern Kentucky and, to a much lesser extent, in northern Tennessee, western West Virginia, and southeastern Ohio.

Gas fields producing from this play occur in the eastern Kentucky counties of Clay, Bell, Montgomery, Morgan, Wolfe, Bath, Lee, Knox, Leslie, Jackson, Owsley, Breathitt, Powell, Menifee, Rowan, and Lewis (Figures DSu-1, DSu-2). Twenty-two significant fields in this play have produced or presently produce gas (Figure DSu-2). No other known gas production occurs from this play in the Appalachian basin.

Production History

Gas was discovered from the Lower Devonian-Upper Silurian unconformity play around the turn of the century. Approximately 20 percent of gas production in eastern Kentucky comes from this play (excluding Devonian shale production). The two earliest fields—Grassy Creek, discovered in 1902, and Rothwell, discovered in 1904—are located in Morgan and Menifee counties, Kentucky, respectively. However, Hunter (1955) states that Burning Springs Consolidated field, in Clay County, Kentucky, was discovered in 1898. Grassy Creek field (Figure DSu-2) is still producing. The Rothwell field was depleted and utilized as a gas storage facility as early as 1919, and was apparently abandoned in 1974. Discoveries in this play continued sporadically into the mid-1980s.

Early production data are scarce, especially from older fields. However, information occasionally can be found in the literature. For example, Munn (1913) stated that Rothwell field produced 25 MMcfg/d in June 1912 from 90 wells at a reservoir pressure of 60 psi.

Tables DSu-1 and DSu-2 contain field and reservoir data, including production data if available, on all major fields in this play in eastern Kentucky. Because of the confidentiality of production data and the inability to contact many small operators, the cumulative production information represents minimum values. It is estimated that the cumulative production may range from about 80 to 110 bcfg.

Stratigraphy

To date, production has been concentrated in the western portion of the Appalachian basin in eastern Kentucky (Figure DSu-1). No significant production has been found in other parts of the basin. Lateral equivalents of the producing formations in Kentucky are shown in Figure DSu-3. Type logs for east-central and eastern Kentucky, shown in Figures DSu-4 and DSu-5, reveal a significant change in thickness of the Corniferous between the two wells.

Two major producing formations, the Silurian Salina (Cayugan) and Lockport (Niagaran) dolomites, and two minor producing formations, the Middle Devonian Onondaga and the Lower Devonian Helderberg limestones, contribute to this play. These are collectively known as the Corniferous (Figure DSu-3). This term originated because some of the rocks in this interval appeared similar in outcrop to the Corniferous section of New York. Corniferous is not a formal name and in Kentucky is considered a drillers' term. Unless otherwise noted, Corniferous will be used only when referring to the gross interval from the base of the Ohio Shale to the base of the Lockport Dolomite.

The major unconformity at the base of the late Devonian Chattanooga and Ohio Shale is the primary influence on reservoirs for this play. Erosion and subaerial exposure of the underlying Corniferous units and the development of secondary porosity by telogenetic processes account for many reservoirs (Freeman, 1951). Units that subcrop below the shale range from the Devonian Onondaga, Oriskany, and Helderberg toward the east to the upper Ordovician in the west along the Cincinnati arch (Figures DSu-3, DSu-6). Subsequently, updip truncation of these reservoir rocks against the impermeable, organic-rich Devonian shale is responsible for trapping significant quantities of oil and gas.

Carbonates, sandy carbonates, and dolomitic sandstones form the reservoirs in this play. The Lockport is a fine- to medium-grained, slightly argillaceous, crystalline dolomite, with the lower portion becoming sandy and locally containing as much as 50 percent sand. This sand fraction may be equivalent to the Big Six (Keefer Sandstone) or may represent a sandy facies of the Lockport Dolomite. The facies relationship between the Lockport and Big Six is complex, and its analysis is not within the scope of this description. Here, if the sand fraction is less than 50 percent, the formation will be designated Lockport Dolomite. If the sand fraction is equal or greater than 50 percent, the formation will be called Big Six. In cases where dolomitic sandstone is bounded by two fine crystalline dolomites (for example, Artemus-Himyar Consolidated field) and when the identity of the Big Six is in question, it will be designated Lockport-Big Six? to indicate that no distinction has been made between the two.

Locally, the lower Lockport becomes fossiliferous and can contain abundant pyrite (Freeman, 1951; Currie, 1981). Recognition of pyrite is important because it can affect the resistivity reading on electrical logs and cause significant errors in water-saturation calculations.

The Lockport Dolomite represents the transition from a normal, shallow-marine environment with clastic influences to the more restricted marine environment of the overlying Salina Dolomite. The Lockport was deposited on a carbonate shelf and includes the associated environments of ooid bars, skeletal

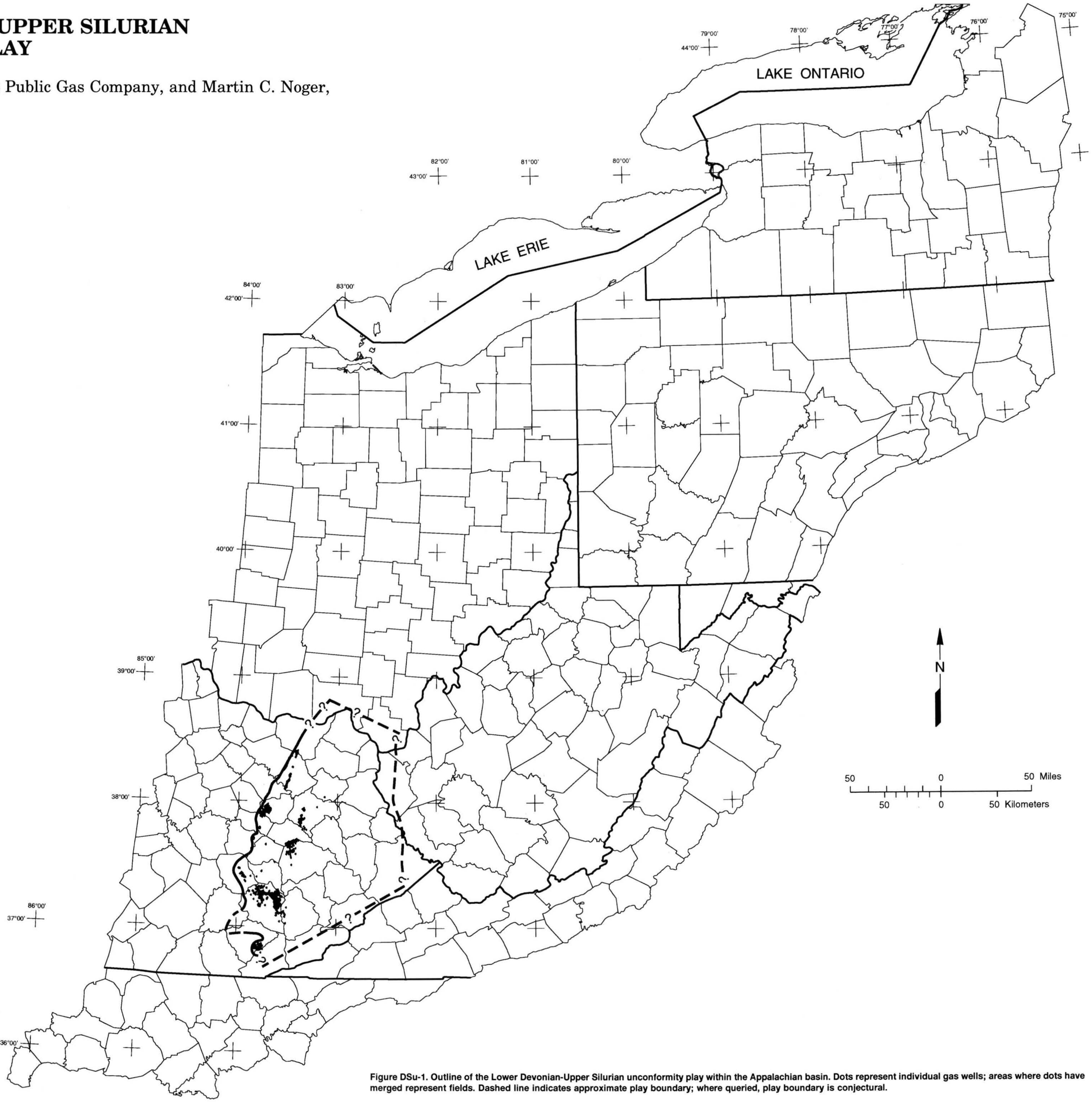


Figure DSu-1. Outline of the Lower Devonian-Upper Silurian unconformity play within the Appalachian basin. Dots represent individual gas wells; areas where dots have merged represent fields. Dashed line indicates approximate play boundary; where queried, play boundary is conjectural.

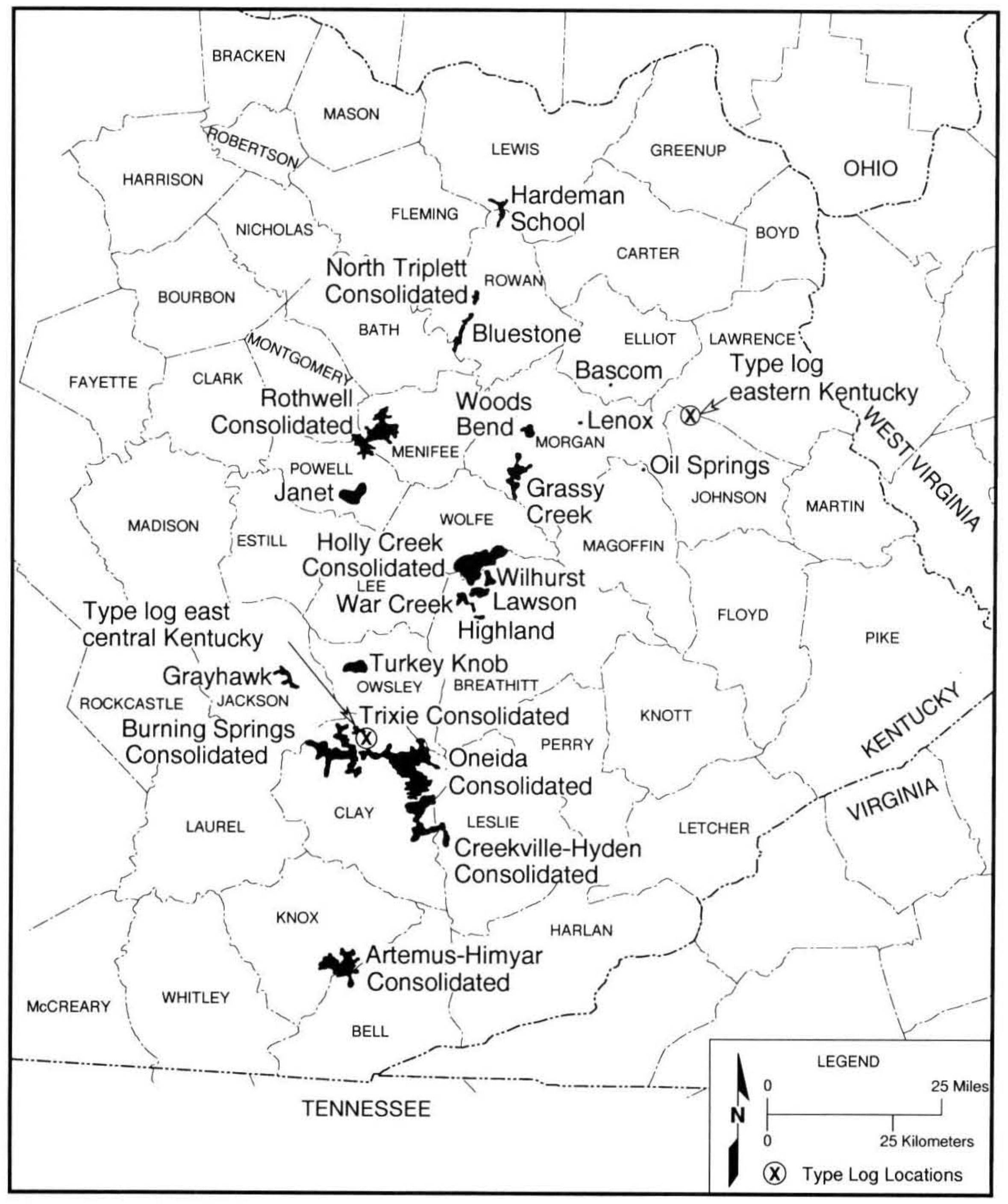


Figure DSu-2. Location of type logs and significant gas fields discussed in text or listed in Table DSu-1. Other productive areas illustrated in Figure DSu-1 are not shown.

sand shoals, lagoons, mud banks, and sabkhas. These different facies were probably caused by changes in relative sea level (Smosna and others, 1989).

The Salina Dolomite is a dense to very fine crystalline dolomite; evaporites are scattered throughout but occur with higher frequency in the upper part. The Salina is variable in thickness, with regional thinning to the west, primarily because of erosion. The boundary between the Lockport Dolomite and the Salina Dolomite represents a change from a more normal, open-marine environment to a restricted hypersaline environment. The Salina depositional environments ranged from supratidal to shallow subtidal, as evidenced by the very fine crystal size, mud cracks, evaporites, and restricted fauna (Currie, 1981).

The Helderberg is a very finely to finely crystalline limestone with occasional chert and medium- to coarse-grained quartz sand. The Devonian Onondaga is a very finely to moderately crystalline, cherty limestone. These formations represent a return to a more normal, shallow open-marine environment. As noted previously, the Helderberg and Onondaga are difficult to differentiate in the subsurface where the Oriskany is not present. For the most part, with respect to this play, the Oriskany is identifiable and present only in Lawrence, Johnson, Martin, and Pike counties of eastern Kentucky (Freeman, 1951).

The Devonian Boyle Dolomite, approximate time-equivalent to the Onondaga, is located in the extreme western portions of the basin in eastern Kentucky. An unconformity at the base of the Boyle is similar to that of the Onondaga. The Boyle Dolomite overlies an anomalously thick section of Salina and Lockport dolomites in Jackson County and parts of Owsley, Lee, and Estill counties. The Boyle is a finely to moderately crystalline dolomite with some chert. The depositional environment was probably normal, open marine.

The Devonian units (Helderberg and Onondaga), occurring immediately below the Ohio Shale in extreme eastern Kentucky, are absent in east-central Kentucky but may be present again as the Boyle Dolomite in the extreme western portions of the Appalachian basin in Kentucky (Figures DSu-6, DSu-7). The Boyle Dolomite may represent nothing other than erosional remnants along the western subcrop of the Onondaga or Helderberg. Discussion of this complex situation is not within the scope of this description. Refer to Freeman (1951), McFarlan and White (1952), and Helton (1968) for more detailed discussions.

Structure

A southeast regional dip is the primary structural fabric in this portion of the basin. There are, however, discontinuities such as faults, folds, uplifts, and the Rome trough that disrupt regional dip (Figure DSu-8). The major faults in the area include the Kentucky River and Irvine-Paint Creek fault systems. Both fault systems are characterized by a series of east-northeast-trending basement faults downthrown to the south. Numerous faults associated with both fault systems help concentrate hydrocarbons along the crests of plunging anticlines caused by drape over these basement faults.

The Pine Mountain fault is a thrust located in extreme southeastern Kentucky. It is not known how or if the thrust has had an effect on hydrocarbon accumulation.

TABLE DSu-1

		Grayhawk KY	Oneida Consolidated KY	Burning Springs Consolidated KY	Artemus-Himyar Consolidated KY	Creekville Hyden Consolidated KY	Trixie Consolidated KY	Bluestone KY	Hardeman School KY	Rothwell Consolidated KY
BASIC RESERVOIR DATA	POOL NUMBER	1600817	1601461	1600320	1600056	1600487	1602002	1600215	1600880	1601700
	DISCOVERED	1933	1918	1928	1931	1954	1983	1938	1937	1904
	DEPTH TO TOP RESERVOIR	1,100	2,000	1,400	2,250	2,440	1,408	240	525	600
	AGE OF RESERVOIR	Silurian	Silurian	Silurian	Silurian	Silurian	Silurian	Silurian	Silurian	Silurian
	FORMATION	Salina	Lockport	Lockport	Lockport/ Big Six	Lockport	Lockport	Lockport	Lockport	Lockport
	PRODUCING RESERVOIR	Salina	Lockport	Lockport	Lockport/ Big Six	Lockport	Lockport	Lockport	Lockport	Lockport
	LITHOLOGY	dolomite	dolomite	dolomite	dolomite/ sandstone	dolomite	dolomite	dolomite	dolomite	dolomite
	TRAP TYPE	stratigraphic unconformity	stratigraphic unconformity	stratigraphic unconformity	combination unconformity & structure	stratigraphic unconformity	stratigraphic unconformity	stratigraphic unconformity	stratigraphic unconformity	stratigraphic unconformity
	DEPOSITIONAL ENVIRONMENT	shallow open-restr. marine	shallow open-marine	shallow open-marine	shallow open-marine	shallow open-marine	shallow open-marine	shallow open-marine	shallow open-marine	shallow open-marine
	DISCOVERY WELL IP (Mcf)	84	780	304	1,400	80		30	425	460
	DRIVE MECHANISM	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion
	NO. PRODUCING WELLS	38	166	67	106	57	15		7	0
	NO. ABANDONED WELLS		12	2	9	1		41	11	93
	AREA (acreage)	571	22,546	10,524	7,117	9,464	1,651	2,334	1,884	11,314
	OLDEST FORMATION PENETRATED	Knox	Knox	Knox	Copper Ridge	Rose Run	Knox	Ordovician	Clinton	Ordovician
	EXPECTED HETEROGENEITY DUE TO:	diagenesis	diagenesis	diagenesis	depositional diagenesis	diagenesis	diagenesis	diagenesis	diagenesis	diagenesis
RESERVOIR PARAMETERS	AVERAGE PAY THICKNESS (ft.)	10	17	5	11	12	12.5			
	AVERAGE COMPLETION THICKNESS (ft.)	16	25	25	32	31	43	8	15	22
	AVERAGE POROSITY–LOG (%)	9.5	9	8	7.4	8	9			
	MINIMUM POROSITY–LOG (%)	4	4	4	4	4	4			
	MAXIMUM POROSITY–LOG (%)	15.5	15	12	16	14	15.5			
	NO. DATA POINTS	1	56	14	8	34	11			
	POROSITY FEET									
	RESERVOIR TEMPERATURE (°F)	71	79	65	87	80	70			
	INITIAL RESERVOIR PRESSURE (psi)	142	300	170	300	332	270	22	31	85
	PRODUCING INTERVAL DEPTHS (ft.)	981-1,163	1,391-2,671	1,259-1,584	1,928-2,851	2,030-3,247	1,260-1,645	143-375	332-655	345-836
	PRESENT RESERVOIR PRESSURE (psi) / DATE	120/1991	75/1991	140/1991	45/1991	230/1992	220/1991			
FLUID & GAS PROPERTIES	Rw (Ωm)	0.06	0	0.06	0.07	0.06	0.06	0.15		0.1
	GAS GRAVITY (g/cc)	0.646	1		0.676					0.616
	GAS SATURATION (%)		85	76		77	88			
	WATER SATURATION (%)		15	24		23	12			
	COMMINGLED	no	332BIGL 341NALB 368BKMN	368KNOX 341NALB 332BIGL 365STRV	332BIGL 332MAXN 341CHAT	341NALB 332BIGL 339BRBD 357CLNT	368KNOX 332BIGL 341NALB	no	no	no
	ASSOCIATED OR NONASSOCIATED	nonassociated	nonassociated	associated	nonassociated	nonassociated	associated	nonassociated	nonassociated	nonassociated
	Btu/scf	1,115	1,202		1,183					1,019
VOLUMETRIC DATA	STATUS (producing, abandoned, storage)	producing	producing	producing	producing	producing	producing	abandoned	producing	abandoned
	ORIGINAL GAS IN PLACE (Mcf)	176,000	45,475,000	1,882,000	27,044,000	7,275,000	1,554,000	227,700	690,000	11,300,000
	ORIGINAL GAS RESERVES (Mcf)	136,000	39,108,000	1,372,000	23,000,000	5,700,000	1,205,000	37,000	400,000	11,000,000
	PRODUCTION YEARS	1933-1994	1918-1992	1928-1994	1931-1992	1954-1991	1984-1991	1938-?	1937-1994	1937-1974
	REPORTED CUMULATIVE PRODUCTION (Mcf)		36,700,000		22,987,000	2,000,000	2,266			11,000,000
	NO. WELLS REPORTED		178		115	11	2			93
	ESTIMATED CUMULATIVE PRODUCTION (Mcf)	130,000	37,000,000	1,100,000	23,000,000	3,800,000	800,000	35,000	393,000	11,000,000
	REMAINING GAS IN PLACE (Mcf)/DATE	46,000/ 1994	8,475,000/ 1994	782,000/ 1992	4,044,000/ 1992	3,475,000/ 1994	754,000/ 1994	192,700/ 1994	297,000/ 1994	300,000/ 1994
	REMAINING GAS RESERVES (Mcf)/DATE	6,000/ 1994	2,108,000/ 1994	272,000/ 1992	0/ 1994	1,900,000/ 1994	405,000/ 1994	2,000/ 1994	7,000/ 1994	0/ 1994
	RECOVERY FACTOR (%)	77	86	75	85	78	78	16	58	97
	INITIAL OPEN FLOW (Mcf/d)	450	440	125	1,269	182	175	57	191	498
	FINAL OPEN FLOW (Mcf/d)	450	440	125	1,269	182	175	57	191	498

		North Triplett Consolidated KY	Janet KY	Turkey Knob KY	Grassy Creek Consolidated KY	Holly Creek Consolidated KY	War Creek Consolidated KY	Lawson KY	Woods Bend KY
BASIC RESERVOIR DATA	POOL NUMBER	1601419	1601046	1602010	1600811	1600977	1602070	1601137	1602155
	DISCOVERED	1934	1929	1923	1902	1923	1920	1949	1922
	DEPTH TO TOP RESERVOIR	290	486	1,225	1,355	1,400	1,488	1,400	1,305
	AGE OF RESERVOIR	Silurian	Silurian	Silurian	Silurian	Silurian	Silurian	Silurian	Silurian
	FORMATION	Lockport	Lockport	Salina	Salina	Salina	Salina	Salina	Salina
	PRODUCING RESERVOIR	Lockport	Lockport	Salina	Salina	Salina	Salina	Salina	Salina
	LITHOLOGY	dolomite	dolomite	dolomite	dolomite	dolomite	dolomite	dolomite	dolomite
	TRAP TYPE	stratigraphic unconformity	stratigraphic unconformity	stratigraphic unconformity	stratigraphic unconformity	stratigraphic unconformity	stratigraphic unconformity	stratigraphic unconformity	stratigraphic unconformity
	DEPOSITIONAL ENVIRONMENT	shallow open-marine	shallow open-marine	shallow open-restr. marine	shallow open-restr. marine	shallow open-restr. marine	shallow open-marine	shallow open-restr. marine	shallow open-restr. marine
	DISCOVERY WELL IP (Mcf)	150		650		450 (com)	90	100 (com)	375
	DRIVE MECHANISM	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion
	NO. PRODUCING WELLS				34	31	7		6
	NO. ABANDONED WELLS	18	36		1	1	2	24	2
	AREA (acreage)	859	7,653	9,969	5,009	12,512	1,820	2000	1,483
	OLDEST FORMATION PENETRATED	Ordovician	Clinton	Ordovician	Ordovician	Clinton	Rose Hill	Clinton	Clinton
	EXPECTED HETEROGENEITY DUE TO:	diagenesis	diagenesis	diagenesis	diagenesis	diagenesis	diagenesis	diagenesis	diagenesis
RESERVOIR PARAMETERS	AVERAGE PAY THICKNESS (ft.)		8		12	6	7	7	
	AVERAGE COMPLETION THICKNESS (ft.)	16	8	12.6	18	24	19	8	16
	AVERAGE POROSITY–LOG (%)		7		10.2	8.8	8.3		
	MINIMUM POROSITY–LOG (%)		4		4	4	4		
	MAXIMUM POROSITY–LOG (%)		10.5		16	19	11		
	NO. DATA POINTS		1		3	4	3		
	POROSITY FEET								
	RESERVOIR TEMPERATURE (°F)				68	81	65	77	
	INITIAL RESERVOIR PRESSURE (psi)	42		285	430	425		485	380
	PRODUCING INTERVAL DEPTHS (ft.)	204-360	333-635	884-1,392	1,269-1,469	1,254-1,730	1,312-1,620	1,296-1,648	1,230-1,403
	PRESENT RESERVOIR PRESSURE (psi) / DATE	19/1945	100/1988		150/1986	422/1966	225/?	100/1966	
FLUID & GAS PROPERTIES	Rw (Ωm)		0.10	0.06	0.04	0.04	0.04	0.04	
	GAS GRAVITY (g/cc)			0.698	0.644	0.68	0.68	0.68	0.641
	GAS SATURATION (%)				60	71	50		
	WATER SATURATION (%)				40	29	50		
	COMMINGLED	no	no	no	341OHIO	341OHIO 355LCKP 355BGSX	332BIGL 355LCKP	355BGSX	355LCKP
	ASSOCIATED OR NONASSOCIATED	nonassociated	nonassociated	nonassociated	associated	nonassociated	associated	nonassociated	
	Btu/scf			1,170	1,005	1,081	1,081	1,081	1,005
VOLUMETRIC DATA	STATUS (producing, abandoned, storage)	abandoned	abandoned	abandoned	producing	producing	producing	abandoned	producing
	ORIGINAL GAS IN PLACE (Mcf)	167,600	1,568,000	8,839,000	5,068,000	8,986,000	510,000	2,293,000	2,158,000
	ORIGINAL GAS RESERVES (Mcf)	27,600	942,000	7,530,000	4,570,000	8,000,000	439,000	2,088,000	1,919,000
	PRODUCTION YEARS	1934-?	1929-?	1923-?	1902-1994	1964-1991	1920-1994	1966-1978	1922-1994
	REPORTED CUMULATIVE PRODUCTION (Mcf)					1,467,000		28,168	
	NO. WELLS REPORTED					28		1	
	ESTIMATED CUMULATIVE PRODUCTION (Mcf)	26,000	940,000	7,500,000	4,400,000	7,000,000	436,000	2,085,000	1,916,000
	REMAINING GAS IN PLACE (Mcf)/DATE	141,600/ 1994	628,000/ 1994	1,339,000/ 1994	668,000/ 1994	1,986,000/ 1994	74,000/ 1994	208,000/ 1994	242,000/ 1994
	REMAINING GAS RESERVES (Mcf)/DATE	1,600/ 1994	2,000/ 1994	30,000/ 1994	170,000/ 1994	1,000,000/ 1994	3,000/ 1994	3,000/ 1994	3,000/ 1994
	RECOVERY FACTOR (%)	16	60	85	90	89	86	91	89
	INITIAL OPEN FLOW (Mcf/d)	124	500	1,155	65	222	159	203	373
	FINAL OPEN FLOW (Mcf/d)	124	500	1,155	65	222	159	203	373

The Rome trough is a major northeast-southwest Cambrian age extensional basin that extends from Pennsylvania through West Virginia into eastern Kentucky (McGuire and Howell, 1963; Harris, 1975; 1978). The Kentucky River fault system forms the northern and western boundary of the Rome trough, but the southern boundary is less well-defined. Faults associated with the Rome trough had significant influence during Silurian-Devonian time on both sedimentation and erosion. Abrupt changes in thickness of the Corniferous are believed to be a reflection of paleostructure influenced by reactivation of faults associated with the Rome trough. These abrupt changes in thickness allow specific hydrocarbon-bearing reservoirs that have been erosionally truncated to be repeated updip, thus forming another unconformity trap.

Major uplifts include the Pike and Perry uplifts in Pike and Perry counties and the Rockcastle uplift in parts of Clay, Laurel, and Owsley counties (Figure DSu-8). In some cases, the reservoirs are truncated along the flanks of the uplifts forming an unconformity trap. The Waverly arch (Figure DSu-8), a north-south-trending feature, is another major structure. It is not known if this feature has had an effect on unconformity traps.

Structure is not the main trapping mechanism of the Lower Devonian-Upper Silurian unconformity play. However, in a few cases structure significantly enhances hydrocarbon entrapment. An example of structural involvement is found in the Artemus-Himyar Consolidated field in Knox and Bell counties, Kentucky, where low-amplitude folding of the unconformity is thought to have significantly enhanced the hydrocarbon accumulation.

Fractures may locally enhance production. The formation of production enhancement fractures and their relation to major structural features is possible but has not been demonstrated. Many of the fractures could be due to collapse over karst features that developed during periods of exposure and erosion on the Lower Devonian-Upper Silurian unconformity.

Reservoir

The primary stratigraphic trapping element for the reservoirs of this play, as the title indicates, is the unconformity. Many major oil and gas field reservoirs show a close relationship between the producing formations and an associated unconformity (Levorsen, 1967; Moody and others, 1970). The distribution of fields relative to the subcrop map pattern of the producing formations on the unconformity surface (Figure DSu-6) and the relationship of the producing formations, the reservoirs, the unconformity surface, and the overlying sealing

TABLE DSu-2	Creekville Hyden Consolidated KY	Holly Creek Consolidated KY
AVERAGE POROSITY–CORE (%)	7.1	8.8
MINIMUM POROSITY–CORE (%)	2.6	4.5
MAXIMUM POROSITY–CORE (%)	11.7	15.6
NO. DATA POINTS	3	3
AVERAGE PERMEABILITY (md)	15.3	54.1

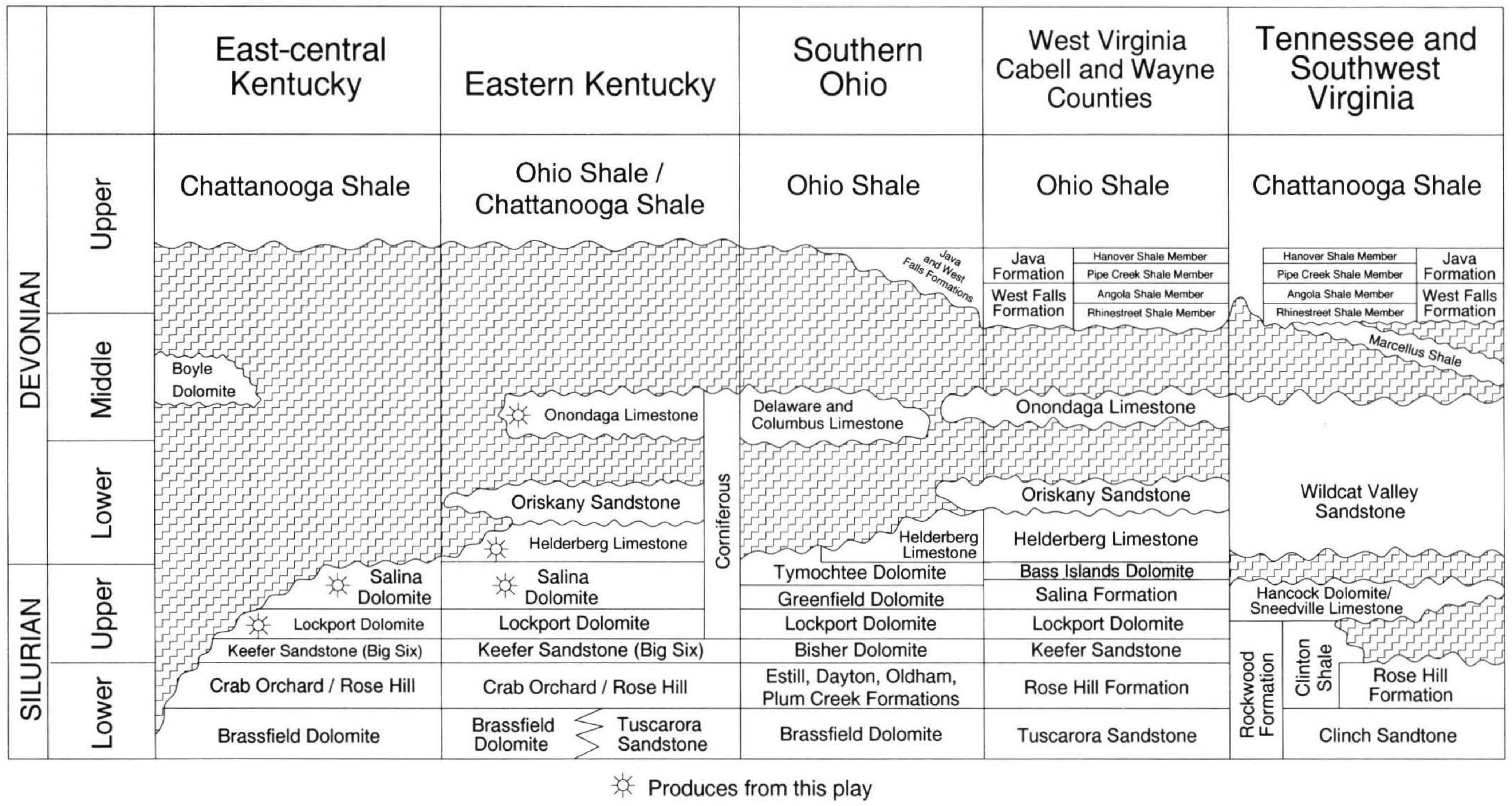


Figure DSu-3. Generalized stratigraphic column showing equivalent formations. Modified from Patchen and others (1985a; 1985b).

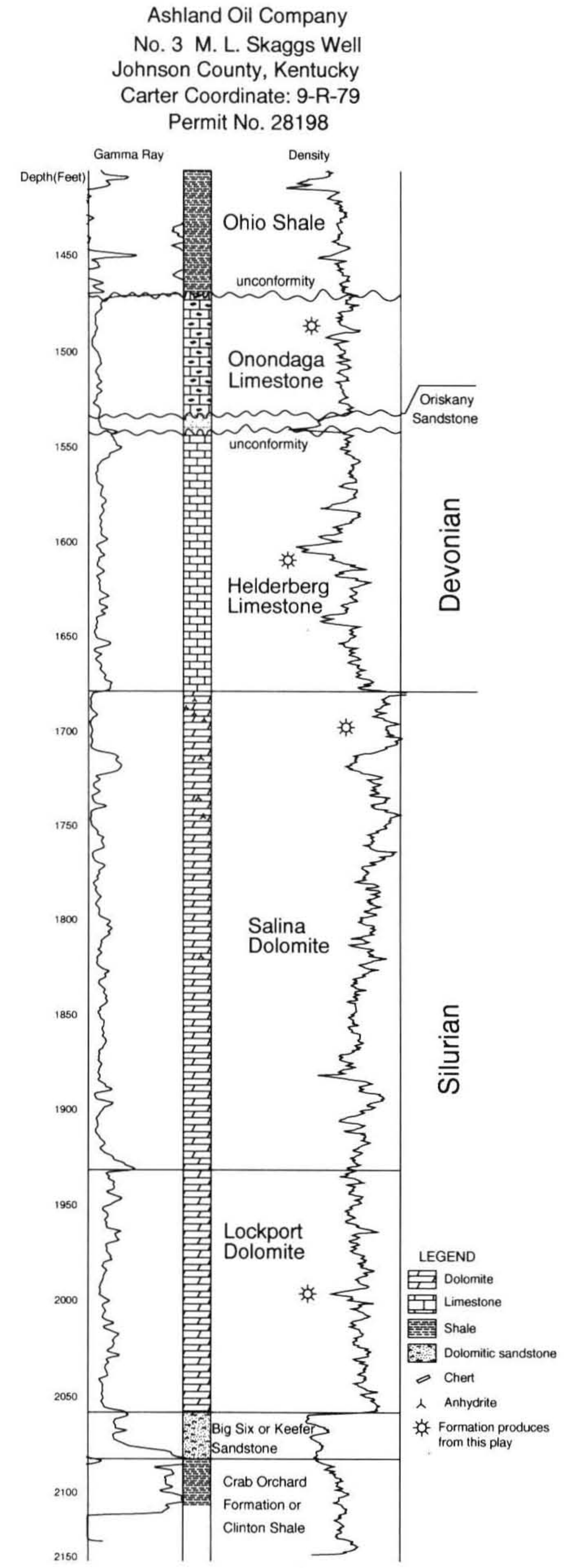


Figure DSu-4. Type log for a well (No. 3 M.L. Skaggs) in eastern Kentucky.

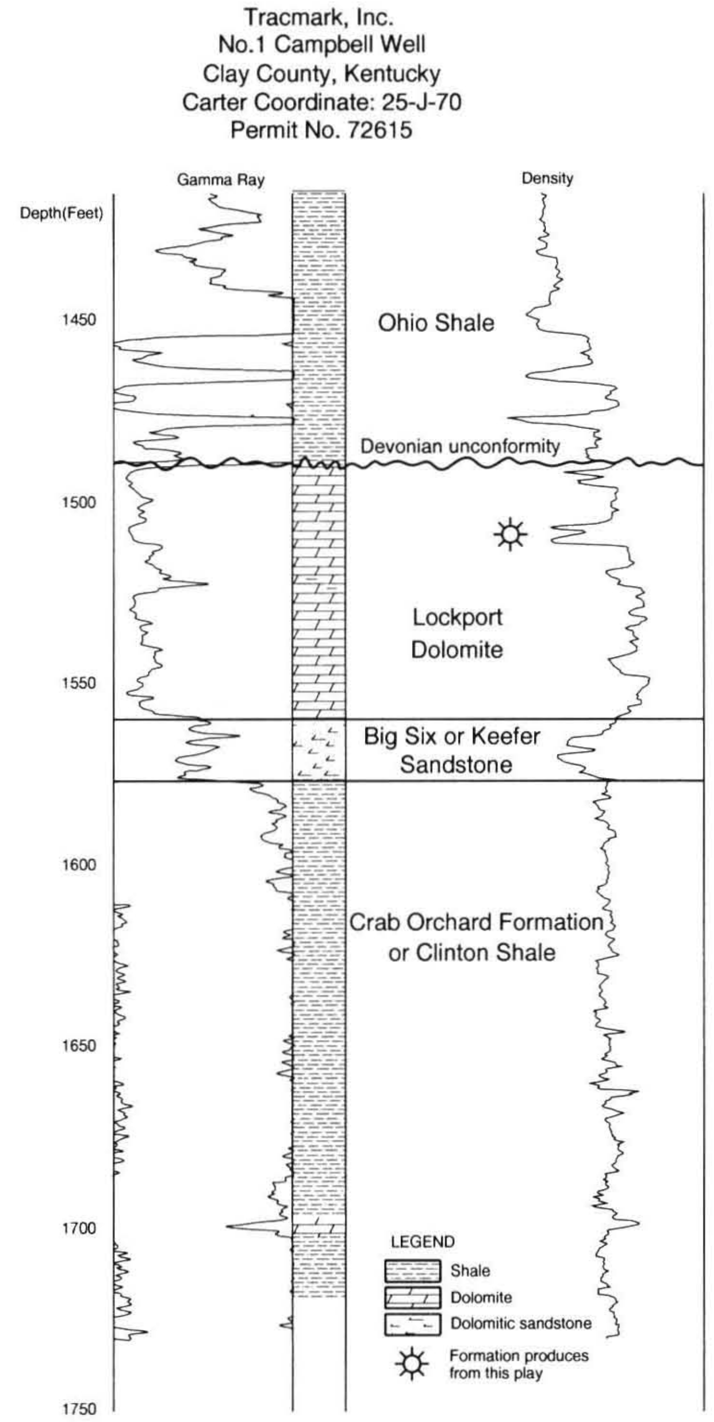


Figure DSu-5. Type log for a well (No. 1 Campbell) in east-central Kentucky.

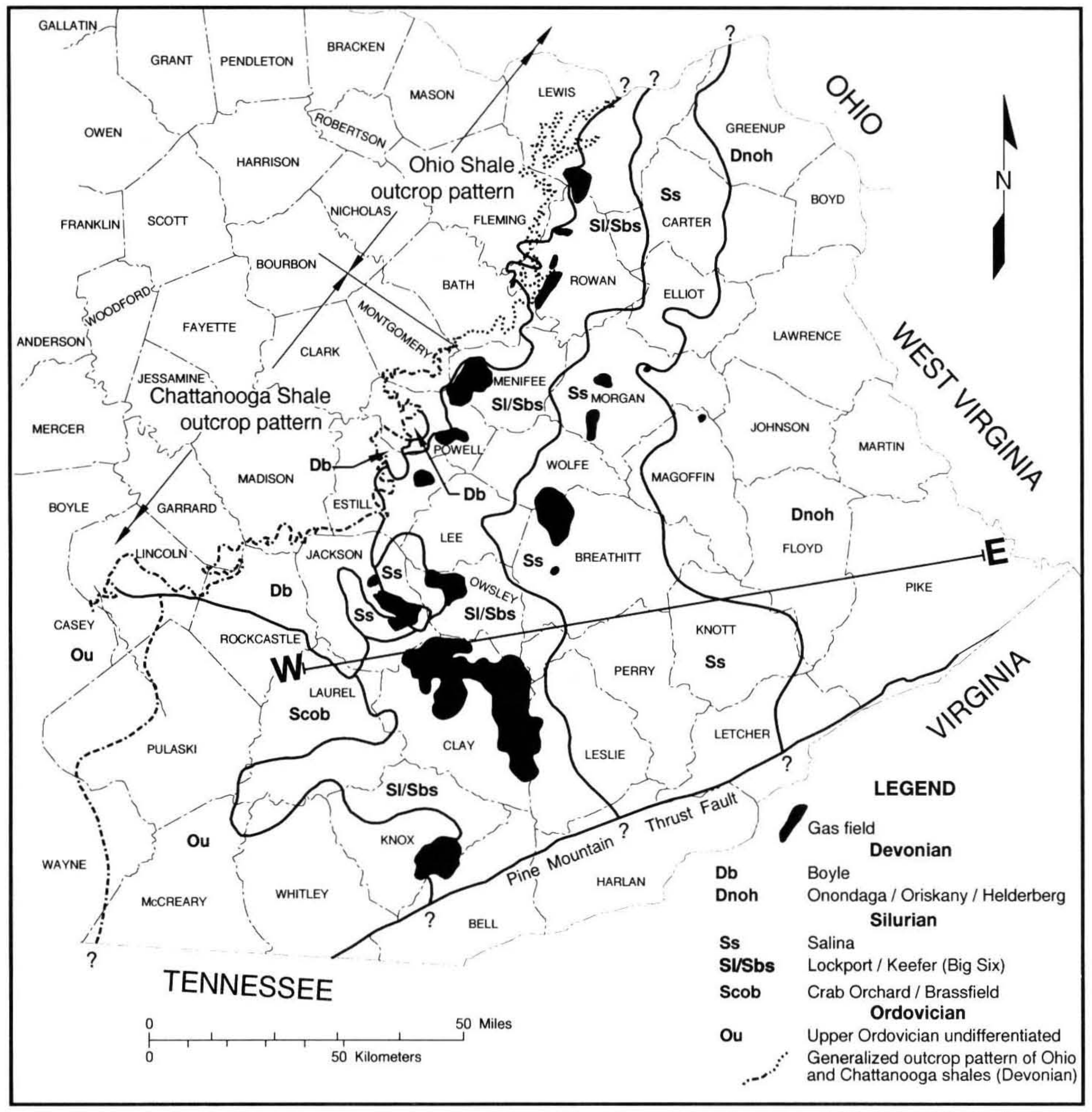


Figure DSu-6. Subcrop map of eastern Kentucky showing rock units and associated gas fields below Middle Devonian unconformity.

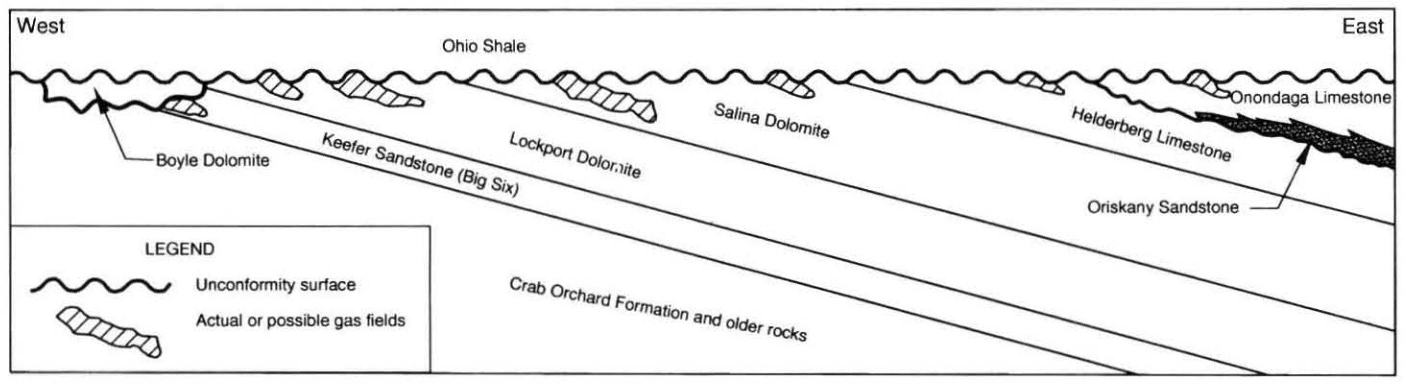


Figure DSu-7. West-east cross section illustrating conceptual model of Devonian unconformities. No scale.

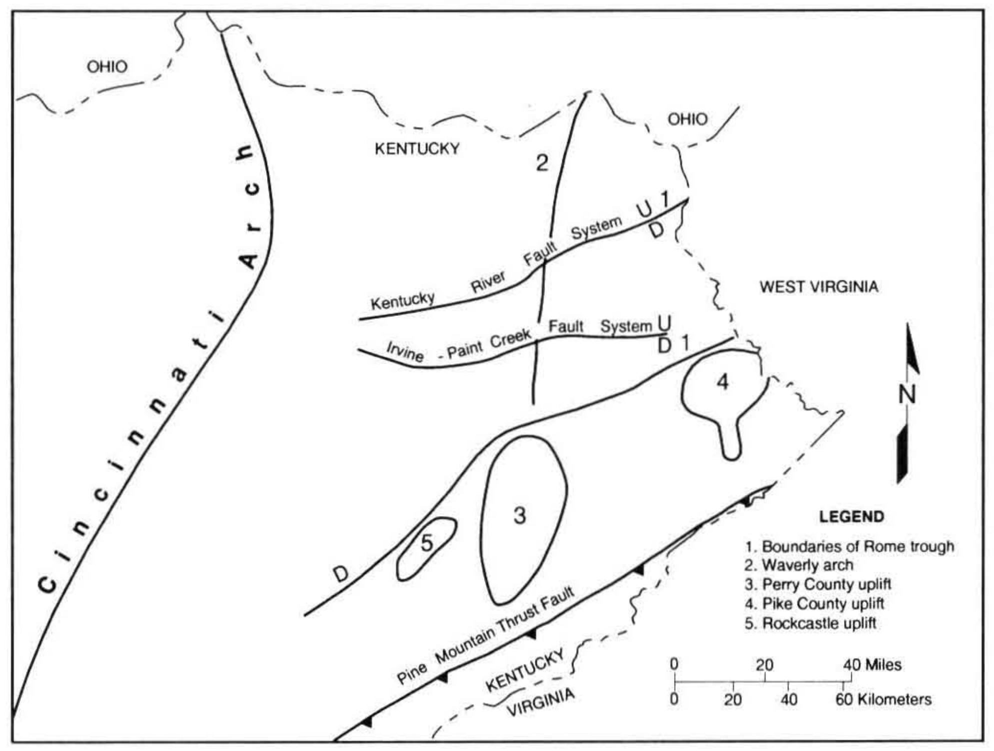


Figure DSu-8. Approximate location of major structural features. Modified from Currie (1981). Boundary of Rome trough from Ammerman and Keller (1979). Boundary of Waverly arch from Woodward (1961).

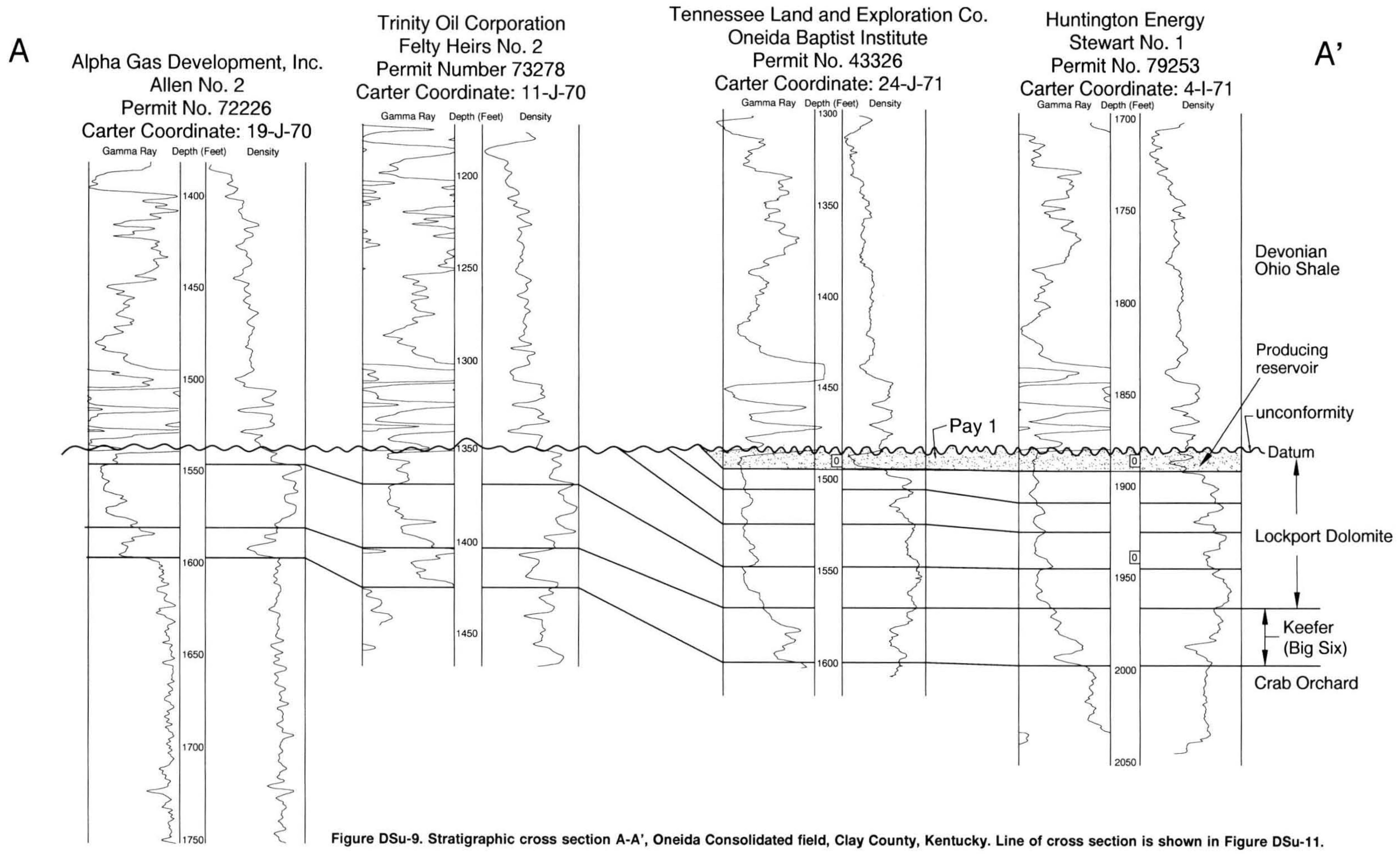


Figure DSu-9. Stratigraphic cross section A-A', Oneida Consolidated field, Clay County, Kentucky. Line of cross section is shown in Figure DSu-11.

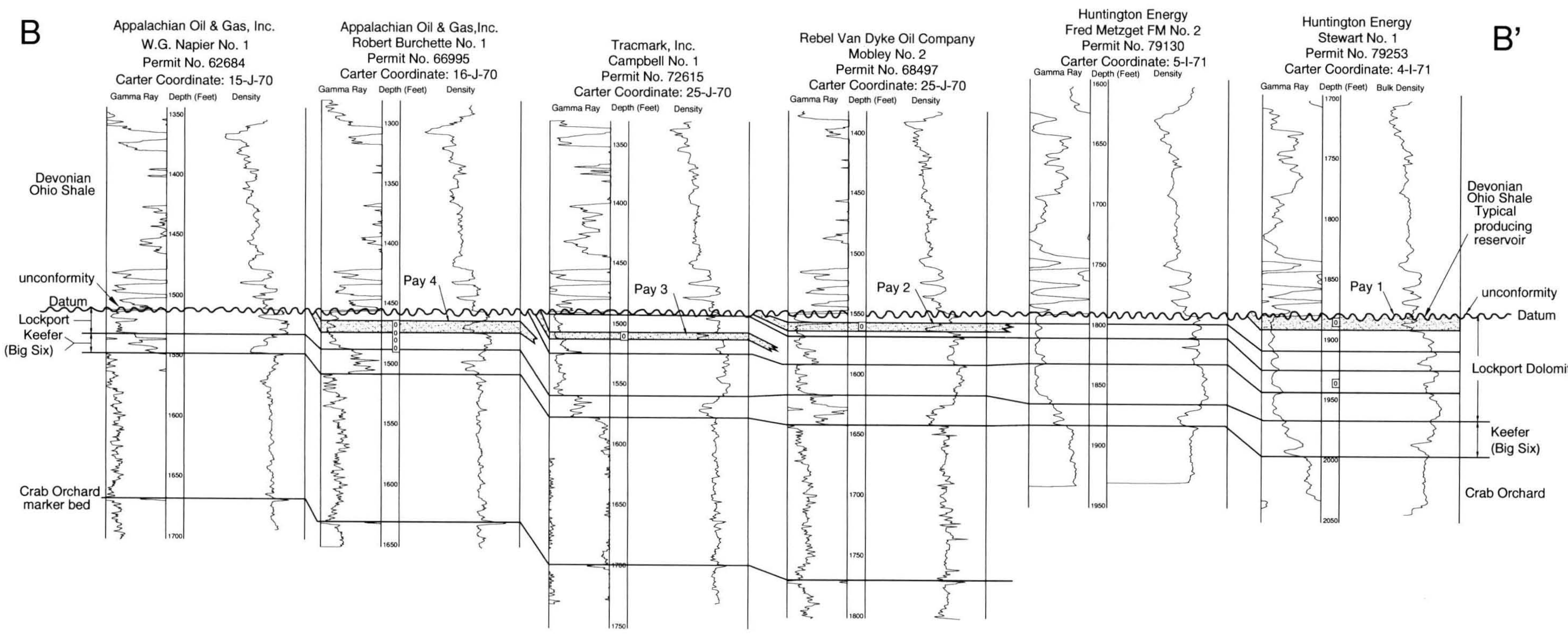


Figure DSu-10. Stratigraphic cross section B-B', Oneida Consolidated field, Clay County, Kentucky. Line of cross section is shown in Figure DSu-11.

formation (Figure DSu-7) indicate a stratigraphic and, specifically, an unconformity trapping mechanism for the reservoirs. Adjunct to the unconformity trapping for some reservoirs in this play is the structural folding of the rocks above and below the unconformity forming a combination trap, thus enhancing the trapping capabilities of the unconformity. An example of the unconformity trap is the Oneida Consolidated field, Clay County, Kentucky (Figures DSu-9, DSu-10, DSu-11, DSu-12, DSu-13, DSu-14). Additional examples of unconformity traps in eastern Kentucky can be found in Huffman (1966) and Weaver and McGuire (1973). The combination trap, an unconformity with anticlinal closure, is illustrated by the Artemus-Himyar Consolidated field in Knox and Bell counties (Figures DSu-15, DSu-16, DSu-17).

The source of hydrocarbons for this play is believed to be the organic-rich Devonian Ohio Shale (Weaver and McGuire, 1973). Fluid migration is believed to have occurred from deeper in the basin to the east along faults, fractures, and possibly unconformities.

Drilling depths range from 240 feet in the Bluestone field in the north to 2,440 feet in the Creekville-Hyden Consolidated field in the south. The deepest formation penetrated by drilling in any field in this play is the Cambrian Copper Ridge Dolomite in the Artemus-Himyar field in Knox and Bell counties.

Pay thickness was difficult to determine because of a lack of good data. Many fields do not have adequate logs to determine exact pay thickness. In most cases, the only data available are completion intervals, which are normally thicker than actual pay zones. To solve this problem, data is reported for both categories. The average pay thickness based on log analysis is 10 feet with a range in thickness of 4 to 17 feet. The average pay thickness based on completion interval is 20 feet with a range in thickness of 8 to 43 feet. Completion intervals were based on gauged intervals reported in drillers' logs and completion intervals reported in completion forms. Whenever possible, pay thickness was calculated using geophysical logs. Large open-hole completion intervals were not included in the calculations.

Rock pressure varied tremendously throughout the play. The observed variance is due to the lack of quality control for the data reported and to differences in producing depths and heterogeneity of the reservoirs. Nevertheless, the average initial rock pressure was 191 psi, with a range of 22 to 615 psi. In all cases, the initial rock pressure was significantly less than the normal pressure gradient.

Final open flow data are, at best, suspect. In most cases, no data is available to document how the operator determined final open flow values. In addition, many of the reported final open flow data were from commingled zones that included one or more of the following: Maxon Sandstone, Big Lime, Ohio Shale, Big Six, Stones River, and Knox. Here, final open flow values cited are not from commingled zones. The average final open flow was 361 Mcf/d with a range from 57 to 1,269 Mcf/d. Average cumulative gas production per well is approximately 175 MMcf, and the average life per well is approximately 20 years. The average production per acre-foot is approximately 100 Mcf/acre-foot.

Porosity in the most productive formation, the Lockport Dolomite, has probably varied several times through various diagenetic processes. Primary porosity consisting of intraskeletal, intergranular, and intercrystalline porosity was formed by early dolomitization. Most of the primary porosity was later destroyed by eogenetic carbonate cements (Smosna and others, 1989). The majority of the porosity preserved is secondary porosity formed by telogenetic processes immediately below the Devonian unconformity. Telogenetic porosity was formed primarily by the leaching of fossils in the Lockport Dolomite and the dissolution of anhydrite in the Salina Dolomite (Freeman, 1951). The average porosity for the producing zones in the Lockport and the Salina is 8.4 percent and 9.5 percent, respectively. The porosity ranges from 4 to 17 percent for the Lockport Dolomite and 4 to 19 percent for the Salina Dolomite.

Completion strategies and stimulation practices vary widely throughout this play because of its long development history and the economic considerations of individual operators. Today, the most common practice is to set 7-inch casing in the Big Lime, effectively shutting off water-bearing zones encountered above. If the well is thought to have potential, it is perforated through casing or simply open-hole completed. Occasionally, a well has been stimulated by hydraulic fracturing techniques; however, this has yet to be very successful. In earlier years, wells were often stimulated using some form of nitroglycerin in the open hole.

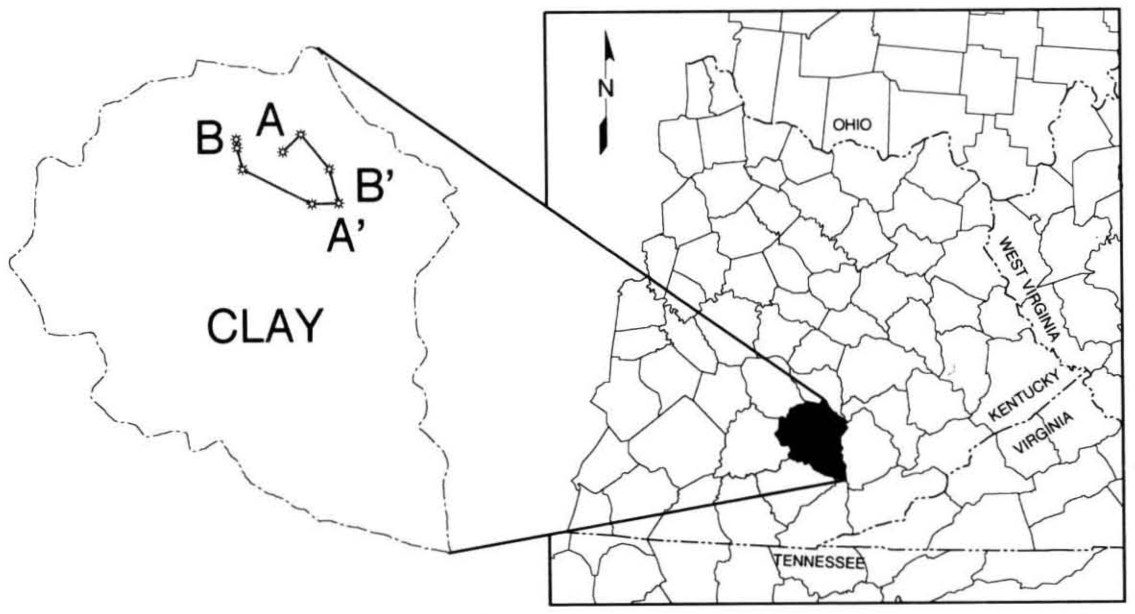
Logging procedures vary considerably and are based on operators' budgets. The most common practice is to run a gamma-ray log along with some type of porosity and temperature log. In most cases, resistivity logs have not been run. In fact, only about 10 percent of all logs run have been resistivity logs. This makes it very difficult to obtain reliable water saturation values. In some cases, no geophysical logs are available for any well in an entire field.

Description of Key Fields

Oneida Consolidated field: The Oneida Consolidated field in Clay County, Kentucky, is the center portion of a much larger field complex that includes the Burning Springs Consolidated and Creekville-Hyden Consolidated fields (Figure DSu-2). It is an excellent example of reservoirs formed by an unconformity. The field produces from four different Silurian Lockport Dolomite reservoirs, as shown in cross sections A-A' and B-B' (Figures DSu-9, DSu-10). The reservoirs are designated pays 1 through 4 on the cross sections and isopach maps. A structure map drawn on the base of the Ohio Shale represents the underlying unconformity. The structure map illustrates a general east-southeast dip for the surface (Figure DSu-11). The minor amount of relief on the surface may be due to differential erosion or incipient structural folding. No major closures were noted. Structurally, the field is located on the flank of the Rockcastle uplift (Miles, 1972).

An isopach map of the Lockport-Big Six interval illustrates the updip truncation of this interval across the field (Figure DSu-12). The thickness varies from more than 130 feet in the eastern part of the field to less than 40 feet in the northwestern part of the field. This dramatic change in thickness is a result of the erosional unconformity. Cross sections A-A' and B-B' (Figures DSu-9, DSu-10) also depict this regional angular unconformity.

Based on cross sections and geophysical and drillers' logs, four Lockport pay zones and traps have been defined (Figures DSu-9, DSu-10). The pay isopach map (Figure DSu-13) shows the areal extent of each pay zone and where the updip truncation or porosity pinchout is interpreted to occur. The interpreted truncation of each pay zone was based on pay thickness, final open flow values,



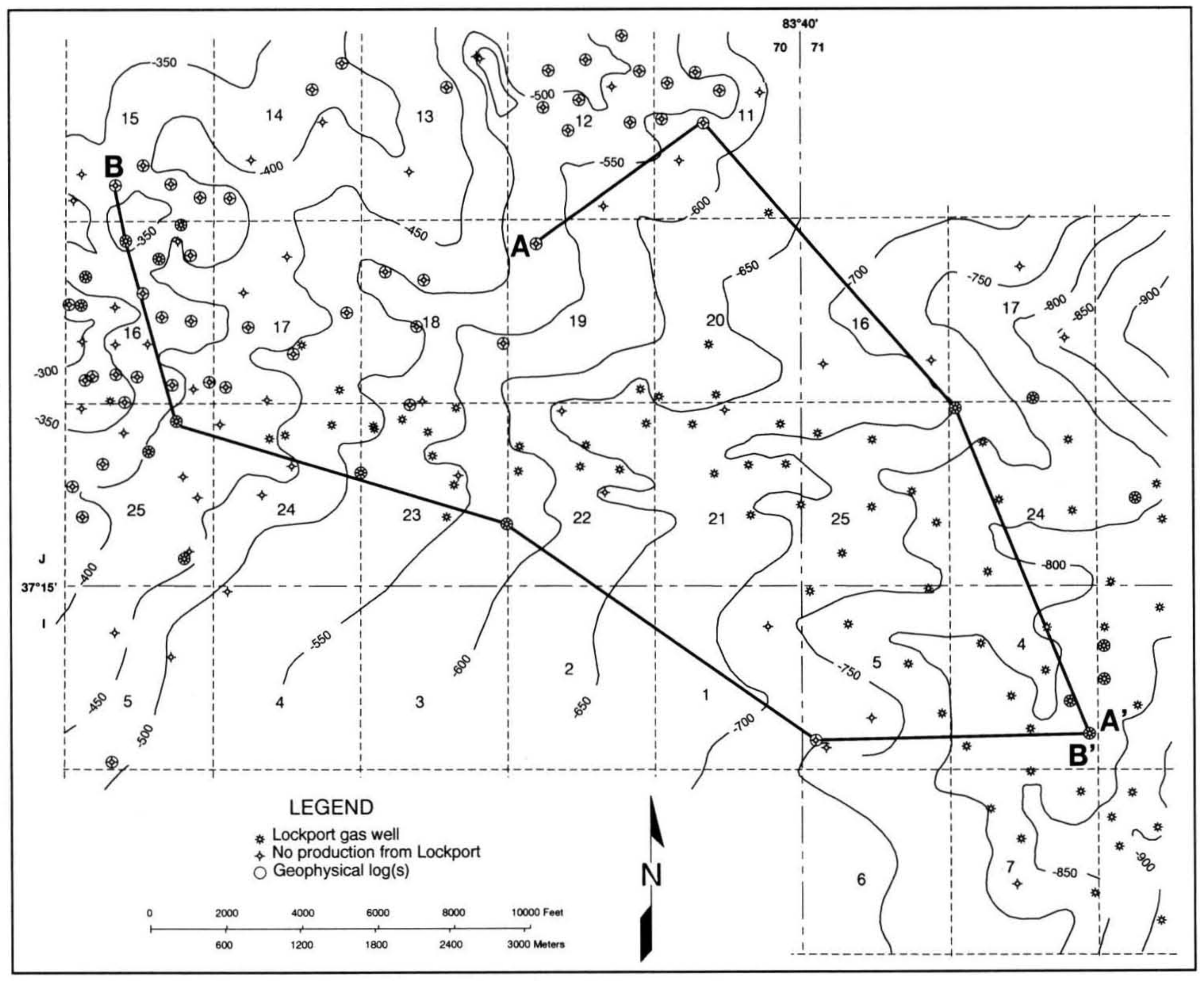


Figure DSu-11. Structure on the base of the Devonian Ohio Shale (unconformity surface), Oneida Consolidated field, Clay County, Kentucky. Contour interval = 50 feet. Lines of cross sections A-A' (Figure DSu-9) and B-B' (Figure DSu-10) are also shown.

and location of the pay zone with respect to the unconformity when geophysical logs were not available. In some cases, as in pay zone 2, the trapping mechanism is facilitated by the sealing of the effective porosity by the onlaping of the shale on the pay zone exposed at the unconformity surface. In addition to this, the trapping may be partially caused by the lack of effective porosity in an updip location. By far, pay 1 displays the largest areal extent and is believed to be the most prolific producer.

The four reservoirs in the Oneida Consolidated field are very heterogeneous because of the imbricate or shingling effect of multiple reservoirs. Cross section B-B' (Figure DSu-10) illustrates reservoirs (pays 1 through 4) within a given stratigraphic interval that are at or near the unconformity interface. When traced in a downdip direction away from the unconformity, they become nonporous. The net result is the shingling effect below the unconformity. Telogenic processes are believed to be the primary cause for development of porosity in these reservoirs.

Paleostructure plays an important role in the truncation geometry of the Lockport-Big Six. Cross section B-B' (Figure DSu-10) illustrates the paleostructure on top of a Crab Orchard marker bed. Within the subcrop belt of the Lockport-Big Six (Keefer Sandstone), the thickness of the Lockport-Big Six is related to the Clinton paleostructure. The higher the Clinton paleostructure, the thinner the Lockport-Big Six. Conversely, the lower the Clinton paleostructure, the thicker the Lockport-Big Six. This relationship is seen in many areas in eastern Kentucky and is believed to be a critical concept and, when used in conjunction with geophysical techniques, can be an excellent exploration and development tool, especially in areas of sparse well control.

Cumulative gas production from 178 wells in the Oneida Consolidated field is estimated at 36.7 bcf. It is estimated that reserves of 2.1 bcf remain to be recovered. A type decline curve for an average Lockport well in the Oneida Consolidated and Creekville-Hyden Consolidated fields is shown in Figure DSu-14.

Artemus-Himyar Consolidated field: The Artemus-Himyar Consolidated field, located in Knox and Bell counties, Kentucky, is an example of a combination trap, the truncation of a reservoir rock by an unconformity and structural nose and or an anticlinal closure. This trapping mechanism has also been noted by others (Miles, 1972; Weaver and McGuire, 1973).

The pay in the Artemus-Himyar Consolidated field varies from a sandy dolomite to a dolomitic sandstone. It has not been determined if this sandy interval is the Big Six or just a sandy facies of the Lockport Dolomite. Therefore, this interval will be referred to as the Lockport-Big Six? pay zone.

To illustrate the trapping mechanism, two maps and one cross section were constructed. A structure map on the base of the Ohio Shale (unconformity surface) exhibits a prominent northwest-southeast-trending anticline with at least 100 feet of closure (Figure DSu-15). This structural feature has a surface expression that has been mapped by Rice (1974) on the Artemus geologic quadrangle map (Rice, 1974), and has been discussed by Jillson (1931). It appears that structure is an important enhancement to the trapping mechanism.

Stratigraphic cross section C-C' (Figure DSu-16) illustrates the truncation of the Lockport-Big Six? pay zone as well as the Corniferous section. The Corniferous isopach map (Figure DSu-17) illustrates the truncation of the

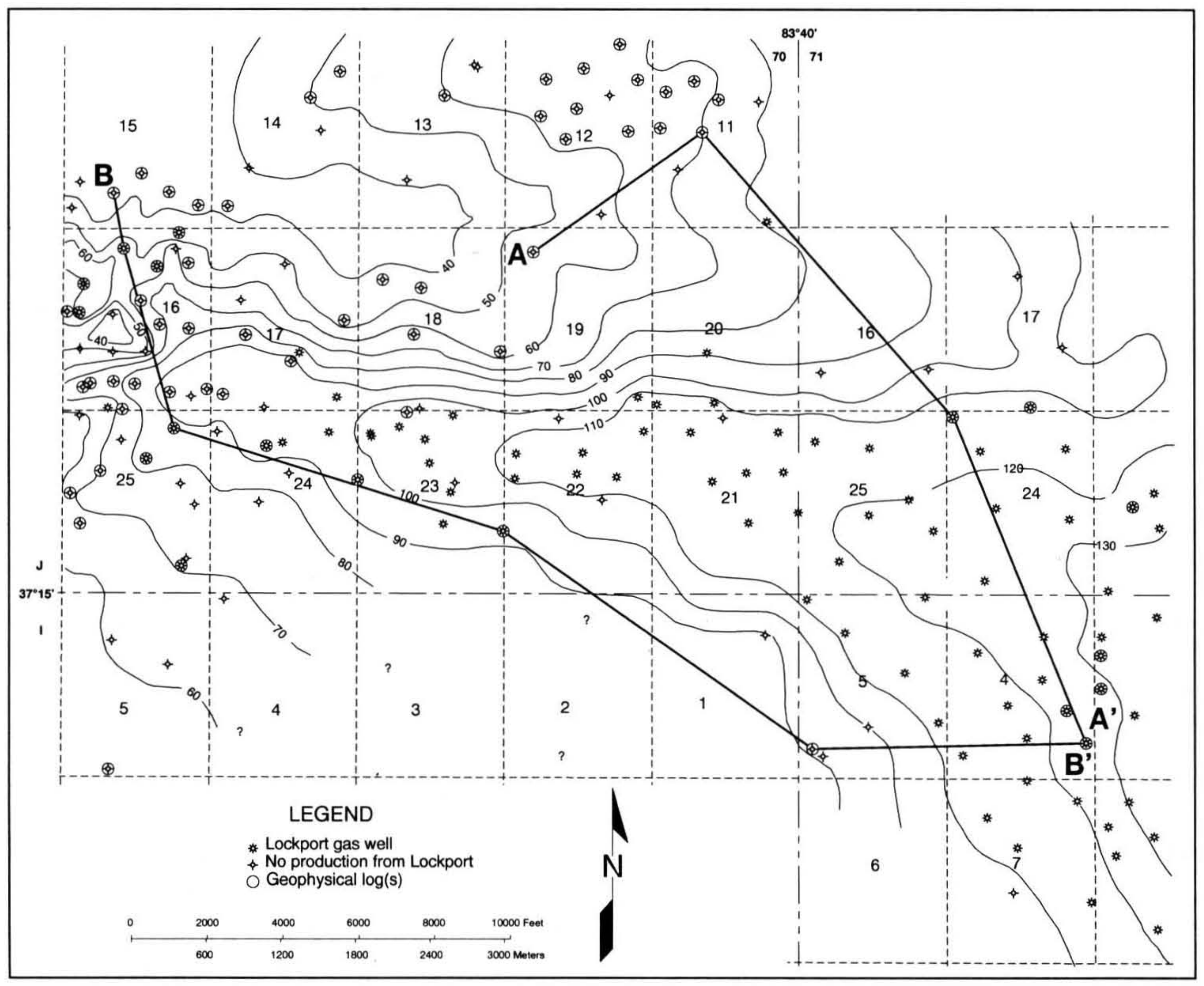


Figure DSu-12. Isopach map of the Lockport Dolomite/Keefer (Big Six), Oneida Consolidated field, Clay County, Kentucky. Contour interval = 10 feet. See Figure DSu-11 for location.

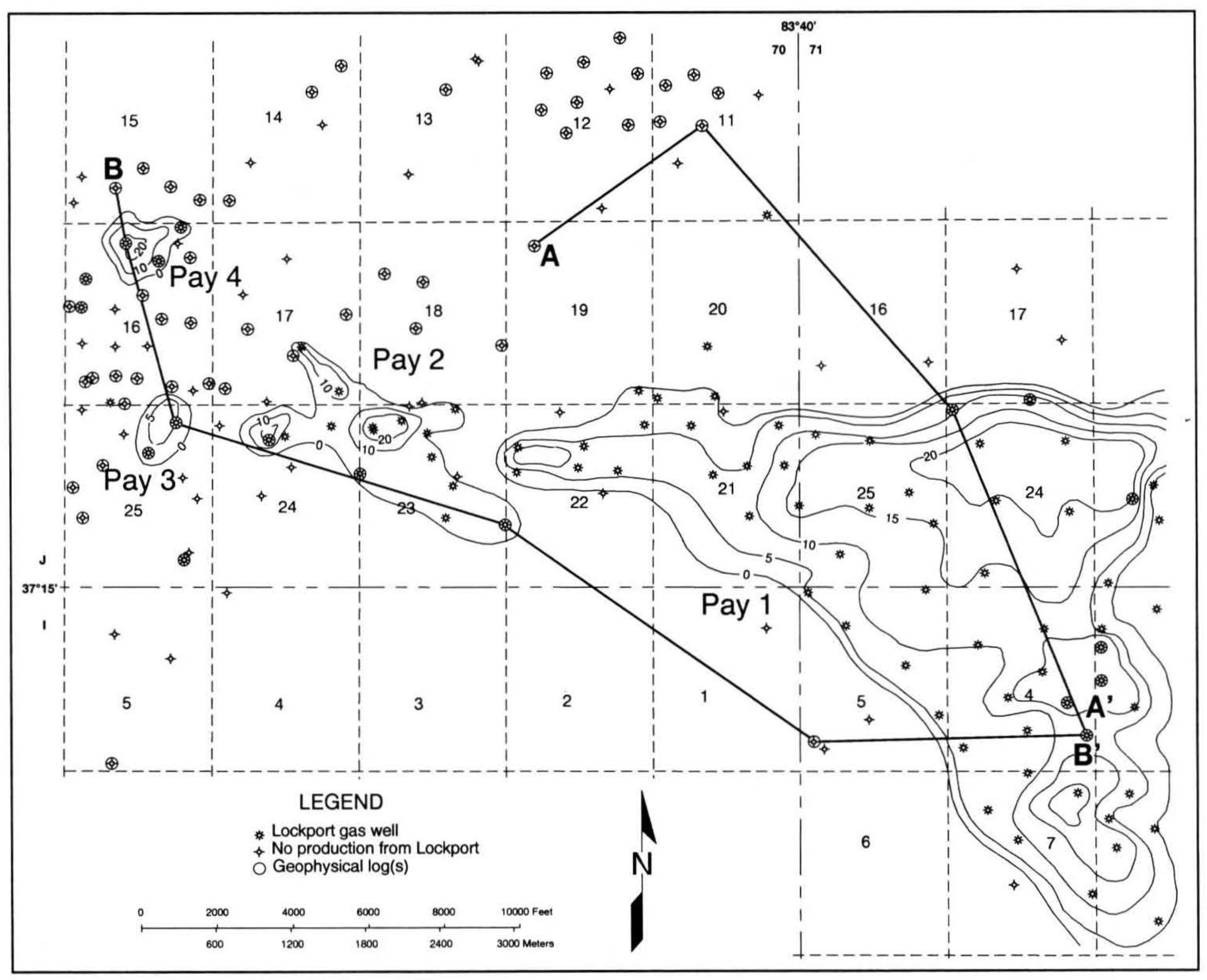


Figure DSu-13. Isopach map of pays 1 through 4, Oneida Consolidated field, Clay County, Kentucky. Contour interval = 5 feet. For pays 2 and 4, contour interval = 10 feet. See Figure DSu-11 for location.

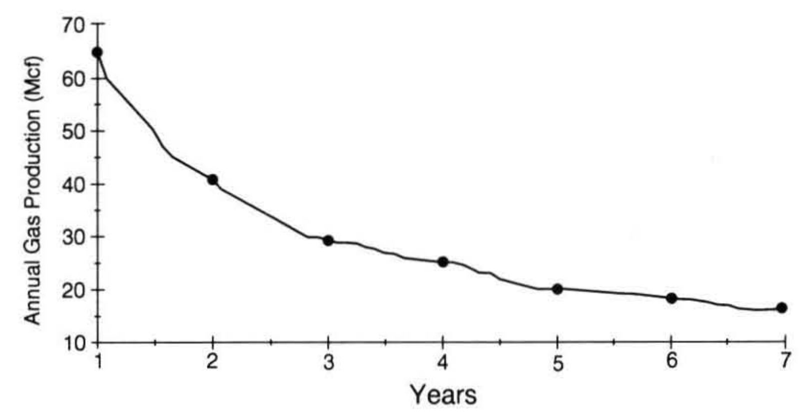
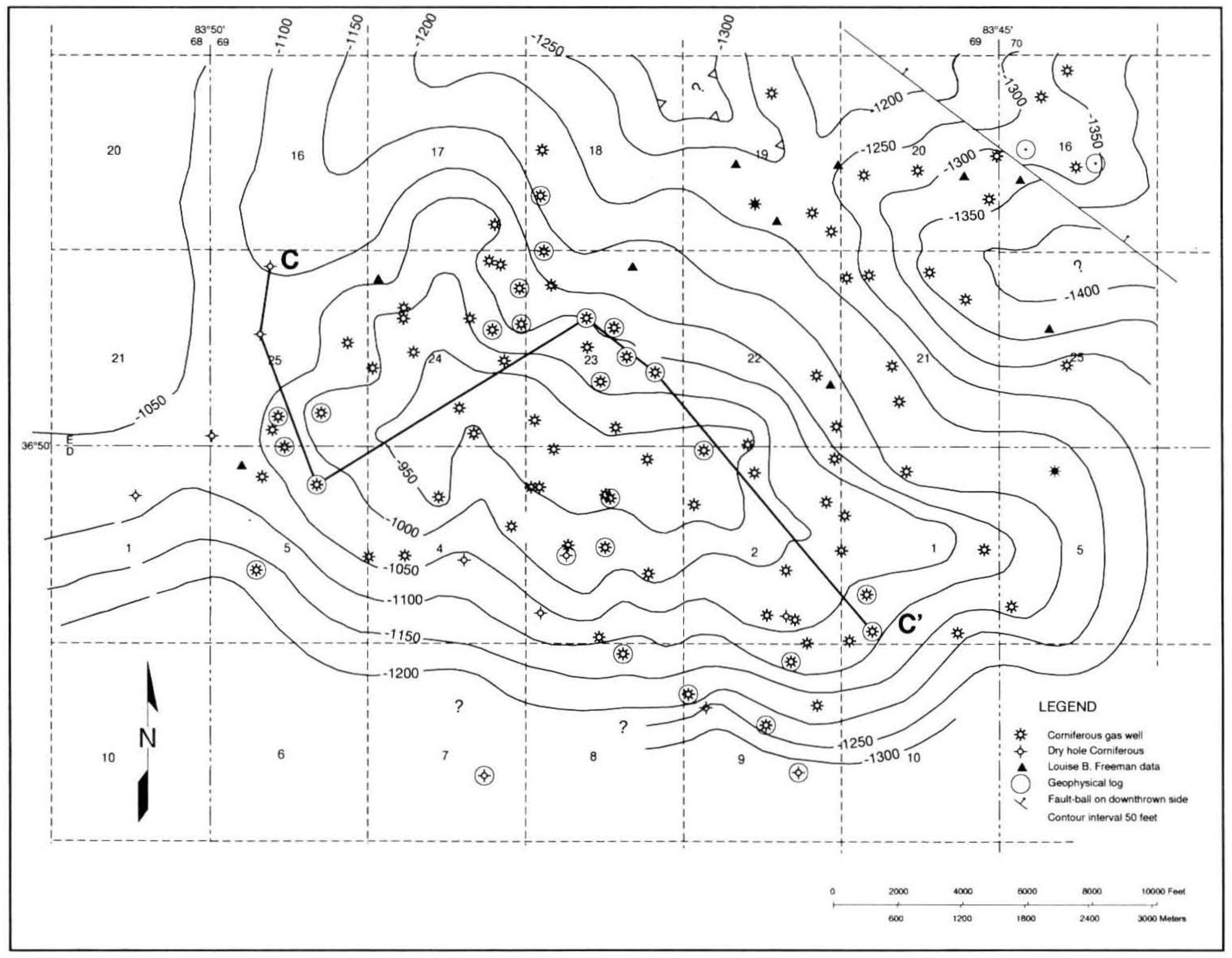


Figure DSu-14. Type decline curve for average Lockport well in Oneida Consolidated and Creekville-Hyden Consolidated fields, Clay and Leslie counties, Kentucky.



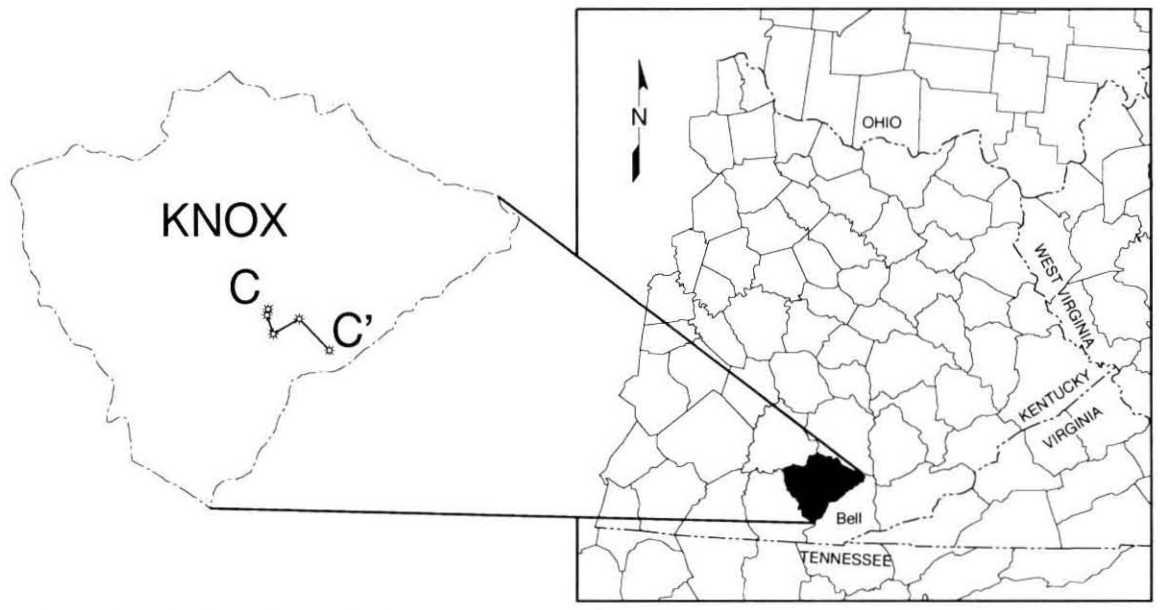


Figure DSu-15. Structure on the base of the Devonian Ohio Shale (unconformity surface), Artemus-Himyar Consolidated field, Knox and Bell counties, Kentucky. Contour interval = 50 feet. Line of cross section C-C' (Figure DSu-16) is also shown.

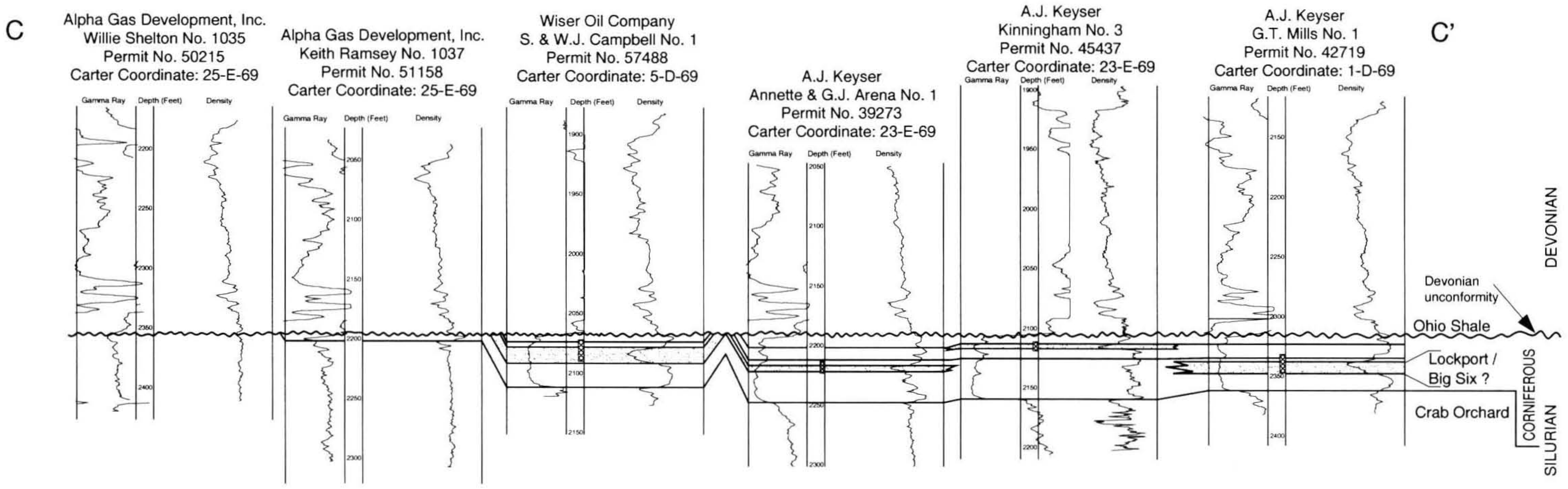


Figure DSu-16. Stratigraphic cross section C-C', Artemus-Himyar Consolidated field, Knox and Bell counties, Kentucky. Line of cross section is shown in Figure DSu-15.

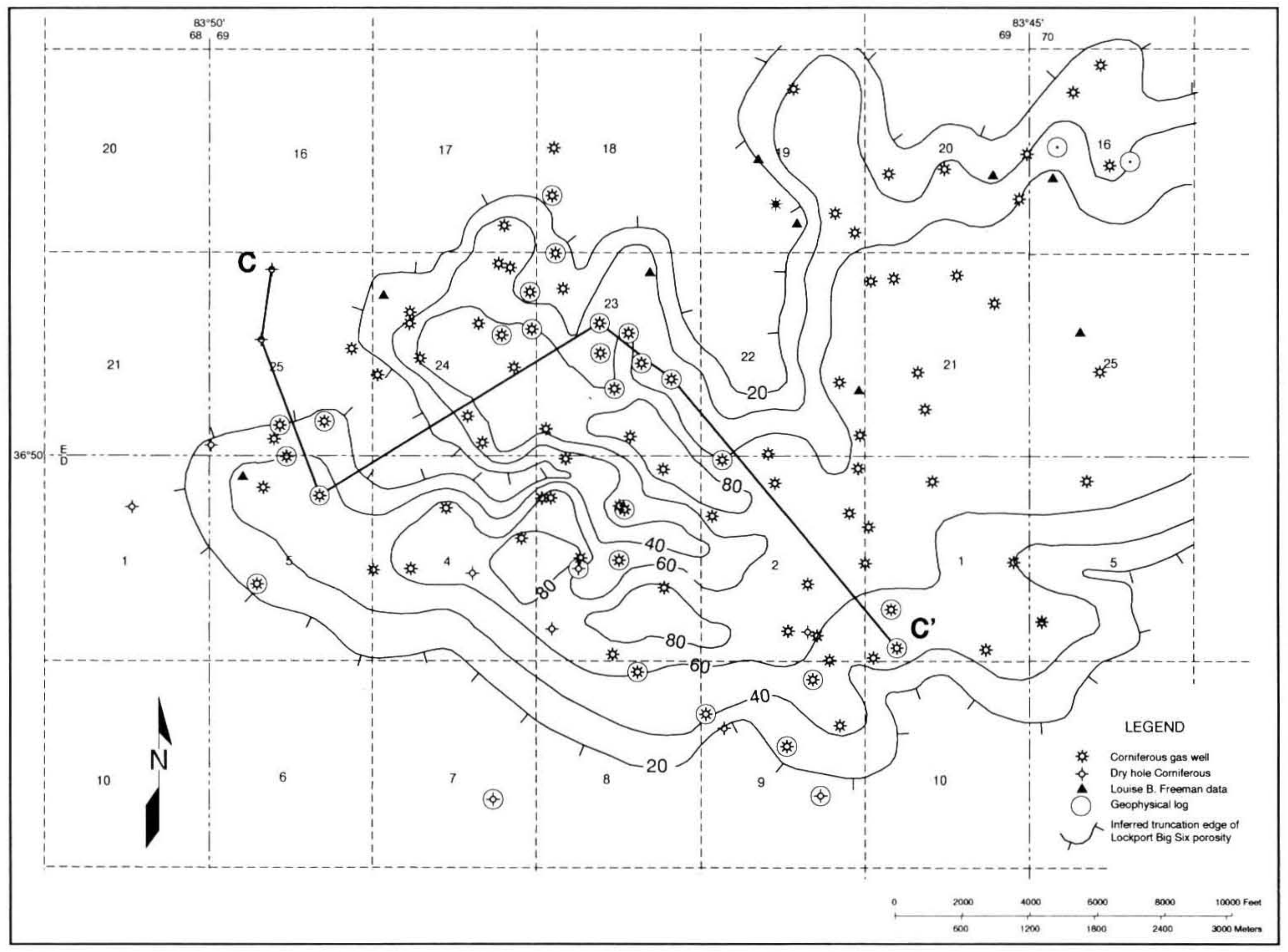


Figure DSu-17. Isopach map of Corniferous, Artemus-Himyar Consolidated field, Knox and Bell counties, Kentucky. See Figure DSU-15 for location.

Corniferous seen on the cross section (Figure DSu-16). Also shown on the Corniferous isopach map (Figure DSu-17) is the inferred truncation edge of the Lockport-Big Six? pay zone.

Cumulative gas production from 115 wells in Artemus-Himyar Consolidated field is estimated at 22.9 bcf. Due to very low formation pressure, no significant reserves remain to be produced.

Resources and Reserves

Gas-in-place and reserves were difficult to calculate because of the lack of reservoir data in many fields, the early development of many fields, and the confidential nature of production data reported by operators to the State of Kentucky. Thus, the results are somewhat questionable. A conservative number, based on limited production information (428 wells), is that 74.2 bcfg have been produced from Salina, Lockport, and Lockport-Big Six reservoirs as of December 1992. Volumetric calculations of abandoned and producing fields along the Salina and Lockport subcrop indicate 126 bcf of original gas-in-place and 102 bcf of recoverable gas reserves, based on an average recovery factor of 81 percent. Remaining recoverable gas reserves is estimated to be 23.7 bcf.

Gas production has been reported from the Devonian Onondaga and Helderberg limestones. The Onondaga has produced gas from the Lenox field in Morgan County, Kentucky, and the Helderberg has produced gas from the Oil Springs Consolidated field in Magoffin County, Kentucky (Figure DSu-2). Many wells were open-hole completions of an interval of several hundred feet and included the Onondaga and Helderberg limestones. No cumulative production data are available for either the Onondaga or Helderberg Limestone. Reserve calculations were based on analogies of Salina and Lockport fields and a few geophysical logs that indicated better porosity development in the Onondaga and Helderberg limestones compared to the Salina and Lockport dolomites. Original gas-in-place reserves for the Onondaga and Helderberg limestones in the two fields are estimated to range from 0.85 to 3.65 bcf. Recoverable gas reserves are estimated to range from 0.7 to 3 bcf. It is important to note that in the Oil Springs Consolidated field high concentrations of hydrogen sulfide have been reported from Helderberg-Salina producing intervals.

Gas production from the Devonian Boyle has not been documented. It is possible that many wells having been reported as producing from the Salina or Lockport in and around Jackson County have actually produced from the Boyle.

The Silurian Salina Dolomite (Cayugan) is a major producing formation compared to the Helderberg and Onondaga limestones. However, it is minor compared to the Lockport Dolomite. This conclusion is based on very limited and questionable production and completion data. In reality, the Salina may be more significant than the data suggest.

Future Trends

It is possible that additional gas reserves of 100 bcf exist in many new areas along the Silurian and Devonian subcrop (Figure DSu-6). The primary exploration tool is the integration of magnetic, gravity, and seismic surveys and surface and subsurface geologic mapping. This exploration method will help define the paleostructure and paleotopography that are significant in the formation of the trap geometry and development of secondary porosity.

To date, most production has been from the Silurian Lockport Dolomite. However, the most favorable areas for future discoveries are along the north-northeast- to south-southwest-trending Salina Dolomite and Devonian subcrop (Figure DSu-6). This potentially rewarding trend is located from eastern Lewis and Greenup counties, Kentucky, on the north to eastern Leslie, Perry, and Letcher counties, Kentucky, on the south. The Lockport Dolomite is also attractive in unexplored areas along the Lockport subcrop (Figure DSu-6). In addition, existing fields should be reevaluated for compartmentalized reservoirs that have been overlooked or underdeveloped. An example is the large field complex that includes Burning Springs Consolidated, Oneida Consolidated, and Creekville-Hyden Consolidated fields. These reservoirs are economically attractive and can be found with detailed subsurface work.

In southeastern Ohio, no production has been reported from the Lower Devonian-Upper Silurian unconformity play. The Devonian and Silurian subcrops trend into southeastern Ohio; however, the Silurian Salina and Lockport dolomites are at shallow depths and the rock pressure is probably less than 25 psi, too low for economical production. The Devonian Onondaga and Helderberg limestones have the most potential, since they are deeper and should have higher rock pressure.

PLAY Sns: THE UPPER SILURIAN NEWBURG SANDSTONE PLAY

by Douglas G. Patchen, West Virginia Geological and Economic Survey

Location

The Upper Silurian Newburg sandstone (drillers' term) play created an extreme amount of interest and drilling in the Appalachian basin during the 1960s and early 1970s. The play was mainly confined to Boone, Jackson, Putnam, and Kanawha counties in West Virginia and Meigs County, Ohio (Figure Sns-1), although one small area of production was developed in Wirt County, West Virginia as well. Unsuccessful Newburg tests have been drilled in these and 10 surrounding counties in an attempt to extend this prolific play.

Production History

Although gas was discovered in the Newburg sandstone in Boone County, West Virginia, as early as 1939, the actual Newburg play began in 1964 when the first significant well was drilled in what is now Kanawha Forest field. This well, the Cities Service No. 14 Waller C. Hardy (West Virginia permit number Kanawha 1997) was a structural test located near the axis of the Warfield anticline. It tested 119 Mcf/d natural and was completed with an initial open flow of 7,838 Mcf/d after acid treatment. The rock pressure measured after four days was 2,070 psi. Production was from perforations (four shots per foot) through the entire 18-foot-thick Newburg interval.

The initial well was unusual in that the Newburg section was cored and logged and two drill stem tests were run prior to running 4.5-inch casing to total depth in the upper part of the McKenzie Formation. Information gained from this well, however, led to the rapid development of the field along the axis of the Warfield anticline during the next few years. By the end of the decade, the limits of the 16,000-acre field had been fully defined, and by 1973 more than 47 bcfg had been produced from the 46 field wells. In addition, seven other Newburg fields had been discovered in a narrow north-south trend from Boone County to Jackson County, West Virginia, and adjacent Meigs County, Ohio (Figure Sns-2). These fields included Rocky Fork and South Ripley, discovered in 1966; Cooper Creek and Wheaton Run, discovered in 1968; Groundhog Creek Northwest, discovered in 1969; and Groundhog Creek Southeast and North Ripley, discovered in 1970 (Figure Sns-2). Wheaton Run was a one-well oil field, one of only two oil producers in the play, but four gas wells have now been completed west of the discovery well, under the shallow Silverton field, and one gas well has been completed east of the oil well. The seven gas fields include approximately 300 productive wells that drain more than 70,000 acres. Cumulative production through 1973 was 290.4 bcf, or approximately 1 bcf per well. Even though the average well-head price was only 32 cents per Mcf when most of the wells went on line, these relatively shallow (5,500 foot) wells were so prolific that many paid out in only six to eight weeks.

Stratigraphy

The name Newburg was first used in Ohio (Stout and others, 1935) for the first porous zone below the Salina evaporite section that contained either gas or salt water. However, the stratigraphic position of this first zone of porosity is variable. Thus, the Ohio Newburg is either one or two zones (Second Newburg) in the upper part of the Lockport Dolomite that probably has no stratigraphic significance in Ohio (Ulteig, 1964). In the subsurface of West Virginia, however, the drillers' Newburg is a thin, white to gray, very fine- to fine-grained, well-sorted sandstone consisting mainly of rounded quartz grains. This sandstone is developed within Ulteig's (1964) Salina C zone (Haney, 1970; Patchen, 1971), a thin, shaly interval that can be traced across the basin from eastern West Virginia into central Ohio. In some areas, thin Salina A and B units can be correlated below the Newburg and above the top of the Lockport. However, in subsurface drilling terminology, the Newburg is usually defined as the thin sandstone that separates the Salina evaporites from the Lockport Dolomite (Figure Sns-3).

Early studies (Haught, 1959; 1960; Woodward, 1959; Overbey, 1961) resulted in the erroneous correlation of the Newburg with the Williamsport Sandstone (Reger, 1924) outcrops of Grant County, West Virginia. The Williamsport occurs throughout Mineral and Grant counties where it ranges in thickness from 8 to 50 feet, and averages about 20 feet. In this area, it can be described as a massive bedded, hard, very fine-grained, red, green, and brown sandstone containing the large ostracod Leperditia alta. This sandstone commonly is associated with green and occasionally red shales. Farther east, the Williamsport is considered to be a non-red tongue of the Bloomsburg Formation.

Farther to the south, in Pocahontas and Greenbrier counties, a thick white to brown sandstone is present between the McKenzie Limestone and the Wills Creek Shale. Price (1929) correlated this sandstone with the Bloomsburg, and Woodward (1941), noting the presence of Leperditia alta in the lower sandstone beds, identified the sandstone as Williamsport. Woodward also extended the name Williamsport even farther south, to Alvon in Greenbrier County, where 45 feet of fine-grained sandstone containing Leperditia alta are present.

Swartz and Swartz (1940) used the name Crabbottom Sandstone for a thick sandstone present between the Wills Creek Formation and McKenzie Limestone near Crabbottom, Highland County, Virginia. This sandstone does not resemble the Williamsport Sandstone of Grant and Mineral counties, but is identical to the sandstone occurring at the same stratigraphic position in Pocahontas and Greenbrier counties. However, Woodward (1941) pointed out that the older term Williamsport had priority and recommended that the name Crabbottom be abandoned. The assumption was, of course, that the Williamsport and Crabbottom were correlative in the eastern outcrop areas from Mineral County south to Greenbrier County. Although Patchen (1971) accepted the surface correlations as correct, he noted the distinct difference between the Williamsport Sandstone and the coarser-grained, more mature white sandstone to the south,

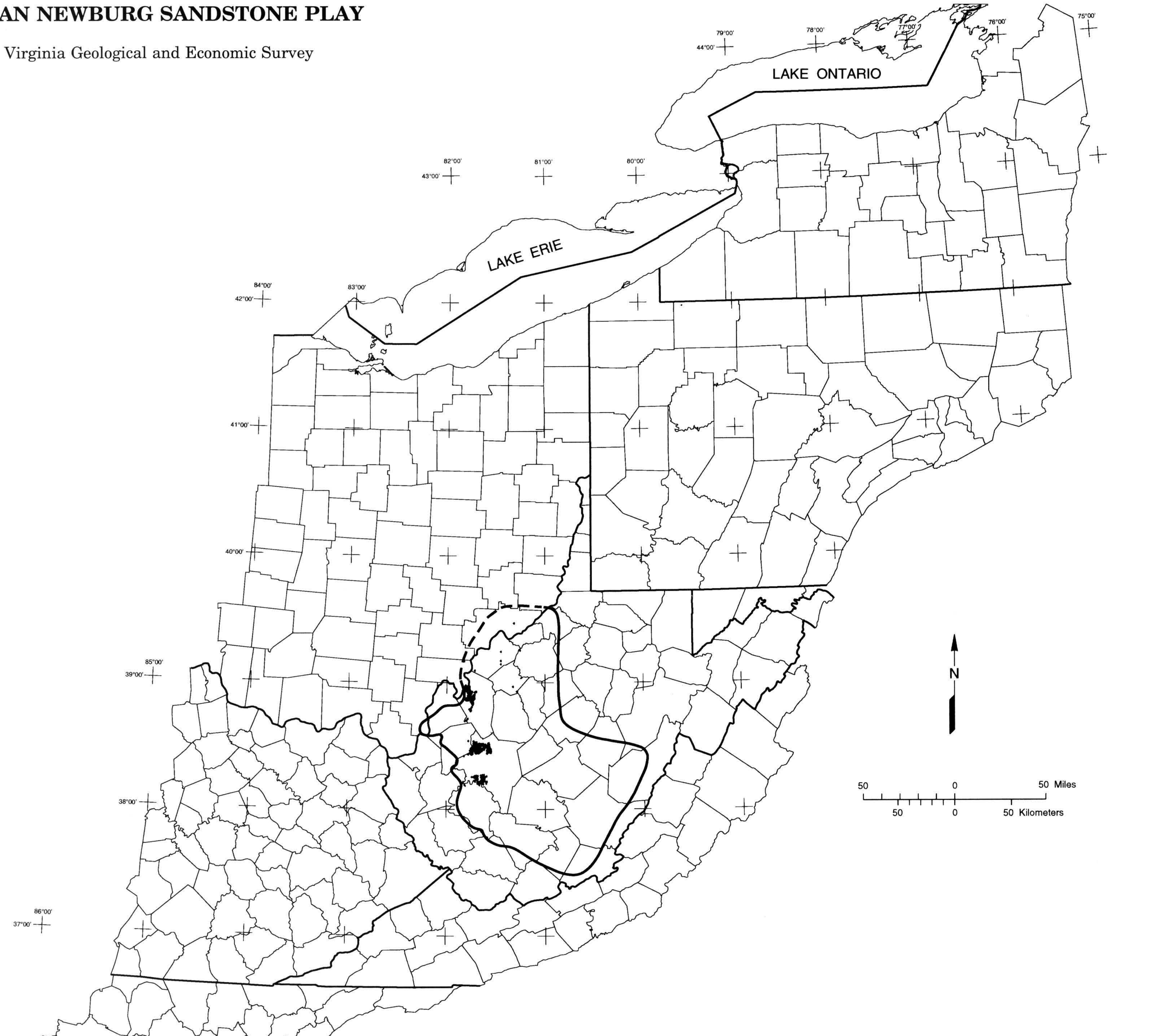


Figure Sns-1. Outline of the Upper Silurian Newburg sandstone gas play within the Appalachian basin, and the locations of gas fields (clusters) and individual gas wells (dots) within the play area. Geographic limits of the play are based on sandstone thickness and structural styles. Where dashed, play boundary is inferred.

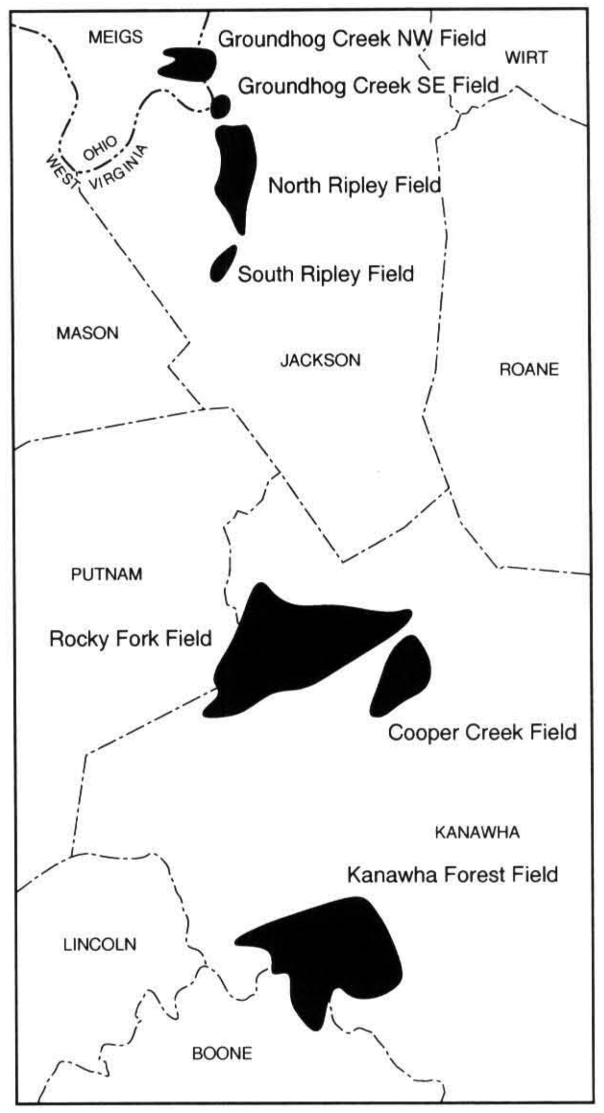


Figure Sns-2. Location of Newburg gas fields discussed in the text or listed in Table Sns-1. Other areas of production illustrated in Figure Sns-1 are not shown.

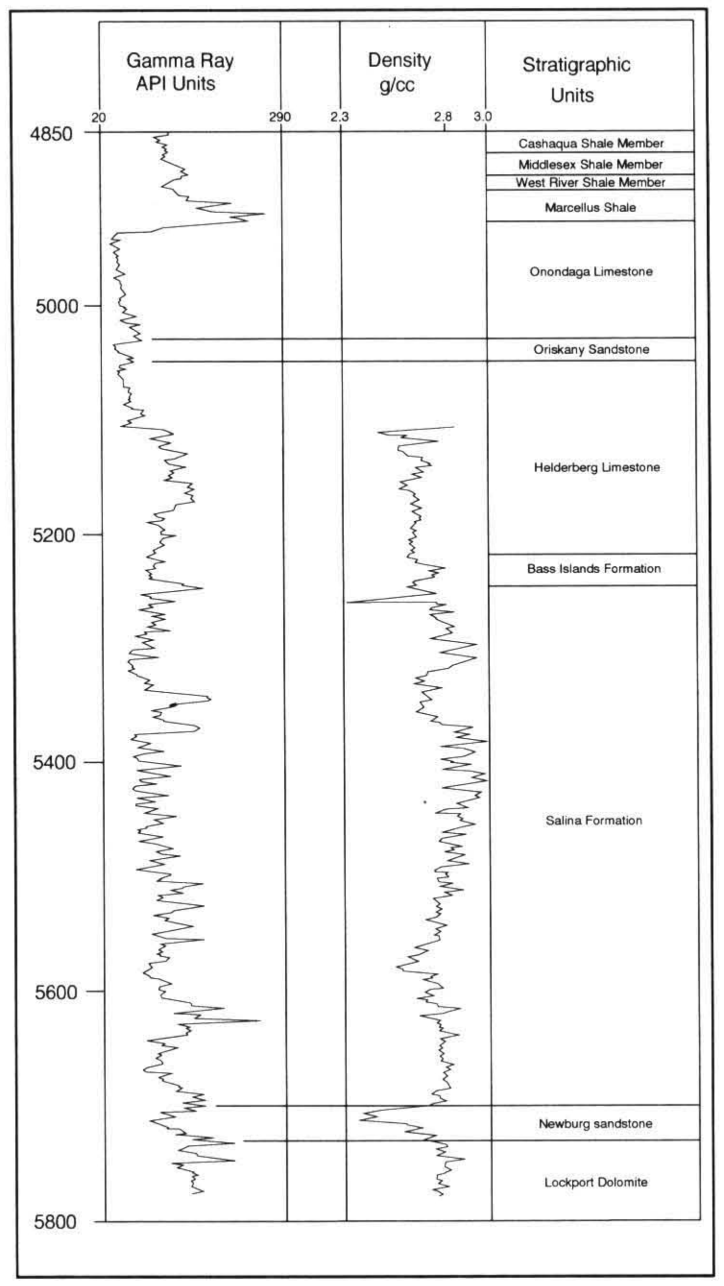


Figure Sns-3. Type logs (gamma-ray and density) through the Upper Silurian section showing the log character and stratigraphic relations of the Salina, Newburg and upper McKenzie (Lockport). The Newburg is developed within a shaly interval that correlates with the Salina "C" zone. Where it is productive, the Newburg is characterized by a thin porous interval near the top of the sandstone.

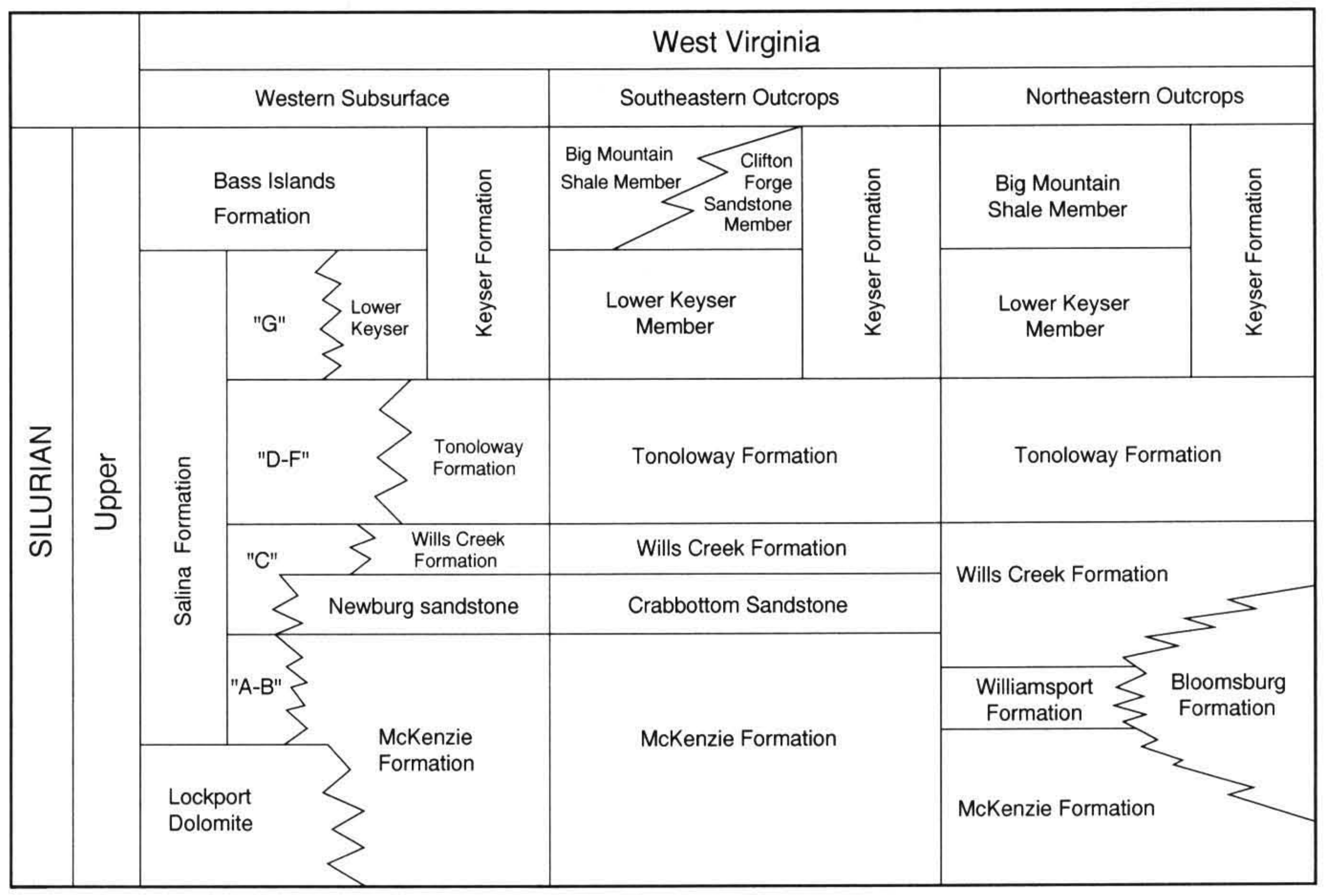
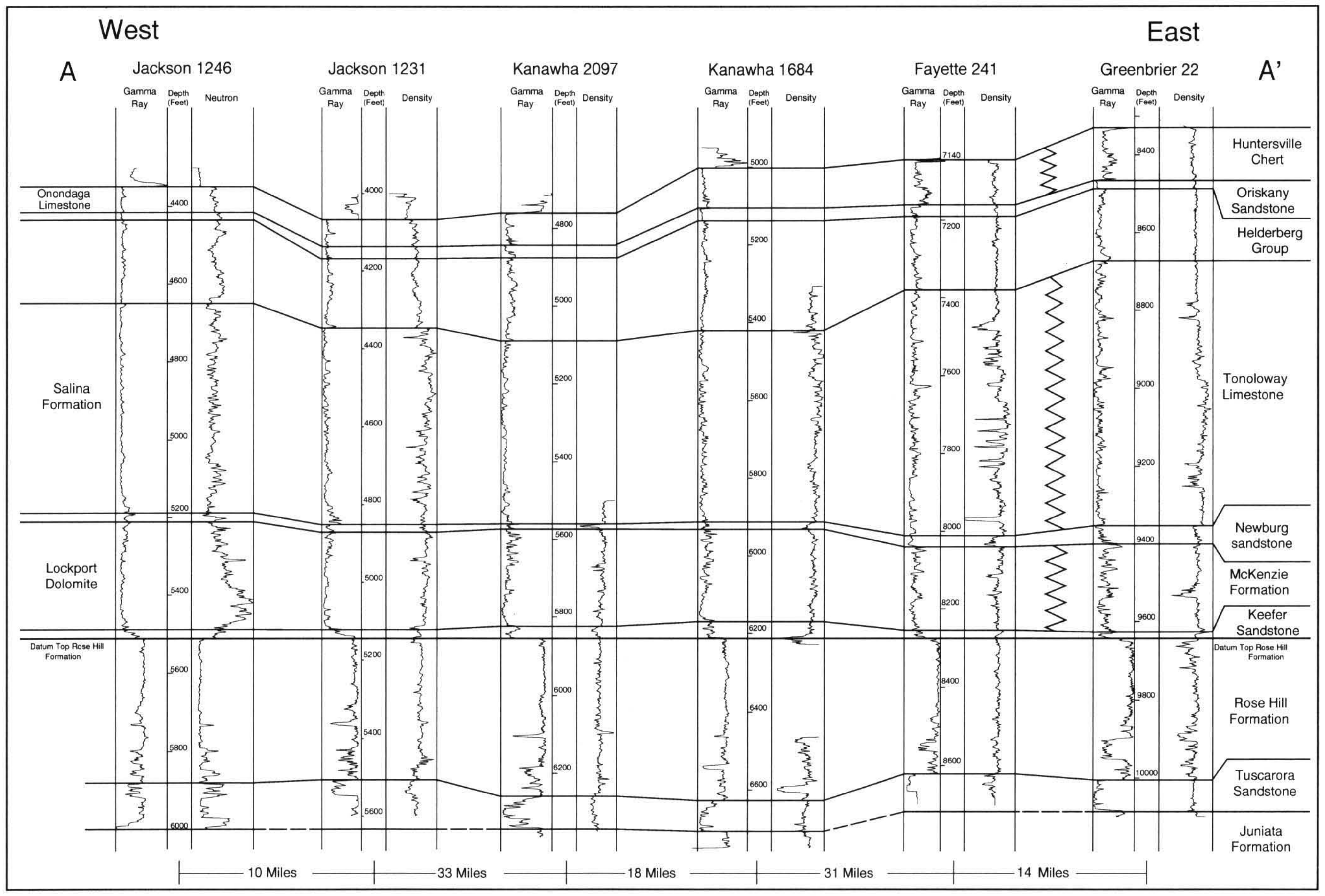


Figure Sns-4. Nomenclature used in outcrop and subsurface areas. In northeastern West Virginia outcrops, the name Williamsport is used to denote an argillaceous sandstone or siltstone above the McKenzie Formation. This unit can be traced into the near subsurface (Preston and Monongalia counties). In southeastern West Virginia outcrops, the name Crabbottom is preferred for a clean, fine-grained, slightly younger sandstone that can be traced into the subsurface of western West Virginia where it is referred to as the Newburg sandstone by drillers.



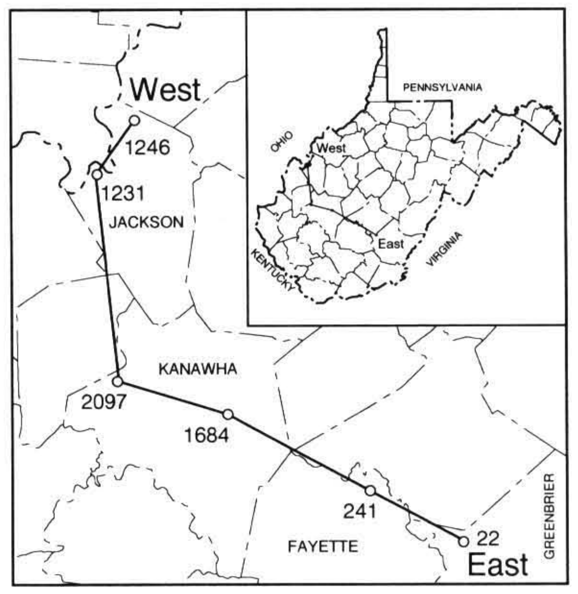


Figure Sns-5. Regional stratigraphic cross section A-A' of the interval from the top of the Huntersville Chert/Onondaga Limestone to the top of the Ordovician (Juniata Formation) illustrating the stratigraphic position of the Newburg sandstone.

and experienced difficulty in closing subsurface correlations from Greenbrier County westward to Kanawha and Jackson counties and then eastward to Williamsport outcrops. The change in log character from wells in the western subsurface to wells in the eastern counties of Preston and Tucker was attributed to the change in lithology from a clean, white sandstone to a brownish-gray, very fine sandstone to siltstone, and the correlation was accepted.

Later correlations, made when more geophysical and sample logs were available, revealed that the Newburg sandstone of the western subsurface did correlate with the white sandstone of outcrops in Greenbrier and Pocahontas counties, and with the Crabbottom Sandstone in Highland County, Virginia. However, it did not correlate with the Williamsport Sandstone outcrops of Grant and Mineral counties, or with a zone defined as Williamsport or Newburg in wells in Preston County (Smosna and others, 1977). This same conclusion was reached by Warner (1979) in a subsurface study, and by Patchen and others (1984) during the compilation of the Correlation of Stratigraphic Units of North America (COSUNA) project. It is suggested herein that the name Crabbottom Sandstone be revived and used as the surface correlative of the informal term Newburg sandstone used by drillers in the subsurface (Figure Sns-4).

As redefined, the Newburg sandstone of the drillers is a thin Upper Silurian sandstone developed near the base of the Salina Formation in the western subsurface of West Virginia that can be traced through sparse well control back to outcrops in Greenbrier and Pocahontas counties, West Virginia and Highland County, Virginia (Figure Sns-5). Its lateral correlative is the Crabbottom Sandstone in those outcrops. The sandstone pinches out into shales and carbonates of the Salina C zone in the subsurface west of the productive trend, and to the north and northeast in central West Virginia (Figure Sns-6).

Examination of cores taken in Boone, Kanawha, and Jackson counties suggests that the clean, well-sorted, well-rounded sandstone was deposited in high-energy, shallow-water environments, probably on a shallow sandstone shelf. The thin sheet sandstone probably developed as a result of reworking of several environments of deposition, including beach, shelf, submarine bar and, perhaps, barrier island (Figure Sns-7). Thickness patterns (Figure Sns-6) suggest that the sand was derived from a source area to the southeast and distributed westward across the basin in a relatively narrow trend that curved northward, around the basin center, in the productive area. This shift in depositional pattern may be due to northeastward-flowing currents (Patchen, 1971).

Both wind and wave action are thought to have had an effect on the deposition of the Newburg and associated rocks. Quartz grains in the upper part of the sandstone commonly are described as frosted. Also, during drilling, light green, dolomitic shales are encountered immediately above the sandstone and, in areas where the sandstone is poorly developed, large, well-rounded, frosted quartz grains are embedded in this green shale (R. Pryce, Carl E. Smith, Inc, written commun., 1993) that has replaced the Newburg. Furthermore, the effect of storm action is indicated by detailed mapping of sandstone thickness (R. Pryce, written commun., 1993) that suggests the presence of wash-over fans and perhaps both flood and ebb tidal deltas associated with sand bars. These ebb delta deposits may be responsible for the western, updip extension of productive sandstone in the Groundhog Creek Northwest field. The sand in this area could have been moved from the east, accounting for the poorly developed sandstone in the Silverton area of Jackson County west of Wheaton Run field (R. Pryce, written commun., 1993).

Structure

Regional structure mapped on top of the Newburg (Patchen, 1966; Cardwell, 1971) confirms the strong structural control on the location of gas fields in the Newburg, as well as the location of combination stratigraphic-structural traps (Figure Sns-8). The main structural features in the area are the Warfield anticline, underlying the Kanawha Forest field in Boone and Kanawha counties (Figure Sns-9); the so-called Sissonville high, underlying Rocky Fork field in Putnam and Kanawha counties (Figure Sns-10); and the Milliken anticline, underlying.Cooper Creek field in Kanawha County (Figure Sns-10).

Fields in Jackson County are developed on the regional dip that is down to the east. However, more detailed structural mapping (Cardwell, 1971) confirms the presence of minor structural noses beneath South Ripley and Groundhog Creek Northwest fields (Figure Sns-11). This subtle structure is responsible for the separation of South Ripley and North Ripley fields, and the two Groundhog Creek fields. Small anticlines also control Newburg gas accumulation in areas west and east of Wheaton Run field (Figure Sns-11).

Reservoir

The only structural trap in the Newburg play trend is the closed anticline that controls the location of Cooper Creek field in Kanawha County (Figure Sns-10). The field is nearly completely surrounded by a downdip gas-salt water contact. Salt water may or may not extend completely through the structural low on the north edge of the field that separates Cooper Creek from Rocky Fork field. Kanawha Forest, Rocky Fork, South Ripley, and Groundhog Creek Northwest fields are classified as combination stratigraphic-structural traps. Each is developed on a structural high and each field is bounded by a downdip gas-salt water contact. However, in each field the updip productive limit is due to thinning and eventual pinchout of permeable sandstone.

North Ripley and Groundhog Creek Southeast fields are classified as stratigraphic traps in which permeable sandstone pinches out updip to the west, although North Ripley does have downdip salt water at approximately -4,850 feet (Figure Sns-11). The small area of Newburg gas production under the shallow Silverton field west of Wheaton Run field (Figure Sns-11) is a combination stratigraphic-structural trap. Gas accumulated on a small anticlinal nose with updip (westward) production limited by tight sandstone. Wheaton Run also is developed on a small structure, but the productive limit has not yet been defined (Figure Sns-11). The small area of production known as the Sanoma field in Wirt County is associated with two minor structural noses (Cardwell, 1971), although Fenestermaker (1968) suggested that gas accumulation in that area had to be due, at least in part, to stratigraphic trapping. Fenestermaker reasoned that a porosity-permeability barrier must exist to separate the discovery well from water in updip wells.

Thick intervals of black, organic-rich shales occur in two parts of the stratigraphic section in the subsurface of West Virginia: the Upper and Middle Devonian shale section, and the Upper Ordovician Martinsburg-Reedsville section.

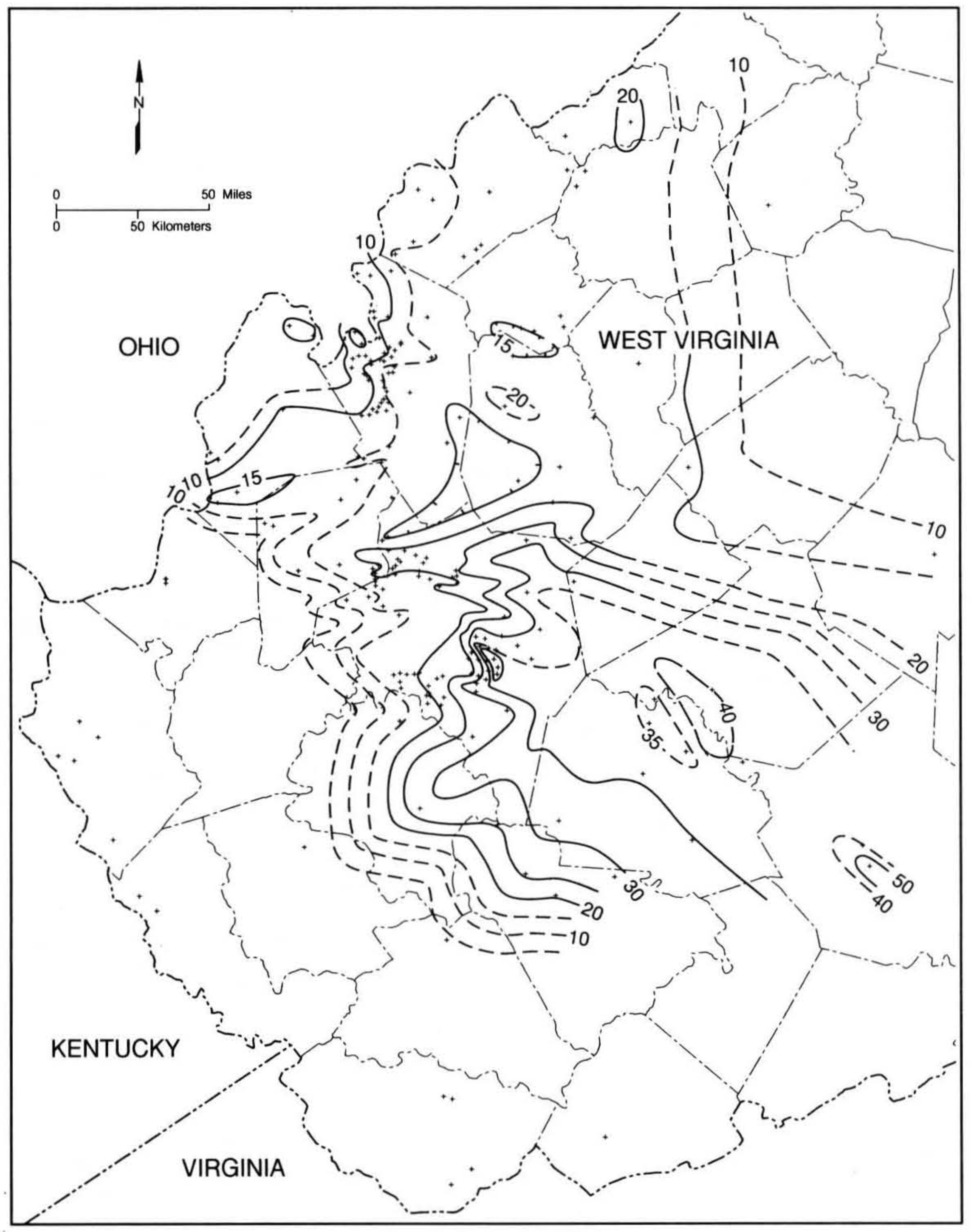


Figure Sns-6. Regional isopach map of the Newburg sandstone, based on data from gamma-ray logs. Thickness values are for the entire Newburg interval, not just the upper, clean sandstone in which porosity and good reservoir qualities are developed.

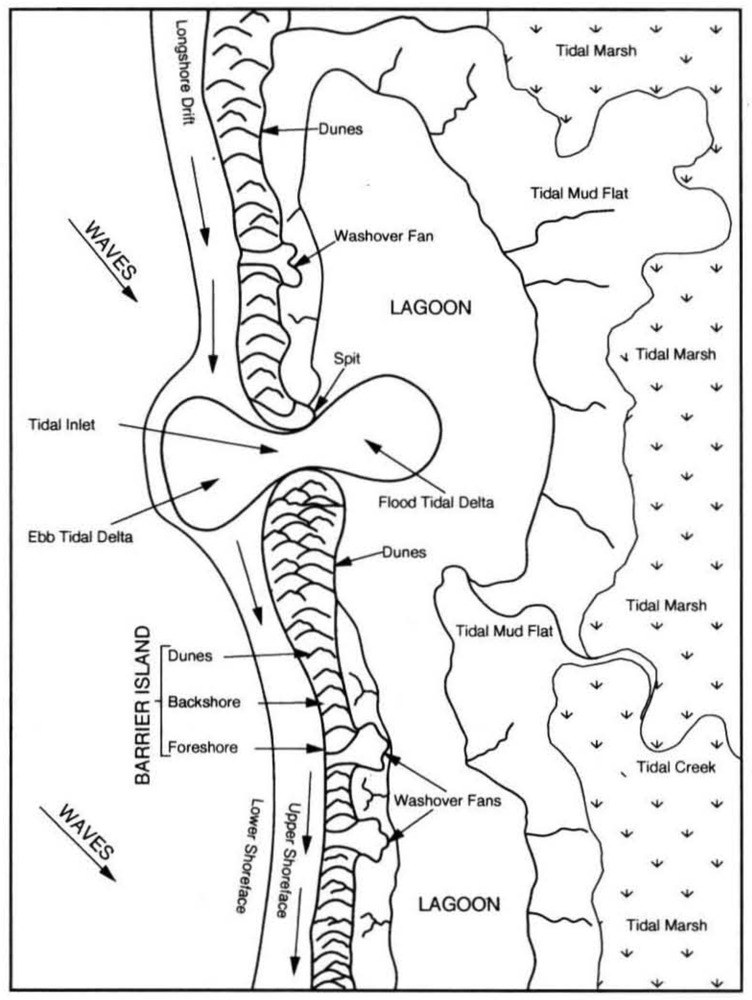


Figure Sns-7. Model for the depositional environments of the Newburg sandstone. Key elements are the barrier island setting, where wind and waves can create a well-rounded, well-sorted, supermature sandstone with frosted, windblown sand grains, and the ebb tidal delta that extends westward of the maximum extent of the barrier island sands.

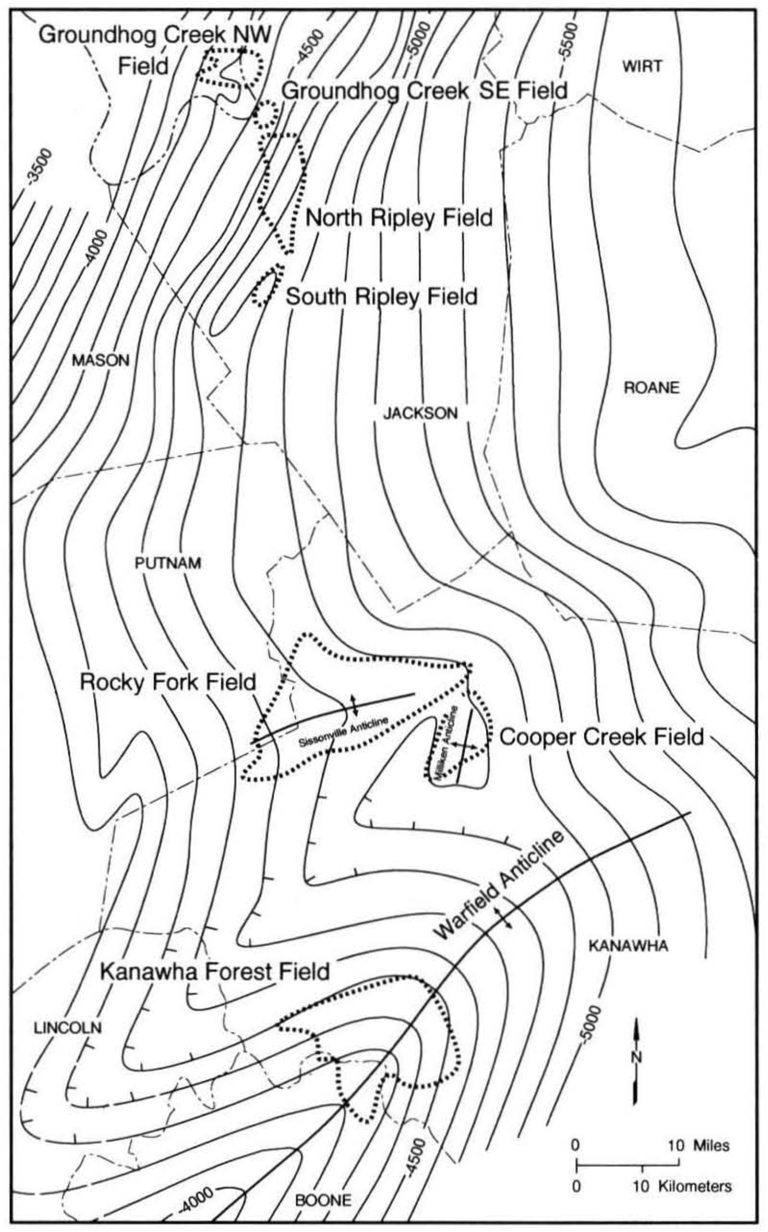


Figure Sns-8. Regional structure mapped on the top of the Newburg sandstone, and locations of Newburg gas fields. Locations of at least five of the seven gas fields are controlled by structure. With the exception of Cooper Creek field, updip loss of permeability is a second trapping mechanism. From Cardwell (1971). See Figure Sns-2 for location.

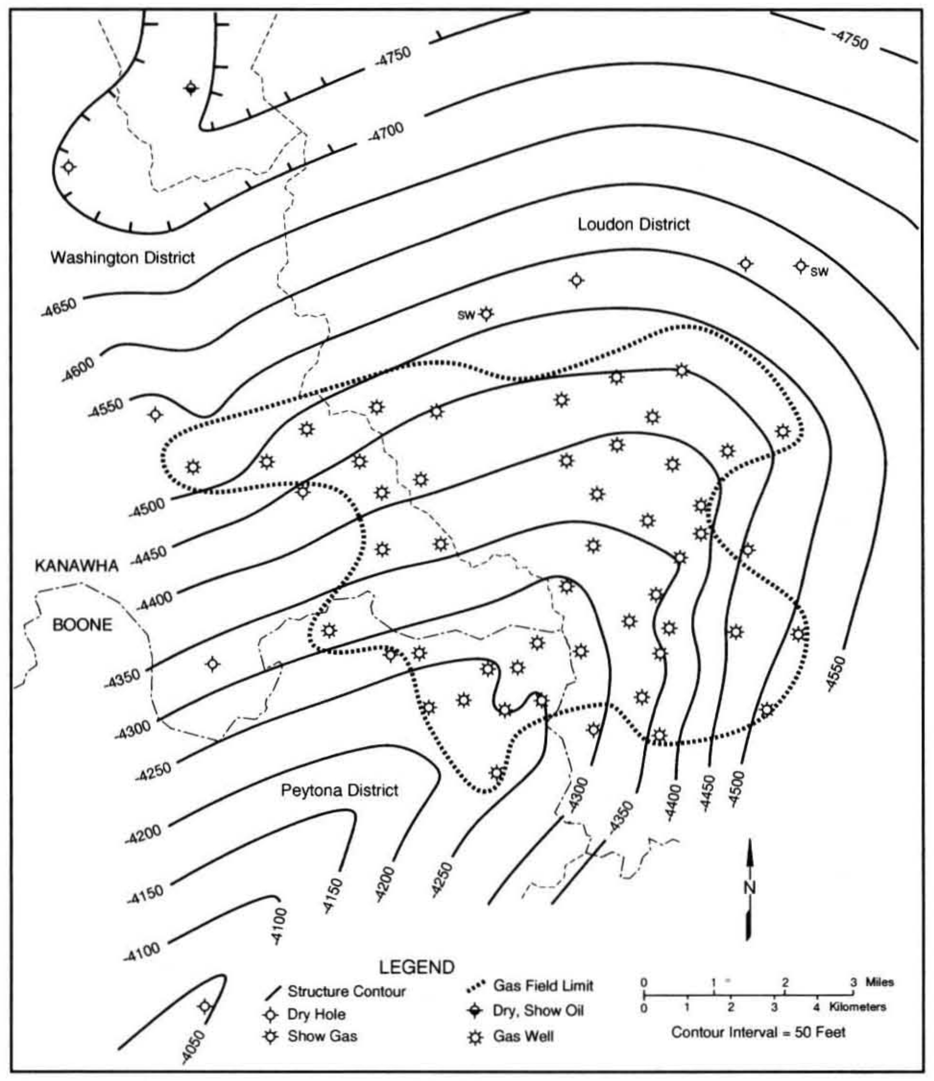


Figure Sns-9. Structure mapped on the Newburg sandstone in Kanawha Forest field illustrating the combination of structure and updip permeability pinchout as trapping mechanisms. Salt water was reported in a few downdip wells, and production is confined to areas higher than -4,525 feet subsea elevation. From Cardwell (1971). See Figure Sns-2 for location.

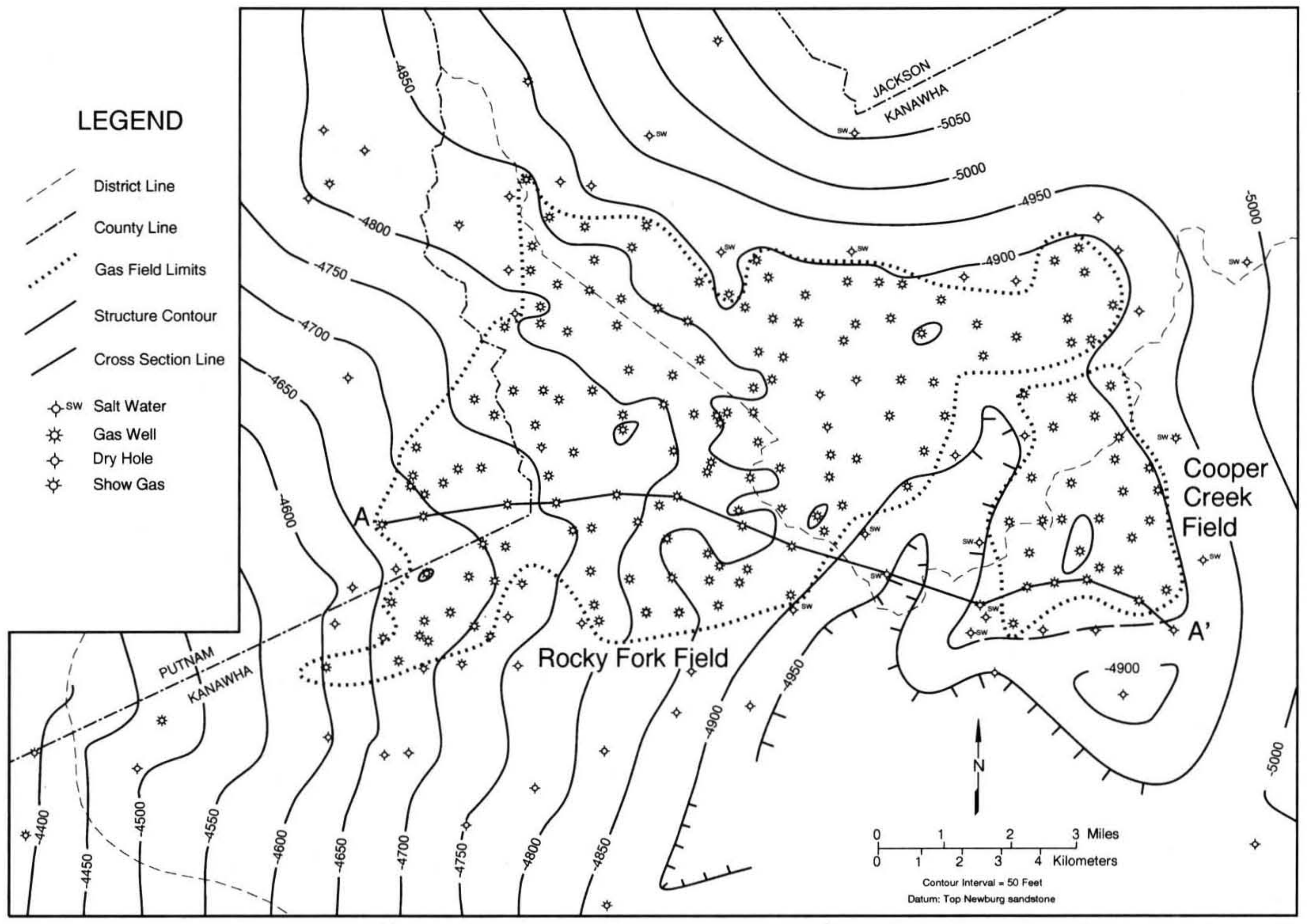


Figure Sns-10. Structure mapped on the Newburg sandstone in Rocky Fork and Cooper Creek fields. Cooper Creek is a structural trap with a salt water drive. A salt water drive also is present in Rocky Fork field, but updip production must be limited by a loss of permeability as the sandstone thins westward. The southern edge of the field also must be controlled by loss of porosity and permeability. From Cardwell (1971). Line of structural cross section A-A' (Figure Sns-18) is also shown. See Figure Sns-2 for location.

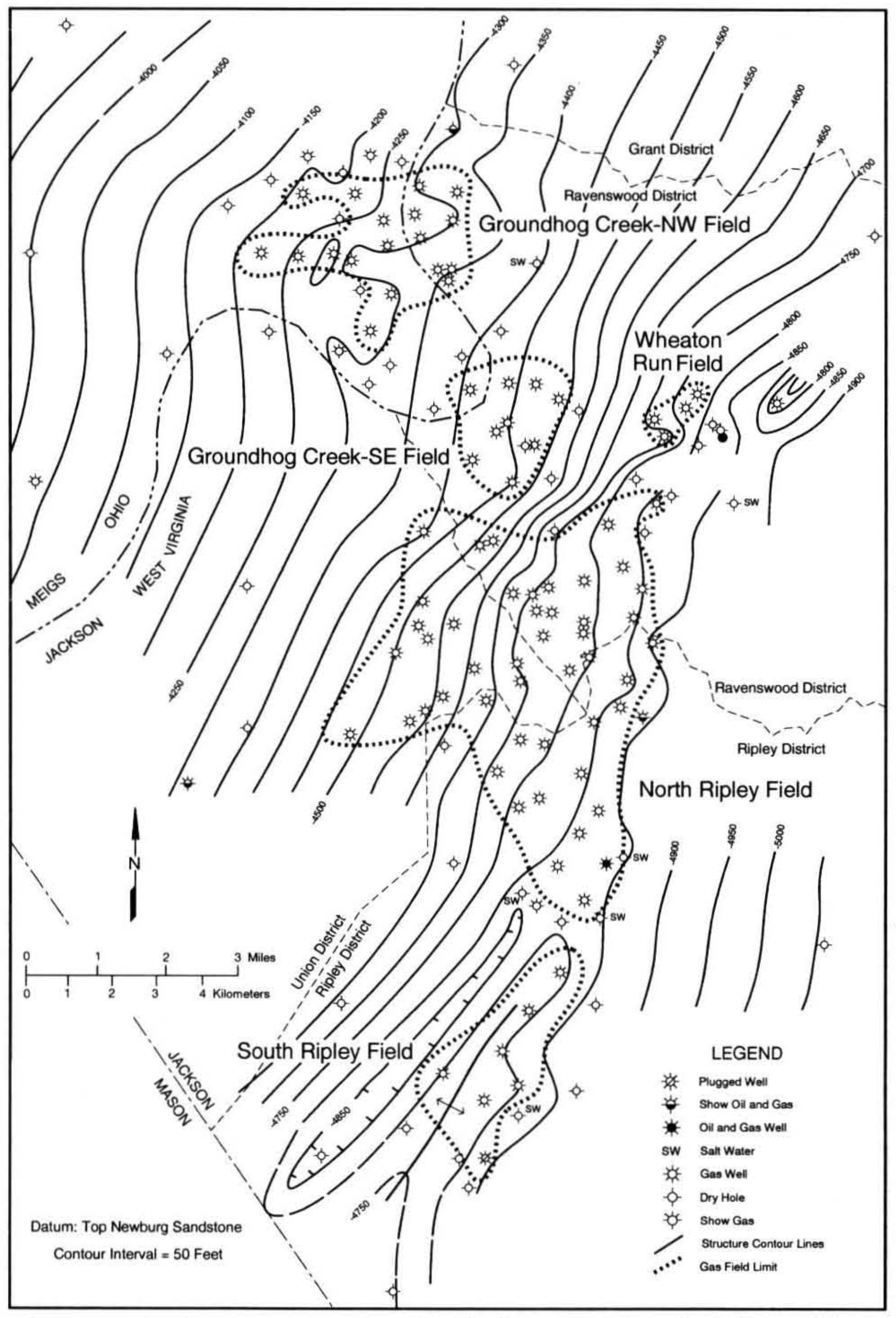


Figure Sns-11. Structure mapped on the Newburg sandstone in Jackson County, West Virginia. A small anticlinal nose is responsible for gas accumulation in South Ripley field, with salt water present to the east, north and west. Two smaller anticlinal noses are present in Groundhog Creek Northwest field. Groundhog Creek Southeast and North Ripley fields are stratigraphic traps, although a salt water drive is present in both fields. Modified from Cardwell (1971). See Figure Sns-2 for location.

Black shales in the Upper and Middle Devonian (Huron Member of the Ohio Shale, Rhinestreet Member of the West Falls Formation, Marcellus Shale) are known to be both source beds and reservoirs (Shumaker, 1978; Patchen and Hohn, 1993). The gas in the Newburg may have migrated from these shales. The theory is that because the Devonian clastic wedge thickens to the east, the weight of the increased section depressed the Silurian section more to the east than to the west, and eventually gas migration occurred horizontally from black shales in the east into the Newburg to the west.

Gas also could have migrated either horizontally from the east or vertically beneath the Newburg fields from the stratigraphically lower Martinsburg or Reedsville Shale. A thick, black shale unit within this section that correlates with the Utica Shale of New York (Wallace and Roen, 1989) may have been the source of gas now contained in both Tuscarora and Newburg reservoirs in the area. However, gas within the Tuscarara in Indian Creek field on the Warfield anticline is high in carbon dioxide, whereas the gas in the Newburg has a higher Btu content. Thus, the Newburg gas may have migrated from a different source.

The Newburg reservoir in Jackson County fields ranges in depth from 4,800 feet on the west to 5,800 feet on the east. Average drilling depths within these fields are 4,875 feet in the Groundhog Creek fields, 5,500 feet in North Ripley, and 5,650 feet in South Ripley (Table Sns-1). To the south in Kanawha County, the average depth to the Newburg is 5,400 feet in Rocky Fork field, comparable to the average depth of 5,350 feet in Kanawha Forest field, whereas eastward in Cooper Creek field the average depth increases to 5,650 feet.

Examination of cores from several Newburg fields, thin sections made from these cores, and numerous density-porosity logs confirms that the pay zone within the Newburg sandstone is usually a thin (3 to 10 feet) interval near the top of the unit (Figure Sns-12). In general, the average pay thickness is less in fields that were developed farther to the west, and greater in fields that are downdip to the east (Table Sns-1). Pay thickness also decreases to the southwest along the axis of the Warfield anticline, and westward along the axis of the Sissonville high. The thickest average pay zone is in Kanawha Forest field (8 feet) and the thinnest in Groundhog Creek Northwest field (3 feet).

The thickness of the Newburg sandstone as reported by drillers and entered into the West Virginia Geological and Economic Survey's oil and gas database ranges from 0 to 49 feet in Kanawha County, but thicknesses of more than 30 feet are rare. The sandstone is best developed in Kanawha Forest field where the average well penetrated 20 feet of sandstone. In Rocky Fork field, the sandstone thins noticeably to the west, and the average well penetrated only 15 feet of sandstone. The Newburg thickens eastward into Cooper Creek field where the average thickness is 18 feet.

The Newburg thins northward throughout the productive trend, and reported thicknesses in excess of 20 feet are rare in Jackson County; the range in reported thicknesses is 5 to 19 feet. The thickest intervals are usually in downdip wells that are dry or contain salt water. The combined average thickness for all five Jackson County fields is 12 feet of sandstone. The Newburg continues to thin

TABLE Sns-1

		Kanawha Forest WV	Rocky Fork WV	Cooper Creek WV	South Ripley WV	North Ripley WV	Groundhog Creek NW WV	Groundhog Creek SE WV
BASIC RESERVOIR DATA	POOL NUMBER	47305535	47312535	47331535	47311535	47342535	47337535	
	DISCOVERED	1964	1966	1968	1966	1970	1969	1970
	DEPTH TO TOP RESERVOIR	5,430	5,575	5,690	5,575	5,530	4,945	5,030
	AGE OF RESERVOIR	Late Silurian	Late Silurian	Late Silurian	Late Silurian	Late Silurian	Late Silurian	Late Silurian
	FORMATION	Salina	Salina	Salina	Salina	Salina	Salina	Salina
	PRODUCING RESERVOIR	Newburg	Newburg	Newburg	Newburg	Newburg	Newburg	Newburg
	LITHOLOGY	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone
	TRAP TYPE	combination	combination	structural	combination	stratigraphic	combination	stratigraphic
	DEPOSITIONAL ENVIRONMENT	shallow shelf	shallow shelf	shallow shelf	shallow shelf	shallow shelf	shallow shelf	shallow shelf
	DISCOVERY WELL IP (Mcf)	7,838	63,000	7,100	6,782	22,000	6,200	10,000
	DRIVE MECHANISM	salt water	salt water	salt water	salt water	salt water	salt water	salt water
	NO. PRODUCING WELLS	38	99	2	3	29	2	0
	NO. ABANDONED WELLS	9	37	28	5	48	6	9
	AREA (acreage)	16,000	32,800	6,000	2,200	12,000	2,900	1,600
	OLDEST FORMATION PENETRATED	Juniata	Juniata	Juniata	McKenzie	Juniata	Juniata	Juniata
	EXPECTED HETEROGENEITY DUE TO:	stratigraphy diagenesis	stratigraphy diagenesis	stratigraphy diagenesis	structure stratigraphy diagenesis	structure stratigraphy diagenesis	structure stratigraphy diagenesis	structure stratigraphy diagenesis
RESERVOIR PARAMETERS	AVERAGE PAY THICKNESS (ft.)	8	5	6	4	7	3	4
	AVERAGE COMPLETION THICKNESS (ft.)							
	AVERAGE POROSITY-LOG (%)	11	18	15	8	14	11	11
	MINIMUM POROSITY-LOG (%)							
	MAXIMUM POROSITY-LOG (%)							
	NO. DATA POINTS	39	56	15	10	30	5	1
	POROSITY FEET	0.88	0.90	0.90	0.32	0.98	0.33	0.44
	RESERVOIR TEMPERATURE (°F)	130	130	130	130	130	130	130
	INITIAL RESERVOIR PRESSURE (psi)	2,070	2,240	2,260	2,180	2,145	2,110	
	PRODUCING INTERVAL DEPTHS (ft.)	4,940-5,940	5,220-6,000	5,560-6,150	5,400-5,700	5,010-5,780	4,800-5,300	5,000-5,300
	PRESENT RESERVOIR PRESSURE (psi) / DATE							
FLUID & GAS PROPERTIES	Rw (Ωm)							
	GAS GRAVITY (g/cc)	0.602			0.615	0.648	0.642	
	GAS SATURATION (%)	84						
	WATER SATURATION (%)	16						
	COMMINGLED							
	ASSOCIATED OR NONASSOCIATED	nonassociated	nonassociated	nonassociated	associated	associated	nonassociated	nonassociated
	Btu/scf	1,064			1,060	1,134	1,108	
VOLUMETRIC DATA	STATUS (producing, abandoned, storage)	producing	producing	abandoned	producing/ abandoned	producing/ abandoned	abandoned	abandoned
	ORIGINAL GAS IN PLACE (Mcf)	59,320,000	160,170,000	21,274,000	107,646,000		14,750,000	
	ORIGINAL GAS RESERVES (Mcf)	53,388,000	144,153,000	19,147,000	96,881,000		13,280,000	
	PRODUCTION YEARS	1964-1973	1966-1973	1968-1973	1966-1973	1970-1973	1969-1973	1970-1973
	REPORTED CUMULATIVE PRODUCTION (Mcf)	49,185,000	136,451,000	17,752,000	86,654,000 combined	86,654,000 combined	10,177,000 combined	
	NO. WELLS REPORTED							
	ESTIMATED CUMULATIVE PRODUCTION (Mcf)							
	REMAINING GAS IN PLACE (Mcf)/DATE	10,135,000	23,719,000	3,522,000	20,992,000		4,573,000	
	REMAINING GAS RESERVES (Mcf)/DATE	4,203,000	7,702,000	1,395,000	10,227,000		3,103,000	
	RECOVERY FACTOR (%)	90	90	90	90	90	90	90
	INITIAL OPEN FLOW (Mcf/d)	1,294	12,866	13,464	1,113	12,393	8,008	10,392
	FINAL OPEN FLOW (Mcf/d)	5,845	31,012	38,852	5,594	40,464	10,242	20,857

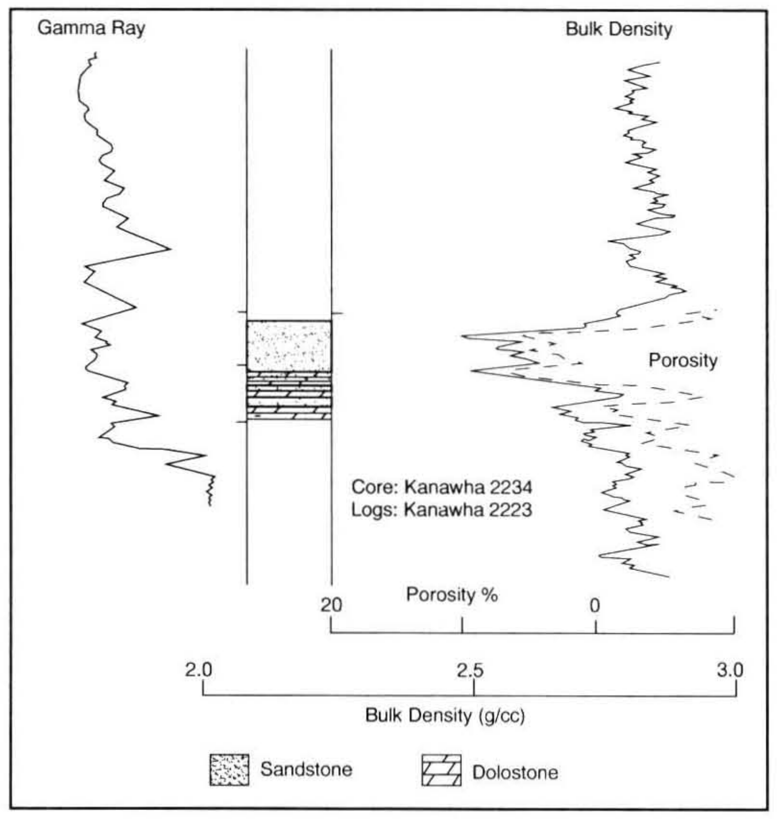


Figure Sns-12. Gamma-ray, bulk density, and porosity logs for Rocky Fork field. Logs are correlated to a core from a nearby well. Porosity is developed in the upper portion of the Newburg, but not in the lower portion where dolomite is interbedded with thin beds of sandstone. These logs are typical of wells in all Newburg fields.

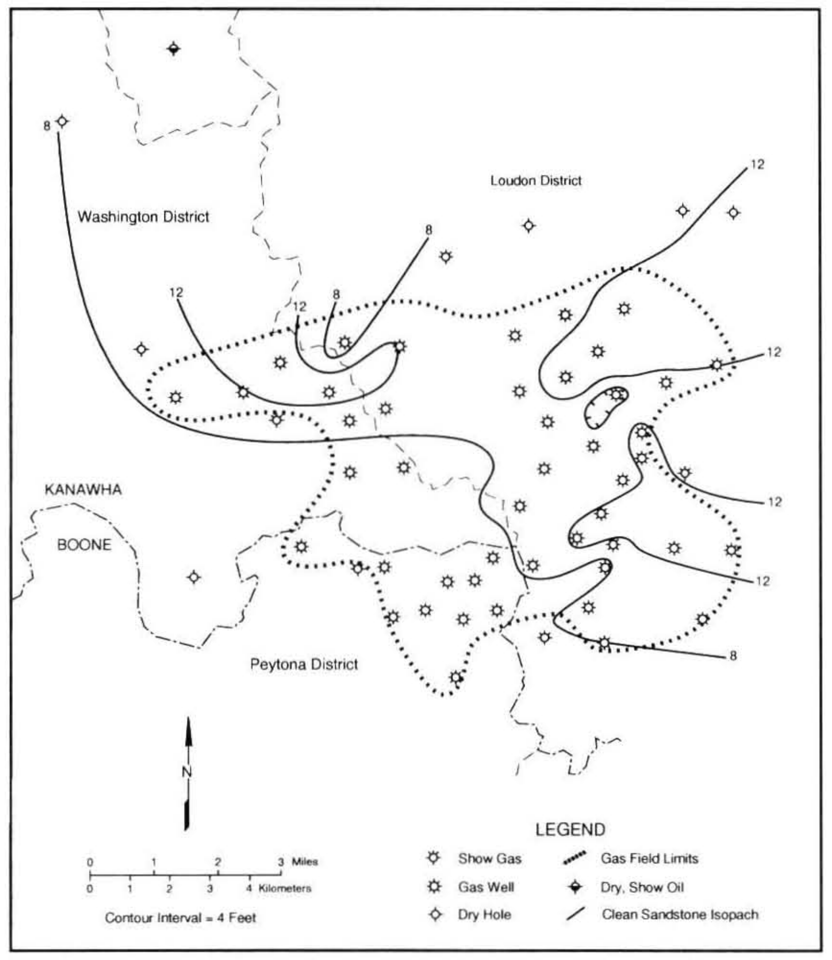


Figure Sns-14. Thickness of the upper, clean sandstone in Kanawha Forest field. Thickness values (from Cardwell, 1971) were interpreted from gamma-ray logs. See Figure Sns-2 for location.

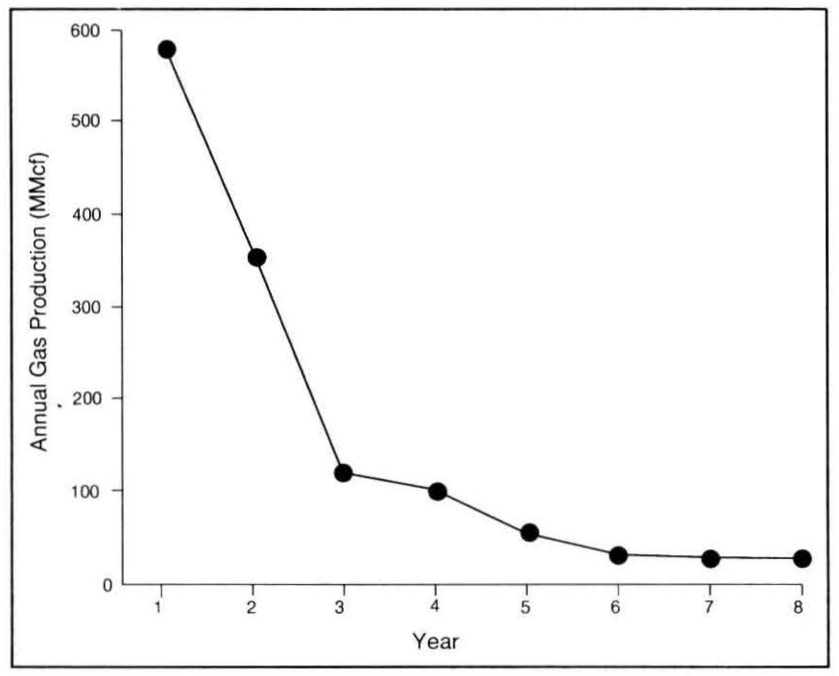


Figure Sns-13a. Typical production decline curve for the Newburg play. The decline curve is an average using data from 34 wells in year one but only 18 by year eight. Sixteen wells were abandoned before producing for eight years.

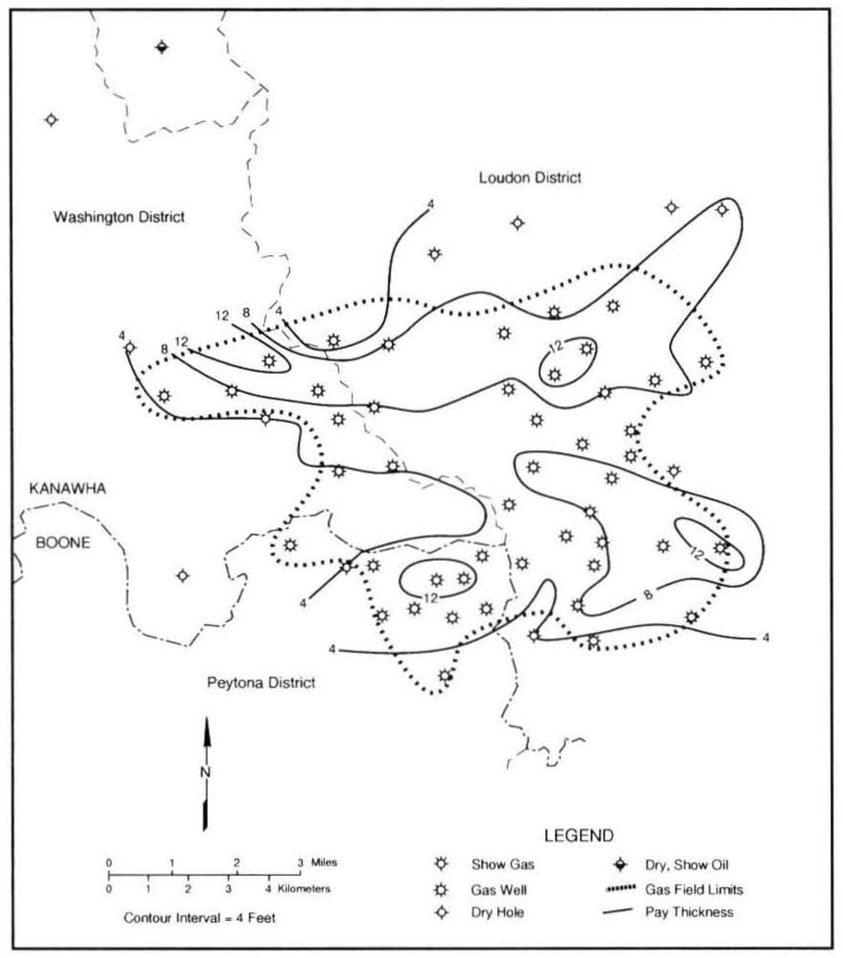


Figure Sns-15. Thickness of the distinctive uppermost porosity zone (illustrated in Figure Sns-12) for the Newburg sandstone in Kanawha Forest field. Thickness values (from Cardwell, 1971) were interpreted from porosity logs, but no porosity cutoff value was given. See Figure Sns-2 for location.

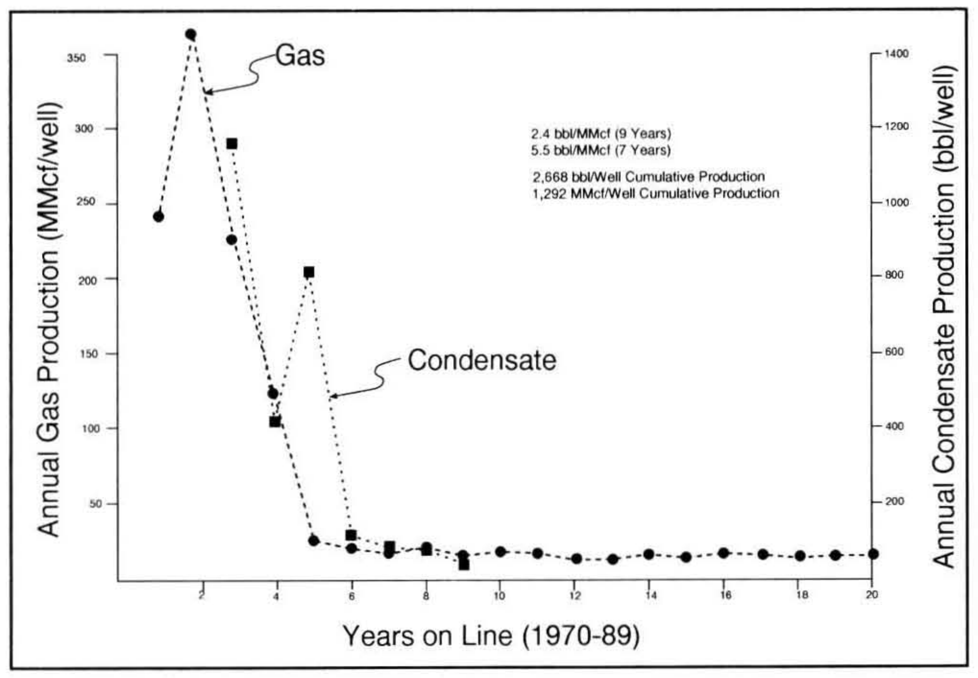


Figure Sns-13b. Data from a single company were used to plot production decline over a longer well life, and to compare the production of condensate to gas production. All wells in the data set produced only gas the first two years but began producing condensate during the third year.

northward into Meigs County, Ohio, where the average thickness reported by drillers is only 6 feet.

Production occurs where at least 8 to 10 feet of clean sandstone are developed, although thinner intervals have been productive in a few wells in Rocky Fork field (4 feet minimum), Cooper Creek field (6 feet minimum), and both Groundhog Creek fields (5 feet minimum). Production occurs in Kanawha Forest field where sandstone thickness ranges from 13 to 28 feet; in Rocky Fork where thickness ranges from 4 to 29 feet; and in Cooper Creek where sandstone thickness ranges from 6 to 28 feet. In the extension of Groundhog Creek Northwest field into Meigs County, Ohio, the sandstone is poorly developed and the success rate of development wells was only one in three. The successful wells encountered between 4 and 14 feet of sandstone, whereas only three unsuccessful wells encountered more than 10 feet of sandstone, and 17 encountered less than 10 feet. The Newburg was not recognized in several of these wells. Thus, sandstone thickness, particularly the decrease in thickness westward and northward within the trend, is a second factor that controlled production within the Newburg play.

Appalachian basin reservoirs commonly are slightly underpressured relative to their depths, but the Newburg is an exception. Rock pressures reported by drillers usually exceed 2,000 psi in all fields. Average field pressures (Table Sns-1) range from 2,070 psi in Kanawha Forest field to 2,260 psi in Cooper Creek field. The pressure to depth ratios range from 0.379 psi/foot in North Ripley field to 0.433 in Groundhog Creek (combined) field. Plots of rock pressure versus open flows indicate that, in general, lower rock pressures correlate with higher calculated open flows of Newburg wells. However, wells with higher rock pressure had higher cumulative production than wells with lower pressure.

The Newburg play was characterized by the largest open flows ever reported in West Virginia, both for natural completions and completions following stimulation. Natural flows as high as 63 MMcf/d were reported, with natural flows greater than 1 MMcf/d common. The reservoir responded well to stimulation, and the average well was improved by more than 100 percent following fracturing. Final open flows as high as 168 MMcf/d were reported, with five wells testing more than 100 MMcf/d, and more than 50 wells testing at least 50 MMcf/d. The average per well IP in Cooper Creek field exceeded 33 MMcf/d, and the average per well IP in North Ripley field exceeded 40 MMcf/d (Table Sns-1).

Newburg wells were characterized by high initial production that declined rapidly during the first three years before production stabilized (Figure Sns-13a). Most Newburg wells produced less than 10 years, with six or seven years the norm. This type of production profile suggests a reservoir with high permeability and good porosity, leading to rapid production, high recovery, and short payback time.

In much of the play, gas is associated with condensate. Although production records are not available to calculate a precise ratio throughout the productive trend, some operators estimated that they produced six barrels of condensate per MMcfg. Data for five wells that began producing condensate in their third year of production and produced both gas and condensate for the next seven years were used to plot decline curves (Figure Sns-13b). Over this seven-year period, 5.5 barrels of condensate were produced for each MMcfg produced. If the higher gas volumes for the first two years are added before calculating the ratio, then only 2.4 barrels of condensate were produced for each MMcfg produced over the initial nine years.

Estimates of porosity for Newburg fields (Table Sns-1) may be quite conservative. In the better wells, no log or core porosity values are available, especially for wells drilled with air rotary. Natural open flows in these wells were so high that the reservoir sandstone literally blew out of the hole with the gas, creating a "sand storm" at the surface and enlarging the hole through the pay (P. Brown, oral commun., 1993). Large flows in the best wells actually raised the drill bit, which then fell 5 to 10 feet through the pay zone. The best wells could not be logged, and in several cases they could not be cored, either. Attempts to core the pay zone failed because the sandstone came apart due to its high friability. Samples retrieved from these zones resembled disaggregated sand, and contained coarser grains than the more well-cemented zones that could be cored. Thus, in the best wells there was too much gas and porosities were too high to log or core with air, or even to core with mud. If drillers went to mud before
log or core with air, or even to core with mud. If drillers went to mud before
drilling into the pay zone, however, good logs could be obtained. In the final analysis, many of the best wells are not included in the data set used to generate an average value for field porosity, yielding a conservative estimate of porosity from this prolific pay zone.

Description of Key Fields

Kanawha Forest field: Kanawha Forest field is a combination stratigraphic-structural trap on the Warfield anticline in southwestern Kanawha County and adjacent Boone County (Figure Sns-9). Salt water is present downdip at approximately -4,525 feet. Production to the southwest, up the axis of the anticline, is limited by a decrease in effective sandstone and pay zone thickness. Clean sandstone, as determined from gamma-ray and bulk density logs (Cardwell, 1971) ranges from 6 to 15 feet within the field and decreases to the southwest (Figure Sns-14). The thickness of the porous zone within this sandstone ranges from 3 to 15 feet within the field, although most wells are in the 6- to 10-foot range (Figure Sns-15). Three areas have been mapped where both effective sandstone and porous sandstone thickness increase (Figures Sns-14, Sns-15). Areas of high IP (Figure Sns-16) correlate with all three areas and with structural position. IPs tend to be highest in downdip wells (Figures Sns-9, Sns-16).

Forty-six productive wells have been drilled within the 16,000 acres that define the field. From 1964 to 1973, these 46 wells produced more than 47 bcf (Cardwell, 1971) from a thin (8 feet) pay zone at the top of the Newburg. The average porosity of the pay zone is 11 percent.

Although natural flows as high as 4,408 Mcf/d were measured and the average natural flow was 1,294 Mcf/d, most wells were stimulated by fracturing a thin perforated interval. Seven wells were acidized, and one of these was later fractured. Stimulation increased the average final open flow to 5,845 Mcf/d. Wells within the field vary dramatically in production performance. At the low end, data on United Fuel's No. 3969 (Kanawha 2048) indicate cumulative production of less than 200 MMcf after nearly nine years on line. At the other extreme, United Fuel's No. 5252 (Kanawha 1018-D) produced more than 5 bcf in 10 years. This latter well was a good producer for its first five years (4.6 bcf produced), and then the cumulative production curve flattened. The well was an oddity in that peak annual production occurred in the third year. Newburg wells in the field typically decline rapidly from the first to third year and then tend to flatten in performance at low rates. The average recovery factor for wells in this field exceeded 90 percent.

Reservoir heterogeneity within Kanawha Forest field is indicated by the high variability in initial open flows and cumulative production. Heterogeneity due to minor structural variations on the Warfield anticline is assumed to be low, with variations in sandstone thickness and diagenetic effects more significant. Examination of two cores in the field, and thin sections from the cores, indicates that the Newburg is a fine- to very fine-grained quartz arenite with rounded and subrounded grains. Cements are predominantly quartz and calcite with some anhydrite near the top. The amount of calcite cement increases downward with quartz and anhydrite more common in the pay zone (Figure Sns-17). Zones with predominantly carbonate cement have very poor porosity, whereas zones with little or no carbonate cement have porosity. In the pay zones, quartz cement is greater than calcite cement, and porosity increases or decreases inversely to the amounts of quartz cement.

Rocky Fork and Cooper Creek fields: Rocky Fork field is the largest of the Newburg fields, occupying an area of nearly 33,000 acres (Table Sns-1). It is separated from the smaller Cooper Creek field (6,000 acres) to the east by a narrow salt water leg in a structural low (Figures Sns-10, Sns-18). Rocky Fork is developed on the broad structural high known informally as the Sissonville high, and Cooper Creek is developed on the Milliken anticline. The updip (westward) limit of production in Rocky Fork field is controlled by thinning and an apparent loss of porosity and permeability. Downdip, salt water is present along the northern edge of Rocky Fork field at an approximate subsea elevation of -4,900 feet and continues around the eastern edge of Cooper Creek at this same elevation. A subtle structural low on the south edge of the productive area separates the two fields and contains salt water at the -4,900 foot level (Figure Sns-10).

The average thickness of net clean sandstone within these fields is 7 feet in Rocky Fork and 8 feet in Cooper Creek. The average thickness of the porous pay zone developed in the top of this clean sandstone is 5 feet in Rocky Fork and 6 feet in Cooper Creek. In general, thickness of clean sandstone tends to increase from west to east, although narrow elongated areas of thicker sandstone extend

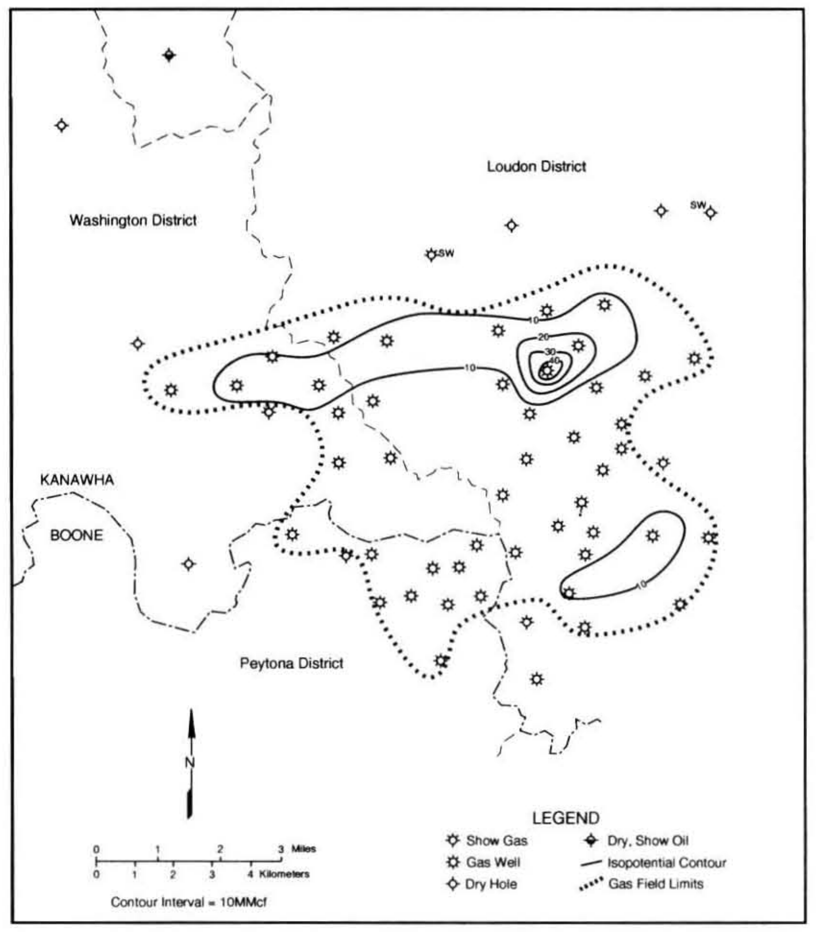


Figure Sns-16. Distribution of final open flow values in Kanawha Forest field. Values (from Cardwell, 1971) are post-stimulation for wells that were treated. Natural open flow values were used for unstimulated wells. See Figure Sns-2 for location.

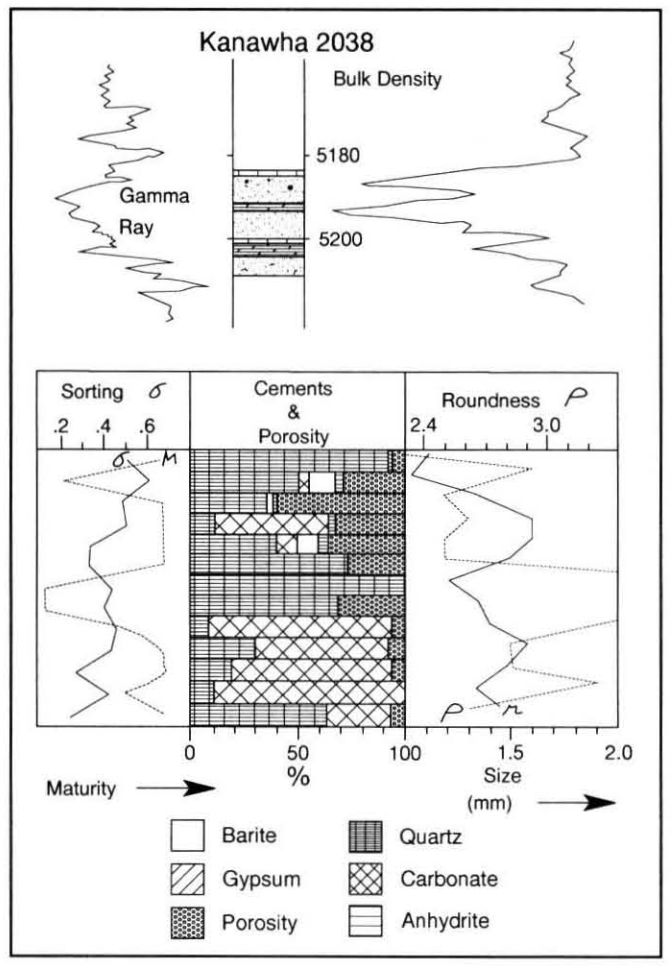


Figure Sns-17. Distribution of cements and porosity in a Newburg core from a well (Kanawha 2038) in Kanawha Forest field correlated with other textural parameters, including size, sorting, and roundness of sand grains, and maturity of the sandstone. Porosity is highest in zones with quartz cement and minor amounts of anhydrite and barite cement. Porosity is lowest in zones with predominantly carbonate cement and no evaporite cements. From Patchen (1971).

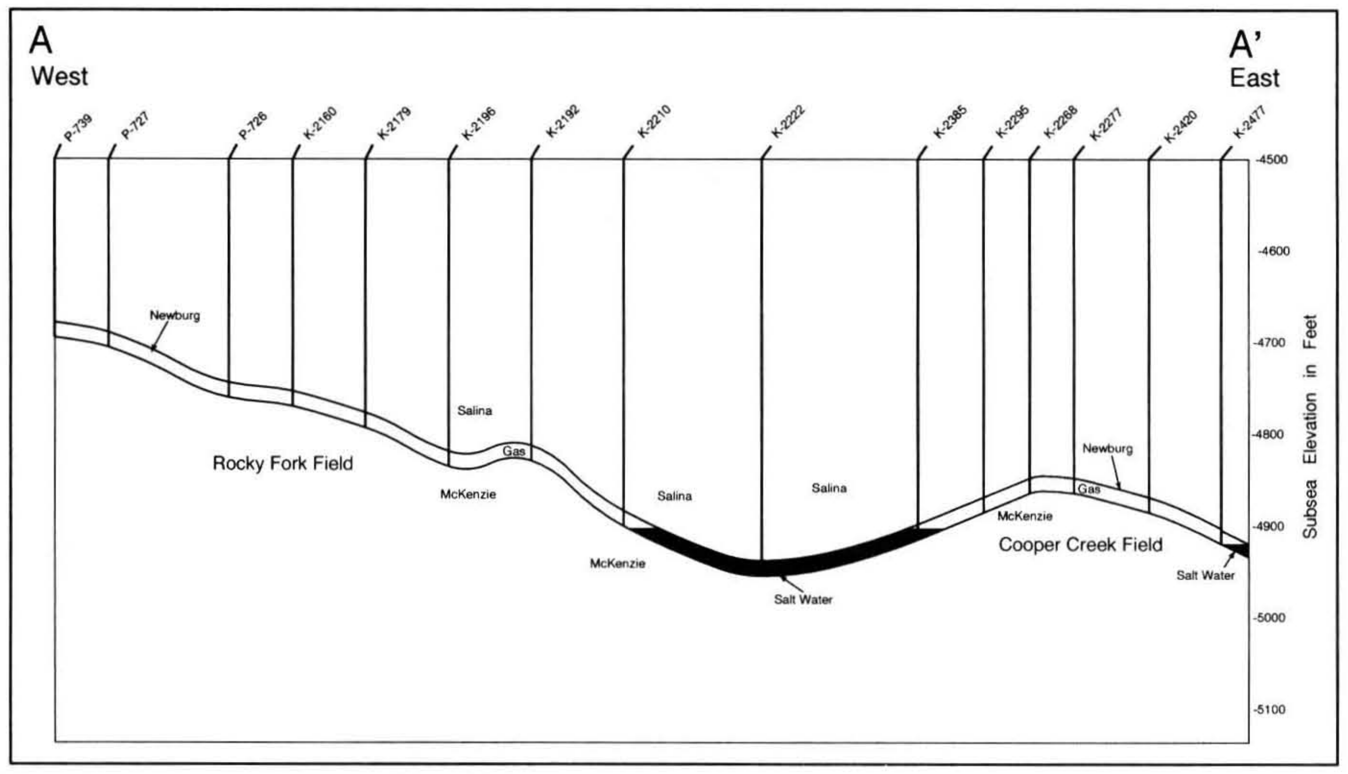


Figure Sns-18. Structural cross section A-A' through Rocky Fork and Cooper Creek fields illustrating salt water in the structural low between the fields as well as downdip to the east of Cooper Creek field. Cooper Creek is a pure structural trap, whereas Rocky Fork exhibits both structural and stratigraphic trapping mechanisms. Location of cross section shown in Figure Sns-10.

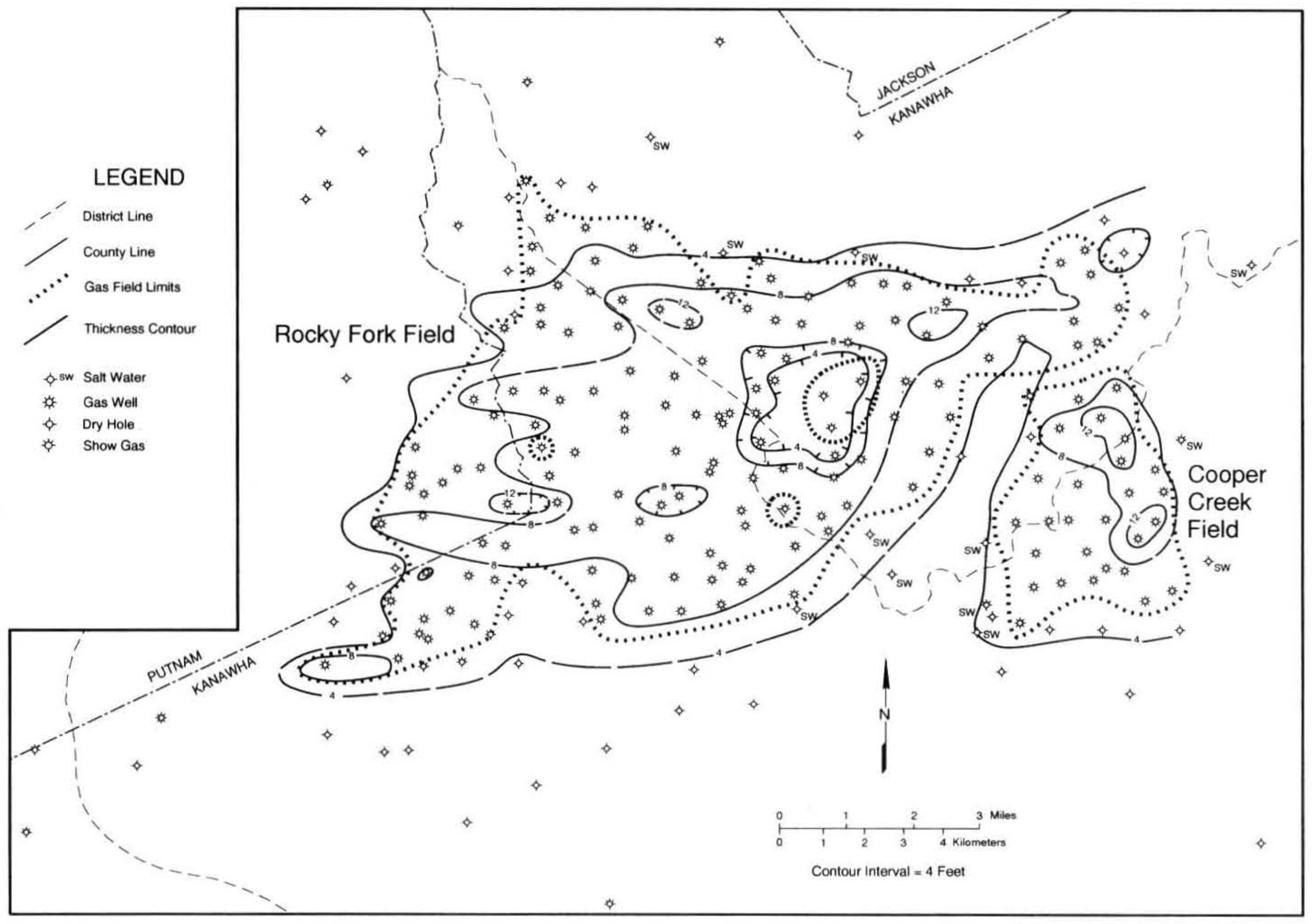


Figure Sns-19. Thickness of the upper, clean sandstone in Rocky Fork and Cooper Creek fields. Values (from Cardwell, 1971) were interpreted from gamma-ray logs. See Figure Sns-2 for location.

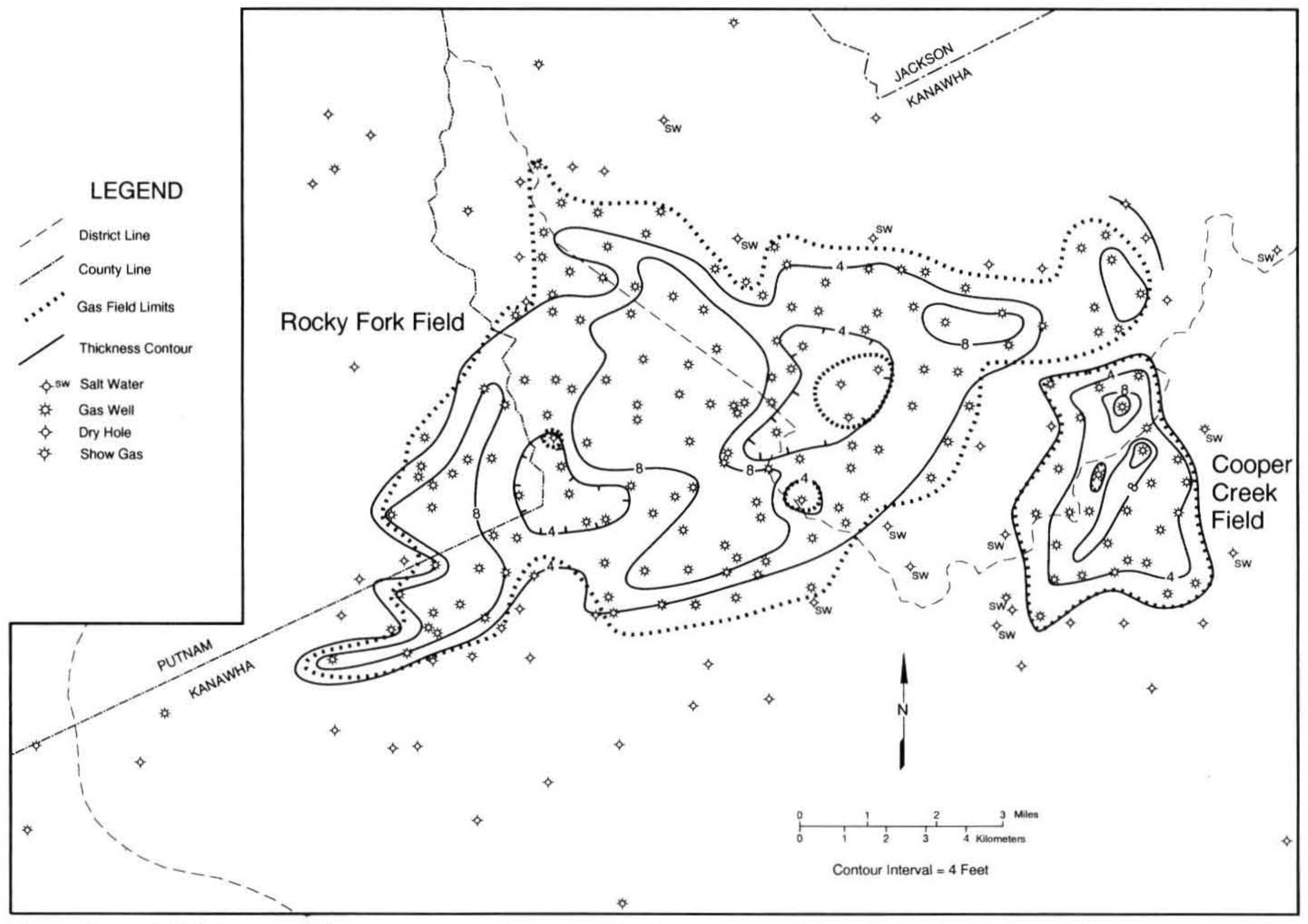


Figure Sns-20. Thickness of the porous zone developed in the upper sandstone in Rocky Fork and Cooper Creek fields. Values (from Cardwell, 1971) were interpreted from porosity logs, but no porosity cutoff value was given. See Figure Sns-2 for location.

nearly to the western edge of the field (Figure Sns-19). An area of thin sandstone occurs near the center of the productive area. A map of porous zone thickness (Figure Sns-20) is nearly identical to the map of sandstone thickness, and helps to explain the overall shape of the productive acreage. Production to the west, up the axis of the Sissonville high, is limited by the decrease in net sandstone and pay thickness. Net sandstone and porous sandstone thickness also appear to thin in the structural low between the two fields.

The distribution of initial open flows (Figure Sns-21) correlates closely with the maps of sandstone and porous zone thickness. In the central area of thin clean sandstone and a corresponding thin porosity zone, three nonproducers were drilled; in areas of thicker sandstone, wells were completed with very high IPs. The maximum IP following stimulation reported for any well in Rocky Fork field was 110 MMcf/d; the highest in Cooper Creek was 168 MMcf/d.

Both fields are characterized by very high initial open flows. Of the 133 producing wells in Rocky Fork field, all but five tested in excess of 1 MMcf/d; 33 tested between 1 and 10 MMcf/d, and 29 had reported IPs greater than 50 MMcf/d (Cardwell, 1971). Although natural flows as high as 32 MMcf/d were reported, most wells were fractured, increasing production by 100 percent in most cases (Cardwell, 1971). The average open flow of wells in Cooper Creek field was 33 MMcf/d (Cardwell, 1971). Seven of the 27 producing wells were completed with IPs in excess of 50 MMcf/d, and 13 others had IPs greater than 10 MMcf/d. The average natural open flow for Cooper Creek wells was 13,464 Mcf/d; the average open flow following stimulation was 38,852 Mcf/d.

At least 160 productive wells have been drilled in these two fields. Cumulative production from 1966 to 1973 was approximately 150 bcf, just under 1 bcf per well. Production correlates strongly with rock pressure and somewhat with initial open flow. The best wells are in areas of thicker sandstone; structural position is less of a factor than sandstone thickness for both IPs and cumulative production.

Wells in Rocky Fork field exhibit a typical rapid decline in production from the first through third years on line, maintain good production at lower rates during the fourth and fifth years, and then tend to have flat curves during the sixth to eighth years (Figure Sns-13a). Few wells produce more than eight or nine years.

Reservoir heterogeneity within these fields is illustrated by the distribution of initial potential and cumulative production. Structural factors determine the location of the two fields but probably not the distribution of gas within the fields. Sandstone thickness is probably the key factor in intrafield heterogeneity, and diagenetic effects may be important in interwell heterogeneity.

Examination of two cores in Rocky Fork field reveals mineralogic and textural characteristics similar to Kanawha Forest cores. The Newburg is a clean, brown to white, fine- to very fine-grained quartz arenite with quartz, calcite and anhydrite cement. The distribution of cements (Figure Sns-22) is similar to the reservoir in Kanawha Forest field; calcite increases downward and the pay zone is cemented by quartz and anhydrite.

Jackson County Newburg fields: At first glance, Newburg gas production in Jackson County appears to be from one continuous north-south trend (Figure Sns-1). However, there are actually five separate areas of gas production (Figure Sns-11). These fields are developed on the regional dip slope, which is down to the east, but subtle structure is a key factor in determining the location and extent of the fields. South Ripley field is a combination stratigraphic-structural trap located on a small northeast-plunging anticline that is paired with a narrow syncline to the northwest (updip). Salt water is present along the eastern, downdip edge of the field, and also around the nose of the structure into the adjacent syncline (Figure Sns-11). This narrow salt water leg separates production in South Ripley field from North Ripley field.

North Ripley field is a stratigraphic trap with a strong water drive. Downdip wells with a subsea elevation approaching -4,850 contain water; updip production is limited by a decrease in sandstone thickness and thickness of a porous zone near the top of the sandstone. North Ripley field is separated from Groundhog Creek Southeast field by a narrow zone of dry wells along its northern edge where the Newburg is thinner. However, the fields actually may be joined at their updip edges between -4,400 and -4,500 feet subsea elevation. Wells above -4,500 feet subsea elevation are productive in Groundhog Creek Southeast field, but water was not reported from the downdip, dry holes.

The two Groundhog Creek fields are separated by a narrow area containing five dry holes. Groundhog Creek Northwest field is located between subsea elevations -4,200 and -4,350 feet, with water present in the sandstone in one well at -4,400 feet. Structure mapped on the Newburg (Figure Sns-11) indicates two small anticlinal noses present in the field that are responsible for the outline of the field. Updip production is limited by sandstone pinchout.

The Newburg sandstone is poorly developed in this area relative to Kanawha County fields. The average thickness of clean sandstone in these fields ranges from 10 feet in North Ripley field to 7 feet in South Ripley, 5 feet in Groundhog Creek Southeast, and only 3 feet in Groundhog Creek Northwest. Thickness trends in North and South Ripley fields (Figure Sns-23) correspond to trends in porosity thickness (Figure Sns-24) and to areas of higher than average initial potential (Figure Sns-25).

The average natural open flow in these four fields ranged from a low of 1,400 Mcf/d per well in South Ripley field to 12,390 Mcf/d in North Ripley field. The two Groundhog Creek fields had average per well natural open flows of 8,000 Mcf/d and 10,400 Mcf/d. In spite of these high natural flows, most wells were treated and final open flows after stimulation at least doubled in all fields. Average per well final open flows are 6,500 Mcf/d in South Ripley, 10,240 Mcf/d in Groundhog Creek Northwest, 20,850 Mcf/d in Groundhog Creek Southeast, and 40,450 Mcf/d in North Ripley field.

Cumulative production from these four fields exceeds 93 bcf. Of this total, more than 85 bcf was produced from the 55 gas wells in the two Ripley fields, an average of more than 1.5 bcf per well. However, the 27 Groundhog Creek gas wells that drain a much thinner reservoir averaged less than 300 MMcf per well cumulative production. Production decline curves for wells in North Ripley field are similar in shape and magnitude to Rocky Fork wells to the south. Production declines rapidly from the first through the third year, and then levels off. The typical well produced only six or seven years.

Reservoir heterogeneity within the Jackson County fields is suggested by the variability in initial open flows, but is not as obvious as in fields to the south. Subtle structure is a key element in production, as well as sandstone thickness and cementation of the reservoir sandstone.

One full diameter core from a well in South Ripley field and one set of sidewall cores from a well in North Ripley field were examined. The Newburg sandstone in these fields is similar to the Newburg reservoir in Kanawha County fields. Porosity is developed at the top of the thin sandstone where the dominant cements are quartz and anhydrite. Calcite cement increases downward toward the underlying McKenzie (Lockport) Formation (Figure Sns-26).

Resources and Reserves

Remaining reserves and resources in the Newburg sandstone are classified as proven reserves if they remain in producing wells; probable resources if they are present in undrilled areas of existing fields; and possible resources if they exist in undrilled, currently unproductive areas of the play.

Existing Newburg fields were discovered between 1966 and 1970 and were developed to their present limits within a few years. Few additional discoveries have been made since 1970; consequently, no new fields of any appreciable size have been developed. Also, with the exception of North Ripley field, few infill and extension wells have been drilled in existing fields. The conclusion is that few companies have expressed interest in continuing the search for Newburg gas, probably because any Newburg discoveries in the future will result in fields with 10 or fewer wells and less than 10 bcf reserves. Thus, exploration and development drilling over the past 20 years suggests adoption of a conservative approach when estimating reserves and resources for this play.

Using data from existing fields to create a model of expected results from new discoveries may not be consistent with a conservative approach because of the prolific production from early wells in this play. Using data from all fields, a typical Newburg well produced nearly 1 bcfg, and gas reserves per acre (more than 4,000 Mcf) and per acre-foot (nearly 700 Mcf) are difficult to project into undrilled areas if one is to be conservative.

Two approaches were used in calculating possible resources within the Newburg play area. The first approach involved assuming certain values for a set of parameters and using the data in a volumetric calculation. In this method, it was assumed that additional productive acreage would not exceed 50 percent of current productive acreage (70,000 acres). Given the results of exploratory drilling during the past 20 years, this assumption may be optimistic. In any event, 35,000 acres were assumed to have production potential, under which the Newburg sandstone would average 5 feet in pay thickness with 8 percent porosity. Reservoir pressure was assumed to be 2,200 psi, temperature was assumed to be 110 degrees, and gas saturation was set at 60 percent. This volumetric method resulted in an estimate of 50 bcf of possible gas resources within the play area (Figure Sns-27). Fifty wells would be required to develop this resource, assuming that future wells in areas that currently are nonproductive would be as productive as wells drilled earlier in the play. If future wells are only half as productive, 100 wells would be required. Assuming a small field size (6 to 10 bcf), five to eight fields would have to be discovered and developed.

The second approach involved creating a model of expected results based on historical data for the entire play. In developing this model, data from all seven Newburg fields were used to develop a typical well, one which would produce 959 MMcf per well, recovering 4,057 Mcf per acre, and 692 Mcf per acre foot. These numbers were calculated using 298,190 bcf production from 311 wells, 73,500 acres, and 175,000 acre-foot. Three separate estimates were calculated for possible gas resources using these numbers. Resources based on gas per acre (35,000 acres multiplied by 4,057 Mcf/acre) were 141,995 MMcf. Resources based on an expected 959 MMcf per well were 134,260 MMcf (140 wells on 250-acre spacing on 35,000 acres). Resources based on acre-feet were 121,100 MMcf (35,000 acres multiplied by 5 feet pay multiplied by 692 Mcf per acre-foot). Averaging these three calculations resulted in possible gas resources of 132,452 MMcf, or 132 bcf, as a high end estimate. Again assuming a small field size, 13 to 22 fields would have to be discovered and developed to produce this resource.

Although many of the wells in the seven Newburg fields have been abandoned or converted to storage, and few extension wells have been drilled since 1973 when reserves for these fields were calculated, some proven reserves and probable resources remain. In 1973, ultimate recoverable resources were estimated at 318 bcf, of which nearly 32 bcf remained as proven reserves and probable resources. Since 1973, at least 8 bcfg have been produced from these seven fields, so proven reserves and probable resources would be approximately 24 bcf. Thus, total proven reserves and probable and possible resources may range from 74 to 156 bcf.

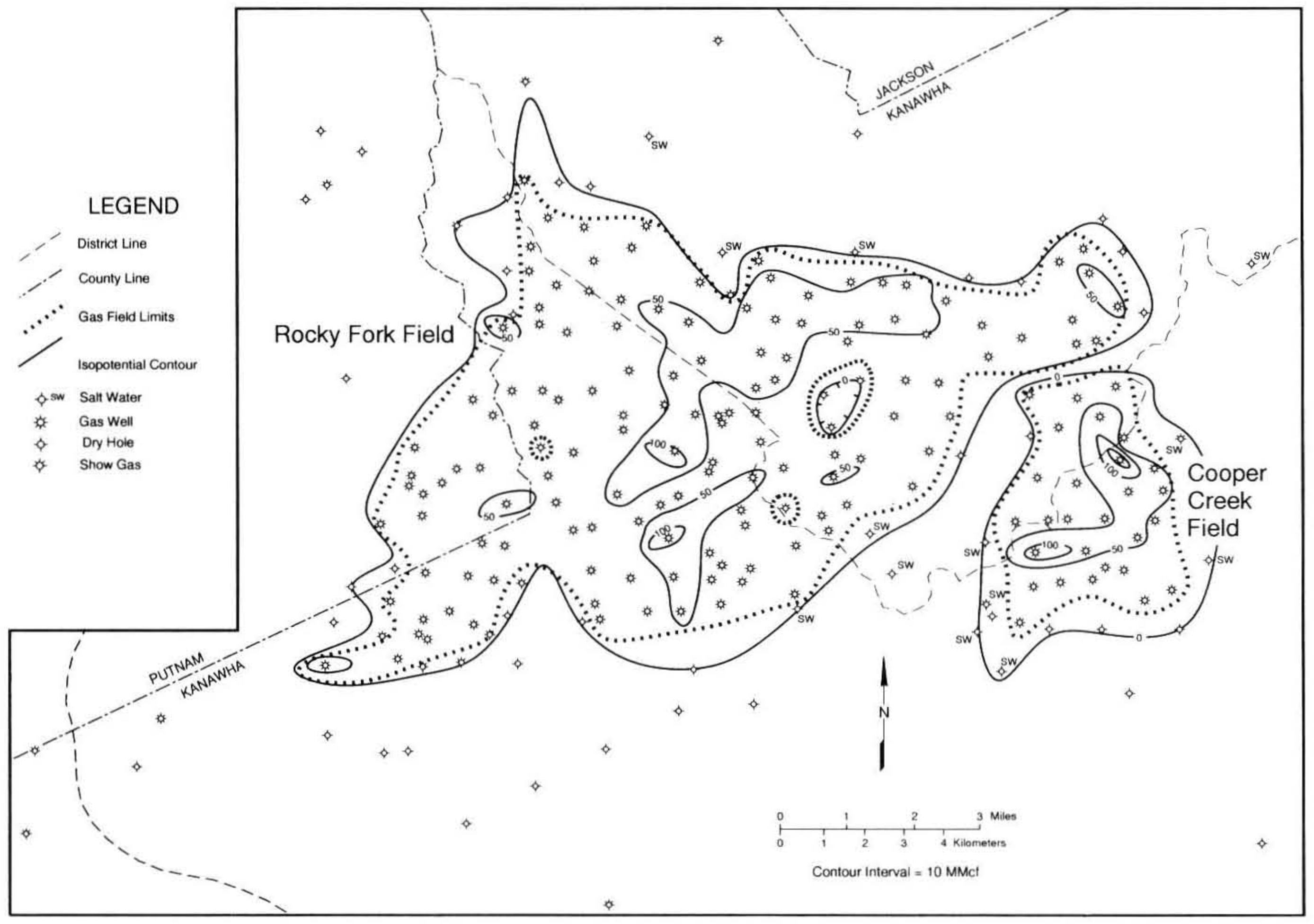


Figure Sns-21. Distribution of open flows in Rocky Fork and Cooper Creek fields. Values (from Cardwell, 1971) are post-stimulation for treated wells. Natural open flows were used for unstimulated wells. See Figure Sns-2 for location.

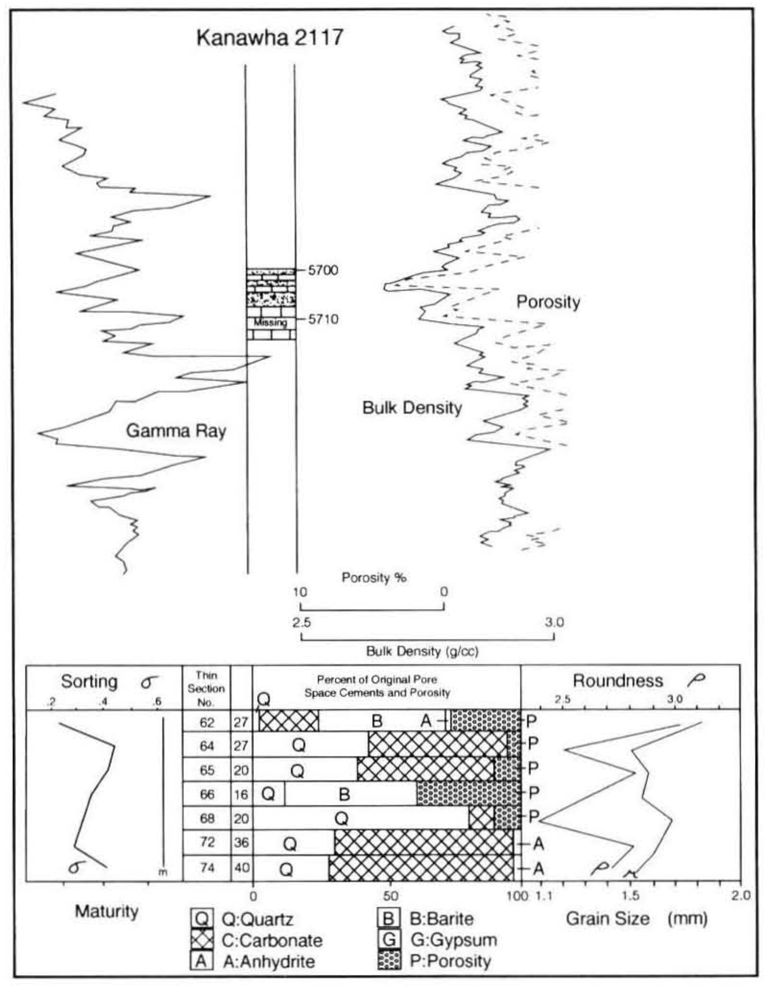


Figure Sns-22. Distribution of cements and porosity in a Newburg core from a well (Kanawha 2117) on the southwestern edge of Rocky Fork field correlated to other textural parameters, including size, shape, and sorting of sand grains, and maturity of the sandstone. Porosity is not well developed in this well, which was a dry hole due to the presence of carbonate cement throughout the sandstone.

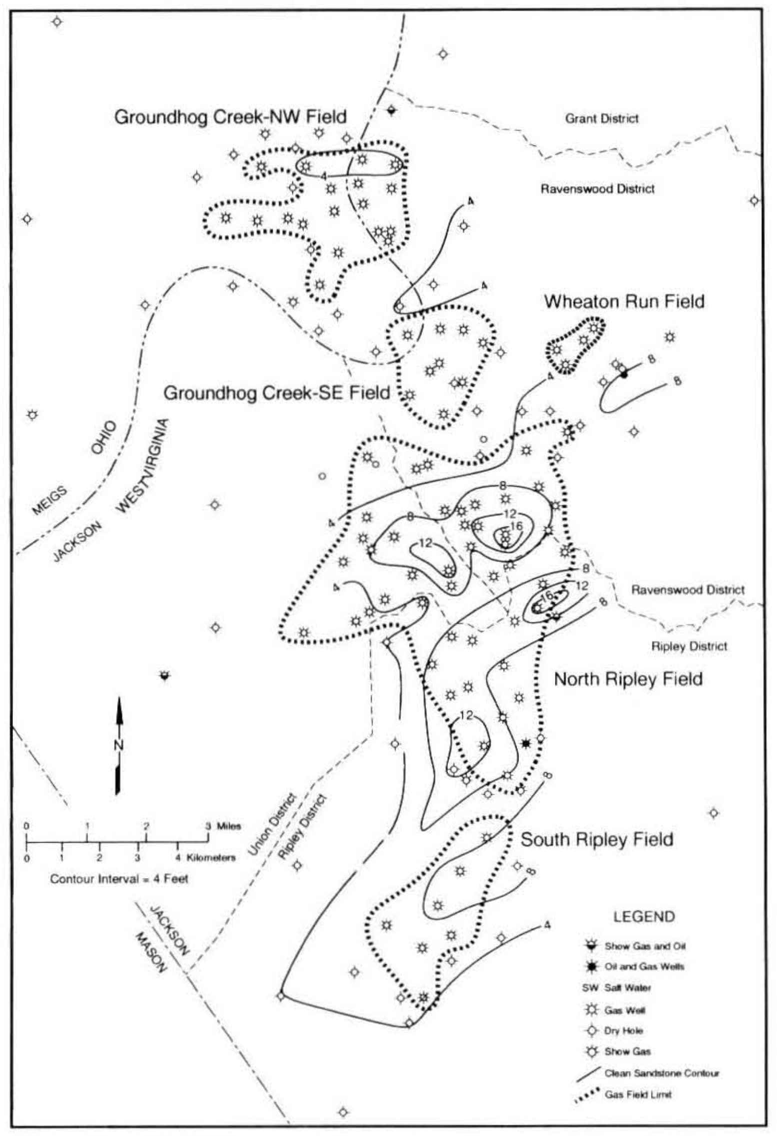


Figure Sns-23. Thickness of the upper, clean sandstone in Jackson County fields. Values (from Cardwell, 1971) were interpreted from gamma-ray logs. See Figure Sns-2 for location.

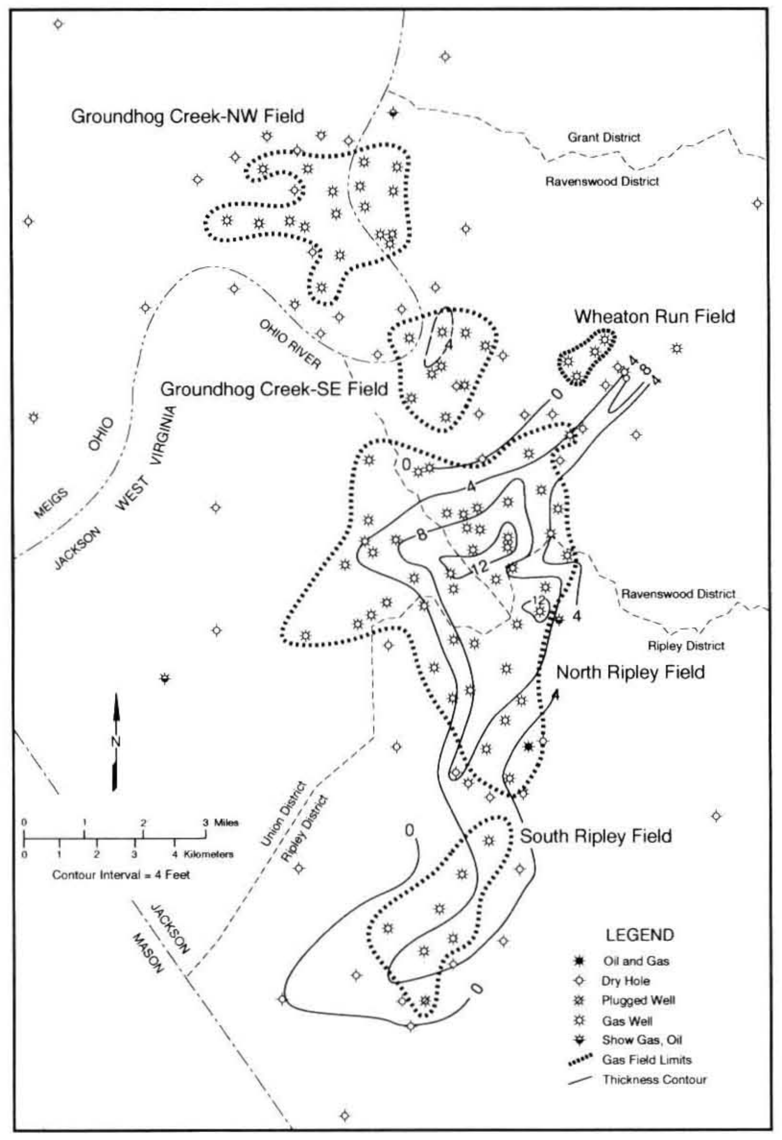


Figure Sns-24. Thickness of the porous zone developed in the upper sandstone in Jackson County fields. Values (from Cardwell, 1971) were interpreted from porosity logs but no porosity cutoff value was given. See Figure Sns-2 for location.

Future Trends

Most of the productive wells in this once-prolific play have been abandoned or converted to storage. All fields are clearly defined by dry holes or downdip wells with salt water, so the likelihood of drilling additional acreage is low. Although proved reserves and probable resources within the play are low, undiscovered possible resources may be located within the area of well-developed Newburg sandstone (Figure Sns-6), especially on structural highs. A key factor in future exploration may be drilling subtle structural highs mapped on the shallower Oriskany Sandstone to find anticlinal noses similar to those that control production in South Ripley and Groundhog Creek Northwest fields. Projecting thickness trends also is important because productivity is directly related to sandstone development, and porosity may be related to the edges of the sandstone deposit.

In West Virginia, porosity is best developed in the Newburg in a relatively narrow, north-south trend in Jackson and Kanawha counties just east of the pinchout of the sandstone. However, a second porosity trend may exist to the east in Wirt and Roane counties. The small area of gas production in Wirt County (Sanoma field) is an example of downdip production from this second porosity trend on the eastern side of the area of Newburg sandstone development.

There are examples (such as Groundhog Creek Northwest field) where updip gas production is separated from structurally lower gas fields by a downdip water drive. This suggests that gas and water were present in the porous Newburg sandstone prior to formation of the small folds that then segregated the fluids in discrete structural traps. Thus, downdip Newburg production east of Jackson and Kanawha counties, West Virginia cannot be ruled out.

Barring further discoveries between existing fields in the western porosity trend from Kanawha to Jackson County, or in a downdip porosity trend similar to Wirt County, the Newburg play may be over. Recovery in existing fields exceeded 90 percent of the calculated reserves. The future for this permeable sandstone may be as a storage area for gas produced from shallower gas reservoirs. The two largest stratigraphic-structural traps, Kanawha Forest and Rocky Fork fields, may be the best suited for gas storage.

Cardwell (1971) divided West Virginia into four areas when discussing future potential. Of these, all existing production is in the western area (Figure Sns-27). Geophysical logs of wells drilled in Roane and Clay counties indicate 6 to 9 feet of effective sandstone and up to 5 feet of porous sandstone. Similar sandstone development may exist in undrilled portions of Calhoun County. The Newburg sandstone also is well developed in the western part of Wood County and the adjacent portion of Athens County, Ohio. However, within this Wood County-Athens County area the Newburg is unproductive due to the presence of salt water in the porous zone. Good gas shows (1 MMcf/d and 1.5 MMcf/d) were reported in two updip wells in Athens County, but both wells were abandoned when they began producing salt water (Pryce, written commun., 1993). Pryce (written commun., 1993) believes that the northern limit of the Newburg play has yet to be defined. Porosity may be developed adjacent to the northern pinchout of sandstone in Wood County and Athens County. As Cardwell (1971) noted, wherever good porosity along with favorable trap conditions can be encountered, the prospects for Newburg gas productions are good.

The opportunity for Newburg gas production in the central area of West Virginia (Figure Sns-27) is less than in the western area even though well-pronounced structures are present. The Newburg sandstone is developed only in the southern portion of the area, so structures in Fayette, Nicholas, and Greenbrier counties offer more possibility than structures of similar magnitude to the north. Combination stratigraphic-structural traps may be present along the northern pinchout of the Newburg. The sandstone thickness increases toward the east and southeast, but porosity decreases. However, the possibility exists for fractured reservoirs (a fractured anticlinal play) on the tighter anticlines to the east. Shows of gas have been reported from the Newburg in wells in Nicholas and Greenbrier counties, and salt water was present in the Newburg in a Raleigh County wildcat, attesting to the development of porosity in these areas.

Opportunity for Newburg production in the east-central and eastern panhandle areas of West Virginia (Figure Sns-27) is very poor. In those areas, the Newburg or Crabbottom Sandstone is poorly developed, and the sandstone that occurs in a similar stratigraphic position is the less mature Williamsport Sandstone. The reservoir quality of the Williamsport is poor, at best.

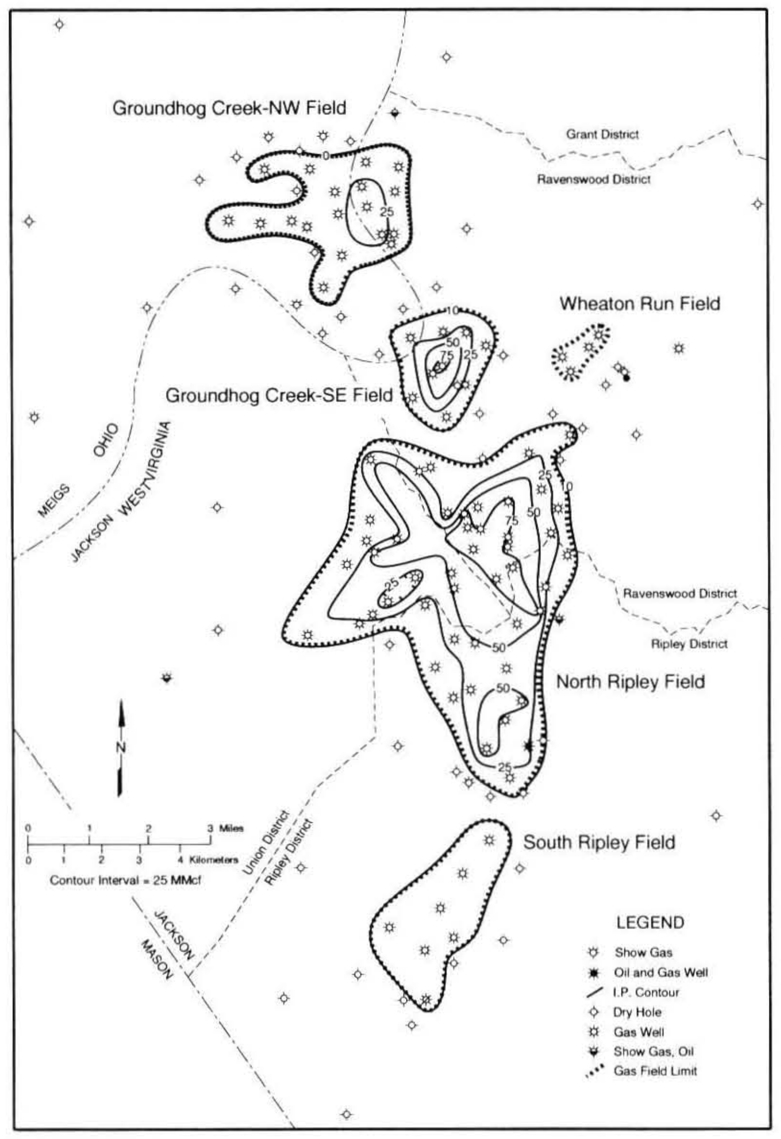


Figure Sns-25. Distribution of open flows in Jackson County fields. Values (from Cardwell, 1971) are post-stimulation for treated wells. Natural open flows were used for untreated wells. See Figure Sns-2 for location.

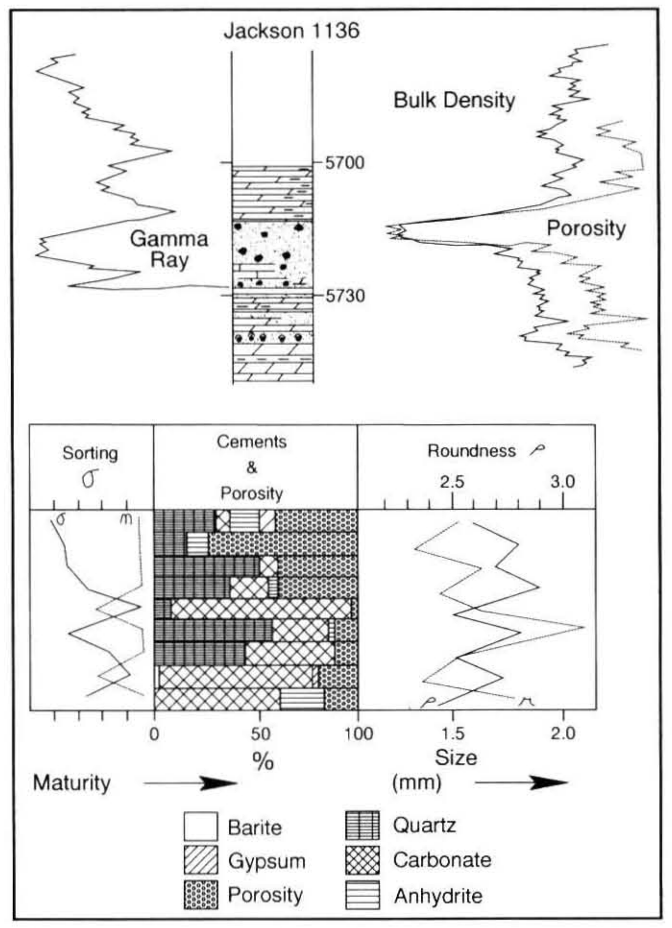


Figure Sns-26. Distribution of cements and porosity in a Newburg core from a well (Jackson 1136) in South Ripley field correlated to other textural parameters, including size, shape, and roundness of sand grains, and maturity of the sandstone. Porosity is highest in beds that are cemented by quartz, anhydrite, and gypsum, and lower in beds with higher percentages of carbonate cement. From Patchen (1971).

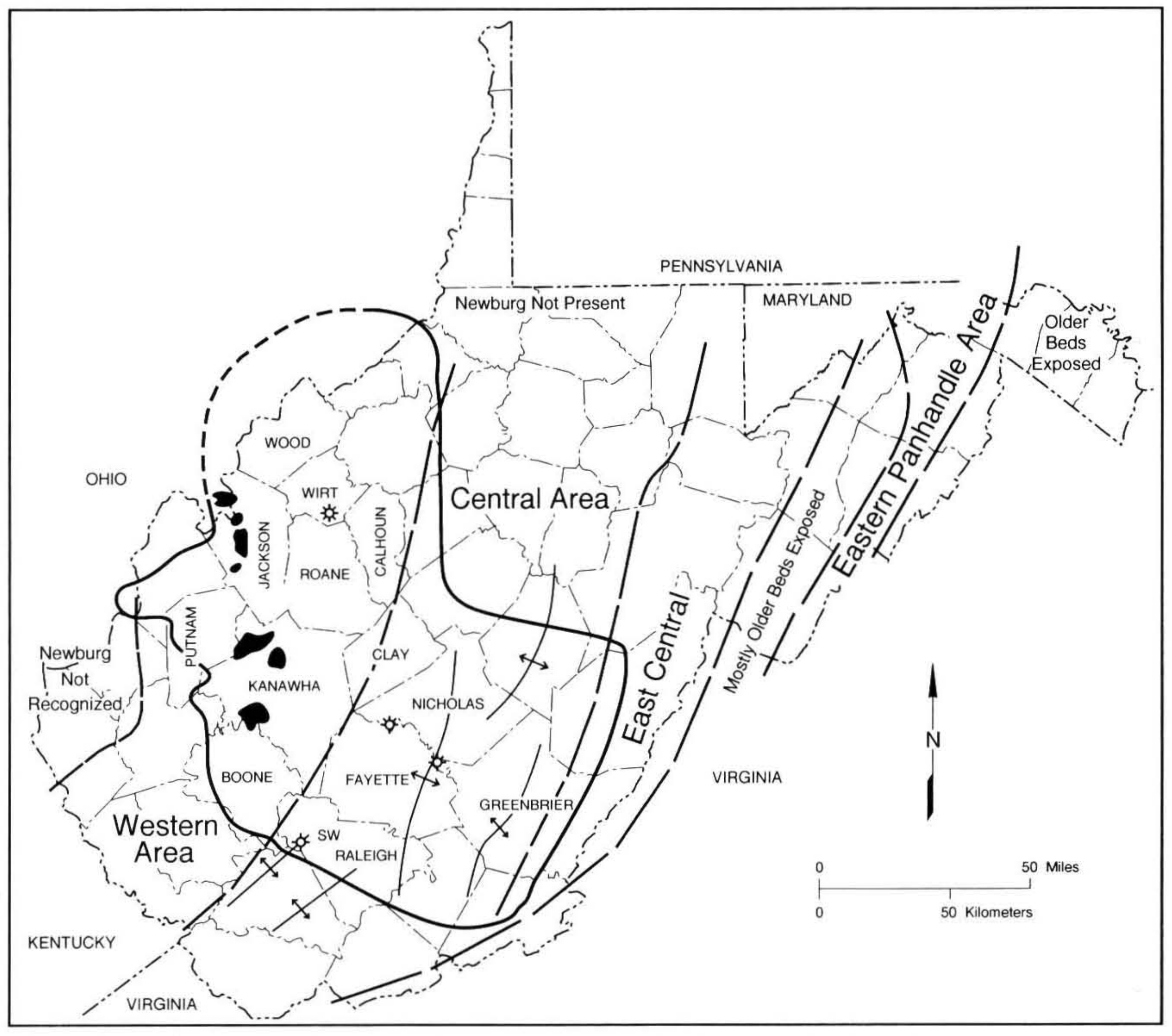


Figure Sns-27. Areas of West Virginia with similar potential for future production of gas from the Newburg sandstone. The highest potential is in the western area. Lowest potential is in the east-central and eastern panhandle area where the Williamsport, not the Newburg, is present. Anticlines in the southern half of the central area may have potential if porosity is developed in the thick, clean, upper portion of the Newburg sandstone. Modified from Cardwell (1971).

PLAY Sld: UPPER SILURIAN LOCKPORT DOLOMITE-KEEFER (BIG SIX) SANDSTONE

by Martin C. Noger, Consultant; Joseph F. Meglen, Peoples Public Gas Company; Matthew Humphreys, Kentucky Geological Survey; and Mark T. Baranoski, Ohio Division of Geological Survey

Location

The Upper Silurian Lockport Dolomite and Keefer Sandstone gas play covers a broad area on the western flank of the Appalachian basin, stretching from eastern Kentucky to southern Ontario, Canada. This play includes all Lockport Dolomite and Keefer Sandstone gas reservoirs not associated with the Lower Devonian-Upper Silurian unconformity play (see J.F. Meglen and M.C. Noger, Lower Devonian-Upper Silurian unconformity play, this atlas). The focus of this play description is on gas reservoirs in the United States portion of the Appalachian basin. The Lockport Dolomite has produced gas from 60 fields located predominantly in eastern Ohio and eastern Kentucky (Figure Sld-1). The Keefer Sandstone has produced gas from 15 fields in eastern Kentucky and extreme western West Virginia, with most of the producing fields located in eastern Kentucky (Figure Sld-2). Significant Lockport Dolomite and Keefer Sandstone gas fields are identified in Figures Sld-3 and Sld-4, respectively.

Production History

Successful gas well completions in the Lockport Dolomite and Keefer Sandstone play began in 1889 in southern Ontario, Canada, and spread south through Ohio into Kentucky. The play expanded eastward into West Virginia, northeastward into New York, and finally eastward into Pennsylvania. Not surprisingly, the producing depths generally increased as the play progressed, especially in West Virginia and Pennsylvania. The cumulative production for the United States portion of the Lockport Dolomite and Keefer Sandstone play was extrapolated from limited production data, and was estimated to be at least 118.9 bcfg for the period from 1917 to 1993. In this extrapolated estimate, the Lockport Dolomite accounted for 100.7 bcfg, which was produced from 917 wells. It should be noted that the actual cumulative production for the Lockport Dolomite was 38.2 bcfg from 213 wells that had production data available. The actual cumulative production for the Keefer Sandstone was 18.2 bcfg from 142 wells, for which production data are available. However, a total of 363 wells have produced gas from the Keefer Sandstone. Because of the confidentiality of production data and the inability to contact many small operators, cumulative production data represents minimum values.

Gas was first produced from the Guelph-Lockport Group in 1889, at the Kingsville-Leamington field (Ontario Geological Survey, 1982) in southern Ontario, Canada (Figure Sld-3). Depth to the top of the reservoir was approximately 900 feet. Seventeen years elapsed before the play expanded southward into Ohio. The earliest reported gas production from the Lockport Dolomite in Ohio was at the Mansfield field in 1906. The producing depth was 1,950 feet. It was not until 1912 that the play began to expand significantly. Ten new fields were discovered in Ohio between 1912 and 1923, including South Martinsburg, Newburgh Heights, Canaan-Wayne, and South Newark fields (Figure Sld-3). During this same period, the Lockport Dolomite play area continued to expand southward with the discovery of the Isonville Consolidated and Redbush Consolidated fields in Kentucky (Figure Sld-3). In 1918, gas was first discovered from the Silurian Keefer Sandstone at the Taulbee Consolidated field in Kentucky by the Big Six Gas Company (Hunter, 1955). Subsequently, the new producing sandstone (Keefer Sandstone) was named Big Six, a name used by drillers since.

In the mid-1920s, no new Lockport Dolomite or Keefer Sandstone fields were established. However, from 1927 to 1943 the play gradually began to move eastward from the known producing areas, with several new gas fields being discovered at intervals of two to four years. During this period, the new Lockport Dolomite gas fields included: Mayfield, Canal Fulton, and Thurston fields in Ohio; Cordell Consolidated, Mine Fork, Auxier District of Big Sandy, and Barnetts Creek Consolidated fields in Kentucky; Whites Creek-Gragston field in West Virginia; and Geneva field in New York (Figure Sld-3). The Keefer Sandstone gas fields found during this period included Stevenson and Barnetts Creek Consolidated fields in Kentucky, and the Whites Creek-Gragston field in West Virginia, where the deepest known Keefer Sandstone production was established at a depth of 3,865 feet (Figure Sld-4).

During the mid-1940s, three Keefer Sandstone gas fields were discovered in Kentucky, including Puncheon Camp Creek Consolidated, Royalton, Van Lear District of Big Sandy, and Beetree fields (Figure Sld-4). These same three fields also produced variable amounts of gas from the Lockport Dolomite. In 1947, Keefer Sandstone production was discovered at the Beetree field (Figure Sld-4). The pace of new field discoveries was slow from the late 1940s until the mid-1950s with only four new field successes in Ohio. However, during the period from 1957 to 1969, newly discovered Lockport Dolomite fields included Woodbury and Franklin fields in Ohio, and Taulbee Consolidated and Holly Creek Consolidated fields in Kentucky (Figure Sld-3). In 1966, the deepest known Lockport Dolomite gas production was discovered at the Wolf Creek field (Kilgore pool) in Pennsylvania, at a depth of 5,341 feet (Figure Sld-3). The only significant Keefer Sandstone field discovered during the decade of the 1960s was the Ary District of Big Sandy field in Kentucky (Figure Sld-4).

Exploration results in the Lockport Dolomite and Keefer Sandstone play have been sporadic since the late 1960s. The most recent Lockport Dolomite gas production discovered was in 1981, at the Conneaut field (Cranesville pool) in Pennsylvania (Figure Sld-3). The latest Keefer Sandstone field to be discovered was in 1982, at the Mine Fork field in Kentucky (Figure Sld-4). Currently, exploration and development drilling in the Lockport Dolomite and Keefer Sandstone play continues, but at a slow pace.

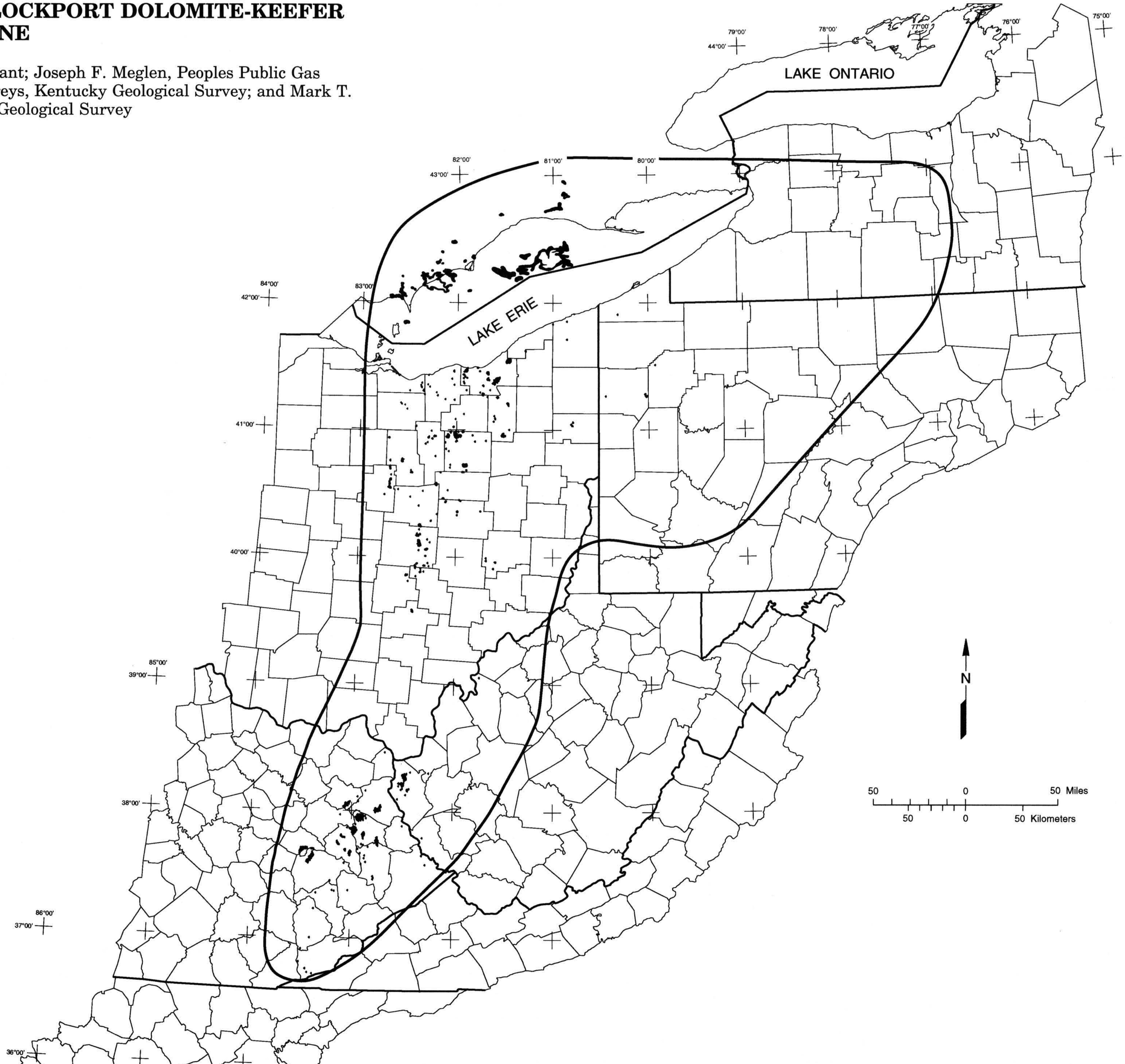


Figure Sld-1. Outline of Upper Silurian Lockport Dolomite and Keefer Sandstone play area within the Appalachian basin. The Keefer Sandstone (Big Six) portion, as shown in Figure Sld-2, is within the play area. Dots represent individual gas wells; areas where dots have merged represent fields. Only the Lockport Dolomite gas fields and gas wells are shown in Figure Sld-1. The Keefer Sandstone (Big Six) gas fields and gas wells are shown in Figure Sld-2.

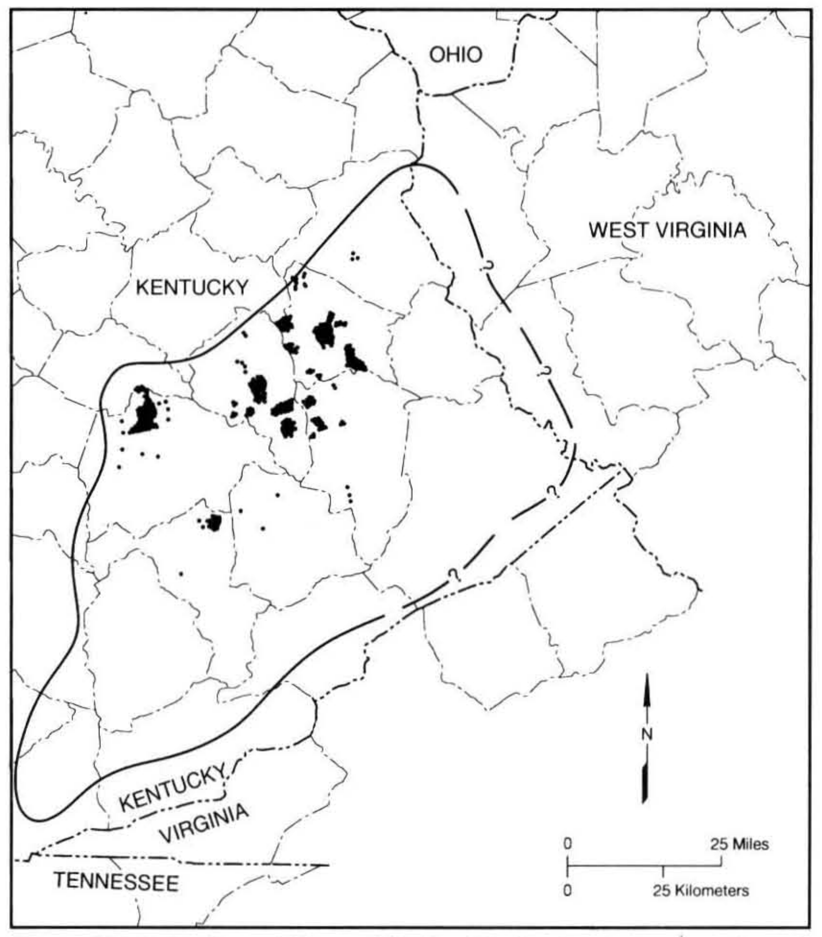


Figure Sld-2. Outline of Upper Silurian Keefer Sandstone portion of play area within the Appalachian basin. Dots represent individual gas wells; areas where dots have merged represent fields.

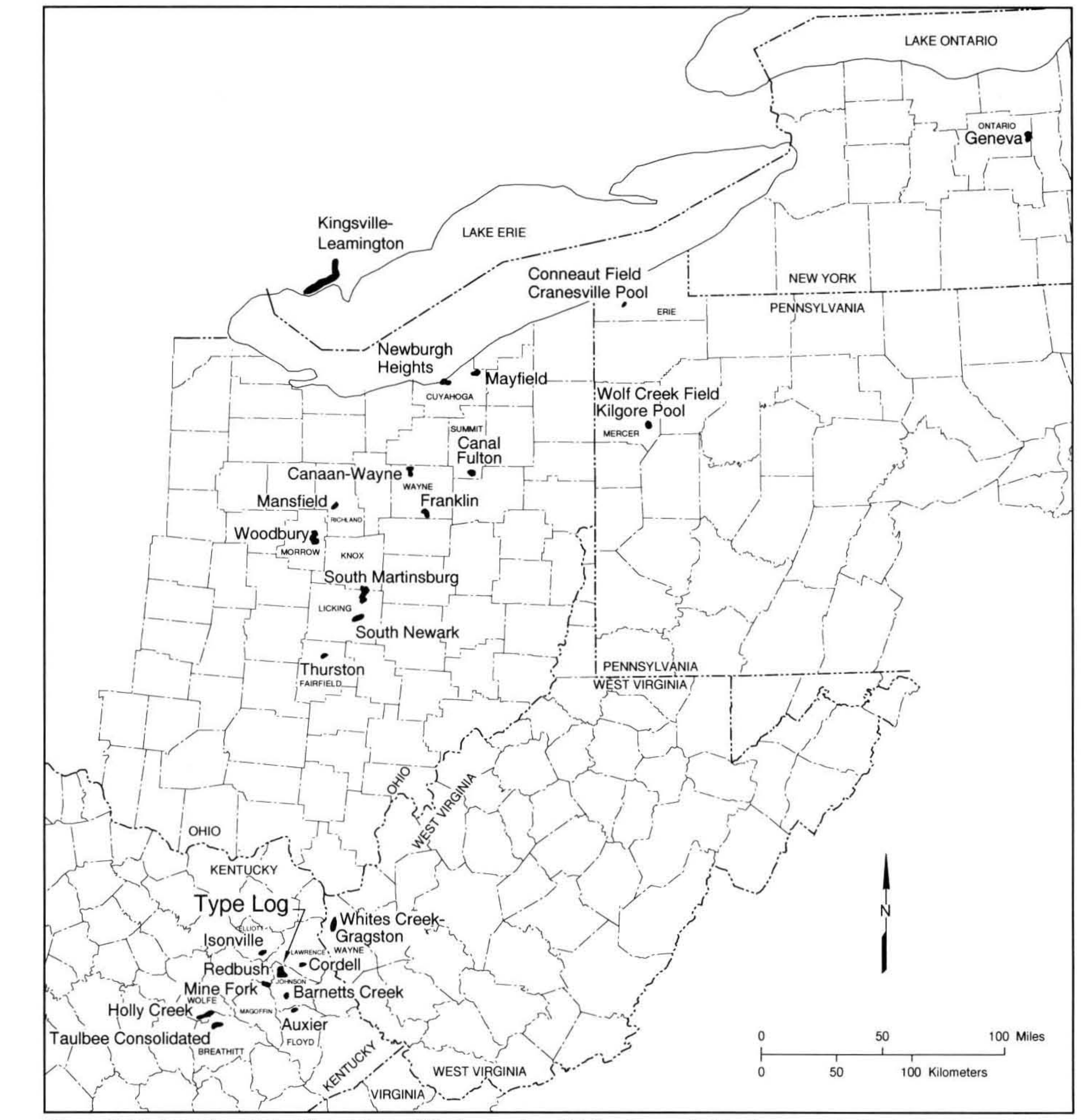


Figure Sld-3. Location of significant Upper Silurian Lockport Dolomite gas fields discussed in the text or listed in Table Sld-1. Location of type log from Redbush field in eastern Kentucky (Figure Sld-6) is shown.

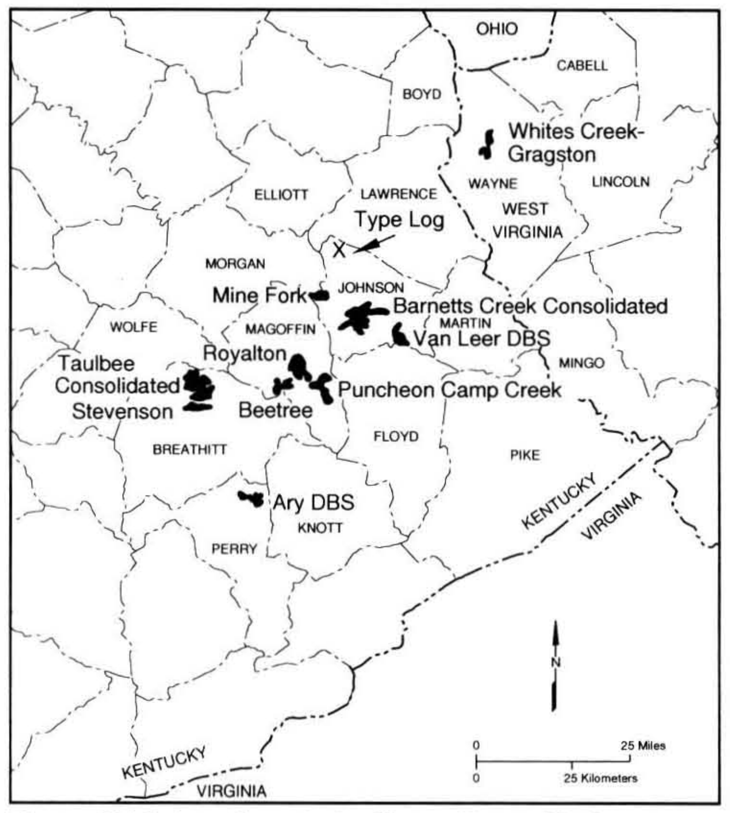


Figure Sld-4. Location of significant Upper Silurian Keefer Sandstone gas fields discussed in text or listed in Table Sld-1. Several counties in eastern Kentucky and western West Virginia are identified for reference purposes.

		Eastern Kentucky	Western West Virginia	Central and Eastern Ohio	Southwest Ontario, Canada	Western Pennsylvania	Central New York
SILURIAN	Upper	Salina Dolomite	Bass Islands Dolomite Salina Dolomite	Bass Islands Dolomite Salina Dolomite	Salina Group	Bass Islands Dolomite Salina Group	Rondout Formation Salina Group
		☼ Lockport Dolomite	☼ Lockport Dolomite	☼ Lockport Dolomite	☼ Guelph-Lockport Group	☼ Lockport Dolomite	☼ Lockport Group
		☼ Keefer Sandstone ("Big Six")	☼ Keefer Sandstone			Keefer Sandstone	Rochester Shale
	Lower	Crab Orchard Formation (Clinton Shale)	Rose Hill Formation	Rochester Shale	Rochester Shale	Rochester Shale	

☼ Produces Gas from this Formation

Figure Sld-5. Stratigraphic correlation chart for the Upper Silurian Lockport Dolomite and Keefer Sandstone. Chart is based on information from state and provincial geological surveys, and modified from Patchen and others (1985b). See Figure Sld-6 for drillers' terms commonly used to describe the Lockport Dolomite and Keefer Sandstone.

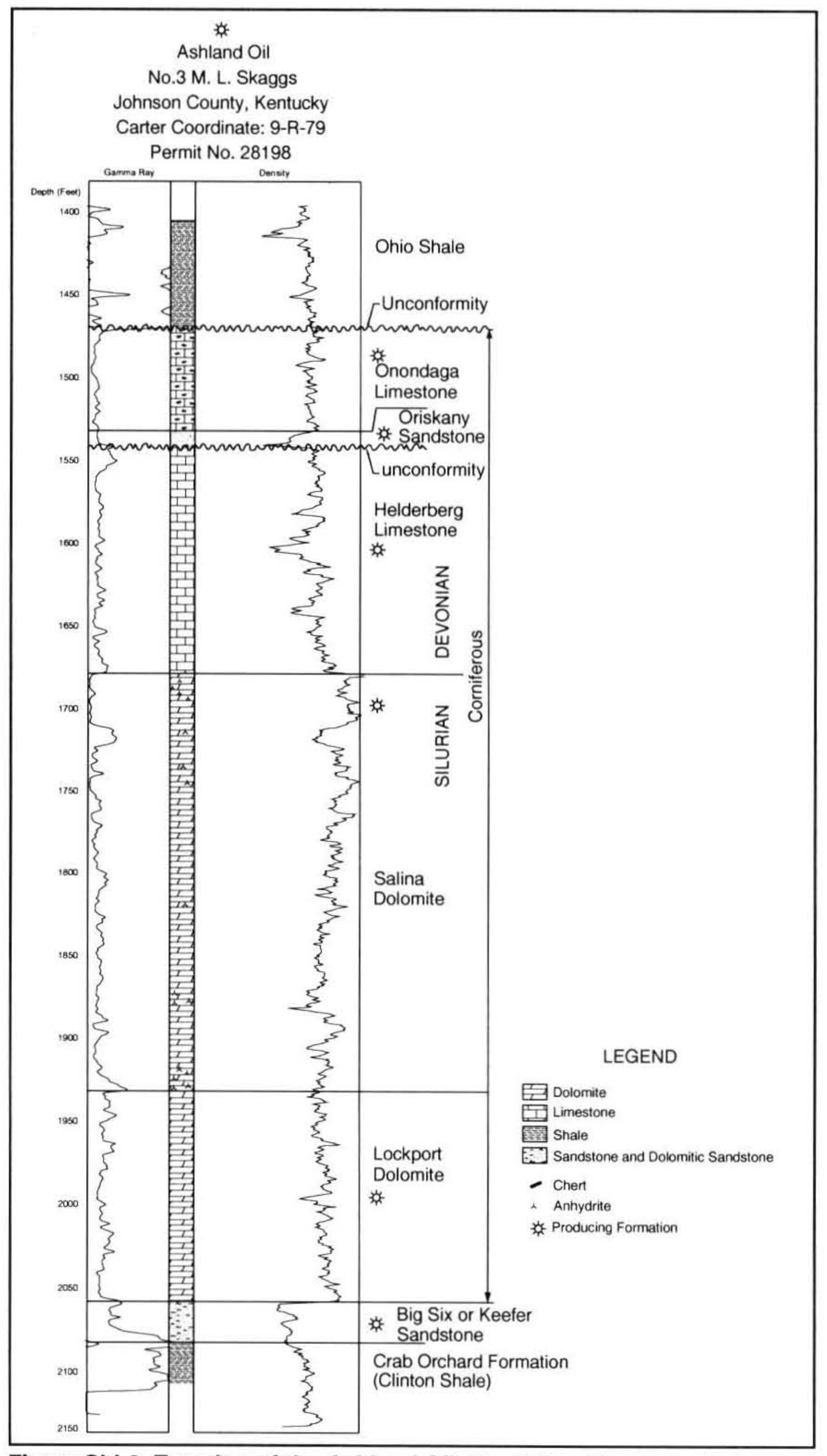


Figure Sld-6. Type log of the Ashland Oil, No. 3 M.L. Skaggs well, located in Redbush field in Johnson County, Kentucky, showing the vertical succession of formations from the Ohio Shale to the Crab Orchard Formation. The gamma-ray curves, density curves, and interpreted lithologies are also shown. The intervals representing the drillers' terms Corniferous and Big Six are also shown.

Stratigraphy

The stratigraphic nomenclature for the Lockport Dolomite and Keefer Sandstone is fairly consistent throughout the play area. In western West Virginia, the Lockport Dolomite is equivalent to the Lower McKenzie Formation, but both formation names are sometimes used interchangeably by operators. Lateral stratigraphic equivalents of the Lockport Dolomite and Keefer Sandstone are shown in Figure Sld-5. The Lockport Dolomite is often referred to as Newburg by Ohio drillers, and Corniferous by Kentucky drillers. The vertical succession of formations is depicted by the type log for eastern Kentucky shown in Figure Sld-6. The Lockport Dolomite is overlain by the Upper Silurian Salina Dolomite and underlain by the Upper Silurian Keefer Sandstone. The Keefer Sandstone overlies the Lower Silurian Crab Orchard Formation (Clinton Shale), which is a greenish-gray, red shale with occasional fine laminations of siltstone and lenses of crinoidal debris. The contact between the Keefer Sandstone and the Crab Orchard is sharp. In Kentucky, the boundary between the Keefer Sandstone and the Lockport Dolomite represents a change in depositional environments from coastal, shallow marine shelf, dominated by siliciclastics of the Keefer Sandstone, to open marine carbonate environments of the Lockport Dolomite. The boundary between the Lockport Dolomite and the Salina Dolomite represents a change from normal, open marine carbonate environments to restricted hypersaline environments.

The Lockport Dolomite is a fine- to medium-crystalline, slightly argillaceous and fossiliferous dolomite that was deposited in a carbonate shelf setting. During the Upper Silurian, several patch reef trends extended southwestward from Ontario, Canada, to eastern Kentucky. Associated depositional facies included ooid bars, skeletal sand shoals, patch reef bioherms, lagoons, mud banks, and sabkhas. The location and extent of these facies were probably influenced by changes in sea level, relict topographic highs, and syndepositional fault movements (Smosna and others, 1989). Patch reef bioherms, consisting of corals, stromatoporoids, bryozoan, and crinoids, are important as gas reservoirs in the Lockport Dolomite, especially in Ohio and Pennsylvania (Figure Sld-7). In the southern portion of the play area, specifically West Virginia, carbonate buildups are also predominantly patch reef bioherms (Smosna and others, 1989). However, these Lockport carbonate buildups change in character from patch reef bioherm facies in West Virginia to skeletal sand shoal facies in Kentucky (Smosna and others, 1989).

The Keefer Sandstone ranges in color from a light tan to pale brown to locally greenish-tan. Regionally, the lithology varies from a poorly to very well-sorted, very fine- to medium-grained, subangular to rounded sandstone and dolomitic sandstone with locally thin conglomerate beds consisting predominately of well-rounded to subrounded, frosted, milky quartz and occasional chert. The cementing agents include quartz, dolomite, calcite, and ankerite. The Keefer Sandstone undergoes facies changes from coarse-grained sandstones in southeastern Kentucky to fine-grained sandstones, siltstones, and sandy dolomites in east-central and northeastern Kentucky (Currie, 1981). The Keefer

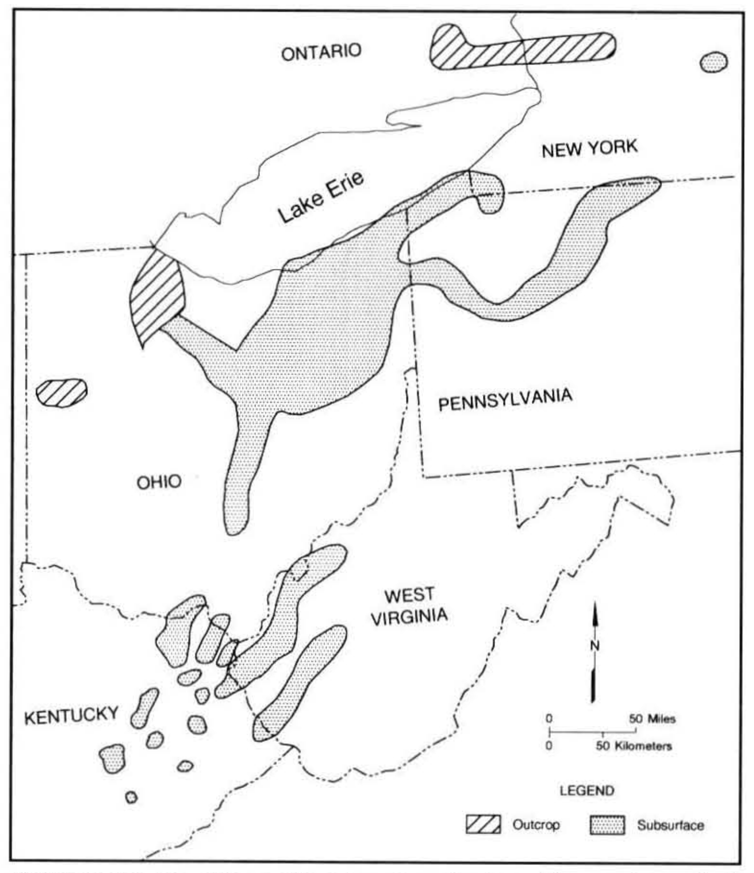


Figure Sld-7. Locations of Lockport reefs along the western shelf of the Appalachian basin. Coral-stromatoporoid reefs are important gas reservoirs in the Lockport Dolomite, especially in Ohio and Pennsylvania. From Smosna and others (1989).

Sandstone is a complex facies assemblage representing many different depositional environments found in coastal marine and shallow marine settings (Smosna, 1983; Meyer and others, 1992).

Structure

Much of the Lockport Dolomite and Keefer Sandstone play is predominantly characterized by eastwardly dipping strata on the west flank of the Appalachian basin intersected by zones of high-angle basement faulting, especially in the southern portion of the play area. In the northern portion of the play area, gas production is exclusively from the Lockport Dolomite and is dominated by stratigraphic traps in porous carbonate buildups (Smosna and others, 1989).

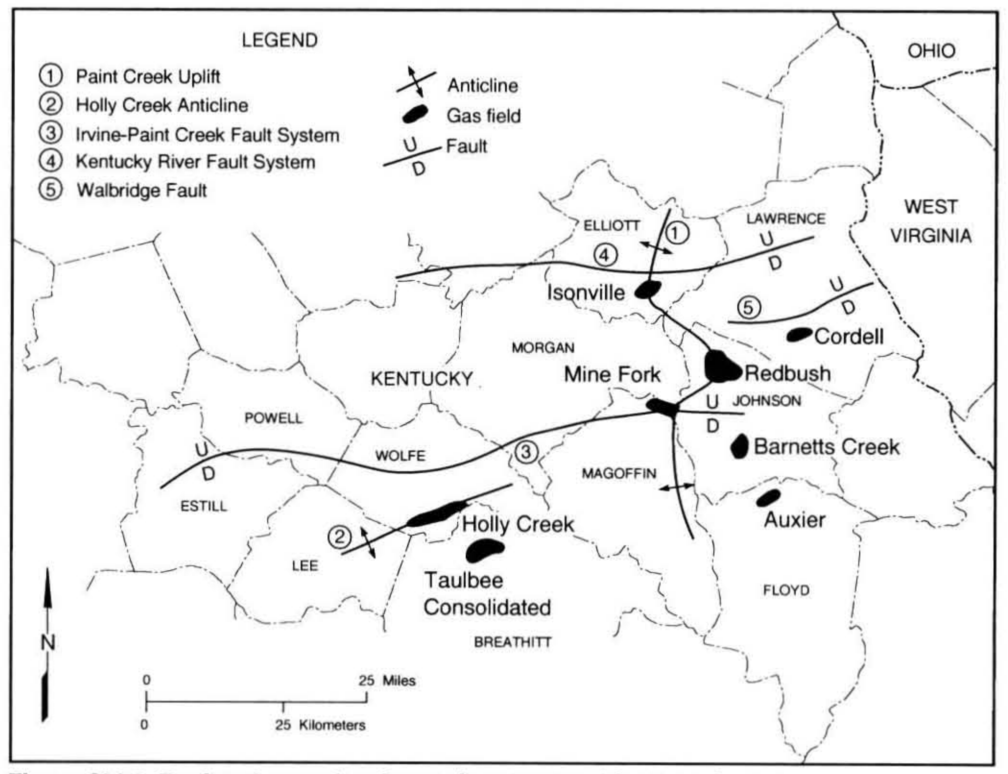


Figure Sld-8. Regional map showing major structural features in eastern Kentucky and several Lockport Dolomite and Keefer Sandstone gas fields. Structure influenced the trapping of gas in the fields shown.

However, Lockport Dolomite gas production may be enhanced locally by fractures and structural closures along minor basement faults. In contrast, structural complexity increases in the southern portion of the play area, where several anticlinal uplifts are associated with three major east-west trending basement fault zones. In eastern Kentucky, much of the gas production from the Lockport Dolomite appears to be structurally controlled by the anticlinal uplifts and faults, whereas the Keefer Sandstone in this region is dominated by combination stratigraphic-structural traps. Major structural features that influenced gas entrapment in Lockport Dolomite and Keefer Sandstone reservoirs are the Paint Creek uplift, Holly Creek anticline, the Irvine-Paint Creek and Kentucky River fault systems, and Walbridge fault (Figure Sld-8).

The Paint Creek uplift, in eastern Kentucky (Figure Sld-8), is a north-south trending anticline (Browning, 1921; Hudnall and Williams, 1924; Hudnall and Pirtle, 1927; Robinson, 1927; Robinson and others, 1928) with about 250 feet of closure near the surface on the Fire Clay coal bed (McFarlan, 1943). Subsurface studies indicate that significant structural closure persists on several other horizons along the uplift (Miller and Withers, 1926; Hauser, 1953; Dohm, 1963). Isonville Consolidated, Redbush Consolidated, and Mine Fork fields are located near the axis of the Paint Creek uplift (Figure Sld-8), and produce gas from Lockport Dolomite reservoirs that have anticlinal or fault closure. The Holly Creek field in Kentucky (Figure Sld-8) is associated with the Holly Creek

TABLE Sld-1		Redbush Consolidated KY	Cordell Consolidated KY	Isonville Consolidated KY	Taulbee Consolidated KY	Mine Fork KY	Auxier DBS KY	Holly Creek Consolidated KY	Whites Creek Gragston WV	Woodbury OH
BASIC RESERVOIR DATA	POOL NUMBER	1601630 355 LCKP	1600478 355 LCKP	160135 355 LCKP	1601955 355 LCKP	1601319 355 LCKP	1600066 355 LCKP	1600977 355 LCKP	47229545 MCKZ	973
	DISCOVERED	1918	1927	1917	1967	1931	1931	1961	1932	1964
	DEPTH TO TOP RESERVOIR	1,680	2,521	1,538	1,705	1,423	2,781	1,485	3,795	1,550
	AGE OF RESERVOIR	Silurian	Silurian	Silurian	Silurian	Silurian	Silurian	Silurian	Silurian	Silurian
	FORMATION	Lockport	Lockport	Lockport	Lockport	Lockport	Lockport	Lockport	McKenzie Lockport	Lockport
	PRODUCING RESERVOIR	Lockport	Lockport	Lockport	Lockport	Lockport	Lockport	Lockport	Lockport	Lockport
	LITHOLOGY	dolomite	dolomite	dolomite	dolomite	dolomite	dolomite	dolomite	dolomite	dolomite
	TRAP TYPE	structural	combination	structural	combination	structural	combination	structural	stratigraphic	combination
	DEPOSITIONAL ENVIRONMENT	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine
	DISCOVERY WELL IP (Mcf)	50		100	30	103	521	273	994	2,600
	DRIVE MECHANISM	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	water
	NO. PRODUCING WELLS	63	24	33	14	19	16	14	6	17
	NO. ABANDONED WELLS	9	9	0	2	0	0	1	11	6
	AREA (acreage)	6,480	2,970	1,820	980	1,610	1,120	1,200		
	OLDEST FORMATION PENETRATED	Rome	Clinton	Clinton	Ordovician	Conasauga	Ohio Shale	Clinton	Rose Hill	Rome
	EXPECTED HETEROGENEITY DUE TO:	structure diagenesis	deposition structure	structure deposition	fracture diagenesis	structure diagenesis	structure deposition	structure deposition	deposition diagenesis	deposition structure
RESERVOIR PARAMETERS	AVERAGE PAY THICKNESS (ft.)	11	11		9	6	9	5	12	15
	AVERAGE COMPLETION THICKNESS (ft.)	291	311	79	18	279	30	8		
	AVERAGE POROSITY--LOG (%)	8	11		10	8		13		10
	MINIMUM POROSITY--LOG (%)	2	4		6	3		10		5
	MAXIMUM POROSITY--LOG (%)	17	13		14	15		15		20
	NO. DATA POINTS	69	3	0	2	7	0	2		3
	POROSITY FEET									
	RESERVOIR TEMPERATURE (°F)	73	86		77	74		81		70
	INITIAL RESERVOIR PRESSURE (psi)		610/ 1959			485	475		1,005	500
	PRODUCING INTERVAL DEPTHS (ft.)	1,420-2,200	1,896-2,930	1,346-1,756	1,468-1,870	1,285-1,565	2,300-3,178	1,359-1,760	3,537-3,887	1,500-1,600
	PRESENT RESERVOIR PRESSURE (psi) / DATE	380/ 1993	490/ 1967	305/ 1930	325/ 1985	450/ 1991	505/ 1940	285/ 1991		
FLUID & GAS PROPERTIES	Rw (Ωm)	0.05	0.04		0.05	0.05	0.06	0.06		0.20
	GAS GRAVITY (g/cc)	0.635	0.635	0.635		0.635	0.635			
	GAS SATURATION (%)	74	88			75		85		75
	WATER SATURATION (%)	26	12			25		15		25
	COMMINGLED	yes	yes	yes	yes	yes	yes	yes		no
	ASSOCIATED OR NONASSOCIATED	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated		nonassociated
	Btu/scf	990	990	990		990	990			
VOLUMETRIC DATA	STATUS (producing, abandoned, storage)	producing	producing	producing	producing	producing	producing	producing	producing	producing
	ORIGINAL GAS IN PLACE (Mcf)	6,400,000	5,900,000	1,900,000	1,200,000	1,400,000	4,800,000	1,100,000		2,000,000
	ORIGINAL GAS RESERVES (Mcf)	5,300,000	4,800,000	1,600,000	1,100,000	1,250,000	4,000,000	900,000		1,700,000
	PRODUCTION YEARS	1976-1992				1982-1992	1931-1953		1981-1992	
	REPORTED CUMULATIVE PRODUCTION (Mcf)	3,920,000				1,210,000	4,000,000		86,285	809,000
	NO. WELLS REPORTED	51					16		3	8
	ESTIMATED CUMULATIVE PRODUCTION (Mcf)									1,400,000
	REMAINING GAS IN PLACE (Mcf)/DATE	2,480,000/ 1992				190,000/ 1992	800,000/			600,000/ 1993
	REMAINING GAS RESERVES (Mcf)/DATE	1,380,000/ 1992				40,000/ 1992	0/ 1953			300,000 1993/
	RECOVERY FACTOR (%)	83	81	84	92	89	83	82		85
	INITIAL OPEN FLOW (Mcf/d)									500
	FINAL OPEN FLOW (Mcf/d)	236	251	370	33	277	511	173	319	500

TABLE Sld-1		Mayfield OH	Canaan-Wayne OH	Franklin OH	Newburgh Heights OH	Canal Fulton OH	Newark South OH	Thurston OH	Mansfield OH	Martinsburg South OH	Wolf Creek-Kilgore PA	Geneva NY
BASIC RESERVOIR DATA	POOL NUMBER	323	421	460	333	294	569	625	890	536		
	DISCOVERED	1938	1917	1957	1912	1927	1921	1938	1906	1912	1966	1932
	DEPTH TO TOP RESERVOIR	2,820	2,560	3,050	2,570	3,550	2,150	1,950	1,950	2,200	5,341	950
	AGE OF RESERVOIR	Silurian	Silurian	Silurian	Silurian	Silurian	Silurian	Silurian	Silurian	Silurian	Silurian	Silurian
	FORMATION	Lockport	Lockport	Lockport	Lockport	Lockport	Lockport	Lockport	Lockport	Lockport	Lockport	Lockport
	PRODUCING RESERVOIR	Lockport	Lockport	Lockport	Lockport	Lockport	Lockport	Lockport	Lockport	Lockport	Lockport	Lockport
	LITHOLOGY	dolomite	dolomite	dolomite	dolomite	dolomite	dolomite	dolomite	dolomite	dolomite	dolomite	dolomite
	TRAP TYPE	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	combination	stratigraphic
	DEPOSITIONAL ENVIRONMENT	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine
	DISCOVERY WELL IP (Mcf)	750		848	12,500	4,500		300	1,100	1,300	177	1,200
	DRIVE MECHANISM	water	water	water	water	water	water	water	water	water		gas expansion
	NO. PRODUCING WELLS	0	23	1	0	0	5	0	1	7	14	0
	NO. ABANDONED WELLS	43	64	32	49	18	3	22	17	16	0	30
	AREA (acreage)	814		641	358		20	138		429		900
	OLDEST FORMATION PENETRATED	Knox	Trempealeau	Rome	Queenston	Queenston	Queenston	Trempealeau	Queenston	Queenston	Queenston	Black River
	EXPECTED HETEROGENEITY DUE TO:	deposition structure	deposition fracture	deposition structure	deposition structure	deposition structure	deposition structure	deposition structure	deposition diagenesis	deposition diagenesis	fracture	diagenesis
RESERVOIR PARAMETERS	AVERAGE PAY THICKNESS (ft.)	45	15	25	20	20	17	10	15	15		20
	AVERAGE COMPLETION THICKNESS (ft.)											20
	AVERAGE POROSITY--LOG (%)		9	4								
	MINIMUM POROSITY--LOG (%)		6	2								
	MAXIMUM POROSITY--LOG (%)		17	15								
	NO. DATA POINTS		5	1								
	POROSITY FEET											
	RESERVOIR TEMPERATURE (°F)	85			85	95			80		55	
	INITIAL RESERVOIR PRESSURE (psi)	1,100	880	1,275	1,100	1,465			635	800	1,490	940
	PRODUCING INTERVAL DEPTHS (ft.)	2,760-2,850	2,560-3,075	2,940-3,120	2,460-2,750	3,450-3,650	2,050-2,200	1,930-1,990	1,925-1,975	2,000-2,320	5,341-5,370	950-1,100
	PRESENT RESERVOIR PRESSURE (psi) / DATE		420/ 1961	750/ 1989				700/ 1955	340/ 1975	580/ 1940		
FLUID & GAS PROPERTIES	Rw (Ωm)		0.055									
	GAS GRAVITY (g/cc)				0.617							
	GAS SATURATION (%)		40									
	WATER SATURATION (%)		30	28								
	COMMINGLED	yes	yes	no	no	yes	no	no	yes	no		
	ASSOCIATED OR NONASSOCIATED	nonassociated	associated	nonassociated	nonassociated	nonassociated	associated	associated	nonassociated	nonassociated		nonassociated
	Btu/scf				1,053							
VOLUMETRIC DATA	STATUS (producing, abandoned, storage)	abandoned	producing	producing	abandoned	abandoned	producing	abandoned	producing	producing		abandoned
	ORIGINAL GAS IN PLACE (Mcf)	17,700,000	23,700,000	4,800,000	3,100,000	3,180,000	1,570,000	2,070,000	1,270,000	2,160,000		150,000
	ORIGINAL GAS RESERVES (Mcf)	15,000,000	20,200,000	4,080,000	2,600,000	2,700,000	1,330,000	1,760,000	1,080,000	1,840,000		
	PRODUCTION YEARS	1938-1948	1917-1992			1928-1937						
	REPORTED CUMULATIVE PRODUCTION (Mcf)	11,894,000	1,237,000			1,363,000					5,800,000	100,000
	NO. WELLS REPORTED	36	8			4						
	ESTIMATED CUMULATIVE PRODUCTION (Mcf)	15,000,000	19,200,000	4,080,000	2,600,000	2,700,000	1,320,000	1,760,000	1,075,000	1,830,000		
	REMAINING GAS IN PLACE (Mcf)/DATE	2,700,000/ 1993	4,500,000/ 1993	40,000/ 1993	500,000/ 1993	480,000/ 1993	250,000/ 1993	310,000/ 1993	195,000/ 1993	330,000/ 1993		
	REMAINING GAS RESERVES (Mcf)/DATE	0/ 1993	1,000,000/ 1993	0/ 1993	0/ 1993	0/ 1993	10,000/ 1993	0/ 1993	5,000/ 1993	10,000/ 1993		
	RECOVERY FACTOR (%)	85	85	85	85	85	85	85	85	85		
	INITIAL OPEN FLOW (Mcf/d)	500	300	800		1,000	100	500		700		450
	FINAL OPEN FLOW (Mcf/d)	1,000	200	1,500			100	250	500	200		75

TABLE Sld-1		Taulbee Consolidated KY	Stevenson KY	Ary DBS KY	Puncheon Camp Ck. Consolidated KY	Mine Fork KY	Van Lear DBS KY	Beetree KY	Barnetts Creek Consolidated KY	Royalton KY	Whites Creek Gragston WV
BASIC RESERVOIR DATA	POOL NUMBER	1601955 355 BGSX	1601896 355 BGSX	1600057 355 BGSX	1601596 355 BGSX	1601319 355 BGSX	1062038 355 BGSX	1600156 355 BGSX	1600095 355 BGSX	1601710 355 BGSX	47229355 KEFR
	DISCOVERED	1918	1927	1969	1945	1982	1945	1947	1933	1946	1930
	DEPTH TO TOP RESERVOIR	1,889	2,014	2,969	2,666	1,885	2,826	2,536	2,404	2,228	3,865
	AGE OF RESERVOIR	Silurian	Silurian	Silurian	Silurian	Silurian	Silurian	Silurian	Silurian	Silurian	Silurian
	FORMATION	Keefer	Keefer	Keefer	Keefer	Keefer	Keefer	Keefer	Keefer	Keefer	Keefer
	PRODUCING RESERVOIR	Keefer	Keefer	Keefer	Keefer	Keefer	Keefer	Keefer	Keefer	Keefer	Keefer
	LITHOLOGY	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone
	TRAP TYPE	combination	combination	combination	combination	combination	combination	combination	combination	combination	combination
	DEPOSITIONAL ENVIRONMENT	coastal marine	coastal marine	coastal marine	coastal marine	coastal marine shallow shelf	coastal marine shallow shelf	coastal marine	coastal marine shallow shelf	coastal marine	shallow shelf
	DISCOVERY WELL IP (Mcf)	5,750	500	1,163	1,243	416	67	33	213	561	
	DRIVE MECHANISM	gas expansion water	gas expansion water	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion water	gas expansion	gas expansion water	gas expansion
	NO. PRODUCING WELLS	83	32	13	27	11	3	12	41	56	20
	NO. ABANDONED WELLS	10	2	1	5	0	10	2	13	3	28
	AREA (acreage)	7,440	2,040	1,120	1,500	1,100	1,560	840	5,400	4,720	
	OLDEST FORMATION PENETRATED	Clinton	Clinton	Clinton	Rose Hill	Copper Ridge	Clinton	Clinton		Clinton	Rose Hill
	EXPECTED HETEROGENEITY DUE TO:	deposition diagenesis	deposition diagenesis	deposition diagenesis	deposition diagenesis	deposition diagenesis	deposition diagenesis	deposition diagenesis	deposition diagenesis	deposition diagenesis	deposition diagensis
RESERVOIR PARAMETERS	AVERAGE PAY THICKNESS (ft.)	14	29	7	10	8			10	8	28
	AVERAGE COMPLETION THICKNESS (ft.)	40	36	49	42	37	43	35	52	35	
	AVERAGE POROSITY--LOG (%)	14	13	9	13	11			11	9	
	MINIMUM POROSITY--LOG (%)	8	4	4	5	3			4	8	
	MAXIMUM POROSITY--LOG (%)	24	18	14	18	15			17	13	
	NO. DATA POINTS	61	7	5	1	12			6	4	
	POROSITY FEET										
	RESERVOIR TEMPERATURE (°F)	77	74	90		74			78	77	
	INITIAL RESERVOIR PRESSURE (psi)	560		510	660	425		660	800	665	
	PRODUCING INTERVAL DEPTHS (ft.)	1,610-2,412	1,680-2,465	2,890-3,088	2,442-2,940	1,715-2,100	2,744-3,049	2,326-2,688	2,404-2,759	2,129-2,452	3,725-4,065
	PRESENT RESERVOIR PRESSURE (psi) / DATE	170/1992		275/1972	456/1961	410/1993	450/1971		295/1969	305/1985	
FLUID & GAS PROPERTIES	Rw (Ωm)	0.05	0.05		0.05			0.05		0.05	
	GAS GRAVITY (g/cc)	0.691	0.691	0.691	0.643	0.698	0.615	0.643	0.615	0.643	
	GAS SATURATION (%)	70	76		66	78			72	65	
	WATER SATURATION (%)	30	24		34	22			28	35	
	COMMINGLED	yes	yes	yes	yes	yes	yes		yes	yes	
	ASSOCIATED OR NONASSOCIATED	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated
	Btu/scf	1,122	1,122	1,061	1,061	1,147	990	1,061	990	1,061	
VOLUMETRIC DATA	STATUS (producing, abandoned, storage)	producing	producing	producing	producing	producing	producing	producing	producing	producing	producing
	ORIGINAL GAS IN PLACE (Mcf)	18,760,000	10,360,000	3,090,000	6,780,000	1,020,000	4,710,000	3,240,000	10,740,000	16,200,000	
	ORIGINAL GAS RESERVES (Mcf)	16,840,000	9,320,000	2,780,000	6,100,000	914,000	4,240,000	2,920,000	9,670,000	14,560,000	
	PRODUCTION YEARS	1969-1990	1980-1990	1992	1992	1984-1992	1992		1945-1992		1979-1993
	REPORTED CUMULATIVE PRODUCTION (Mcf)	4,940,000+	790,000+	1,770,000+	4,680,000+	20,000+	390,000+		2,090,000+		275,087
	NO. WELLS REPORTED	26	10	6	20	2	8		36		15
	ESTIMATED CUMULATIVE PRODUCTION (Mcf)										
	REMAINING GAS IN PLACE (Mcf)/DATE	565,000	715,000	<1,320,000	<2,100,000	<1,000,000	<4,320,000		<8,650,000		
	REMAINING GAS RESERVES (Mcf)/DATE	526,000	643,000	<1,010,000	<1,420,000	<894,000	<3,850,000		<7,580,000		
	RECOVERY FACTOR (%)	90	90	90	90	90	90	90	90	90	
	INITIAL OPEN FLOW (Mcf/d)										
	FINAL OPEN FLOW (Mcf/d)	907	428	1,287	573	414	172	6,327	292	3,479	337

TABLE Sld-2	Mayfield OH	Franklin OH	Wolf Creek Kilgore PA	Taulbee Consolidated KY	Puncheon Camp Ck. Consolidated KY	Barnetts Creek Consolidated KY
AVERAGE POROSITY--CORE (%)	14	4	3.4	14.4	11	10.2
MINIMUM POROSITY--CORE (%)	5	1		6	8	6.5
MAXIMUM POROSITY--CORE (%)	37	15	9.6	28	14	11.6
NO. DATA POINTS	1	1		3	1	1
AVERAGE PERMEABILITY (md)		<1	50.6	9.3	3	

anticline and the Irvine-Paint Creek fault system (McGuire, 1964). The Cordell Consolidated field in Kentucky is located on the downthrown side of the Walbridge fault (Figure Sld-8).

The degree to which structure contributes to gas entrapment in the Keefer Sandstone varies from field to field and within individual fields. In most cases, structural noses or closures help localize gas production in the Keefer Sandstone. Several fields in eastern Kentucky where gas production from the Keefer Sandstone is at least partially controlled by structure are Beetree, Royalton (Young, 1949), Ary District of Big Sandy, Mine Fork, and Redbush Consolidated fields (Figures Sld-4, Sld-8). It is important to note that structure may have influenced Keefer Sandstone deposition locally, particularly along faults associated with the Rome trough.

Reservoir

Field and reservoir data, including production if available, for all major fields in the Upper Silurian Lockport Dolomite and Keefer Sandstone play are shown in Tables Sld-1 and Sld-2. Stratigraphic, structural, and combined stratigraphic-structural traps are responsible for hydrocarbon accumulations in the Lockport Dolomite and Keefer Sandstone play. In Lockport Dolomite reservoirs, stratigraphic and combined stratigraphic-structural traps are common throughout much of the play area. Many of these traps are developed in porous patch reef bioherms or skeletal sand shoals encased in impermeable argillaceous dolomite. However, structure plays an important role in trapping gas in the Lockport Dolomite gas fields of eastern Kentucky. In this area, anticlinal and fault closures form many traps. Keefer Sandstone gas reservoirs are dominated by combination stratigraphic-structural traps, caused by porous and permeable zones draping over a structural nose or closure. Locally, traps also exist where porosity and permeability pinch out up dip or along the flanks of structures.

Reservoir lithologies in the Lockport Dolomite and Keefer Sandstone play include carbonate mudstones, wackestones, packstones, grainstones, boundstones and siliciclastic sandstones. Porosity development in Lockport Dolomite reservoirs was primarily controlled by depositional facies and diagenetic history. The patch reef bioherm and skeletal sand shoal facies form the most porous reservoirs throughout the play area. Average log calculated porosities for gas productive intervals in the Lockport Dolomite are typically 8 to 10 percent. Maximum porosities are commonly 14 percent and minimum porosities are 5 percent. The most significant types of porosity in terms of reservoir storage capacity are moldic, vuggy, interparticle, and intercrystalline porosity (Rhinehart, 1979; Maxwell, 1985; Smosna, 1986; Conrad, 1987; Laughrey, 1987; Smosna and others, 1989; Brett and others, 1991). Secondary fractures enhance gas production in some Lockport Dolomite fields. Early secondary moldic and intercrystalline porosity developed as a result of subaerial exposure during sea-level fluctuations. The influx of meteoric waters selectively leached out corals and stromatoporoids, creating moldic porosity (Smosna and others, 1989). Intercrystalline porosity developed in the mixing zones between fresh and marine waters. Vugs formed by solution enlargement of existing fossil molds after burial (Smosna and others, 1989). Fracture porosity developed as a result of tectonic stress after burial (Conrad, 1987). Reservoirs that produce gas from bioherms in coral-stromatoporoid boundstone facies in West Virginia have a few large vugs and some open horizontal fractures (Smosna and Patchen, 1980).

Intergranular porosity is the main porosity type encountered in Keefer Sandstone reservoirs. The porosity is primary in origin and frequently enhanced by secondary dissolution of rock fragments and feldspars. Diagenesis has played the role of both porosity enhancer and reducer. The major Keefer Sandstone

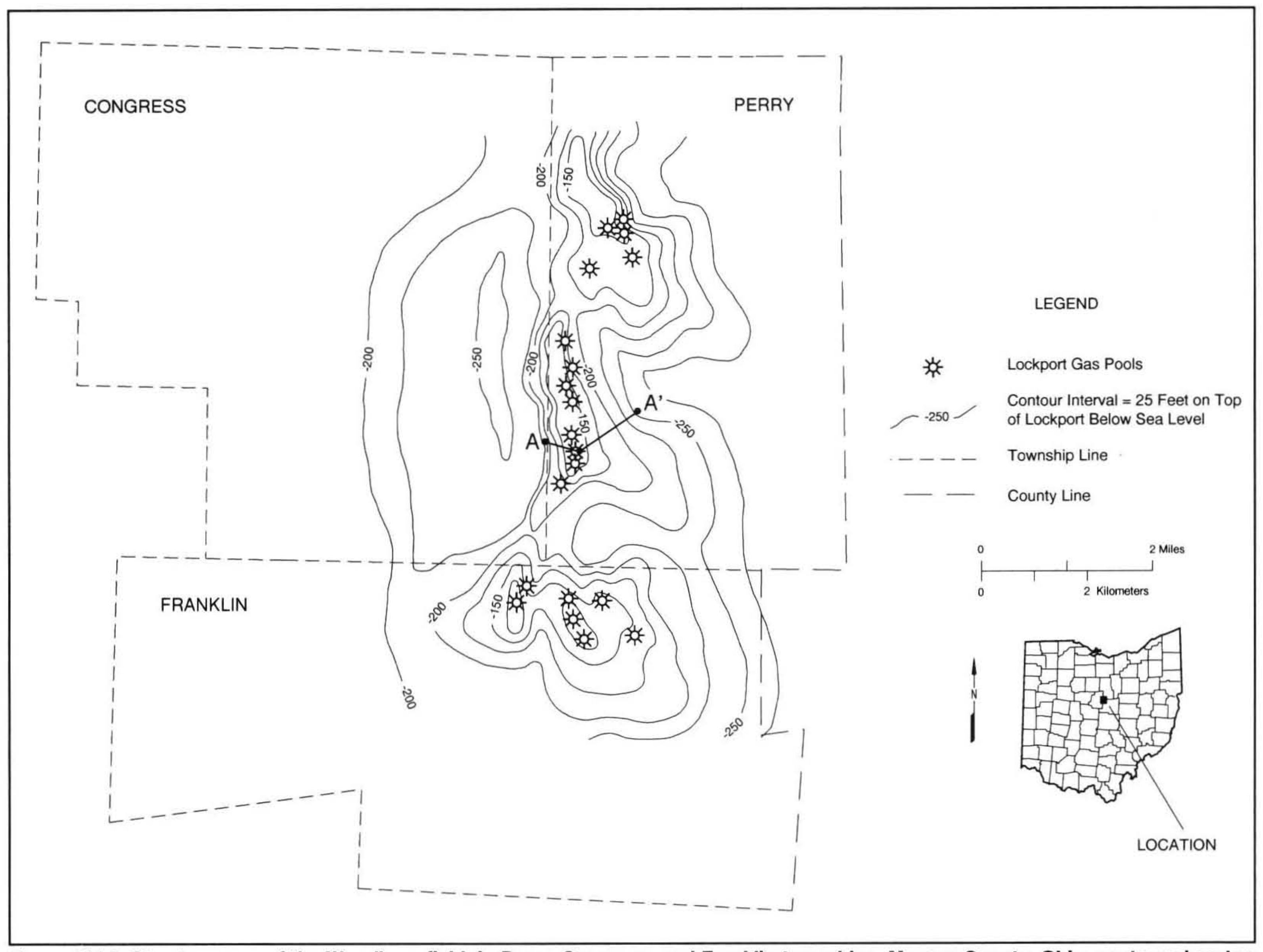


Figure Sld-9. Structure map of the Woodbury field, in Perry, Congress, and Franklin townships, Morrow County, Ohio, contoured on top of the Upper Silurian Lockport Dolomite. Apparent structural highs correlate to Lockport gas pools that produce from carbonate bioherm reservoirs. Line of cross section A-A' (Figure Sld-10) is also shown. Structure map is courtesy of Ohio Energy Assets, Inc., Columbus, Ohio.

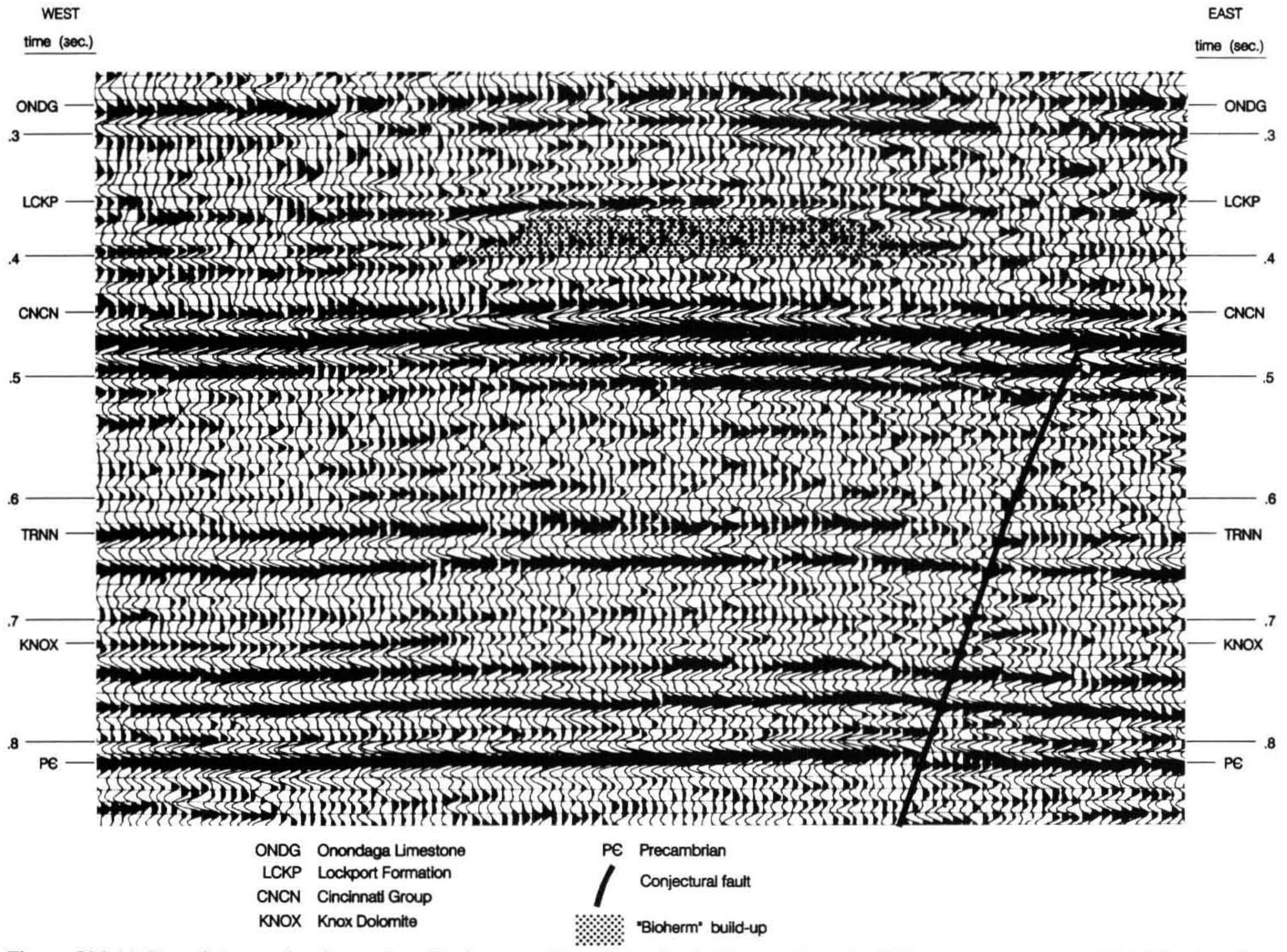


Figure Sld-11. Proprietary seismic section display over Woodbury field, Morrow County, Ohio; source-rammer, 30-fold, migration, normal polarity. Carbonate bioherm is located in the middle of the figure at 0.34 seconds. An approximately 10-millisecond increase in isochron thickness occurs between the top of the "Cincinnati" and Lockport reflectors. Conjectural fault east of the bioherm may have enhanced bioherm growth. Seismic section is courtesy of Ohio Energy Assets, Inc., Columbus, Ohio.

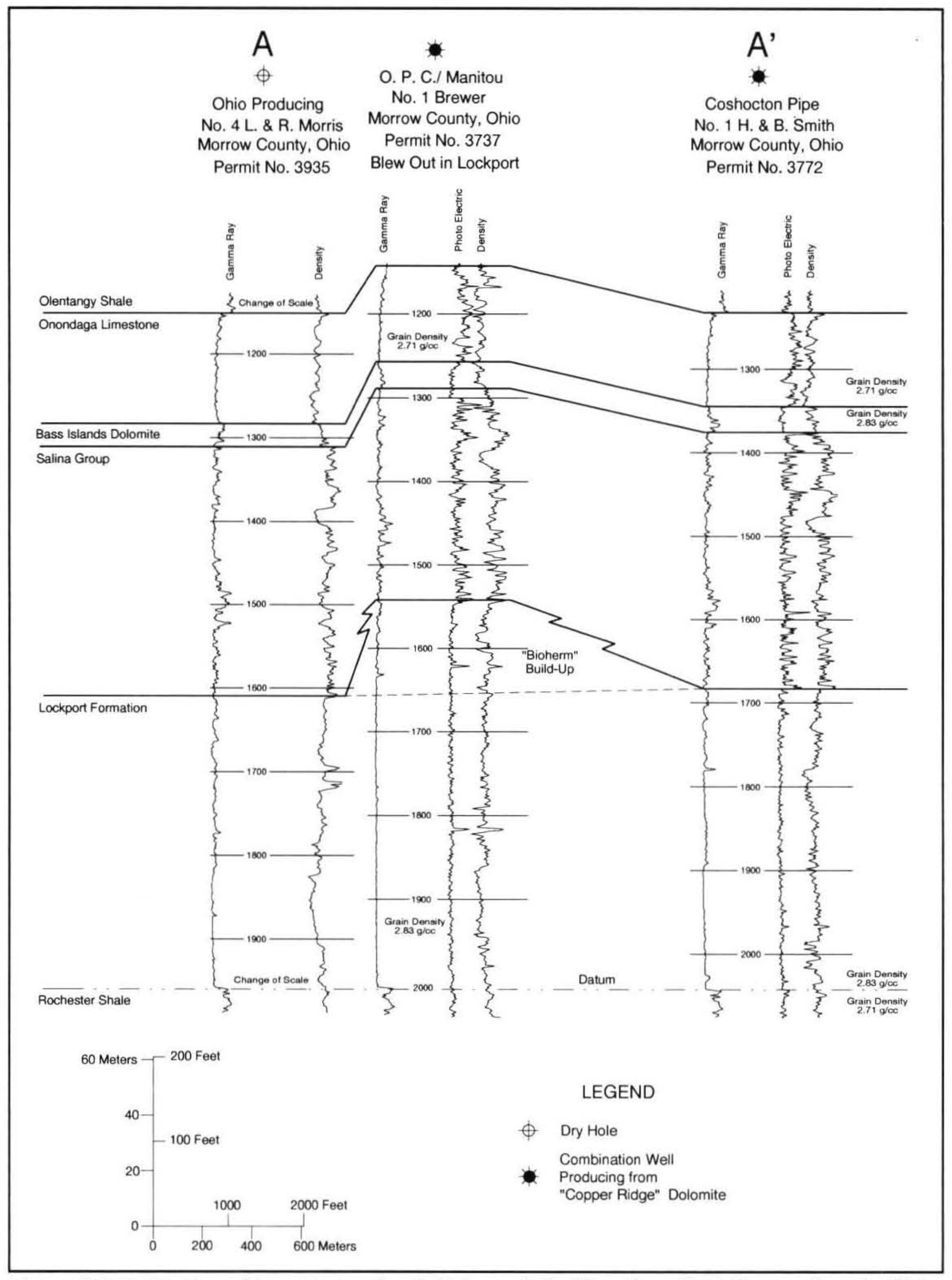


Figure Sld-10. Stratigraphic cross section A-A' through the Woodbury field, Morrow County, Ohio, illustrating the thickening of the Lockport Dolomite caused by biohermal buildups. Stratigraphic datum is the top of the Rochester Shale. Line of cross section is shown in Figure Sld-9.

cementing agents are quartz (in the form of overgrowths) and ankerite. These two major cements are associated with different depositional facies. The quartz-cemented sandstones reflect a coastal facies, whereas the ankerite-cemented sandstones reflect a marine-shallow shelf facies. The relationship between cementing agents and facies also has been observed in northeastern West Virginia and western Maryland (Meyer and others, 1992). The average calculated log porosity for the producing zone is 12 percent with a range from 9 to 15 percent. Maximum porosity ranges from 13 to 28 percent; minimum porosity ranges from 3 to 9 percent. The average permeability based on five cores in three fields is 7.06 md with a range of 0.81 to 50 md. The maximum permeability ranges from 7 to 133 md. Heterogeneity is significant in both Lockport Dolomite and Keefer Sandstone reservoirs. In these reservoirs, heterogeneity was caused by a combination of varied depositional environments, diagenesis, and structure.

Seals for entrapment of hydrocarbons in the Lockport Dolomite are provided by impermeable carbonate mudstones in the Lockport Dolomite lagoonal facies and overlying Salina evaporites. Dense carbonate mudstones of the inter-reef facies and restricted-lagoonal facies, within the Lockport Dolomite, could provide a lateral seal (Conrad, 1987). Reservoir seals in the Keefer Sandstone are provided by impermeable Keefer Sandstone facies and the overlying impermeable facies of the Lockport Dolomite. Lateral seals in the Keefer Sandstone are caused by facies changes that significantly reduce porosity and permeability. The source of hydrocarbons in the Lockport Dolomite and Keefer Sandstone play is believed to be Devonian Ohio Shale (Zielinski and McIver, 1982). Additional sources may exist in the Lockport Dolomite itself or in the Crab Orchard (Clinton Shale). Geochemical oil to source rock correlations, done by Cole and others (1987), suggest that some Silurian oils in Ohio may have been generated from the Devonian Ohio Shale, and possibly the Upper Ordovician Point Pleasant Shale. Migration of hydrocarbons could have occurred along fracture zones, unconformities, and possibly within permeable stratigraphic units such as the Silurian "Clinton" Sandstone (Cole and others, 1987).

Drilling depths to the top of the Lockport Dolomite are typically between 1,500 and 3,000 feet, and range from 950 to 5,341 feet (Table Sld-1). Drilling depths to the top of the Keefer Sandstone range from 1,882 feet in Holly Creek Consolidated field in Kentucky to 3,865 feet in Whites Creek-Gragston field in West Virginia (Table Sld-1).

The average pay thickness for the Lockport Dolomite is 15 feet, with a range from 4 to 45 feet. On a regional basis, the pay intervals are thicker (20 feet) in the northern portion of the play area as compared to the pay intervals (8 feet) in the southern portion of the play area. This contrast in thicknesses may be related to depositional facies, as well as gross thickness of the Lockport Dolomite. In the northern region, the Lockport Dolomite is generally thicker (52 to 587 feet thick) and has more Lockport Dolomite reservoirs in patch reef bioherms that grew vertically, thus forming thicker reservoirs. In the southern area, especially in Kentucky, the Lockport is thinner (0 to 230 feet thick) and has several reservoirs formed by skeletal sand shoals that developed horizontally rather than vertically. The average pay thickness for the Keefer Sandstone is 14 feet with a range from 3 to 63 feet. The average completion interval for the Keefer Sandstone is 38 feet with a range from 28 to 52 feet.

Shut-in pressures varied throughout the play due to differences in producing depths and heterogeneity of reservoirs. The average initial shut-in pressure reported for the Lockport Dolomite was 875 psi. Average initial shut-in pressures in the northern region (1,103 psi) were generally higher than those in the southern region (615 psi). Final open flow values average 347 Mcfg/d, with a range from 33 to 2,000 Mcfg/d. The Keefer Sandstone reservoirs had an average initial shut-in wellhead pressure of 617 psi, with a range from 285 to 1,127 psi. The average final open flow was 1,111 Mcfg/d, with a range from 15 to 23,750 Mcfg/d.

Logging procedures varied considerably throughout the Lockport Dolomite and Keefer Sandstone play. For many years, the most common practice was to run a gamma-ray/caliper log along with a compensated formation density/neutron and temperature log. Relatively few resistivity logs were run. More recently, dual induction, litho-density, and ultrasonic gas detector logs have been run. Unfortunately, many wells have never been logged. Geophysical log curves, especially the gamma-ray signature of the Keefer Sandstone, can be misleading. In many cases, the best porosity, permeability, and production are associated with sandstone reservoirs that exhibit high natural radiation on the gamma-ray log. However, in other cases the high gamma-ray readings are a direct indication of shale. The high radioactivity in the sandstones may be caused by uranium in the more permeable intervals. Care must be taken when interpreting gamma-ray signatures to avoid significant errors in the identification of lithologies and depositional environments. These gamma-ray anomalies in the Keefer Sandstone also have been observed by Zelt (1983).

Completion and stimulation practices varied throughout the play area. The most common completion practice was to set 6.63-inch casing through shallow water-bearing zones and complete the well open hole, or set 4.5-inch casing over the pay zone and perforate. In the early years, most Lockport Dolomite producers were stimulated by nitroglycerine or completed natural. Since the late 1950s, most Lockport Dolomite wells were stimulated by an acid treatment. In comparison, many Keefer Sandstone wells have been stimulated by hydraulic fracturing techniques. The two most common methods were water/sand, and nitrogen foam/sand hydraulic fracture stimulation. Often, Keefer Sandstone, Lockport Dolomite, and other zones up-hole were commingled.

Description of Key Fields

Woodbury field: Woodbury field, in Morrow County, Ohio (Figure Sld-3), is a an example of a combination trap in the Lockport Dolomite that is dominated by stratigraphic factors. Bioherm development and dolomitization were the most important controls for hydrocarbon entrapment. However, structural movement along pre-existing basement faults may have contributed to reef growth during the Silurian.

Although discovered in 1964 during drilling for Copper Ridge paleoremnant production (see M.T. Baranoski and others, Cambrian-Ordovician Knox Group unconformity play, this atlas), significant drilling did not take place until the 1980s after the O.P.C./Manitou No.1 Brewer (permit no. 3737) in Morrow County, Ohio, blew out near the top of the Lockport Dolomite. Estimated cumulative gas production from the field is 1.4 bcfg for the period from 1964 to 1993. Structural mapping on the top of the Lockport Dolomite indicates up to 75 feet of closure as a result of the bioherm buildup (Figure Sld-9). The stratigraphic thickening caused by the biohermal buildup in the Lockport Dolomite is displayed in an east-west stratigraphic cross section A-A' (Figure Sld-10) through the central portion of Woodbury field. An east-west proprietary seismic section (Figure Sld-11) illustrates the carbonate buildup in the Lockport Dolomite, between 0.3 and 0.4 seconds, and later structural movement. Isochron mapping is very useful in determining the productive extent of the field. Unfortunately, isopach mapping is not practical in the development of some areas because the productive Lockport Dolomite wells are typically not drilled down through to a marker bed. The average depth to the top of the reservoir is 1,550 feet. Average initial and final open flows are 500 Mcfg/d.

The reservoir is a clean dolomite that has interconnected vuggy to pinpoint porosity. Average porosity is 10 percent and ranges from 5 to 20 percent. The producing reservoir is generally developed near the top of the Lockport Dolomite in stratigraphically discontinuous zones. An estimated gas/water column is 50 feet thick in the main portion of the field. Wells were typically completed natural, or acidized through perforations in casing. The drive mechanism is water. Gas production requires scrubbing for hydrogen sulfide. The field is currently shut-in due to low gas prices.

Redbush Consolidated field: The Redbush Consolidated field, in Johnson County, Kentucky (Figure Sld-3), was selected as a key field because it is an excellent example of a structurally controlled trap that produces from the Lockport Dolomite (Corniferous) and Keefer Sandstone (Big Six). It should be noted that the drillers' term Corniferous (see J.F. Meglen and M.C. Noger, Lower Devonian-Upper Silurian unconformity play, this atlas) is often used in Kentucky to describe the stratigraphic section from the Middle Devonian Onondaga Limestone to the Upper Silurian Lockport Dolomite (Figure Sld-6). At Redbush field, the Lockport Dolomite is the primary producing zone in the Corniferous interval. The field is located on the axis of the Paint Creek uplift in eastern Kentucky (Figure Sld-8) and was discovered in 1918. Early development drilling concentrated on the shallow Lower Mississippian Weir Sandstone, resulting in only five Lockport Dolomite gas wells being completed in the period from 1918 to 1932, and one Keefer Sandstone (Big Six) well completed in 1950. Undoubtedly, the presence of hydrogen sulfide gas, probably from the Salina Dolomite, hindered the pace of development drilling in the Lockport Dolomite reservoir. It was not until 1974 that development drilling in the Lockport Dolomite increased substantially. During the period from 1974 to 1993, 67 gas wells were completed from the Lockport Dolomite (Corniferous), including eight wells commingled with the Keefer Sandstone (Big Six). The cumulative production from the Lockport Dolomite and Keefer Sandstone reservoirs in the field is 3.92 bcfg from 51 wells from 1976 to 1992.

The trap at Redbush Consolidated field is a domal anticline with approximately 160 feet of structural closure on top of the Lockport Dolomite (Figure Sld-12). Structural mapping on numerous horizons, including the Keefer Sandstone, Salina Dolomite, Onondaga Limestone, Big Lime (Hauser, 1953) and Fire Clay coal, indicates a structural closure of similar magnitude. The average depth to the top of the Lockport Dolomite reservoir is 1,680 feet.

In the Redbush field, the Lockport Dolomite can be divided into five zones on the basis of gamma-ray log signatures (Figure Sld-13). Log calculations indicate that zone 4 is the primary pay zone, containing the thickest gas productive intervals that have porosity exceeding 4 percent. Zone 4 productive intervals range in thickness from 2 to 19 feet (Figure Sld-14) and have an average porosity of 8 percent. The maximum porosity observed on logs for zone 4 was 17 percent. In general, the thickest pay intervals within zone 4 occur near the crest or draped partially down the west side of the structural closure. Based on facies interpretations (Conrad, 1987) of a Lockport Dolomite core from the Wright-Ramsey No. 1-R well (Figure Sld-13), the zone 4 reservoir is composed of crinoidal and coral-stromatoporoid packstones and wackestones, which were deposited as a carbonate skeletal sand bank. Intercrystalline (dolomitic), moldic, and vuggy porosity are significant in the reservoir rock (Maxwell, 1985). Reservoir continuity is only fair due to depositional and diagenetic effects on the distribution of porosity.

Most Lockport Dolomite producing wells were completed open hole with 7-inch casing set in the top of the Onondaga Limestone (top of the Corniferous interval), or in the basal part of the Ohio Shale. In many wells, the entire Corniferous section was stimulated with nitroglycerin or acidized. Produced gas was commingled. Occasionally, casing was set through the Lockport Dolomite,

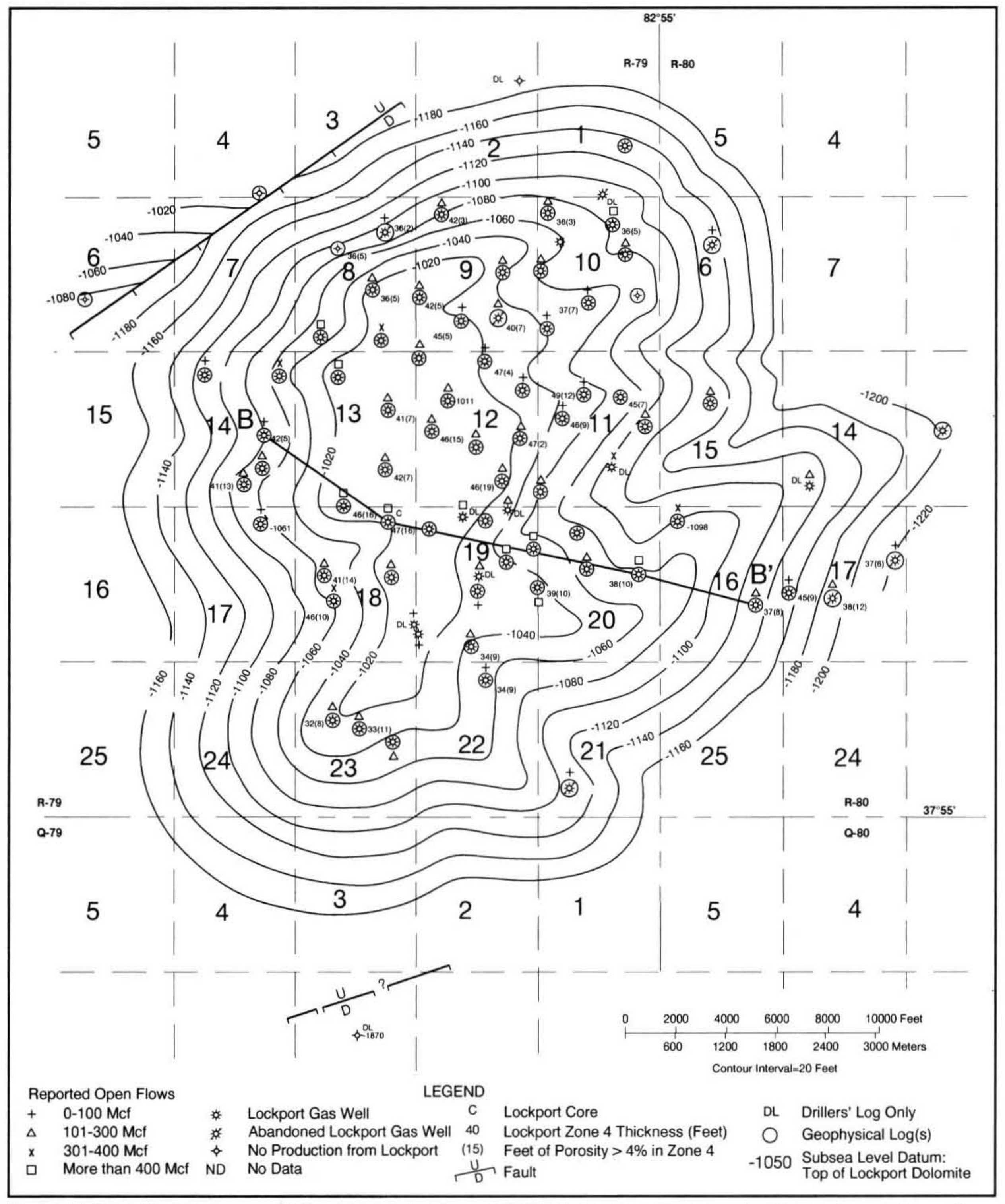


Figure Sld-12. Structure map of the Redbush Consolidated field, Johnson County, Kentucky, contoured on top of the Upper Silurian Lockport Dolomite. Most of the gas wells are located within the closure defined by the -1,080 subsea contour. See Figure Sld-8 for location. Line of cross section B-B' (Figure Sld-13) is also shown.

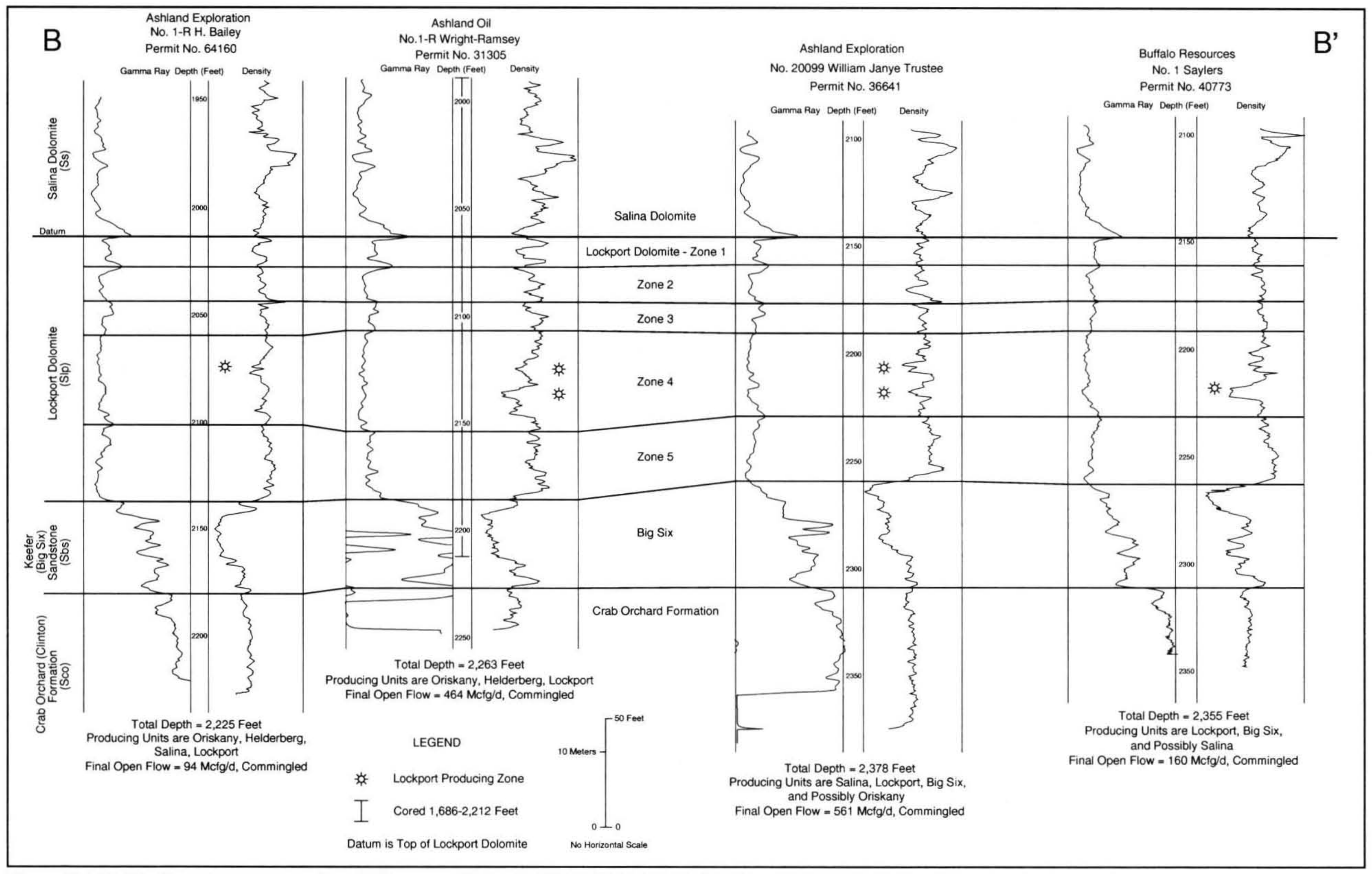


Figure Sld-13. Stratigraphic cross section B-B' across Redbush Consolidated field, Johnson County, Kentucky. The primary gas producing interval is zone 4 in the Lockport Dolomite. Line of cross section is shown in Figure Sld-12.

and selectively perforated and stimulated. Average final open flow for Lockport Dolomite wells was 236 Mcfg/d, with a range from 15 to 579 Mcfg/d. The Keefer Sandstone (Big Six) produced from at least nine wells, predominantly located on the flanks of the anticline. However, it is not known how much gas was actually produced from the Keefer Sandstone reservoir, because eight wells were commingled with the Lockport Dolomite.

Taulbee Consolidated field: Taulbee Consolidated field, in Breathitt County, Kentucky, is a good example of a combination stratigraphic-structural trap in the Keefer Sandstone. The field is actually parts of two fields separated by dry holes (Figures Sld-4, Sld-15). For the purposes of brevity, the northernmost field will be illustrated as an example of a combination stratigraphic-structural trap in the Keefer Sandstone. The southernmost field is partially shown in Figure Sld-15. Both fields are the same in regard to trap type and reservoir characteristics. Note that the northern and southern portions of the field are combined as Taulbee Consolidated field in Table Sld-1. The interpretation of the northern part of the field, referred to as North Taulbee field in this section, is based on 47 geophysical logs, three cores, and numerous drillers' logs.

North Taulbee field produces from two separate and distinct upper and lower zones in the Keefer Sandstone, as shown in cross section C-C' (Figure Sld-16). A structure map on the base of the Ohio Shale, an unconformity surface, shows numerous east-southeast plunging noses and occasional small structural closures, both of which play important roles in trapping gas in the Keefer Sandstone (Figure Sld-15). Some apparent structural relief on the base of the Ohio Shale may be due to erosion. However, erosional relief is not thought to be more than 15 feet over local structural features.

As illustrated by cross section C-C' (Figure Sld-16), two distinct zones produce in the field: the upper Keefer Sandstone, and the lower Keefer Sandstone. Net isopach maps (porosity greater or equal to 10 percent) of the upper and lower Keefer Sandstone reservoirs are shown in Figures Sld-17 and Sld-18, respectively. Porosity, in general, is continuous over the trend; however, the quality of the porosity changes significantly over short distances. Average porosity is 15 percent with a range of 6 to 29 percent.

Although porosity in general is continuous along mapped trends, permeability in many cases is less so. For example, in one area, a porosity of 18 percent is associated with a permeability of 50 md. However, in other areas or within the same well, that same 18 percent porosity is associated with a permeability of only 0.1 md. This is shown graphically by the porosity versus permeability plot (Figure Sld-19). Permeability seems to be controlled as much or more by diagenesis than by original depositional environments.

The trap occurs where porosity and permeability pinch out up dip, along flanks of structures or where porous and permeable zones are draped over structural noses or closures. Based on limited core and sample data, porosity in

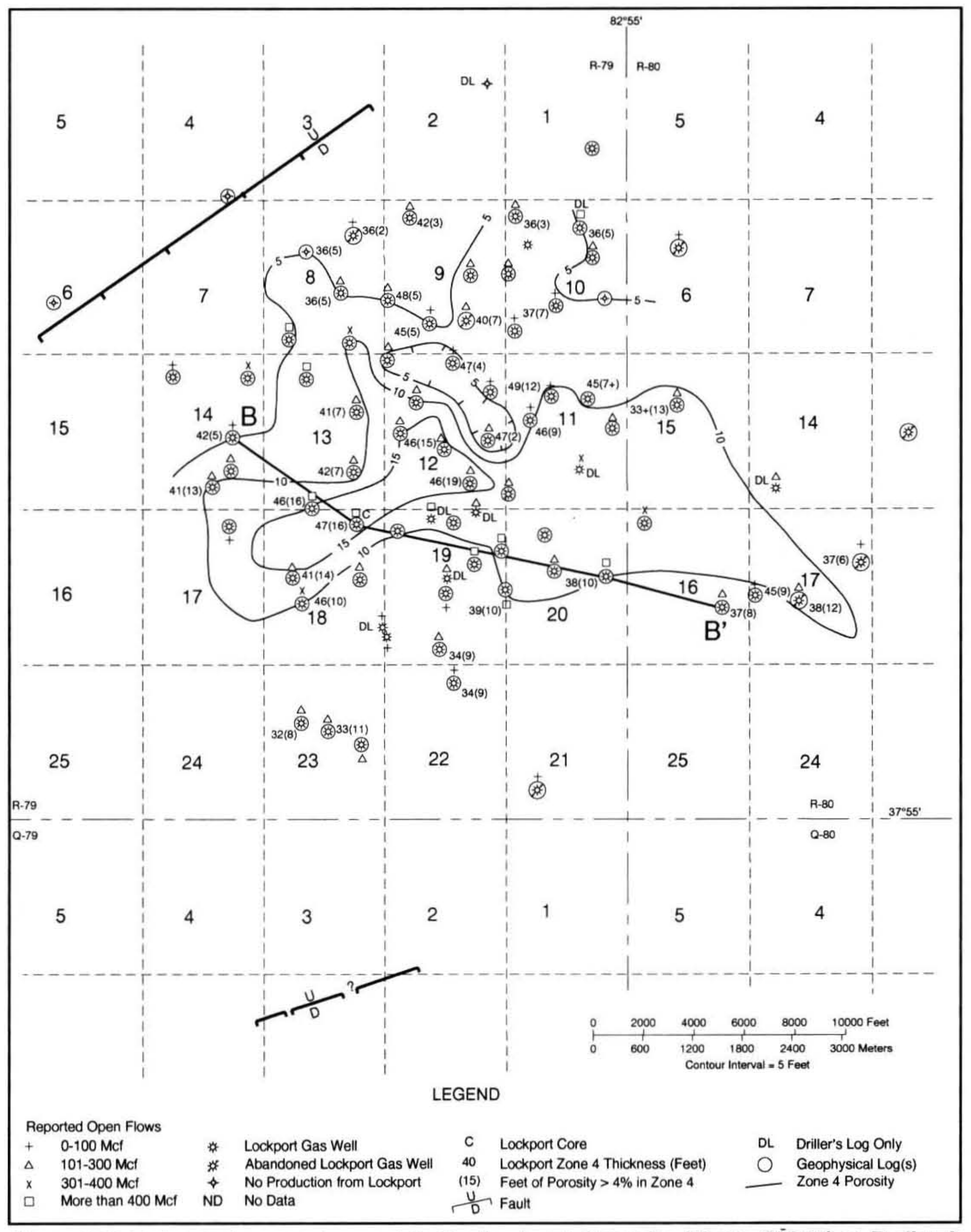


Figure Sld-14. Isopach map of zone 4 in the Lockport Dolomite (Figure Sld-13) at Redbush Consolidated field, Johnson County, Kentucky, showing net feet of porosity greater than or equal to 4 percent. See Figure Sld-8 for location.

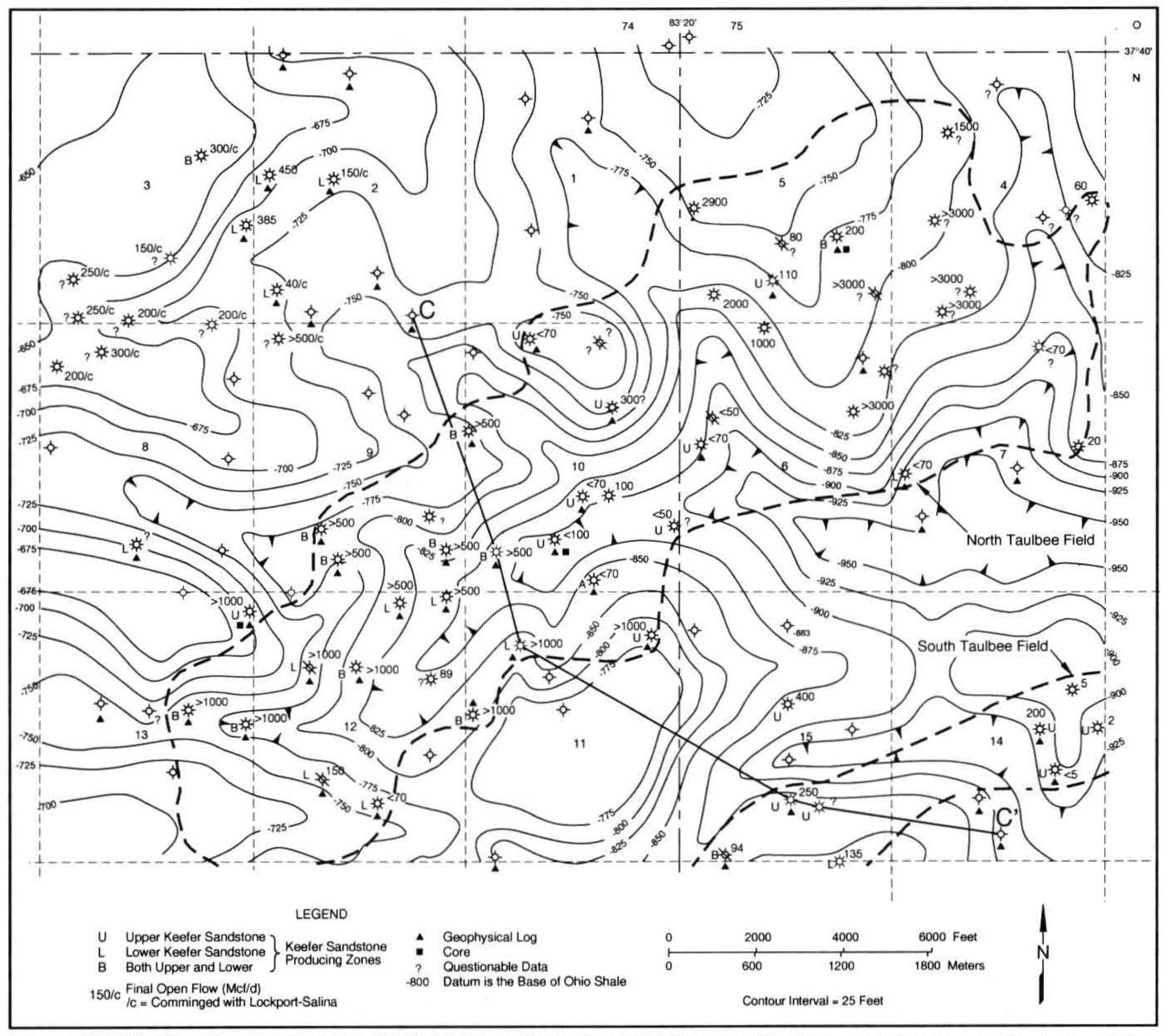


Figure Sld-15. Structure map of the North Taulbee field, Breathitt County, Kentucky, contoured on the base of the Devonian Ohio Shale (unconformity surface), showing small structural closures and east-southeast plunging anticlines. See Figure Sld-8 for location. Line of cross section C-C' (Figure Sld-16) is also shown.

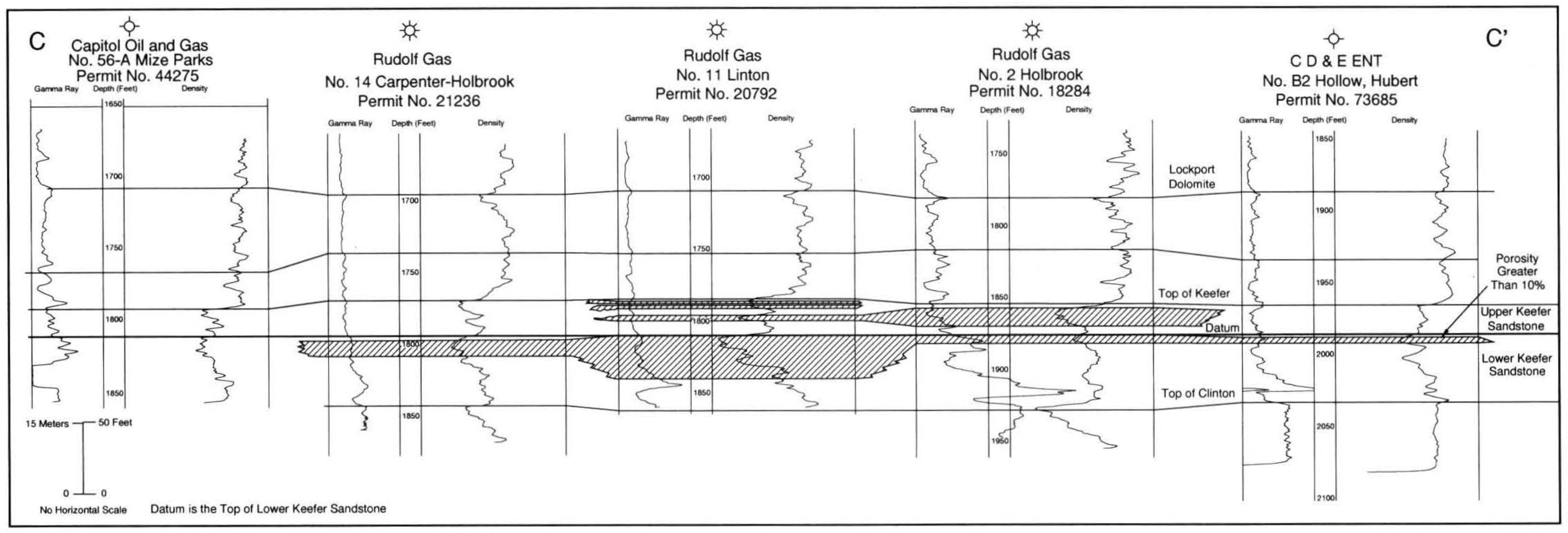


Figure Sld-16. Stratigraphic cross section C-C' over North Taulbee field, Breathitt County, Kentucky, illustrating upper and lower Keefer Sandstone producing intervals. Line of cross section is shown in Figure Sld-15.

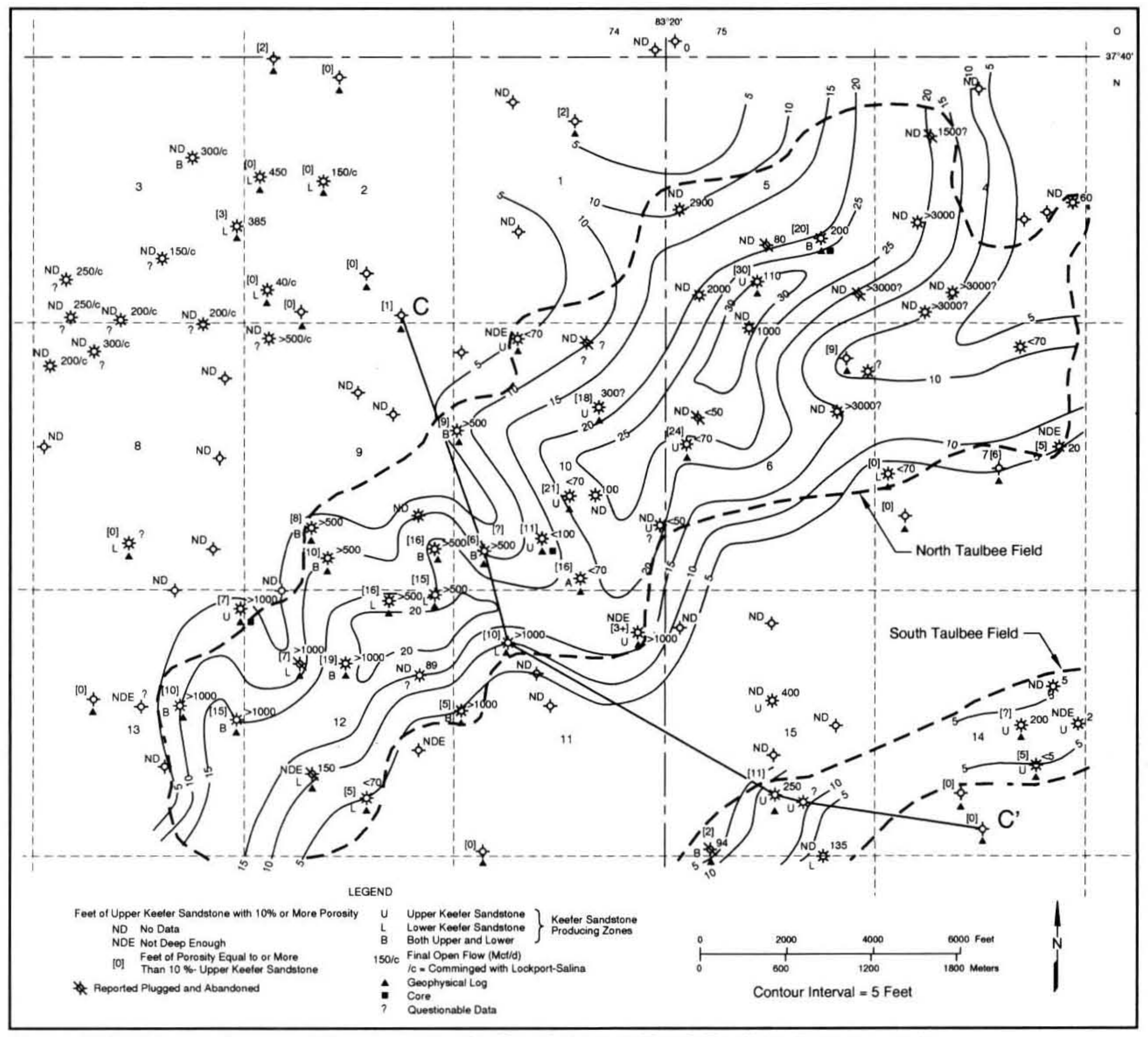


Figure Sld-17. Isopach map of the upper Keefer Sandstone at North Taulbee field, Breathitt County, Kentucky, showing net feet of porosity greater than or equal to 10 percent. See Figure Sld-8 for location. Line of cross section C-C' (Figure Sld-16) is also shown.

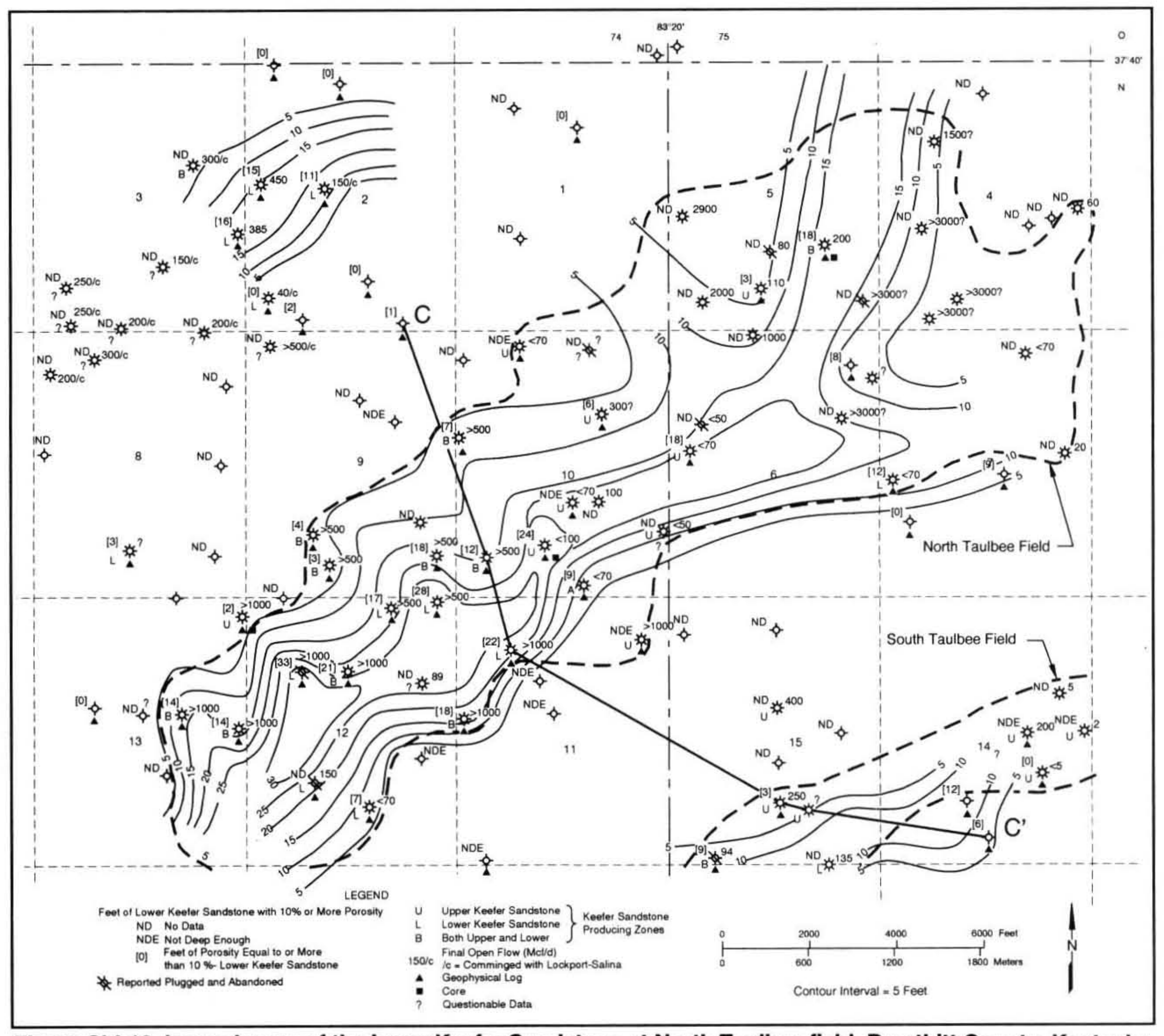


Figure Sld-18. Isopach map of the lower Keefer Sandstone at North Taulbee field, Breathitt County, Kentucky, showing net feet of porosity greater than or equal to 10 percent. See Figure Sld-8 for location.

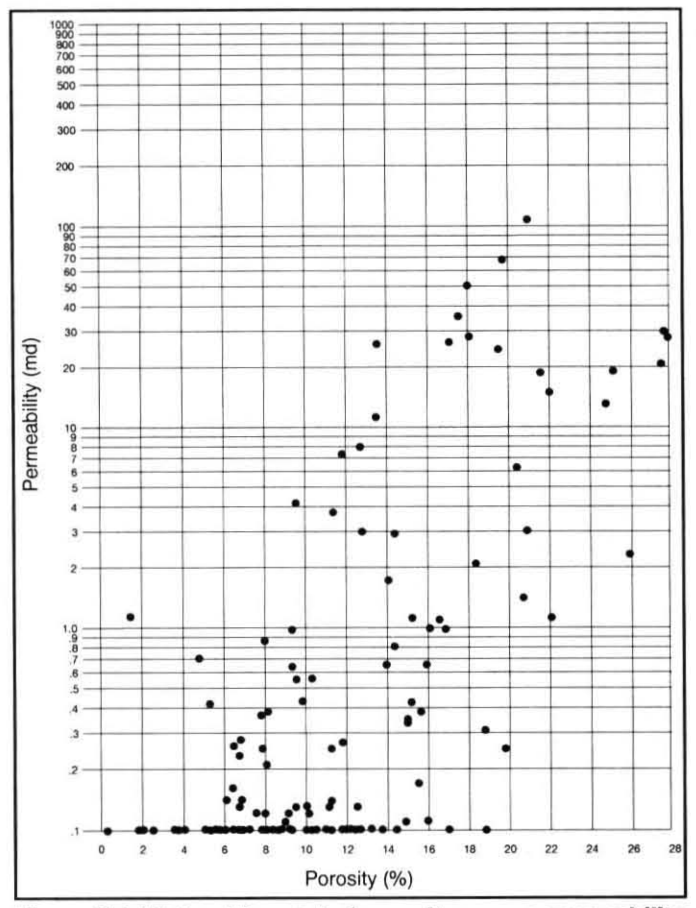


Figure Sld-19. Semi-log plot of porosity versus permeability for six Keefer Sandstone cores in eastern Kentucky. Note scattering of points.

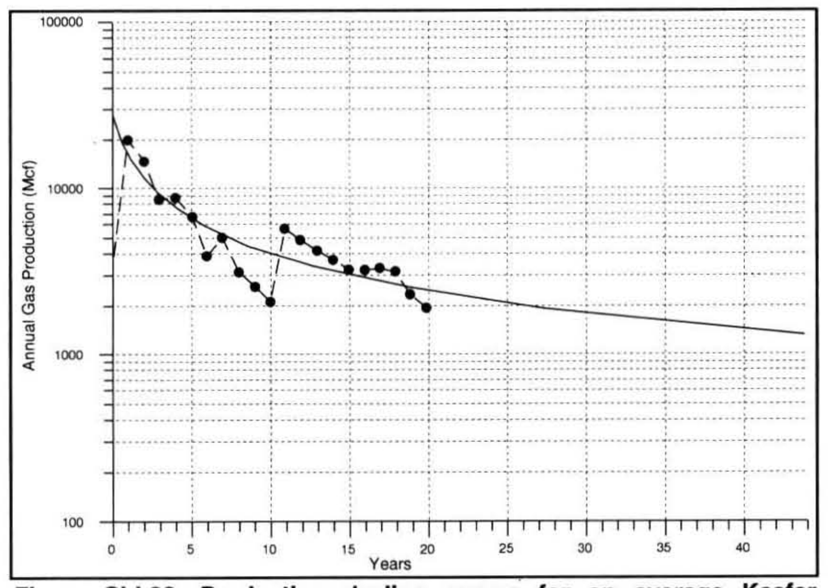


Figure Sld-20. Production decline curves for an average Keefer Sandstone well in Breathitt County, Kentucky. Actual data curve (small dots) and best fit curve (continuous line) are shown.

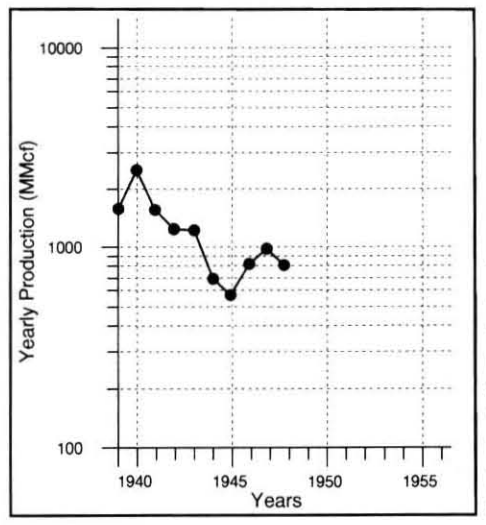


Figure Sld-21. Decline curve for Lockport Dolomite (Newburg) gas production at the Mayfield field in Cuyahoga County, Ohio. The decline curve represents an average of 26 producing gas wells in 1940, steadily increasing to a high of 42 producing wells during the mid-1940s, and then decreasing to 18 active gas wells by the end of 1948. Data provided by Benedum-Trees Oil Company and published by Rothrock (1949). No data are available after 1948.

the Keefer Sandstone is a function of sorting, grain size distribution, and type of cementation. These same criteria were previously noted by Young (1949) in older fields in Magoffin County, Kentucky.

In this particular field, porosity and permeability are believed to be associated with tidal channels formed in coastal plain and marine-shallow shelf environments. The upper Keefer Sandstone represents a coastal plain environment, whereas the lower Keefer Sandstone represents a marine-shallow shelf environment.

Cumulative gas production from 12 wells in North Taulbee field as of October 1990 is estimated to be at least 3.60 bcf. It is estimated that reserves of 1.1 bcf remain to be recovered. A production decline curve for an average Keefer Sandstone well in North Taulbee field is shown in Figure Sld-20.

Completion procedures in North Taulbee field were quite varied. The most common practice was to set 7-inch casing in the Big Lime to shut off water flow from above. The wells were either completed open hole or perforated through 4.5-inch casing set at total depth or just below the productive zone. Once perforated, some wells were stimulated by water/sand or nitrogen/sand hydraulic fracturing techniques. In some cases, Keefer Sandstone gas production was commingled with Lockport and/or Salina dolomites. In this situation, the well was completed open hole, perforated, or selectively perforated and stimulated through 4.5-inch casing. Recent logging suites include a gamma-ray/caliper/litho-density/neutron/temperature log, along with dual induction and ultrasonic gas detector logs.

Resources and Reserves

Gas-in-place and reserves were difficult to calculate because of the lack of reservoir data in many fields, the early development of many fields, and the proprietary nature of production data in some states. Volumetric calculations of abandoned and producing fields indicated approximately 212.3 bcf of original gas-in-place, and 184.6 bcf of original gas reserves in the Lockport Dolomite and Keefer Sandstone play. The Lockport Dolomite accounted for 129.2 bcf of original gas-in-place and 109.8 bcf of original gas reserves. The Keefer Sandstone had approximately 83.1 bcf of original gas-in-place and 74.8 bcf of original gas reserves. Cumulative gas production for an average Lockport Dolomite producer typically ranges from 0.12 to 0.18 bcfg, with the highest per well average being 0.35 bcfg at the Mayfield field in Ohio. A gas production decline curve for the Lockport Dolomite in the Mayfield field in Ohio is shown in Figure Sld-21. Cumulative gas production for an average Keefer Sandstone well was estimated to be 0.21 bcfg, with cumulatives possibly as high as 0.9 bcfg in the best wells.

In the United States portion of the Appalachian basin, the Lockport Dolomite is estimated to have 98 bcf in undiscovered recoverable gas resources. The Keefer Sandstone is estimated to have 90 bcf of undiscovered recoverable resources, mostly from eastern Kentucky. These resource estimates are based on historical production data, and speculation of favorable producing facies distribution, in the Lockport Dolomite and Keefer Sandstone.

Future Trends

The future limits of the Lockport Dolomite and Keefer Sandstone play should expand to areas where the depositional environments, diagenesis, and structural history result in favorable reservoir and trapping conditions. Smosna and others (1989) mapped several promising areas in eastern Kentucky, where the Lockport Dolomite is thick and has good potential for porosity development. One of these mapped areas (Trend A in Figure Sld-22) defined a 20-mile-wide band of thick Lockport Dolomite, extending north from Elliott County through western Carter, eastern Lewis, and western Greenup counties, Kentucky. This trend should extend into adjacent southern Scioto County, Ohio. Another prospective trend (Trend B in Figure Sld-22) was mapped along the Kentucky-West Virginia border, and extends from western Wayne County, West Virginia, through eastern Lawrence and Boyd counties, Kentucky (Smosna and others, 1989). This trend may extend into Lawrence County, Ohio. The Lockport Dolomite also has potential for new gas reserves in more structurally complex areas where faults, anticlinal closures, and structural noses coincide with carbonate buildups, such as patch reef bioherms and skeletal banks. The play could continue to expand in structurally complex areas (Trend C in Figure Sld-22) such as Morgan, Elliott, Lawrence, and Johnson counties, Kentucky (Smosna and others, 1989). In West Virginia, porous coral-stromatoporoid reefs of the Lower Lockport Dolomite (McKenzie Formation) have potential for gas (Patchen and Smosna, 1975; Smosna and Patchen, 1980; Smosna and others, 1989) in two southwest to northeast trends (Trends D and E in Figure Sld-22). Gas shows have been encountered in several wells (Figure Sld-22) penetrating the Lockport Dolomite in western West Virginia (Patchen and Smosna, 1975). In northwestern Pennsylvania, hydrocarbon shows have been reported from numerous wells that penetrated biohermal and lithostromal facies of the Lockport Dolomite (Laughrey, 1987). Unfortunately, the potential extension of the Lockport Dolomite producing fairway from northern Ohio and Pennsylvania into Lake Erie is currently off-limits to drillers by law (Figures Sld-1, Sld-3, Sld-7).

Significant gas potential exists in the Keefer Sandstone in the area between Taulbee Consolidated and Barnetts Creek fields in eastern Kentucky (Figure Sld-4). This area is thought to contain excellent reservoir quality in the Keefer Sandstone and the necessary structural features to enhance hydrocarbon entrapment. Potential for new gas reserves in the Keefer Sandstone decreases north and east of Barnetts Creek field into Ohio and West Virginia, primarily due to the decrease in reservoir quality of Keefer Sandstone.

Opportunities still exist for the discovery of new reserves in the established producing areas throughout much of the Lockport Dolomite and Keefer Sandstone play. Stratigraphic interpretations using improved seismic techniques and detailed subsurface mapping will no doubt result in several new field discoveries in the old producing fairways. In addition to continued exploratory success, considerable recompletion potential exists for behind-the-pipe gas zones in the Lockport Dolomite, especially in Ohio and Pennsylvania. Here, thousands of wells have been drilled through the Lockport Dolomite in an effort to test the primary objectives in the deeper Clinton-Medina sandstones. Many of these wells had hydrocarbon shows in the Lockport Dolomite but were completed in the Clinton-Medina sandstones (Laughrey, 1987). A careful re-examination of drillers' logs and geophysical logs (Laughrey, 1987) could result in new gas reserves in old wells.

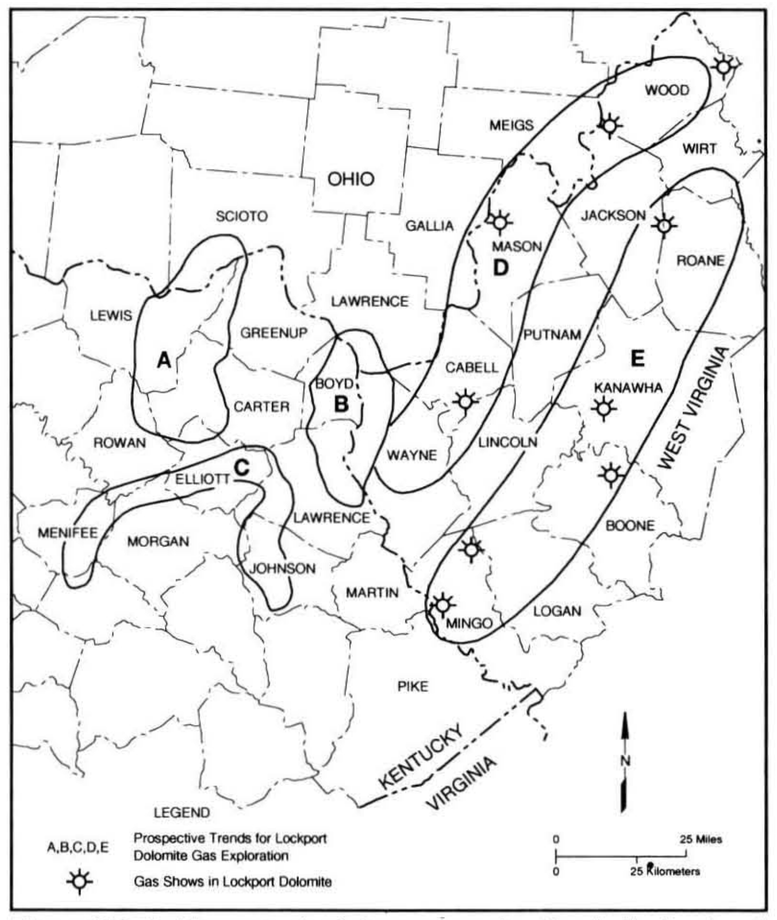


Figure Sld-22. Five areas for future gas exploration in the Lockport Dolomite, in eastern Kentucky, western West Virginia, and southern Ohio. Prospective trends and gas shows are based on Patchen and Smosna (1975), Smosna and Patchen (1980), and Smosna and others (1989).

PLAY Sts: THE LOWER SILURIAN TUSCARORA SANDSTONE FRACTURED ANTICLINAL PLAY

by Katharine Lee Avary, West Virginia Geological and Economic Survey

Location

The Lower Silurian Tuscarora Sandstone fractured anticlinal play is located in a broad area across Pennsylvania and West Virginia where the Tuscarora Sandstone is preserved and where there are anticlines in which the brittle, quartz-cemented sandstone is highly fractured (Figure Sts-1). The six fields and one pool currently included in this play are Devils Elbow, Black Moshannon, and Runville fields and Heyn pool in Pennsylvania, and Leadmine, Cucumber Creek, and Indian Creek fields in West Virginia (Figure Sts-2; Table Sts-1). The productive areas are located in the Allegheny Frontal zone at the juncture of the Valley and Ridge and the high amplitude fold province and in the low amplitude fold province, along fractured and/or faulted anticlines.

Production History

Two main phases of Tuscarora exploration have occurred. The first was in the 1960s, when several major oil and gas companies undertook exploration programs in the Appalachian basin. The second phase of Tuscarora exploration took place in the early 1980s, when major companies once more engaged in exploratory drilling in the Appalachian basin, probably inspired by successes in the Rocky Mountain overthrust drilling programs as well as high gas prices. During both phases of exploration, the potential targets were the shallower Oriskany Sandstone (generally 1,500 feet stratigraphically above the Tuscarora) and the Tuscarora Sandstone. An area where dual potential exists in both sandstones remains more promising than an area where the Tuscarora is the lone potential reservoir.

More than 170 wells have penetrated the Tuscarora in West Virginia and Pennsylvania (Figure Sts-3). About 30 percent of these wells were unsuccessful. The first Tuscarora field, Leadmine, was discovered in 1963 in Preston and Tucker counties, West Virginia (Figure Sts-2). The Heyn pool was discovered in Fayette County, Pennsylvania in 1964. The development of Indian Creek field began in 1973, although a number of Tuscarora wells were drilled in the 1930s and 1940s along the axis of the Warfield anticline.

The three Centre County, Pennsylvania, Tuscarora fields were discovered as a result of eastern overthrust belt drilling programs in the late 1970s and early 1980s. Fettke (1950; 1956), Patchen (1968a), and Cardwell (1977) present in-depth histories of early Tuscarora drilling in Pennsylvania and West Virginia.

Total reported cumulative production attributed to the Tuscarora is approximately 28 bcfg. Of this, nearly 20 bcf has been produced from Indian Creek field, Kanawha County, West Virginia.

Stratigraphy

The Tuscarora Sandstone occurs at the base of the Silurian system in West Virginia, Maryland, and southwestern and central Pennsylvania (Piotrowski, 1981) (Figure Sts-4). The name Tuscarora was first published by Darton (1896); however, the first reference to the type locality on Tuscarora Mountain in central Pennsylvania was made by Clark (1897). The Tuscarora is characterized by massive beds of quartzite separated by thin beds of shale. The Tuscarora is generally a quartz-cemented, fine-grained to conglomeratic quartz sandstone, with minor amounts of chlorite, illite, and feldspar. The Tuscarora becomes increasingly more shaley from east to west across Pennsylvania and West Virginia (Figures Sts-5, Sts-6). The thickness of the unit ranges from less than 100 feet in southwestern West Virginia to more than 1,000 feet in northeastern Pennsylvania (Smosna and Patchen, 1978) (Figure Sts-7). The Tuscarora conformably overlies the Juniata Formation throughout most of West Virginia and Pennsylvania; the basal contact is unconformable to the east and south in Pennsylvania (Figure Sts-6). The Tuscarora is conformably overlain by the Rose Hill Formation (Figures Sts-4, Sts-5, Sts-6).

In northwestern Pennsylvania, western New York, and northeastern Ohio, rocks of the same age are included in the Medina Group (see M. McCormac and others, Lower Silurian Cataract/Medina Group ("Clinton") sandstone play, this atlas) (Figure Sts-4). In east-central and southeastern Ohio (Figure Sts-4), the drillers' term "Clinton" sandstone was thought to be a correlative of the Tuscarora (Patchen, 1968a). Here, the name "Clinton" is misapplied by drillers. The Clinton Group actually overlies the Lower Silurian Tuscarora correlatives in east-central Ohio (Figure Sts-4). For many years, the name White Medina was used to refer to the Tuscarora in West Virginia.

In eastern Kentucky and south-central Ohio, the stratigraphic equivalent of the Tuscarora is the Brassfield Limestone (Horvath, 1970). In southwestern Virginia and eastern Tennessee, the basal Silurian sandstone is called the Clinch Sandstone (Dennison, 1970). In western Virginia, the Tuscarora equivalent is the Massanutten Sandstone. In eastern Pennsylvania and northern New Jersey, the Shawangunk Formation is the coarser-grained Tuscarora correlative.

The relatively porous productive zones are found at various intervals throughout the Tuscarora. Porosity and permeability are typically low; hence, the Tuscarora has been considered tight (Finley, 1984). However, no applications have been filed for official Federal Energy Regulatory Commission tight formation designation.

The Tuscarora Sandstone is generally considered to be of fluvial and/or littoral origin (Smosna and Patchen, 1978). In eastern Pennsylvania, the Shawangunk Formation is a coarser-grained eastern facies deposited in a braided stream environment (Smosna and Patchen, 1978). Smosna and Patchen (1978) showed an eastern West Virginia coastal plain grading westward into deltaic shaley sandstone in central West Virginia and, finally, in western West Virginia grading into marine-bar sandy shale (Figure Sts-7).

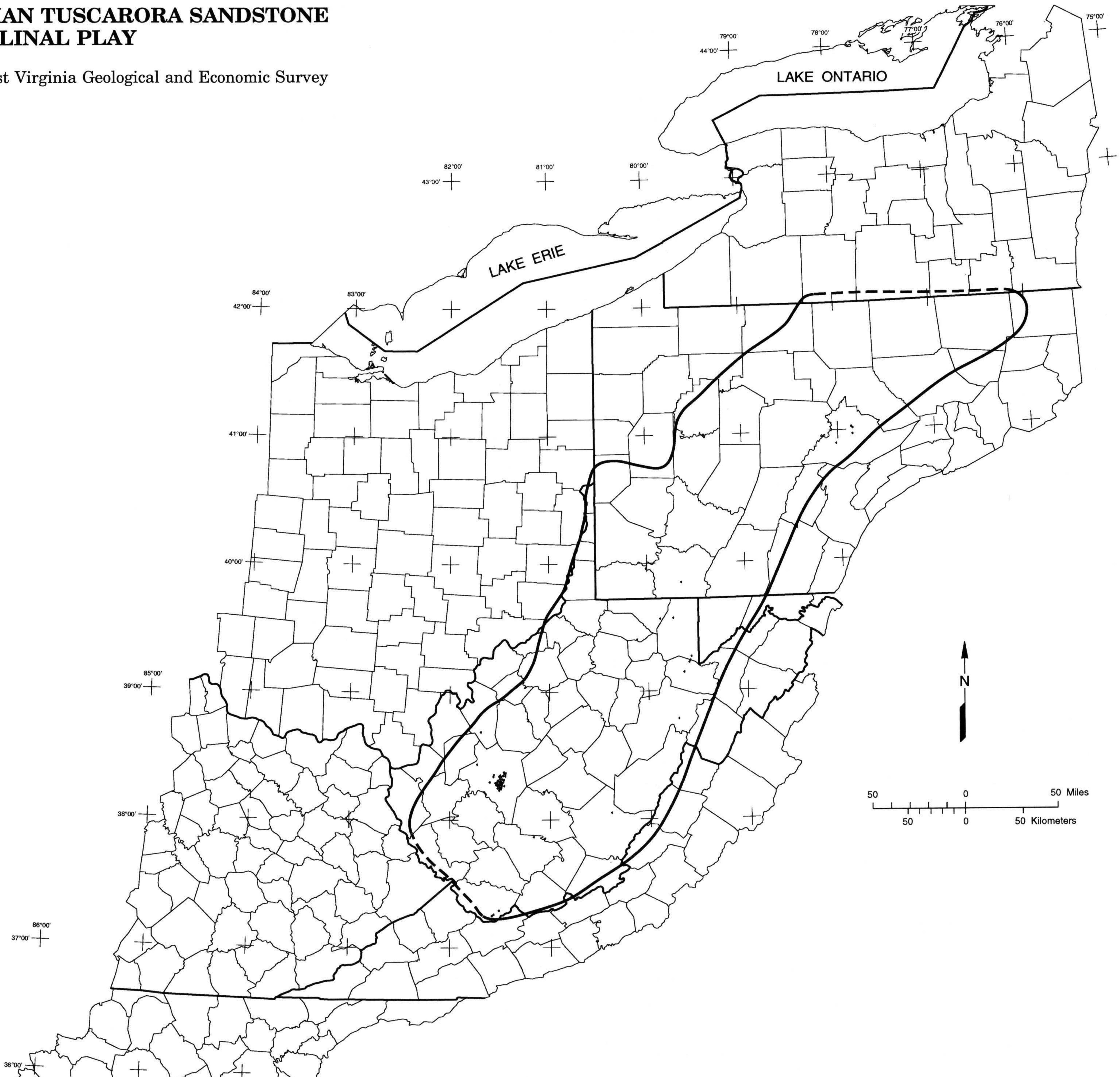


Figure Sts-1. Location of the Lower Silurian Tuscarora Sandstone fractured anticlinal play within the Appalachian basin. Dots represent individual gas wells; areas where dots have merged represent fields. Dashed line indicates inferred play boundary.

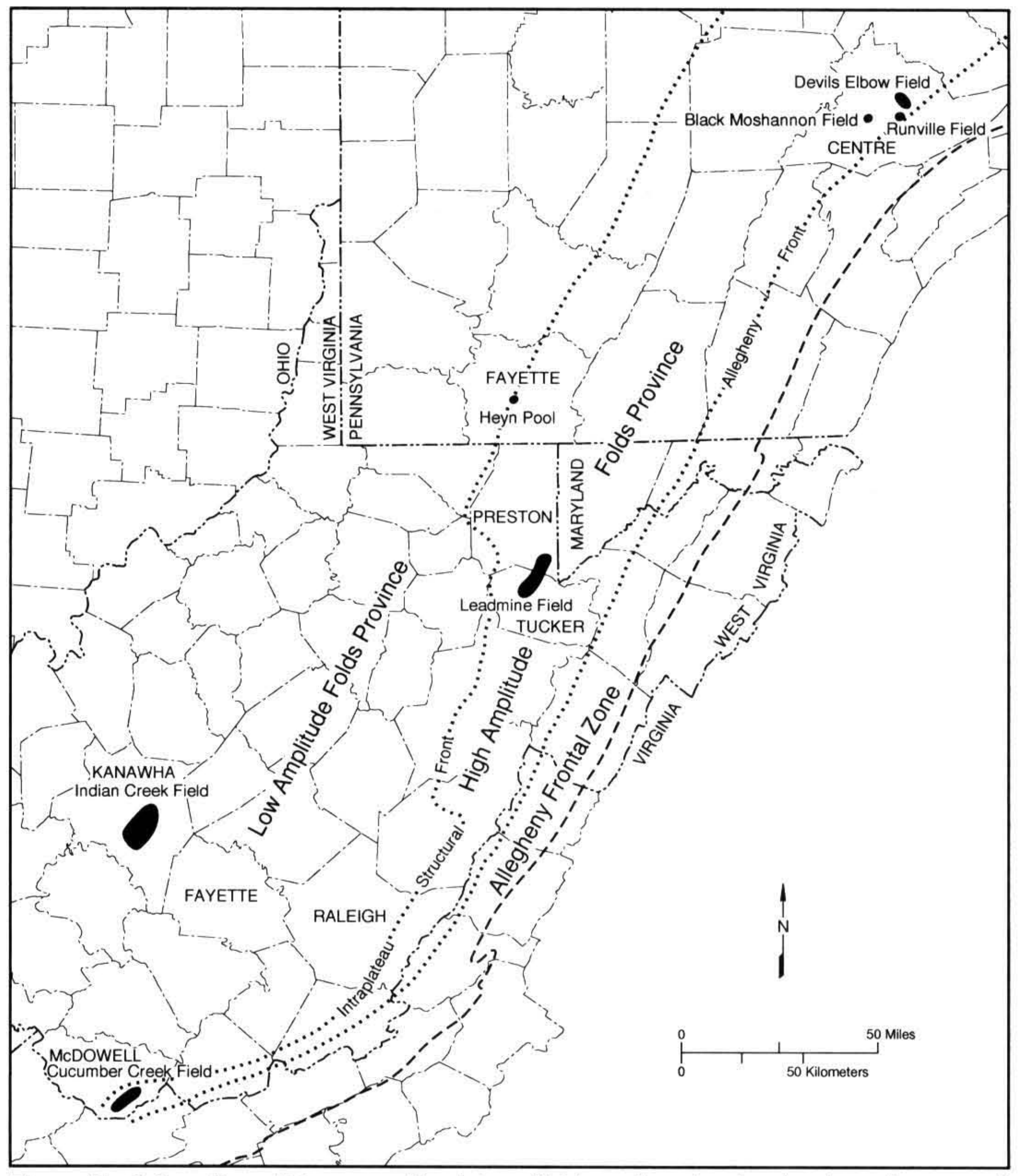


Figure Sts-2. Location of Tuscarora Sandstone fields and pools, structural provinces, and names of counties discussed in text or listed in Table Sts-1. Intraplateau structural front in West Virginia is modified from Kulander and Dean (1986).

As the result of a detailed outcrop study of the Tuscarora in central Pennsylvania, Cotter (1983) recognized a variety of shoreline and nearshore features (Figure Sts-8).

From a petrologic study of a lower Tuscarora core from Kanawha County, West Virginia, just east of Indian Creek field, Bruner (1983) concluded that the Tuscarora was deposited as a coastal sand in an environment characterized by high and fluctuating energy levels, shallow water, and high sedimentation rates.

Structure

The gas found in the Tuscarora occurs in anticlines; however, the structures vary in magnitude and complexity. The eastern part of the play area, the Allegheny Frontal zone (Figure Sts-2), is characterized by blind thrusts, hidden subsurface anticlines, duplexes, asymmetrical folds, and intense fracturing. The high amplitude folds province (Figure Sts-2) is located west of the Allegheny Frontal zone, and east of the intraplateau structural front of Kulander and Dean (1986). Further to the west is the low amplitude folds province (Figure Sts-2) with less intense fracturing.

Tuscarora fields in Pennsylvania are located in the Allegheny Frontal zone. Heyn pool and Leadmine and Cucumber Creek fields are located in the high amplitude folds province, and Indian Creek field is located in the low amplitude folds province of southwestern West Virginia.

Three cross sections (Figures Sts-9, Sts-10, Sts-11) illustrate the complexity of the structural style in the eastern part of the play area. Berg and others (1980) showed the structure in Centre County, Pennsylvania, which is reproduced here (Figure Sts-9). This is an example of the structurally complex Allegheny Frontal zone.

A portion of section 8 by T.H. Wilson, published in Woodward and others (1985) (Figure Sts-10), drawn just south of Leadmine field, showed the Deer Park anticline in the high amplitude folds province just west of the Allegheny Frontal zone. Section 12 from Kulander and Dean (1986) is slightly modified (Figure Sts-11) to show the fault encountered in the discovery well (Conoco Incorporated No. 1 Clarence Billups, West Virginia state permit number McDowell 909) for Cucumber Creek field.

Reservoir

Available reservoir data are limited to drillers' logs, some wireline log suites, a few sample descriptions, and two cores in West Virginia (which are not from the productive part of the Tuscarora).

The trap type for the Tuscarora Sandstone fields is structural—anticlines with fracture-enhanced porosity. The open fractures in addition to intra- and intergranular porosity provide space for gas storage. The overlying Rose Hill Formation forms a seal for the Tuscarora reservoirs.

The most likely source rocks for the Tuscarora gas are the Upper Ordovician dark, organic-rich shales of the Utica (Antes) Shale, Martinsburg Shale, or Reedsville Formation that occur several hundred feet below the Tuscarora (Gautier and Varnes, 1993).

Gas from these source rocks probably migrated up-section into the Tuscarora Sandstone. Perhaps gas also could have migrated laterally, from west to east, from the Ordovician organic-rich shales into the Tuscarora Sandstone at the same elevation.

Depth to the top of the Tuscarora pay zone varies due to structure and topography, as well as stratigraphic thickness variations of the overlying Pennsylvanian to Devonian sediments, and increases from west to east across the Appalachian Plateau (Table Sts-1). The shallowest average depth is in the westernmost field, Indian Creek (about 6,700 feet); the deepest Tuscarora production is at Heyn pool (more than 11,000 feet) due to a combination of the structural and topographic relief on the Chestnut Ridge anticline.

Pay zone thicknesses range from a few feet in Indian Creek to more than 150 feet in the Pennsylvania fields (Table Sts-1). The overall thickness of the Tuscarora decreases gradually from east to west, as does the percentage of sandstone (Figure Sts-7).

Tuscarora fields vary from under- to overpressured, with reported initial rock pressures ranging from 2,100 psi in Cucumber Creek to 6,699 psi in Devils Elbow (Table Sts-1). The average pressure gradient ranges from 0.28 psi/foot for Cucumber Creek to 0.60 psi/foot for Devils Elbow. The Centre County fields are overpressured, probably due to the degree of tectonic deformation in the Allegheny frontal zone.

Many Tuscarora wells are characterized by large initial natural open flows of gas. However, often not all of this gas is methane, but varying proportions of carbon dioxide or nitrogen. The carbon dioxide content reported for the Tuscarora

TABLE Sts-1		Leadmine WV	Indian Creek WV	Cucumber Creek WV	Heyn PA	Runville PA	Black Moshannon PA	Devils Elbow PA
BASIC RESERVOIR DATA	POOL NUMBER	47325357	47358357	47377357	371040357	37634357		37633357
	DISCOVERED	1963	1973	1984	1964	1980	1982	1977
	DEPTH TO TOP RESERVOIR	6,866	6,661	7,347	11,285	8,172	11,072	10,756
	AGE OF RESERVOIR	Early Silurian	Early Silurian	Early Silurian	Early Silurian	Early Silurian	Early Silurian	Early Silurian
	FORMATION	Tuscarora Sandstone	Tuscarora Sandstone	Tuscarora Sandstone	Tuscarora Sandstone	Tuscarora Sandstone	Tuscarora Sandstone	Tuscarora Sandstone
	PRODUCING RESERVOIR	Tuscarora Sandstone	Tuscarora Sandstone	Tuscarora Sandstone	Tuscarora Sandstone	Tuscarora Sandstone	Tuscarora Sandstone	Tuscarora Sandstone
	LITHOLOGY	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone
	TRAP TYPE	structural	structural	structural	structural	structural	structural	structural
	DEPOSITIONAL ENVIRONMENT	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine
	DISCOVERY WELL IP (Mcf)	696		2,373	311			20,000
	DRIVE MECHANISM	water	water	water	water	water	water	water
	NO. PRODUCING WELLS	2	34	3	0	1	0	2
	NO. ABANDONED WELLS	2	2	0	1	0	1	0
	AREA (acreage)	2,353	18,497	1,528	220	220	220	440
	OLDEST FORMATION PENETRATED	Juniata	Juniata	Juniata	Tuscarora	Juniata	Juniata	Reedsville
	EXPECTED HETEROGENEITY DUE TO:	fractures structure	fractures structure	fractures structure	fractures structure	fractures structure	fractures structure	fractures structure
RESERVOIR PARAMETERS	AVERAGE PAY THICKNESS (ft.)							
	AVERAGE COMPLETION THICKNESS (ft.)	23	10	100	54	159	164	95
	AVERAGE POROSITY--LOG (%)		10.44		7.57			
	MINIMUM POROSITY--LOG (%)		7.82		1.24			
	MAXIMUM POROSITY--LOG (%)		15.63		13.80			
	NO. DATA POINTS		13		1			
	POROSITY FEET							
	RESERVOIR TEMPERATURE (°F)	139	126.5	151.3	196	138	167	154
	INITIAL RESERVOIR PRESSURE (psi)	2,620	3,000	2,100	4,457	4,173	5,952	6,699
	PRODUCING INTERVAL DEPTHS (ft.)	6,628-7,435	6,162-7,176	7,110-8,042	11,285-11,458	8,172-8,427	11,072-11,394	10,756-11,086
	PRESENT RESERVOIR PRESSURE (psi) / DATE		1,246/ 1991					
FLUID & GAS PROPERTIES	Rw (Ωm)				0.05			0.05
	GAS GRAVITY (g/cc)	0.6415	1.214		0.6253	0.62	0.6941	0.652
	GAS SATURATION (%)		57		58.3			
	WATER SATURATION (%)		43		41.7			
	COMMINGLED	no	no	no	no	no	no	no
	ASSOCIATED OR NONASSOCIATED	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated
	Btu/scf	841.35	305		883	916	704.5	829.5
VOLUMETRIC DATA	STATUS (producing, abandoned, storage)	shut-in	producing	shut-in	abandoned	producing	abandoned	producing
	ORIGINAL GAS IN PLACE (Mcf)							
	ORIGINAL GAS RESERVES (Mcf)	16,000,000	60,000,000	5,400,000	1,800,000	1,800,000	1,800,000	3,600,000
	PRODUCTION YEARS	1963-1992	1982-1992		1964	1982-1989		1980-1992
	REPORTED CUMULATIVE PRODUCTION (Mcf)	2,600,000	20,000,000		1,500,000	854,000		3,133,000
	NO. WELLS REPORTED	2	33	0	1	1	0	2
	ESTIMATED CUMULATIVE PRODUCTION (Mcf)	2,600,000	20,000,000		1,500,000	854,000	0	3,133,000
	REMAINING GAS IN PLACE (Mcf)/DATE							
	REMAINING GAS RESERVES (Mcf)/DATE	13,400,000/ 1992	40,000,000/ 1992	5,400,000/ 1992	300,000/ 1964	946,000/ 1989	1,800,000/ 1992	467,000/ 1992
	RECOVERY FACTOR (%)				83			
	INITIAL OPEN FLOW (Mcf/d)	10,662	4,477	260	311			10,750
	FINAL OPEN FLOW (Mcf/d)	12,282	3,068	1,312	1,917	2,050	700	4,250

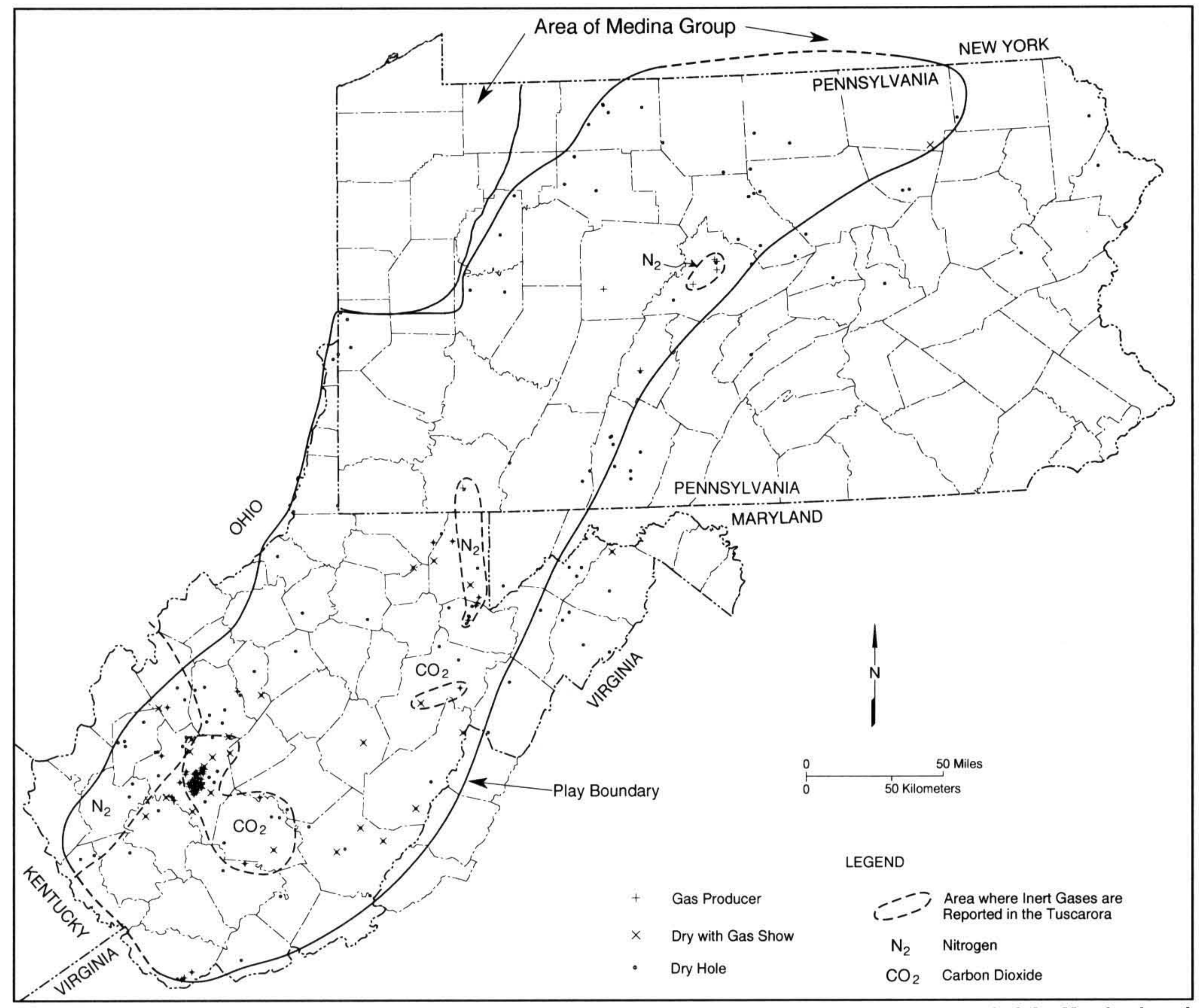


Figure Sts-3. Map showing the locations of wells penetrating the Tuscarora Sandstone in Virginia, West Virginia, Maryland, and Pennsylvania. The reported distribution of nitrogen and carbon dioxide in the Tuscarora is also shown.

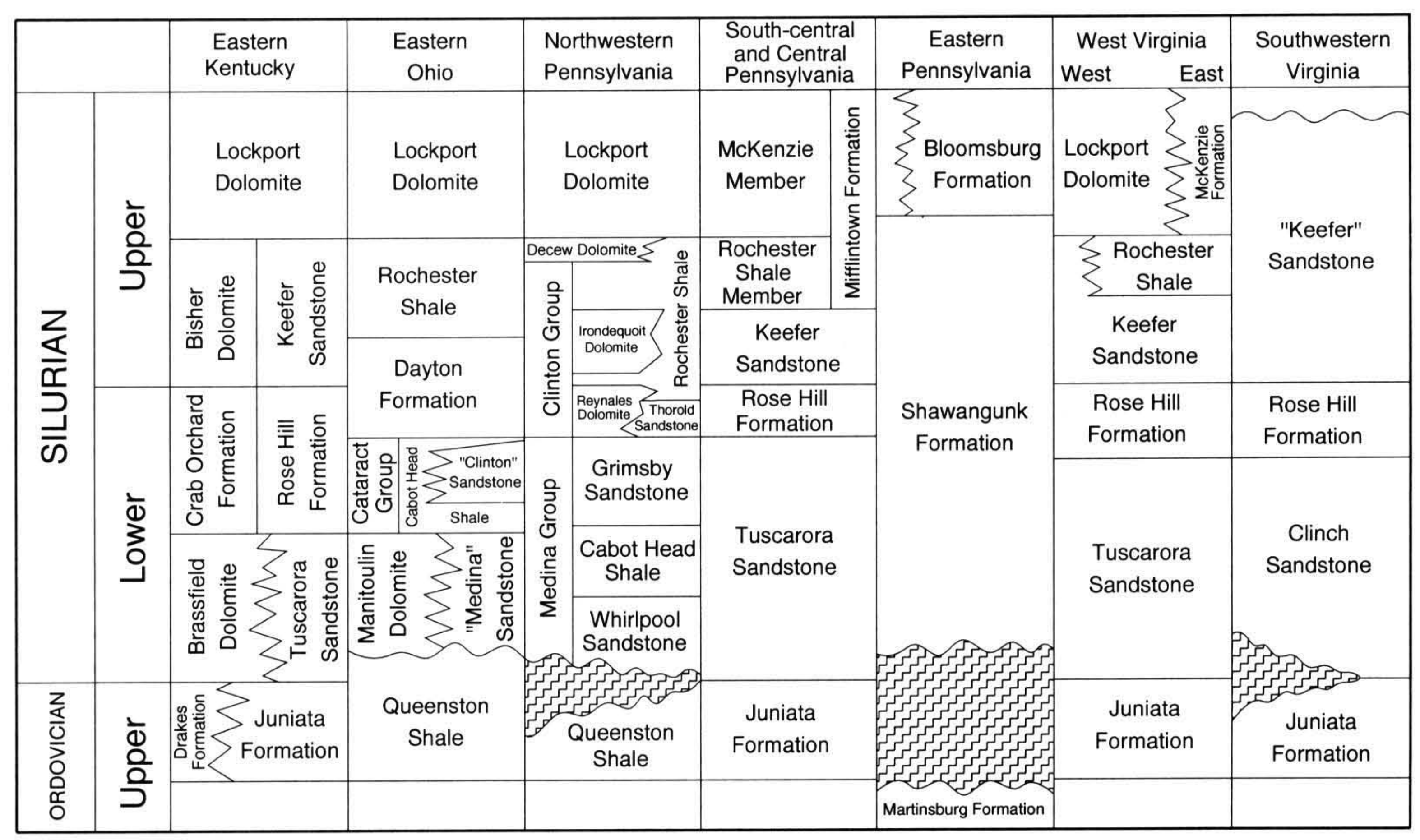
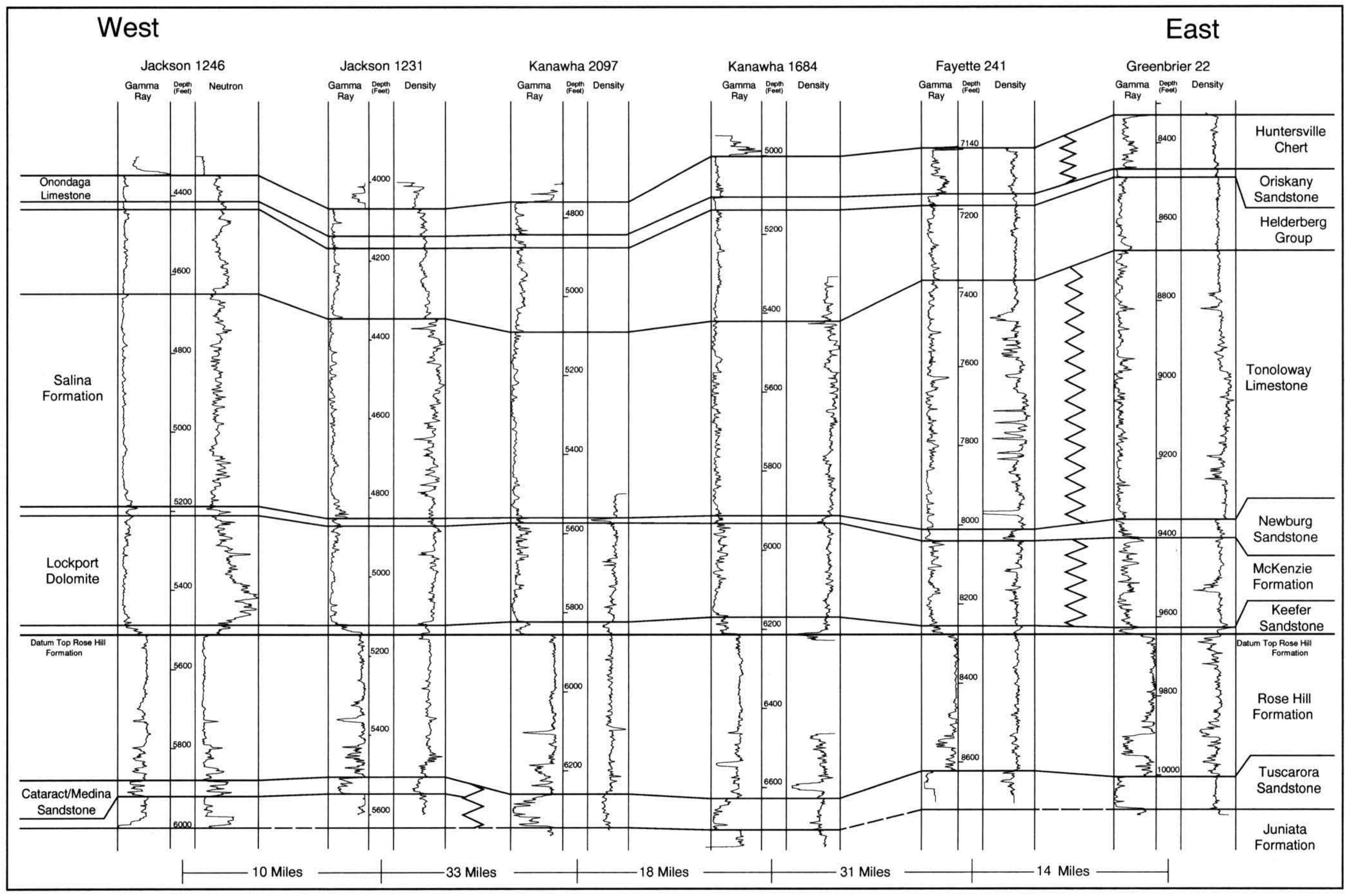


Figure Sts-4. Stratigraphic correlation chart showing the Tuscarora Sandstone and its stratigraphic equivalents. Modified after Patchen and others (1985a).



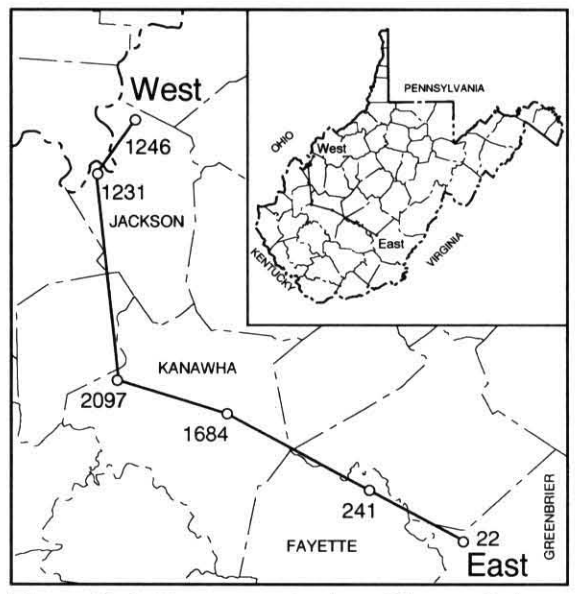


Figure Sts-5. Tuscarora stratigraphic correlations across southern West Virginia, showing the increase in shale content and decrease in thickness of the Tuscarora Sandstone from east to west. The upper part of the Lockport interval also includes the Salina "A" and "B" at the top. Columbia Gas Transmission Corporation No. 8804 Fee (Kanawha 1684) is the designated discovery well for Indian Creek field. The two westernmost wells (Jackson 1246 and Jackson 1231) are outside the play boundary and fall within the Lower Silurian Cataract/Medina Group ("Clinton") sandstone play (see M. McCormac and others, this atlas).

ranges from 44 to 83 percent. The reported nitrogen content ranges from 13.9 to 35 percent. Average reported natural initial open flow potentials for all Tuscarora fields range from 260 to 20,000 Mcf/d (Table Sts-1). The largest initial open flow was reported to be 22,000 Mcf/d from Cities Service Oil Company No. T-1 (GW-1499) United States of America (Tucker 34) in Leadmine field. Reported final post-stimulation open flow potentials for individual wells range from 0 to 24,800 Mcf/d, while the field averages range from 0 to 12,282 Mcf/d (Table Sts-1). The largest reported final open flow after acidizing was 24,800 Mcf/d from Cities Service Oil Company No. A-1 (GW-1611) L.E. Mullenax and others (Tucker 38). in Leadmine field.

Wescott (1982) identified four types of porosity in the Tuscarora: intergranular, moldic secondary, microporosity, and fracture porosity. Intergranular porosity can be classified into four subgroups (Wescott, 1982): relict primary, secondary intergranular, interlaminar, and vuggy porosity. Wescott (1982) concluded that, especially in the Allegheny Frontal zone, secondary intergranular porosity or fractures, or combinations of both, make the best reservoirs in the Tuscarora sandstone.

Heald and Andregg (1960) described differential cementation in Tuscarora outcrop samples. They suggested the differential cementation was caused by the presence of pockets or lenses of gas that inhibited cementation and led to the preservation of porosity. Heald and Larese (1974) suggested that the presence of clay coatings may also have inhibited quartz cementation in the Tuscarora, preserving primary porosity. However, clays may have an adverse effect on reservoir quality by reducing permeability (Wescott, 1982). Wescott also suggested that clays might affect water saturation calculations due to the water molecules bound in the clay mineral lattices.

The Tuscarora was cored in Cities Service Oil Company No. Q-1 (GW-1466) United States of America (Preston 119) in Leadmine field; however, the core was taken starting at the base of the productive zone reported in the Tuscarora. The porosity reported for this core ranges from 1.0 to 8.9 percent. According to Bruner (1983), the average porosity measured for Columbia Gas Transmission Corporation No. 64 (20344-T) David Ward (Kanawha 2751) is 8.2 percent. This well is located southeast of the productive limit of Indian Creek field, and only the lower 51 feet of the 90 feet of Tuscarora present were cored.

Wescott (1982) listed the expected permeability associated with each of the porosity types he described. The highest permeabilities are associated with secondary intergranular porosity and fracture porosity. The horizontal permeability reported for the core from Leadmine field ranges from 0 to 10.7 md; the vertical permeability ranges from 0 to 12.2 md. The limited data indicate that for those areas studied, the permeability of the Tuscarora Sandstone is nil to only fair, and the porosity is negligible to poor. As a result, the storage and productive capabilities of Tuscarora reservoirs are largely dependent on structural deformation.

The critical reservoir property, especially in the eastern Tuscarora fields, appears to be fracturing. Fracturing is generally more intense in orthoquartzites (Mitra, 1988) such as the Tuscarora, and pressure solution is less intense in coarse-grained orthoquartzite than in fine-grained argillaceous limestone. Mitra (1988) noted that secondary fracture and dissolution porosity are common in the Tuscarora in the Allegheny Frontal zone, while Tuscarora fractures in the Valley and Ridge are quartz-filled.

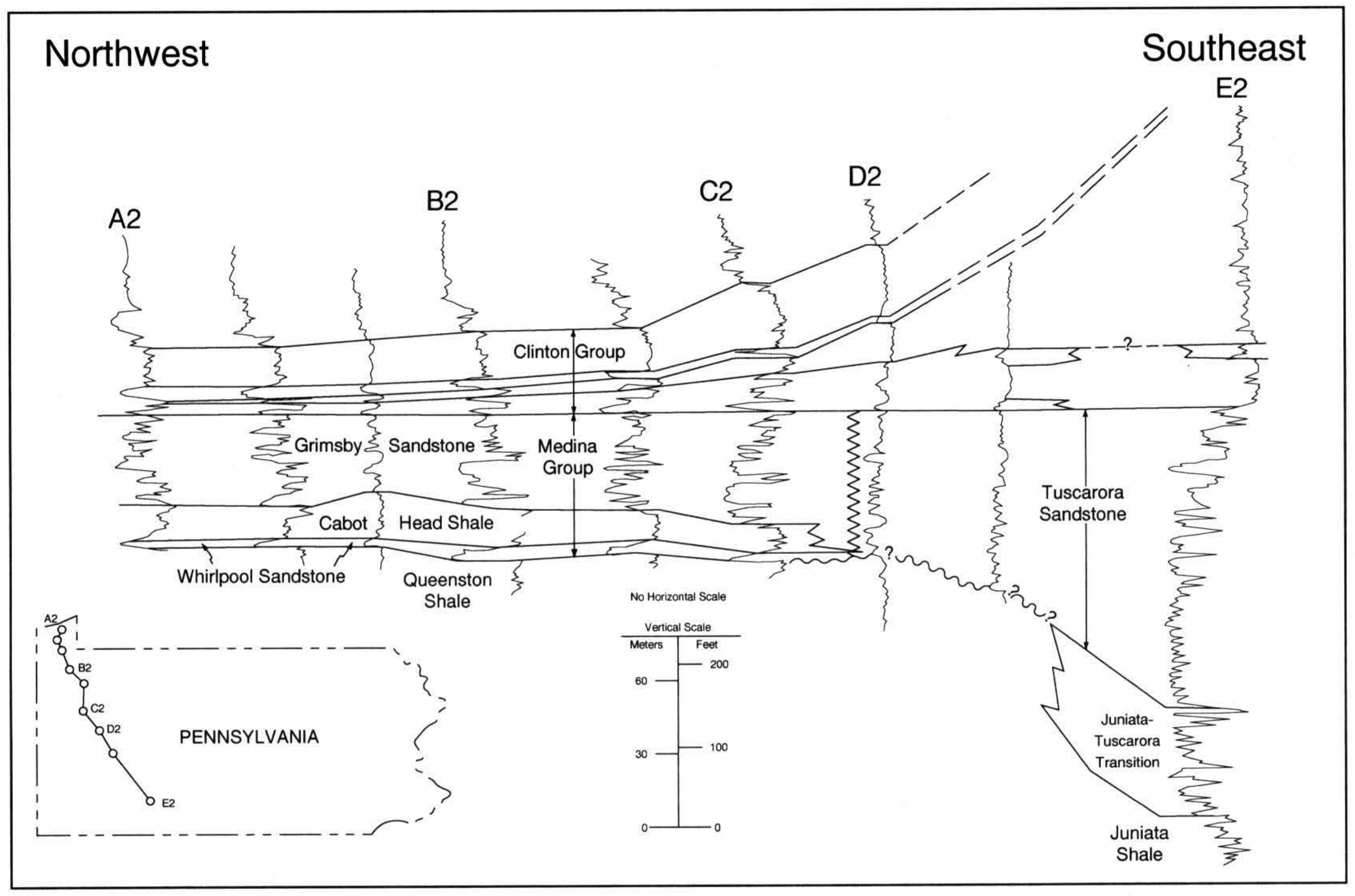


Figure Sts-6. Tuscarora stratigraphic correlations across Pennsylvania. Modified from Piotrowski (1981). This cross section shows an increase in shale content and decrease in thickness from southeast to northwest similar to that shown in Figure Sts-5.

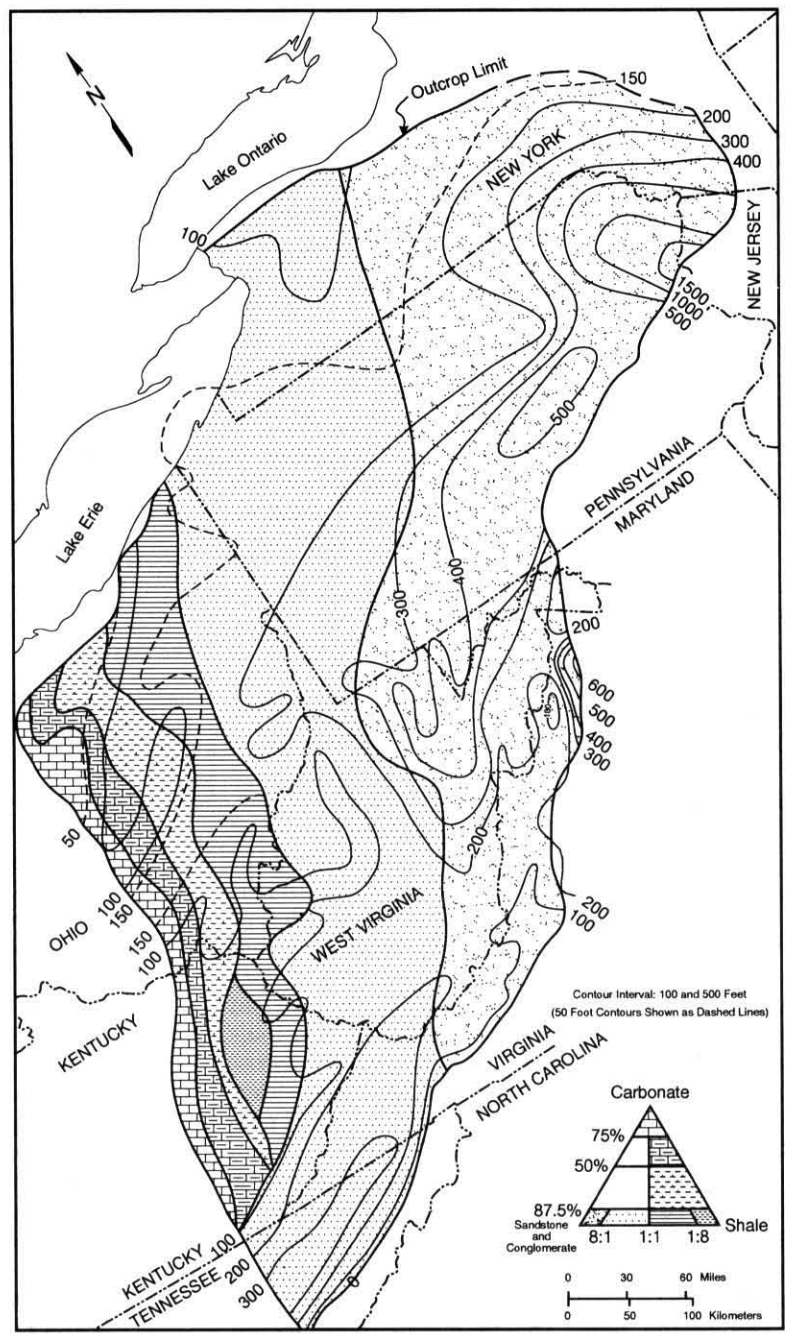


Figure Sts-7. Isopach and lithofacies map of the Lower Silurian series, Appalachian basin. Redrawn from Finley (1984). Note the decrease in thickness and sandstone content from east to west.

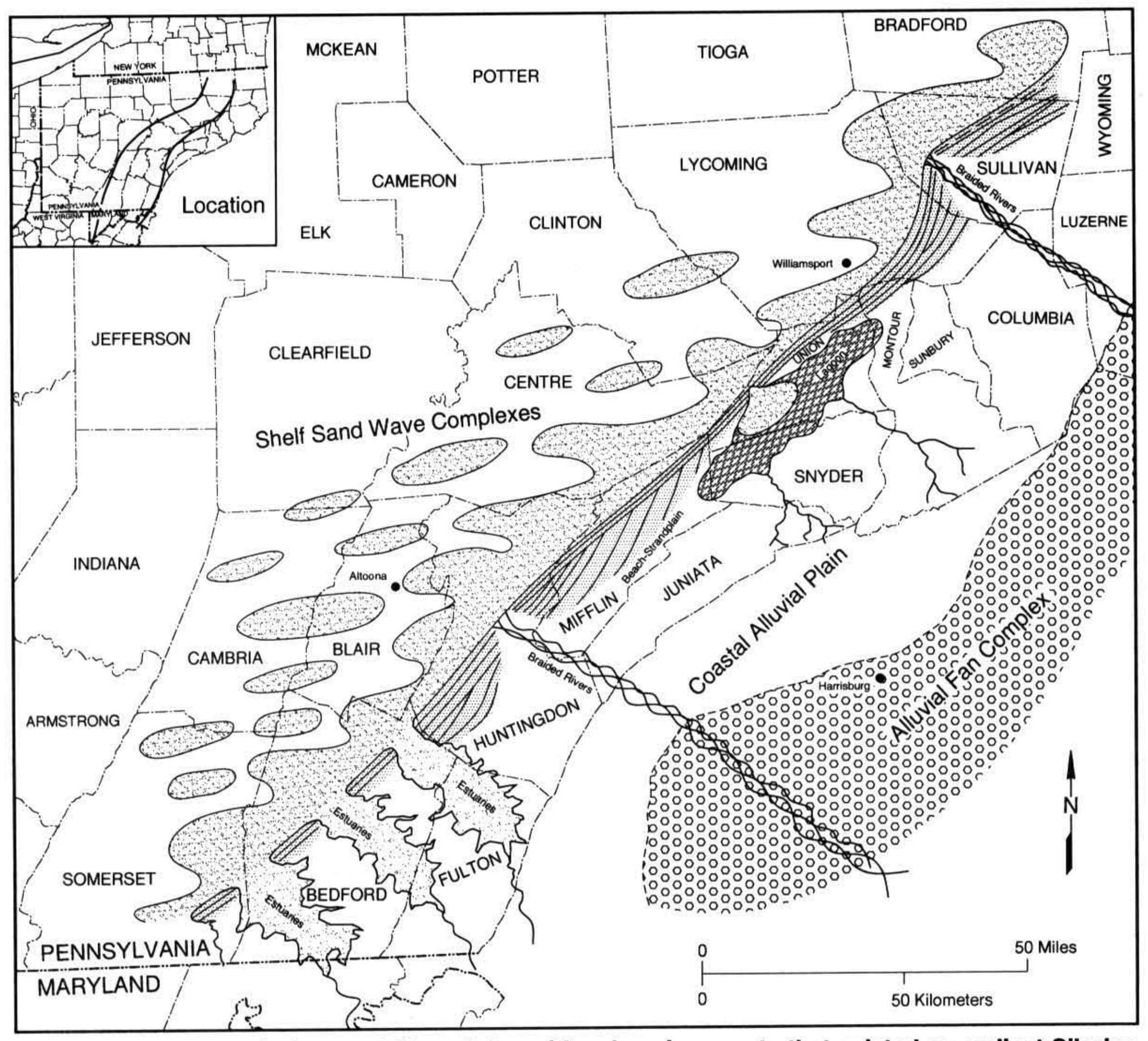


Figure Sts-8. Schematic interpretation of depositional environments that existed as earliest Silurian (Llandovery) sea-level rise caused southeastward retrogradation of shoreline and shelf over coastal alluvial plain. The two river systems shown are diagrammatic and do not necessarily relate to the two major input centers demonstrated by the work of Yeakel (1962). Redrawn from Cotter (1983), with the addition of county outlines.

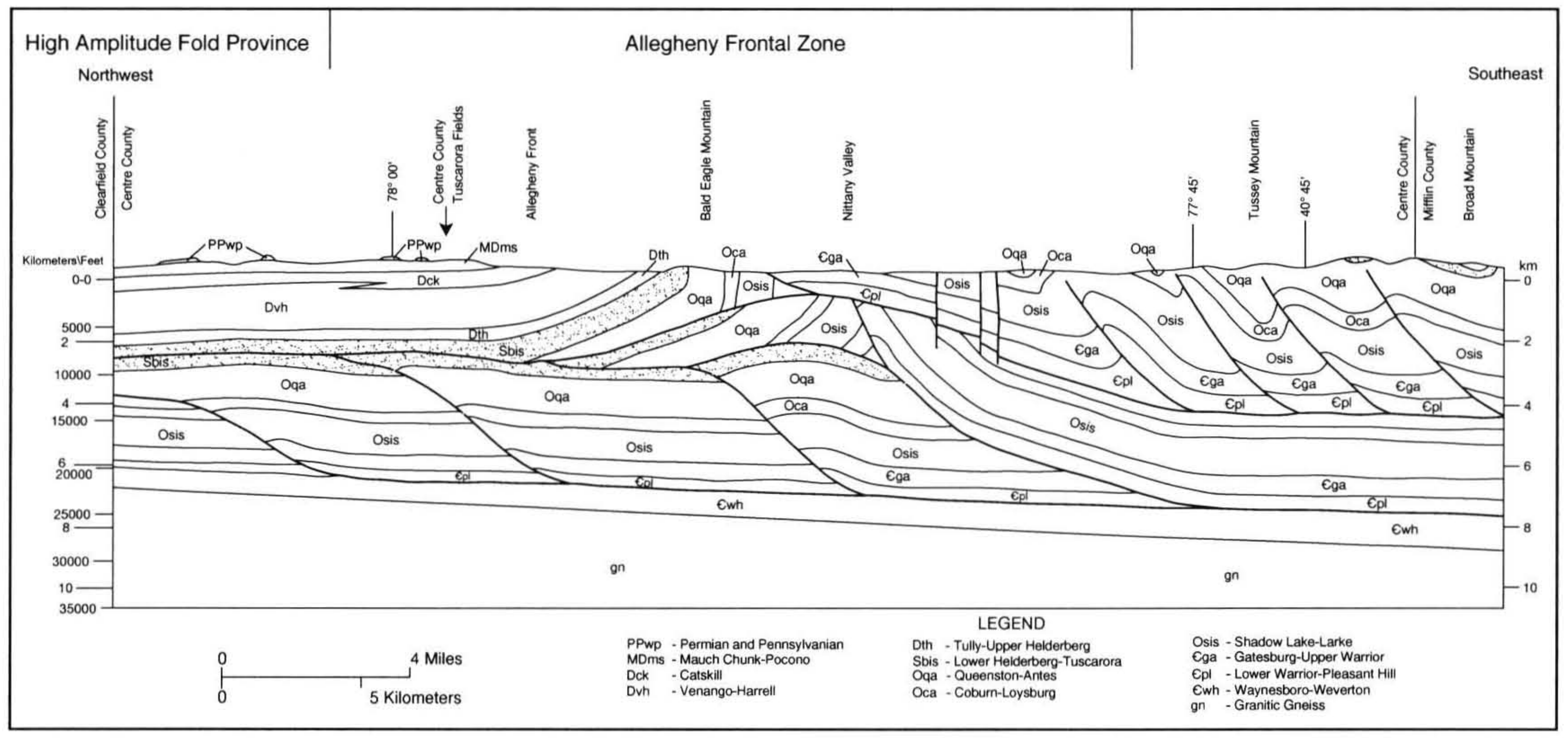


Figure Sts-9. Northwest to southeast structural cross section, Centre County, Pennsylvania, from Berg and others (1980), showing structural style in the vicinity of the Allegheny Front. Line of cross section is shown in Figure Sts-19.

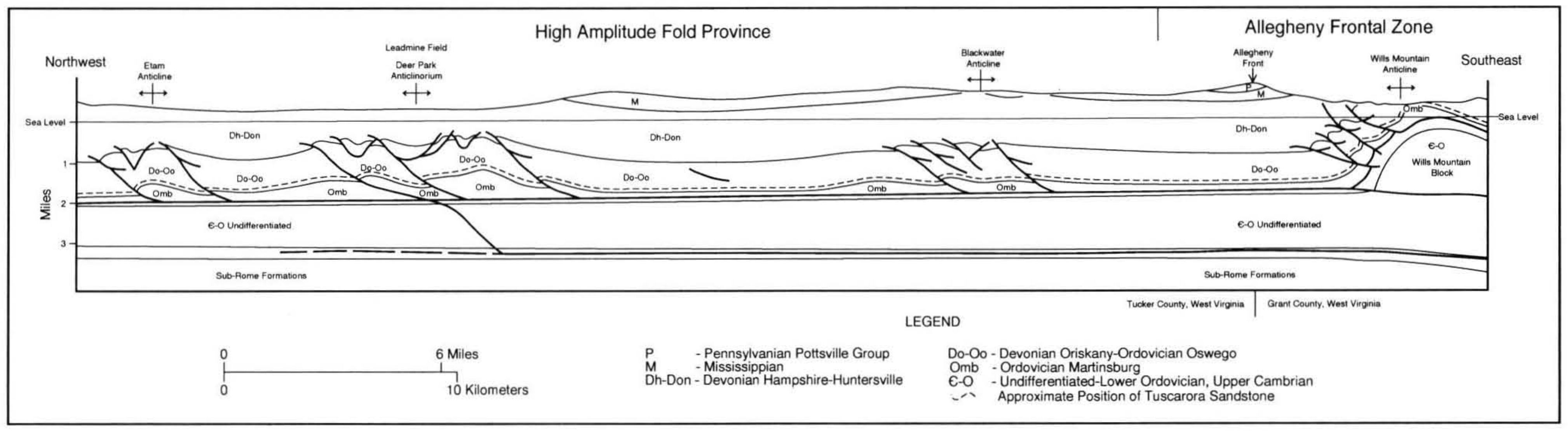
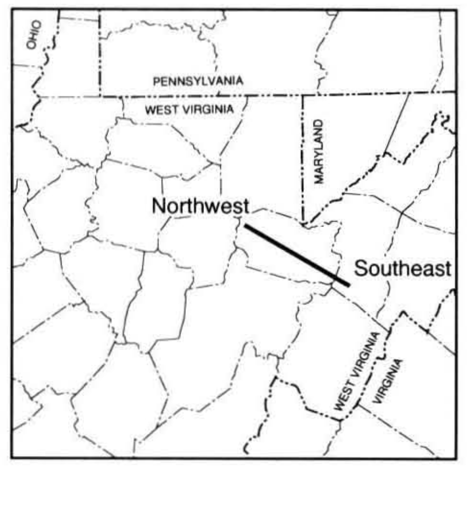


Figure Sts-10. Structural cross section across the Deer Park anticline from Woodward and others (1985), illustrating the structural setting of Leadmine field, Tucker and Preston counties, West Virginia.



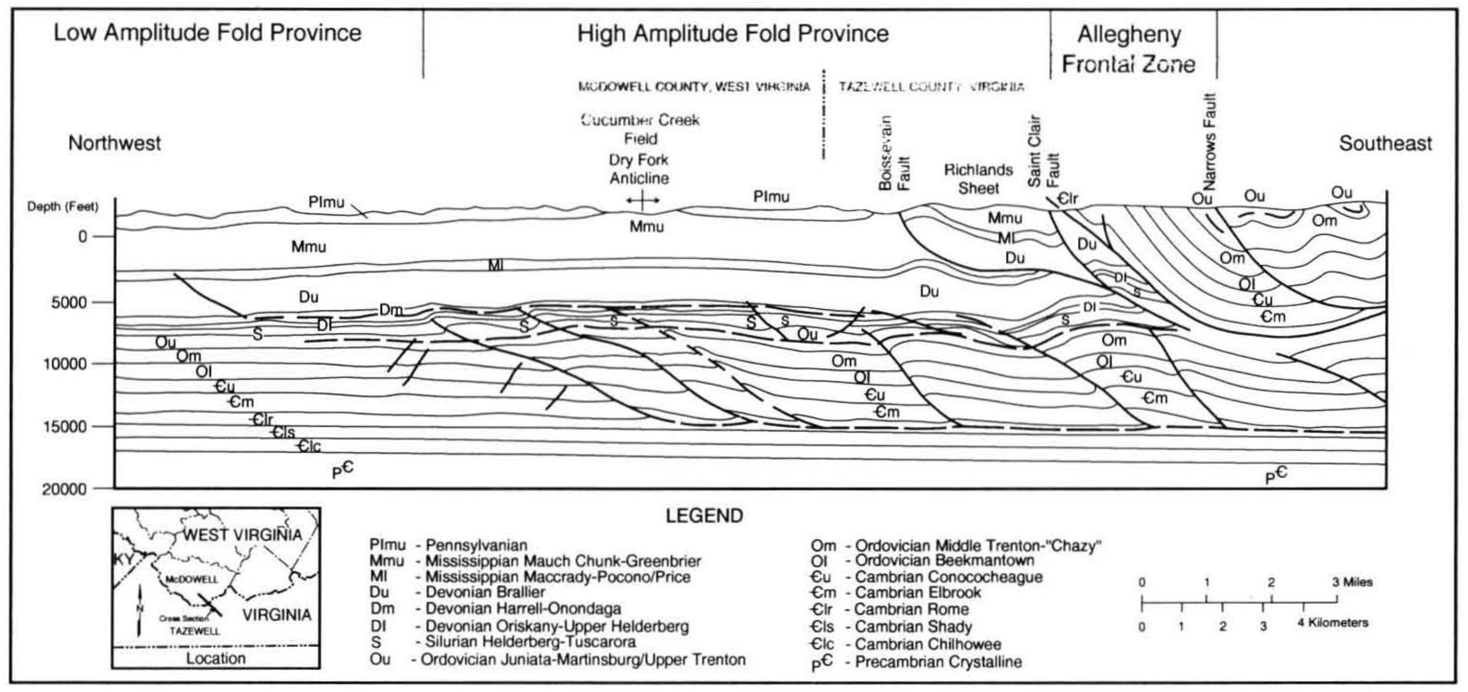


Figure Sts-11. Structural cross section across the Dry Fork anticline modified from Kulander and Dean (1986), illustrating the structural setting and the duplication of the Tuscarora Sandstone by thrust faulting in the Cucumber Creek field, McDowell County, West Virginia.

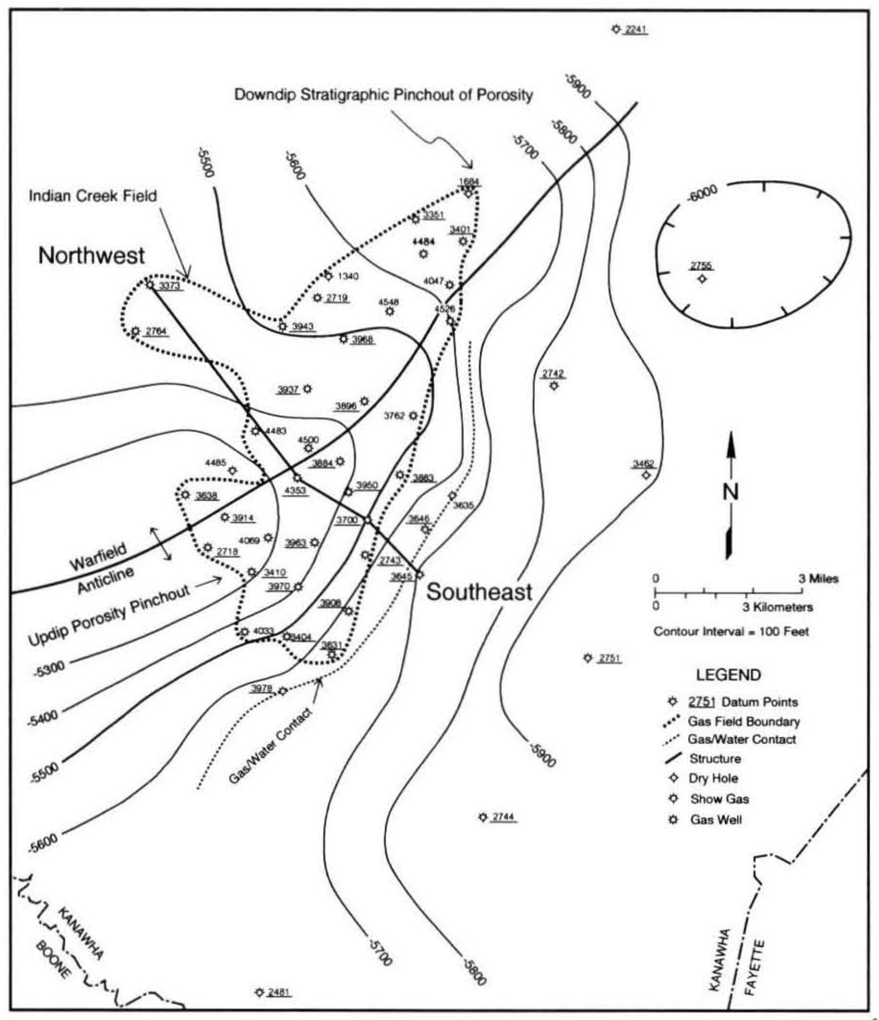


Figure Sts-12. Structure contour map on the top of the Tuscarora Sandstone, Indian Creek field, Kanawha County, West Virginia showing the Warfield anticline, the gas/water contact in the field, the limits of production and the porosity pinchout. Line of cross section (Figure Sts-14) is also shown.

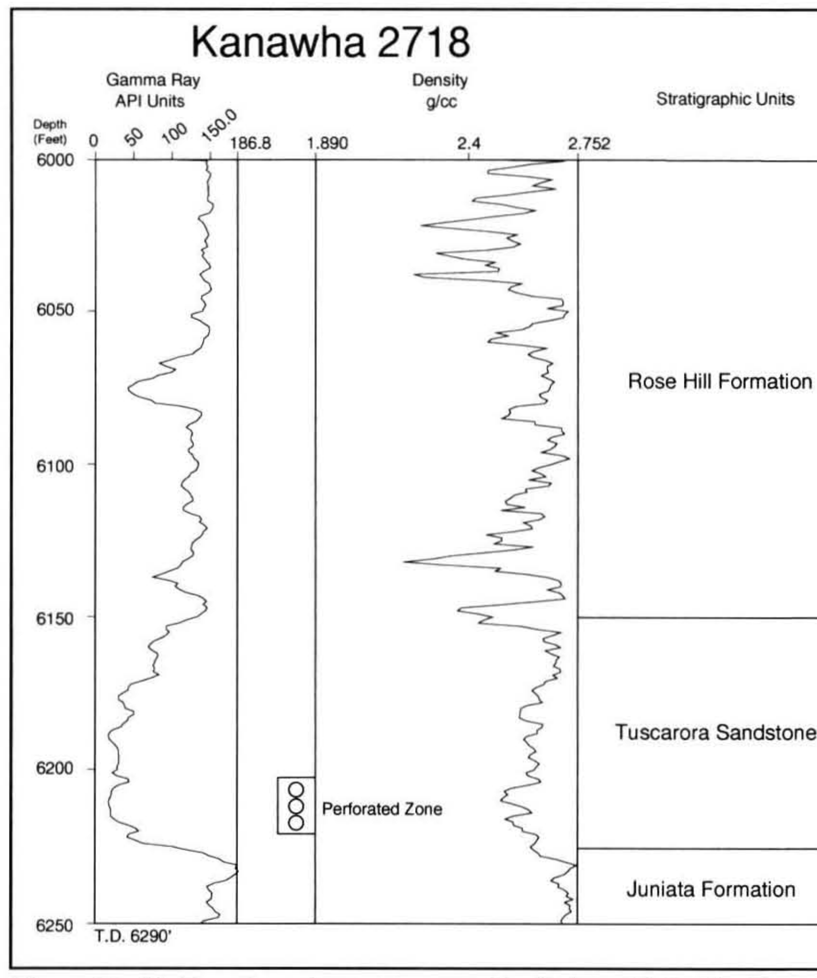


Figure Sts-13. Type logs (gamma-ray and bulk density) for the Tuscarora Sandstone, Indian Creek field, Columbia Gas Transmission Corporation No. 5 (20307-T) Fee (Kanawha 2718) Kanawha County, West Virginia, showing porous productive zone in the lower portion of the formation. The thinner, shaley nature of the Tuscarora can be compared to the thicker, sandier Tuscarora in the type logs from Cucumber Creek field, West Virginia (Figure Sts-18), and Leadmine field, West Virginia (Figure Sts-16).

Apparently, the necessary elements for Tuscarora production in the Allegheny Frontal zone are the fractures associated with the major structural transition zone to provide the reservoir and the anticline to provide the trap.

In the low amplitude folds province, broad open folds generally may not have sufficient structural relief or associated fracturing, but the relatively higher relief on the Warfield anticline in the low amplitude folds province provides the trap, and an area of increased fracture porosity for Indian Creek field.

The Tuscarora reservoirs are water driven (Table Sts-1); salt water is reported off the southeast side of Indian Creek field. Some notes on the Cucumber Creek discovery well from the West Virginia Oil and Gas Conservation Commission (Huzzey, 1985) indicate water production during production testing.

In general, the completion reports for most Tuscarora wells indicate hydrofracture treatments often with some perforation clean-up using acid. However, some wells with large natural open flows were not stimulated.

Gas discovered in the Tuscarora Sandstone contains at least some inert component in addition to methane (Figure Sts-3). In the Pennsylvania fields, Leadmine in northern West Virginia, and several wells in Wayne County, West Virginia, just west of the play boundary (Figure Sts-1), the inert gas is nitrogen (Headlee, 1949; Patchen, 1968a; Youse, 1970; Cardwell, 1977). In Indian Creek field, and in a Tuscarora well in Fayette County, West Virginia, and one in Raleigh County, West Virginia (Hamak and Sigler, 1991), the Tuscarora gas is composed of carbon dioxide and methane. The possible origin of associated nitrogen gas is the reaction of ferric oxide with nitrogen-bearing organic compounds (Hunt, 1979). The possible sources of the ferric oxide and nitrogen-bearing organics are the underlying Juniata red shales and the organic-rich shales of the Martinsburg, respectively. The carbon dioxide was most likely derived from very high thermal maturation of organic matter in source rocks and thermal dissolution of carbonates (Hunt, 1979). As both the source rocks for the Tuscarora gas and the Cambro-Ordovician carbonates beneath the Tuscarora have been subjected to very high thermal levels—mature to post-mature (Epstein and others, 1977; Harris and others, 1978)—they are likely sources for the carbon dioxide gas.

Description of Key Fields

Key fields were chosen to represent the various types of Tuscarora fields: Indian Creek is the low amplitude folds province field; Leadmine is a representative northern high amplitude folds province field; Cucumber Creek is in the southernmost high amplitude folds province; and Devils Elbow represents the Allegheny Frontal zone fields. Leadmine is a field from the 1960s period of exploration and Devils Elbow and Cucumber Creek are from the 1980s period of exploration.

Indian Creek field: Indian Creek field, Kanawha County, West Virginia, is located in the low amplitude folds province, on the northeast plunging nose of the Warfield anticline (Figure Sts-12). The first Tuscarora well drilled along the Warfield anticline was Owens-Libby-Owens No. 13 (500) Bull Creek Coal (Boone 402), completed in August 1939. This well was plugged back and completed as the discovery for the Kanawha Forest Newburg field (see D. Patchen, Upper Silurian Newburg Sandstone play, this atlas). In 1973, Columbia Gas Transmission Corporation reworked No. 8804 Fee (Kanawha 1684), an old Tuscarora well originally drilled, plugged, and abandoned in 1959, initiating their development of the Indian Creek field. Although reworked wells are usually not discovery wells, this well is considered to be the discovery well by the operator. Drilling of the field continued until 1987. The wells were drilled on about one-mile spacing. To date, 36 wells have been drilled in the field.

The Tuscarora in Indian Creek field is relatively thin compared to the Tuscarora in the eastern fields such as Leadmine or Devils Elbow (Figure Sts-13; Table Sts-1). Structurally, Indian Creek field is located on the westernmost major anticline in West Virginia, the Warfield, which is generally considered to mark the southeastern boundary of the Rome trough (Milici, 1980). Gao (1994) suggested that the hanging wall of the Rome trough margin fault moved relatively upward during the Middle Devonian, creating the ancestral Warfield anticline. Possibly this structural setting is the reason for the development of sufficient reservoir-quality fracture porosity in the Tuscarora here.

A number of the wells in Indian Creek field have been completed open hole as natural wells, with high reported natural initial open flows. The maximum initial potential reported in Indian Creek to date is 22,444 Mcf/d (Columbia Natural Resources No. 21143 Blue Creek Coal Company, Kanawha 4526). Average IP for 10 unstimulated Indian Creek wells is 8,172 Mcf/d; the range is 1,384 to 22,444 Mcf/d.

Indian Creek (Figure Sts-12) contains the highest number of wells of any of the Tuscarora fields, and probably has had the greatest commercial success in spite of the high carbon dioxide content. Published U.S. Bureau of Mines gas analyses (Hamak and Sigler, 1991; Hamak and Gage, 1992) showed an average carbon dioxide content of 65.8 percent, an average heating value of 305 Btu/cf, and an average gas gravity of 1.214 g/cc for the Indian Creek Tuscarora gas. Jenden and others (1993) showed a carbon dioxide content of 61.33 percent for one Indian Creek Tuscarora gas sample. The reason for the commercial success is a nearby market for the carbon dioxide at Liquid Carbonic Carbon Dioxide Corporation, where the carbon dioxide is upgraded to food quality and sold. Initially, some of the carbon dioxide from Indian Creek was used in an enhanced oil recovery carbon dioxide flood operated by Columbia Natural Resources in the Granny Creek-Stockly field in Clay County, West Virginia. Granny Creek-Stockly oil field is a Mississippian Big Injun field located about 25 miles northeast of Indian Creek field.

The Tuscarora in the wells downdip on the southeast side of the asymmetric Warfield anticline are water wet and nonproductive (Figure Sts-14). Also, downdip to the northwest and off the northeast plunging nose of the Warfield anticline, the Tuscarora is nonproductive, probably due to a pinchout of reservoir-quality porosity. Approximately 20 bcfg has been produced from 33 Indian Creek wells from 1981 through 1992, making Indian Creek the largest Tuscarora field both in terms of number of wells and amount of gas produced. The average estimated ultimate yield for Indian Creek wells is about 1.8 bcf per well; the average of remaining reserves is about 1.2 bcf per well.

Leadmine field: Leadmine field, Tucker and Preston counties, West Virginia (Figure Sts-15), in the high amplitude folds province, was discovered in 1963 when Columbian Carbon Company completed the No. N-1 (GW-1374) United States of America well (Preston 99) (Figure Sts-16) with an open flow of 696 Mcf/d after fracturing. An open flow of 492 Mcf/d was reported from the Oriskany Sandstone in this same well. The well was drilled to a total depth of 12,030 feet and plugged back to 7,409 feet. Gwinn (1964) stated that Preston 99 penetrated an over-thickened Silurian sequence, as if the drill had penetrated beds dipping 20 to 25 degrees. However, Gwinn (1964) also noted that the underlying Juniata redbeds at the bottom of the well were 4,200 feet thick, 3.5 to 4.5 times thicker than the normal 900 to 1,200 feet, with the bottom of the formation not penetrated. Gwinn (1964) concluded that this thickening was produced in the core of a detached decollement fold near the decollement or by drag and thrust duplication near a sole thrust.

Two additional wells in the field, Cities Service No. Q-1 (GW-1466) United States of America (Preston 119), completed March 17, 1964, and Cities Service No. T-1 (GW-1499) United States of America (Tucker 34), completed August 21, 1964, were drilled. A third productive well, Cities Service No. A-1 (GW-1611) L.E. Mullenax (Tucker 38), completed November 11, 1971, is located about 1.5 miles to the southwest, separated by two intervening dry holes (Tucker 13 and Tucker

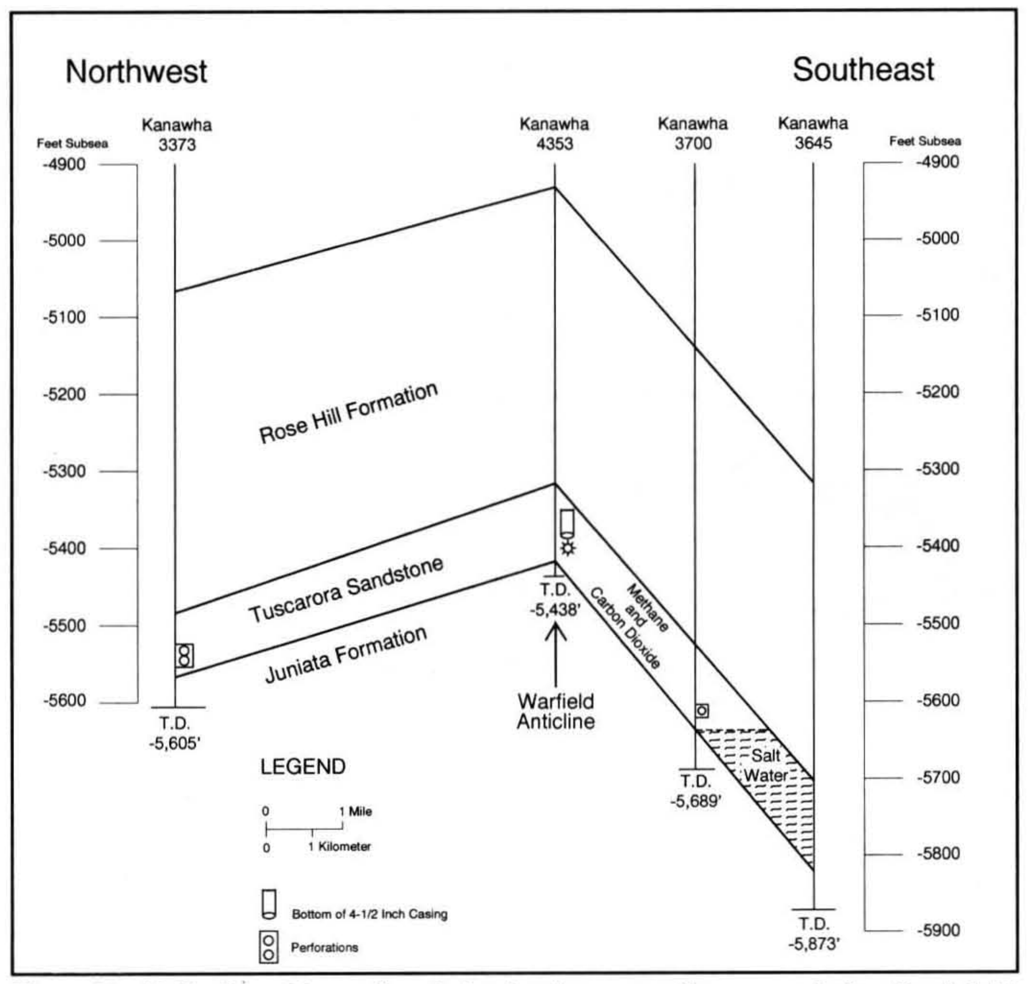


Figure Sts-14. Northwest to southeast structural cross section across Indian Creek field, showing the presence of water in the Tuscarora downdip to the southeast. Line of cross section is shown in Figure Sts-12.

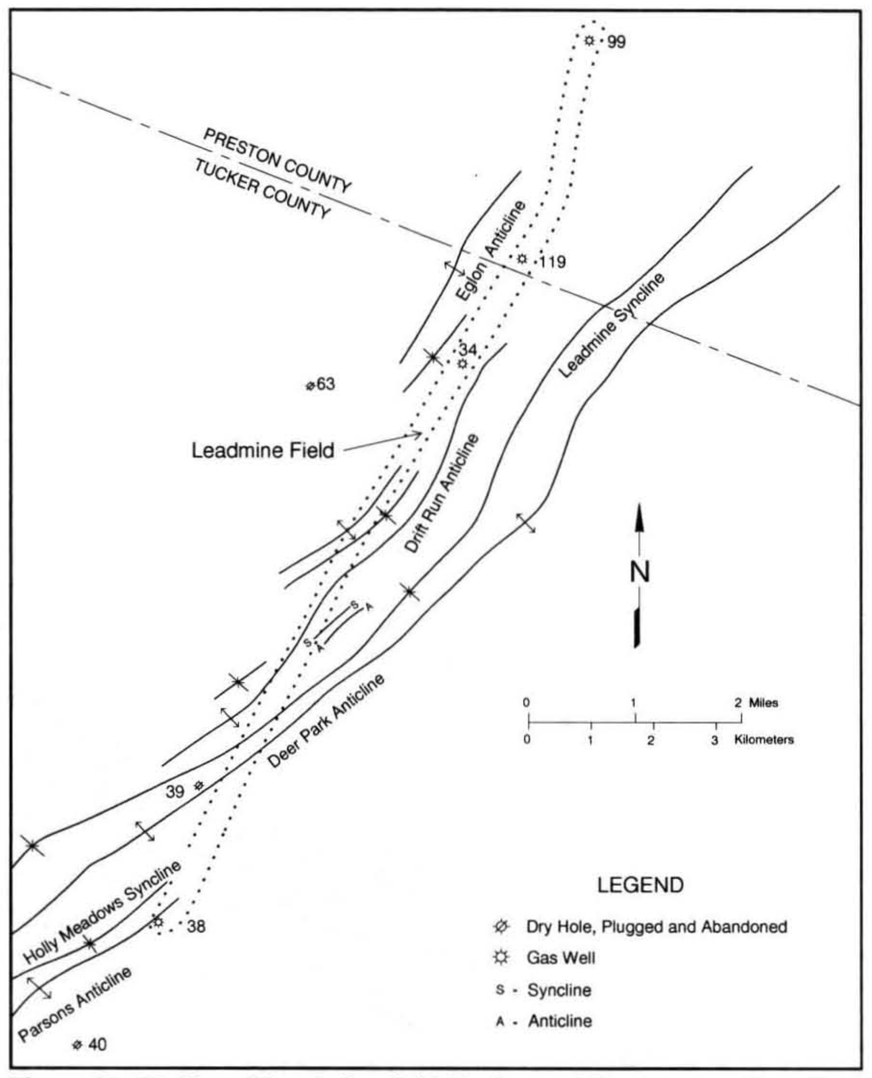


Figure Sts-15. Map of Leadmine field, Tucker and Preston counties, West Virginia, showing producing wells and dry holes referred to in the text, as well as surface structural axes (after Reger,1923).

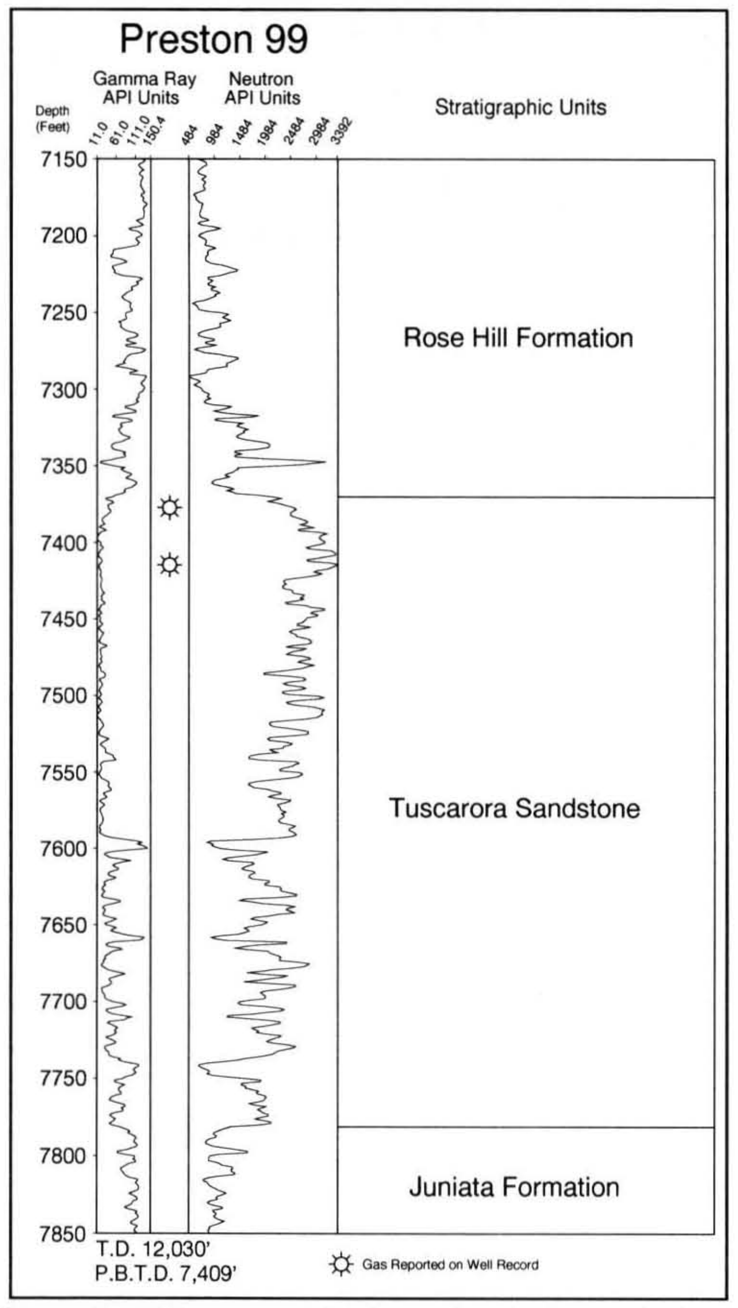


Figure Sts-16. Gamma-ray-laterolog-neutron log from Columbian Carbon Company No. N-1 (GW-1374) United States of America (Preston 99) showing the Tuscarora Sandstone in Leadmine field, Preston County, West Virginia.

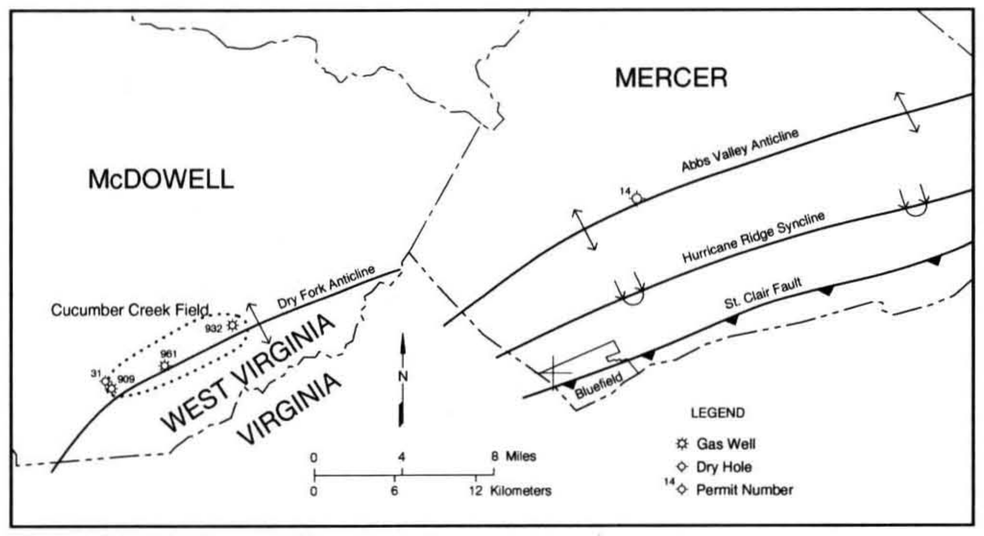


Figure Sts-17. Map of Cucumber Creek field, McDowell County, West Virginia, showing locations of the productive wells and dry holes. See Figure Sts-2 for location of Cucumber Creek field.

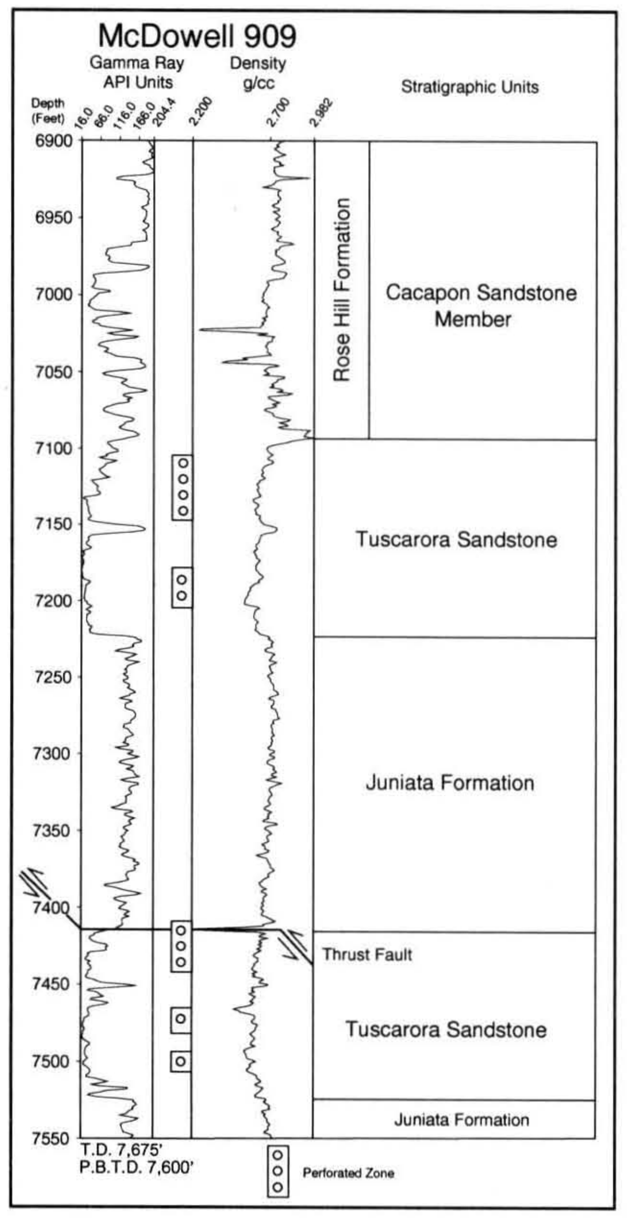


Figure Sts-18. Portion of the gamma-ray and bulk density logs for Conoco Inc. No. 1 Clarence Billups (McDowell 909), Cucumber Creek field discovery well, McDowell County, West Virginia, showing repetition of the Tuscarora Sandstone by thrust faulting.

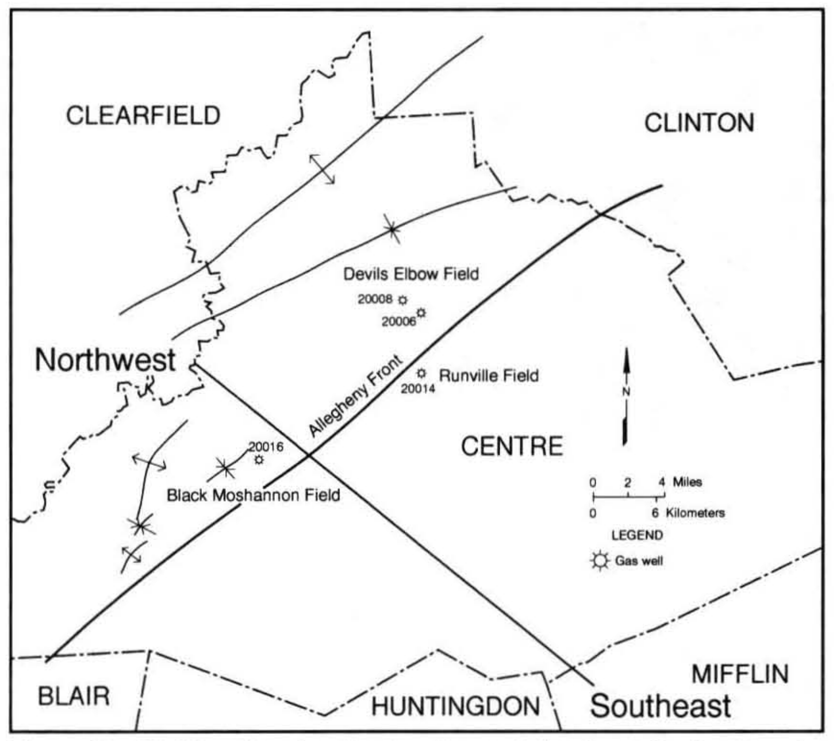


Figure Sts-19. Map showing the locations of the three Centre County, Pennsylvania, Tuscarora Sandstone fields and the position of the Allegheny Front. Location of cross section (Figure Sts-9) is also shown.

39). Salt water was reported in the Tuscarora in both of these wells. About two miles south of Tucker 38, another unsuccessful Tuscarora well, Cities Service No. A-1 (GW-1715) Alonzo Tennant (Tucker 40), was completed August 17, 1972, at a total depth of 7,395 feet. Tucker 40 is located about 1.5 miles west-southwest of Tucker 34. An attempted field extension, Cities Service No. T-2 (GW-1939) United States of America (Tucker 63), was completed February 19, 1983, at a total depth of 9,594 feet in the Tuscarora. The well was plugged back to 5,849 feet, and the Huntersville Chert was perforated, acidized, and fractured with no result.

The Tuscarora in Leadmine field is much thicker than it is in Indian Creek field (Figures Sts-5, Sts-13), and Leadmine appears to be a much more structurally complex field than Indian Creek (Figure Sts-10). The Deer Park anticlinorium is characterized by blind thrust faults with anticlinal slices serving as traps. Perhaps Preston 99, Preston 119, and Tucker 34 are on the western anticlinal slice, while Tucker 38 is on the eastern anticlinal slice as shown in Figure Sts-10. The shut-in pressure reported with 1982 annual production data for Tucker 34 was 800 psi, while the shut-in pressure reported for Tucker 38 was 2,515 psi. This difference in shut-in pressures might be considered evidence of two structurally separate compartments within the field. The structures mapped at the surface also suggest a structurally compartmentalized field. The major detachment zone here is in the Ordovician Martinsburg Formation (Figure Sts-10).

Gas analyses revealed a high nitrogen content in the Tuscarora gas from Leadmine field. An analysis with the well record for Preston 119 showed 16.73 percent nitrogen, a heating value of 848.9 Btu/cf, and a specific gravity of 0.636 g/cc. An analysis with the well record for Tucker 34 showed 18.23 percent nitrogen, a heating value of 819.65 Btu/cf, and a specific gravity of 0.641 g/cc. Analyses reported by the U.S. Bureau of Mines for Tucker 34 and 38 indicate an average nitrogen content of 17.5 percent, an average heating value of 855.5 Btu/cf, and an average specific gravity of 0.6475 g/cc. High initial natural open flows were reported for Preston 119 (16.3 MMcf/d) and Tucker 34 (22 MMcf/d). Tucker 38 had a final open flow of 24.8 MMcf/d after acid treatment.

About 2.6 bcfg has been produced from two Leadmine wells, Tucker 34 and Tucker 38. Apparently, neither Preston 99 nor Preston 119 have ever produced. Preston 119 and Tucker 38 were plugged in 1985. In early 1995, Preston 99 and Tucker 34 have "future use" status, according to the West Virginia Division of Environmental Protection, Office of Oil and Gas database.

Cucumber Creek field: Cucumber Creek field, McDowell County, West Virginia, also in the high amplitude folds province, is the most recently discovered Tuscarora field. It was discovered in 1984, when Conoco, Inc. completed the No. 1 Pocahontas Land well (McDowell 909) at a total depth of 7,675 feet, on the axis of the Dry Fork anticline (Figures Sts-17, Sts-18). The well was plugged back to a depth of 7,600 feet and a final open flow potential of 2,373 Mcf/d after acid treatment was reported. Perforations were made in upper and lower zones to take advantage of the repetition of the Tuscarora by faulting (Figure Sts-18). Eight weeks of flow testing the well at various tubing pressures resulted in the production of 65,903 Mcfg and 1,058.6 barrels of water (Webb, 1985). A field extension well (Conoco No. A-1 Pocahontas Land, McDowell 932), located about 3.5 miles northeast of the discovery well, was completed in October 1985, with a much smaller final open flow reported (250 Mcf/d after acidizing and fracturing) and apparently no repetition of the Tuscarora. A third well (Conoco No. 2 Pocahontas Land, McDowell 961), located between the other two wells, was completed in December 1985. No completion data were reported on the drillers' log for this well. However, on one of the wireline logs, perforations are listed from 7,132 to 7,192 feet. The wells have not been reported as plugged, but no production has been reported to the West Virginia Division of Environmental Protection. In 1988, the operator of record became Phoenix Diversified. No pipeline exists in the area, and apparently the wells are shut in while the decision to either build a pipeline or plug the wells is being made.

The Tuscarora in Cucumber Creek field (Figure Sts-18) is similar in thickness to that in Leadmine field (Figure Sts-16), and thicker than it is in Indian Creek field (Figure Sts-13). The thrust fault encountered in the discovery well (Figures Sts-11, Sts-18) indicates the complexity of the structural deformation in this field. The major detachment here is in the Cambrian Rome Formation (Figure Sts-11), as compared to the Martinsburg in Leadmine field and the Devonian shales in Indian Creek field.

Devils Elbow field: Devils Elbow field, Centre County, Pennsylvania, located in the Allegheny Frontal zone, was the first Tuscarora field discovered as a result of an eastern overthrust belt program conducted by Amoco and partners (Figure Sts-19). The field discovery well, Amoco No. 1 Texasgulf (Pennsylvania state permit number Centre 20006), was completed December 18, 1977, at a total depth of 11,187 feet. The natural open flow was estimated at 20 MMcfg/d; the open flow, measured through a choke, was reported as 7 MMcfg/d after nitrogen removal. The well was perforated at 10,759 to 10,866 feet, and from 10,941 to 10,974 feet and acidized. A U.S. Bureau of Mines gas analysis (Hamak and Sigler, 1991) showed a heating value of 809 Btu/cf, a gas gravity of 0.662 g/cc, and nitrogen content of 22.3 percent for a sample taken from the Tuscarora in this well.

A second well, Amoco No. 2 Texasgulf (Centre 20007), located about 0.5 miles southeast of the discovery well, was completed July 7, 1978, at a total depth of 13,052 feet, as an unsuccessful deeper pool test probably through the Bald Eagle and into the Reedsville Shale. The well was permitted to a depth of 13,000 feet, but there is no indication in the records of the Pennsylvania Bureau of Topographic and Geologic Survey of the intended target formation. The well was plugged back, and the Tuscarora was perforated from 10,696 feet to 10,915 feet and acidized with no results. The well was plugged and abandoned.

A third well, Phillips No. 1 C & K Coal (Centre 20008), was completed October 18, 1978. This well, located about 1.15 miles northwest of the field discovery, was drilled to a total depth of 11,170 feet. The well was perforated at several zones, ranging from 10,756 feet to 11,086 feet in depth and acidized. The after treatment open flow was 1,500 Mcf/d.

Stratigraphically, the Tuscarora is characteristically thicker and sandier here, closer to the eastern source area. Structurally, Devils Elbow field is located in the narrow zone of complexly deformed thrust blocks in a duplex structure, in the Allegheny Frontal zone (Figure Sts-9).

Production records available at the Pennsylvania Bureau of Topographic and Geologic Survey show that, from 1980 to 1992, gas production from the two wells in the Devils Elbow field totalled 3.133 bcf.

Resources and Reserves

Tatlock (1983) estimated 165.9 bcfg as possible recoverable resources from the Tuscarora in Pennsylvania (Centre, Fayette, McKean and Potter counties), with a speculative recoverable resource estimate of 542.6 bcfg for the Tuscarora and deeper units. Only 10 percent or less of these possible or speculative recoverable resources is attributed to the Cambro-Ordovician by Tatlock. Adding 488.3 bcfg (90 percent of 542.6 bcfg) to 165.9 bcfg yields a total recoverable resource estimate of 654.2 bcfg for the Tuscarora in Pennsylvania.

A similar approach in West Virginia involves visually estimating the percentage of each county's area that has the play's geologic attributes, calculating the area in square miles that this percentage represents, summing the square miles included (18,746 square miles) and converting the sum to acres (11,997,440 acres), assuming 1 percent of the acreage to be productive (119,974 acres), using a per acre yield of 3502 Mcf/acre. The calculation indicates a possible recoverable resource of 420 bcfg. The yield per acre was derived from Indian Creek field.

Total recoverable resources for the Tuscarora in Pennsylvania and West Virginia is estimated as 1,074 bcf.

Future Trends

Economically viable new Tuscarora gas prospects will need to be in areas having well-developed intergranular and fracture porosity, structural traps, and manageable amounts of inert gases. Seismic data will be necessary in most cases to locate drilling prospects and structures not reflected at the surface. Also, the most favorable areas may occur in central and south-central Pennsylvania, and perhaps northeastern West Virginia where structures of the Allegheny Frontal and high amplitude fold zones are coincident with the shelf sand wave complexes postulated by Cotter (1983) (Figure Sts-8). A number of unsuccessful Tuscarora tests were completed in the early and mid-1980s, but there still remain many acres of untested and potentially productive Tuscarora. Higher gas prices and improved technology to pinpoint the fractured anticlines not necessarily evident at the surface will help to fuel future Tuscarora exploration.

PLAY Scm: LOWER SILURIAN CATARACT/MEDINA GROUP ("CLINTON") SANDSTONE PLAY

by Michael P. McCormac, George O. Mychkovsky, Steven T. Opritza, Ronald A. Riley, Mark E. Wolfe, Glenn E. Larsen, and Mark T. Baranoski, Ohio Department of Natural Resources

Location

The Lower Silurian Cataract/Medina Group sandstone play is one of the most significant gas plays in the Appalachian basin. Producing fields are located in a broad trend extending from northeastern Kentucky north into Ohio to the Canadian portion of Lake Erie and southwestern Ontario, and into northwestern Pennsylvania and western New York (Figures Scm-1, Scm-2). Cataract/Medina Group sandstones are widely known as "Clinton" by Appalachian basin operators as a result of miscorrelations that occurred during the early development of the play.

Production History

Gas was accidently discovered in the "Clinton" during Ohio's Trenton oil and gas boom of the late 1800s. A wildcat Trenton well drilled in February 1887, near Lancaster in Fairfield County, Ohio, struck "Clinton" gas at 1,957 feet. The well had an IP of 74.8 Mcfg/d with a large quantity of salt water. Subsequent wells drilled had sufficient production to supply the City of Lancaster with natural gas. However, demand was great during the winter of 1888 and the supply of gas appeared inadequate. In 1889, Theodore Mithoff drilled inside the corporate limits of Lancaster, Ohio, in an attempt to secure a gas supply for his machine shop and encountered gas that flowed 12 MMcfg in the first 24 hours. This well started a drilling boom resulting in 17,679 "Clinton" wells drilled in Ohio by 1926 (Denman, 1942).

Discoveries were also being made in the Grimsby Sandstone of the Medina Group in Erie and Chautauqua counties, New York in 1887 (Van Tyne, 1974) and Welland County, Ontario, Canada in 1889 (Cochrane and others, 1986). The relatively shallow and permeable pay sands could be produced naturally or with minimal stimulation. The proximity of these fields to large natural gas markets such as Cleveland, Ohio; Buffalo, New York; and Hamilton, Ontario provided the impetus to this initial stage of drilling.

Overdrilling was common due to an absence of spacing requirements and lack of knowledge of reservoir engineering principles. For example, "Clinton" gas wells in the Cleveland, Ohio, area were commonly drilled on two-acre spacing; the wells were sometimes as close as 100 feet apart. As a result, the reservoir pressure dropped from 1,100 psi to as little as 150 psi from 1912 to 1915. This led to excessive waste, with the average "Clinton" well producing less than three years. Many wells were abandoned without being plugged, which also contributed to the depletion of reservoir pressures (Rogers, 1917; Van Horn, 1917). From 1936 to 1963, in areas where drilling records were complete and abandoned wells adequately plugged, existing wells were commonly converted to gas storage wells.

Historically, there were three main stages of development. During the initial phase of drilling, the existing technology placed a depth limitation on drilling. Furthermore, a lack of modern stimulation technologies meant that only higher quality reservoirs could be economically developed. For example, of the 2,600 holes drilled in New York to the Medina Group by the end of World War II, approximately 40 to 50 percent were dry holes. If a well did not produce approximately 100 Mcfg/d naturally, it was plugged and abandoned (Van Tyne and Copley, 1983). Development in the Cleveland, Ohio, area during this phase resulted in the abandonment of wells that had initial productions of less than 250 Mcf/d (Rogers, 1917). As these fields were fully developed, many were converted to gas storage fields.

The second major phase of drilling commenced in the 1940s, driven largely by improvements in technology, such as rotary drilling (1946), hydraulic fracturing (1950s), and electric well logging (1958). Drilling activity pushed east and southeast to greater depths as a result of the discovery of the historic Canton field in east-central Ohio in 1945. One year later, the first "Clinton" gas field in Kentucky, the Ashland-Mavity field in Boyd County, was discovered. Grimsby production in Pennsylvania soon followed, with the discovery of the Corry field in Erie County in 1947. Also during this period, offshore drilling on the Canadian side of Lake Erie began. The Grimsby in Ontario is virtually devoid of oil, with only 43,000 barrels of oil production reported through 1981 (Cochrane and others, 1986). It should be noted that Ontario requires offshore wells to be plugged back from zones with oil shows (T. Carter, oral commun., 1994). Other notable field discoveries during this time included the East Canton Consolidated field in 1953 and the Conneaut field of northwestern Pennsylvania in 1957.

In the 1970s and early 1980s, another drilling boom occurred, which was motivated by higher oil and gas prices, available investor money, and a federal tax credit for production from tight formations. During the early 1970s, fuel shortages led to higher prices and increased exploration and development. The Cataract/Medina Group sandstones were designated "tight" by the Federal Energy Regulatory Commission in portions of eastern Ohio in 1980, Pennsylvania in 1981, and New York in 1982 and 1983. To qualify, the reservoir sandstone had to have an estimated average *in situ* gas permeability throughout the pay section of 0.1 md or less. This incentive prompted increased drilling in eastern Ohio, western Pennsylvania, and western New York where the sandstone is deeper and less permeable.

Ohio has 186 "Clinton-Medina" sandstone gas fields with approximately 60,000 wells having produced more than 5 tcf through 1992. In Kentucky, 48 "Clinton" sandstone wells have cumulatively produced more than 3 bcf. In New York through 1983, approximately 4,900 Medina Group wells produced 440 bcf from 60 fields. In Pennsylvania through 1992, an estimated 5,500 Medina Group wells produced 342.3 bcf from 95 fields. For onshore Ontario, approximately 5,400

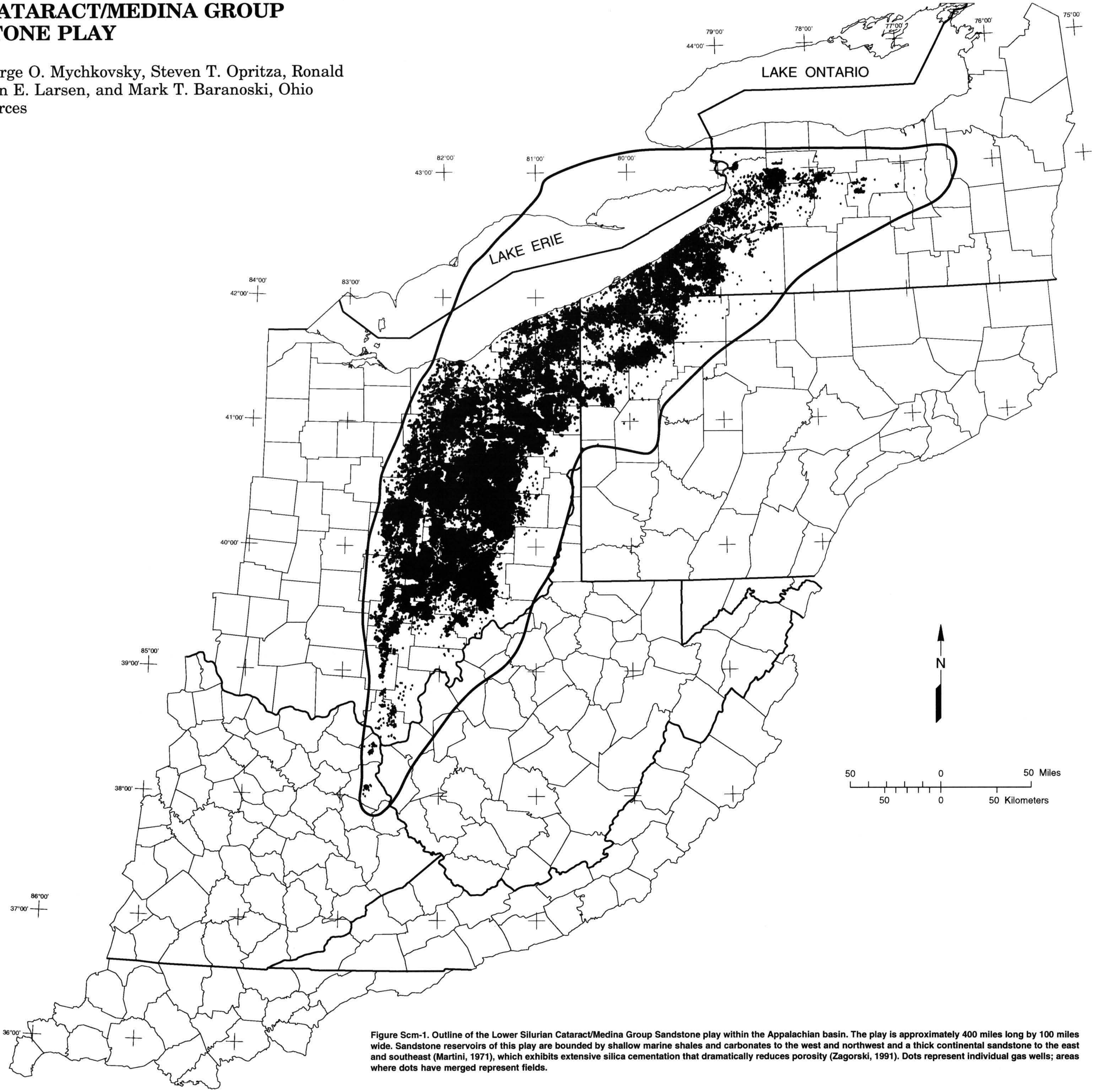


Figure Scm-1. Outline of the Lower Silurian Cataract/Medina Group Sandstone play within the Appalachian basin. The play is approximately 400 miles long by 100 miles wide. Sandstone reservoirs of this play are bounded by shallow marine shales and carbonates to the west and northwest and a thick continental sandstone to the east and southeast (Martini, 1971), which exhibits extensive silica cementation that dramatically reduces porosity (Zagorski, 1991). Dots represent individual gas wells; areas where dots have merged represent fields.

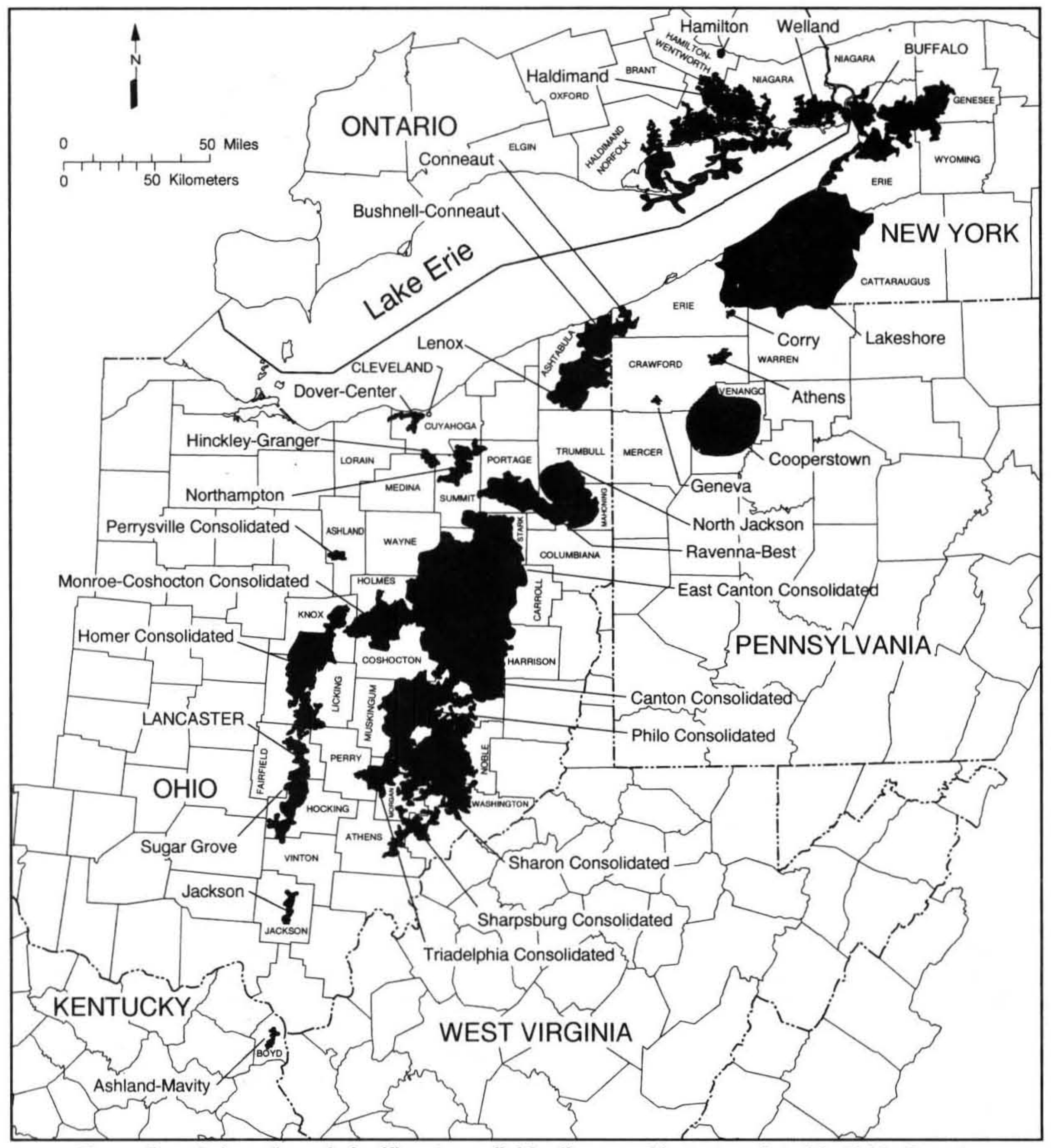


Figure Scm-2. Location of significant gas fields discussed in text or listed in Table Scm-1.

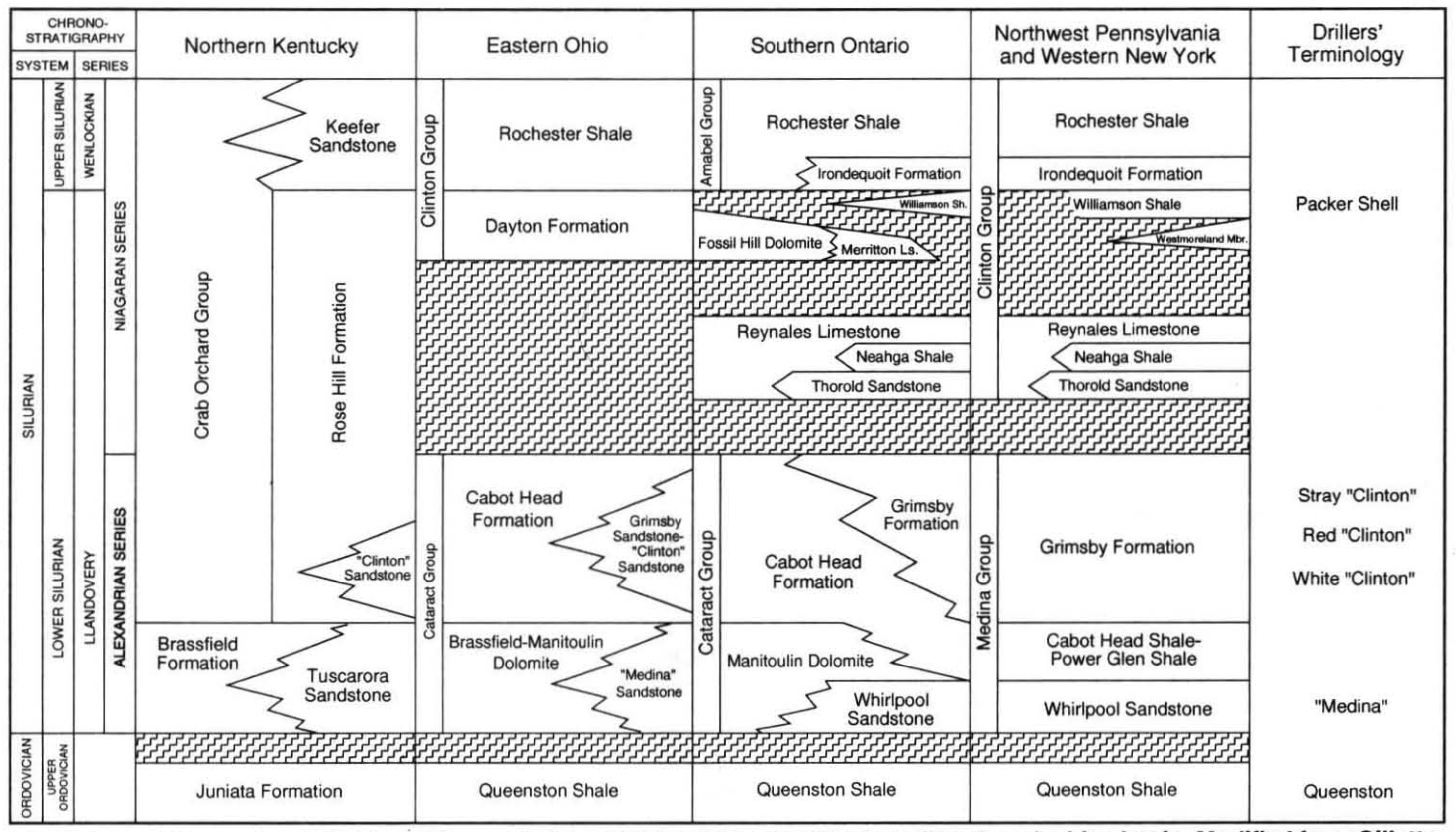


Figure Scm-3. Generalized stratigraphic correlation chart for the Lower Silurian of the Appalachian basin. Modified from Gillette (1947), Janssens (1977a), Kleffner (1985), Patchen and others (1985a), and Brett and others (1991). The "Clinton" sandstones are commonly divided by Ohio drillers' terminology using color and stratigraphic position into the uppermost Stray (if present), upper or first Red, and lower or second White. Each Red and White unit may consist of a single bed of sandstone or up to five separate sandstone beds with interbedded shales. Individual sandstone beds are not mappable on a county basis due to depositional-related heterogeneities. For example, in the Canton Consolidated field, it is believed that individual porous sandstone lenses may range in length from a quarter of a mile to several miles and from 300 feet to 1 mile in width based on rock pressures of adjacent wells (Pepper and others, 1953).

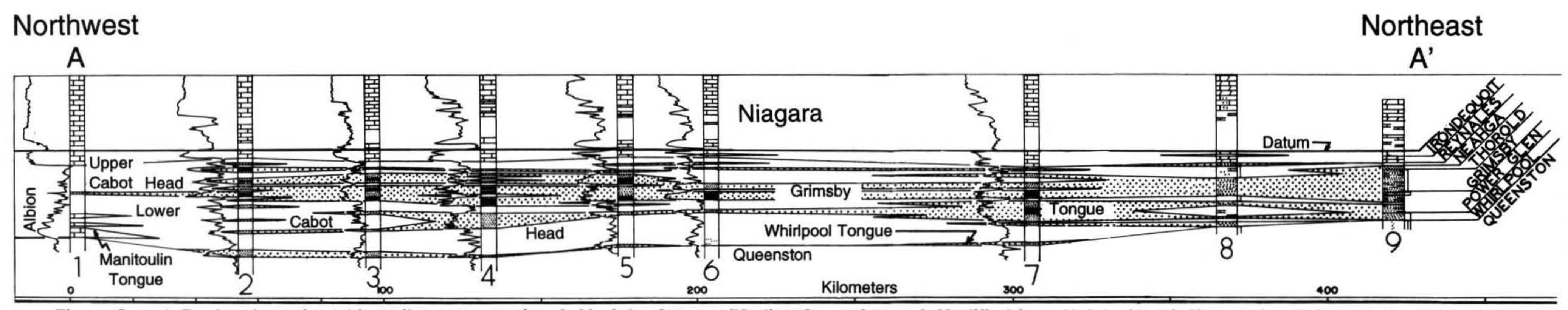


Figure Scm-4. Regional stratigraphic strike cross section A-A' of the Cataract/Medina Group interval. Modified from Knight (1969). Nomenclature is that of Knight (1969).

Grimsby wells in 21 pools produced 214 bcf through the end of 1981. For offshore Ontario, 594 Grimsby wells in 83 pools located in the central and eastern portions of Lake Erie produced 72 bcf in the 25-year period from 1957 through 1981. Approximately 76,442 Cataract/Medina Group sandstone wells have produced an estimated 6 tcfg basinwide.

Stratigraphy

The stratigraphic interval of this play is known as the "Clinton" in Kentucky, the "Clinton" and Cataract Group in Ohio, the Cataract Group in Ontario, and the Medina Group in Pennsylvania and New York. A basinwide correlation chart helps to clarify the varied Lower Silurian stratigraphic nomenclature used for this interval (Figure Scm-3).

Use of the name "Clinton" in Kentucky and Ohio has caused confusion for both geologists and producers over the years. As the following historical account relates, the name "Clinton" was mistakenly applied to the sandstones of the Medina Group in Ohio. Bownocker (1916, p. 316) explained the misapplication: "At first (in the Lancaster, Ohio, discovery well) the gas-rock was thought to be limestone and from its position was named the 'Clinton,' but it was later found to be sandstone and is now known everywhere in Ohio as the 'Clinton sand.' Later studies have shown that the rock is not a part of the Clinton (Group) but of the underlying formation, the Medina (Group), but the old name is too firmly established to be supplanted." Since then, the name "Clinton" has become thoroughly entrenched within the industry and the literature. The standard North American Silurian reference section in New York defines the Clinton Group as lying stratigraphically above the Medina Group (Fisher, 1954). Medina-age (lower Llandoverian) rocks consist of clastics, whereas Clinton-age (upper Llandoverian) rocks are dominantly carbonates.

The Cataract/Medina Group is generally recognized to be Early Silurian, Llandoverian age (Kleffner, 1985) based on conodont studies of samples from wells in Ohio. Kleffner (1985) dates the Stray "Clinton" and Dayton Formation (drillers' Packer Shell) between 432 to 428 million years ago. Correlations are based on lithostratigraphic data, particularly two key marker beds: the top of the Queenston Shale and the base of the Dayton Formation.

The sandstones of this play are not "blanket" sands, as the distribution of pools and fields on Figure Scm-1 might imply, but rather a series of interbedded sandstones, siltstones, and shales. These rocks do not crop out in Kentucky, Ohio, or Pennsylvania. Shale and limestone equivalents of the "Clinton" crop out in southwestern Ohio, while the sandstone pinches out along a north-south line through central Ohio. Pepper and others (1953) studied the subsurface "Clinton" sands of eastern Ohio and correlated the beds to the rocks that crop out in the Niagara Gorge of New York. In New York and Pennsylvania, the rocks are included within the Medina Group (Piotrowski, 1981; Laughrey, 1984). The Medina Group was first named by Vanuxem (1840) in New York. Shales and carbonates of the Middle Silurian Clinton Group overlie the Medina Group that unconformably overlies the Ordovician Queenston Shale (Figure Scm-3). The Medina Group of New York and Pennsylvania and the Cataract Group of Ontario are subdivided in descending order as follows: the Grimsby Sandstone, the Cabot Head Shale, and the Whirlpool Sandstone (Figure Scm-3). In Ohio, equivalent rocks are assigned to the Cataract Group consisting of the "Clinton" sandstone wedge interfingering with the Cabot Head Shale. The basal unit of the Cataract Group is the Whirlpool Sandstone (also known as the "Medina" sandstone in Ohio) (Figure Scm-3). The dolomitic facies of the Whirlpool is interpreted to be equivalent to the Manitoulin Dolomite by Coogan (1991).

The Thorold and Grimsby sandstones of New York, Pennsylvania, and Ontario (Figure Scm-4) are commonly correlated to the Stray "Clinton" and Red and White "Clinton" sandstones, respectively (Figure Scm-3). It should be noted, however, that some authors place the Thorold Sandstone in the Clinton Group (Figure Scm-3).

To the east, the Medina Group correlates with the Tuscarora Formation of Pennsylvania and West Virginia (Rittenhouse, 1949) (Figure Scm-5). The change in formation terminology coincides approximately with the pinchout landward (eastward) of the Cabot Head Shale (Piotrowski, 1981).

Lithologically, the "Clinton"/Grimsby Sandstone is a white to gray to red, medium- to very fine-grained, monocrystalline quartzose sandstone (Frech, 1983; Smiraldo, 1985). The grain shapes range from subangular to subrounded. The degree of sorting is highly variable. Most sandstone lenses are well cemented. Secondary silica is the major cementing agent, although carbonates, hematite, and evaporites may also be present. The Whirlpool Sandstone is a white to light gray to red, fine- to very fine-grained quartzose sandstone. Sand grains tend to be subangular to subrounded and moderately well sorted. The source area of the sands is from the east-southeast, where uplift took place as a result of a dying pulse of the Taconic orogeny. Ensuing erosion provided the influx of clastic material into the depositional basin (Overbey and Henniger, 1971; Piotrowski, 1981).

The Whirlpool Sandstone is the basal unit that uncomformably overlies the Queenston Shale (Piotrowski, 1981). This relationship is interpreted on the gamma-ray curve as a sharp lower contact (Figure Scm-6). Coogan (1991) divides the Whirlpool interval into three major lithofacies: sandstone, calcareous shale, and dolomite. The sandstone facies present in New York, Pennsylvania, southwest Ontario, and northeastern and southeastern Ohio (Figure Scm-7) represents a transgressive marine sheet sandstone (Martini, 1971; Piotrowski, 1981; Kearney, 1983). The sandstone facies is divided into an upper and lower section. The upper section is interpreted as marine wave dominated nearshore sediments. The lower section records a fluvial, braided-river environment (Zagorski, 1991; Cheel and Middleton, 1993). The calcareous shale facies occurs west of the Whirlpool Sandstone and is the principal facies encountered in most Ohio wells. A dolomitic facies (the Manitoulin Dolomite) occurs further west. The calcareous shale and the dolomite facies are considered shallow marine shelf deposits (Coogan, 1991). Continued deepening of the sea following Whirlpool deposition resulted in the marine shelf siltstones and shales of the Cabot Head Shale in a prodelta environment (Piotrowski, 1981; Zagorski, 1991).

Subsequent Grimsby and equivalent reservoir sandstones (Red and White "Clinton") were deposited in a complex deltaic to shallow marine environment during an overall regressive sequence (Overbey and Henniger, 1971). Figure Scm-8 displays the extent of sand deposition. This depositional environment includes various sub-environments such as fluvial, delta-front, barrier island, and shelf sands (Coogan, 1991). The relative influence of these sub-environments varies geographically and stratigraphically because of the complex interplay of the depositional settings and the effects of marine reworking. As an example, Shadrach (1989) suggested that the "Clinton" of Medina County, Ohio, was deposited on a lower delta plain. The White "Clinton" sand was deposited initially as offshore subaqueous bars and then as a barrier system on a shallow marine shelf. Sedimentation prograded westward, and the overlying Red "Clinton" sand was deposited in a channel environment as point bar, channel fill, and mouth bar deposits. Additionally, porosity and permeability are best developed when the sands are reworked in the marine environment (Piotrowski, 1981). Porous zones occur in areas of better sorting where wave action was greatest such as beaches, bars, or channels (Pepper and others, 1953).

The facies changes responsible for forming the stratigraphic traps in Ontario and Ohio were brought about by the Algonquin and Findlay arches, respectively. These positive structural features impeded the northern and western transport of coarser sediments out of the basin. As a result, sandstones are restricted to the basin proper, whereas siltstones, shales, and carbonates occur on the flanks and crest of the arches.

Structure

The Cataract/Medina Group play is located on the northwest flank of the Appalachian basin (Figure Scm-9). In general, structure is not the dominant controlling factor.

Historically, geologists have attributed varying degrees of importance to the relationship of structure and production. Linn (1959) mapped an anticlinal nose in the Bushnell-Conneaut field, Ashtabula County, Ohio. He concluded that both producing and poorly producing wells are found regardless of local structure (Linn, 1962). Other geologists also have downplayed the importance of structure in the trapping of hydrocarbons (Knight, 1969; Piotrowski, 1981; Cochrane and others, 1986). Coogan (1991) suggested that a series of northeast-southwest-trending growth faults, which are offset by northwest-southeast-trending cross-strike faults, have influenced "Clinton" deposition and hydrocarbon production in eastern Ohio. Locally, natural fracture systems are thought to enhance gas production as in the Cooperstown gas field in Crawford and Venango counties, Pennsylvania (Zagorski, 1991).

Although the play is considered primarily stratigraphic, locally structure has been shown to influence production. Wilson (1988) used production data to study two areas within Portage County, Ohio. One area is structurally low (border of Mantua and Shalersville townships) and the other area is structurally high (southern section of Ravenna Township). He concluded that wells located on the structurally high area have an estimated ultimate gas recovery of twice that of wells on the low area. The relationship between structure and production is also exhibited along the East Ohio fault system. Production mapping of wells in the Ravenna-Best field shows trends of wells averaging in excess of 200 MMcfg roughly parallel to the East Ohio fault system with two wells reporting more than 1 bcfg. It should be noted that although the best reported gas producing trends were located on the northern upthrown block, some areas adjacent to the fault are characterized by poor production on both the upthrown and downthrown blocks. This negative correlation between faulting and production has been recently seen in the Mercer County area of Pennsylvania, particularly near the Henderson dome (W. Zagorski, oral commun., 1995).

Reservoir

The trapping mechanism is primarily stratigraphic, and commercial hydrocarbon production is strongly related to porosity and permeability variations of the reservoir (Pepper and others, 1953; Kelley and McGlade, 1969; Knight, 1969). In general, porosity and permeability increase in the updip direction. Fields developed prior to hydrofracturing tend to delineate trends of maximum porosity and permeability. Most of the early gas fields were discovered in a narrow zone parallel to the updip pinchout in central Ohio and southern Ontario. Here, optimum reservoir conditions such as high gas saturation, lower shale content, a higher degree of sorting of sand grains, and increased porosity and permeability resulted in excellent production. Many of the newer fields in Ohio and Pennsylvania occur at depths of 5,000 to 6,500 feet. In these deeper fields, water block has been suggested by Davis (1984) and Zagorski (1991) as a possible trapping mechanism for gas. This type of trap is created by low-permeability sandstone sequences where gas is found down-dip from water. They propose that basin center or "deep basin" trapping may play a significant role in controlling the regional distribution of hydrocarbons. Zagorski (1991) studied the Cooperstown field and concluded it is an example of the basin center trapping mechanism.

Knight (1969), Piotrowski (1981), and Pees (1983) speculated that the Cabot Head Shale is the source for hydrocarbons in the "Clinton"/Grimsby reservoir. Martini (1971) suggested that the deeper Ordovician shales be considered as source rocks. Cole and others (1987) conducted geochemical studies to determine potential source rocks in the Paleozoic of Ohio and concluded that the Silurian through Middle Devonian rocks contain marginal amounts of source material. They postulated that the Ordovician Point Pleasant shales and Devonian Ohio Shale are the most likely sources of hydrocarbons in the "Clinton"/Grimsby sandstones.

Total interval thickness ranges from less than 100 feet to approximately 225 feet. Depth to pay ranges from less than 1,000 feet to 6,700 feet below the surface in the U.S. The shallowest Grimsby wells are located in Ontario in the Welland field at depths of only a few hundred feet. The deepest offshore wells are located in central Lake Erie at depths of more than 2,200 feet (Cochrane and others, 1986). Average depth to pay in the basin is 4,100 feet. Thickness of combined pay sands range from 3 to 50 feet and average 23 feet. Figures Scm-10 and Scm-11

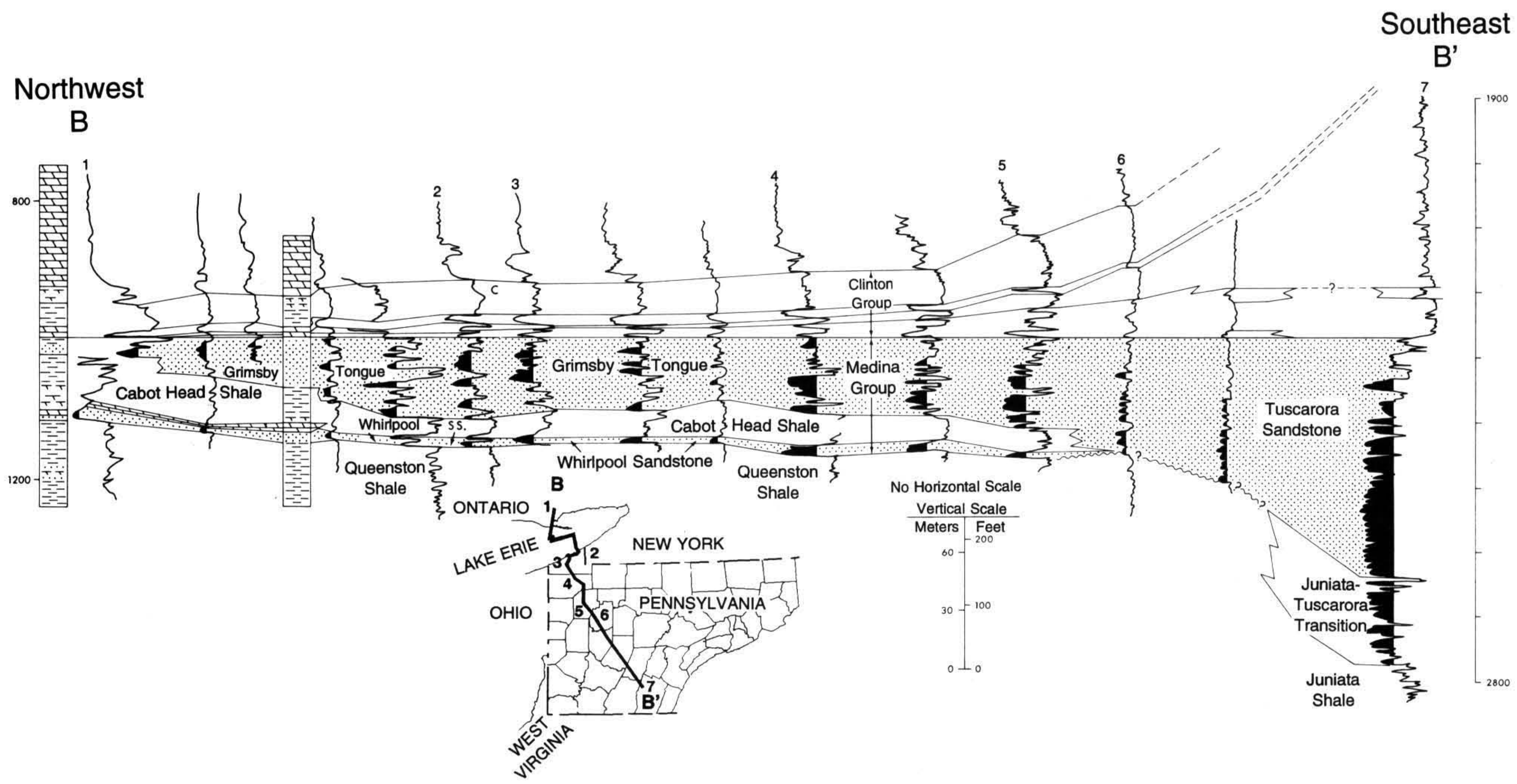


Figure Scm-5. Regional stratigraphic dip cross section B-B' of the Cataract/Medina Group interval. Modified from Piotrowski (1981). Nomenclature is that of Piotrowski (1981).

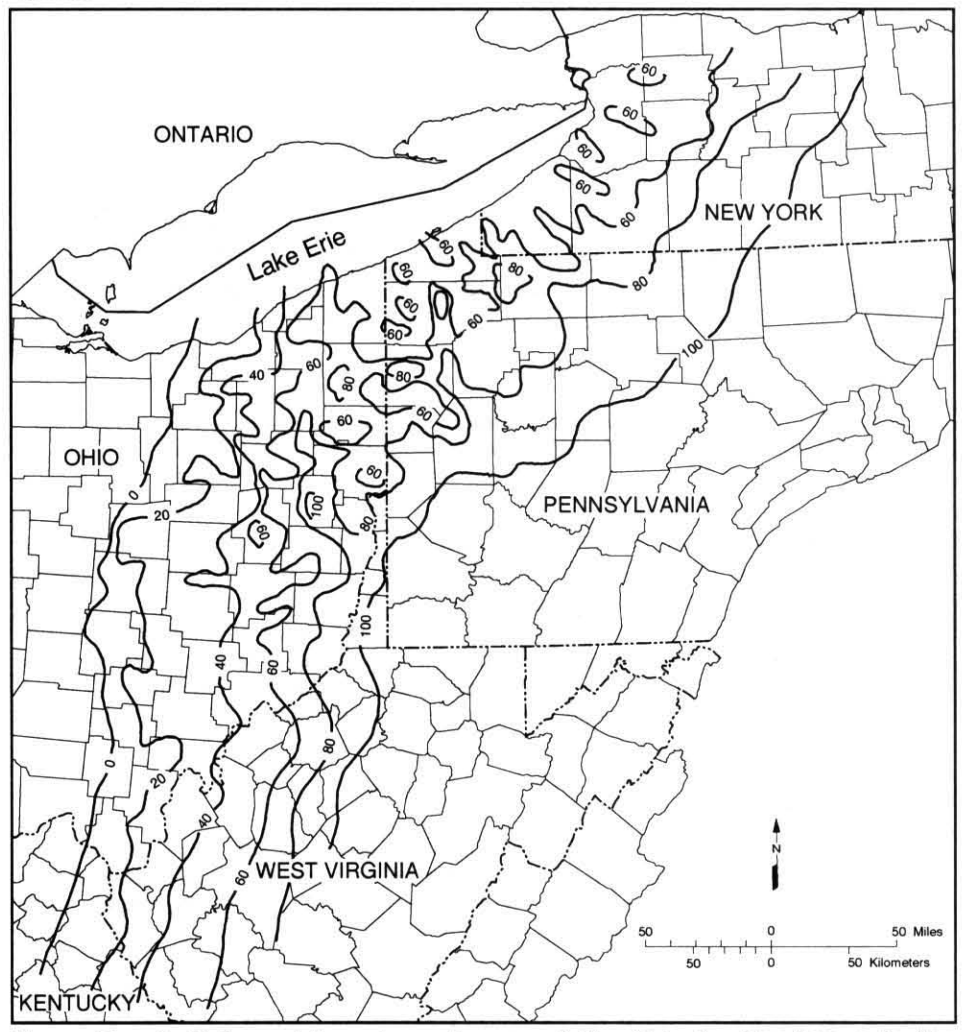


Figure Scm-8. Net sandstone isopach map of the Grimsby Sandstone in the Appalachian basin. Modified from Boswell and others (1993). Map is based on 433 well locations evenly spaced throughout the study area. Contour interval = 20 feet. Net sandstone is defined as greater than 50 percent shale-free on the basis of the gamma-ray log.

display regional net pay for the Whirlpool and "Clinton"/Grimsby sandstones. Initial open flows range from 45 to 25,000 Mcfg/d and average 1,325 Mcfg/d. Final open flows range from 150 to 2,775 Mcfg/d, averaging 785 Mcfg/d.

Reservoir heterogeneity was recognized early. Russell (1926) made the following observations from "Clinton" wells: sandstone beds cannot be correlated between wells; the presence of oil at higher levels than gas in the same sandstone in adjacent wells; and the great variations in initial reservoir pressures. He noted that pressures vary within short distances from about 200 psi to nearly 1,200 psi in Ohio gas fields and that wells with the higher initial pressures have been drilled after a field was discovered. He concluded the "Clinton" is composed of disconnected sandstone lenses. The lateral and vertical discontinuities of the individual sandstone bodies and wide variations in porosity and permeability are also recognized in southwestern Ontario (Cochrane and others, 1986).

Factors controlling reservoir heterogeneity are grain size, clay content, degree and type of cementing, pay thickness, and pore geometry (Overbey and Henniger, 1971). A combination of depositional and diagenetic processes have created porosity and permeability variations throughout the "Clinton" reservoir (Sitler, 1969; Laughrey, 1984). Interbedded shale created permeability barriers that resulted in both horizontal and vertical segregation of the Stray, Red, and White "Clinton" sandstone reservoirs.

Authigenic silica and carbonate cementation resulted in almost complete occlusion of primary intergranular porosity; therefore, porosity is mostly

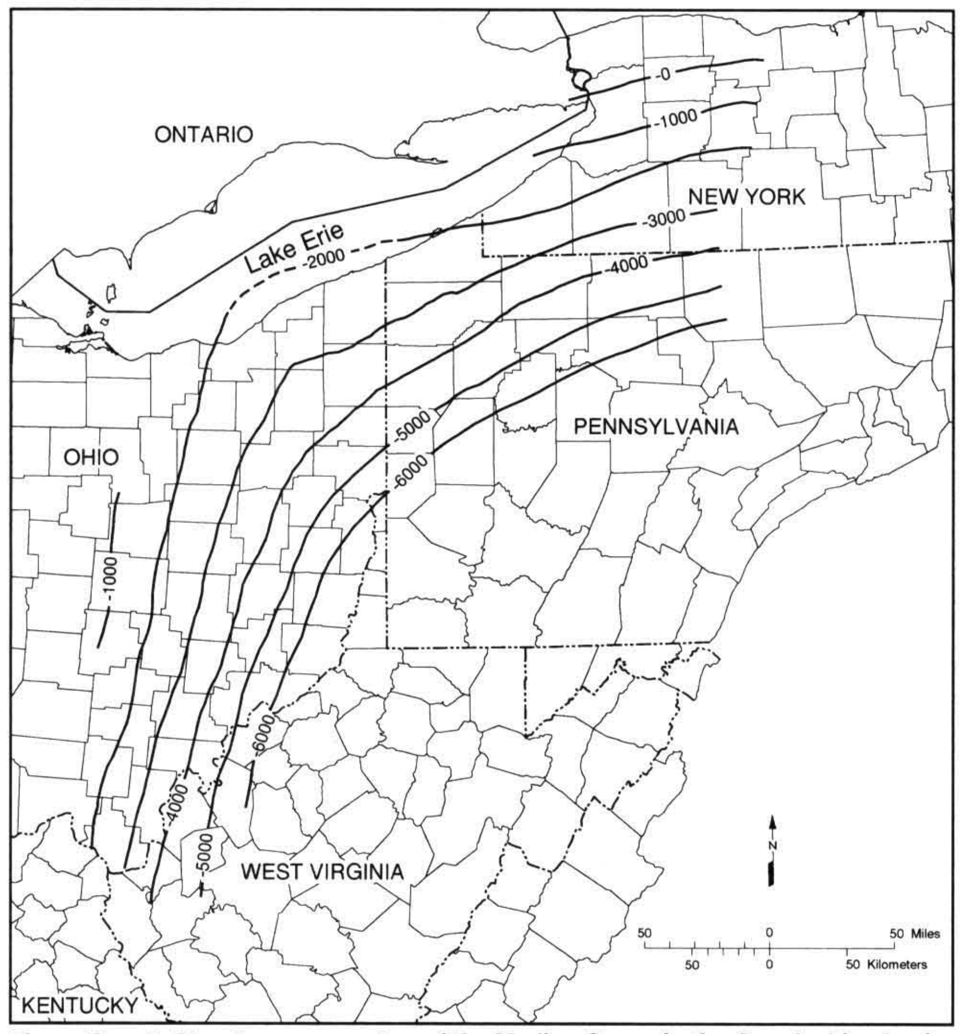


Figure Scm-9. Structure map on top of the Medina Group in the Appalachian basin. Modified from Boswell and others (1993). Map is based on 433 well locations evenly spaced throughout the study area. Contour interval = 1,000 feet. The sandstone interval thins westward and eventually pinches out in central Ohio at a depth of approximately 1,000 feet below sea level. The regional structure is monoclinal, with strike ranging from N11°E in the Sugar Grove field to N75°E in the Lakeshore field. Dip ranges from approximately 32 feet per mile to 65 feet per mile southeast, increasing toward the basin axis.

secondary in northeast Ohio and Pennsylvania (Burford and Frech, 1982; Frech, 1983; Laughrey, 1984). Silica cementation is more important regionally, whereas carbonate cementation is more important locally. The predominant porosity types are secondary intergranular porosity related to partial dissolution of primary calcite cement and grain margins and moldic porosity related to selective dissolution of feldspars and corrosion of silica cement. In a study of the Cooperstown gas field, Zagorski (1991) found the best porosity development to be within the Thorold-upper Grimsby interval. The primary mechanism for porosity development was identified as dissolution of unstable feldspars in the sandstone. Peak porosity trends tend to be linear and align with major surface lineaments that are believed to be expressions of deep-seated fractures and fault zones, indicating the influence of structure on porosity. Deep-seated fluids travelling along the fracture and fault planes reacted with the feldspars to create the secondary porosity. Zagorski (1991) noted that porosity was found to have a greater impact on initial production than did 70 percent clean sandstone thickness. Generally, little or no relationship was found to exist between high porosity trends and sandstone deposition.

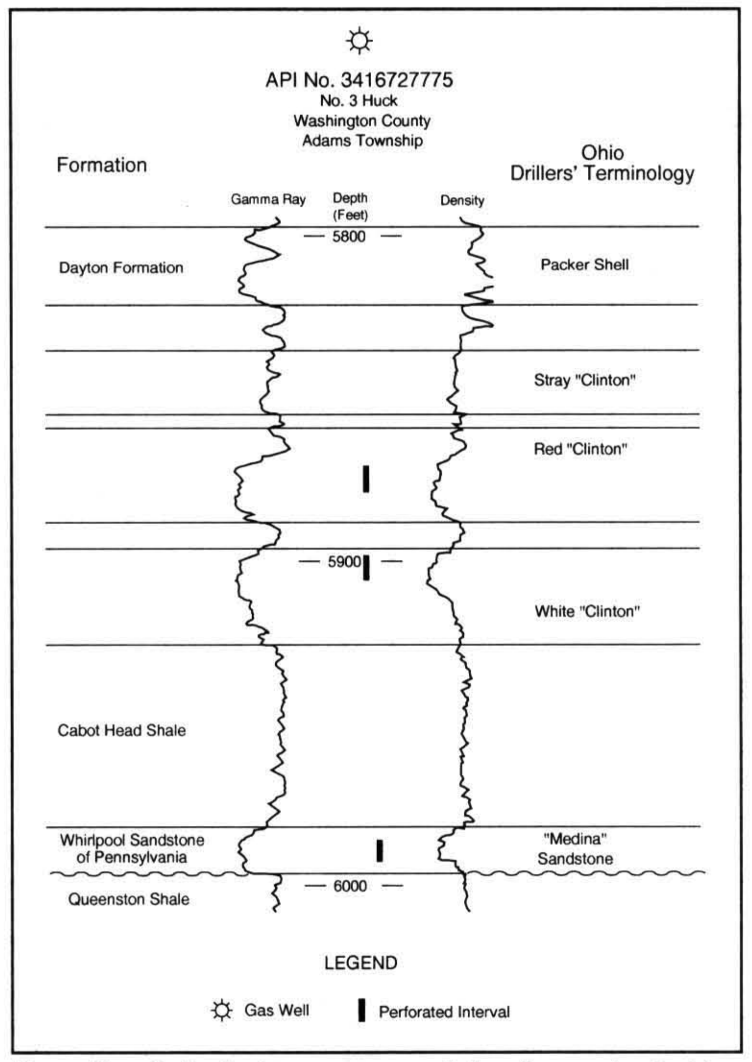


Figure Scm-6. Typical gamma-ray and density geophysical log curves showing "Clinton" and "Medina" sandstones in the Ohio L. & M. Co. Inc., No. 3 Huck well (Washington, 7775) in the Sharon Consolidated field, Ohio. The "Clinton" and "Medina" sandstones are separated by 50 to 60 feet of gray, silty Cabot Head Shale. The "Medina" tends to have less shale than the "Clinton", has a higher percentage of carbonate cement and is much more uniform in its well-to-well distribution within any given area of the Sharon Consolidated field. Thickness of the "Medina" ranges from 4 to 12 feet and porosity is similar to that of the "Clinton."

Other types of porosity that have been recognized in cores from the Athens field of Pennsylvania include relict primary porosity, intraconstituent porosity, microporosity, and fracture porosity (Laughrey, 1984). Minor secondary fracture porosity is also recognized elsewhere in the Appalachian basin (Ortega, 1978; Piotrowski, 1981; Pees, 1983). Frech (1983) noted that the best porosity commonly occurs near shale interbeds.

Porosity values range from 2 to 23 percent and average 7.8 percent. Initial reservoir pressure ranges from less than 500 psi to greater than 1,800 psi and averages about 1,200 psi.

Zagorski (1991) concluded that Medina Group sandstone gas fields in northwestern Pennsylvania were underpressured relative to the normal hydrostatic gradient of 0.46 psi/foot for most reservoirs. Reservoir temperatures generally range from 85°F to 118°F, although Zagorski (1991) indicates temperatures reach as high as 140°F.

Secondary silica cementation has resulted in porosity reduction. In some instances, chlorite coatings on quartz grains served to preserve porosity by inhibiting the development of authigenic quartz (Frech, 1983). In other cases, silica cements actually engulfed grain coats and destroyed primary porosity (Laughrey, 1984).

Relatively few cores have been taken from the "Clinton"/Grimsby sandstones, in part because of the existing vast body of knowledge from extensive drilling and partially because the marginal economic nature of its production that precludes additional expenditures. From the cores and pressure build-up tests taken in this reservoir, average permeabilities range from 0.1 to 40 md, with individual intervals occasionally exceeding 200 md. Laughrey (1984) studied several cores from the Athens and Geneva fields of northwestern Pennsylvania and found that most rocks had permeability of less than 0.1 md.

Early researchers (Rogers, 1917; Russell, 1926) reported no brine associated with hydrocarbon production in the western "Clinton" gas fields of central Ohio; thus, a gas expansion drive is inferred. Kelly (1966) asserts that gas expansion is the primary drive mechanism in the Conneaut field of Pennsylvania. Gas expansion also appears to be the primary drive mechanism in Ontario (Cochrane and others, 1986). In the eastern Ohio fields, where gas and oil are co-produced, the drive is solution gas (Boley and others, 1965; Schrider and others, 1970).

Various studies have determined cumulative production for an average "Clinton"/Grimsby well. In Ohio, average ultimate recovery using 11,000 wells is approximately 75 MMcfg and 2,000 barrels of oil per well (Cumberlidge and McCullough, 1985). Cumulative production from a study of 29 wells in Pennsylvania averaged 157 MMcfg per well (Pees and Burgchardt, 1985), whereas in New York cumulative production averaged 154 MMcfg for 100 wells (Copley, 1980). Kentucky's largest "Clinton" field averages 93 MMcfg per well. In Ontario, a study of 146 wells in Haldimand-Norfolk County drilled since the late 1950s showed cumulative production averaging 70 MMcf per well through 1981. Offshore in Lake Erie, production averaged approximately 121 MMcf per well from 1957 to 1981. Furthermore, a production decline analysis of 50 pools indicates an average decline rate of 10.92 percent per year (Cochrane and others, 1986). A study undertaken of 2,258 wells by the Ohio Oil and Gas Association (1977) showed almost 60 percent of the total production occurs in the first five years (Figure Scm-12).

Before hydraulic fracturing, "Clinton" and Whirlpool wells either relied on natural flow or were shot with nitroglycerin. Since the 1950s, common completion

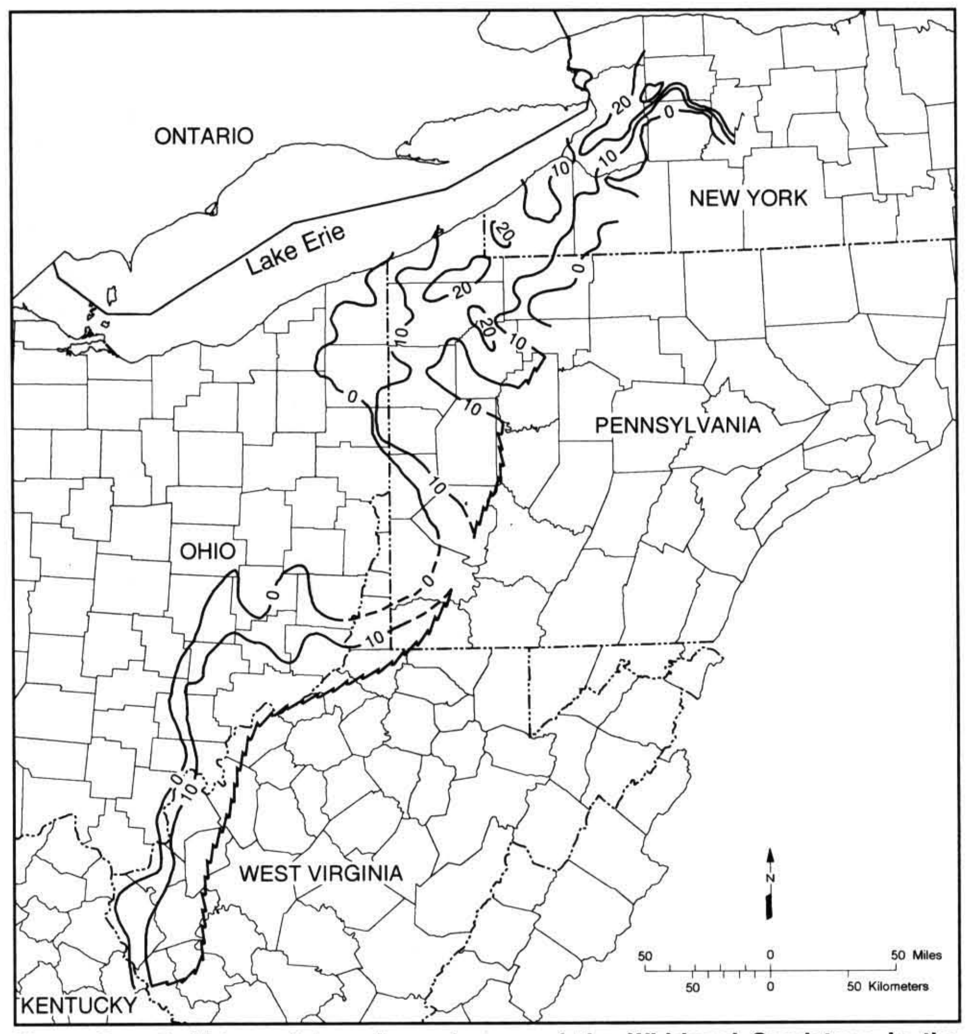


Figure Scm-7. Net sandstone isopach map of the Whirlpool Sandstone in the Appalachian basin. Modified from Boswell and others (1993). Map is based on 433 well locations evenly spaced throughout the study area. Contour interval = 10 feet. Jagged line indicates boundary limits are unknown. Net sandstone is defined as greater than 50 percent shale-free on the basis of the gamma-ray log. Northeast-to-southwest trends are present in Pennsylvania (Zagorski, 1991) and New York (Metzger, 1981). Deposition of the Whirlpool in northwestern Pennsylvania is believed to be strongly influenced by basement structure (Zagorski, 1991).

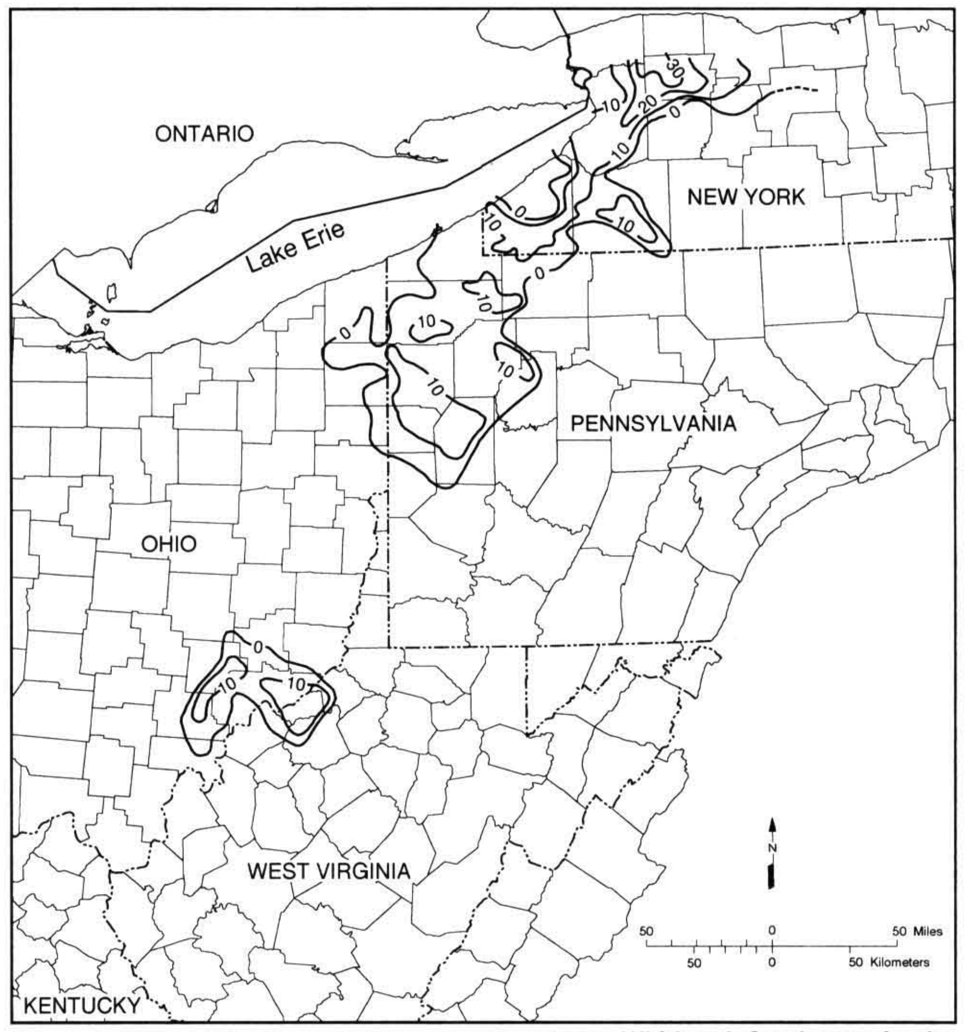


Figure Scm-10. Net gas pay isopach map of the Whirlpool Sandstone in the Appalachian basin. Modified from Boswell and others (1993). Map is based on 433 well locations evenly spaced throughout the study area. Contour interval = 10 feet. Net gas pay is defined as greater than 50 percent shale-free on the basis of the gamma-ray log, 4 percent or greater porosity, and the sum of water and oil saturation totalling less than 60 percent.

practice is to set production casing through the interval and perforate and hydrofracture, thus enabling many of these tight wells to produce commercially. Hydraulic fracturing with sand as a proppant is commonly used to stimulate production because of low-matrix permeabilities and apparent lack of natural fracture communication between wells (Sitler, 1969; Schrider and others, 1970). There are several areas (Figure Scm-11) where the Whirlpool Sandstone is the primary completion target (see the Sharon Consolidated field).

Description of Key Fields

Tables Scm-1 and Scm-2 contain a listing of 22 significant fields. Eight gas fields have been selected as key fields because they illustrate either a typical or unique aspect of the play. Ashland-Mavity and Sugar Grove fields represent

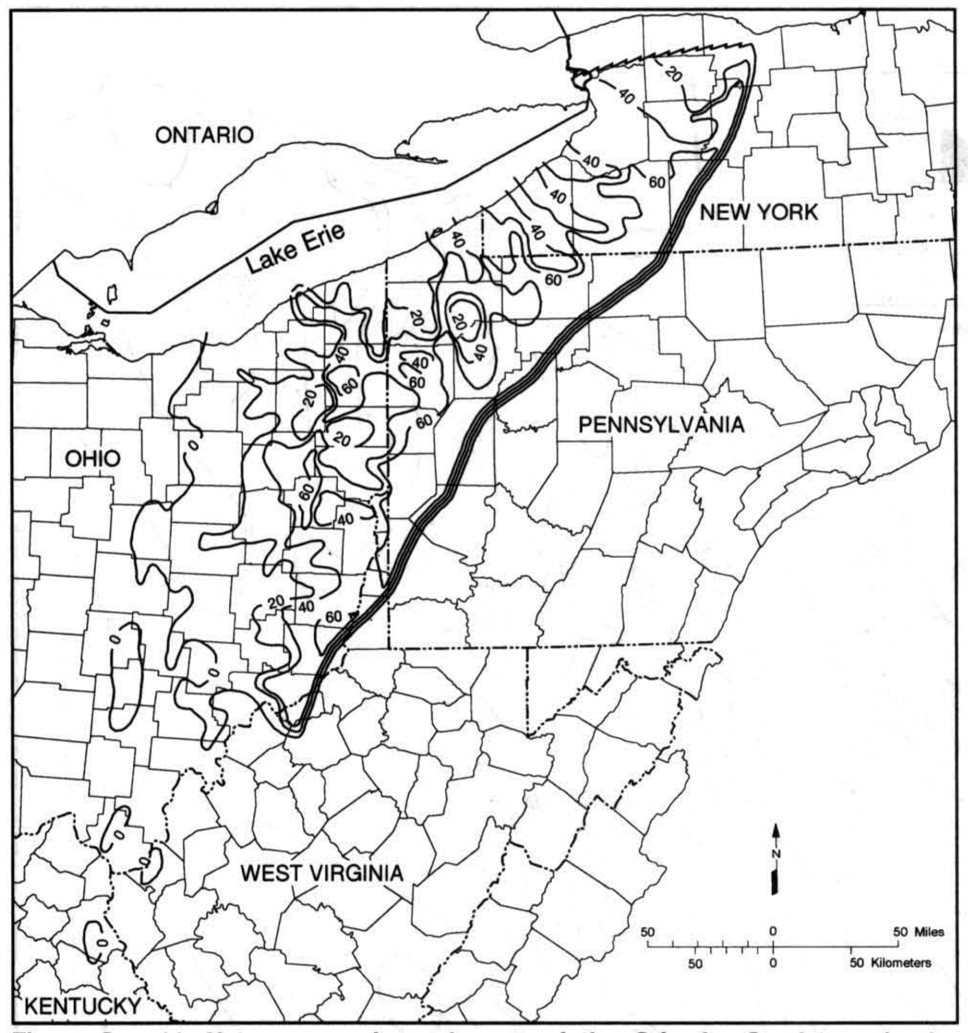


Figure Scm-11. Net gas pay isopach map of the Grimsby Sandstone in the Appalachian basin. Modified from Boswell and others (1993). Map is based on 433 well locations evenly spaced throughout the study area. Contour interval = 20 feet. Net gas pay is defined as greater than 50 percent shale-free on the basis of the gamma-ray log, 4 percent or greater porosity, and the sum of water and oil saturation totalling less than 60 percent.

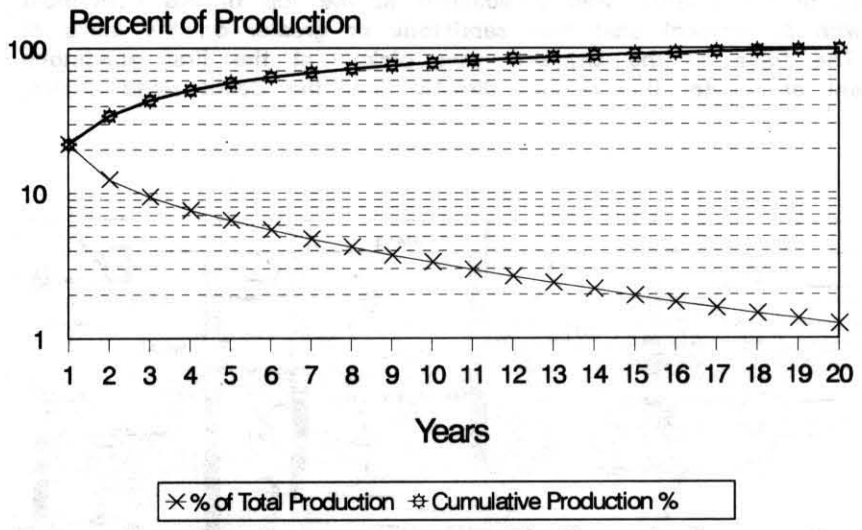


Figure Scm-12. Average gas production decline curve percentages for the "Clinton" sandstone in Ohio based on study conducted by Ohio Oil and Gas Association (1977). A typical Ohio "Clinton" well averages 75 MMcfg (Cumberlidge and McCullough, 1985).

typical fields along the western extent of the play. The Hinckley-Granger field reflects the influence of structure. The East Canton field is an example of a gas and oil producing field and depicts a stratigraphic trapping mechanism. The Sharon Consolidated field is an example of significant gas production in the Whirlpool Sandstone. The North Jackson field represents a significant discovery in the last quarter century and illustrates typical pressure decline in a field. The Canton and Lakeshore fields are the two largest and account for the greatest amount of gas production. Specific parameters for these fields are shown in Tables Scm-1 and Scm-2.

Ashland-Mavity field: The Ashland-Mavity field (Figures Scm-2, Scm-13) in Boyd County, Kentucky, is the southernmost significant "Clinton" field in the Appalachian basin. It was discovered in 1946 when the Inland Gas Co. Inc., No. K-27 Inland Gas Co. Inc. was completed with an initial open flow of 127 Mcf/d (Watson, 1979). Intensive development began in 1963 when hydraulic fracturing procedures became readily available. The field has 27 producing wells and eight dry holes. In nearly all cases, wells exhibit high flush production with a very rapid decline to a stabilization point followed by a fairly long period of nearly constant production rates. The initial decline rate in this field is more rapid than a typical "Clinton" well (Figure Scm-12). Cumulative gas production through 1992 is 2.5 bcf, or an average of 93 MMcfg per well. Gas composition is primarily methane (95 percent) and nitrogen (2.5 percent).

Structurally, the field is located north of the Rome trough on a north-south-trending monocline that is terminated by a deep-seated growth fault on its southern end (Figure Scm-14). No production has occurred on the downthrown side (Watson, 1979).

Lakeshore field: The Lakeshore field is located in Chautauqua County in extreme southwestern New York (Figure Scm-2) where the structure takes a more prominent east-to-west trend (Figure Scm-9). The Lakeshore field is the northeasternmost significant gas field in the U.S. portion of the Appalachian basin. The first Medina Group test well in this field was completed in 1887 by the Fredonia Gas and Fuel Company, but the field was not actively developed until 1903 (Van Tyne, 1974).

TABLE Scm-1		Ashland-Mavity KY	Lakeshore NY	Bushnell-Conneaut OH	Canton Consolidated OH	Dover Center OH	East Canton Consolidated OH	Hinckley-Granger OH	Homer Consolidated OH	Jackson OH
BASIC RESERVOIR DATA	POOL NUMBER	1600060357		3400999357	3401049357	3400337357	3401042357	3400350357	3401020357	3400751357
	DISCOVERED	1946	1887	1929	1930	1908	1966	1928	1900	1908
	DEPTH TO TOP RESERVOIR	2,834	3,000	2,700	3,700	2,330	4,825	3,063	2,100	2,550
	AGE OF RESERVOIR	Silurian	Silurian	Silurian	Silurian	Silurian	Silurian	Silurian	Silurian	Silurian
	FORMATION	Clinton	Grimsby Whirlpool	Clinton	Clinton	Clinton	Clinton	Clinton	Clinton	Clinton
	PRODUCING RESERVOIR	Clinton	Grimsby Whirlpool	Clinton/ Medina	Clinton	Clinton	Clinton	Clinton	Clinton	Clinton
	LITHOLOGY	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone
	TRAP TYPE	structural	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	structural	stratigraphic	stratigraphic
	DEPOSITIONAL ENVIRONMENT	shallow marine	shallow marine	fluvial-deltaic	fluvial-deltaic	shallow marine	fluvial-deltaic	fluvial-deltaic	fluvial-deltaic	shallow marine
	DISCOVERY WELL IP (Mcf)	127		100		662	134	559	1,000	1,852
	DRIVE MECHANISM	gas expansion	gas expansion	solution gas	solution gas	solution gas	solution gas	solution gas	solution gas	gas expansion
	NO. PRODUCING WELLS	26	4,000	380	5,908	27	2,541	106	419	22
	NO. ABANDONED WELLS	1		63	985	700	332	47	1,365	138
	AREA (acreage)	2,600	398,466	21,799	321,566	9,199	154,803	5,592	34,375	5,391
	OLDEST FORMATION PENETRATED	Precambrian		Knox	Conasauga	Queenston	Copper Ridge	Precambrian	Knox	Copper Ridge
	EXPECTED HETEROGENEITY DUE TO:	deposition structure		deposition structure fractures	deposition structure fractures	deposition	deposition structure fractures	deposition structure	deposition structure fractures	deposition
RESERVOIR PARAMETERS	AVERAGE PAY THICKNESS (ft.)	3	24	35	15	15	43	20	18	11
	AVERAGE COMPLETION THICKNESS (ft.)	3		35	15	15	43	20	18	11
	AVERAGE POROSITY-LOG (%)	10	6.3	7.5	7	6.6	8	7.5	9.5	10
	MINIMUM POROSITY-LOG (%)	4	1.5	6	2	5	2	5.2	4	7.5
	MAXIMUM POROSITY-LOG (%)	15	11.2	9.3	13	7.5	13	11.6	17	11.5
	NO. DATA POINTS	18	2	35	105	1	18	40	12	1
	POROSITY FEET	0.3	1.51	2.6	1.05	0.99	3.44	1.5	1.71	1.1
	RESERVOIR TEMPERATURE (°F)	86		90	102	86	104	88	89	
	INITIAL RESERVOIR PRESSURE (psi)	1,035		1,050	1,400	1,100	1,500	1,240	950	780
	PRODUCING INTERVAL DEPTHS (ft.)	2,834-3,319		2,700-3,580	3,700-6,200	2,330-2,850	4,825-5,770	3,063-3,677	2,100-3,000	2,550-2,700
	PRESENT RESERVOIR PRESSURE (psi) / DATE	790		850/1984	900	125/1915	900	700/1954		
FLUID & GAS PROPERTIES	Rw (Ωm)			0.035	0.035	0.035	0.035	0.035	0.035	0.035
	GAS GRAVITY (g/cc)	0.582			0.641	0.636	0.657		0.642	
	GAS SATURATION (%)	53	57	30	65		30	30	46	
	WATER SATURATION (%)	47	40	45	25		30	21	31	37
	COMMINGLED	yes	no	no	no	no	no	yes	no	no
	ASSOCIATED OR NONASSOCIATED	nonassociated	nonassociated	associated	associated	associated	associated	associated	associated	nonassociated
	Btu/scf	1,013		994	1,050	1,095	1,094		1,086	
VOLUMETRIC DATA	STATUS (producing, abandoned, storage)	producing	producing	producing	producing	producing	producing	producing	producing	producing
	ORIGINAL GAS IN PLACE (Mcf)			40,900,000	1,477,071,000	75,000,000	544,500,000	47,400,000	242,913,000	25,000,000
	ORIGINAL GAS RESERVES (Mcf)		616,000,000	26,600,000	1,033,950,000	56,300,000	381,150,000	30,800,000	194,330,000	17,500,000
	PRODUCTION YEARS	1946-1992	1887-1992	1972-1986	1930-1992	1912-1915	1966-1992	1928-1992	1900-1992	1925-1992
	REPORTED CUMULATIVE PRODUCTION (Mcf)			337,000	58,847,000	31,000,000	14,516,000	10,360,000	23,649,000	16,819,000
	NO. WELLS REPORTED			25	1,412	535	1,290	49	214	113
	ESTIMATED CUMULATIVE PRODUCTION (Mcf)	2,500,000	426,000,000	25,300,000	723,765,000	56,000,000	266,805,000	24,600,000	178,784,000	16,819,000
	REMAINING GAS IN PLACE (Mcf)/DATE			15,600,000	753,306,000	19,000,000	277,695,000	22,800,000	64,129,000	8,181,000
	REMAINING GAS RESERVES (Mcf)/DATE		190,000,000	1,300,000	310,185,000	300,000	114,345,000	6,200,000	15,546,000	681,000
	RECOVERY FACTOR (%)			65	70	75	70	65	80	70
	INITIAL OPEN FLOW (Mcf/d)	485		500	451	2,000		250	3,000	810
	FINAL OPEN FLOW (Mcf/d)	340		2,200	279	1,500	35	350	317	

TABLE Scm-1 (continued)		Lenox OH	Monroe Coshocton Consolidated OH	Northampton OH	North Jackson OH	Perrysville Consolidated OH	Philo Consolidated OH	Ravenna-Best OH	Sharon Consolidated OH	Sharpsburg Consolidated OH	Sugar Grove OH	Tridelphia Consolidated OH	Athens PA	Conneaut PA
BASIC RESERVOIR DATA	POOL NUMBER	3400868357	3401004357	3401046357	3400951357	3401056357	3401036357	3401040357	3401037357	3401051357	3401012357	3401033357	3729165357	37157832357
	DISCOVERED	1959	1917	1935	1963	1905	1928	1949	1970	1970	1893	1929	1979	1957
	DEPTH TO TOP RESERVOIR	3,180	2,825	3,370	4,300	2,390	3,600	4,150	4,450	4,600	1,980	3,550	4,453	2,736
	AGE OF RESERVOIR	Silurian	Silurian	Silurian	Silurian	Silurian	Silurian	Silurian	Silurian	Silurian	Silurian	Silurian	Silurian	Silurian
	FORMATION	Clinton	Clinton	Clinton	Clinton	Clinton	Clinton	Clinton	Clinton	Clinton	Clinton	Clinton	Grimsby Whirpool	Grimsby Whirpool
	PRODUCING RESERVOIR	Clinton/ Medina	Clinton	Clinton	Clinton	Clinton	Clinton/ Medina	Clinton	Clinton/ Medina	Clinton/ Medina	Clinton	Clinton/ Medina	Clinton	Clinton
	LITHOLOGY	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone
	TRAP TYPE	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	stratigraphic	straigraphic
	DEPOSITIONAL ENVIRONMENT	fluvial-deltaic	shallow marine	fluvial-deltaic	fluvial-deltaic	shallow marine	fluvial-deltaic	fluvial-deltaic	shallow marine	fluvial-deltaic	shallow marine	fluvial-deltaic	fluvial-deltaic	fluvial-deltaic
	DISCOVERY WELL IP (Mcf)	135	414	39	200	4,700			330	1,805		290	7,898	916
	DRIVE MECHANISM	solution gas	solution gas	solution gas	solution gas	gas expansion	solution gas	solution gas	solution gas	solution gas	gas expansion	solution gas	gas expansion	gas expansion
	NO. PRODUCING WELLS	1,363	1,656	626	1,595	1,014	1,869	1,436	2,245	276	419	276	165	
	NO. ABANDONED WELLS	136	734	80	19	264	987	128	542	22	694	215		
	AREA (acreage)	68,834	73,972	27,534	108,318	3,928	97,022	96,252	102,080	11,449	19,337	14,118	23,456	128,050
	OLDEST FORMATION PENETRATED	Precambrian	Precambrian	Knox	Queenston	Knox	Knox	Knox	Rose Run	Knox	Clinton	Knox	Queenston	Queenston
	EXPECTED HETEROGENEITY DUE TO:	deposition structure fractures	depositiona structural fractures	depositional structural fractures	depositional structural	depositional structural fractures	depositional structural fractures	depositional structural fractures	depositional structural	depositional structural	depositional structural fractures	depositional	diagenesis depositional structural	structural fractures
RESERVOIR PARAMETERS	AVERAGE PAY THICKNESS (ft.)	40	12	50	50	9	18	40	20	20	14	21	42	12
	AVERAGE COMPLETION THICKNESS (ft.)	40	12	50	50	9	18	40	20	20	14	21		
	AVERAGE POROSITY-LOG (%)	7.5	8.1	7.6	7.8	10	8.2	7.5	6	8	12.5	7.9	5.6	10
	MINIMUM POROSITY-LOG (%)	5.9	3.4	3	5.3	3	2	6	4.4	6	4	2	2	3
	MAXIMUM POROSITY-LOG (%)	9.6	16.2	11	9.9	21	17	9.7	12	12.3	23	19	9	18
	NO. DATA POINTS	77	29	14	69	17	18	75	20	24	11	7	30	
	POROSITY FEET	3	0.97	3.8	3.9	0.9	1.48	3	1.2	1.6	1.75	1.66	2.35	1.2
	RESERVOIR TEMPERATURE (°F)	95	97	94	108	88	106	102	118	115	85	101	106	104
	INITIAL RESERVOIR PRESSURE (psi)	1,200	1,040	1,075	1,450	1,300	1,360	1,400	1,375	1,585	900	1,190	1,220	1,100
	PRODUCING INTERVAL DEPTHS (ft.)	3,180-3,990	2,825-3,850	3,370-3,930	4,300-5,900	2,390-3,010	3,600-5,700	4,150-5,550	4,450-6,300	4,600-5,700	1,980-2,620	3,550-4,410	4,453-5,214	2,736-4,374
	PRESENT RESERVOIR PRESSURE (psi) / DATE	450/1983	600/1993		410	157/1972	650/1978	450			28/1966	600/1986		
FLUID & GAS PROPERTIES	Rw (Ωm)	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.05	0.035		
	GAS GRAVITY (g/cc)	0.63			0.608		0.644	0.63	0.645		0.59	0.659		
	GAS SATURATION (%)	40	36	28	68		48	45	55	50	61	48	58	49
	WATER SATURATION (%)	45	35	30	20		31	30	35	35	39	40	40	42
	COMMINGLED	no	no	yes	no	no	no	no	yes	no	no	no	no	
	ASSOCIATED OR NONASSOCIATED	associated	associated	associated	associated	nonassociated	associated	associated	associated	associated	nonassociated	associated	nonassociated	nonassociated
	Btu/scf	1,060	1,149		1,049	1,120	1,070	1,073	1,038	1,045		1,015		
VOLUMETRIC DATA	STATUS (producing, abandoned, storage)	producing	producing	producing	producing	storage	producing	producing	producing	producing	storage	producing	producing	producing
	ORIGINAL GAS IN PLACE (Mcf)	185,000,000	357,000,000	86,892,000	358,123,000	142,980,000	527,262,000	212,300,000	364,453,000	34,000,000	106,000,000	83,092,000	79,819,000	
	ORIGINAL GAS RESERVES (Mcf)	120,000,000	249,900,000	56,480,000	232,780,000	114,380,000	342,720,000	148,600,000	236,895,000	23,800,000	85,000,000	54,010,000	63,855,000	
	PRODUCTION YEARS	1970-1992	1926-1992	1983-1992	1972-1993	1924-1992	1930-1992	1958-1993	1972-1992	1983-1989	1925-1992	1930-1992	1979-1992	1957-1992
	REPORTED CUMULATIVE PRODUCTION (Mcf)	28,219,000	17,108,000	457,000,000	81,471,000	6,971,000	31,215,000	33,457,000	81,531,000	45,000,000	5,595,000	15,590,000		
	NO. WELLS REPORTED	679	694	21	662	77	818	376	1,024	5	63	146	165	
	ESTIMATED CUMULATIVE PRODUCTION (Mcf)	98,200,000	242,400,000	45,184,000	174,585,000	114,380,000	299,300,000	118,900,000	189,516,000	16,700,000	85,000,000	83,092,000	16,114,000	68,979,000
	REMAINING GAS IN PLACE (Mcf)/DATE	86,800,000	114,600,000	41,708,000	183,538,000	28,620,000	227,962,000	93,400,000	174,937,000	17,300,000	21,000,000	34,483,000	63,705,000	
	REMAINING GAS RESERVES (Mcf)/DATE	21,800,000	7,500,000	11,296,000	58,195,000	0	43,420,000	29,700,000	47,379,000	7,100,000	0	5,401,000	47,741,000	
	RECOVERY FACTOR (%)	65	7	65	65	80	65	70	65	70	80	65	80	
	INITIAL OPEN FLOW (Mcf/d)	2,750	1,292			842	1,340	2,700	45		1,175	1,320		588
	FINAL OPEN FLOW (Mcf/d)	500	1,331	191	1,000	2,775	650	150	308	300	1,028	315	880	859

TABLE Scm-2	Lakeshore NY	East Canton Consolidated OH	Hinckley-Granger OH	Homer Consolidated OH	Lenox OH	Monroe Coshocton Consolidated OH	North Jackson OH	Perrysville Consolidated OH	Philo Consolidated OH	Sharon Consolidated OH	Sharpsburg Consolidated OH	Sugar Grove OH	Triadelphia Consolidated OH	Athens PA	Conneaut PA
AVERAGE PERMEABILITY (md)	3.4	0.1	0.6	20	4	2.4	8.55	111	2.3	0.36	0.1	40	6.2	1.76	0.3

Grimsby and Whirlpool sandstone gas production are commonly commingled. Figure Scm-15 is a typical well log of a Grimsby/Whirlpool Sandstone well. Production trends northeast to southwest and is strongly correlated to deposition. Isopach mapping reveals that both the Grimsby and Whirlpool were deposited in elongate thick areas that are interpreted as tidal current ridges or tidal dominated deltaic deposits such as distributary mouth bars (Metzger, 1981) (Figures Scm-16, Scm-17). A gas expansion drive is inferred because early wells reported producing no salt water.

The Lakeshore field has produced approximately 426 bcfg from 4,000 wells. For 1984 through 1994, the number of producing wells ranged from 2,855 to 3,326 and produced 187.1 bcf (Figure Scm-18). Estimated remaining reserves equal approximately 190 bcfg. National Fuel Gas Supply operates three gas storage areas with a total storage capacity of 16.1 bcfg.

Canton Consolidated field: The Canton Consolidated field encompasses approximately 320,000 acres across eight counties of east-central Ohio (Figure Scm-2). The discovery well, the M.B. Belden No. 1 Stark County Infirmary (Ohio county permit number Stark 351), was completed in 1945 with a natural initial flow of 2,400 Mcfg. After being shot with 60 quarts of nitroglycerine, it had an open flow of 5,126 Mcfg. The Canton Consolidated field is primarily a gas-producing field, although there is some scattered oil production. Cumulative production from the "Clinton" in this field as of 1992 is estimated at approximately 723 bcfg.

Accumulation of hydrocarbons is controlled primarily by stratigraphic traps (Knight, 1969; Ortega, 1978) (Figure Scm-19). Isopach mapping indicates isolation of individual sandstone bodies that are effectively compartmentalized by loss of permeability (Figure Scm-20). Rock pressures of adjacent wells indicate that individual porous sandstone lenses may range in length from a quarter of a mile to several miles and vary in width from 300 feet to 1 mile (Pepper and others, 1953). Regionally, structure plays a minor role in hydrocarbon accumulation. Locally, small anticlinal noses and associated fractures may influence hydrocarbon production.

Commercially significant porous and permeable zones generally are in the lower Red "Clinton" and the upper White "Clinton," with the upper White "Clinton" being the most prolific producing unit (Knight, 1969; Krueger, 1971; Ortega, 1978). Porosities range from 2 to 13 percent with an average of 7 percent. Locally, fracture porosity may be a controlling factor in gas production. Permeabilities typically are less than .1 md. The Stray "Clinton" is not commercially significant.

Based on an average life expectancy of 15 to 20 years for the best wells,

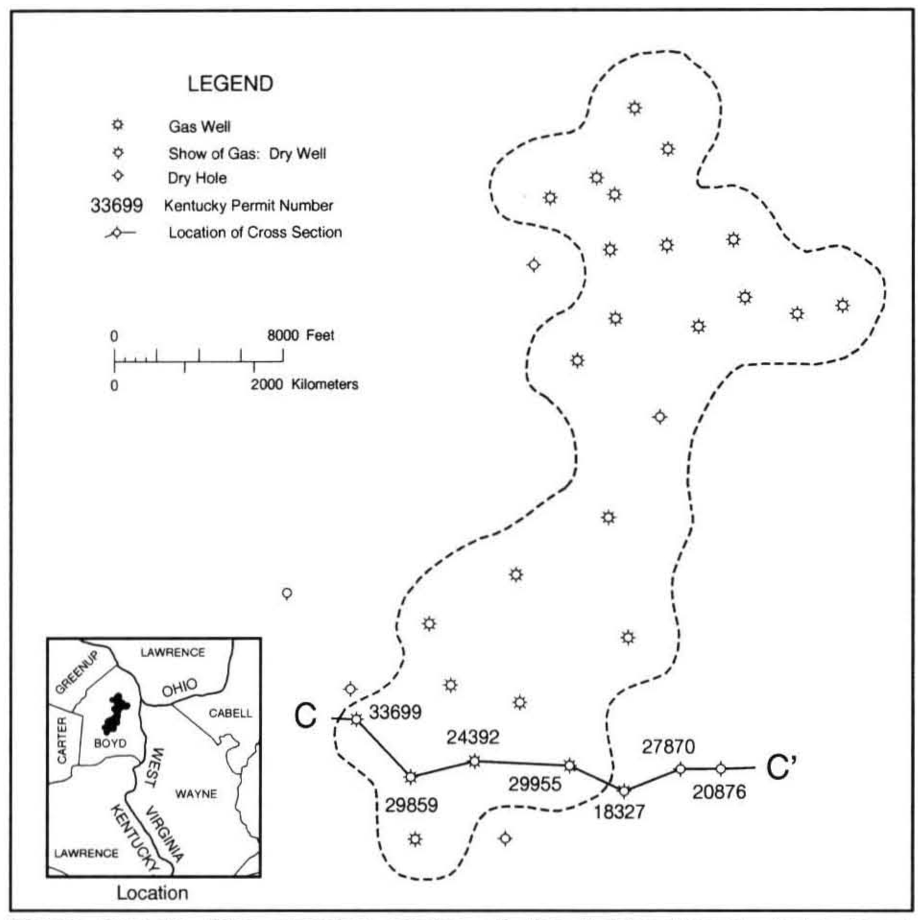


Figure Scm-13. Map showing outline of the Ashland-Mavity field, Boyd County, Kentucky and location of cross section C-C' (Figure Scm-14). Modified from Watson (1979).

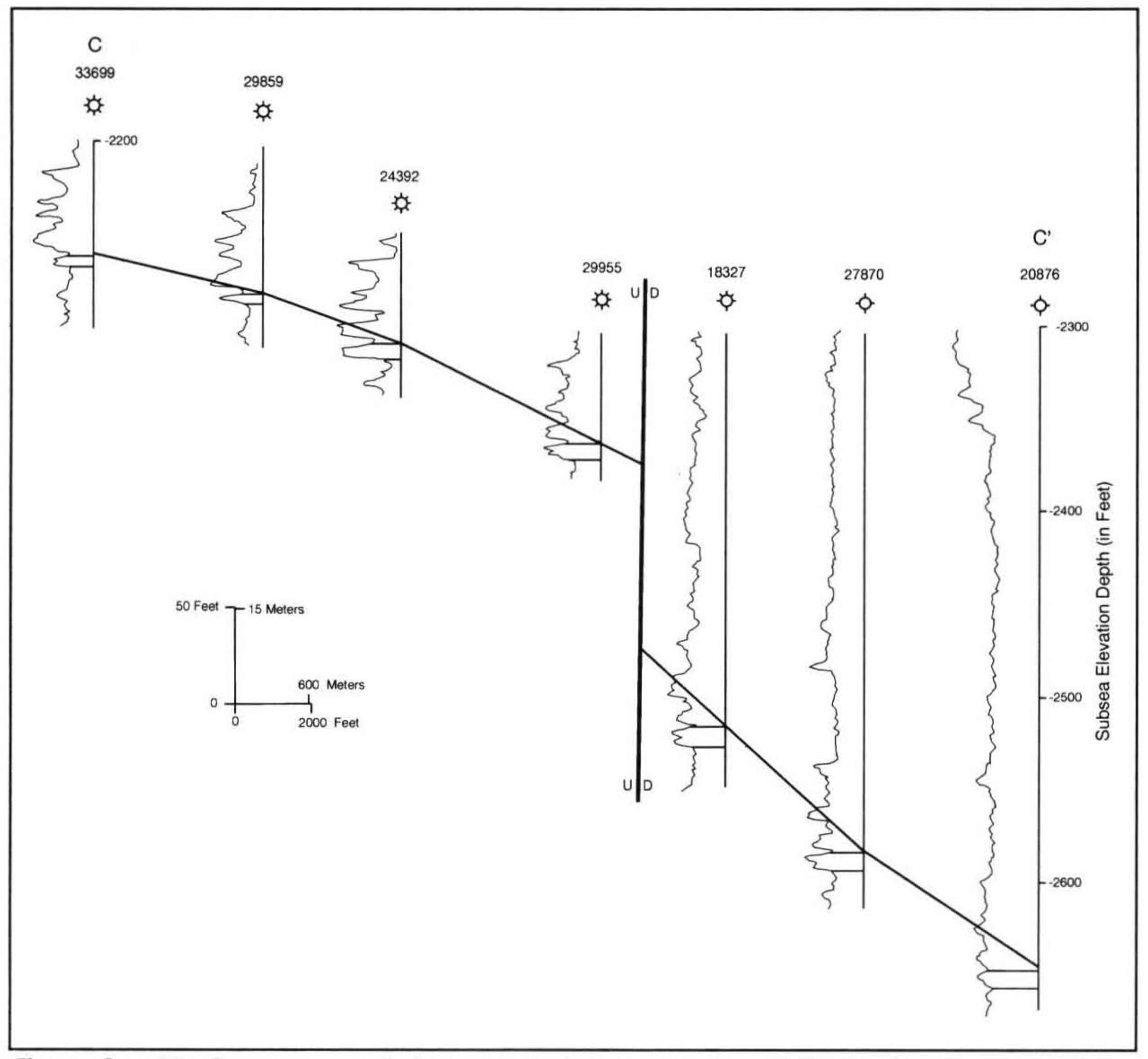


Figure Scm-14. Gamma-ray well log structural cross section C-C' showing the top of the "Clinton" sandstone in the Ashland-Mavity field, Boyd County, Kentucky. Modified from Watson (1979). Location of cross section is shown in Figure Scm-13.

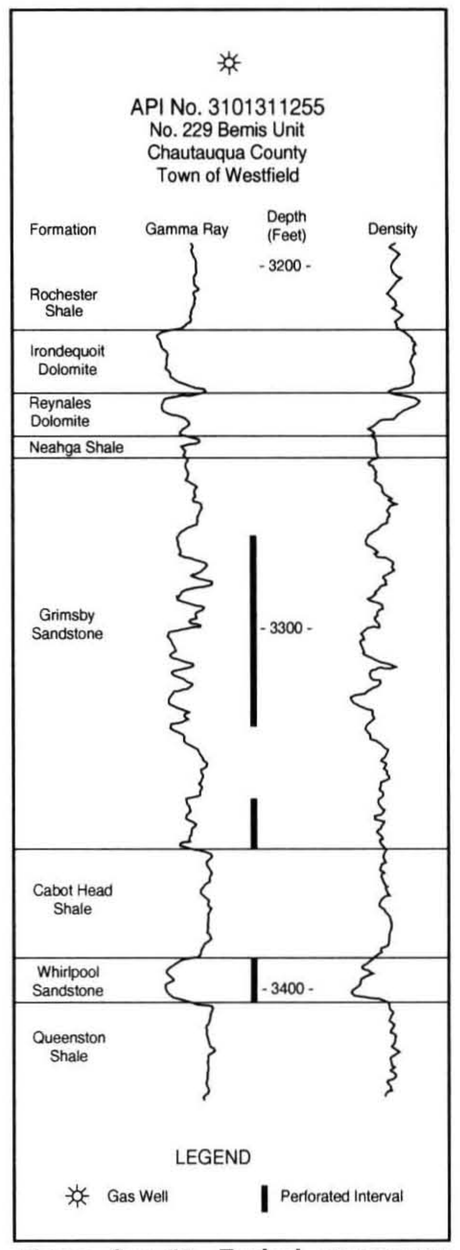


Figure Scm-15. Typical gamma-ray and density geophysical log curves showing Grimsby and Whirlpool sandstones in the Paragon Resources Inc., No. 229 Bemis unit well in the Lakeshore field, New York.

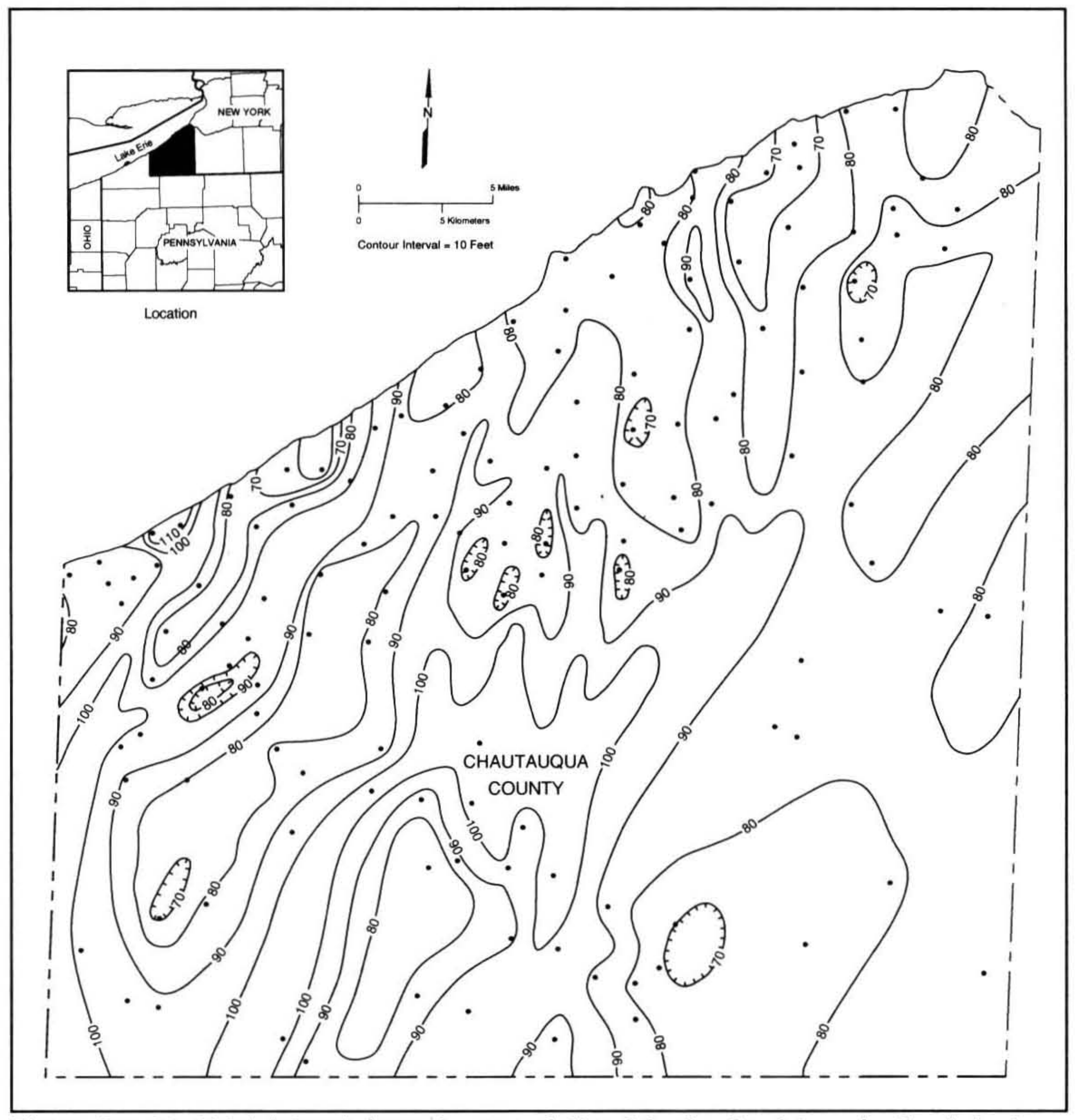


Figure Scm-16. Total interval isopach map of the Grimsby Sandstone in the Lakeshore field, Chautauqua County, New York. Modified from Metzger (1981). Map is based on 138 well locations. The top of the interval was established at the top of the uppermost sandstone deflection with 50 percent shale-free sandstone or greater on the basis of the gamma-ray log. The base of the Grimsby was picked at the first sandstone deflection of 50 percent or greater that occurs directly over the Cabot Head shales. See Figure Scm-15.

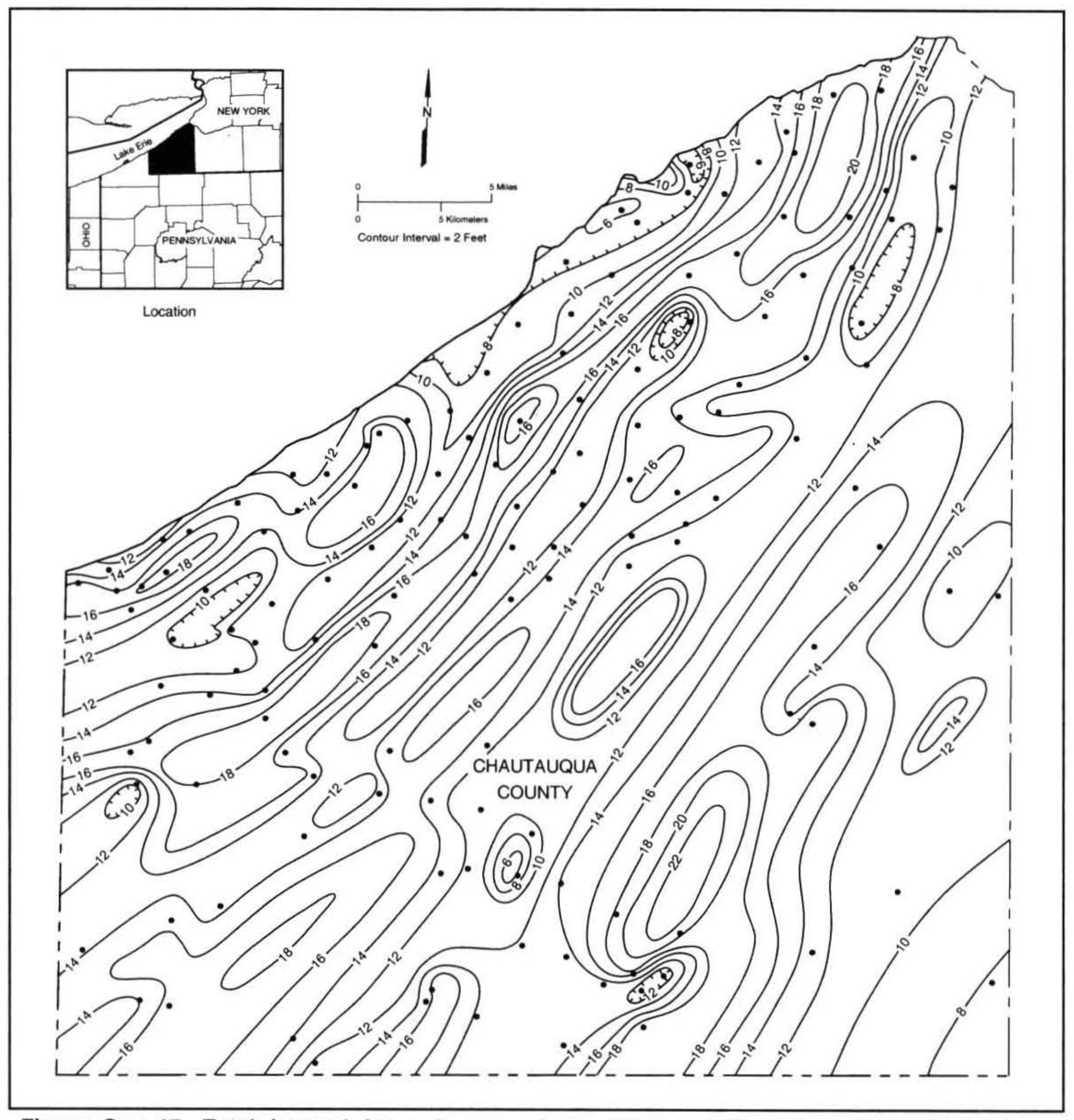


Figure Scm-17. Total interval isopach map of the Whirlpool Sandstone in the Lakeshore field, Chautauqua County, New York. Modified from Metzger (1981). Map is based on 138 well locations. The Whirlpool Sandstone and Queenston Shale tops were picked midway between the minimum and maximum deflections. See Figure Scm-15.

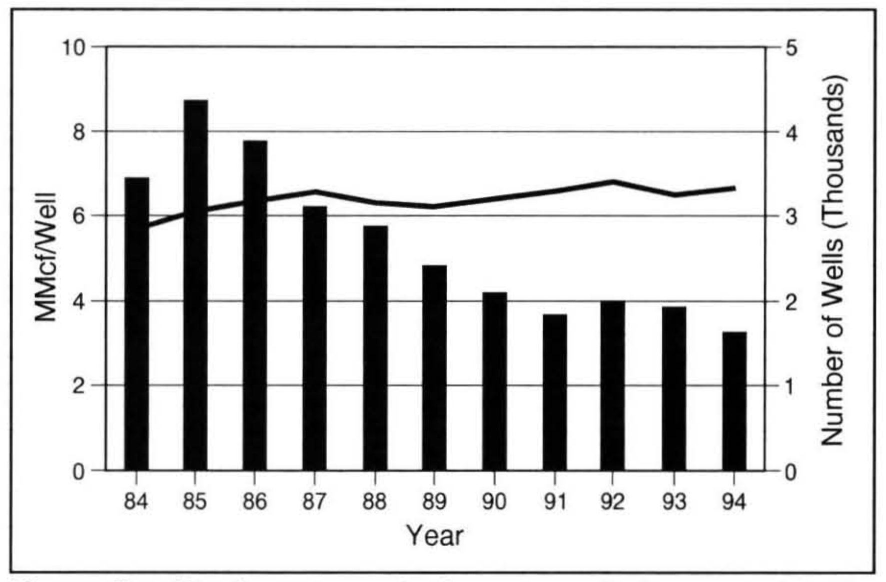
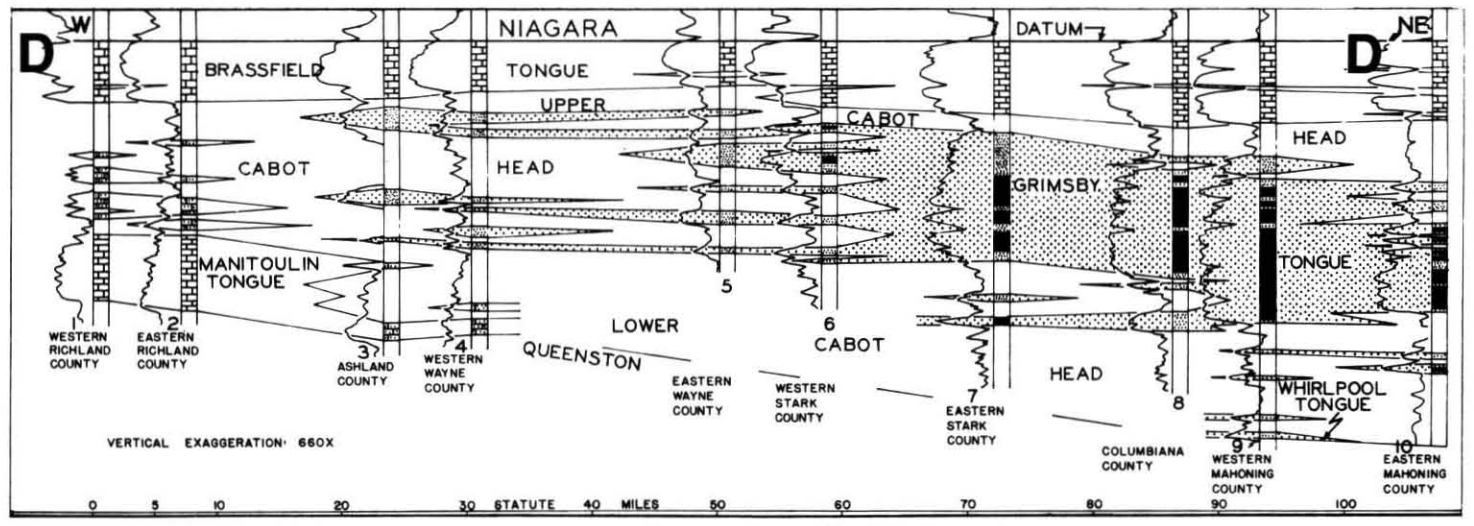


Figure Scm-18. Average production per well by year for the Lakeshore field, New York, based on reported production for years 1984 to 1994, from New York State oil and gas drilling and production annual reports. Total field production for this time period was 187.1 bcf.



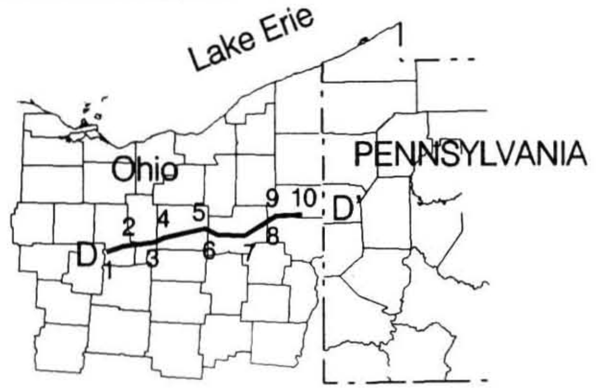


Figure Scm-19. Stratigraphic cross section D-D' of the "Clinton"-Medina interval through Canton Consolidated (well log no. 6) and East Canton Consolidated (well log no. 7) fields, Ohio. Modified from Knight (1969). Nomenclature is that of Knight (1969).

average production per well is approximately 150 MMcfg. Estimated remaining reserves for the entire field are approximately 310 bcfg. Gas cap or solution gas is the dominant drive mechanism (Knight, 1969; Ortega, 1978).

East Canton Consolidated field: The East Canton Consolidated field (Figure Scm-2) was discovered in 1953. Active drilling and development of this field did not begin until 1966 and continues today. At present, the proven productive area is approximately 125,000 acres in four counties of east-central Ohio. Located immediately east of the Canton Consolidated field, it is primarily an oil producing field, with significant associated gas production. A review of literature did not yield an explanation for the non-oil/oil boundary between these two fields. An estimated cumulative production of 266 bcfg and 86 million barrels of oil have been produced through 1992.

The primary trapping mechanism for the "Clinton" sandstone in the East Canton field is from stratigraphic traps produced by the updip thinning and pinchout of the "Clinton" sandstone lenses (Figure Scm-19) (Sitler, 1969; Knight, 1969). Historically, the best production from this field is from the Red sandstone and the uppermost portion of the White sandstone due to high porosity (6 to 8 percent) and permeabilities (.2 to 3.1 md) (Sitler, 1969; Knight, 1969; Watts and others, 1970). In the more argillaceous sections of the reservoir such as the Stray sandstone, porosities (less than 5 percent) and permeabilities (less than .1 md) are typically too low for commercial production of hydrocarbons (Knight, 1969; Watts and others, 1970).

The predominant drive mechanism in the East Canton field is solution gas (Schrider and others, 1970). There appears to be poor communication between the East Canton field and the Canton Consolidated field to the west. Permeability is so low that the gas cap drive from the Canton Consolidated field is not present in East Canton. High water saturations are present in the East Canton field; however, the lack of increasing water-producing rates indicates a water drive is absent. Based upon log-derived analyses from approximately 180 wells in the East Canton field, water saturation ranges from 15 to 50 percent and averages 30 percent.

Based upon a 30-well study in Rose Township, Carroll County, the gas-oil ratio averages 400 cubic feet per barrel of oil with a maximum of 5,000 cubic feet per barrel in 11 years (Figure Scm-21). The increase in the gas-oil ratio during the first 11 years of production is probably due to greater opportunity for by-passing of the oil by gas in the reservoir rock after flow channels have been partly drained, or it may be due to general reduction in field pressure. The decline in the gas-oil ratio after the eleventh year is probably a result of exhaustion of gas in the formation with the gas being drained from the reservoir more rapidly than the oil. Ultimate recoverable gas production per well is approximately 150 MMcfg (Sitler, 1969) and between 28,000 to 63,000 barrels per well for oil production (Schrider and others, 1970). Estimated ultimate reserves for the entire field through primary recovery are approximately 380 bcfg and 140 million barrels of oil.

Hinckley-Granger field: The Hinckley-Granger field illustrates the influence of local structure on "Clinton" gas production in Ohio. The field is centered in Hinckley Township, Medina County, along the Middleburg fault, and extends northward into Cuyahoga County and eastward into Summit County (Figures Scm-2, Scm-22). The discovery well for this field was the Ohio Fuel Gas Co. No.1 Mattingly, drilled in 1928.

In the Hinckley-Granger field, 154 wells have produced from the "Clinton," of which 47 wells have been plugged. Cumulative production through 1992 was estimated at 24.6 bcfg. Average cumulative production per well is approximately 200 MMcfg.

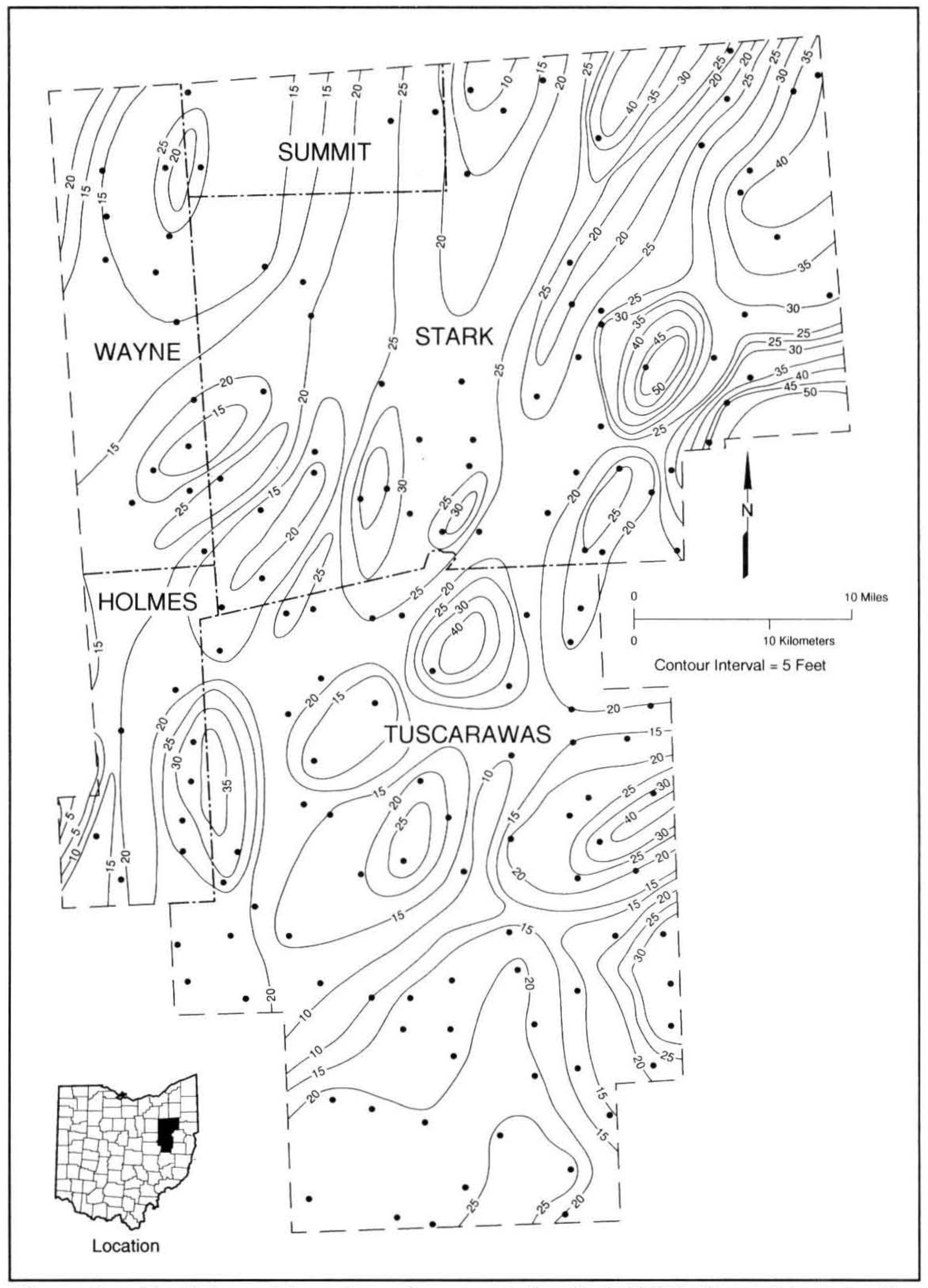


Figure Scm-20. Net sandstone isopach map of the Red "Clinton" sandstone in the Canton Consolidated field, Ohio. Modified from Ortega (1978). Map is based on 150 well locations. Net sandstone is defined as greater than 50 percent shale-free on the basis of the gamma-ray log.

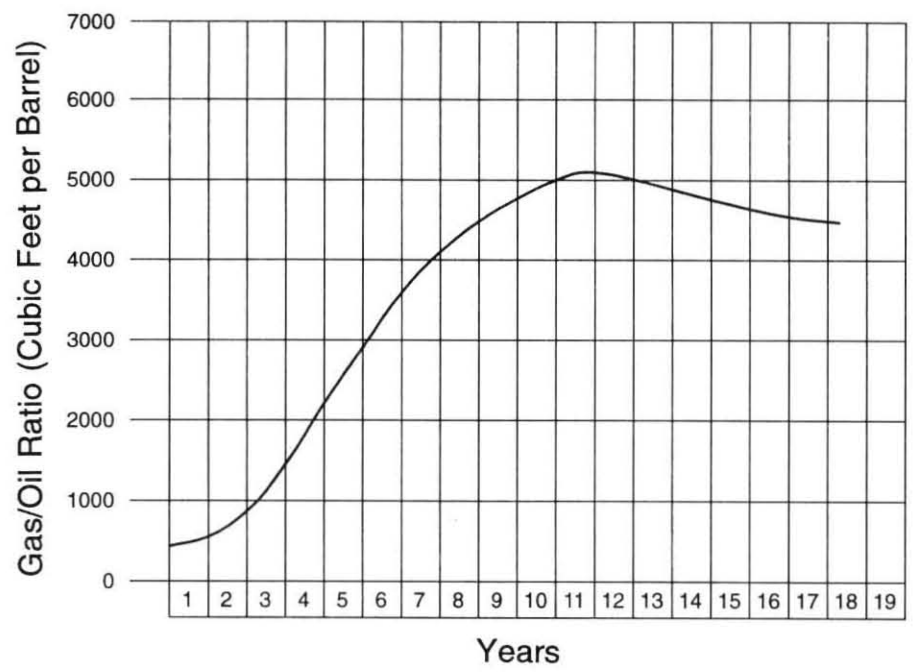


Figure Scm-21. Calculated gas-oil ratio by year based on 30 "Clinton" sandstone oil wells, Rose Township, Carroll County, Ohio in the East Canton Consolidated field (Sitler, 1969).

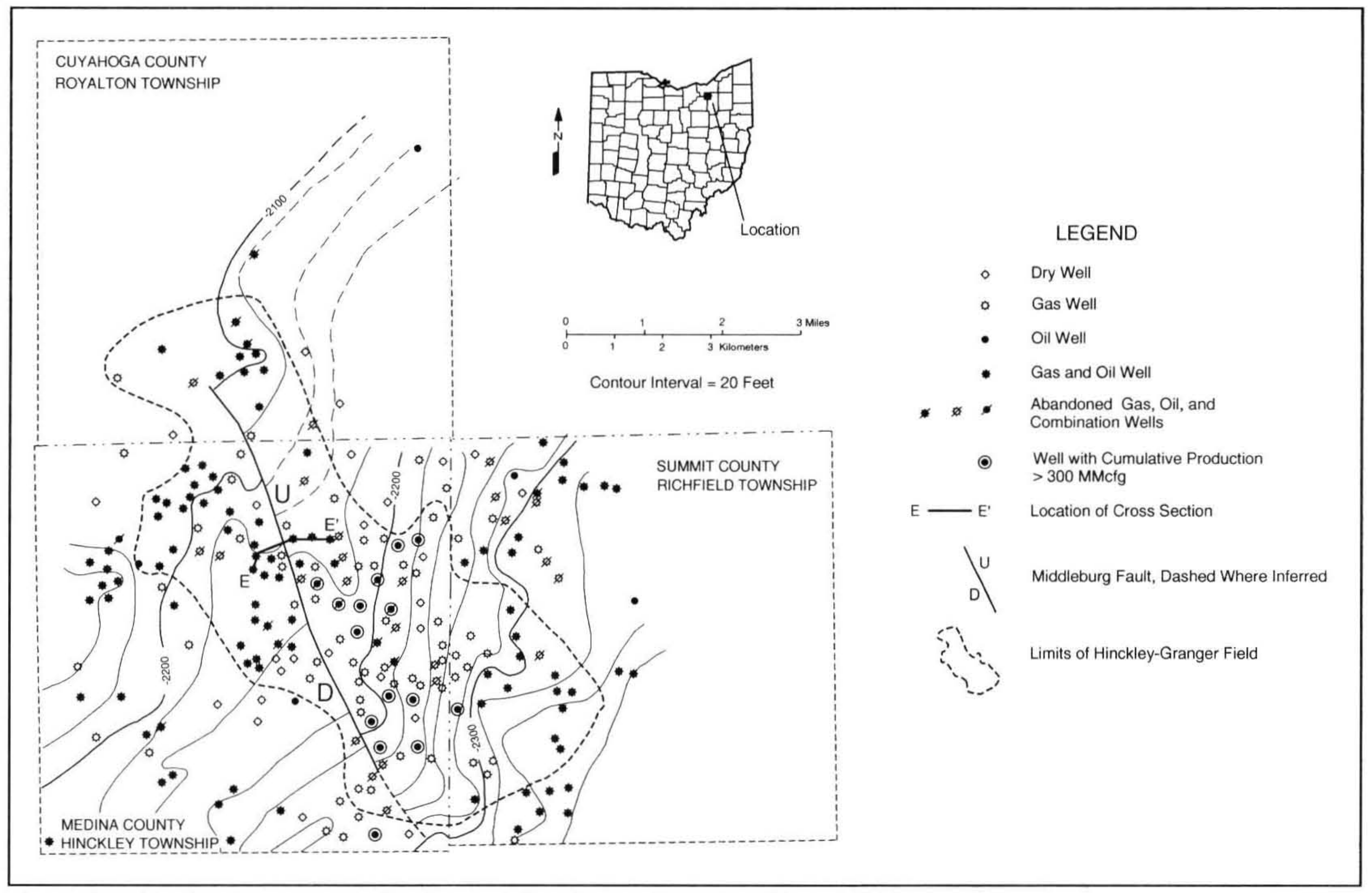


Figure Scm-22. Structure map on the base of the Dayton Formation (Packer Shell) in the Hinckley-Granger field, Cuyahoga, Medina and Summit counties, Ohio, illustrating the relationship of the Middleburg fault to this field. Location of cross section E-E' (Figure Scm-23) is also shown. The Middleburg fault is believed to be the westernmost extension of the Transylvania fracture zone which extends over 248 miles southeastward to the Gettysburg basin in south-central Pennsylvania (Root, 1992). This fracture zone is interpreted to be a major crustal feature which extends from the Precambrian basement and has undergone recurrent faulting during Paleozoic sedimentation.

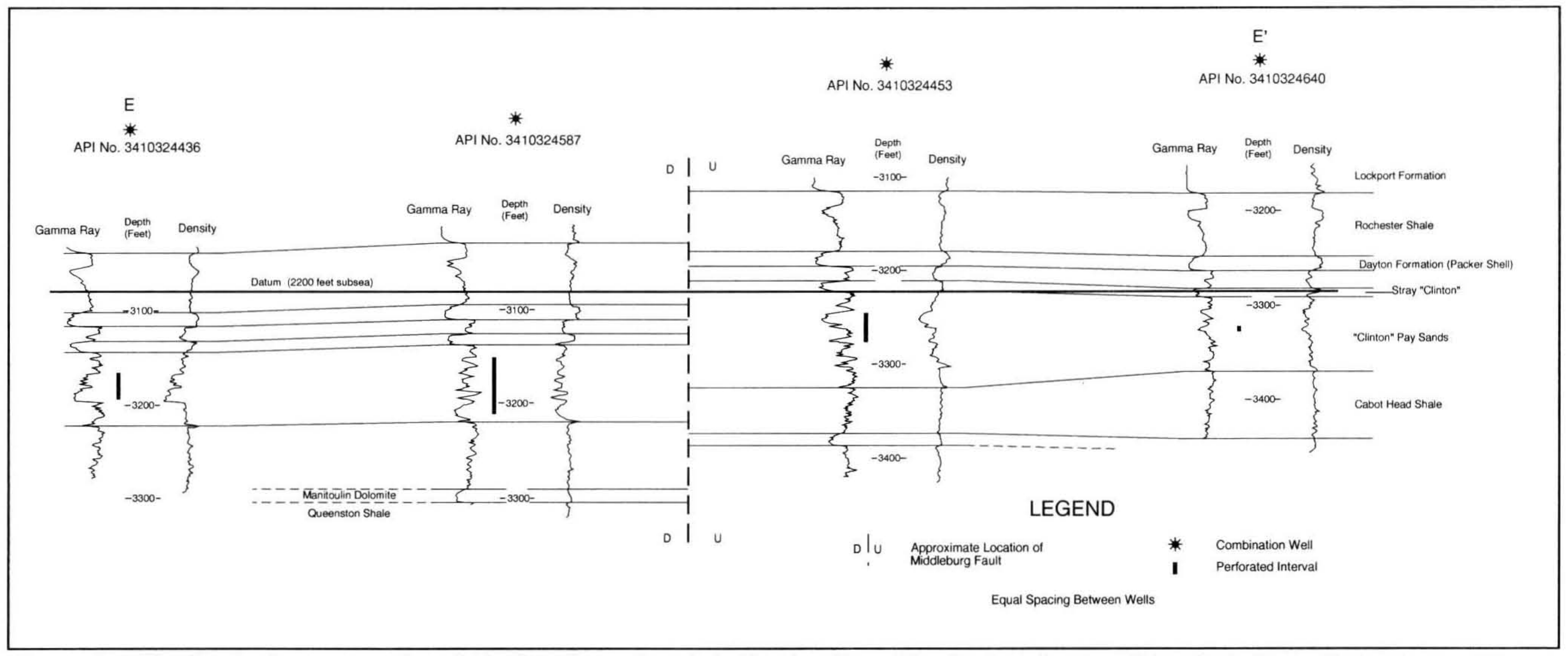


Figure Scm-23. Structural cross section E-E' through north-central Hinckley Township, Medina County, Ohio, illustrating offset of the "Clinton" interval along the Middleburg fault in the Hinckley-Granger field. Location of cross section is shown in Figure Scm-22. The eastern block is upthrown, with as much as 70 feet of vertical offset.

Most of the production comes from clean, porous sand lenses located 40 feet to 105 feet below the base of the Dayton Formation. The Stray "Clinton" is usually nonproductive, being a nonporous calcareous sandstone. Production from the Stray "Clinton" occurs in the northern portion of the field. Production also occurs from Devonian Ohio Shale and Oriskany Sandstone, Silurian Lockport Dolomite, Dayton Formation, and Cambrian Knox Dolomite.

The Dayton Formation (drillers' Packer Shell) (Figure Scm-3) has been a significant secondary target since the discovery of gas in the fractured carbonates of the Dayton by the Ohio Fuel Gas No. 1 Bowman well in 1931. Following the discovery of the No. 1 Bowman, commercial production from the Dayton began in 1941 from the Ohio Fuel Gas No. 2 Alonzo well, which was completed in the Dayton and the "Clinton." The trapping mechanism is thought to be facilitated by fracture porosity within the Dayton carbonate that is sealed by the overlying ductile Rochester Shale. The fracturing is associated with the Middleburg fault system (Figure Scm-22). At the end of 1992, 92 wells reporting Dayton production have been drilled in the Hinkley-Granger field. Of these 92 wells producing from the Dayton, 43 were still producing in 1992. Cumulative Dayton production from 1943 to 1972 from six wells was 638 MMcf.

The Hinckley-Granger field has a regional dip to the southeast at 44 feet per mile. The field is defined by a south-southeast-plunging anticline along whose crest trends the nearly vertical Middleburg fault (Gray, 1982) with a strike of approximately N20°W (Figures Scm-22, Scm-23), as mapped on the base of the Dayton Formation.

Virtually all of the "Clinton" wells with reported cumulative production in excess of 300 MMcfg are located on the northeastern upthrown block of the Middleburg fault (Figure Scm-22). Gas-oil-water contacts are not discernible within the sandstone of the "Clinton" interval on a field-wide basis. Nevertheless, structure appears to have controlled hydrocarbon migration to the extent that most of the gas production is reported from the upthrown eastern block.

North Jackson field: The North Jackson field encompasses approximately 108,000 acres over 15 townships in Mahoning and Trumbull counties, Ohio (Figure Scm-2). The discovery well was the East Ohio Gas Company No. 1 H. & H. Cain Community (Mahoning 200) completed in 1963. A few offset wells were drilled, but the real development of this field began in the early 1970s. Numerous wells were drilled north and east of the discovery area. Figure Scm-24 is a type well log showing the better developed, productive Red "Clinton" sandstone. Cumulative production from "Clinton" reservoirs in this field as of 1992 is estimated at approximately 175 bcfg.

General Motors Corporation has developed the majority of the field located west of Meander Creek reservoir. This area is informally known as the "Lordstown" field and has 460 wells that have produced approximately 69 bcf. An average well produces approximately 205 MMcf (W.J. Lallo, oral commun., 1994) (Figure Scm-25).

Rock pressures average 1,450 psi for wells drilled in the 1970s and 1,250 psi for wells drilled in the 1980s (W.J. Lallo, oral commun., 1994). Pressure build-up tests conducted in 1993 indicate current reservoir pressure of approximately 400 psi (Figures Scm-26, Scm-27).

Sharon Consolidated field: The Sharon Consolidated field is located in southeastern Ohio and covers 102,080 acres in parts of five counties (Figure Scm-2). This field is noteworthy among the "Clinton" fields of Ohio because in this part of the state, the "Medina" (Whirlpool Sandstone) has excellent reservoir characteristics and is commonly completed with the "Clinton" (Figure Scm-28). The field is also notable because it represents the deepest commercial production from the "Clinton" in Ohio up to 1994.

The first successful "Clinton" sandstone well drilled in the Sharon Consolidated field was the Industrial Gas Corporation No. 1 Charles Reeder (Morgan 259). Completed in November 1942, the well had a natural flow of 330 Mcfg at 4,462 feet and gauged 1,902 Mcfg after being shot with nitroglycerin. Rock pressure was recorded at 1,148 psi after a 24-hour test. Total depth was 4,491 feet and the "Medina" Sandstone was not penetrated.

Scattered tests of the "Clinton" were drilled throughout the 1940s and 1950s as exploration expanded eastward. As a rule, if the "Clinton" was dry, drilling continued for approximately 80 feet to test the "Medina," which often was oil productive. The economic constraints imposed by the greater depths limited the extent of development of the Sharon Consolidated field until after the advent of hydraulic fracturing technology. The deepest part of the field in southern Noble and Washington counties did not receive much activity until the early 1980s after the price incentives for "tight formation" gas went into effect.

The productive "Clinton" reservoir is typically 40 to 90 feet below the Packer Shell. Net sandstone thickness ranges from 10 to 20 feet or more and can vary considerably between offsetting wells. Shale content controls net effective pay thickness. Figure Scm-6 is a typical well log of a "Clinton-Medina" well in northern Washington County. Natural fractures within the reservoir enhance porosity and permeability and appear to be the principal governing factor to productivity, especially in the deeper wells in the field. Core (1986) associated this fracturing with local structural anomalies such as dip reversals and nosing that can be mapped on the Packer Shell surface. This suggests that local faulting may have caused the anomalous features. Wells drilled on these anomalies tend to produce better and longer than those which are drilled off-structure. Downhole camera work and cores taken of the "Clinton" section confirm the presence of

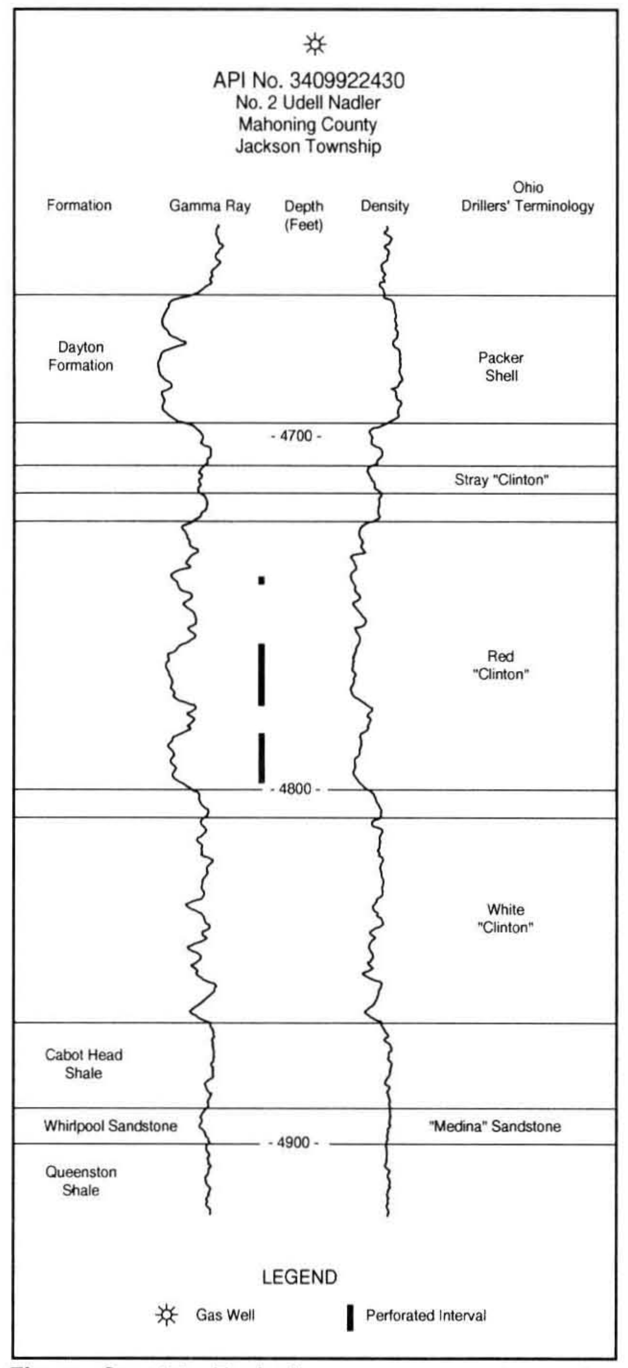


Figure Scm-24. Typical gamma-ray and density geophysical log curves showing "Clinton" and "Medina" sandstones in the General Motors Corporation No. 2 Udell Nadler well (Mahoning, 2430) in the North Jackson field, Ohio.

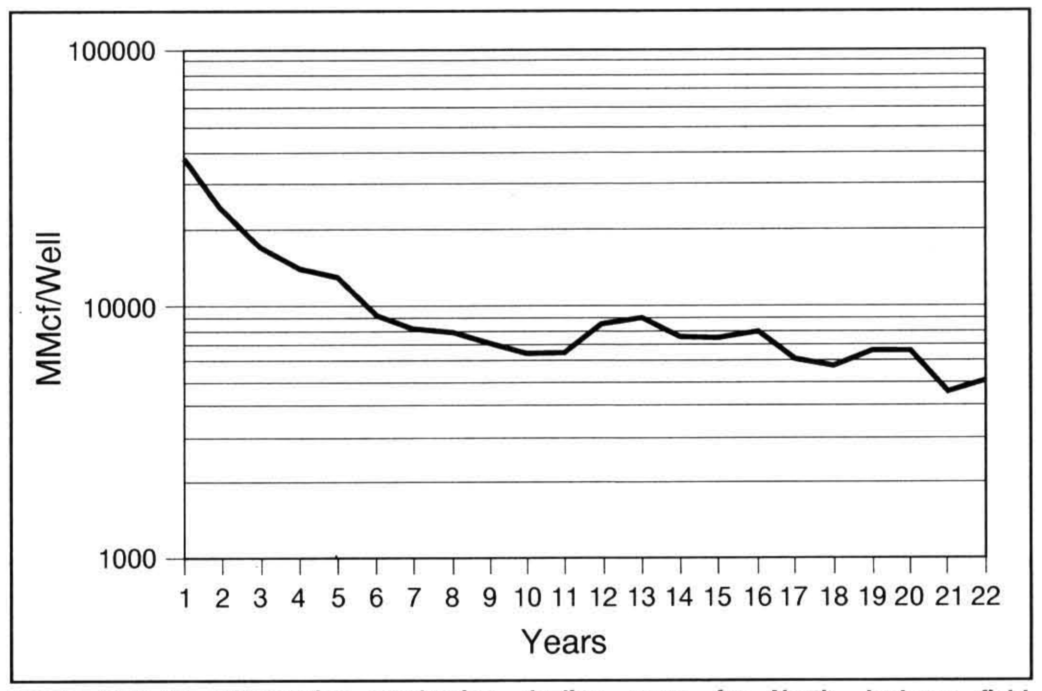


Figure Scm-25. Cumulative production decline curve for North Jackson field, Ohio. The number of wells ranged from 28 wells with first-year production to two wells with 22 years of production.

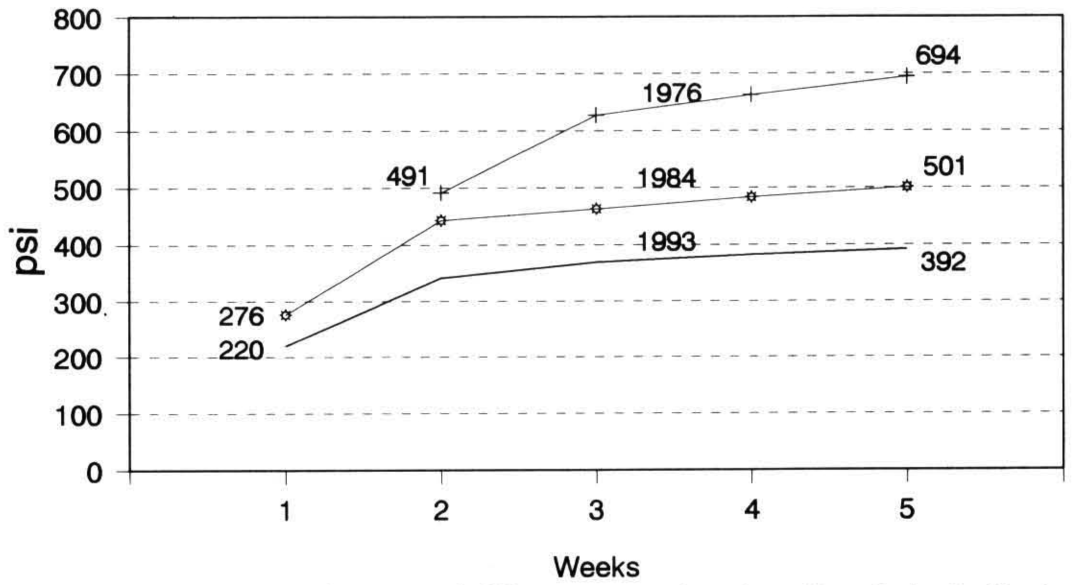


Figure Scm-26. Results of pressure build-up tests conducted on 10 wells in the North Jackson field, Ohio (W. J. Lallo, written commun., 1994). The wells were completed between January 1972 and March 1974.

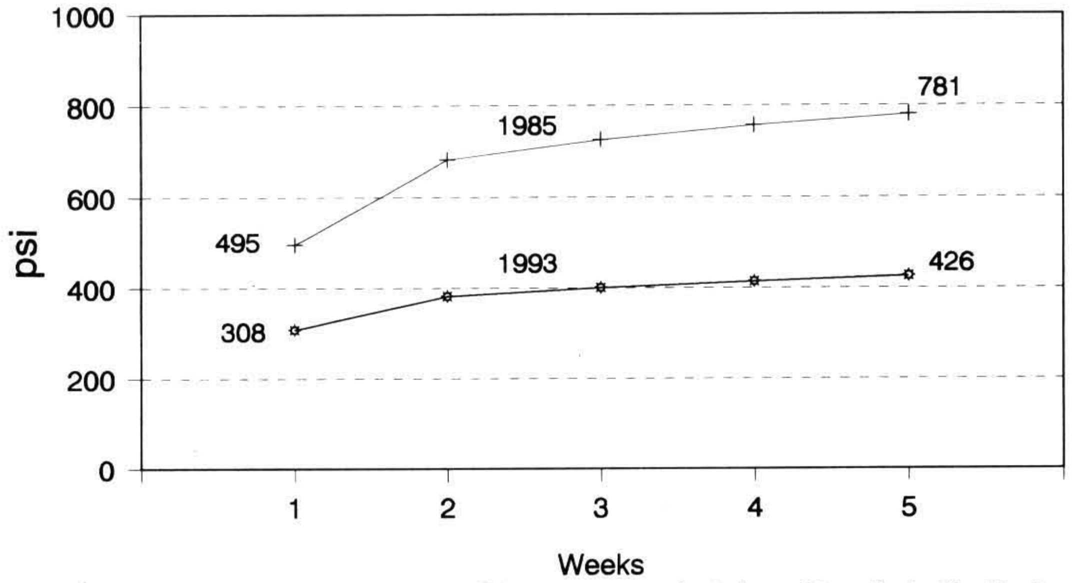


Figure Scm-27. Results of pressure build-up tests conducted on 12 wells in the North Jackson field, Ohio (W. J. Lallo, written commun., 1994). The wells were completed between July 1983 and October 1984.

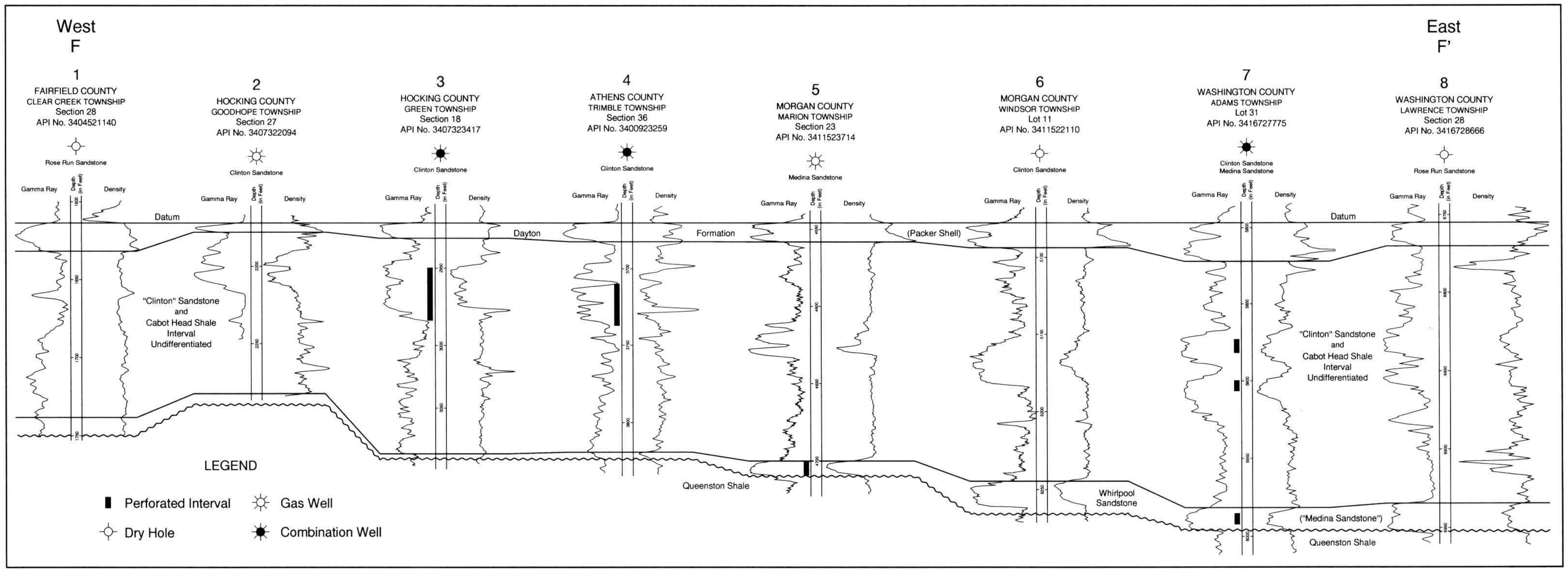


Figure Scm-28. Stratigraphic cross section F-F' of the "Clinton"-"Medina" sandstone interval through Sugar Grove Consolidated (well log no. 2) and Sharon Consolidated (well log no. 7) fields, Ohio. The cross section begins west of the "Clinton" sandstone pinchout (the pinchout occurs between well log no. 1 and no. 2) and ends in an as-yet unproductive area. Note the development of the Whirlpool sandstone between well log no. 4 and no. 8.

reservoir micro fractures in Washington County, Ohio (Core, 1986).

Sugar Grove Consolidated field: The Sugar Grove Consolidated field is located in south-central Fairfield County, west-central Hocking County, and northernmost Vinton County, Ohio (Figure Scm-2). This field is significant historically because some of the earliest "Clinton" sandstone gas production in the Appalachian basin occurred here. It is also a typical example of the "Clinton" along its western depositional edge (Figure Scm-28). Figure Scm-29 is a type log showing the stratigraphic relationships for the "Clinton" along the western edge. The present-day field configuration is 27 miles by 8 miles, with a productive area of 19,337 acres.

The discovery well was drilled in 1893 on the Meesbarger farm, 3 miles northeast of the village of Sugar Grove (Bownocker, 1903b). This well was drilled as a result of the enormous success of wells to the immediate north near Lancaster. By 1902, many companies were actively developing the Sugar Grove field, making it one of the most active gas plays at the time. The field was producing an estimated 60,000 Mcfg/d from approximately 230 wells (Bownocker, 1903a; 1903b). In 1902, the Sugar Grove field was 16 miles long (north-south) by 11 miles wide (east-west) at a maximum (Bownocker, 1903a). The initial reservoir pressure was 900 psi, but reservoir pressures declined rapidly to 100 psi or less within five years (Figure Scm-30). Initial open flows averaging 6,687 Mcfg/d had also declined rapidly to 2,432 Mcfg/d within four years (Bownocker, 1903a).

Paska (1981) asserted that the "Clinton" of the Sugar Grove area represents barrier islands trending northeast to southwest. According to Osten (1982), the few channel deposits are probably subaqueous channel deposits in a shallow marine environment. There is a possibility of north-south preferential permeability resulting from sand deposition in river-mouth bars sorted by longshore currents (Overbey and Henniger, 1971).

Water saturations average approximately 39 percent, with gas saturations of 61 percent. These factors, combined with production characteristics of the Sugar Grove field, indicate a gas expansion drive reservoir. The field began conversion to a gas storage field in 1936, with final completion in the 1980s.

Resources and Reserves

Proved reserves have been estimated using the Delphi method. The data used—estimated cumulative production, recovery factor, and average life of well—are listed in Table Scm-3 and are thought to be typical for an average Cataract/Medina Group sandstone reservoir. Estimated original gas in place and proved reserves are summarized in Table Scm-3.

Future gas resources were identified for the Cataract/Medina Group sandstones based on three classifications established by the Potential Gas Committee (1990) for unconfirmed and undiscovered recoverable gas resources. These classifications include probable resources (for extensions and new pools), possible resources (new fields in similar geologic conditions), and speculative resources (new fields in nonproductive formations). Probable reserves will occur in the present producing trend defined by Cataract/Medina Group pools and fields (Figure Scm-31). The western and northern limits are defined by the sandstone pinchout. The eastern limit of probable resources is near the eastern limit of present production, generally not exceeding a depth of 6,500 feet. A trend of undiscovered possible resources is located in lightly explored and unexplored deeper areas east of the probable trend extending east to the Tuscarora Formation (Figure Scm-31). A category for speculative gas resource does not pertain due to the well defined limits of this densely drilled play.

Published reserve reports exist for every state and province except Ohio. An updated reserve number was arrived at by subtracting gas production through 1992 since the year of the reserve report. Probable gas reserves for Kentucky through 1979 are 4.6 bcf (Watson, 1979), adjusted to 4 bcf. Van Tyne and Copley (1983) estimated probable gas reserves for New York through 1983 as 1,378 bcf, adjusted to 1,348 bcf. Ohio probable reserves are estimated at 2,000 bcf. The probable gas reserve estimate for Ontario as of the end of 1981 was 760 bcf (Cochrane and others, 1986), adjusted to 664 bcf. The offshore portion of Ontario accounted for 96 percent of the total, while onshore areas accounted for just over 3 percent, mostly in Haldimand-Norfolk County. The probable gas reserve estimate for Pennsylvania as of the end of 1983 was 350 bcf (Geomega, 1983), adjusted to 265 bcf. These numbers in combination with a Monte Carlo Estimation program (Cowan, 1984) were used to calculate possible gas resources in Table Scm-4.

Future Trends

Drilling to greater depths (see the "possible" area in Figure Scm-31) in extreme eastern Ohio, northern Pennsylvania, and western New York could become more common. Even though the recent expiration (1992) of the tax credit for tight sandstone removes a major incentive, higher gas prices and improved exploration, drilling, and completion technology may stimulate interest in these low-permeability reservoirs.

The best areas for future Grimsby drilling in Ontario lie offshore in the central and eastern portions of Lake Erie, as is reflected by the percentage of remaining potential reserves discussed previously. The potential for significant future onshore resource is limited by the extensive depletion of the onshore pools

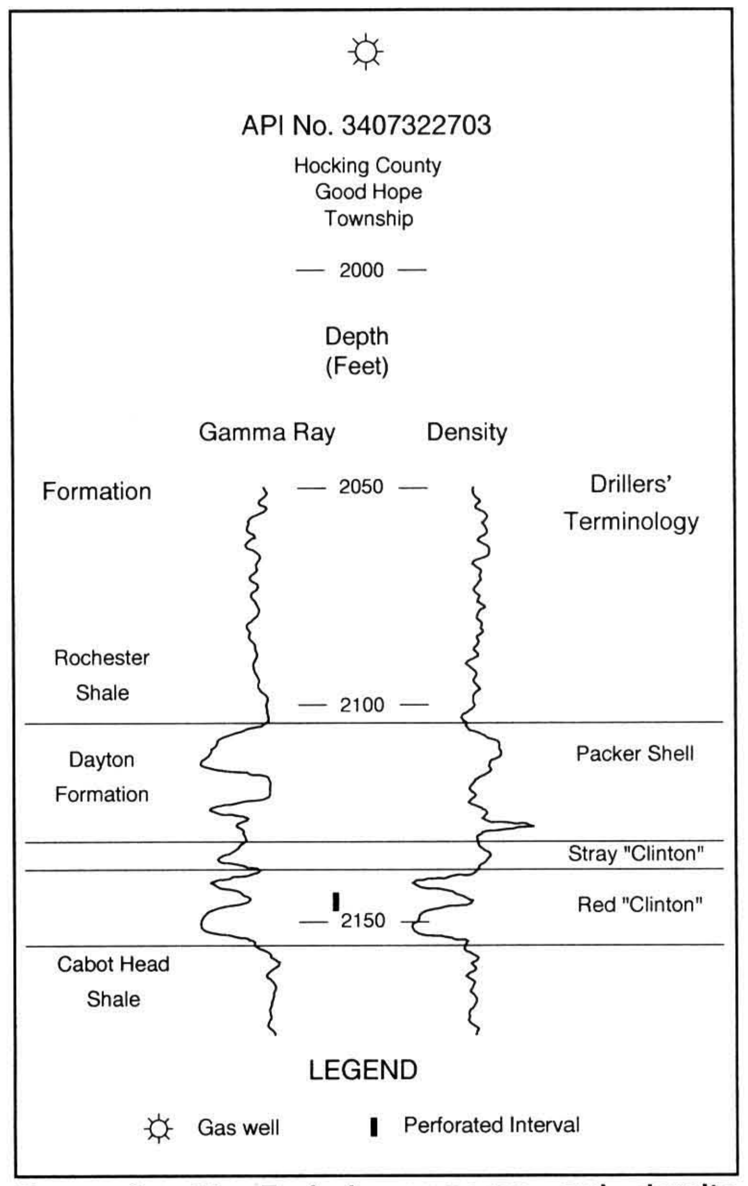


Figure Scm-29. Typical gamma-ray and density geophysical log curves showing "Clinton" sandstones in the Columbia Gas Transmission Corp., No. 12279 Robert J. Thompson (Hocking 2703) in Sugar Grove field, Ohio.

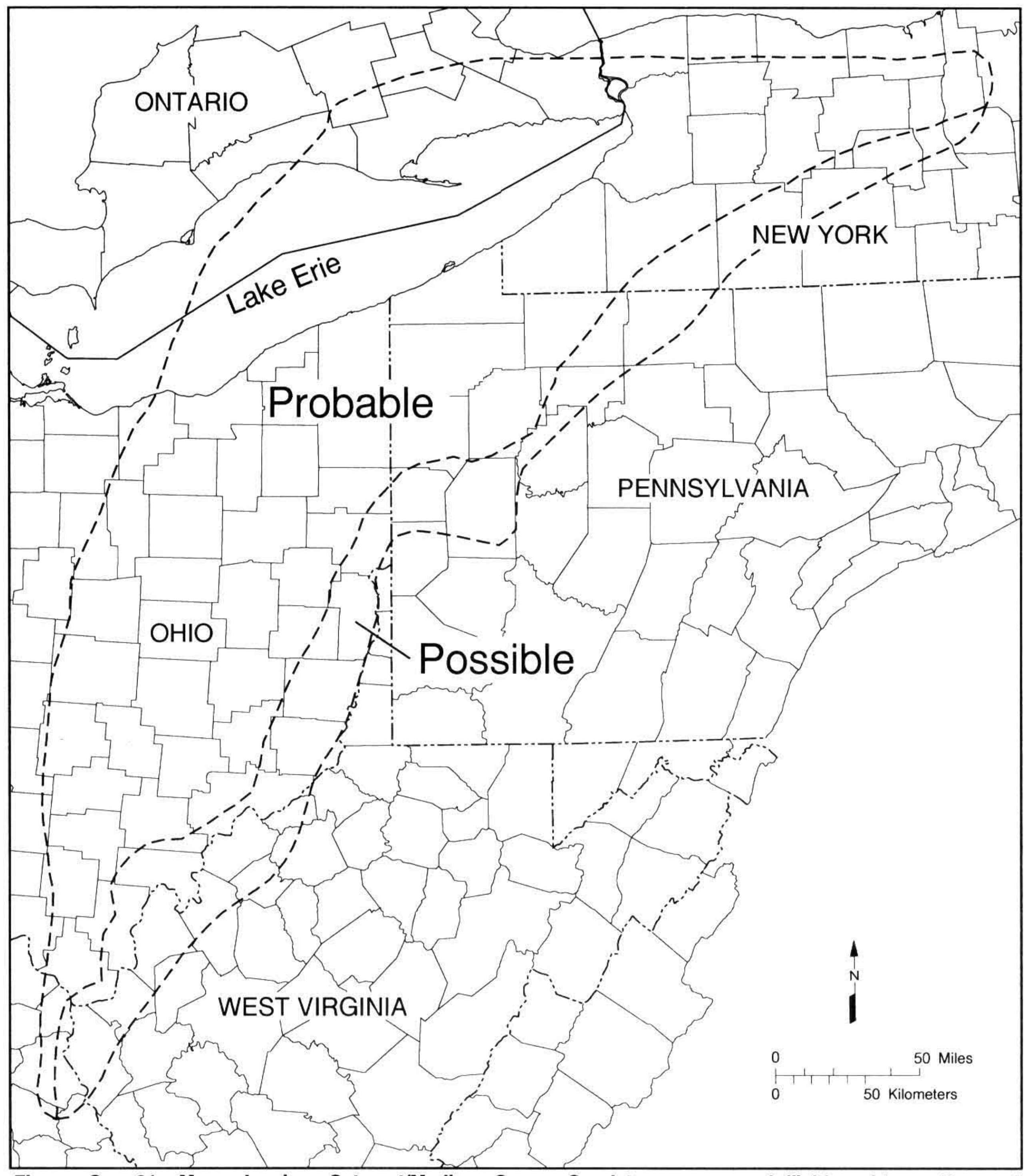


Figure Scm-31. Map showing Cataract/Medina Group Sandstone gas pools/fields with outlines of probable and possible reservoir trends in the Appalachian basin. The eastern boundary for possible reserves is the interpreted change from the Medina facies to Tuscarora facies. Modified from Piotrowski (1981) and Boswell and others (1993).

Table Scm-3. Proved gas reserves estimated for the Cataract/Medina Group Sandstone play in the Appalachian basin.

Lithology	Number of Wells	Estimated Cumulative Production Per Well	Recovery Factor	Total Estimated Drainage Area for All Wells	Original Gas in Place	Gas Reserves	Average Life of Well
Sandstone	76,091	120 MMcfg	6.5%	2,300,000 acres	14,000 bcf	9,100 bcf	15-20 years

Table Scm-4. Estimated undiscovered recoverable probable and possible gas resources for the Cataract/Medina Group Sandstone play in the Appalachian basin.

Trend Type	Gross Area in Acres	Estimated Net Productive Area in Acres	Estimated Gas Recovery Per Acre	Estimated Recoverable Gas Resources	Probability of Recovery
Probable	22,200,000	1,430,000	3 MMcfg	4,300 bcf	85%
Possible	6,600,000	780,000	5 MMcfg	3,900 bcf	15%

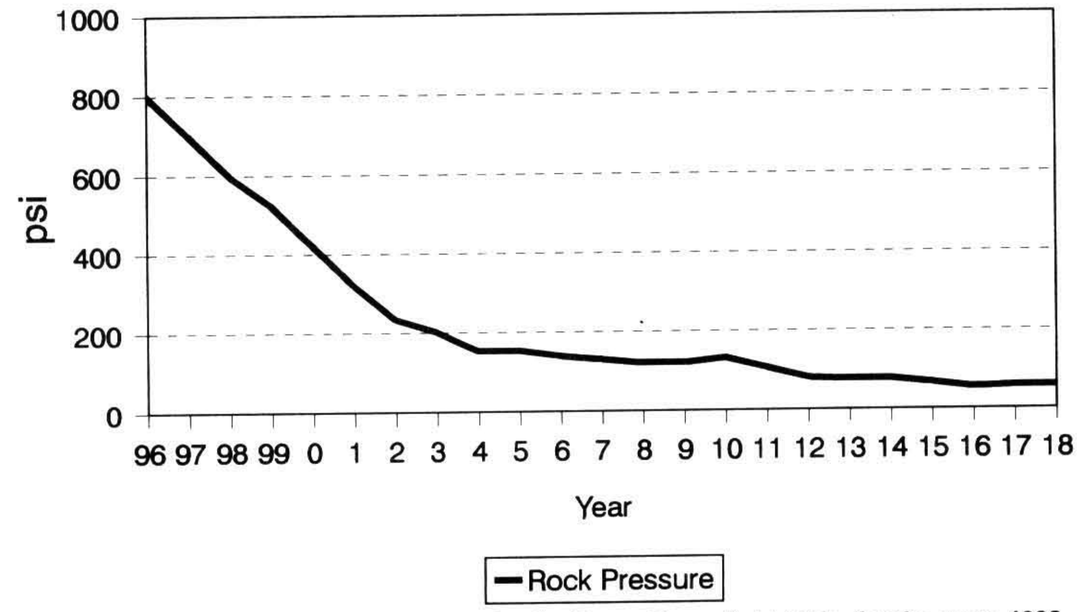


Figure Scm-30. Average rock pressure for the Sugar Grove field, Ohio, for the years 1896 through 1918 (Bownocker, 1920).

and by the sand pinchout to the north and the erosional limit of Silurian rocks to the east at the Niagara escarpment. More than 99 percent of onshore Ontario production has been obtained from five pools, with more than half of the production, or 109 bcf, coming from the Haldimand Pool in Haldimand-Norfolk County. Insofar as offshore Grimsby wells were customarily drilled on 630-acre spacing, recovery factors for these wells average only about 15 percent, while wells in onshore pools show recovery factors in excess of 95 percent. As a result of the low-recovery factor of offshore wells, considerable reserves can be produced from future infill drilling. Core data from the Clear Creek 062 pool just south of Haldimand-Norfolk County indicate favorable offshore reservoir conditions, with 32 feet net pay and 8.4 percent average porosity (Cochrane and others, 1986). There is presently a moratorium on drilling in Lake Erie in the U.S.

Directional drilling is used to target areas where vertical drilling cannot be used. From 1991 to 1994, 120 "Clinton" wells have been directionally drilled in Ohio. This technology is used to drill under areas that are covered by water, in residential areas, or to avoid environmentally sensitive areas such as wetlands. Many of these wells have encountered near-original reservoir pressures and above-average production characteristics due to the distance from existing wells. In Pennsylvania, a few directional wells have been drilled as well as one horizontal well in the Athens field.

Belden and Blake Company, in part funded by the U.S. Department of Energy, recently drilled a horizontal well in Mahoning County, Ohio (Mahoning 2576). The intent was to encounter higher fracturing and thereby enhance production. At this time, results are unknown.

Companies will continue to take a close look at infill drilling, particularly in newer fields located in the deeper part of the play. Infill drilling in the older fields will be limited significantly due to extensive over-drilling that has severely depleted the reservoir pressure, as in the Cleveland gas field (Rogers, 1917). In Ohio, the possibility of leasing the mineral rights for state and additional federal lands (situated in prime gas production areas) is being considered.

Secondary targets above the Cataract/Medina play should be considered in future drilling programs and the re-entry of existing wells. Of particular interest is the carbonate rocks in the interval above the Cataract/Medina Group and below the Rochester Shale (Figure Scm-3). The Dayton Formation (drillers' Packer Shell) is present in the subsurface of eastern Ohio and locally produces gas in the Hinckley-Granger field of northeast Ohio. The production from the Dayton in northeast Ohio is generally commingled with the "Clinton". Final open flows range from 652 to 910 Mcf/d. Structural settings similar to the Hinckley-Granger field that are found in other localities of the play area might provide the necessary porosity for the Dayton to be gas bearing. The other units in this interval above the Cataract/Medina play are the Irondequoit Limestone/Dolomite and the Reynales Dolomite (Figure Scm-3). The Irondequoit in the Tonawanda field in Erie County, New York (Figure Scm-2), is thought to produce from a bioherm reservoir (Van Tyne, 1966; 1984). Fifty wells have been drilled in the Tonawanda area with flows of 15 to 60 Mcf/d (Van Tyne, 1984). Similar reservoirs produce from the Irondequoit of Ontario, Canada (Van Tyne, 1984; T. Carter, oral commun., 1995). Shows of gas have been reported from the Irondequoit and Reynales of northwestern Pennsylvania (S. Pees, oral commun., 1995). The detailed stratigraphy and the gas potential of this interval is not well known in the northwestern part of the Appalachian basin and merits future study.

Currently, 25 "Clinton" fields in Ohio have been converted for use as gas storage. More depleted fields probably can be converted for use as gas storage. The Crowland pool of the Welland field in Welland County is the only Grimsby field converted to gas storage in Ontario (T. Carter, oral commun., 1994).

There are 49 "Clinton" wells in Ohio being used as injection wells to dispose of the brine produced along with gas and oil. Many "Clinton" wells likely will be converted to injection wells in the future.

PLAY Obe: UPPER ORDOVICIAN BALD EAGLE FORMATION FRACTURED ANTICLINAL PLAY

by Christopher D. Laughrey and Robert M. Harper, Pennsylvania Bureau of Topographic and Geologic Survey

Location

Fractured sandstones within the Upper Ordovician Bald Eagle Formation produce natural gas at one locality in the central Appalachians, the Grugan field in Pennsylvania. The Bald Eagle Formation and equivalent Oswego Sandstone, however, have good potential for fracture porosity throughout the central Appalachian basin where deformed rocks offer viable targets to explorationists on the Appalachian Plateau (Lacazette, 1991). The best developed porosity in the Bald Eagle Formation should occur in zones containing vertical to subvertical fracture sets that are developed parallel to fold axes on the Appalachian Plateau. Intensely deformed rocks, such as those in the Valley and Ridge Province and those adjacent to large, right-lateral faults on the plateau, probably vented their petroleum to the surface and should be avoided when generating drilling prospects (Lacazette, 1991). Figure Obe-1 shows the extent of the Bald Eagle Formation fractured anticlinal play in the central Appalachian basin. Figure Obe-2 shows the location of the Grugan field.

Production History

Natural gas was first discovered in the Bald Eagle Formation in Grugan Township, Clinton County, Pennsylvania. The discovery well (Texaco State Forest Tract 285) originally was drilled to test Cambrian- and Ordovician-age targets at depths between 15,000 and 20,000 feet. The first significant gas show, however, occurred at 12,900 feet and the mud gas content remained high until total depth at 19,365 feet. Well tests in the deeper horizons were unsuccessful, but the Bald Eagle interval was perforated between 12,900 and 13,462 feet, and the well was then left open to the atmosphere for approximately 22 hours while preparing for acid stimulation efforts. There was no gas flow to the surface during this 22-hour period. The zone was then stimulated with acid and produced 5,497 Mcf/d. The interval from 12,900 to 13,030 feet was later reperforated and 350 gallons of acid were spotted across the perforations. The well was repeatedly shut-in to build pressure and then opened to the atmosphere, but it would not produce. Finally, on December 13, 1982, the perforated interval was successfully stimulated with 14,000 gallons of acid and the well produced at a rate of 3,847 Mcfg/d through a .25-inch choke with a flowing tubing pressure of 2,900 psi. The State Forest Tract 285 discovery well, which established the Grugan field, produced 3.6 bcfg through the end of 1992.

Texaco spudded a second well, the State Forest Tract 289, as an extension in McHenry Township, Lycoming County, and completed it in March 1985. The well had a natural open flow of 1,280 Mcfg/d and an estimated reservoir pressure of 7,021 psi. The well was not stimulated. It produced 3.95 bcf through the end of 1992.

In September 1988, Felmont (now Torch Oil and Gas) completed the State Forest Tract 679 well in Chapman Township, Clinton County, about 11,000 feet southwest of the Texaco discovery well. After treatment, open flow was 110 Mcfg/d. The well was a mechanical failure. Felmont sold the well to another operator, Eastern States Gas Corporation, who has not yet decided its fate. This well has not produced any gas to date and remains shut-in. Eastern States took over control of the two producing wells in Grugan field from Texaco in December 1993 and is the present operator.

In 1985, Pennzoil drilled the No. 1 Pennsylvania State Forest Tract 552 well in Brown Township, Lycoming County, Pennsylvania (Figure Obe-2), as a distant offset to the Grugan field wells. The well was drilled to a total depth of 12,885 feet in the Upper Ordovician Reedsville Formation and was plugged and abandoned without being tested or treated.

In 1988, CNG Development Company drilled the Dieffenbach Unit No. 1 well in Davidson Township, Sullivan County, Pennsylvania (Figure Obe-2), to test the Bald Eagle Formation on a structure similar to that at the Grugan field, but the well was a dry hole and it was plugged and abandoned.

Cumulative production for the Bald Eagle Formation play is 7.55 bcf through the end of 1992.

Stratigraphy

The Bald Eagle Formation is an Upper Ordovician clastic interval formally recognized in central Pennsylvania (Berg and others, 1980; Berg and others, 1986). The Bald Eagle Formation is correlative to the Oswego Sandstone of adjacent West Virginia, Maryland, and New York (Zerrahn, 1978; Ryder, Harris, and Repetski, 1992) (Figure Obe-3). It is approximately latest Maysvillian through earliest Richmondian in age (Ryder, 1992a). The Bald Eagle Formation consists of very fine- to coarse-grained sandstone and conglomerate that occurs between the underlying Reedsville Shale and the overlying Juniata Formation (Figure Obe-3). Both upper and lower contacts are conformable and gradational (Faill and others, 1977).

The Bald Eagle Formation, Reedsville Shale, and Juniata Formation comprise a distinctive Upper Ordovician clastic sequence in central Pennsylvania. This sequence contains well-developed marine lithologic units, formed on the continental margin, and shallow marine to non-marine units deposited on the foreland of the Taconic orogenic belt. Thompson (1970a; 1970b) defined six lithofacies that reflect sedimentary processes active within these diverse depositional systems. The Bald Eagle Formation corresponds to part of Thompson's (1970a; 1970b) lithofacies C, a paralic interval of mixed sandstones and shales, and to lithofacies D, a fluvial interval of fine- to coarse-grained sandstone and conglomerate (Figures Obe-4, Obe-5).

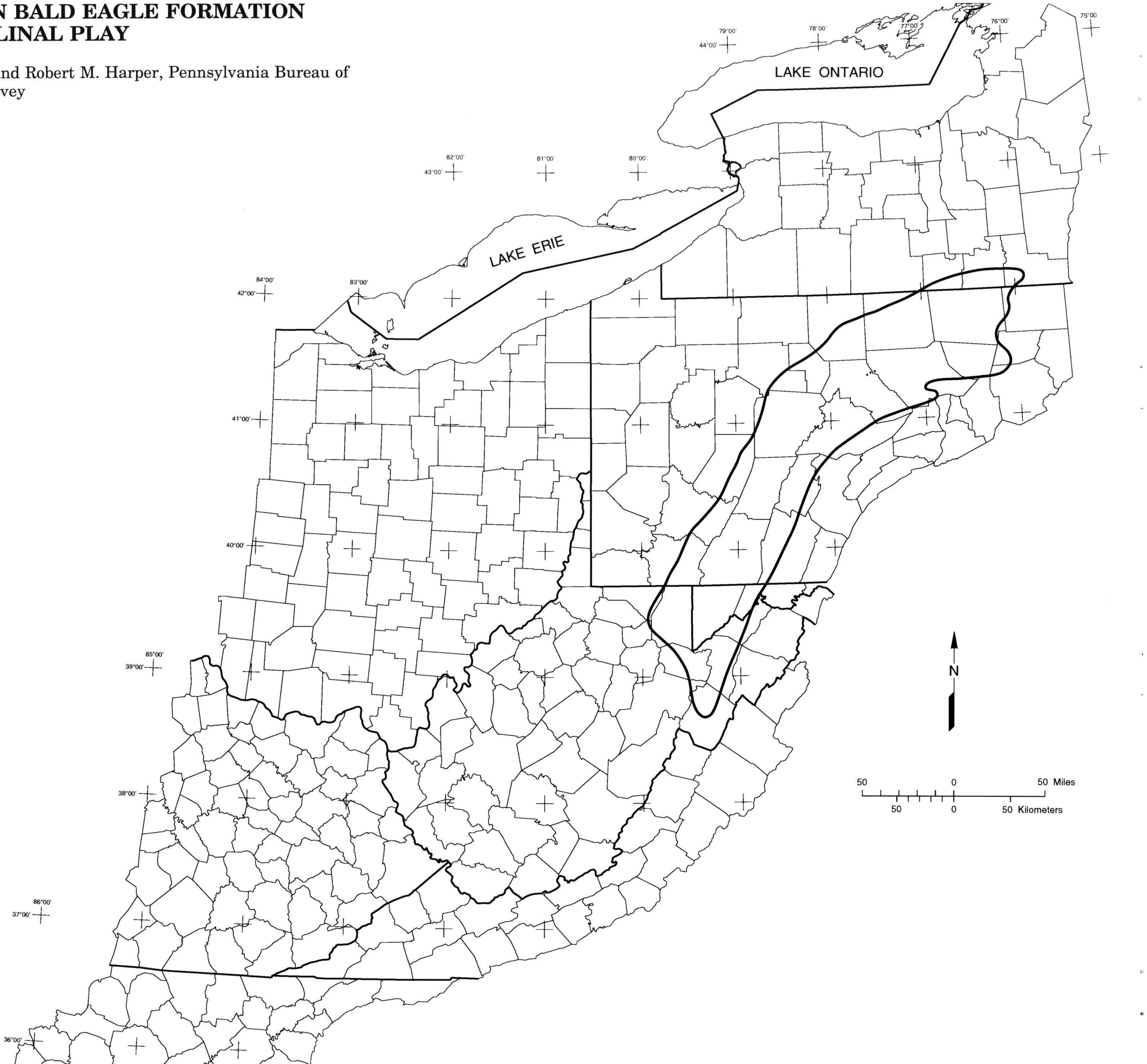


Figure Obe-1. Outline of the Upper Ordovician Bald Eagle Formation fractured anticlinal play within the Appalachian basin. Dots represent individual gas wells.

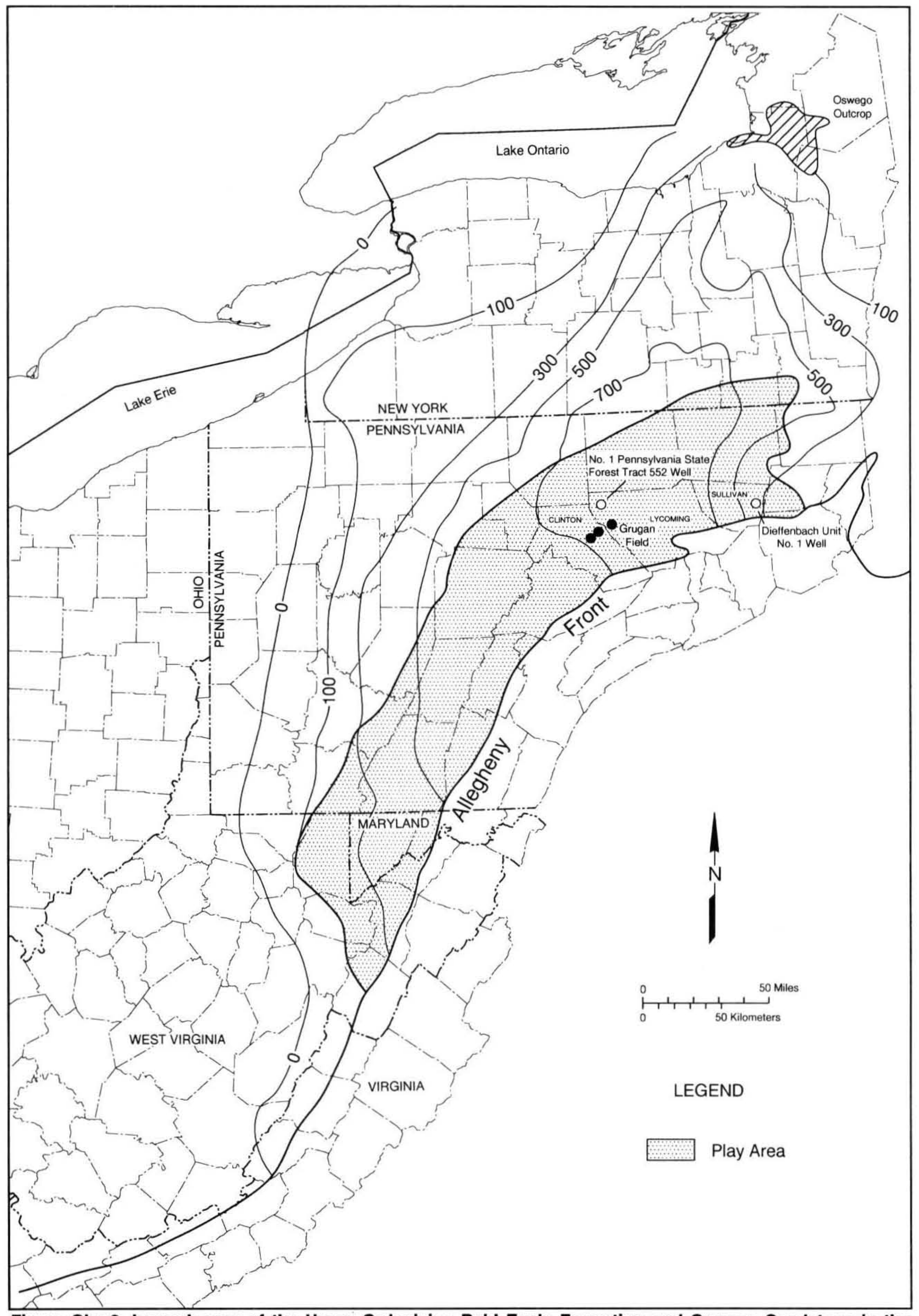


Figure Obe-2. Isopach map of the Upper Ordovician Bald Eagle Formation and Oswego Sandstone in the Appalachian Plateau of the central Appalachian basin. Location of the Grugan field in north-central Pennsylvania is also shown. Potential production from this play is ostensibly limited to deformed rocks where fracturing induced secondary porosity (Mitra, 1988; Lacazette, 1991). Portions of the Appalachian Plateau with structural relief greater than 300 feet and sandstone thickness greater than 100 feet define the play area (shaded) and are prospective. Intensely deformed rocks to the east of the plateau probably vented their hydrocarbons to the surface (Lacazette, 1991). Contour interval is in feet. Isopach data are modified from McCann and others (1968), Chen (1977), and Hayward (1982).

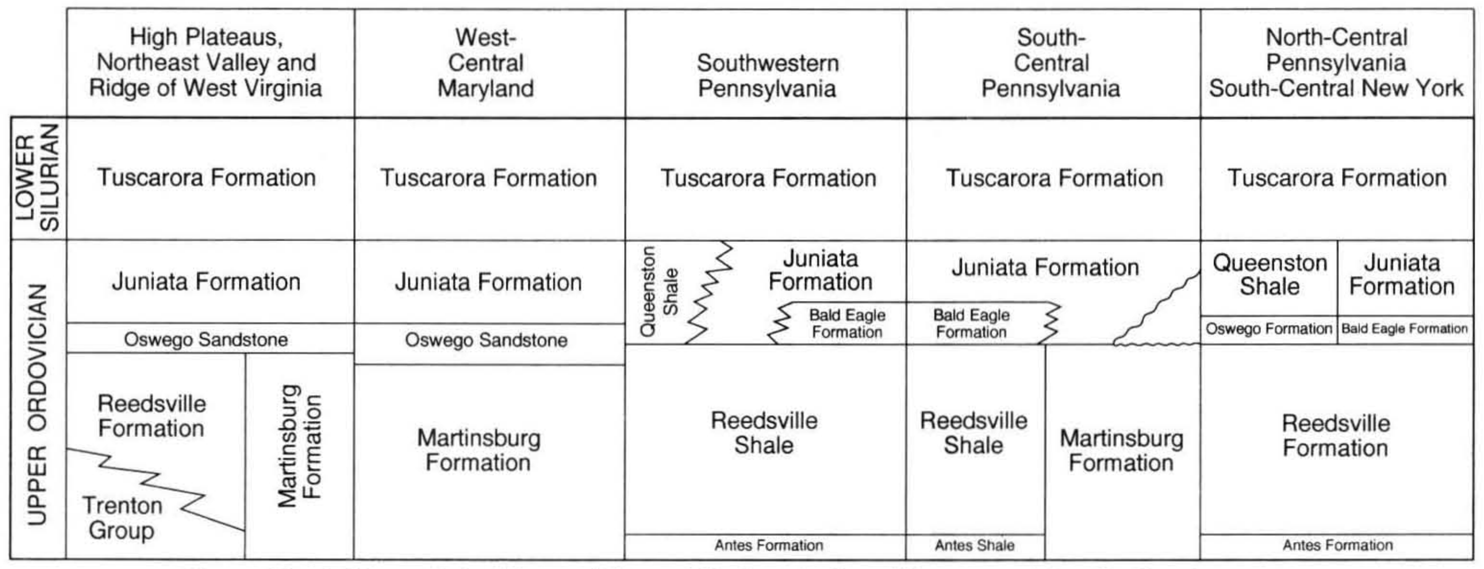


Figure Obe-3. Upper Ordovician and Lower Silurian stratigraphic nomenclature in the play area.

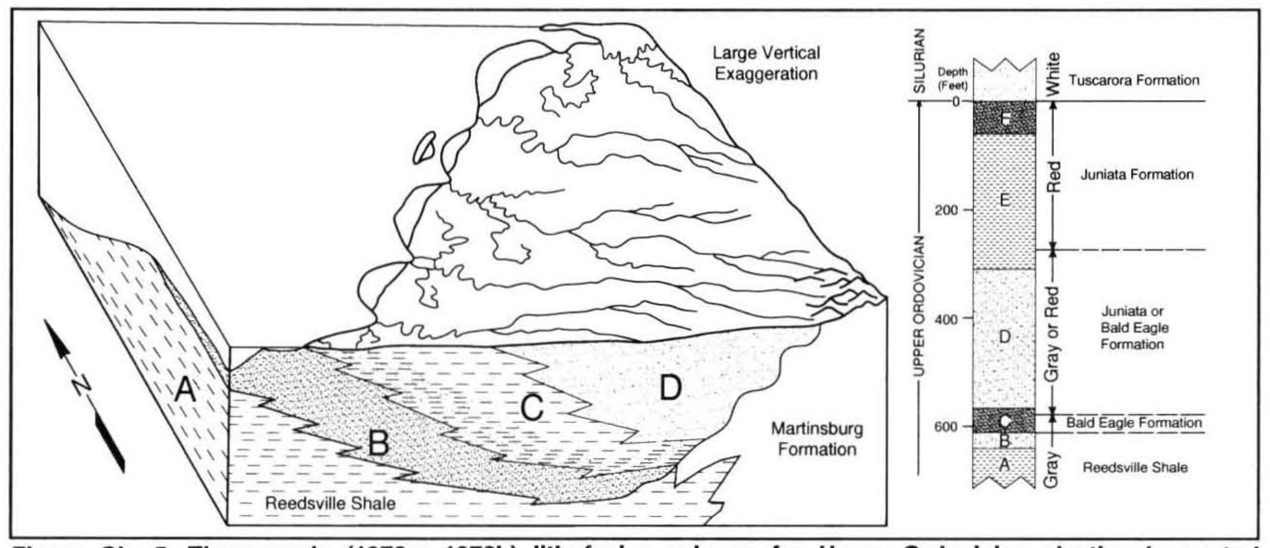


Figure Obe-5. Thompson's (1970a; 1970b) lithofacies scheme for Upper Ordovician clastics in central Pennsylvania and the relation of these lithofacies (B, C, and D) to depositional settings and paleogeography.

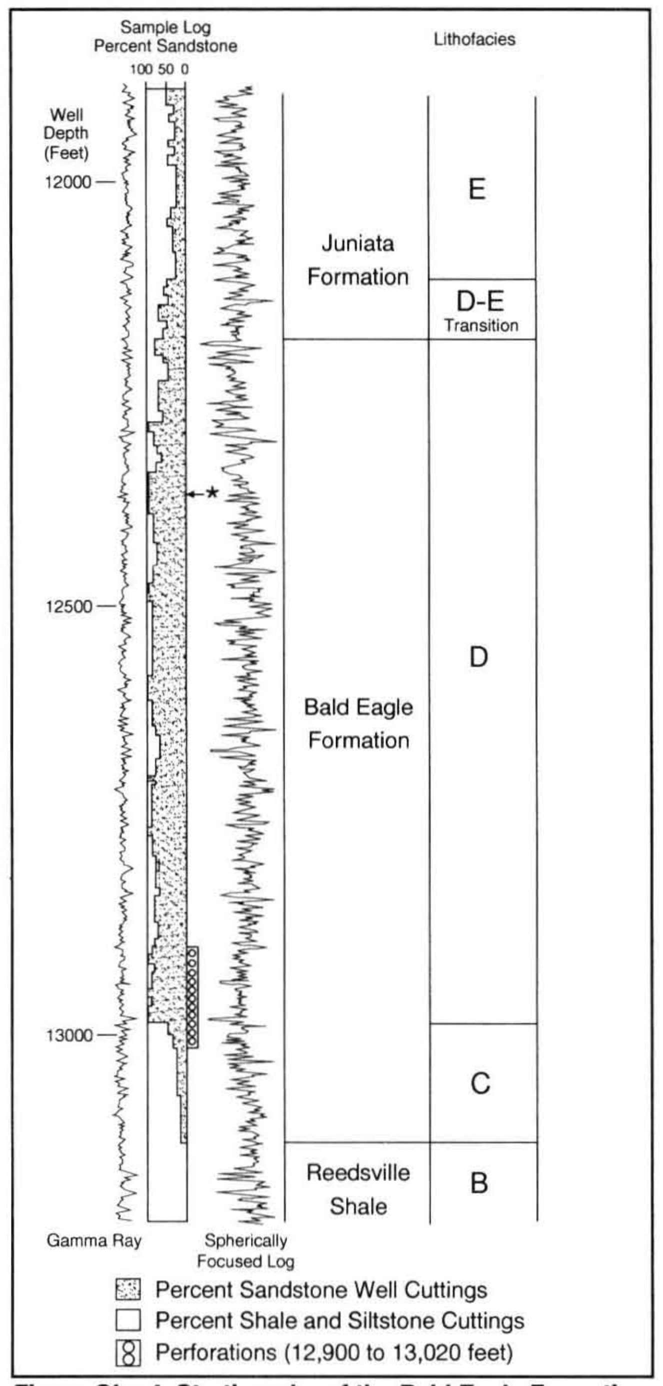
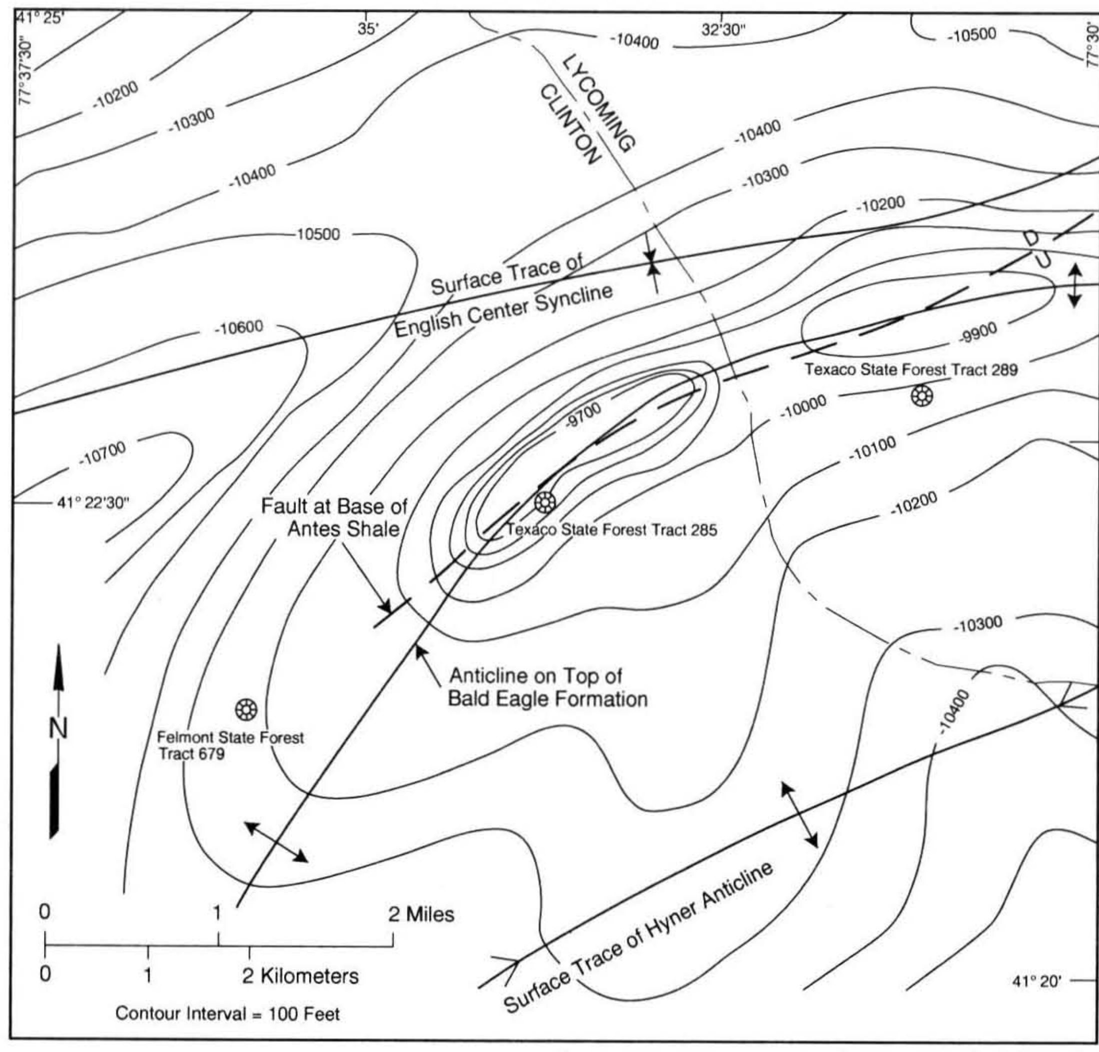


Figure Obe-4. Stratigraphy of the Bald Eagle Formation and adjacent units in the Texaco State Tract 285 well at Grugan field. Lithofacies are those of Thompson (1970a; 1970b). The Bald Eagle top was arbitrarily selected where the well sample log indicated the start of the predominantly sandy section (70 percent or more sandstone). The top selected by Ryder (1992a) for his cross section B-B' (asterisk) is shown for comparison.



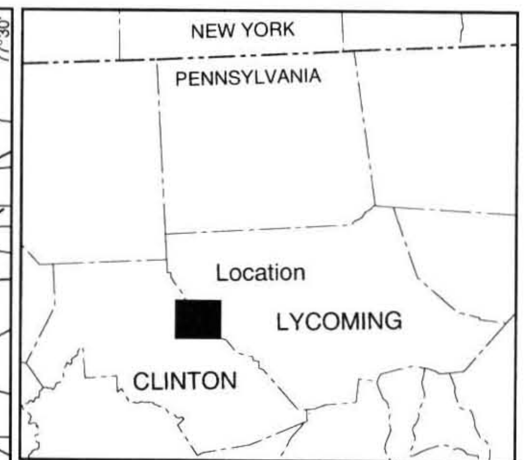


Figure Obe-6. Location of the three wells comprising the Grugan field in central Pennsylvania and structure of the Bald Eagle Formation. The structural contours were determined from seismic data by G.E. King at Texaco and submitted to the Pennsylvania Bureau of Topographic and Geologic Survey; the original map is filed at the Survey's Pittsburgh office. The position of the fault at the base of the Antes Shale was also determined from seismic data (see Figure Obe-7). The axes of surface structures are from Ebright (1952) and are based on the structure of the top of the cliff-forming part of the Lower Mississippian Burgoon Sandstone.

Grabau (1909) originally defined the Bald Eagle Formation as the gray sandstones between the *Orthorhynchula* zone in the Reedsville Formation and the red beds of the overlying Juniata Formation. Horowitz (1965) and Thompson (1970a; 1970b), however, both demonstrated that these rocks, including the Bald Eagle, were initially red, a color that was later leached out by diagenetic processes. The color of the Bald Eagle is only of diagenetic significance and has no stratigraphic importance. The red-grey color boundary occurs at different positions at different localities, varies by up to 656 feet, and crosscuts distinctive lithostratigraphic units (Horowitz, 1965; Thompson, 1970a; 1970b; Lacazette, 1991). Because of this, Faill and others (1977) included the entire sandstone-dominated interval between the Reedsville and the Juniata within the Bald Eagle Formation. Here, the authors utilize this approach in picking the top of the Bald Eagle in Figure Obe-4 and arbitrarily put the top at the beginning of an interval with 70 percent or more sandstone. This differs from the top selected by Ryder (1992a) in the Texaco State Tract 285 well (Figure Obe-4).

Zerrahn (1978) mapped part of the Bald Eagle Formation and equivalent Oswego Sandstone in Pennsylvania and New York. He showed the interval with a maximum stratigraphic thickness approaching 1,000 feet in south-central Pennsylvania. Zerrahn (1978) showed that the Bald Eagle thins rapidly to the east and northeast of its depocenter in south-central Pennsylvania; it thins gradually to the northwest and west.

Chen (1977) prepared a regional map of Bald Eagle and Oswego thickness and lithofacies in south-central Pennsylvania and portions of eastern West Virginia, northwestern Virginia, and western Maryland. He showed the Bald Eagle/Oswego basin striking northeast-southwest between south-central Pennsylvania and a point just to the north of Roanoke, Virginia. Also, he noted the locations of three depocenters along the axis of the Bald Eagle/Oswego basin with the thickest one near State College, Pennsylvania. This depocenter corresponds to the one shown by Zerrahn (1978).

Structure

Grugan field lies on the northwest flank of the Hyner anticline (Figure Obe-6), a northeast extension of the regionally prominent Laural Hill anticline of southwestern Pennsylvania (Ebright, 1952). The Hyner anticline is asymmetric, with steeper dips to the southeast. Seismic data collected across the Grugan field reveal deeper, down to the south thrust faults that sole out in the Salina decollement (Figure Obe-7).

Henderson and Timm (1985) identified deep-seated, down to the north normal faulting on seismic data from the Grugan field area (Figures Obe-6, Obe-7). The faulting involves Precambrian basement rocks and extends upward through Upper Ordovician carbonates and shales (Salona and Coburn limestones, Antes Shale). The trace of the deeper fault coincides with the long axis of a domal closure on the Bald Eagle at Grugan field that occurs along the northwest flank of the Hyner anticline (Figure Obe-6). As defined by the -10,000-foot contour, this dome is approximately 7.5 miles long and 2 to 3 miles wide with a little more than 500 feet of closure (Figure Obe-6).

Lacazette (1991) utilized fracture measurements made with Schlumberger formation microscanner data to study joints in the Bald Eagle, Juniata, and Tuscarora formations in the State Forest Tract 285 well at Grugan field. He determined that strike joints are well developed in the well and strike 227 degrees, with dip 80 degrees to the northwest. Cross-fold joints are largely absent (Lacazette,1991).

Reservoir

Productive sandstones within the Bald Eagle Formation at Grugan field comprise a naturally fractured reservoir. Fractures are vertical to subvertical and run parallel to the fold axis (Lacazette, 1991). Entrapment is structural and the relatively tight, low-porosity sandstone matrix of the Bald Eagle Formation contributes to the seal. Sealing is also due, in part, to partial fracture-filling with syntectonically precipitated minerals such as quartz, hematite, and calcite. In addition to this, shale beds in the Juniata Formation may help seal the reservoirs in the Bald Eagle sandstones. Also, both upward-decreasing grain size and increasing clay content in the Bald Eagle might be another relevant factor in sealing the trap (A.J. Lacazette, written commun., 1993).

The Middle Ordovician Antes Shale is the most probable source of hydrocarbons produced from the Bald Eagle Formation at Grugan field. The Antes is the only unit within the deeper stratigraphic section that contains adequate amounts of organic matter to serve as a petroleum source rock (Wallace and Roen, 1989; Laughrey, 1991) (Figure Obe-8). Kerogen in the Antes Shale in the State Forest Tract 285 well is almost entirely amorphous, suggesting that the organic matter is marine. Figure Obe-8 shows the results of organic carbon analysis and Rock-Eval pyrolysis of Antes Shale samples from the State Forest Tract 285 well. The data indicate that the Antes Shale has good to very good source potential on the basis of total organic carbon (TOC), but has poor potential on the basis of S2 yields. Production indices (S1/+S2) and higher vitrinite reflectance (Ro) values of overlying rocks show that the Antes is overmature; the generative potential of the organic matter is exhausted.

Reconstruction of the probable burial and thermal history of the Paleozoic rocks at Grugan field shows that the Antes Shale entered the oil window approximately 350 Ma when the source rocks were exposed to burial temperatures of 110 to 130°C (Figure Obe-9). Oil generation ended about 325 Ma, before maximum burial of the Antes. Oil remaining in the source rock was cracked to gas between 325 and 290 Ma, still prior to maximum burial in Late Permian time, and further maturation, which would have produced nonassociated thermogenic gas, totally exhausted the kerogens.

The chemical composition of the gases and the isotopic composition of the methane produced from the Bald Eagle sandstones at Grugan field are characteristic of dry gases generated by thermal cracking of kerogens during

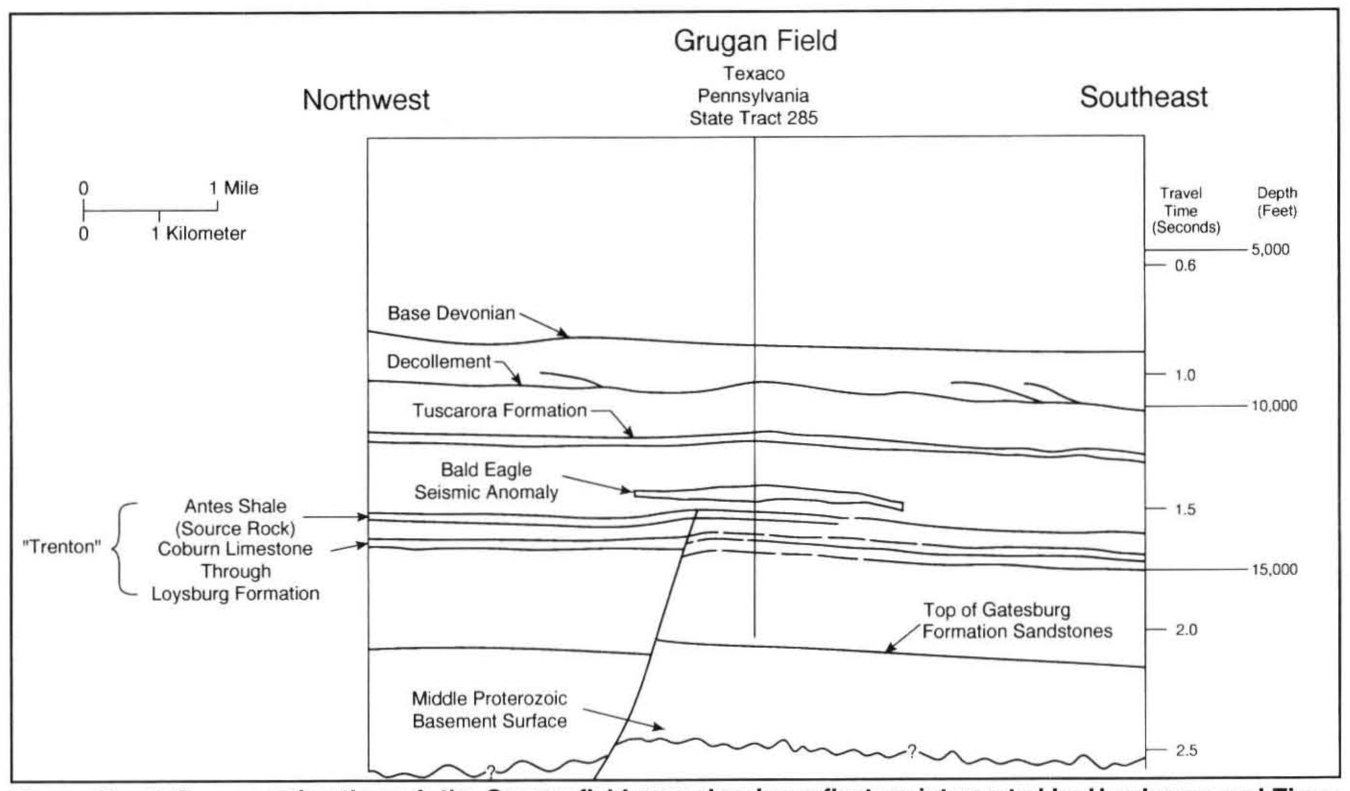


Figure Obe-7. Cross section through the Grugan field area showing reflectors interpreted by Henderson and Timm (1985) from a seismic line. See Figure Obe-2 for location of Grugan field.

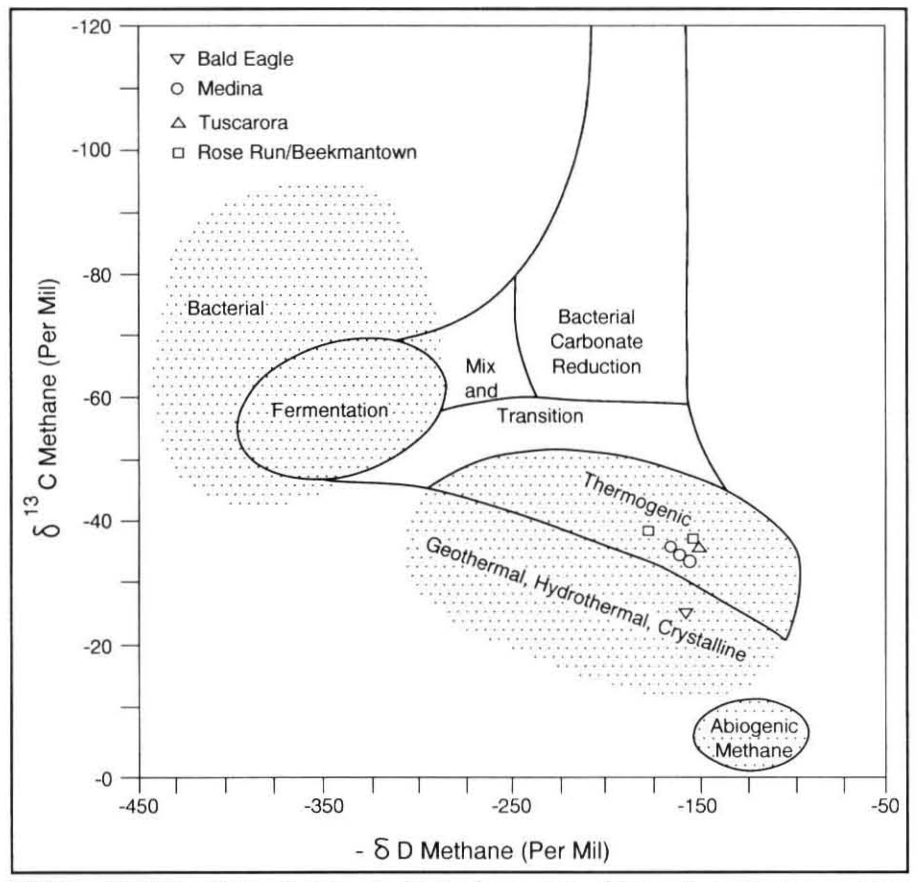


Figure Obe-10. Plot of carbon isotopic composition of methane versus hydrogen isotopic composition of methane from selected deep reservoir rocks in Pennsylvania and Ohio. The Antes/Utica Shale is the probable source rock for the hydrocarbons in these reservoirs. The Bald Eagle gas sample is from Grugan field. The Tuscarora sample is from the Devil's Elbow field, approximately 27 miles southwest of Grugan field. The Medina samples are from northwestern Pennsylvania and the Rose Run/Beekmantown samples are from eastern Ohio. The Bald Eagle gas resembles some geothermal and hydrothermal gases of the northwestern U.S. This resemblance may or may not be superficial. Compositional fields are from Loresson and Kvenvolden (1994). The stippled regions of the plot outside of the principal gas types are less common or well-defined gas isotope signatures (Whiticar, 1994).

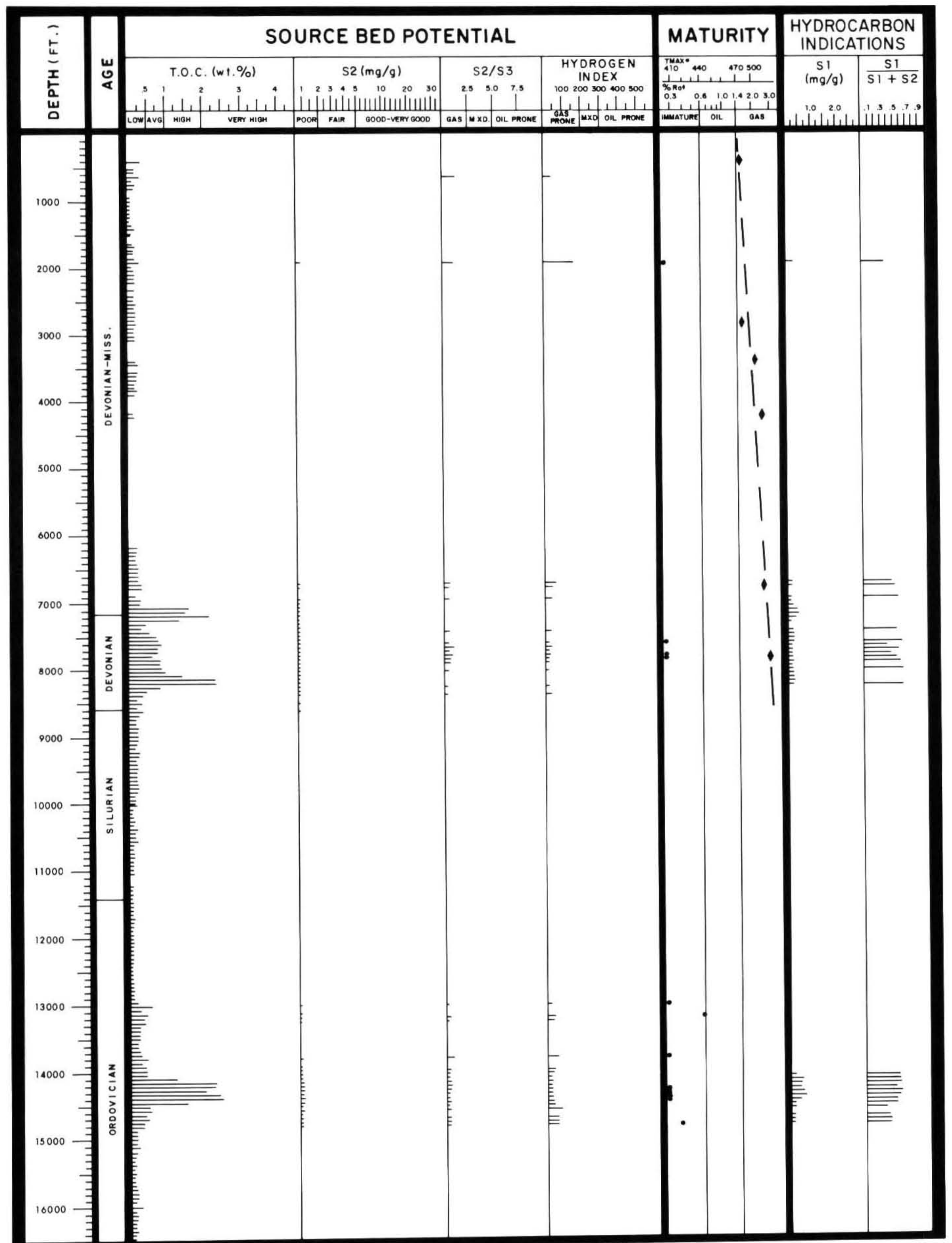


Figure Obe-8. Organic geochemical log of the Pennsylvania State Forest Tract 285 well in the Grugan field. Data courtesy of Brown and Ruth Laboratories.

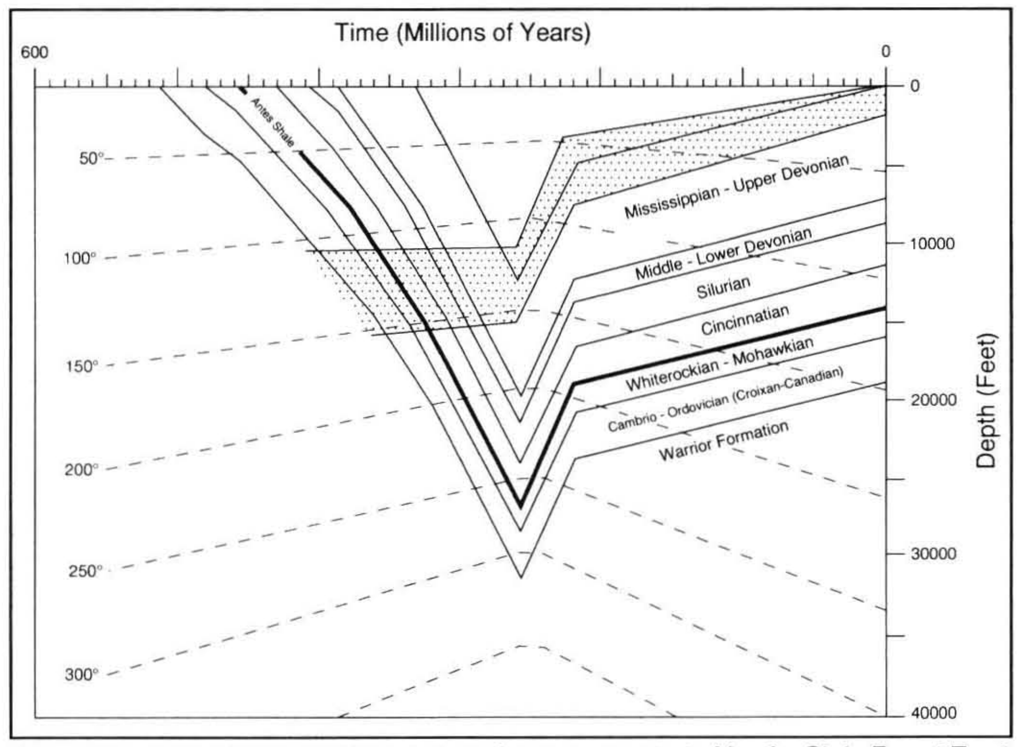


Figure Obe-9. Burial history of the Paleozoic strata penetrated by the State Forest Tract 285 well at Grugan field. Shaded area defines the limits of the oil-generating window. A variable geothermal gradient was used in constructing the time-temperature history shown in the model (present-day gradient is 23.6°C/km; the estimated Late Permian gradient is 31°C/km; the estimated Cambrian gradient is 25°C/km) (see Laughrey, 1995c). Maximum burial depth is based on plots of vitrinite reflectance versus depth extrapolated back to Ro=0.29 percent and sonic travel time versus depth in the Devonian shale section (see Laughrey, 1995c). Kinetic parameters for the generation of petroleum in the Antes Shale and for the conversion of oil to gas are those suggested by Hunt and Hennet (1993).

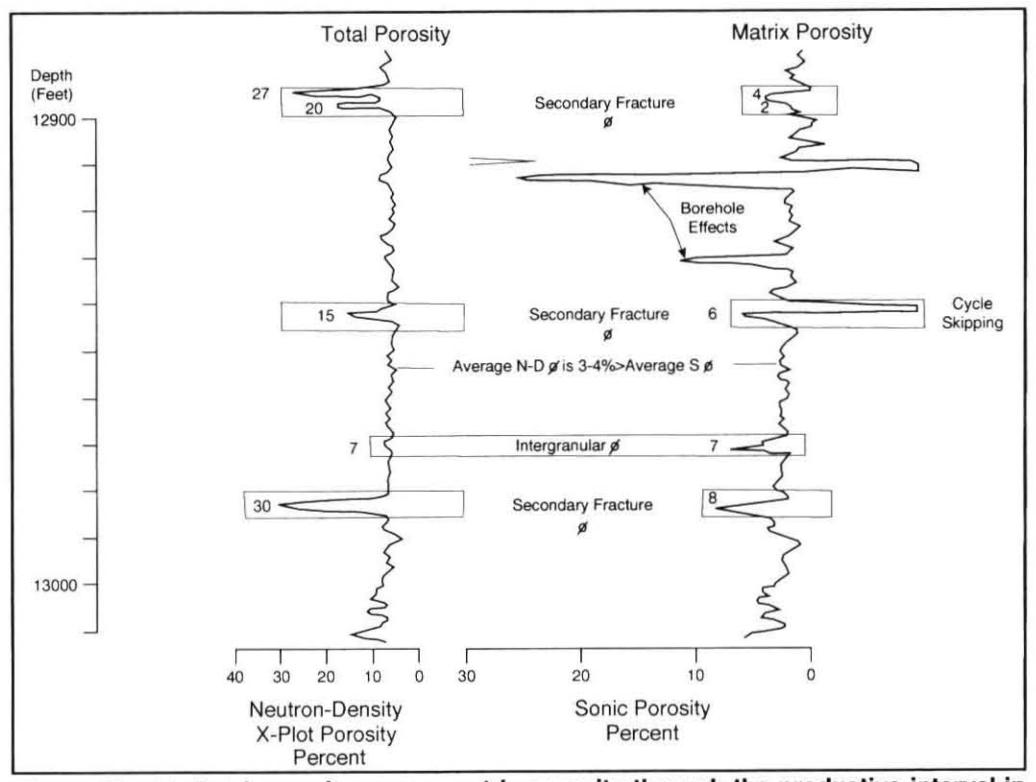


Figure Obe-11. Total porosity versus matrix porosity through the productive interval in the State Tract 285 well at Grugan field.

metagenesis (Tissot and Welte, 1984). The gas consists of 95.9 percent methane, 2 percent ethane, and 0.2 percent propane (Moore and Sigler, 1987). The ratio of methane to total hydrocarbon gases (C1/Cn) is 0.98. The methane has a δ 13 carbon value of -27.24 per mil and a δ deuterium value of -154.9 per mil (Figure Obe-10). A crossplot of these stable isotope values actually falls outside of the field of most thermogenic gases and resembles some methanes associated with hydrothermal and geothermal fluids and gases found in crystalline rocks (Apps and van de Camp, 1994; Lorenson and Kvenvolden, 1994) (Figure Obe-10). This resemblance may or may not be superficial. Minor amounts of nitrogen and trace amounts of hydrogen and carbon dioxide in the gas also support the interpretation of this gas as metagenetic (Hunt, 1979). The small amount of ethane and propane in the gas represent a late catagenetic stage component mixed with the predominate metagenetic methane (Tissot and Welte, 1984).

The geochemical data help to constrain the timing of gas migration into the Bald Eagle reservoir at Grugan field. The transition from late catagenesis to metagenesis in the source rocks occurred at the start of the Permian (Figure Obe-9); this is the earliest time that gases of the observed thermal maturity could have migrated from the Antes Shale into the Bald Eagle Formation. Lacazette (1991) suggested that fracture porosity in the Bald Eagle Formation at Grugan field and elsewhere in central Pennsylvania formed through natural hydraulic fracturing of the rocks by mixtures of highly saline brines and methane vapor during Alleghenian deformation in Permian time. He supported his hypothesis with fluid inclusion data obtained from quartz veins in the Bald Eagle Formation at selected outcrops. High syndeformational fluid pressures associated with overpressures in the Bald Eagle facilitated the fracturing process and caused intense local fracturing (Lacazette, 1991). The deep faulting recognized at Grugan field may have provided migration pathways for fluids moving out of the Antes source rocks as well as from deeper units (Figure Obe-7).

Wells drilled to the pay zone at Grugan field were completed at depths of 12,900 to 13,272 feet, with an average completion depth of 13,121 feet. The thickness of the pay zone ranges from 28 to 130 feet and averages 83.6 feet thick. Measured reservoir pressures in the field range from 5,210 to 9,220 psi and average 7,150 psi. These values are indicative of moderate overpressure in the Bald Eagle (greater than 0.45 psi/foot). Initial open flow was only reported for one well, Texaco's State Forest Tract 289, which came in with a reported natural open flow of 1,280 Mcf/d. Final open flows in the field ranged from 110 to 3,847 Mcf/d and averaged 1,745.6 Mcf/d.

Porosity and permeability in the Bald Eagle formation are extremely heterogeneous. At Grugan field, fracture voids range from an average of 3 to 4 percent greater than the matrix pore volumes to as much as 22 percent more than matrix porosity. Fracture zones in the pay interval have total porosities as high as 30 percent (Figure Obe-11). Type curve analyses by Texaco engineers yielded a matrix permeability of 0.07 md in the reservoir (Tables Obe-1, Obe-2). Fracture permeability delivers all of the commercial hydrocarbons produced at Grugan field.

Geologic and borehole data provide evidence of fracture porosity and permeability in the Bald Eagle at Grugan field. Lacazette (1991) observed that the reservoir has very high permeability parallel to the fold axis of the anticline, suggesting the presence of a well-developed fold axis-parallel joint set. Matrix porosity in the pay interval, determined from the sonic log, is very low whereas total porosity, determined from the neutron and density logs, is substantially higher (Figure Obe-11). A crossplot of the slopes of the sonic velocity versus bulk density (M) and neutron porosity versus bulk density (N) curves from log data (an M versus N crossplot) indicates secondary porosity within the pay zone (Figure Obe-12). Moreover, a plot of formation resistivity (Rt) versus total porosity in this zone has a slope of 1.13, indicating that this secondary porosity can be attributed mostly to fractures (Aguilera, 1980). The slope value (m) of 1.13 is the cementation exponent in the Archie water saturation equation (Asquith, 1982). A crossplot of m versus matrix porosity in the Bald Eagle pay interval indicates that between 70 and 90 percent of the total pore volume in the State Tract 285 well is fracture porosity (Laughrey and others, 1994). Cycle skipping in the sonic log, anomalous resistivity trends in the induction and spherically focused logs, and "busts" in the dipmeter log (Figure Obe-13) all support a fractured reservoir interpretation (Aguilera, 1980; Cray and others, 1987).

In addition to fracture porosity, intergranular porosity occurs in the pore systems of the Bald Eagle sandstones. Most primary intergranular porosity was filled by authigenic cements and reduced through compaction during deep burial. Some intergranular porosity formed through grain and cement dissolution and corrosion, but these voids are quantitatively insignificant in the rocks. Intergranular voids compose the matrix porosity in the reservoir and range from 2 to 8 percent (Figure Obe-11).

Drill-cutting samples of the Bald Eagle sandstones from the pay interval in the State Forest Tract 285 well at Grugan field consist of moderately sorted to well sorted, fine- to medium-grained lithic arenites. Monocrystalline quartz and chert are the dominant detrital grains. Minor amounts of detrital feldspar occur in the samples and consist of K-feldspar (mostly microcline). Authigenic feldspar composed of albite also occurs in the sandstones. Both detrital and authigenic feldspars exhibit varying degrees of alteration to clay minerals, mostly chlorite with minor mixed-layer illite-smectite. Also, some chlorite and mica occur in scattered phyllitic, low-grade metamorphic rock fragments. Carbonate cements, mostly dolomite with some minor calcite, comprise the principal binder in the rocks. The dolomite and calcite show intense orange-red and yellow luminescence that is a function of the high concentrations of Mn and Fe as well as the Fe/Mn ratio in the cements (Walker and Burley, 1991). The sandstones also contain minor authigenic quartz cement that occurs as euhedral overgrowths on detrital grains. Accessories in the sandstones include trace amounts of hornblende and pyrite.

Description of Key Field

Grugan field: The Grugan field is the only gas field producing from the Bald Eagle Formation in the Appalachian basin. This small field (Figures Obe-1, Obe-2, Obe-6) consists of a three-well pool that straddles the boundaries of Clinton and Lycoming counties in the rugged mountainous High Plateaus section of the Appalachian Plateau's physiographic province. The discovery well, Texaco's Pennsylvania State Forest Tract 285 (Clinton County permit number 20276), is in Grugan Township on the Glen Union 7.5-minute topographic quadrangle. The Pennsylvania State Forest Tract 289 (Lycoming County permit number 20029), Texaco's second producing well in the field, was drilled as an extension in McHenry Township, Lycoming County. This well is approximately 12,000 feet northeast of the discovery well. It is on the Slate Run 7.5-minute quadrangle. Felmont Oil Corporation completed the third well in Grugan field, the Pennsylvania State Tract 679 (Clinton County permit number 20375), in Chapman Township, Clinton County, about 11,000 feet southwest of the Texaco discovery well. The Felmont well is on the Glen Union 7.5-minute quadrangle. The Transcontinental Gas pipe line, a Columbia Gas Transmission pipeline, and a Penn Fuel Gas pipeline all cross the southern boundary of Grugan field.

Here, the authors interpret the productive interval at Grugan field to fall within Thompson's (1970a) lithofacies D. This lithofacies is 796 feet thick in the State Forest Tract 285 well (Figure Obe-4). Lithofacies D was deposited within a fluvial complex of shallow, wide, low-sinuosity braided streams (Thompson, 1970a). In outcrop, abundant cross-bedding and scour surfaces reflect constant bar and channel migration and erosion-deposition of the sediment load (Walker and Cant, 1979). Figure Obe-13 shows similar sedimentary features of lithofacies D inferred from the dipmeter data at Grugan field. The petrology of the productive interval, described above, is also consistent with that of lithofacies D.

Figure Obe-7 is a cross section through the Grugan field interpreted from a seismic line (Henderson and Timm, 1985) obtained near Texaco's State Forest Tract 285 well. Pertinent aspects of the section are the position of the decollement zone in the Salina section, Tuscarora and Middle Ordovician

TABLE Obe-1		Grugan Field PA
BASIC RESERVOIR DATA	POOL NUMBER	
	DISCOVERED	12/13/82
	DEPTH TO TOP RESERVOIR	12,897
	AGE OF RESERVOIR	Ordovician
	FORMATION	Bald Eagle
	PRODUCING RESERVOIR	Bald Eagle
	LITHOLOGY	sandstone
	TRAP TYPE	anticlinal
	DEPOSITIONAL ENVIRONMENT	braided fluvial
	DISCOVERY WELL IP (Mcf)	3,847
	DRIVE MECHANISM	water drive
	NO. PRODUCING WELLS	2
	NO. ABANDONED WELLS	1 shut-in
	AREA (acreage)	166
	OLDEST FORMATION PENETRATED	Warrior
	EXPECTED HETEROGENEITY DUE TO:	structure fractures diagenesis
RESERVOIR PARAMETERS	AVERAGE PAY THICKNESS (ft.)	74
	AVERAGE COMPLETION THICKNESS (ft.)	71
	AVERAGE POROSITY–LOG (%)	7.8
	MINIMUM POROSITY–LOG (%)	5
	MAXIMUM POROSITY–LOG (%)	30
	NO. DATA POINTS	3
	POROSITY FEET	5.755
	RESERVOIR TEMPERATURE (°F)	209
	INITIAL RESERVOIR PRESSURE (psi)	8120.5
	PRODUCING INTERVAL DEPTHS (ft.)	12,897-13,186
	PRESENT RESERVOIR PRESSURE (psi) / DATE	1,000/ 1994
FLUID & GAS PROPERTIES	Rw (Ωm)	0.03
	GAS GRAVITY (g/cc)	
	GAS SATURATION (%)	48.6
	WATER SATURATION (%)	51.4
	COMMINGLED	no
	ASSOCIATED OR NONASSOCIATED	nonassociated
	Btu/scf	1.013
VOLUMETRIC DATA	STATUS (producing, abandoned, storage)	producing
	ORIGINAL GAS IN PLACE (Mcf)	9,800,000
	ORIGINAL GAS RESERVES (Mcf)	8,200,000
	PRODUCTION YEARS	1982-1994
	REPORTED CUMULATIVE PRODUCTION (Mcf)	7,550,000
	NO. WELLS REPORTED	
	ESTIMATED CUMULATIVE PRODUCTION (Mcf)	
	REMAINING GAS IN PLACE (Mcf)/DATE	2,250,00/ 1994
	REMAINING GAS RESERVES (Mcf)/DATE	2,000,000/ 1994
	RECOVERY FACTOR (%)	
	INITIAL OPEN FLOW (Mcf/d)	1,280
	FINAL OPEN FLOW (Mcf/d)	

TABLE Obe-2	Grugan Field PA
AVERAGE PERMEABILITY (md)	0.07

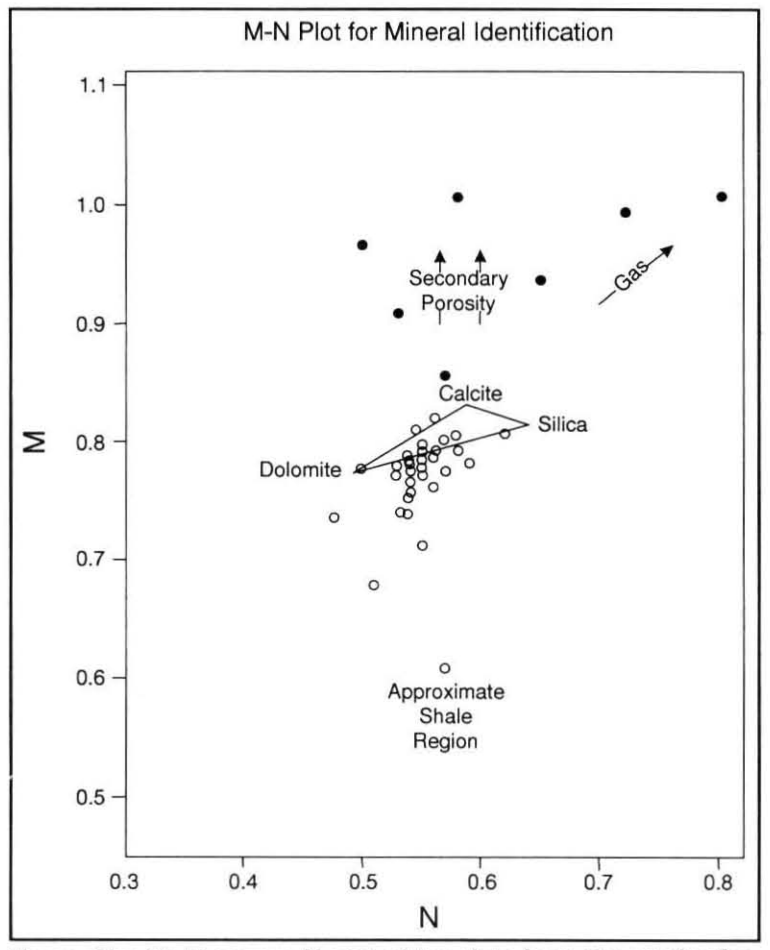


Figure Obe-12. M versus N plot of log data from the productive interval in the Bald Eagle Formation in the State Forest Tract 285 well. M and N are the respective slopes of the individual lithology lines on the sonic-density and density-neutron crossplot charts. See Doveton (1986). This crossplot helps to identify mineral mixtures from sonic, density, and neutron logs. Secondary porosity, including fractures, shaliness, and gas-filled porosity (solid circles) shift the data points with respect to their true lithology.

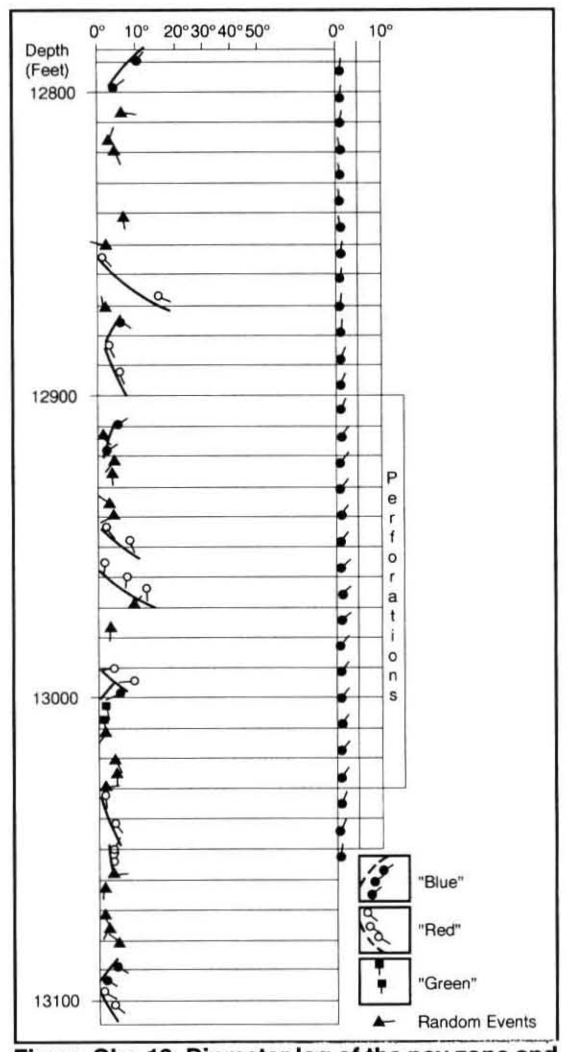


Figure Obe-13. Dipmeter log of the pay zone and adjacent strata in the State Forest Tract 285 well at Grugan field. Drift angle in the right track shows that the borehole is inclined 2.5 degrees to the northeast. The dipmeter vector plot between 12,790 and 13,100 feet reveals highly variable and erratic stratigraphic dip patterns. "Red" patterns indicate increasing dip with depth. "Blue" patterns indicate decreasing dip with depth. "Yellow" patterns are random events. The weak red and blue patterns may reflect trough crossbeds and erosional surfaces; yellow patterns are probably an artifact of the dipmeter detecting nonplanar surfaces within the small diameter of the borehole. Such dipmeter profiles are typical of braided stream deposits (Doveton, 1986). Busts in the dipmeter data might be due to fracturing (Cray and others, 1987).

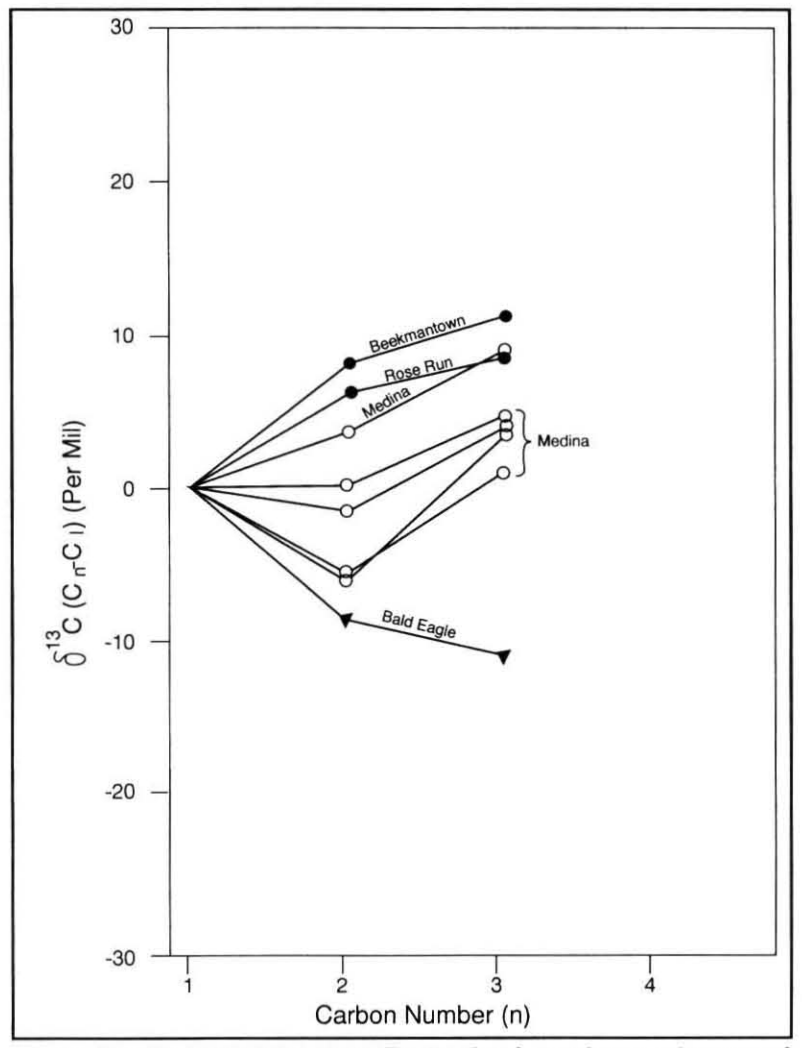


Figure Obe-14. The δ 13 carbon distribution in methane, ethane, and propane in several deep gases from Pennsylvania and Ohio. The Bald Eagle gas sample was collected from the State Forest Tract 289 well in Grugan field. The horizontal axis shows the number of carbon atoms in the specific hydrocarbon (for example, methane, n=1; ethane, n=2). The vertical axis shows the permil difference in δ 13 carbon between the three gases. Most commercial gases generally exhibit an isotopic distribution in which the δ 13 methane is less than (more negative or isotopically "lighter") the δ 13 carbon ethane, which is less than the δ 13 carbon propane. Such a typical distribution is shown for the Beekmantown, Rose Run, and one Medina sample in the upper three curves. The other three Medina gases, in the middle of the graph, show δ 13 carbon methane greater than δ 13 carbon ethane, but still less than the δ 13 carbon propane. Such a methane-ethane isotopic reversal often indicates mixing of different thermogenic gases (Jenden and others, 1994). The Bald Eagle gas displays a complete reverse distribution, with δ 13 carbon methane greater than δ 13 carbon ethane greater than δ 13 carbon propane.

"Trenton" carbonate section reflectors, the Precambrian basement surface, and the position of the down to the north basement fault. The cross section also shows a reflector originating at the base of the Bald Eagle that Henderson and Timm (1985) labeled the "Oswego anomaly," and is here referred to as the Bald Eagle seismic anomaly (Figure Obe-7). Seismic data in the central Appalachians usually do not reveal any strong, continuous reflectors between the top of the Tuscarora Formation and the top of the Middle Ordovician carbonate sequence (Henderson and Timm, 1985). This anomalous reflector appears on several seismic lines over the Grugan field (Henderson and Timm, 1985). The anomalous reflector, however, does not appear on all of the seismic lines run over Grugan field. Efforts by Texaco and Consolidated Natural Gas to duplicate the anomaly in model studies were unsuccessful leading their scientists to discount it as a bright spot (P.E. Towey, written commun., 1993). The cause of the anomaly is unknown, yet this very phenomenon and its relation, if any, to gas accumulations would be helpful for future exploration success.

Resources and Reserves

Gas wells producing from the Bald Eagle sandstones at Grugan field in central Pennsylvania are among the most productive wells in the Appalachian basin. Estimates of the original gas in place and the original gas reserves for these two wells are 9.8 bcf and 8.2 bcf (Table Obe-1).

Ryder (1995) summarized the geology and resource potential of the Bald Eagle Formation fractured anticlinal play in combination with the Upper Ordovician Queenston Formation play of New York. Traps in the latter play are stratigraphic, as opposed to the low-amplitude basement-controlled anticlinal traps of the Bald Eagle Formation in Pennsylvania, but other attributes of play definition such as source rock, migration pathways and timing, and hydrocarbon type are similar enough between these two Ordovician units for Ryder (1995) to have combined these very different reservoirs within the category of one play. He noted that large areas of the Queenston/Bald Eagle Sandstone gas play have been sporadically drilled to the Upper Ordovician intervals, and he speculated that there is potential for a modest number of undiscovered gas fields with greater than 6 bcfg recoverable reserves. Ryder (1995) estimated that there is a 95 percent probability of at least one more gas field being found in the play and a five percent probability of as many as 15 gas fields yet being discovered. Ryder (1995) estimated a median value of 13 bcfg and a mean value of 27 bcfg for undiscovered gas accumulations within the Queenston/Bald Eagle Sandstone gas play.

Accepting Ryder's (1995) probability estimates and considering the respective appraisals of 9.8 bcf of original gas in place and 8.2 bcf of original gas reserves calculated for Grugan field (Table Obe-1), the author conjectures that at least one more field like Grugan containing at least 9 bcf recoverable gas reserves can be found in the central Appalachian basin.

Future Trends

Future discoveries of natural gas in the Bald Eagle Formation, Oswego Sandstone, or other units within the Upper Ordovician clastic interval in the Appalachian basin will depend on the resolution of several enigmatic geologic and geophysical problems: discovering what is the timing of the fracturing in the Bald Eagle sandstones and the timing of the structural development of the trap itself; the role that basement faults and/or Alleghenian deformation had in the development of the reservoir and trap; the date at which the gas now produced from the Bald Eagle reservoir rocks migrated from the source rocks and accumulated at Grugan field; and the nature of the anomalous seismic reflector at the base of the Bald Eagle horizon at Grugan field and elsewhere in the central Appalachians.

The timing of fracture development in the Bald Eagle is a point on which investigators disagree. Towey (written commun., 1993) argued that both Texaco and CNG investigators believed fracture porosity existed in the Bald Eagle Formation as early as Late Silurian/Early Devonian time. They hypothesized that the fractures formed during deformation of the rocks that was caused by drape over the deeper normal fault, and that the hydrocarbons migrated and accumulated well before Alleghenian deformation. Kinetic modeling of petroleum generation in the probable source rocks (Antes Shale) shows that hydrocarbons were quite likely forming and migrating during this time (Figure Obe-9). The chemical and isotopic composition of gas produced at Grugan field, however, requires significantly higher maturation temperatures than hydrocarbons generated during earlier burial would have experienced. Lacazette (1991, p. 95) argued that fracturing in the Bald Eagle Formation "was induced and controlled by remote stresses and/or deformation (strain)-induced stresses associated with the Alleghenian orogeny." Pertinent points of Lacazette's thesis are as follows: formerly red, now green Bald Eagle rocks were altered because they were invaded by fluids, specifically methane-brine emulsions; rocks that were invaded by these fluids were exposed to elevated pore pressures; and elevated pore pressures at least sensitized the rocks to fracturing. Sufficiently high pore pressures could have caused fracturing. Thus, the altered green rocks in the Bald Eagle Formation and equivalent rocks (Oswego) may have good potential for fracture porosity and gas entrapment in other areas of the central Appalachians. The geochemistry of the gases produced at Grugan field clearly support Lacazette's ideas.

Mitra (1988) discussed the likely deformational behavior of potential reservoir lithostratigraphic units in the central Appalachian overthrust belt and noted that the Tuscarora Formation and the Upper Ordovician clastics of the Bald Eagle play comprise a thick, competent interval characterized by limited flexural slip and were likely to develop high fracture volumes during Alleghenian deformation. Along the Allegheny Front, the best developed fracture sets should be subvertical to vertical and trend parallel to fold axes. Such fracture sets should be considered for horizontal drilling (Lacazette, 1991). Lacazette (1991) also cautioned that large, vertical strike-slip faults appear to have served as conduits that drained the deeper stratigraphic horizons of hydrocarbons and these are areas where gas is likely to be absent.

The geochemistry of the gases and kinetic modeling of the burial and thermal histories of source rocks at Grugan field reasonably constrain the timing of earliest migration into the Bald Eagle reservoir. As discussed above, it is unlikely that gas of the observed isotopic composition migrated into the reservoir any earlier than Late Pennsylvanian time. Future efforts to predict similar gas accumulations elsewhere in the Appalachian basin must include a refined understanding of the unusual isotopic composition of the Grugan gases and implications concerning source and migration. The methane also resembles some hydrothermal and geothermal gases (Figure Obe-10). Furthermore, the distribution of carbon isotopes in the Grugan methane, ethane, and propane superficially resemble the patterns observed in some abiogenic gases (Jenden and others, 1994) while the same distributions in other gases generated from the Antes Shale and equivalent Utica Shale do not (Figure Obe-14). The distribution of carbon isotopes observed in the Grugan field gases might be due to heterogeneities in the source rock organic matter, mixing of gases from different sources, and oxidation of biogenic gas (Jenden and others, 1994). A more speculative explanation might involve deep crustal gases and/or ultra mature gases that migrated from further east rather than from obvious sources below (Apps and van de Camp, 1994; Burruss,1994; Lorenson and Kvenvolden, 1994).

PLAY Obc: MIDDLE AND UPPER ORDOVICIAN BIOCLASTIC CARBONATE ("TRENTON") PLAY

by Brandon C. Nuttall, Kentucky Geological Survey

Location

The Middle and Upper Ordovician bioclastic carbonate ("Trenton") play includes both gas and oil produced from stratigraphic and combination traps formed by Ordovician bioclastic carbonate bars (Sullivan and Pryor, 1988) and from secondary porosity developed in linear dolomitized zones (Black, 1986). Middle and Upper Ordovician carbonates of Shermanian (late Champlainian) and Cincinnatian age are present throughout the subsurface of the Appalachian basin. Production from this play is currently reported from nine fields in eastern Kentucky and five fields in central New York (Figure Obc-1). Probable productive limits of the play are shown in Figure Obc-1 and are based on the distribution of argillaceous and clean carbonate facies of Shermanian age from Keith (1988). The estimated total potential area of the play is 72.7 million acres. Within this area, there are 23.7 million acres, primarily in Kentucky, where clean carbonates of Cincinnatian age are present in addition to the Shermanian facies. In addition, this play extends across the Cumberland Saddle in southern Kentucky to the eastern flank of the Illinois basin. Table Obc-1 shows basic data for fields included in this play.

Production History

During the drilling for brine in 1829, oil was discovered in Upper Ordovician rocks of Kentucky with the drilling of the Great American Well on the Stockton lease in Cumberland County. Encouraged by the success of drilling for oil in northwestern Pennsylvania in the early 1860s, several companies were formed to explore southern Kentucky for oil and brines. This activity spread eastward across the Cincinnati arch onto the flanks and core of the Appalachian basin. The earliest drilling activity in the bioclastic carbonates for which a record exists is summarized by Diamond (1943) and Jillson (1946). The Granville Consolidated pool, Clinton County, Kentucky (Figure Obc-2), was discovered in 1861 with the drilling of the Old Matilda Gabbard well to a depth of 264 feet. This well encountered an unnamed pay near the base of the Cincinnatian Series (Jillson, 1946). Its producing zone was later named "Granville" (Figure Obc-3) when the Big Rock Oil Company completed several successful wells on the Granville Williams lease in Clinton County (Diamond, 1943). Also, drilling began in New York in the late 1800s in response to reports of the discovery of oil in the Trenton Limestone near Lima, Ohio (A. Van Tyne, oral commun., 1994), and gas was discovered in the Trenton around the southwestern flank of the Adirondack Mountains east of Lake Ontario (Figure Obc-1). Heck (1948) reported that this gas is produced from dark gray limestones interbedded with thin beds of black or dark gray shale. Upper Ordovician shale and Middle Ordovician Trenton Limestone have been penetrated by drilling in Ohio and West Virginia. Carter and others (1988) and Smosna (1985) described the Trenton carbonate ramp and shelf environments of northwestern West Virginia and southeastern Ohio. However, oil and gas production from these units in West Virginia and Ohio is generally attributed to fractured dolomitized limestone reservoirs as in the Harlem field (Maslowski, 1986; M. Baranoski and others, Cambrian-Ordovician Knox Group unconformity play, this atlas).

Cumulative production data for this play are generally not available. Sparse data available (Division of Mineral Resources, 1987; A. Van Tyne, oral commun., 1994) indicate more than 2 bcfg have been produced from the Pulaski and Sandy Creek fields of New York. Most of the gas wells producing from Middle and Upper Ordovician strata in Kentucky are completed for single residential or agricultural domestic gas, for which no production data exist.

Stratigraphy

Middle and Upper Ordovician bioclastic carbonates are recognized in the Trenton Group (Limestone) of New York, Pennsylvania, Tennessee, and West Virginia and the Lexington Limestone of Kentucky and southern Ohio. Bioclastic carbonate bars are also present in various formations within the Cincinnatian Series in Kentucky and southern Ohio. Figure Obc-3 is a generalized correlation chart that shows the variations in Middle and Upper Ordovician nomenclature from Tennessee to New York. Commonly, the oil- and gas-producing zones in these strata are very local in extent and, thus, are assigned informal drillers' names, such as Granville. In general, the Middle and Upper Ordovician bioclastic carbonate sequence is disconformably underlain by massive Blackriverian-age carbonates and unconformably overlain by Upper Ordovician or Lower Silurian clastic sequences. Facies changes and depositional environments of the Middle and Upper Ordovician sequence in Kentucky are summarized by Freeman (1953), Cressman (1973), Cressman and Noger (1976), and Weir and others (1984), and regional changes are summarized by Keith (1988).

A broad, relatively shallow carbonate shelf existed throughout most of the Appalachian basin at the close of Blackriverian time. This carbonate shelf continued into Champlainian and early Cincinnatian time, but it received periodic influxes of shales, siltstones, and sandstones from the northeast (Figure Obc-3). The clastics interrupted carbonate deposition and resulted in argillaceous carbonates and alternating carbonates and shales over much of the western and southern extent of the platform. These mixed carbonates and shales typically consist of well-cemented bioclastic grainstones and carbonate mudstones separated by relatively thin calcareous shales that developed in shallow-platform and peritidal settings. In high-energy, shallow shelf environments such as shoals and beaches, discontinuous coquinoid lag deposits were winnowed from carbonate muds by wave and tidal activity and accumulated as discrete offshore bars, tidal bars, and channel fills (Sullivan and Pryor, 1988). A generalized depositional model (Figure Obc-4), based on studies by Ginsburg (1975), Wilson (1975), and

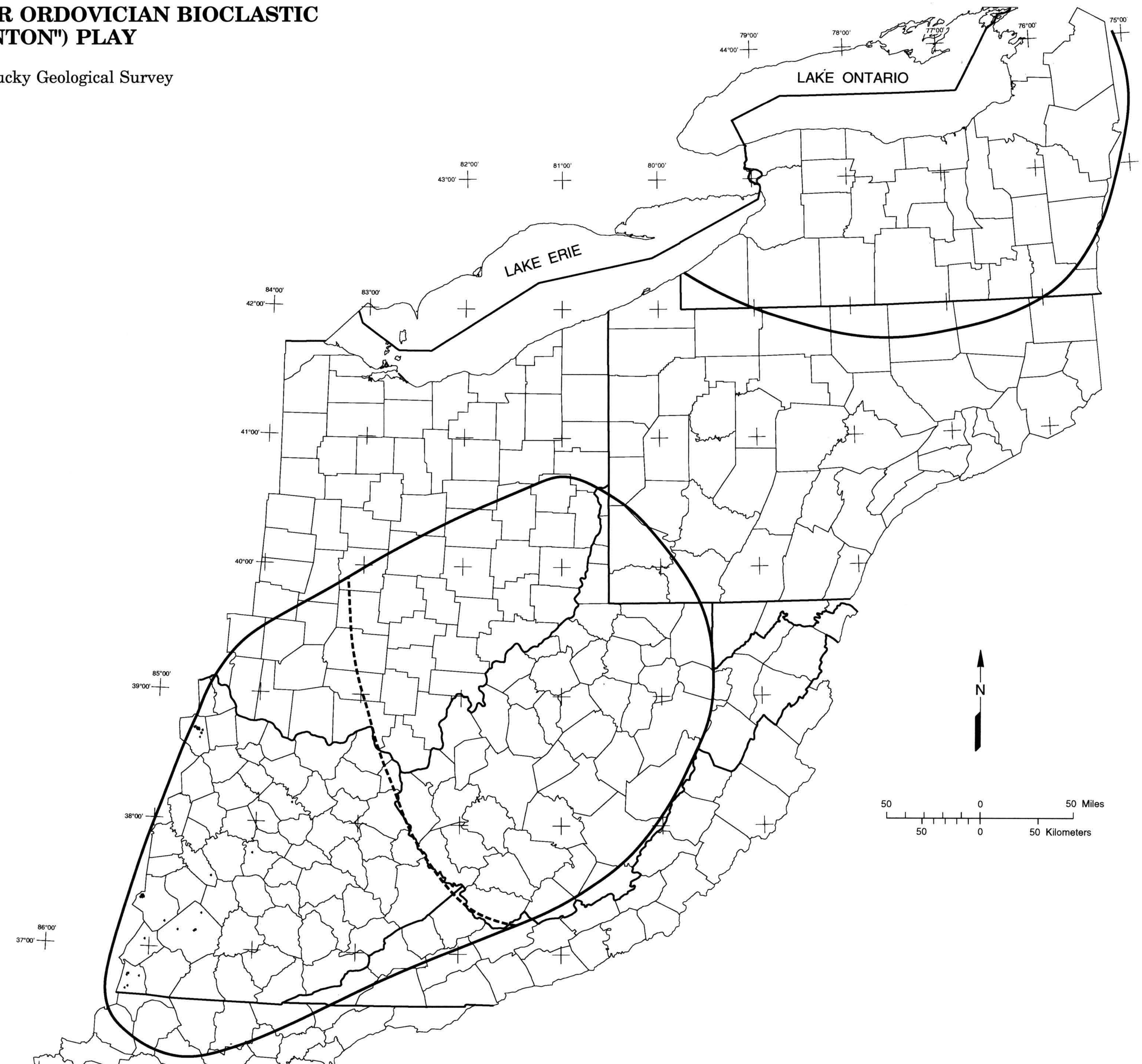


Figure Obc-1. Outline of the Middle and Upper Ordovician bioclastic carbonate (Trenton) limestone play within the Appalachian basin, showing existing pools and the distribution of shallow-shelf, clean carbonate facies. Dots represent individual gas wells; areas where dots have merged represent fields.

TABLE Obc-1		Albany Consolidated KY	Chicken Gizzard KY	Dry Ridge KY	Granville Consolidated KY	Raccoon Mountain KY	Seventy-six Consolidated KY	Sugar Hill KY	Trixie Consolidated KY	Windy City KY
BASIC RESERVOIR DATA	POOL NUMBER	1602248365	1600421361	1600591365	1600809361	1601600365	1601766361	1601920361	1602002365	1602139361
	DISCOVERED	1981	1986	1987	1980	1985	1980	1990	1982	1986
	DEPTH TO TOP RESERVOIR	497	162	325	711	2,190	695	859	2,654	500
	AGE OF RESERVOIR	Ordovician	Ordovician	Ordovician	Ordovician	Ordovician	Ordovician	Ordovician	Ordovician	Ordovician
	FORMATION									
	PRODUCING RESERVOIR	Sunnybrook	Drakes Formation	Lexington Limestone	Granville	Trenton Limestone	Granville	Granville	Trenton Limestone	Leipers Limestone
	LITHOLOGY	limestone	limestone	limestone	limestone	limestone	limestone	limestone	limestone	limestone
	TRAP TYPE	combination	combination	combination	combination	combination	combination	combination	combination	combination
	DEPOSITIONAL ENVIRONMENT	marine	shallow marine shelf	marine	shallow marine shelf	marine	marine	marine	marine	marine
	DISCOVERY WELL IP (Mcf)			10		75	60	154		
	DRIVE MECHANISM	gas	gas expansion	gas	gas expansion	gas	gas	gas	gas	gas
	NO. PRODUCING WELLS	2	14	19	6	1	1	3	2	1
	NO. ABANDONED WELLS	0	0	0	1	0	1	0	0	0
	AREA (acreage)	150	1,050	1,680	770	20	20	150	100	20
	OLDEST FORMATION PENETRATED	Knox	High Bridge	Lexington	Knox	Knox	Granville	Granville	Trenton	Knox
	EXPECTED HETEROGENEITY DUE TO:	fracturing	diagenesis	deposition	deposition	deposition	deposition	deposition	deposition	deposition
RESERVOIR PARAMETERS	AVERAGE PAY THICKNESS (ft.)	29	5	9	9		11	1	12	10
	AVERAGE COMPLETION THICKNESS (ft.)	13	7	15	18	40	13	1	13	10
	AVERAGE POROSITY--LOG (%)			10	14		11		3	13
	MINIMUM POROSITY--LOG (%)			4	4		4		1	4
	MAXIMUM POROSITY--LOG (%)			13	15		11		3	15
	NO. DATA POINTS			4	3		1		2	1
	POROSITY FEET									
	RESERVOIR TEMPERATURE (°F)	66			65			65		
	INITIAL RESERVOIR PRESSURE (psi)		125	50		300	50	260		100
	PRODUCING INTERVAL DEPTHS (ft.)									
	PRESENT RESERVOIR PRESSURE (psi) / DATE	100/ 1991	75/ 1988	50/ 1988						
FLUID & GAS PROPERTIES	Rw (Ωm)									
	GAS GRAVITY (g/cc)			0.642						
	GAS SATURATION (%)									
	WATER SATURATION (%)									
	COMMINGLED	yes	no	no	no	yes	no	no	no	no
	ASSOCIATED OR NONASSOCIATED	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated
	Btu/scf			1,002						
VOLUMETRIC DATA	STATUS (producing, abandoned, storage)	producing	producing	producing	producing	producing	producing	producing	producing	producing
	ORIGINAL GAS IN PLACE (Mcf)									
	ORIGINAL GAS RESERVES (Mcf)									
	PRODUCTION YEARS									
	REPORTED CUMULATIVE PRODUCTION (Mcf)							20,000		
	NO. WELLS REPORTED							3		
	ESTIMATED CUMULATIVE PRODUCTION (Mcf)									
	REMAINING GAS IN PLACE (Mcf)/DATE									
	REMAINING GAS RESERVES (Mcf)/DATE									
	RECOVERY FACTOR (%)									
	INITIAL OPEN FLOW (Mcf/d)					75				
	FINAL OPEN FLOW (Mcf/d)	105	294	314	8		55	53		500

Walker and James (1992), shows the distribution of a variety of carbonate shelf facies that characterize parts of the Middle and Upper Ordovician sequence in the play area. A type log for part of the Middle and Upper Ordovician of Kentucky (Figure Obc-5) shows the Granville in a representative stratigraphic position for reservoirs in this play.

The Cincinnatian Series in Kentucky and southern Ohio consists of interbedded carbonate and clastic lithologies of the Fairview, Leipers, Ashlock, Drakes, Grant Lake Limestone, and Bull Fork formations that often contain bioclastic carbonates associated with this play. Weir and others (1984) summarized the stratigraphy, facies, depositional environments, and paleogeography of the Cincinnatian Series. Figure Obc-6, a generalized facies map of Cincinnatian time, shows the distribution of carbonate and clastic rocks for the eastern U.S. The limestone units represent deposition on a broad, mostly open-marine, shallow to moderate-depth carbonate shelf with local intertidal and supratidal flats. Clastic sediment influx from deltaic and alluvial plains to the northeast modified and sometimes interrupted carbonate deposition. Discontinuous deposits of medium- to coarse-grained calcarenites, often characterized by low-angle crossbedding (as in lithofacies H of Weir and others, 1984), occur throughout the Cincinnatian section, including the Leipers

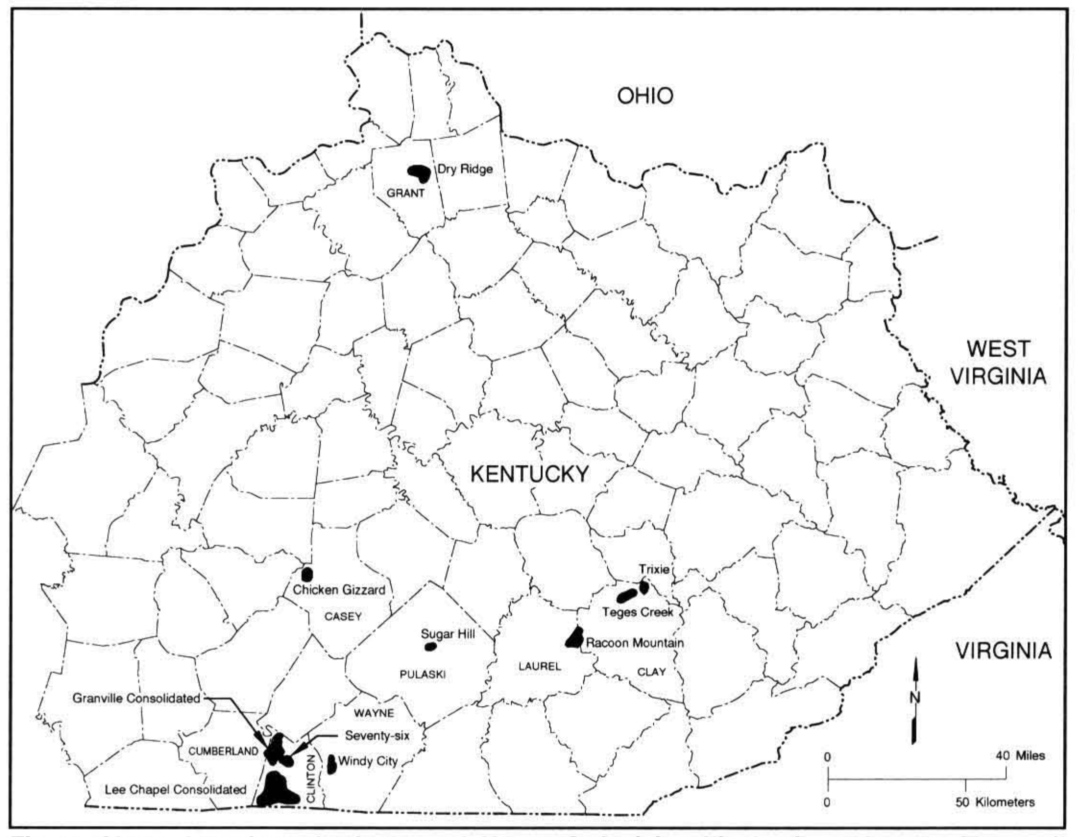


Figure Obc-2. Location of Middle and Upper Ordovician bioclastic carbonate (Trenton) limestone fields and pools of eastern Kentucky producing from bioclastic carbonate bar facies. Other areas of production illustrated in Figure Obc-1 are not shown.

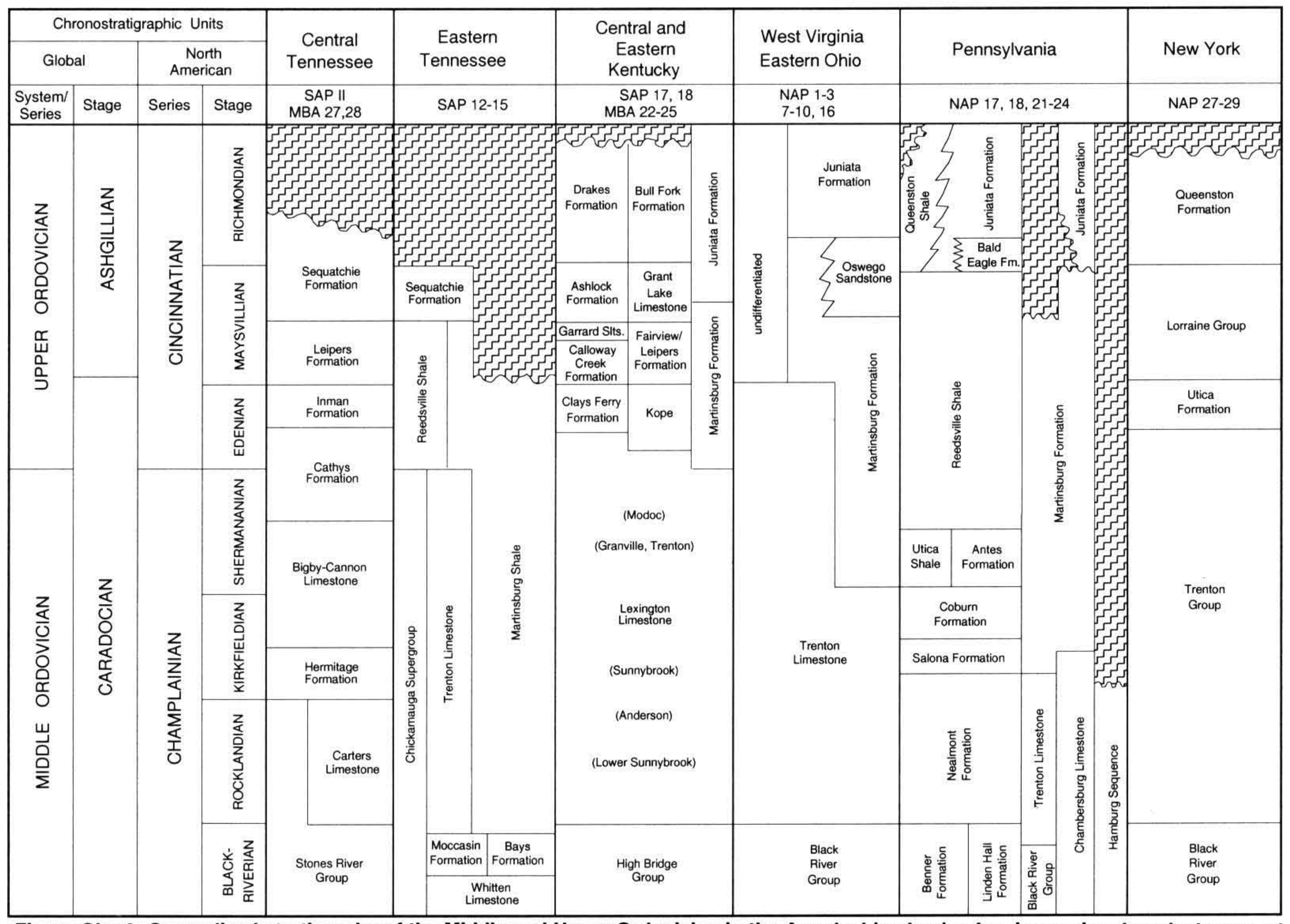


Figure Obc-3. Generalized stratigraphy of the Middle and Upper Ordovician in the Appalachian basin showing regional equivalents and correlations. Modified from Keith (1988), Patchen and others (1985a; 1985b), Shaver (1985), and Harper (1979). Drillers' terms shown in parentheses.

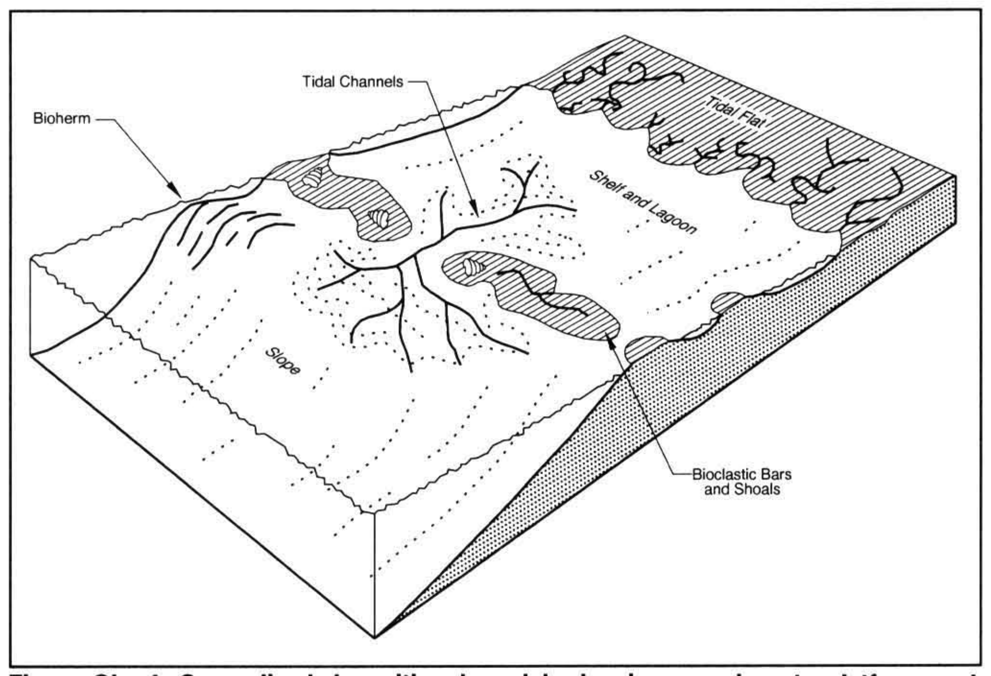


Figure Obc-4. Generalized depositional model, showing a carbonate platform and peritidal depositional environments. After Walker and James (1992).

Formation of southern Kentucky and Tennessee, and the Grant Lake and Drakes formations of northern and northeastern Kentucky.

The Clays Ferry Limestone of northern Kentucky and adjoining Ohio conformably overlies and intertongues with the Lexington Limestone and consists of interbedded thin shales, limestones, and siltstones (Weir and Greene, 1965). It grades upward into the Garrard Siltstone. The Clays Ferry Limestone and Garrard Siltstone units are not part of the bioclastic carbonate play. However, the Garrard Siltstone may be productive and has been mistaken in the subsurface for the Granville, a producing zone in the Lexington Limestone (Wilson and Sutton, 1973).

The Lexington Limestone is a heterogeneous lithologic sequence of dominantly bioclastic, fossiliferous, tabular, gray limestones commonly interbedded with shale that exhibit crossbeds, flow rolls, and other current-related and tidally influenced features (Black and others, 1965). It is correlative with the Trenton Limestone and Trenton Group of Tennessee, West Virginia, Ohio, Pennsylvania, and New York. The Lexington Limestone is often referred to by drillers as the Trenton or Sunnybrook. Pay zones are informally referred to as Granville, Modoc, Anderson, and Lower Sunnybrook. Stacked occurrences of the bioclastic lithology in the Lexington Limestone are often the first or second Granville. Cressman (1973) summarized the stratigraphy of the Lexington Limestone and described several facies within it characterized in part by calcarenites and bioclastic coquinas. Moreover, intertidal calcarenites in the Lexington Limestone with prominent crossbedding are discussed by Hrabar and others (1971). Figure Obc-7 shows the generalized facies distribution for the Shermanian Series in the eastern U.S., the time when the upper part of the Lexington Limestone was deposited. Areas of shoaling indicated by clean carbonate rocks are shown in south-central, southeastern, and northern Kentucky (Figure Obc-7). The Lexington Limestone disconformably overlies the High Bridge Group and is exposed throughout much of the central Blue Grass area of Kentucky.

The High Bridge Group in Kentucky, consisting mainly of massive limestone and dolomite, underlies the bioclastic carbonates of the play. A lithographic limestone developed at the top of the High Bridge Group marks the close of the Middle Ordovician Blackriverian Stage in Kentucky. As described by Cressman and Noger (1976), the finely laminated micrite and dolomite with mudcracks and birdseye calcite in the High Bridge Group are indicative of dominantly intertidal and supratidal environments. The Millbrig (Mud Cave) and Deicke (Pencil Cave) bentonites, near the top of the High Bridge Group (Figure Obc-5), have been identified and correlated from the Mississippi Valley to the Appalachians (Huff and Kolata, 1990) and are utilized as chronostratigraphic marker beds during drilling and for subsurface mapping. When nuclear logs are available and used for correlation, the Millbrig bentonite is assumed to be the top of the High Bridge Group.

Trenton Limestone samples from a well drilled in the Sandy Creek field, northwestern Oswego County, New York, indicate that some of the main gas-producing zones in the area are highly fossiliferous or "shelly" limestone in the otherwise massive Trenton Limestone (A. Van Tyne, oral commun., 1994). The gas in the Trenton Limestone fields of New York is trapped in interskeletal porosity of the bioclastic limestones and sealed by the surrounding impermeable limestone. Van Tyne (oral commun., 1994) suggested that there may have been an arc of shoaling in the onlapping Trenton Limestone around the southern flank of the Adirondacks, where biostromal or coquinitic beds were deposited.

Structure

Subtle geologic structures of the western margin of the Appalachian basin and the Cumberland Saddle of central Kentucky have an important role in the location of the fields of this play. Many of the fields are associated with nosing and flexures on structure contour maps of the Ordovician Pencil Cave bentonite and the top of the Devonian Chattanooga Shale (Figure Obc-8). Diamond (1943) noted the occurrence of production along a north-south structure, the Ill-Will anticline, Clinton County, Kentucky, a part of which is shown on Figure Obc-8. Moreover, Jillson (1946) showed that 12 oil or gas pools productive from the Granville or shallower bioclastic carbonate reservoirs are aligned along this structure. Jillson (1946, p. 23) stated that the rocks of Clinton County dip generally southeast and northwest and "constitute a... monocline... [that] is locally flexed." Figure Obc-8 shows the structure on the top of the Chattanooga Shale in Clinton County, Kentucky, and the alignment of the Granville Consolidated field along positive structural features (Thomas and others, 1950). Many of these subtle structural features are not apparent on regional maps (Potter, 1978).

Alternatively, Black (1986) proposed that some of the oil and gas traps in Kentucky could be expected in narrow, linear, dolomitized zones along normal and strike-slip faults associated with interpreted basement faults in the region. He suggested the Albion-Scipio trend in Michigan as a model for these fault-related dolomitized reservoirs, and demonstrated the occurrence of linear oil and gas fields along the flanks of aeromagnetic highs in Kentucky. Black (1986) concluded that the dolomitized traps occur as grabens or half-grabens, and projects the probability of traps into other parts of eastern Kentucky (see M. Baranoski and others, Cambrian-Ordovician Knox Group unconformity play, this atlas).

According to Van Tyne (oral commun., 1995) the relationship of structure to Trenton production in New York has not been investigated. Some production is believed to be related to fracturing caused by various post depositional tectonics. The Trenton fields of New York associated with this play are bioclastic accumulations with little or no structural components controlling the reservoirs.

Reservoir

State of Kentucky statutes require production data, currently reported to the Kentucky Revenue Cabinet, to be held confidential. Therefore, reservoir data for this play were mainly from drillers' logs, geophysical logs, and accounts of production from the literature.

According to Sullivan (1983), stratigraphic traps of the Upper Ordovician Granville zone are sealed by fine-grained, impermeable strata and tightly cemented grainstones. The primary source of the hydrocarbons in this play is the organic-rich Mississippian-Devonian black shale sequence. An additional local source may be the very dark gray dolomudstones and shales of the Lexington, which have a total organic content up to 2 percent (Sullivan, 1983). Major

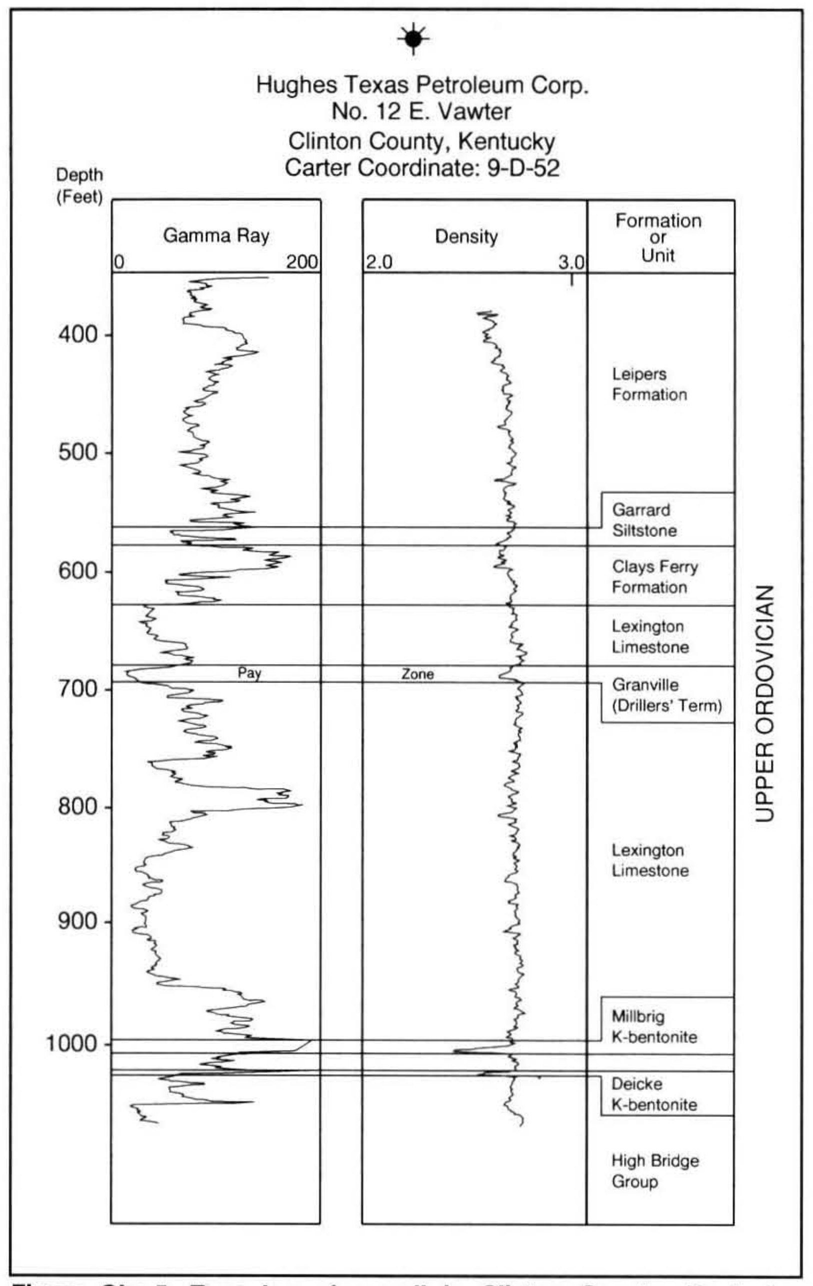


Figure Obc-5. Type log of a well in Clinton County, Kentucky, producing from the Middle and Upper Ordovician bioclastic carbonate (Trenton) play.

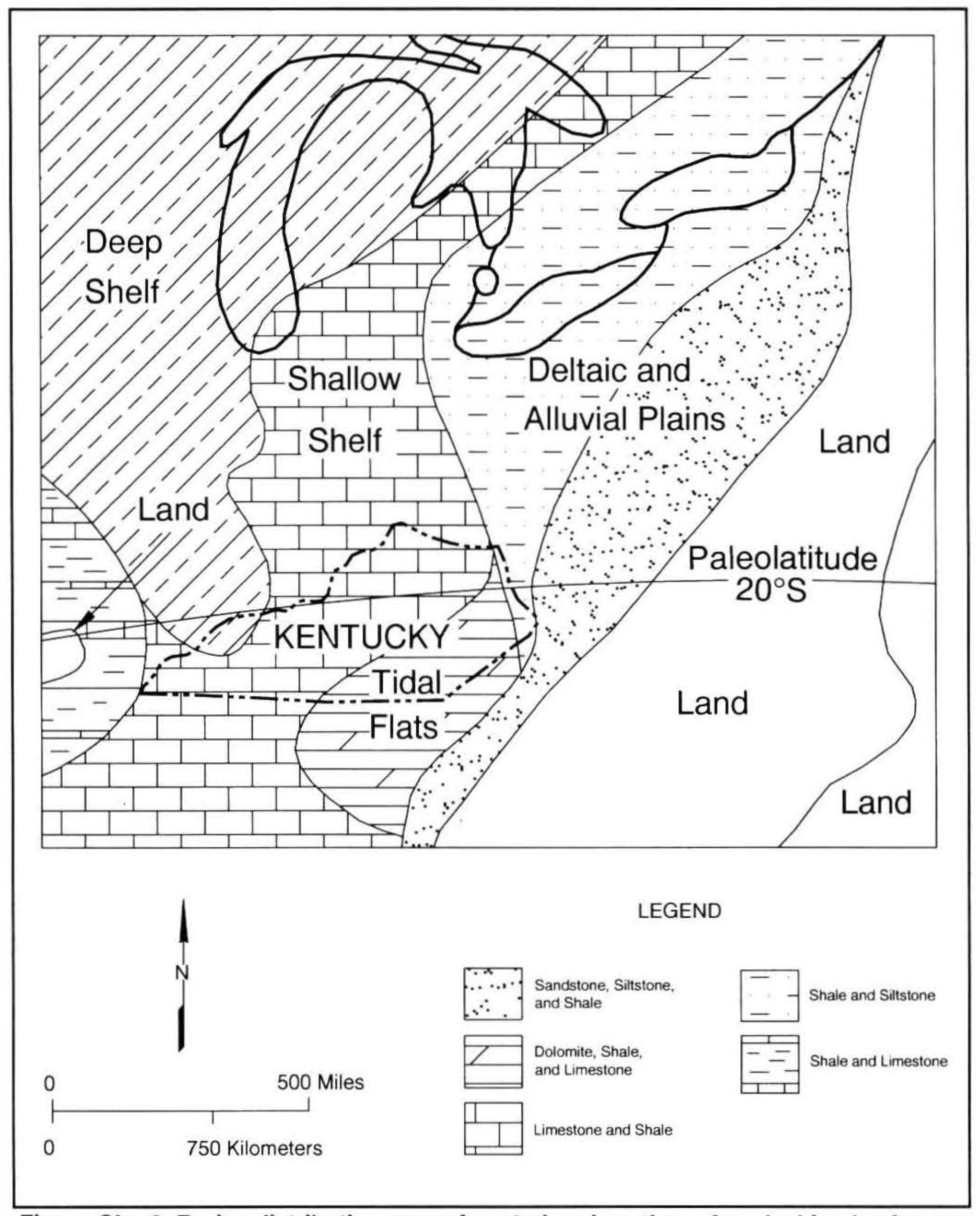


Figure Obc-6. Facies distribution map of central and northern Appalachian basin area during Late Cincinnatian time. After Weir and others (1984).

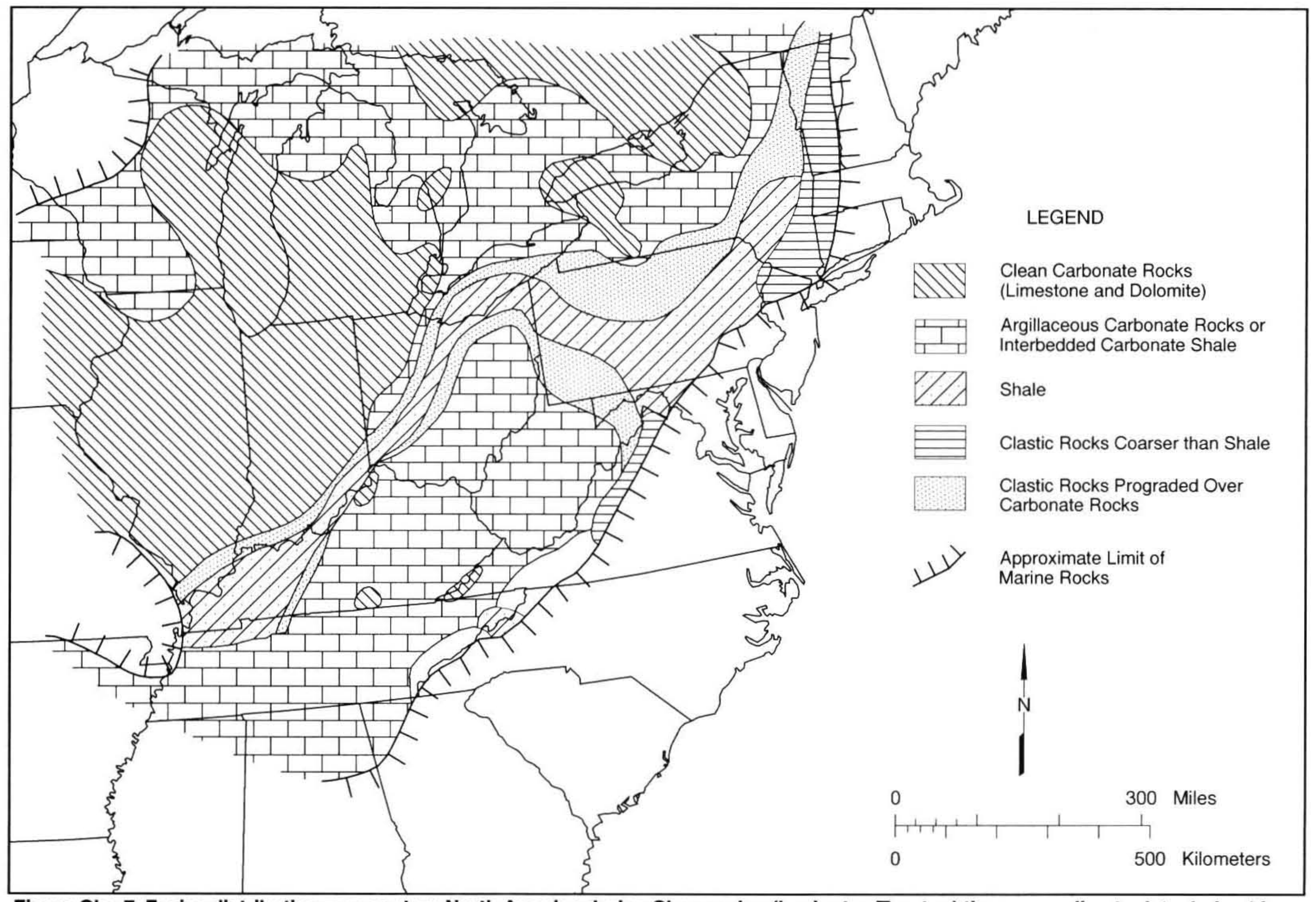


Figure Obc-7. Facies distribution map eastern North America during Shermanian (Lexington/Trenton) time, according to data derived from COSUNA charts by Keith (1988).

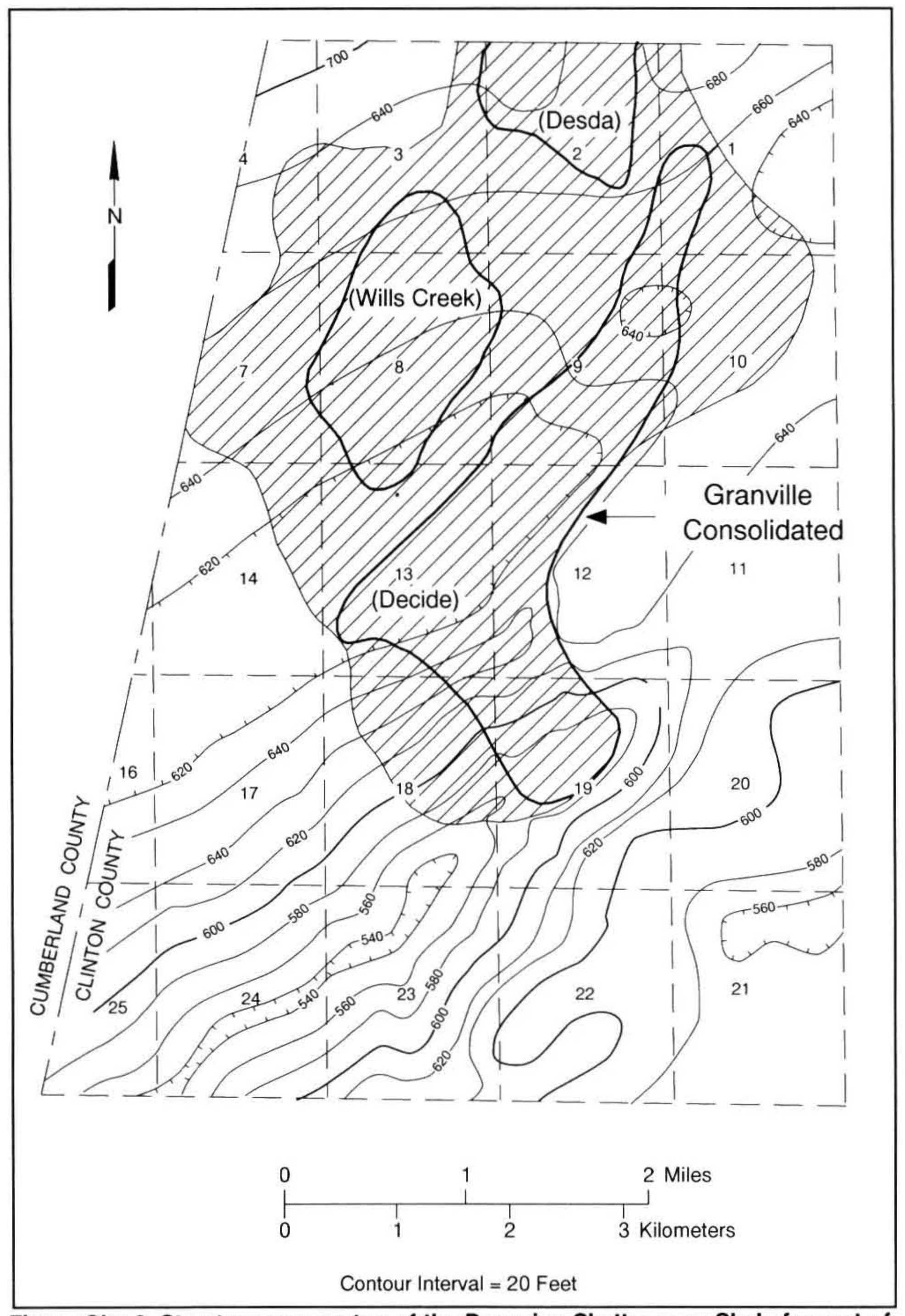


Figure Obc-8. Structure map on top of the Devonian Chattanooga Shale for part of Clinton County, Kentucky. After Thomas and others (1950). See Figure Obc-2 for location.

Table Obc-2. Summary of undiscovered recoverable resource calculations for the Ordovician bioclastic carbonate play.

Category	Acreage: Thousands of Acres	Acreage: Probability (Percent)	Net Pay: Thickness (Feet)	Net Pay: Probability (Percent)	Recovery: Mcf per Acre-Foot	Recovery: Probability (Percent)	Resources (bcf)
Upper Ordovician (Exclusive of Lexington/"Trenton")							
Minimum	1	50	2	25	98	27	0.2
Most Likely	3	40	9	65	327	55	8.8
Maximum	5	10	25	10	556	18	70.7
10th Percentile							0.8
50th Percentile							2.7
90th Percentile							8.8
Weighted Mean							4.0
Lexington/"Trenton"							
Minimum	29	50	2	25	98	27	5.7
Most Likely	92	40	9	65	327	55	270.5
Maximum	155	10	25	10	556	18	2,154.5
10th Percentile							25.5
50th Percentile							85.1
90th Percentile							270.5
Weighted Mean							122.8
Total Undiscovered Resources Estimate for Play Obc							
10th Percentile	(90 percent chance of at least this)						26
90th Percentile	(10 percent chance of at least this)						279
Total Weighted Mean Undiscovered Recoverable Resources (bcf)							**127**

migration avenues for hydrocarbons derived from the Devonian shales in the basin are provided by faults, fractures, and the Ordovician Knox paleokarst system. In Kentucky, where the Middle and Upper Ordovician sequence is a common drilling target, depths to the pay range from less than 200 feet along the crest of the Cincinnati arch to more than 2,000 feet farther east into the Appalachian basin. Where the Middle and Upper Ordovician sequence is greater that 2,000 feet in depth, the bioclastic reservoirs of this play are not usually a primary drilling target. Net pay thickness averages 10 feet, whereas the average completion interval is 15 to 20 feet. According to Jillson (1946, p. 30), the "thickness of oil saturation ranges from 5 to 25 feet; usually 7 to 15 feet. The oil in the Granville is accompanied by gas, frequently in considerable volume."

In the early history of oil and gas development, wells were drilled with cable-tool rigs. According to Jillson (1946, p. 17), when a well encountered gas it was allowed to "blow itself out" in the hope of bringing on commercial amounts of oil, even though this practice was detrimental to the ultimate recovery of oil in the field. Unfortunately, reservoir pressure data are not available for the fields in this play. In current practice, wells are air-rotary drilled and typically completed in the open-hole below 7-inch casing. If stimulation is deemed necessary, most wells are acidized in the open hole.

Average initial open flows, after stimulation, for various fields in the play range between 8 and 500 Mcfg/d, with many less than 100 Mcfg/d. The overall average reported flow is 368 Mcfg/d, and the median flow is 45 Mcfg/d. The maximum flow recorded was 7.5 MMcfg/d from the Tennessee Land and Exploration Company No. 1 Gilbert Bishop and others well, Carter coordinate section 6-J-71, in the Trixie Consolidated field, Clay County, Kentucky. However, low-matrix porosity of the reservoir suggests production may have been enhanced by fracture permeability. The drive mechanism for these Middle and Upper Ordovician bioclastic reservoirs is interpreted to be gas expansion.

Reservoir porosity was calculated from logs available in four fields and from one core analysis. Average matrix porosity for all five fields is 11.8 percent and the maximum porosity is 15 percent. The dominant porosity types are moldic, interparticulate, intraparticulate, and intercrystalline. The core from the Jarvis No. 2 Dickens well, Granville Consolidated pool, Clinton County, Kentucky, indicates an average reservoir permeability of 57.1 md and a maximum permeability of 293 md.

Description of Key Field

Granville Consolidated pool: Reservoirs in the Granville Consolidated pool, Carter coordinate D-52, Clinton County, Kentucky, are typical of the offshore bars developed on the Middle and Upper Ordovician carbonate shelf. The detailed study of the field by Sullivan (1983) is a key to understanding this play. The pool encompasses several older producing pools in the Granville trend that were discovered between 1861 and 1944 (Diamond, 1943; Jillson, 1946; Perkins, 1955). The reservoirs in the pool, the first and second Granville zones, constitute a stacked shoaling sequence (Sullivan, 1983). An isopach map of the first Granville zone is shown in Figure Obc-9 (Sullivan, 1983). The thicker barrier-bar systems have been correlated with areas having the best oil and gas production (Sullivan, 1983). Figure Obc-10 is a north-south cross section through the Granville Consolidated pool area that illustrates the distribution of the Granville zones and associated hydrocarbon production. Expansion of gas, associated with oil production, is the primary reservoir drive. An estimated 770 acres produce nonassociated gas, and an estimated 2,000 acres produce oil. The average spacing, by statute, is 1,000 feet between gas wells. However, many wells were drilled prior to adoption of the current regulations in 1960, and the spacing between these old wells is often 400 feet or less. The producing intervals range from 600 to nearly 800 feet in depth, with an average net pay thickness of 9 feet. Calculated from available logs, the average porosity of the producing intervals is 14 percent.

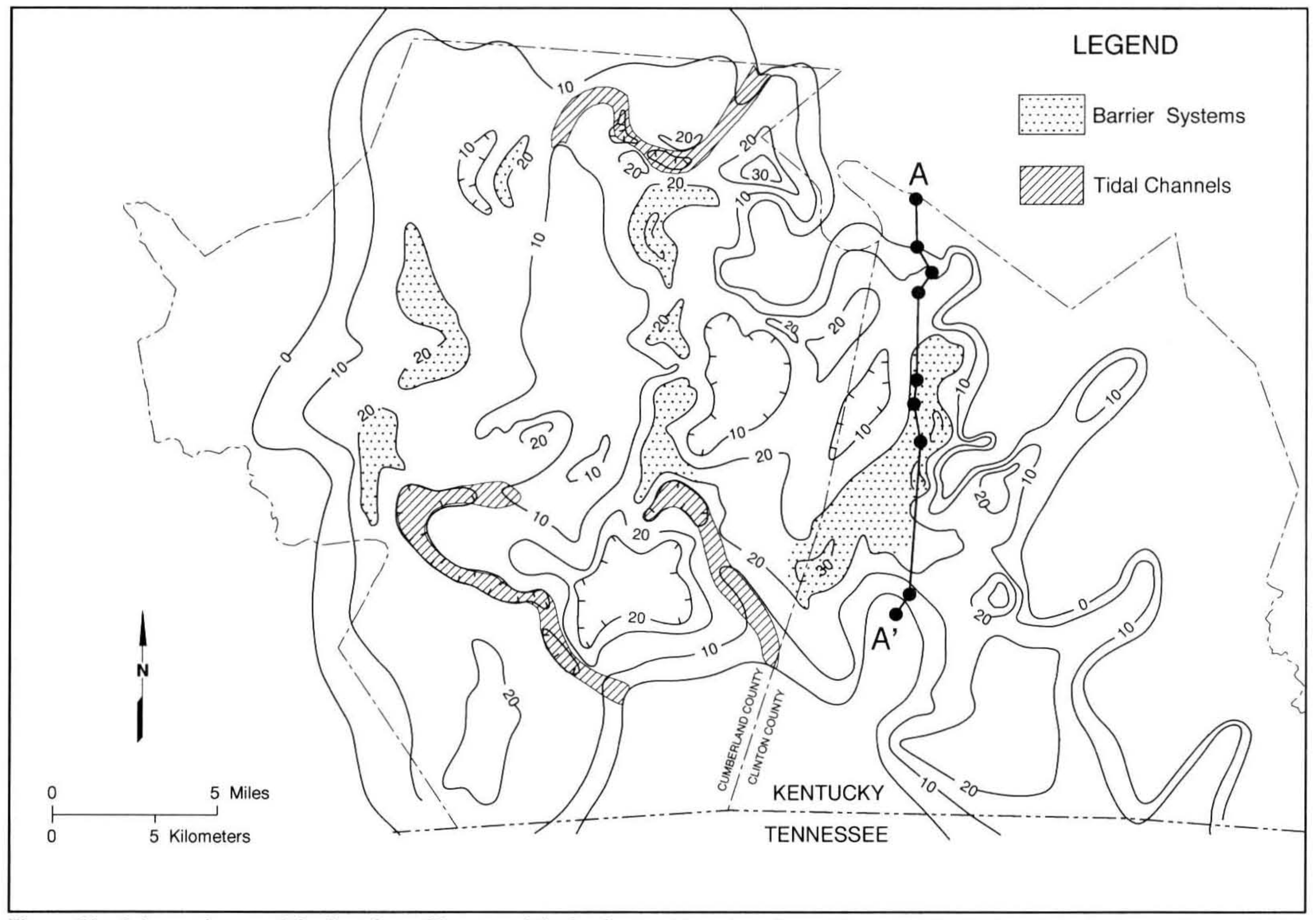


Figure Obc-9. Isopach map of the first Granville zone of the Lexington Limestone in south-central Kentucky, showing barrier bar and tidal channel complexes. Contour interval = 10 feet. From Sullivan (1983). Line of cross section A-A' (Figure Obc-10) is also shown.

Resources and Reserves

Based on regional production data available at the Kentucky Geological Survey, an estimated 50 to 100 MMcfg per year is produced from central Kentucky Trenton reservoirs along the western margin of the Appalachian basin. This estimate does not account for an unknown number of domestic gas supply wells, nor does it account for gas production from Trenton reservoirs in eastern Kentucky pools that is commingled with other producing zones. This general lack of production data makes resource and reserves estimates extremely speculative. Jillson (1946) asserted that as much as 20 to 25 MMcf had been discovered, plugged, and abandoned in the areas of Kentucky he studied. Because of limited reservoir and production data, little is known of the potential for gas in the bioclastic reservoirs of this play in Ohio (M. Baranoski, oral commun., 1994) and West Virginia.

With the potential for additional reservoirs, the proximity of viable source rocks, and sparse drilling in certain localities, this play should have undiscovered recoverable gas resources as defined by Miller and others (1975). The method selected in this report to estimate the undiscovered recoverable gas resources was a statistical-volumetric procedure. Probable limits of the potentially productive argillaceous and clean carbonates deposited in Shermanian and Cincinnatian time are outlined in Figure Obc-1. These areas are estimated to be 72.7 million acres and 23.7 million acres, respectively. Arbitrarily, 50 percent of each potentially productive area was eliminated from consideration. The areas eliminated are located where the reservoir units crop out, are too shallow, are judged too deep to be an economically feasible primary drilling target, or underlie restricted areas such as rivers, cities, and parks. Based on the distribution of current fields, it was estimated that 0.5 percent of the remaining acreage would be potentially productive. Resource calculations were performed for each area separately, and then their total resources were aggregated.

Using the guidelines and triangular distribution methods of Megill (1977), absolute minimum, most likely, and absolute maximum production values for millions of cubic feet of gas per acre-foot; net pay thickness; and productive acreage were selected as the most critical parameters. These data are shown in Table Obc-2. Cumulative frequency distributions were generated from the triangular distribution parameters and used to statistically model the resource parameters for Monte Carlo simulation.

The Monte Carlo simulation was achieved with the RISK program (Cowan, 1984). Each generated cumulative frequency distribution was divided into three classes with the midpoint of each class chosen as the expected minimum, most likely, and expected maximum values for the simulation. The probability of each class was the calculated frequency of the class from the cumulative frequency distribution. Because of the parameters chosen, the probability of the minimum Monte Carlo simulation value exceeded the probability of the most likely value of the acreage estimates skewing the estimates toward more conservative values. RISK generates a data set of resource estimates by selecting each of the three parameters at the given frequencies of occurrence. This data set is then analyzed for percentiles, means, and other statistics.

The undiscovered recoverable resource estimates for the play are probabilistic and range from 26.3 bcf at the 90 percent level of confidence to 279.3 bcf at the 10 percent level of confidence. That is, there is a 90 percent chance that undiscovered resources are at least 26.3 bcf. The estimated total weighted mean for undiscovered recoverable resources for the Lexington Limestone (Trenton) and Cincinnatian Series combined is 127 bcf (from Monte Carlo simulation).

Future Trends

Additional gas-bearing bioclastic reservoirs in the Middle and Upper Ordovician sequence will probably be discovered as lithofacies, structural, and seismic mapping of shoaling sequences improves. Localized structural highs along regional flexures may be a key to finding reservoirs, because the highs may control the location of winnowed bioclastic bars. In general, these reservoirs probably will not be the primary target for future drilling outside of southern and eastern Kentucky along the margin of the basin. Elsewhere, the reservoirs are relatively deep (for example, at drilling depths greater than 2,000 feet), and represent subtle stratigraphic features that will be difficult to detect with seismic or remote-sensing methods. However, as exploration and development continues for Lower Ordovician and Upper Cambrian carbonate reservoirs, these bioclastic carbonate bars will merit further evaluation. In addition, given sufficient reservoir seal, they may represent a potential for development as gas storage fields.

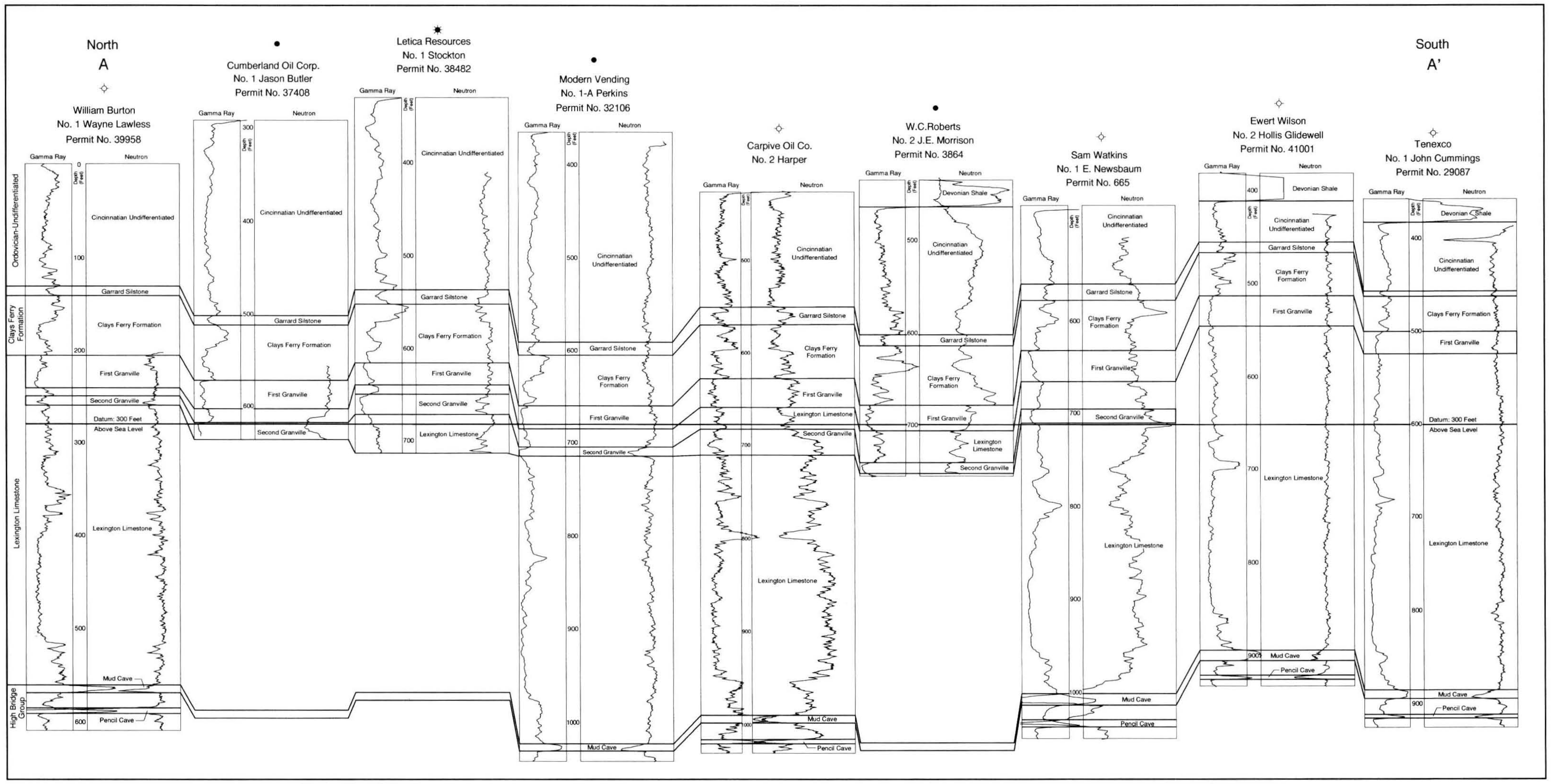


Figure Obc-10. North-south structural cross section A-A' of part of Clinton County, Kentucky, showing the distribution of Granville zone and hydrocarbon production. See Figure Obc-9 for location.

PLAY MOf: MIDDLE ORDOVICIAN FRACTURED CARBONATES

by Lawrence H. Wickstrom, Ohio Division of Geological Survey

Location

Porosity development along faults and fractures characterize the Middle Ordovician fractured carbonate play. Reservoirs of this play are found predominantly associated with large structural features. Fields of this play have been identified along the faulted northwestern and western margin of the Appalachian basin (particularly south-central Ontario, northwestern through central-eastern Ohio, north-central Tennessee, and central Kentucky), in eastern Kentucky within the Rome trough, and in western Virginia associated with the Pine Mountain fault system (Figures MOf-1, MOf-2).

A number of fields are located just west of the crest of the Cincinnati arch and, therefore, are not in the Appalachian basin proper. These include Albany Consolidated, Ashburn Creek South, Chicken Gizzard, Flat Creek, Ida Consolidated, and Mason Consolidated. These fields are included on the maps and in the discussion of this play for completeness; however, they were not included in the calculations for the resources and reserves.

Production History

The Appalachian basin has had a long history of oil and gas production from fractured Ordovician carbonate reservoirs. In 1829, the first gusher of record in North America, the "American Oil Well," was drilled in Cumberland County, Kentucky. This well, not intended to be an oil well, caught fire and flowed into the Cumberland River, setting the river on fire for several miles (Jillson, 1919a). Commercial production of gas from the Middle Ordovician Trenton Limestone began in 1884 in northwestern Ohio near the city of Findlay in Hancock County. The discovery well was drilled by the Findlay Natural Gas Company on the farm of Dr. Charles Oesterlin. The drilling of a well to the Trenton was encouraged by surface seepages of gas in the area. This discovery set off a major drilling boom in northwestern Ohio that spread to eastern Indiana and resulted in the successful giant Lima-Indiana trend (Wickstrom, Gray, and Stieglitz, 1992). This boom resulted in the drilling of an estimated 100,000 wells and production of approximately 485 million barrels of oil and more than 1 tcfg. Most of this giant field is not considered to be in the Appalachian basin, so will not be discussed at length in this volume (for more, see Keith and Wickstrom, 1992). However, the success which Findlay, Ohio, had in luring industry there with cheap fuel provided the impetus for many other discoveries to the east in the Appalachian basin.

From 1885 through the 1930s, exploratory drilling continued on the northwesternmost flank of the Appalachian basin, east of the Lima-Indiana trend. This era of drilling resulted in the discovery of 12 gas fields that produced from fractured Trenton and Black River limestones (some of which produced both oil and gas) in the Appalachian basin. Most of this production was intended for residential and small industrial use, and was distributed by small companies formed by local citizens. Because of this type of development, very few individual wells were gauged, nor was much of the end-use volume measured. Drillers produced as much as they could from the wells, depleting the pressure. Gas from the wells was piped directly to customers, who were charged by the month depending upon the type and number of devices using the gas (Bownocker, 1906). Therefore, gas production figures for these early fields are mostly nonexistent.

Beginning in August 1941 and continuing through the end of 1943, four gas wells were drilled on the "Concord Anticline" in Clinton County, Kentucky. The best producing of these wells, the No. 1 S.F. Stockton, completed in 1943, initially produced 3 MMcfg/d from the Sunnybrook (Lexington Limestone). These wells were subsequently shut-in with hope that a pipeline would be constructed to the area (Diamond, 1944). This hope was not fulfilled and these wells were eventually plugged.

The Rose Hill and Ben Hur fields of Lee County, Virginia, (Figure MOf-2) were discovered in 1942 and 1963, respectively. These fields produce from the Ordovician Trenton Limestone. Although these fields have produced mostly oil, there is associated gas in the wells that is often flared because of a lack of pipelines. The Stonewall Gas Co. No.1 Cope well in the Rose Hill field tested at 4,500 Mcfg/d (Miller and Fuller, 1954; Bartlett, 1988).

In September 1945, the No. 1 Luther Hay (Clinton County, Kentucky) began producing an estimated 3,000 to 4,000 barrels of oil per day and a considerable amount of gas out of a fractured zone within the High Bridge Group (Jillson, 1946). Although it caught fire, the success of this oil well set off a drilling boom that lasted several years in southern Kentucky and northern Tennessee, resulting in the discovery of several additional small pools that have subsequently been combined into the Concord Consolidated field (Figure MOf-2).

In the 1950s, gas production was established from two pools (Acton and Hornby) in Halton County, Ontario, Canada. A little over 500 MMcfg was produced from these pools before being abandoned in the early 1970s (Bailey Geological Services, Ltd. and Cochrane, 1984).

Beginning in the early 1960s, another drilling boom took place in north-central Ohio, spurred on by the discovery of oil in the Cambrian "Copper Ridge" dolomite in the Morrow Consolidated field (see M. Baranoski and others, Cambrian-Ordovician Knox Group unconformity play, this atlas). This drilling activity led to the discovery of three additional Trenton/Black River fracture-controlled fields and re-ignited interest in some of the older producing areas. The main emphasis during this period of drilling was on oil production; therefore, some gas-prone areas of Trenton/Black River production were ignored or downplayed.

In 1965, production was discovered from the Cambrian Rose Run Sandstone in Holmes County, Ohio. While drilling to the Rose Run and other Knox prospects, a number of discoveries within the lower Black River ("Gull River") and Wells Creek Formation occurred. These discoveries are typically small one-well pools, are commingled with Knox Dolomite production, and appear to be

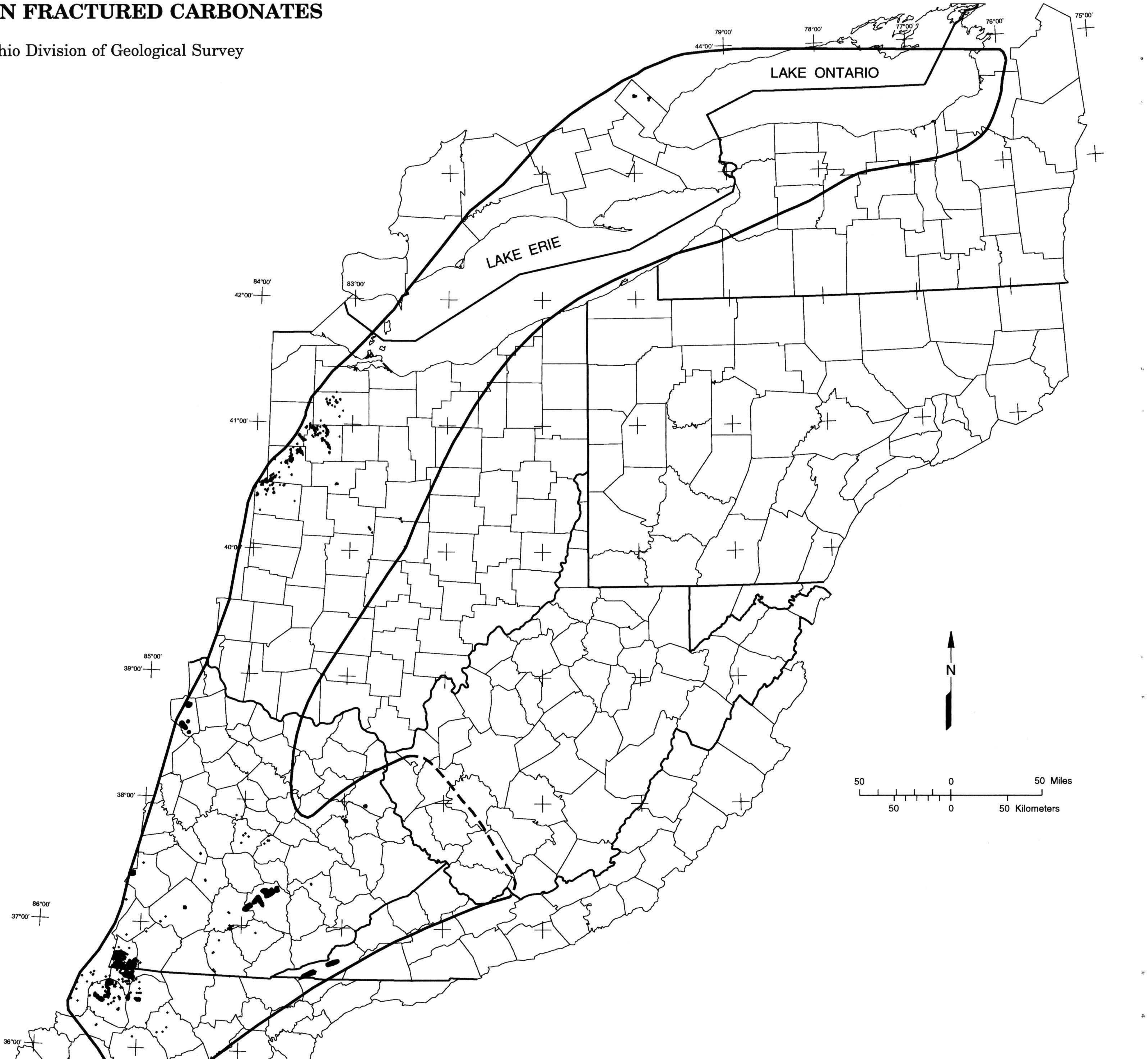


Figure MOf-1. Outline of the Middle Ordovician fractured carbonate play within the Appalachian basin. Dots represent individual wells; areas where dots have merged represent fields. Where dashed, play boundary is inferred.

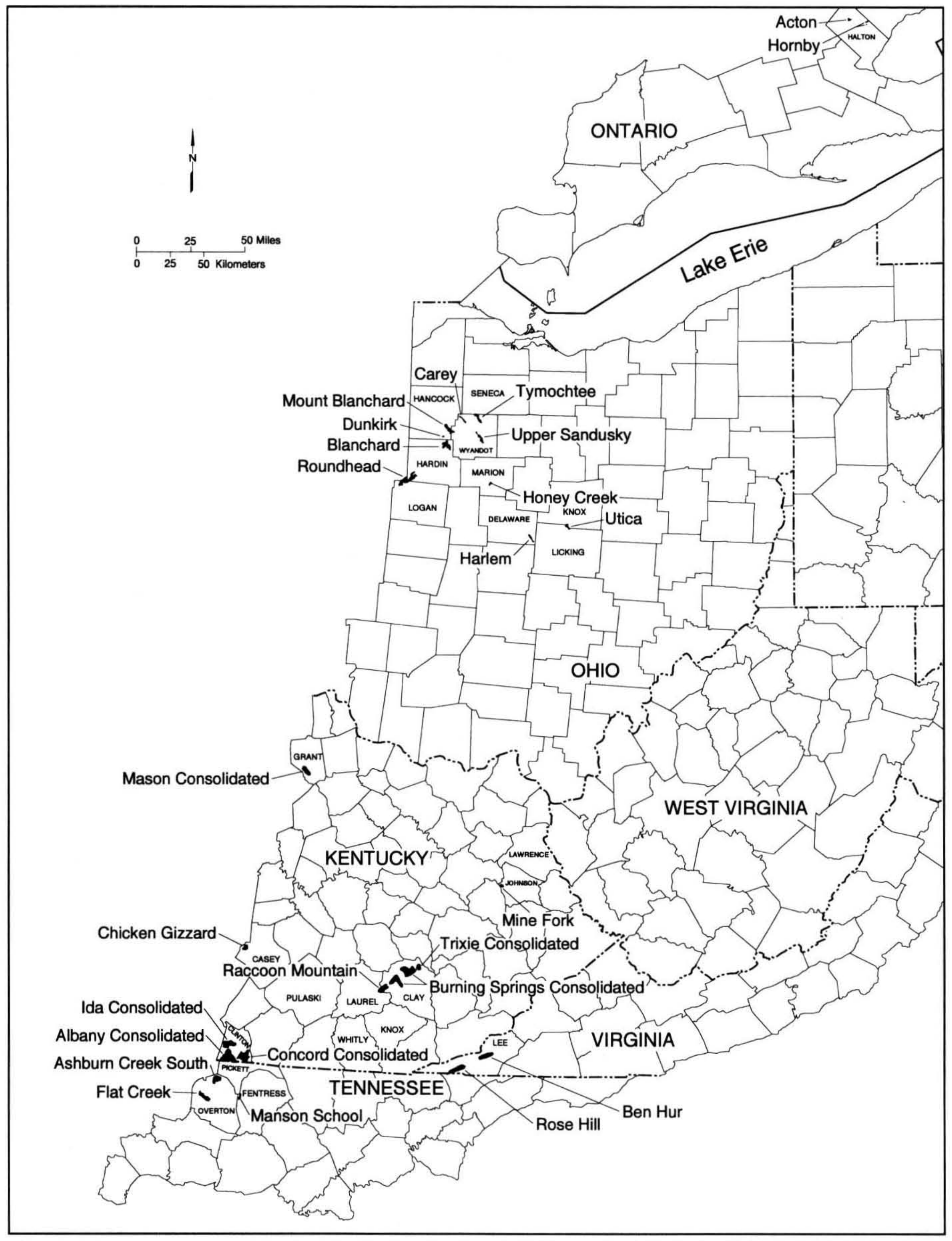


Figure MOf-2. Location of Middle Ordovician fractured carbonate fields mentioned in text or listed in Table MOf-1. Other areas of production illustrated in Figure MOf-1 are not shown.

located along similar fault structures that control the Knox Group production (see M. Baranoski and others, Cambrian-Ordovician Knox Group unconformity play, this atlas). Although there has been production found from this interval in a wide region, only one area to date, the Utica pool of Ohio, has a sufficient number of wells to be classified separately.

During the early to mid-1980s, when prices for both oil and gas were high, drilling activity returned once again to the Trenton/Black River fracture plays of northwestern Ohio. Although a number of prospects were drilled, no new field discoveries were found. However, the Harlem and Honey Creek fields (Figure MOf-2), both mid-1960s discoveries, were developed for their gas potential during this time.

In September 1990, another Ordovician fracture-system discovery occurred in Clinton County, Kentucky (Hamilton-Smith and others, 1990). This well, the Syndicated Options Limited of Austria, No. 9372, Ferguson Brothers, initially produced as much as 400 barrels of oil per hour and recently has begun producing only gas. The large production from this well has set off another drilling campaign in Clinton, Cumberland, and Wayne counties in southern Kentucky and Clay, Fentress, Overton, and Pickett counties in northern Tennessee that still continues. Despite these successes and a large amount of oil production from the area, a reliable market for the produced gas has never been developed. Most gas wells have been allowed to blow down for several days in the hopes that they would begin producing oil. A failure to produce oil resulted in their plugging. Gas produced along with oil is usually flared.

Reliable production figures for this play are generally lacking. However, available figures indicate a cumulative production from this play of at least 44 bcf. Using the analogous production figures from the Albion-Scipio field (Hurley and Budros, 1990) as discussed below yields a cumulative production total of about 120 bcf from this play.

Stratigraphy

The producing units comprising the Middle Ordovician fractured carbonates play are the Utica Shale/Point Pleasant interval, the Trenton Limestone, the Black River Group, and the Wells Creek Formation. Figure MOf-3 illustrates the generalized stratigraphy relevant to this play's discussion, from the Cambrian

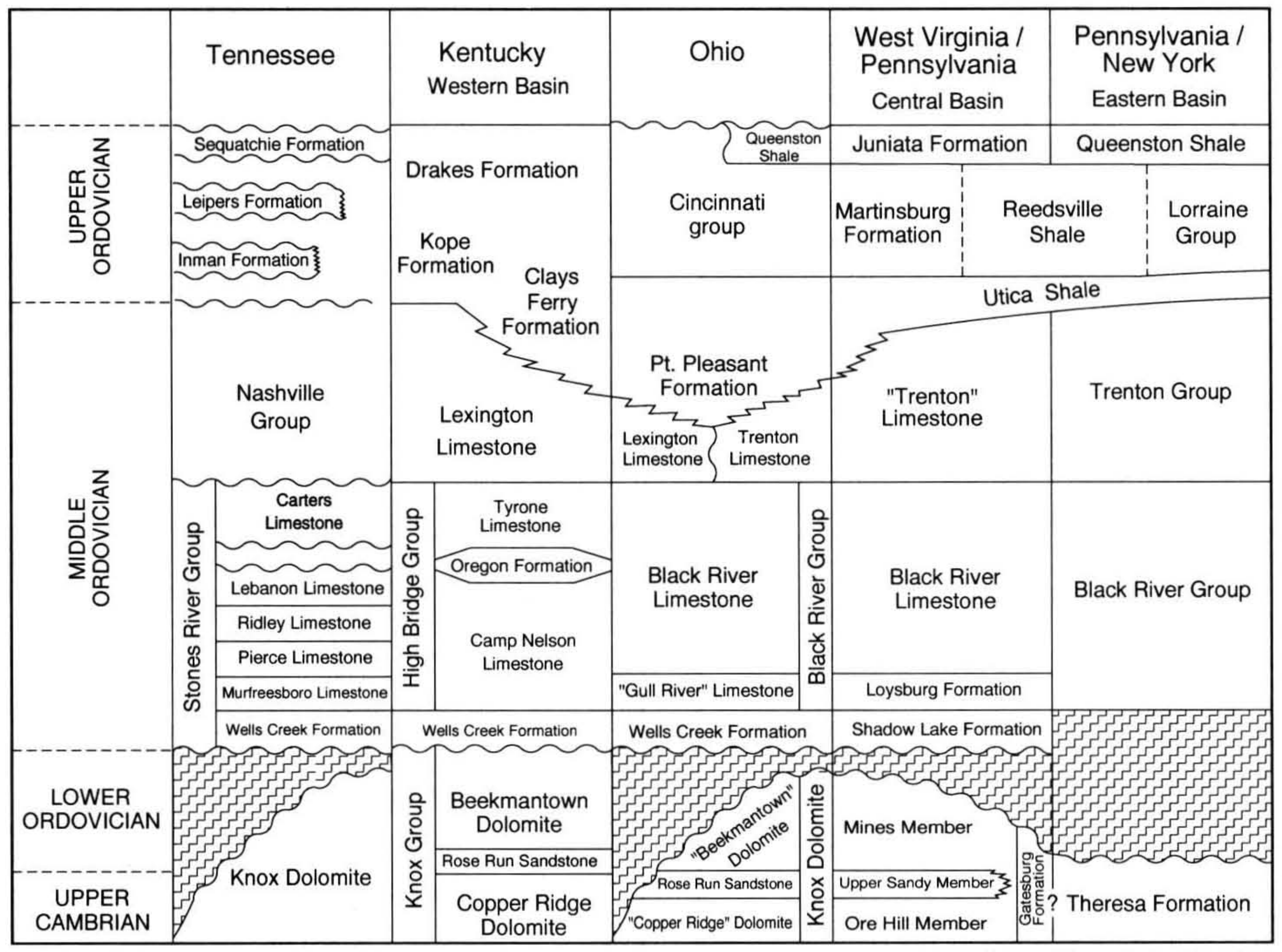


Figure MOf-3. Generalized stratigraphic correlation chart for Upper Cambrian through Upper Ordovician strata. Modified from Janssens (1973; 1977), Rickard (1973), Kentucky Geological Survey (1983), Shaver (1985), Ryder (1992a; 1992b), Wickstrom, Gray, and Stieglitz (1992), Bergstrom and Mitchell (1992), and Riley and others (1993).

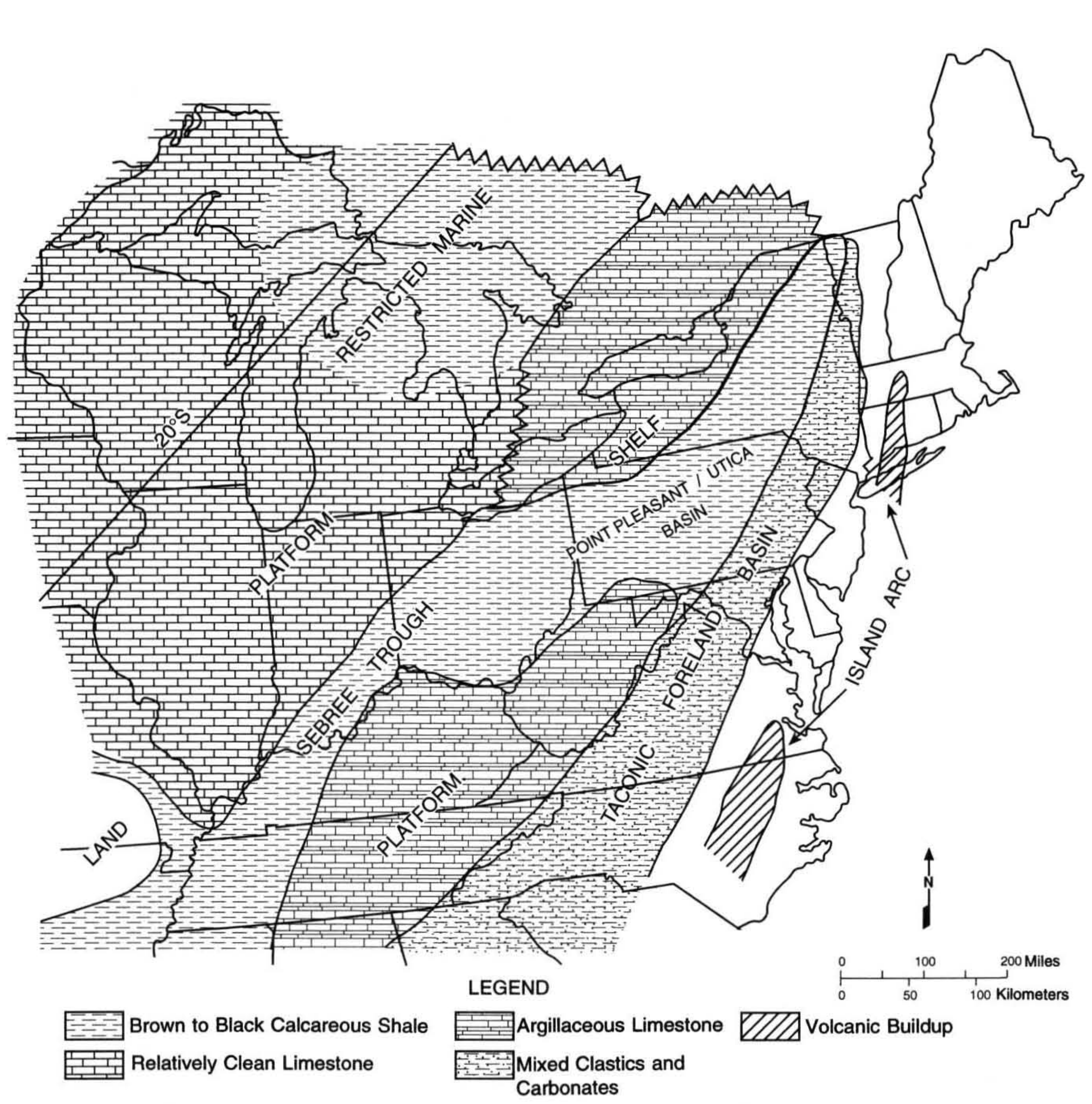


Figure MOf-5. Regional reconstruction of major depositional and tectonic elements present toward the end of Trenton depositional time. The eastern United States was undergoing a compressive pulse of the Taconic orogeny, causing differing water depths and amounts of terrigenous input across the region. Modified from Keith (1988) and Wickstrom, Gray, and Stieglitz (1992).

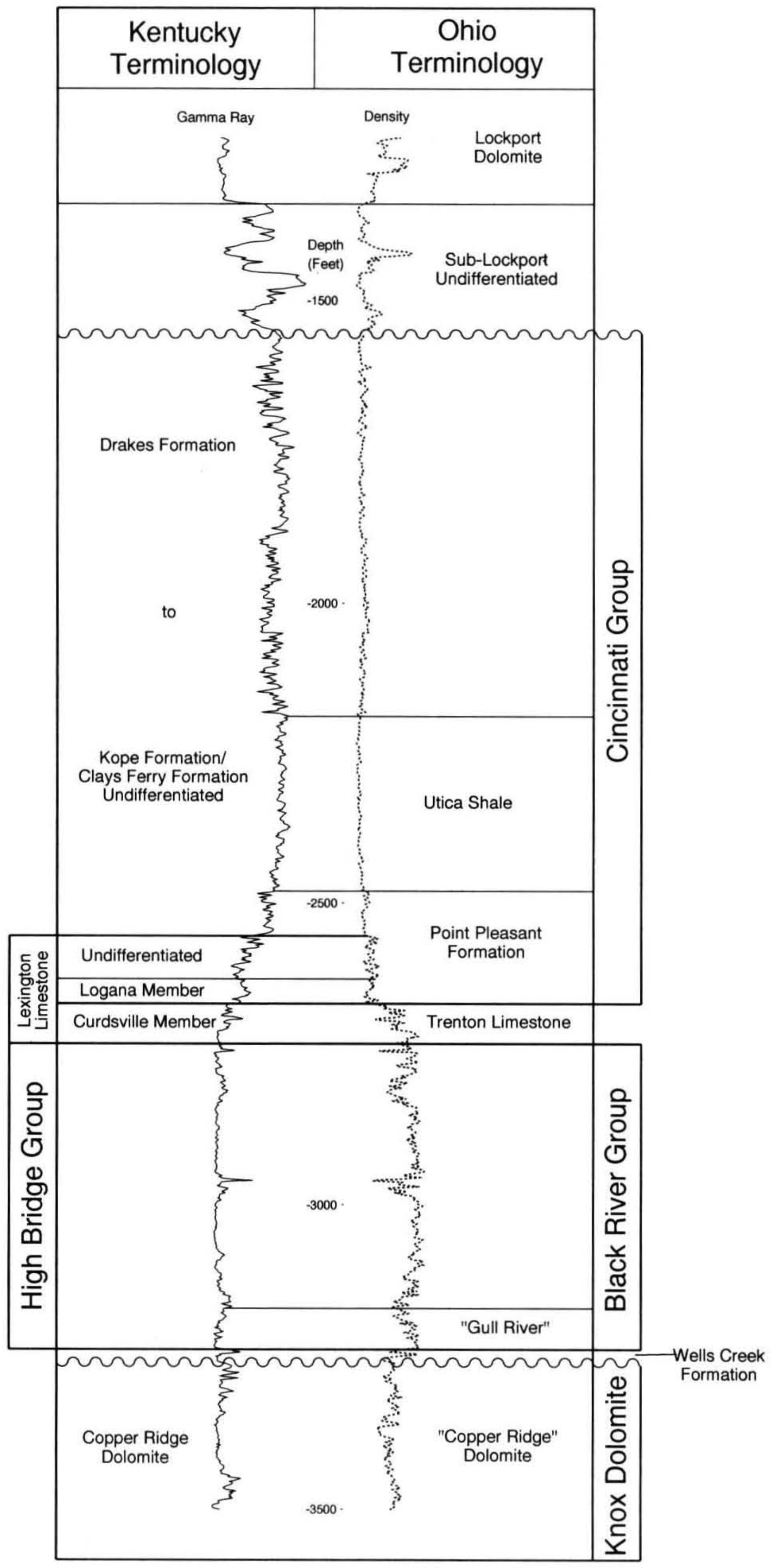


Figure MOf-4. Representative geophysical log curves from a well in Delaware County, Harlem Township, Ohio (permit number 251) illustrating Ohio stratigraphic terminology (right) versus Kentucky stratigraphic terminology (left). Stratigraphic nomenclature from Janssens (1973; 1977), Kentucky Geological Survey (1983), Wickstrom, Gray, and Stieglitz (1992), and Bergstrom and Mitchell (1992).

"Copper Ridge" dolomite through the Upper Ordovician Queenston Shale and their equivalent units across the Appalachian basin. For a more detailed review of the Cambrian and Ordovician stratigraphic framework of the Appalachian basin, refer to Ryder (1991; 1992a; 1992b) and Ryder, Harris, and Repetski (1992).

Overlying and intertonguing with the Utica/Point Pleasant units is a relatively thick sequence of interlayered gray to green calcareous shale, limestone, siltstone, and sandstone of the "Cincinnati" group and its equivalents (Figures MOf-3, MOf-4). This sequence is approximately 1,800 feet thick in central Pennsylvania and thins to about 900 feet on the northwest edge of the basin.

The Utica Shale consists of gray to black and brown shales, finely crystalline dark limestone, and locally, fossiliferous shale and limestone. The Utica represents a major transgression across the eastern United States, but the shales indicate a large influx of organic material, restricted circulation, and low-energy conditions (Bergstrom and Mitchell, 1992). Although the term Utica has been used basinwide for more than a hundred years, only recently have studies been undertaken to demonstrate lithologic and biostratigraphic equivalency of this unit regionally (Bergstrom and Mitchell, 1992; Ryder, 1991, 1992a, 1992b; Ryder, Harris, and Repetski, 1992).

The Utica Shale/Point Pleasant interval was deposited on top of the Trenton and thickens between the Trenton platform areas (Figure MOf-5) (Keith, 1988; Ryder, Harris, and Repetski, 1992; Wickstrom, Gray, and Stieglitz, 1992). The Utica Shale/Point Pleasant interval in northwestern Ohio, at the northwestern flank of the basin, thins to about 100 feet thick, whereas in parts of central Pennsylvania this interval reaches more than 700 feet in thickness (Wallace and Roen, 1989; Wickstrom, Gray, and Stieglitz, 1992). Considerable debate has taken

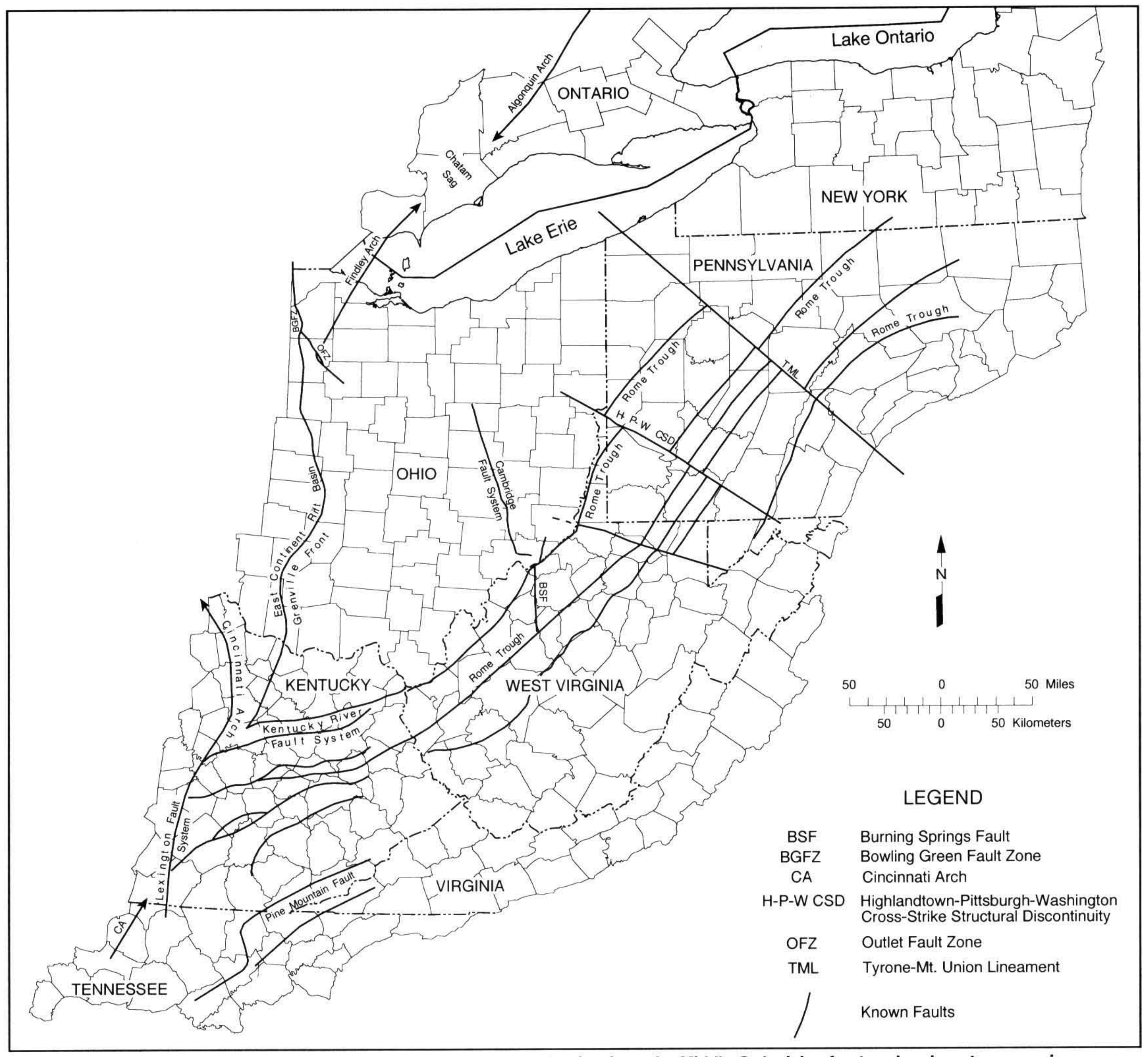


Figure MOf-6. Major structural features that may impact production from the Middle Ordovician fractured carbonate reservoirs.

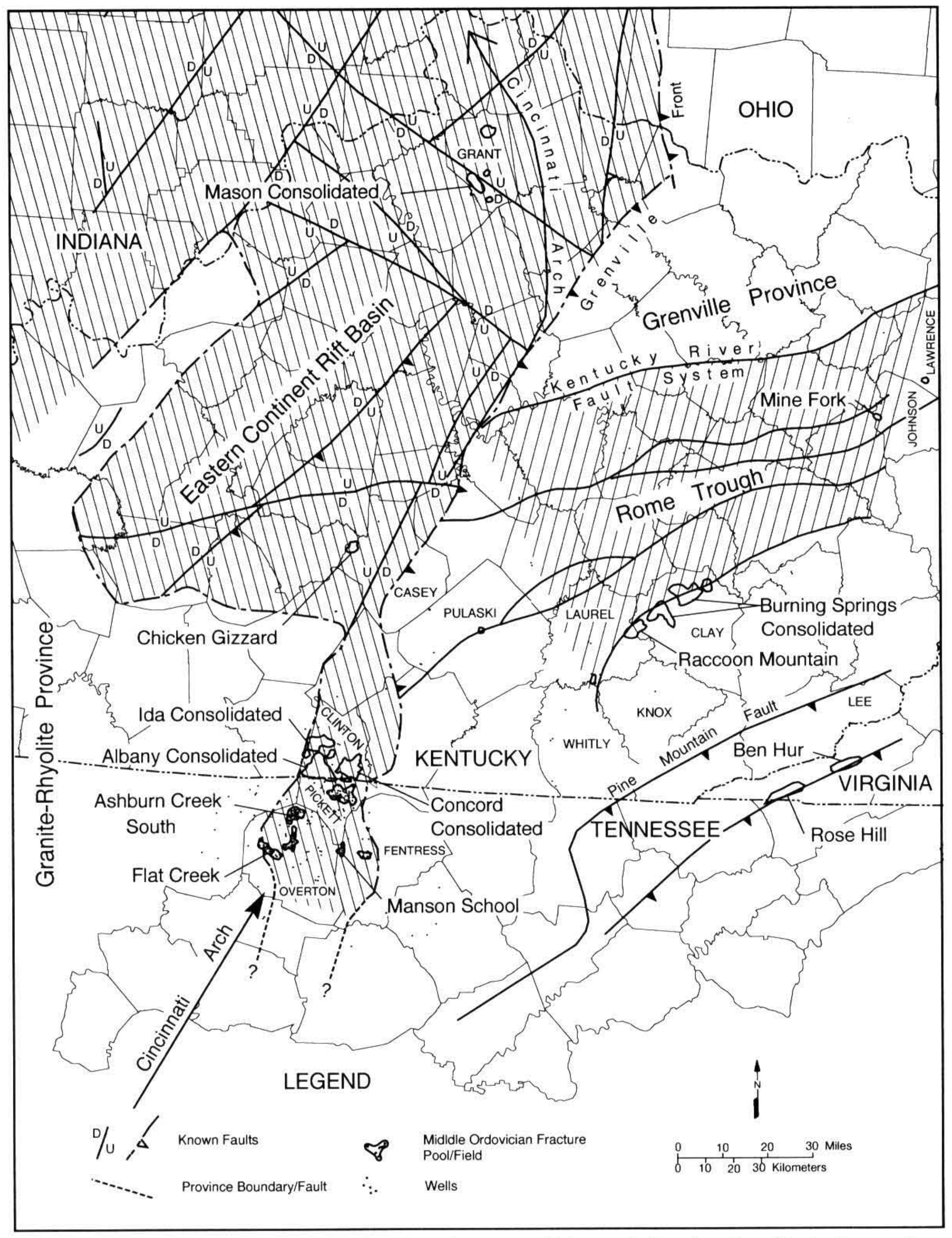


Figure MOf-7. Map of southeastern Indiana, southwestern Ohio, central and eastern Kentucky, western Virginia, and northern Tennessee illustrating the coincidence of location between the Middle Ordovician fractured carbonate fields and mapped faults. Locations of structural features and fault locations are from Drahovzal and others (1992).

place as to whether or not an unconformity exists at the top of the Trenton (see Keith and Wickstrom, 1993), although most modern researchers, including Wickstrom, Gray, and Stielglitz (1992) and Fara and Keith (1989), conclude that the surface is a minor disconformity. Recently, Bergstrom and Mitchell (1992), based on conodont biostratigraphy, have stated that this contact represents a gap corresponding to lower Edenian and possibly upper Mohawkian time, and it represents a period of very slow, or interrupted, deposition in a submarine environment.

The Trenton Limestone overlies the Black River Group within the entire basin. Generally the Trenton consists of light-brown to dark-gray bioclastic to argillaceous micritic limestone with common shale partings and well-defined metabentonite intervals. The thickness of the Trenton Limestone ranges from 220 feet on the northwestern flank of the basin, to less than 40 feet in central Ohio, to 800 feet in north-central New York (Rickard, 1973; Wickstrom, Gray, and Stieglitz, 1992). The Lexington Limestone, a facies equivalent of the Trenton in central Kentucky, outcrops around the Lexington area. The limestone is fossiliferous and phosphatic. The thickness of the limestone ranges from a minimum of 180 feet in the north to a maximum in excess of 320 feet in the north-central part of the state (Cressman, 1973).

The Black River Group is composed mainly of light brown to gray micritic to finely crystalline limestone. Its thickness ranges from approximately 1,100 feet in the Rome trough to about 100 feet on the eastern side of the basin and about 500 feet on the west (Ryder, Harris, and Repetski, 1992; Wickstrom, Gray, and Stieglitz, 1992). The Black River rocks are equivalent to the High Bridge Group of Kentucky usage and are included in the Stones River Group as used in Tennessee (Figure MOf-3).

At the base of the Black River Group is a relatively clean micritic limestone interval bounded below by the Wells Creek Formation and above by an argillaceous zone in the lower Black River (Figure MOf-4). This interval has been called the "Gull River" limestone by Ohio drillers. The name "Gull River" was originally used in Ontario for a unit stratigraphically higher in the Black River Group and has been erroneously applied by drillers to a lower unit at the base of the Black River in Ohio. Currently, use of the term is very prevalent, and production from this interval, primarily from dolomitized zones, continues to be discovered; therefore, the term is used in this discussion.

The Wells Creek Formation varies in composition across the basin and includes waxy, dolomitic, pyritic green shales; argillaceous limestones and dolomites; minor dark shales; and small amounts of sandstone and siltstone. The thickness of the Wells Creek Formation is highly variable because of the relief on the Knox unconformity. Regionally, the Wells Creek ranges in thickness from 0 to 150 feet, thickening to the east. Where the Wells Creek is absent, the Black River Group rests directly on the Knox unconformity or on the Beekmantown Group farther to the east (Ryder, 1992a; Wickstrom, Gray, and Stieglitz, 1992). The Wells Creek is equivalent to the Shadow Lake Formation of western Pennsylvania.

The age relationships between the Utica/Point Pleasant interval and the Trenton Limestone are not fully understood at this time. However, it appears likely that a partial time equivalence exists between the upper Trenton and the lower Point Pleasant units. Using conodont and graptolite biostratigraphy, Bergstrom and Mitchell (1992) have shown a late Middle Ordovician through mid-Late Ordovician age (Maysvillian through Shermanian) for the Utica/Point Pleasant interval. A Middle Ordovician age is assigned to the Trenton Limestone through Wells Creek Formation (Shermanian through Middle Chazyan). Ryder, Harris, and Repetski (1992) presented a thorough synopsis of the faunal work used to establish the Trenton through Wells Creek ages.

The Utica Shale and "Point Pleasant" formation represent a deeper basin, inter-platform, restricted-circulation, anoxic depositional environment (Figure MOf-5). Deposition of these units probably began contemporaneously with the Trenton carbonate buildups in response to compression from the Taconic orogeny, which altered the basin shape and water depths (Wickstrom, Gray, and Stieglitz, 1992). Deposition of these units ceased with complete inundation of the region by deeper water and more normal, open-marine conditions represented by the "Cincinnati" group.

The Trenton was deposited in a wide range of depositional environments across the Appalachian basin because of its contemporaneity with a compressional pulse of the Taconic orogeny. The Trenton was deposited in a clastic-rich shelf environment to the east, a relatively argillaceous platform to the southwest, and a cleaner carbonate platform to the northwest (Figure MOf-5) (Keith, 1988; Wickstrom, Gray, and Stieglitz, 1992). Therefore, thicker accumulations of the Trenton are found on the shelf and platform areas.

The Black River was deposited in shallow epeiric seas in environments ranging from shallow subtidal to tidal flat (Cressman and Noger, 1976; Stith, 1979). The Wells Creek represents a brief interval of mixed clastic and carbonate sedimentation deposited as shallow seas once again covered the previously emergent Knox unconformity surface. The contact between the Wells Creek and the overlying Black River is generally fairly sharp.

Structure

Figure MOf-6 illustrates some of the major structural features affecting the Appalachian basin. Those of prime importance to this play include the Grenville front, East Continent Rift Basin, Rome trough, Bowling Green fault zone, Findlay arch, Cincinnati arch, Lexington fault system, and the Pine Mountain fault.

Much of the fracturing associated with the Middle Ordovician carbonate reservoirs is thought to be due to reactivation of deeper structures (Wickstrom, Drahovzal, and Keith, 1992; Wickstrom, Gray, and Stieglitz, 1992). The exceptions to this are the Rose Hill and Ben Hur fields of Virginia. These fields are located on the folded and fractured upper and lower plates of the Pine Mountain overthrust fault, which is a result of thin skinned tectonics (Bartlett, 1988).

Much of western Ohio and central Kentucky are underlain by a portion of the East Continent Rift Basin, a Proterozoic extensional feature (Drahovzal and others, 1992) (Figure MOf-5). Compression associated with the Grenville orogeny further faulted and folded the East Continent Rift Basin rocks. The Grenville front, the suture between the Grenville province and the East Continent Rift Basin, is a major zone of crustal weakness that has been repeatedly reactivated. Both the Bowling Green fault zone of northwest Ohio and the Lexington fault system of central Kentucky are thought to lie along the Grenville front. The positions of the Cincinnati arch and the Jessamine dome are coincident with the axis of the thickest deposits within the East Continent Rift Basin (over 20,000 feet). This relationship has led to speculation that this extra thickness of the crust was responsible for this area remaining largely unaffected by the later subsidence events in the adjoining Appalachian and Illinois basins (Wickstrom, Drahovzal, and Keith, 1992). East of the Grenville front, Beardsley and Cable (1983) have characterized the Grenville strata as large, thrusted accretionary wedges, emplaced as a result of continental collision.

The locations of many of the fractured reservoirs of central Kentucky and Tennessee are coincident with subsurface features associated with the East Continent Rift Basin and Grenville front. For example, the Flat Creek, Ida Consolidated, and Concord Consolidated fields overlie a portion of the East Continent Rift Basin where it narrows between blocks of the Granite-Rhyolite Province to the west and the Grenville Province to the east (Figure MOf-7). Farther north in central Kentucky, a number of fractured carbonate fields, including Mason Consolidated and Chicken Gizzard, again overlie the East Continent Rift Basin within areas of expected faulting within the rift assemblage. This coincidence of location leads to speculation that the increased density of fractures in these Paleozoic carbonate fields may be due to reactivation of deeper fault systems in the East Continent Rift Basin.

The Rome trough is a large Cambrian extensional feature extending from central Kentucky through West Virginia and Pennsylvania (McGuire and Howell, 1963; Harris, 1978). The Ordovician fractured carbonate fields of eastern Kentucky—Raccoon Mountain, Burning Springs Consolidated, and Mine Fork—lie along mapped faults associated with the Rome trough (Figure MOf-7). This relationship suggests another example of reactivation of older structures.

In northwestern and central Ohio, Wickstrom, Gray, and Stieglitz (1992) proposed a number of northwest-oriented wrench faults that were activated under compressional forces related to the Taconic orogeny; they have also shown a set of northeast-trending fault zones that are postulated to have been extensional in nature in the Cambrian and reactivated by the same compressional forces of the Taconic in the mid to late Ordovician. These fault systems are situated on or near the East Continent Rift Basin and Grenville front. It is along these mapped fault trends that a number of the fracture-controlled fields of this play are located (Figure MOf-8). The Upper Sandusky, Carey, and Roundhead fields (Figure MOf-8) are examples of such structure-related reservoirs.

Reservoir

The primary trap type within this play consists of porosity zones along faults and fractures. It appears that three types of reservoir have been developed in these carbonate fracture systems in the Appalachian basin.

The first type of porosity development/enhancement is a result of secondary mineralization (primarily dolomitization) caused by circulating fluids along faults and fracture systems. The Trenton Limestone-upper Black River Group fields in northwest to central Ohio and south-central Ontario (Figures MOf-1, MOf-2) are prime examples of this reservoir type and represent the most prolific gas production from this play to date. In large fault systems with appreciable gouge zones, the fluid interaction with the gouge resulted in considerable amounts of vugular porosity and thick zones of mineralization. In smaller fault systems with less volume of fluid movement, or farther from the central area of large fault systems, the mineralization and porosity enhancement are less extensive and may result in good intercrystalline porosity development (Wickstrom, Gray, and Stieglitz, 1992). In some cases, later mineralization may have proceeded so far as to seal off multiple pay zones within a single fault system.

In reservoirs of this type, it is not uncommon to find that secondary dolomite has partially to entirely replaced the original limestone, and baroque dolomite crystals typically line vug openings. Gregg and Sibley (1984) attribute this type of dolomite to epigenetic fluid migration. Haefner and others (1988), working with cores from the Carey and Upper Sandusky pool areas of Wyandot County, Ohio, concluded that the mineralization fluids were warm, gravity-driven brines from deeper in the basin.

The second type of reservoir within this play consists of open, largely unmineralized fractures in the Knox Dolomite through Trenton Limestone. In the central Kentucky and Tennessee reservoirs, Hamilton-Smith and others (1990) assume the production is related to open fracture systems, although they acknowledge a possibility of minor enhancement by secondary mineralization. Reactivation of deep-seated faults is thought to be responsible for opening these fracture systems.

The third type is found in scattered wells in Ohio that produce from fractured portions of the lower Black River Group ("Gull River") and the Wells Creek Formation. Secondary dolomitization is prevalent in these reservoirs. The dolomitization fluids probably travelled into these zones from the underlying Cambrian fracture systems and/or along the Knox unconformity.

The vertical seal for all reservoirs of this play is generally the overlying Utica Shale or its equivalent. Horizontally, the trap is provided by tight dolomite or unaltered limestone. Where displacements are sufficient along faults, the overlying shale may provide both vertical and horizontal seals on upthrown blocks.

The primary source rocks for the hydrocarbons in the Ordovician carbonates in the northern portion of the basin is thought to be the overlying dark gray to black Utica Shale and "Point Pleasant" formation (Cole and others, 1987; Wallace and Roen, 1989; Ryder and others, 1991). On the basis of estimates of thermal maturity, the most prolific generating areas were probably in deeper portions of the basin, along the Ohio/West Virginia/Pennsylvania border continuing toward central Pennsylvania. Peak generation of hydrocarbons from this source interval is thought to have occurred during Pennsylvanian to Permian time when much thicker strata provided higher burial temperatures (Cole and others, 1987).

Analyses of oils and potential source intervals from Kentucky indicate that the Devonian black shales have provided the hydrocarbons for the Ordovician reservoirs of southern Kentucky, northern Tennessee, and probably the western Virginia pools (J. A. Drahovzal, written commun., 1994). For both the north and south areas, migration from the deeper portions of the basin was pressure driven and probably occurred by way of interformational flow, faults and fractures, and unconformities.

Depth and pressure of the reservoirs vary widely across the basin (Table MOf-1). In general, the depth to the top of the Middle Ordovician carbonate reservoirs ranges from 100 feet in Tennessee to 4,518 feet in eastern Kentucky with an overall average of 1,258 feet. As with production records, it is difficult to obtain reliable measurements of reservoir pressures and flow rates from the fields of this play. The available data indicate that pressures in this play range from 90 psi at 395 feet to 1,450 psi at 4,518 feet with an average pressure of 365 psi. Most of the fields of this play are underpressured.

Recorded initial open flow values range from 2 Mcf/d to 2,063 Mcf/d with an average of 465 Mcf/d. Final open flow values range from 5 Mcf/d to 4,795 Mcf/d with an average of 368 Mcf/d. Judging from written accounts of early wells, many probably had higher initial production but were not gauged or reported. It should also be noted that it was common practice in the older fields to use nitroglycerine charges for stimulation of wells; while this usually increased, or started, production of oil, the records indicate that it commonly decreased gas production.

Heterogeneity within the reservoirs of this play is a result of two main factors: a dual porosity system may be present, consisting of macrovugs or open fracture cavities and intercrystalline porosity (Keith and Wickstrom, 1992); and pay zones may be very discontinuous both horizontally and vertically because of the nature of porosity development/enhancement and secondary mineralization by circulating brines along fracture systems. Single or multiple pay zones may develop within a reservoir system. The individual pay zones may or may not be well connected to others (Keith and Wickstrom, 1992)

The dominant drive mechanism in the northern fields of this play is solution gas (Table MOf-1). Water encroachment is also more common in the north, indicating a possible contribution from a water-drive system. The fields of central Kentucky and northern Tennessee appear to be dominated by a gas drive system, with some instances of water encroachment reported.

Completion strategies vary widely across the basin and with time. Most of the older wells were completed open hole and were stimulated by shooting with liquid nitroglycerin. The amount of nitroglycerin used differed by operator, from as little as 30 quarts to as much as 400 quarts. In modern wells, both open hole and perforations through casing have been used with success. Likewise, many different types of stimulation treatments have been tried on these carbonate

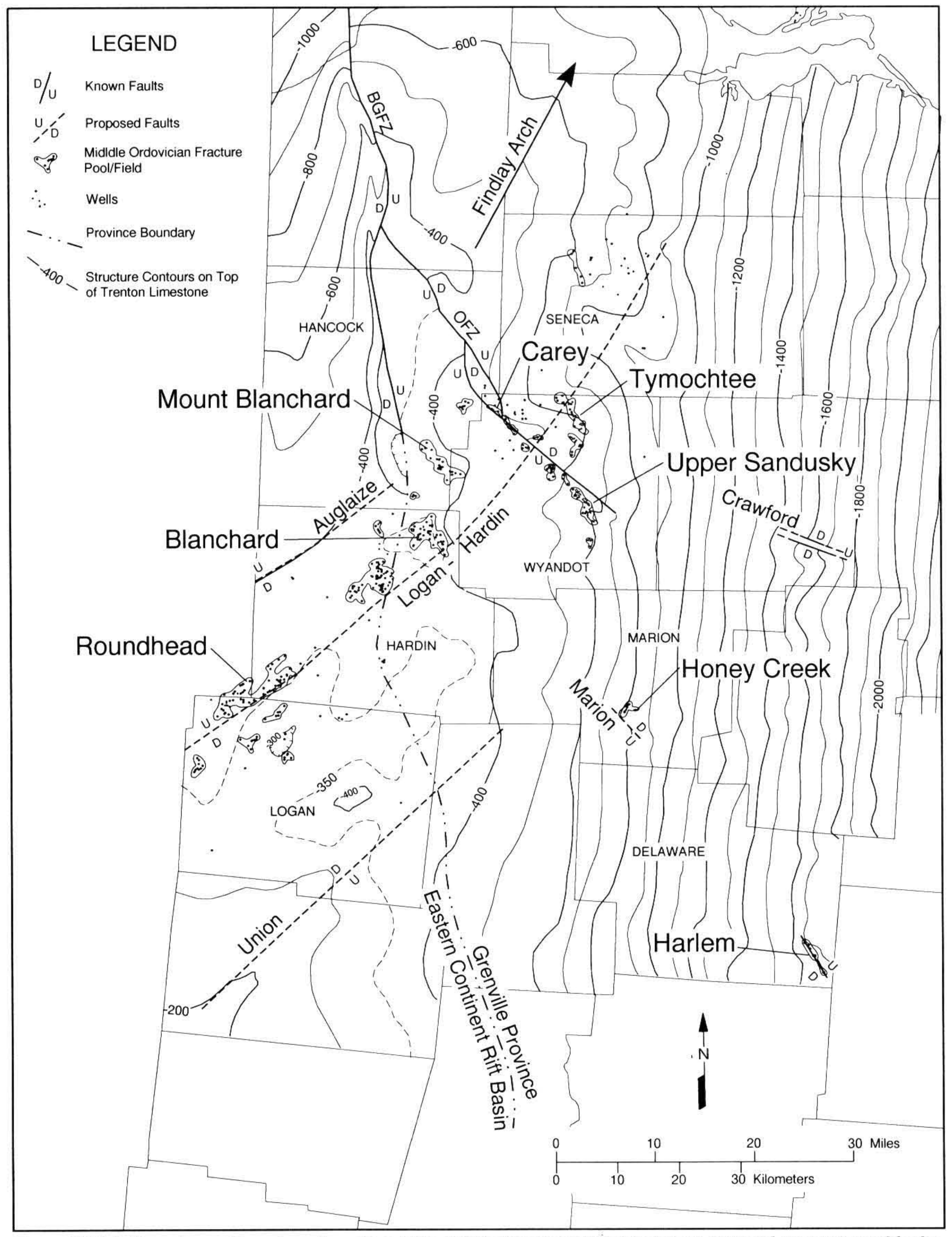


Figure MOf-8. Map of a portion of northwestern Ohio illustrating the relation between mapped structure and faults with the location of Middle Ordovician fractured carbonate gas reservoirs. See Figure MOf-2 for location. Structure contours drawn on top of the Trenton Limestone. Contour interval = 100 feet; where dashed, contour interval = 50 feet. Structure contours and faults are from Wickstrom, Gray, and Stieglitz (1992). Grenville province boundary is from Drahovzal and others (1992).

rocks, including warm acid treatments, acid fracs (with and without nitrogen assists), foam fracs, water with sand proppant, and oil fracs. Schrider and others (1984) published the results of an evaluation program run to test various completion and production practices within the Trenton of northwest Ohio and, in general, found that non-water-based stimulants provide the best results because of less swelling of clays and fewer fines released.

A number of reservoir irregularities have been noted locally within this play. High paraffin content of oils (which may block reservoir pore throats during degassing) appears to be more common in the deeper reservoirs of the play. Sour gas is found in the Honey Creek field and probably occurred in some of the older fields, but records are incomplete. High amounts of mobile fines that may further block pore spaces are also encountered throughout the play and are most notable where the reservoir rock is more argillaceous.

	TABLE MOf-1	Blanchard OH	Carey OH	Dunkirk OH	Harlem OH	Honey Creek OH	Mt. Blanchard OH	Roundhead OH	Tymochtec OH	Upper Sandusky OH	Burning Springs Consolidated KY	Concord Consolidated KY	Mine Fork KY	Raccoon Mountain KY	Trixie Consolidated KY	Manson School TN	Ben Hur VA	Rose Hill VA	Acton Ontario, Canada	Hornby Ontario, Canada
BASIC RESERVOIR DATA	POOL NUMBER	3406500802	3417500777	3406500801	3404100968	3410100976	3406500800	3406500805	3417500778	3417500776	1600320365	1600459365	1601319368	1601600368	1602002368	4104900163				
	DISCOVERED	1885	1880	1888	1964	1964	1886	1922	1890	1889	1966	1941	1984	1955	1983	1979	1963	1942	1954	1959
	DEPTH TO TOP RESERVOIR	1,320	1,216	1,225	2,808	1,710	1,295	1,366	1,339	1,328	2,000	447	4,518	2,720	2,634	500	1,600	1,100	280	1,532
	AGE OF RESERVOIR	Middle Ordovician	Middle Ordovician	Middle Ordovician	Middle Ordovician	Middle Ordovician	Middle Ordovician	Middle Ordovician	Middle Ordovician	Middle Ordovician	Middle Ordovician	Middle Ordovician	Middle Ordovician	Middle Ordovician	Middle Ordovician	Middle Ordovician	Middle Ordovician	Middle Ordovician	Middle Ordovician	Middle Ordovician
	FORMATION	Trenton	Trenton	Trenton	Trenton	Trenton	Trenton	Trenton	Trenton	Trenton	Trenton	Trenton	Knox	Knox	Trenton	Nashville	Trenton	Trenton	Black River	Black River
	PRODUCING RESERVOIR	Trenton	Trenton	Trenton	Trenton	Trenton	Trenton	Trenton	Trenton	Trenton	Trenton	Trenton	Knox/ Stones River	Knox/ Stones River	Knox/ Stones River	Trenton	Trenton	Trenton	Trenton	Trenton
	LITHOLOGY	dolomite	dolomite	dolomite	dolomite	dolomite	dolomite	dolomite	dolomite	dolomite	dolomite	limestone	limestone	limestone	limestone	limestone	limestone	limestone	limestone	limestone
	TRAP TYPE	fractured	fractured	fractured	fractured	fractured	fractured	fractured	fractured	fractured	fractured	structural	structural	structural	structural	fractured	structural	structural	structural	structural
	DEPOSITIONAL ENVIRONMENT	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	Ds	Ds
	DISCOVERY WELL IP (Mcf)		1,500		4,435	1,500				1,889				488	90	45		211	100	2
	DRIVE MECHANISM	solution gas	solution gas	solution gas	solution gas	solution gas	solution gas	solution gas	solution gas	solution gas	gas	gas	gas	gas	gas	gas				
	NO. PRODUCING WELLS	0	0	0	0	0	0	0	0	0	8	19	2	2	3	7		1	15	3
	NO. ABANDONED WELLS	70	63	43	13	7	> 25	79	50	51	2	6	0	0		0			15	3
	AREA (acreage)										1,750	3,850	350	245	4,200					
	OLDEST FORMATION PENETRATED	Trempealeau	solution gas	Trenton	Knox	Kerbel	Knox	Trempealeau	Trempealeau	Black River	Knox	Knox	Rome	Knox	Knox	Knox		Black River	Precambrian	Precambrian
	EXPECTED HETEROGENEITY DUE TO:	fractures	fractures	fractures	fractures	fractures	fractures	fractures	fractures	fractures	fractures	fractures	fractures	fractures	fractures	fractures	fractures diagenesis	fractures diagenesis	fractures	fractures
RESERVOIR PARAMETERS	AVERAGE PAY THICKNESS (ft.)	10	12	2	25	16	25	15	7	16	20	6	32	17	19					
	AVERAGE COMPLETION THICKNESS (ft.)																			
	AVERAGE POROSITY--LOG (%)					10					9	4	7	9	8					
	MINIMUM POROSITY--LOG (%)					10					4	1	1	4	2					
	MAXIMUM POROSITY--LOG (%)					19					20	7	16	15	17					
	NO. DATA POINTS	0	0	0	0	8	0	0	0	0	5	7	4	6	22	0			0	0
	POROSITY FEET																			
	RESERVOIR TEMPERATURE (°F)				94	70					82	73		83					82	62
	INITIAL RESERVOIR PRESSURE (psi)	315	420	460	985	550	452	331	400	350	750		1,450	800	125	185			415	2,586
	PRODUCING INTERVAL DEPTHS (ft.)	1,320-1,423	1,276-1,443	1,225-1,367	2,808-2,976	1,710-1,820	1,295-1,436	1,366-1,430	1,339-1,572	1,328-1,482	2,000-3,645	447-1,510	4,518-4,642	2,720-3,558	2,634-3,875	500-700		1,100-2,150	280-374	1,532-1,615
	PRESENT RESERVOIR PRESSURE (psi) / DATE	61/1947				515/1985	29/1952	185/1955			350/1987		235/1986	245/1991	600/1991				94/1973	
FLUID & GAS PROPERTIES	Rw (Ωm)												0.06	0.06	0.06					
	GAS GRAVITY (g/cc)													0.068	0.656					0.628
	GAS SATURATION (%)					70					80		56	74	62					
	WATER SATURATION (%)					30					20		44	26	38					
	COMMINGLED	no	no	no	yes	no	no	no	no	no	no	no	yes	yes	yes	no			no	no
	ASSOCIATED OR NONASSOCIATED	associated	associated	nonassociated	nonassociated	associated	nonassociated	associated	associated	associated	associated	nonassociated	nonassociated	associated	associated				nonassociated	nonassociated
	Btu/scf													1,076	1,118				1,046	1,336
VOLUMETRIC DATA	STATUS (producing, abandoned, storage)	abandoned	abandoned	abandoned	abandoned	abandoned	abandoned	abandoned	abandoned	abandoned	producing	producing	producing	producing	producing				abandoned	abandoned
	ORIGINAL GAS IN PLACE (Mcf)	8,074,000	6,190,000	4,225,000	2,668,000	1,250,000	1,522,000	3,717,000	4,913,000	5,011,000	2,400,000	550,000	300,000	540,000	590,000					115,000
	ORIGINAL GAS RESERVES (Mcf)	6,460,000	4,950,000	3,380,000	2,135,000	1,000,000	1,217,518	2,974,000	39,300,000	4,001,000	2,000,000	480,000	230,000	440,000	490,000					92,000
	PRODUCTION YEARS	1885-	1880-1957	1888-1951	1964-1993	1964-1992	1886-1952	1922-	1980-	1889-		1941-	1984-present	1955-	1984-1991				1954-1973	1959-1972
	REPORTED CUMULATIVE PRODUCTION (Mcf)	184,559			2,029,000	500,000	194,803	225,834							454,000				490	
	NO. WELLS REPORTED	2	0	0	11	5	4	6	0	0	0	0	0	0		0			15	
	ESTIMATED CUMULATIVE PRODUCTION (Mcf)	6,460,000	4,950,000	3,380,000	2,135,000	1,000,000	1,217,518	2,974,000	3,930,000	4,001,000										
	REMAINING GAS IN PLACE (Mcf)/DATE	1,615,000	1,240,000	845,000	533,000	750,000	304,000	743,000	983,000	1,010,000										
	REMAINING GAS RESERVES (Mcf)/DATE	0	0	0	0	0	0	0	0	0										
	RECOVERY FACTOR (%)	80	80	80	80	80	80	80	80	80	90	90	90	90	90	80				
	INITIAL OPEN FLOW (Mcfd)	124	177	700		2,063		272	190	840						32				
	FINAL OPEN FLOW (Mcfd)	247	370		612	582	379	904	157	728	138	29	364	207	848					

Description of Key Field

Harlem gas field: The Harlem gas field, located in Harlem Township, Delaware County, Ohio (Figures MOf-2, MOf-9), provides an opportunity for detailed examination because it was developed relatively recently and is fairly typical of the fractured carbonate reservoirs. Hydrocarbons have been produced from the Trenton Limestone, Black River Group, and the "Copper Ridge" dolomite in this field, although the "Copper Ridge" production could not be sustained. The discovery well, the Federal Oil and Gas, No. 1 Jenobel Fronk (Ohio county permit number, Delaware 146), was drilled in 1964 in search of additional "Copper Ridge" production to extend the boom from neighboring Morrow County. During drilling, a fault zone was encountered in the well at the approximate position of the Trenton Limestone. Drilling continued to a depth of 3,609 feet in the "Copper Ridge." After acidizing the "Copper Ridge" without result, a plug was set and the "Trenton" zone was tested (the actual Trenton interval is missing in this well). This zone produced 795 Mcfg natural with a pressure of 985 psi on a 12-hour test. After treatment with 5,000 gallons of acid, the well flowed at a rate of 4,435 Mcfg/d on a five-hour test. Other companies unsuccessfully attempted to offset this success over the next couple of years and finally abandoned the area. The Fronk well was sold to the landowner because a pipeline to the township could not be justified for one well. Reportedly, the landowner used this well to start his own mini-utility and sold the gas to surrounding farms.

In the early 1980s, Industrial Natural Gas Company (ING) began evaluating this area, baited by the success of the Fronk well. After acquiring and analyzing both seismic and detailed aeromagnetic surveys over the area, in 1982 they drilled the No.1 Jackson (Delaware 300) well, which had an initial production of 225 Mcfg/d. ING's subsequent drilling program successfully proved the northwest trend of the fault system. After ING demonstrated additional gas reserves in the area, Columbia Gas built a 10-mile pipeline to gather gas from this field. While defining the northern segment of this fault with six gas wells and two dry holes, ING also tried to locate the southern extension of this system. After three dry holes (Delaware 299 is shown on Figure MOf-9 as a gas well, although its productive life was very short), two in Harlem Township and one in neighboring Monroe Township of Licking County, the company abandoned its efforts on this field. The program was acquired by a partnership called Sunbury-Trenton, Inc., who ran additional seismic lines and drilled another four productive wells and three dry holes before also abandoning efforts in this field.

Eleven gas wells, two combination wells, and 18 dry holes have been drilled in and around this field. Cumulative production is 2.1 bcf, of which approximately 1.5 bcf has been produced from the Fronk discovery well.

The main producing units of this field are dolomitized sections of the Trenton Limestone and Black River Group. In some wells, the entire Trenton-Black River sequence has been dolomitized; in others, the dolomite and original limestone are interlayered. The dolomitization and reservoir development have occurred along a northwest-oriented fault with approximately 20 feet of vertical displacement. The fault cuts across a northeast-trending anticline (Figures MOf-9, MOf-10).

The discovery well (Delaware 146) apparently is the only well that has cut the fault plane (Figure MOf-10). Close correlation of the geophysical logs and sample examination reveals that the basal "Point Pleasant" formation, the entire Trenton Limestone, and the upper portion of the Black River Group are not recognized in this well. In their place is a section of dark shale and white calcite rubble. Production from this well is from the fault zone and fractured and dolomitized Black River located directly below the fault zone. In this field, trapping is apparently the result of porous dolomite sections being surrounded by tight dolomite and unaltered limestone sections.

Resources and Reserves

Much of the drilling and production from fields of this play occurred before modern permitting regulations and tax collections. Also, many of the southern fields of this play have not had markets for the produced gas. Therefore, production figures for these gas wells are not available. For these reasons as well as a total lack of gauging in some of the oldest fields, it is nearly impossible to obtain reliable production figures to use for reserve calculations and in constructing representative decline curves. While many of the larger fields in Ohio produced their largest amount of gas from the late 1880s through 1910, the earliest production figures available started in the late 1920s. Of the 42 fields examined as part of this investigation, production from wells within portions of only eight fields was obtained (some of this data is proprietary). Therefore, the following figures are conservative estimates at best. The author believes that a significant sampling of accurate production records for this play would easily double the reserves reported here and may alter some areas by an order of magnitude.

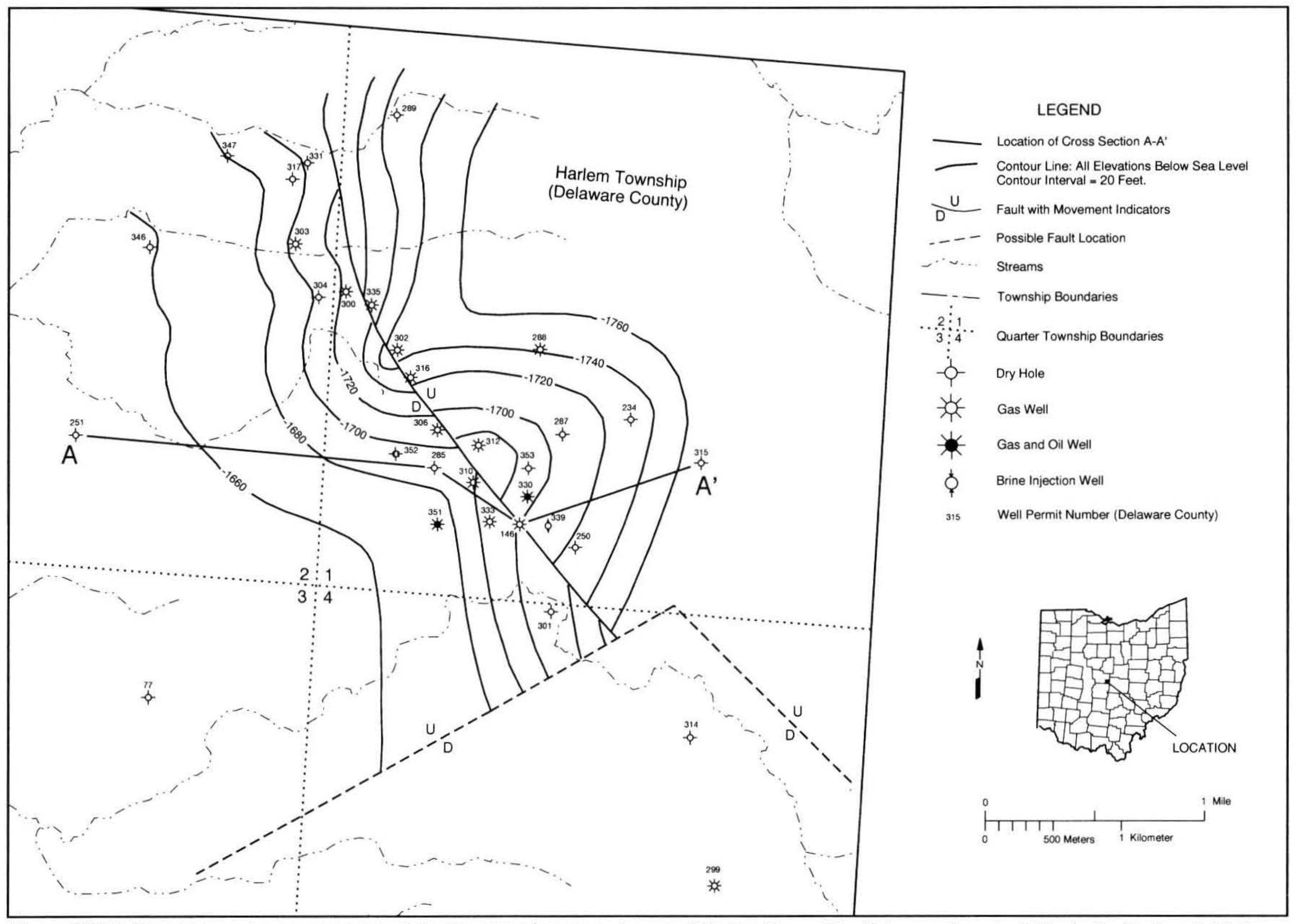


Figure MOf-9. Structure contour map on top of the Trenton Limestone in part of Harlem Township, Delaware County, Ohio. In the Harlem field, there is the apparent correlation of the position of the subsurface structure to surface topography. Map shows the alignment of the stream in the southeast quadrant of the township with the fault trace. The stream that crosses the first and second quarter township boundaries takes a very erratic swing to apparently adjust to the fault. Surface topographic contours are not included, but they also show adjustment to the structure. Over most of this area, the surface contours lie predominantly north-south; however, over the position of the anticlinal nose in the first quarter of the township, they anomalously wrap around the structure. Surface lineaments can also be noticed aligning with subsurface features over many other Ordovician fracture fields (for example, the Honey Creek, Upper Sandusky, Carey, and Roundhead fields). Location of cross section A-A' (Figure MOf-10) is also shown.

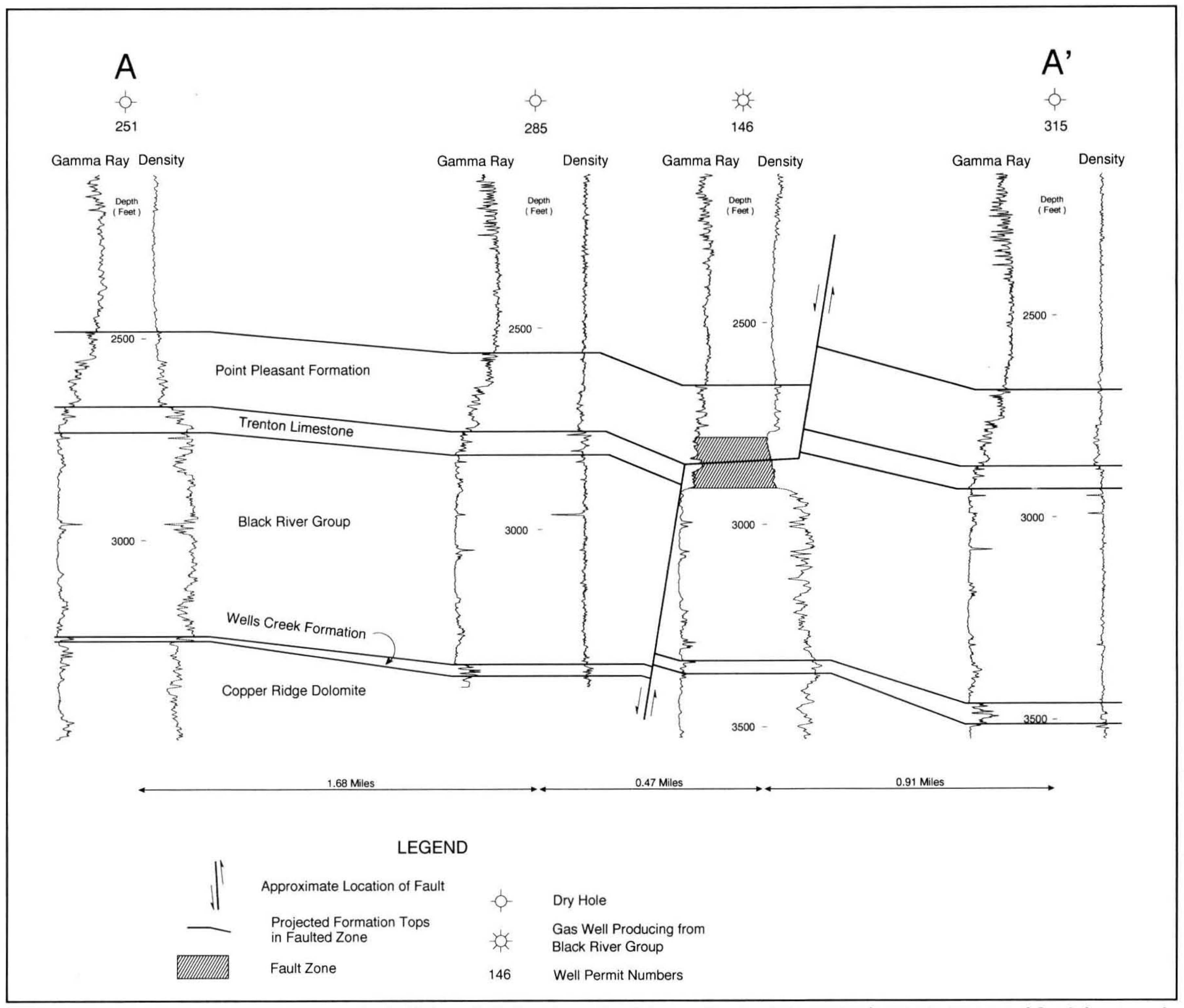


Figure MOf-10. East-west structural cross section A-A' through Harlem Township, Delaware County, Ohio, illustrating strata from top of Cambrian through middle of Upper Ordovician Cincinnati group. The fault that intersects well number 146 is thought to be nearly vertical. For graphical representation, it is shown more horizontal where it cuts through the faulted section of the well. See Figure MOf-9 for location of cross section.

Using the limited production data available yields an average cumulative production per well of 78.604 MMcfg and an average life per well of 15.8 years. The Kentucky Geological Survey provided volumetric estimates of original gas reserves and original gas in place for the fields in its estimates of field production and reserves. For northern fields, an 80 percent recovery factor was used; the Kentucky Geological Survey uses a 90 percent figure, so this was used for all southern fields.

Using the above figures in the calculations yields an estimated original gas reserve of 43.5 bcf and an original gas in place of 54 bcf for the Ordovician fractured carbonate play within the Appalachian basin. Remaining gas in place is estimated at more than 11.5 bcf. Because of the lack of cumulative production data within producing fields, providing a meaningful remaining gas reserve figure for this play is impossible.

To provide more meaningful reserve calculations, comparison to a nearby analogous field with known production might prove helpful. The Albion-Scipio field of southern Michigan is a large fracture-controlled reservoir productive from dolomitized sections of the Trenton and Black River groups. The field was discovered in 1957 and is still productive. In this field, the 961 wells on 20-acre spacing have an ultimate recoverable reserve of 204.5 bcfg and 124 million barrels of oil through 1987 and an original gas in place of 276 bcf (Hurley and Budros, 1990).

The Middle Ordovician fractured carbonate reservoirs examined within the Appalachian basin contain approximately 563 wells (Table MOf-1). A simple well-to-well analogy with the Albion-Scipio production figures yields an original gas reserve of 120 bcf, an original gas in place of 162 bcf, and remaining gas in place of 42 bcf for the Appalachian basin fields.

Future Trends

Despite production from the existing fields of north-central to northwestern Ohio, much of this area remains largely untested for oil and gas. Although the reservoir pressure in many of the proven fields is depleted, compartmentalization is evident; hence, additional production from existing fields is still possible. It is also probable that additional fields along northwest trending fault systems—comparable to the Honey Creek, Upper Sandusky, and Harlem fields—may be discovered in central-northwestern Ohio. However, because of the narrow extent and small displacements associated with these faults, detailed exploration methods will be required for their discovery.

An example of such exploration methods resulted in the discovery of another Trenton fracture-controlled reservoir in 1992 in Sycamore Township, Wyandot County, Ohio. After employing an integrated exploration program utilizing geological, geochemical, and seismic methods, Mitchell Energy Corporation drilled the No. 1 Osborn-Walton (Wyandot 288) discovery well. This well initially produced 12 barrels of oil per day and 11 Mcfg/d after an acid frac. The well produced approximately 1,800 barrels of oil in its first six months; gas production is being used in lease operations and has not been measured. Continued exploration and drilling are expected along this new trend.

Within the last decade, availability of aeromagnetic surveys and large seismic surveys have shed new light on the location and nature of deep-seated features such as the Grenville front, the East Continent Rift Basin, and the Rome trough. Reservoirs in reactivated structures related to these features are quite prolific. Further exploration along these features should yield additional reserves. However, fully utilizing these resources will require aggressive marketing to bring pipelines into some of the more remote areas of southwestern Ohio, south-central Kentucky, and north-central Tennessee.

Most wells with production from the Middle Ordovician fractured carbonates lie on the western flank of the Appalachian basin, where drilling and exploration depths are shallowest. However, scattered discoveries and significant shows deeper in the basin indicate that much more of the basin has potential for new reserves in this play, for example, the discovery and limited production from the Starr fault system in Athens County, Ohio (see Brannock, 1993). As drilling and exploration technology advance, the ability to find and produce the elusive fracture fields should improve.

Lastly, as the search for deeper hydrocarbon resources within the Knox Group continues, additional reservoirs within the overlying "Gull River" and Wells Creek intervals also should be expected.

PLAY Osp: MIDDLE ORDOVICIAN ST. PETER SANDSTONE

by Matthew Humphreys and Anna E. Watson, Kentucky Geological Survey

Location

The Middle Ordovician St. Peter Sandstone gas play includes several small fields consisting of structural traps (Figures Osp-1, Osp-2) that are associated with the Kentucky River and Irvine-Paint Creek fault zones in eastern Kentucky (Figure Osp-3). The prospective area for the play extends from eastern Kentucky into southwestern West Virginia and possibly southern Ohio, generally following the northeast-trending Rome trough.

Production History

The first significant St. Peter Sandstone gas reserves were discovered in 1947 in the Furnace field (renamed Irvine-Furnace Consolidated) in Estill County, Kentucky. The discovery well, the South Central Petroleum Company No. 1 J.M. Garrett, Carter coordinate location 21-P-68, Estill County, Kentucky, was completed in the St. Peter Sandstone at a depth of 2,538 to 2,586 feet and had a final open flow of 8,500 Mcfg/d. The field was developed rapidly, with 14 wells completed by 1949. Only two additional development wells have been completed since 1949: one in 1953 and one in 1986. Gas analyses (McGuire and Howell, 1963) indicate high concentrations of carbon dioxide (25.5 to 41.0 percent), nitrogen (1.4 to 2.3 percent), and hydrogen sulfide (0.0 to 0.56 percent). The presence of these gases results in Btu values ranging from 646 to 765. Because of the low Btu values, gas produced from the St. Peter Sandstone in the Irvine-Furnace Consolidated field was used for pressure maintenance at Big Sinking oil field (McGuire and Howell, 1963). Cumulative production for the period from 1947 to 1960 was reported to be 1.8 bcfg (Price, 1981).

The second major gas field in the St. Peter Sandstone was the Trapp field in Clark County, Kentucky, discovered in 1962. The discovery well was the Smith No. 1 Vernon Chambers, Carter coordinate location 15-Q-66, Clark County, Kentucky. This well was completed from the St. Peter Sandstone at a depth of 1,606 to 1,660 feet and had a final open flow of 2,500 Mcfg/d. Fourteen wells were completed between 1962 and 1986. Cumulative production for the Trapp field was reported to be 0.4 bcfg for the period from 1962 to 1974 (Price, 1981).

In addition to the two major fields, four small fields consisting of one or two wells each have been discovered in Kentucky, the most recent in 1984. It is doubtful that any of these fields have ever produced significant quantities of gas. The Stephens field in Elliott County, Kentucky, however, has one reported St. Peter Sandstone gas well, the Monitor Petroleum No. 1 Cecil Ison, drilled in July 1970, which flowed 5.3 MMcfg/d after stimulation (Price, 1981) from the St. Peter Sandstone, at depths of 4,634 to 4,646 feet and 4,712 to 4,734 feet. The Btu value of the gas was reported to be 1,017 (Price, 1981). The well was never connected to a pipeline (J.D. Silberman, written commun., 1994). Another significant well that has never commercially produced is the Signal No. 1 Elkhorn Coal Corporation in Johnson County, Kentucky. This well was abandoned as a dry hole in 1973 and was reported to have an open flow of 3 to 5 MMcfg/d (1,027 Btu) from the St. Peter Sandstone at a depth of 5,914 to 5,935 feet (Price, 1981; Sutton, 1981). The presence of gas with a high Btu value in both of these wells compared to the low Btu values in the Irvine-Furnace Consolidated and Trapp fields suggests a trend of increasing Btu values from west to east. An awareness of this apparent trend may be beneficial to the explorationist when doing economic evaluations of prospective gas areas in the St. Peter Sandstone. Gas shows have been reported from the St. Peter Sandstone in at least two wells drilled in Wayne and Cabell counties, West Virginia, but no gas fields have resulted (Cardwell, 1977). Currently, Ohio has no gas production from the St. Peter Sandstone. The total cumulative production from 1947 to 1974 for the St. Peter Sandstone gas play is at least 2.2 bcfg. The amount of gas produced from the St. Peter Sandstone play since 1974 is unknown, due to lack of reliable production data.

Stratigraphy

The St. Peter Sandstone of eastern Kentucky and western West Virginia is a dolomite-cemented quartzarenite, which unconformably overlies the Lower Ordovician Beekmantown Dolomite of the Knox Group (Figures Osp-4, Osp-5). In Kentucky, the St. Peter Sandstone grades vertically and laterally into the Middle Ordovician Wells Creek Dolomite. In West Virginia, the "Wells Creek Formation" unconformably overlies the St. Peter Sandstone. In southern Ohio, the Wells Creek Formation occupies the stratigraphic position of the St. Peter Sandstone, due to a lateral facies change. However, a maximum of 50 feet of sandstone, which has been called St. Peter Sandstone, occurs in southern Ohio and northern Kentucky, near the axis of the Cincinnati arch (Carpenter, 1965). Also, scattered pods of sandstone have been encountered in Fayette and Madison counties, Kentucky (Jillson, 1965). These isolated sandstone bodies are interpreted to be within the Beekmantown Dolomite and are not stratigraphically correlative with the St. Peter Sandstone of eastern Kentucky (Patton and Dawson, 1969).

Depositional environments of the St. Peter Sandstone include a variety of well-sorted strandline deposits such as beach sands, eolian dunes, and nearshore sand bars (Price, 1981). Deposition appears to have been influenced by growth faulting along the Kentucky River and Irvine-Paint Creek fault zones in the Rome trough (Woodward, 1961; McGuire and Howell, 1963; Silberman, 1972; Price, 1981; Cable and Beardsley, 1984). A stratigraphic cross section (Figure Osp-6) oriented from north to south across the Kentucky River and Irvine-Paint Creek fault zones illustrates substantial thickening of the Cambrian formations and moderate thickening of the Lower and Middle Ordovician formations. The regional distribution of the St. Peter Sandstone is shown by an isopach map (Figure Osp-7), which indicates several depocenters on the downthrown side of the Kentucky River and Irvine-Paint Creek fault zones. The thickest depocenter (more than 200 feet thick) follows the Kentucky River fault zone in a northeasterly direction across Elliott, Lawrence, and Boyd counties, Kentucky, into Wayne, Cabell, and Mason counties, West Virginia. The Monitor Petroleum

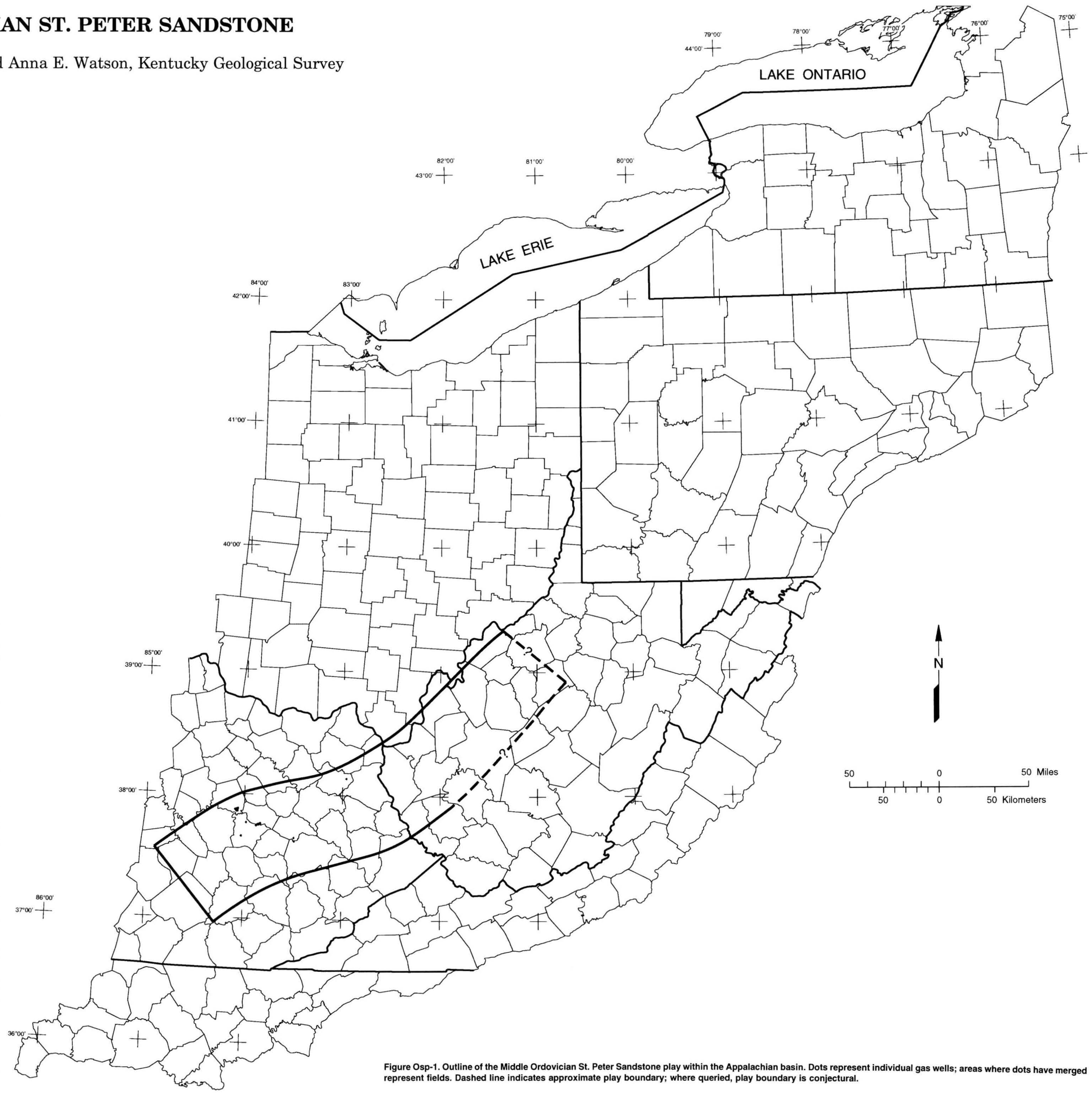


Figure Osp-1. Outline of the Middle Ordovician St. Peter Sandstone play within the Appalachian basin. Dots represent individual gas wells; areas where dots have merged represent fields. Dashed line indicates approximate play boundary; where queried, play boundary is conjectural.

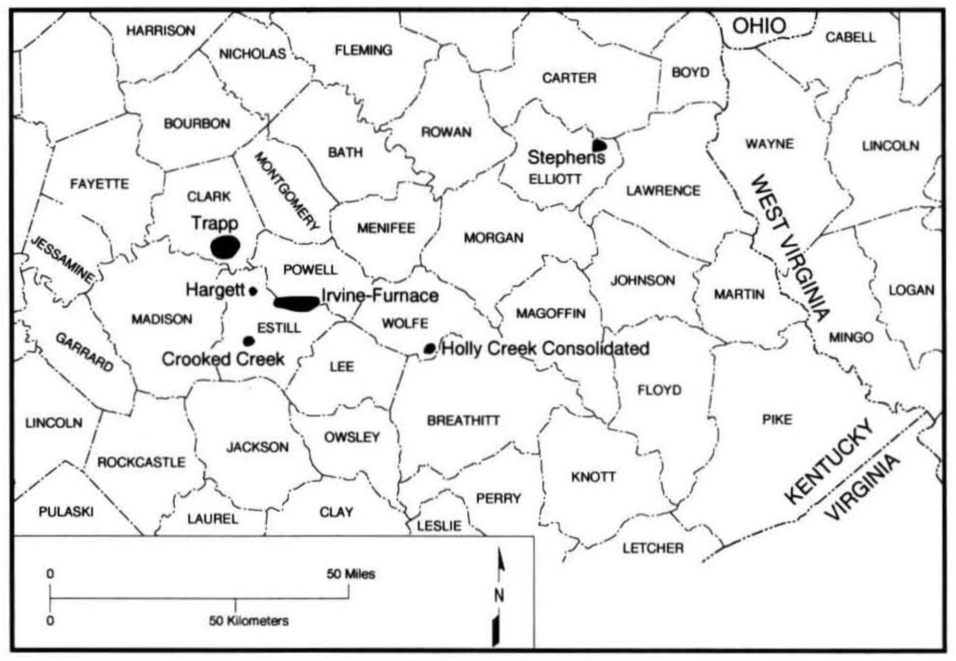


Figure Osp-2. Location of Middle Ordovician St. Peter Sandstone fields discussed in text or listed in Table Osp-1. Counties located in eastern Kentucky and southwestern West Virginia are identified.

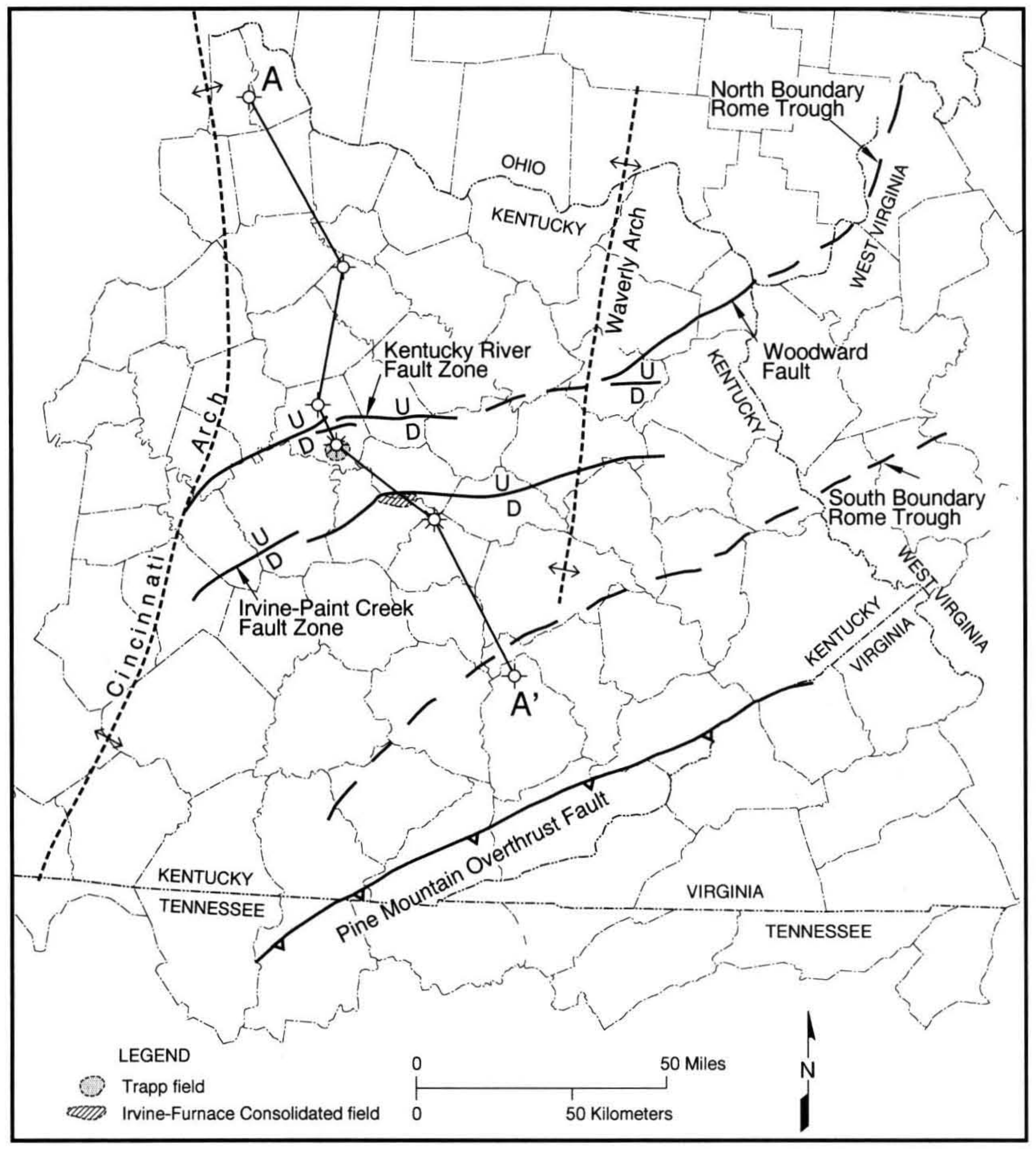


Figure Osp-3. Regional map showing major fault zones and tectonic features in eastern Kentucky, southwestern West Virginia, and southern Ohio. Line of cross section A-A' (Figure Osp-6) is also shown.

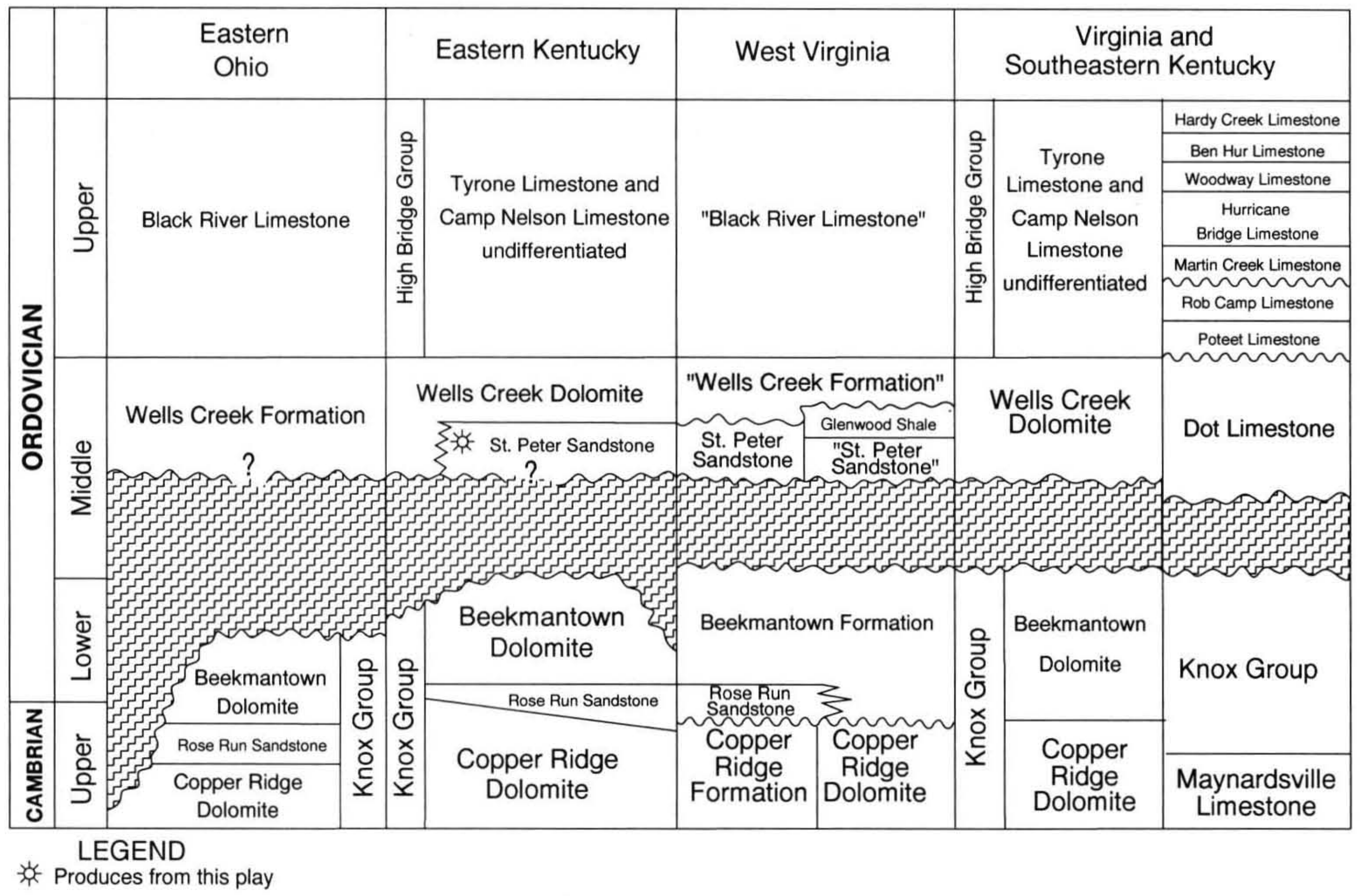


Figure Osp-4. Stratigraphic correlation chart for the St. Peter Sandstone. Modified from Anderson (1984), Noger and others (1984), Patchen and Avary (1984), and Rader (1984).

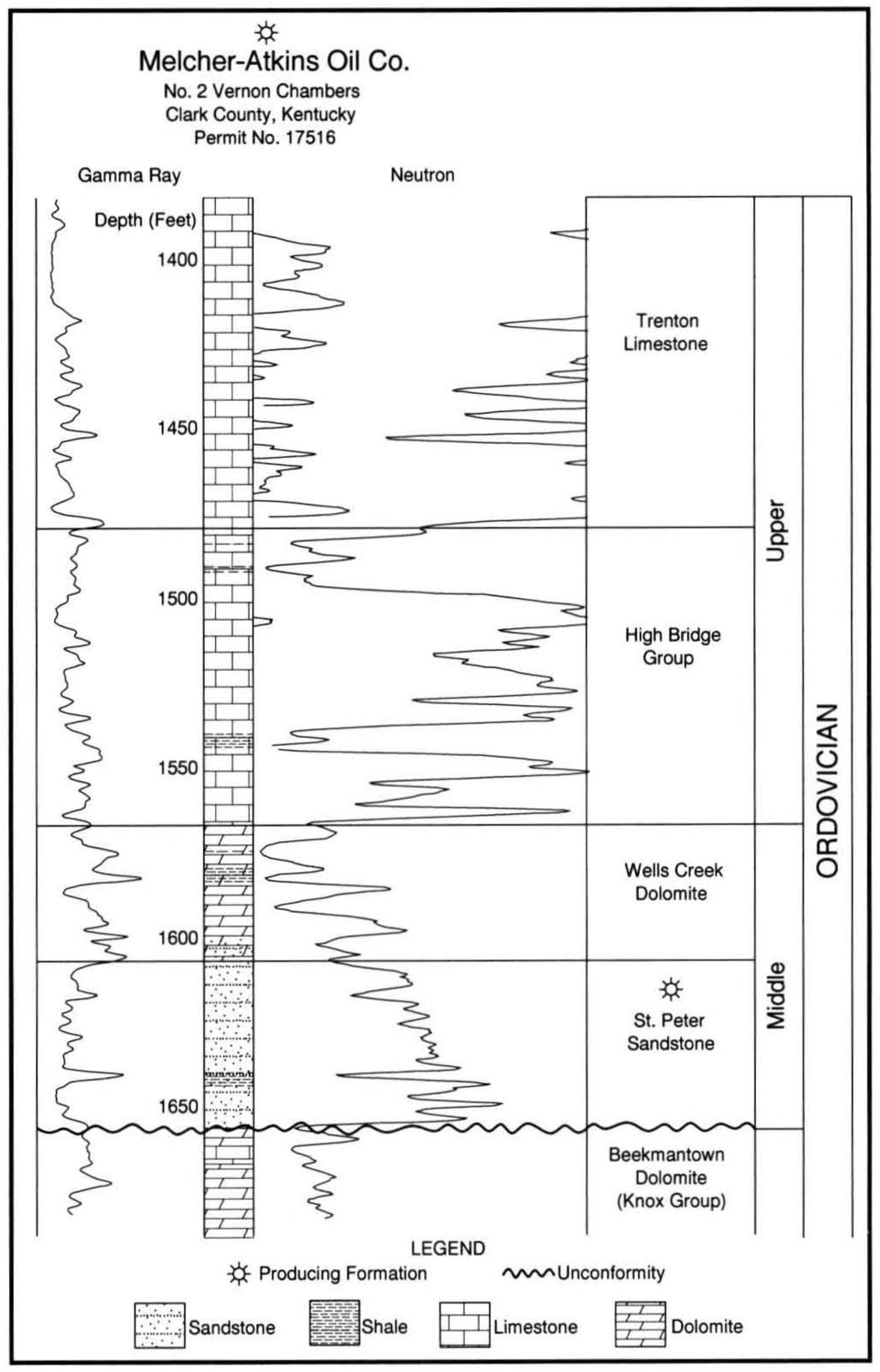


Figure Osp-5. Type log from the Melcher-Atkins Oil Company, No. 2 Vernon Chambers, Clark County, Kentucky, showing the gamma-ray and neutron curves and the interpreted lithologies based on samples of the St. Peter Sandstone. The St. Peter Sandstone has an unconformable lower contact with the Beekmantown Dolomite and a gradational upper contact with the Wells Creek Dolomite.

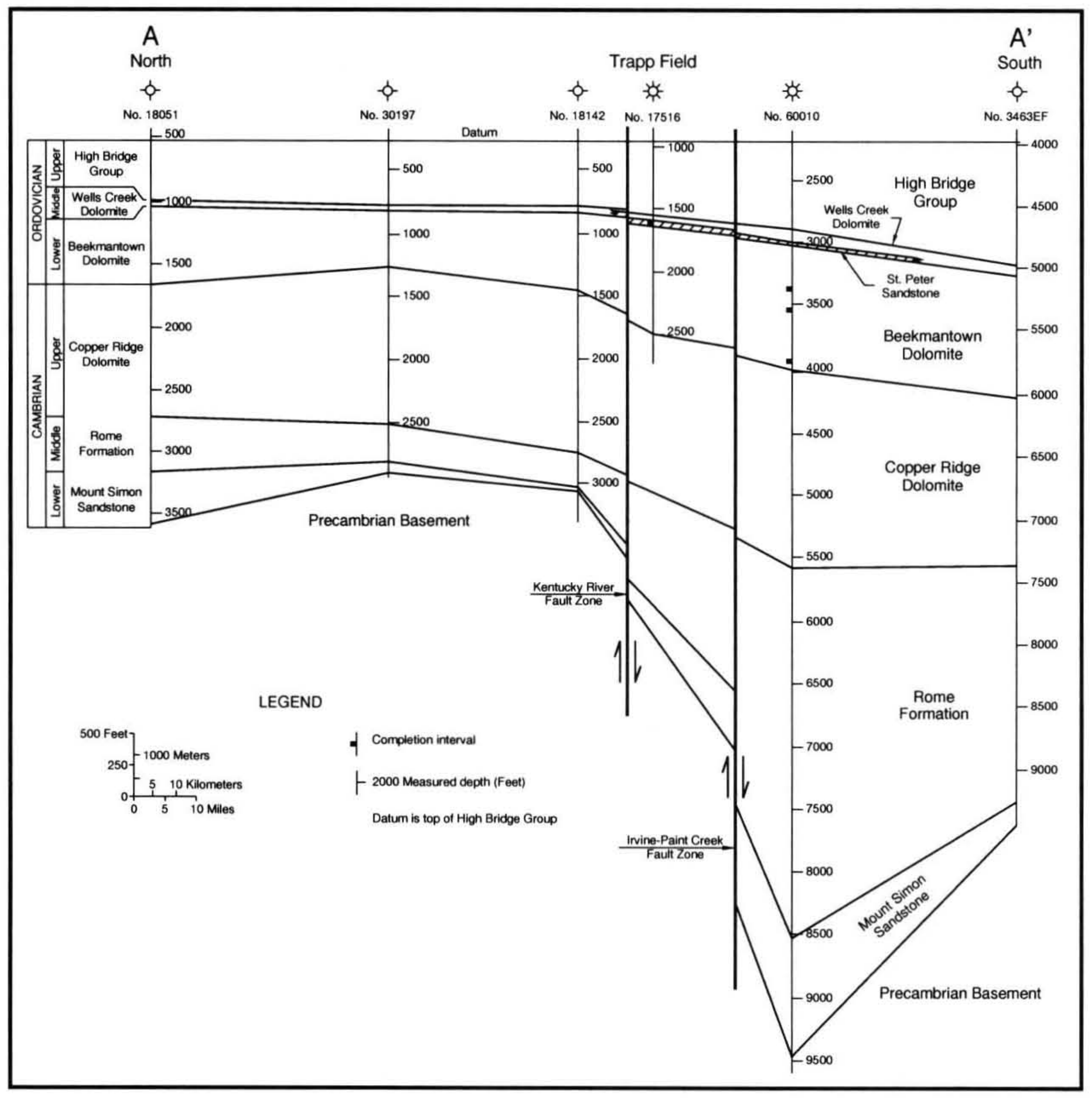


Figure Osp-6. Regional stratigraphic cross section A-A', illustrating the effect of faulting on deposition of the Cambrian and Ordovician formations. Datum is top of the Ordovician High Bridge Group. Line of cross section is shown in Figure Osp-3.

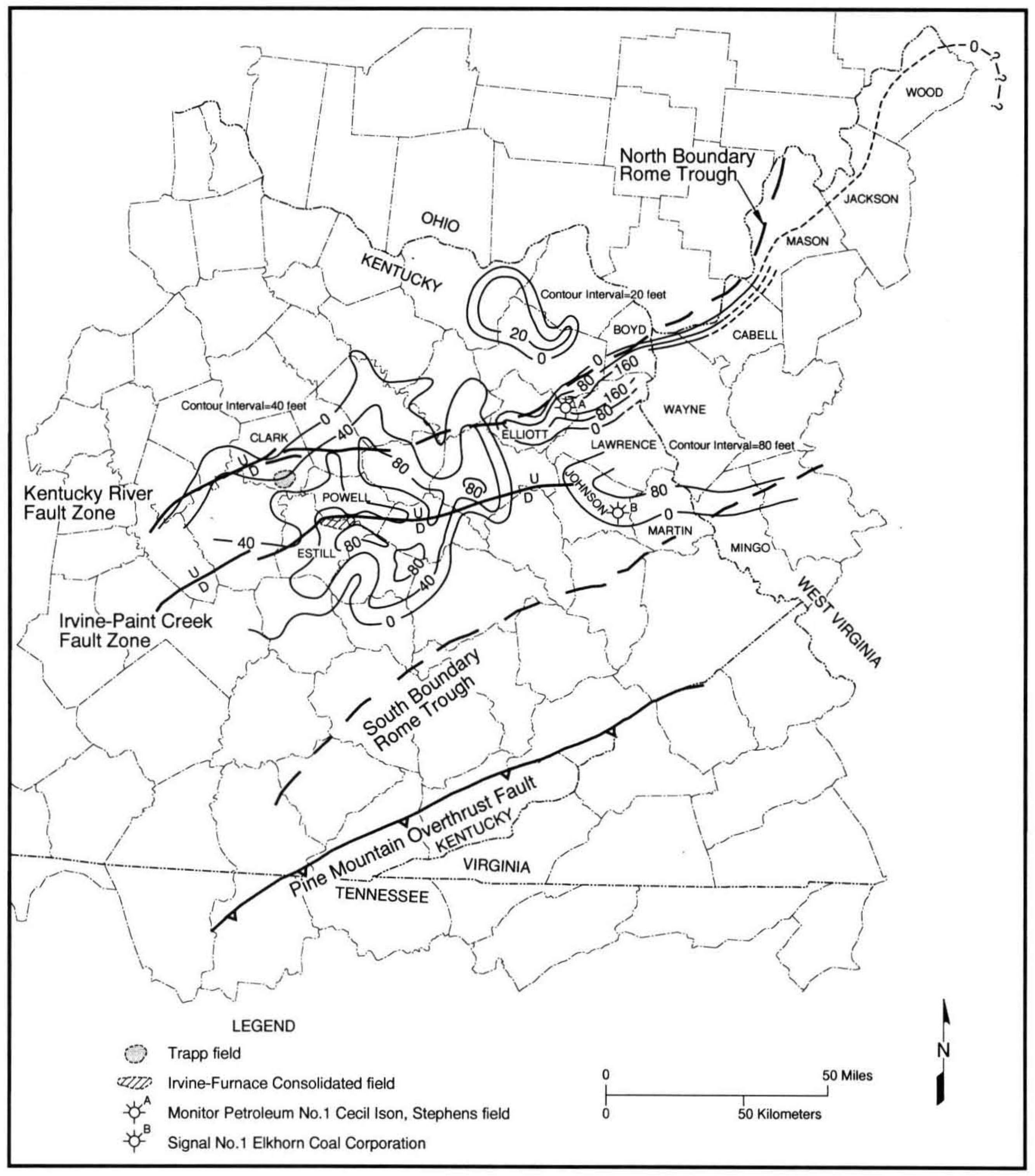


Figure Osp-7. Isopach map showing regional distribution of the St. Peter Sandstone. Modified from Price (1981). Isopach contours are dashed in areas of sparse well control. Major fault zones and county names referred to in text are shown. Contour interval is variable (20, 40, or 80 feet).

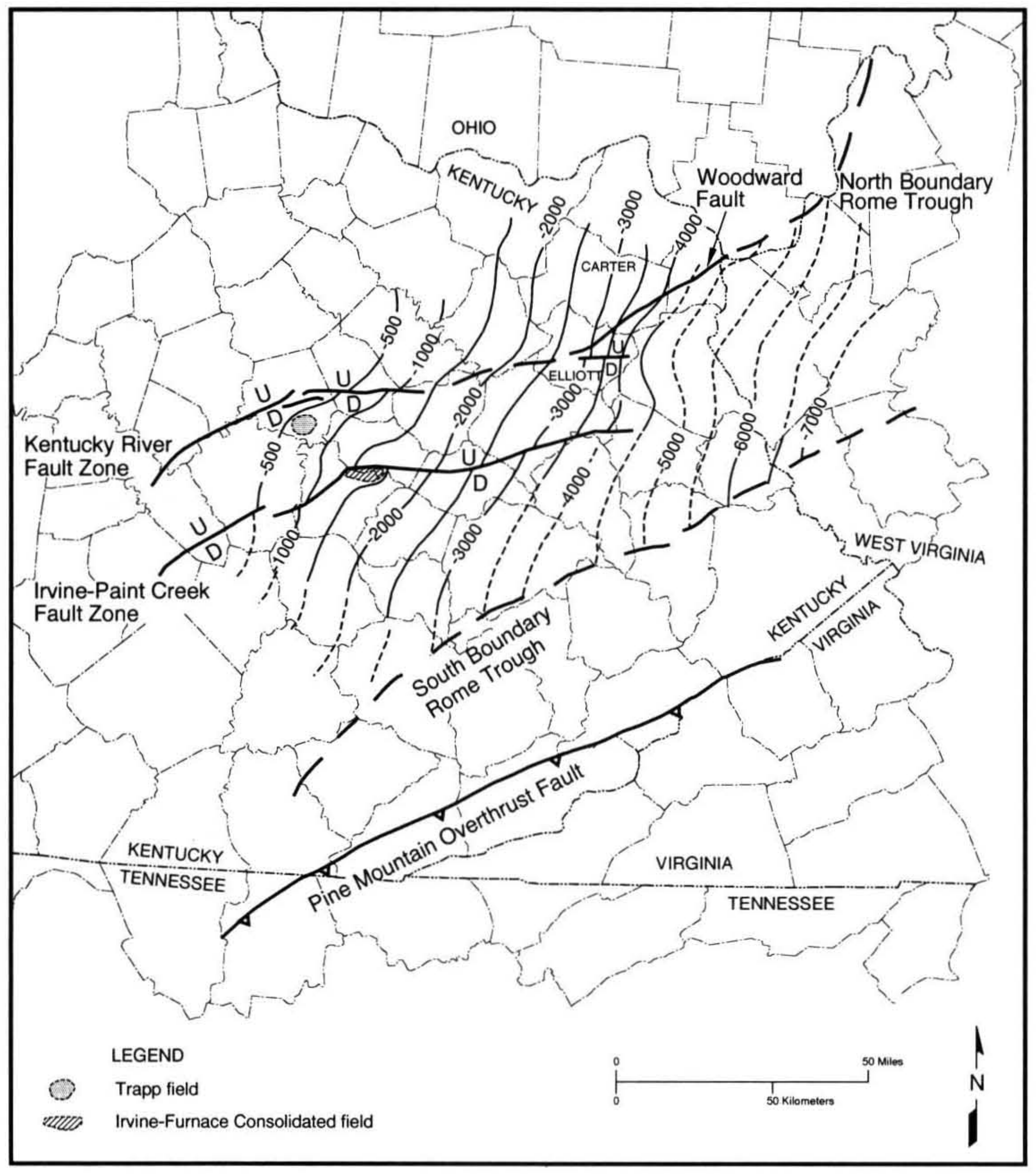


Figure Osp-8. Regional structure map contoured on top of the St. Peter Sandstone. Modified from Price (1981). Structure contours are dashed in areas of sparse well control. Contour interval = 500 feet. Datum is sea level. Major fault zones and county names referred to in text are shown.

No. 1 Cecil Ison drilled in the Stephens field, Elliott County, Kentucky, is located in this depocenter, downthrown to the Woodward fault zone (Silberman, 1981), which locally forms the northern boundary of the Rome trough. This depositional trend may extend as far northeast as Jackson and Wood counties, West Virginia (Cardwell, 1977; Price, 1981; Ryder, 1992). In these counties, an unnamed sandstone on top of the Knox unconformity occurs at depths below 10,000 feet (Ryder, 1992). This unnamed sandstone is probably the stratigraphic equivalent of the St. Peter Sandstone of eastern Kentucky. Due to sparse well control, the limits of this unnamed sandstone were not mapped in detail in Figure Osp-7. Another depocenter is located on the downthrown side of the Irvine-Paint Creek fault zone, in Estill and Powell counties, Kentucky. The St. Peter Sandstone is greater than 80 feet thick immediately south of the Irvine-Furnace Consolidated gas field. In southern Clark County, Kentucky, the Trapp gas field is situated in a depocenter that reaches a thickness of 40 feet downthrown to the Kentucky River fault zone. Limited well control suggests a thick (80 feet) development of St. Peter Sandstone in Johnson and Martin counties, Kentucky, and adjacent Mingo County, West Virginia. The Signal No. 1 Elkhorn Coal Corporation well in Johnson County, Kentucky is located in this depocenter. This well had a significant show of gas from the St. Peter Sandstone.

In the past, the St. Peter Sandstone in eastern Kentucky has been interpreted to be erosional remnants that are laterally equivalent to the St. Peter Sandstone of the Upper Mississippi Valley and Midcontinent Region (Dapples, 1955). However, Price (1981) did a comprehensive study of the regional distribution of the St. Peter Sandstone in eastern Kentucky and concluded that the St. Peter Sandstone in the Rome trough is not stratigraphically related to the Upper Mississippi Valley formation described by Dapples (1955). Freeman (1953) suggested that the St. Peter Sandstone was a transgressive sheet sand derived from erosion of the sandy Knox Dolomite and older dolomites of the Ozark uplift and possibly from the Laurentian uplift in the east. According to this interpretation, the St. Peter Sandstone was deposited in erosional lows on the unconformity surface of the Knox Dolomite. More recent studies (Silberman, 1972; Price, 1981; Cable and Beardsley, 1984) conclude that fault-controlled subsidence during the Middle Ordovician resulted in localized deposition of the St. Peter Sandstone in the Rome trough. Price (1981) described the lithology of the St. Peter Sandstone as a dolomite-cemented quartzarenite with a distinct bimodal distribution of grain sizes. The samples studied typically contained at least 60 percent fine-grained, well-sorted, subrounded sand grains and 15 to 40 percent medium-grained, well-rounded, frosted grains (Price, 1981). Price pointed out that the St. Peter Sandstone of the Upper Mississippi Valley is typically well rounded, extremely well sorted, and not bimodal. He interpreted the St. Peter Sandstone of eastern Kentucky to be a hinge-line, regressive deposit, rather than a transgressive deposit. He suggested sediment from the eroded Rose Run Sandstone and Beekmantown Formation in southern Ohio is a source of texturally mature sand.

Structure

The structure of the prospective area for gas exploration is characterized by regional southeastern dip intersected by the major east-west trending fault zones associated with the Rome trough (Figure Osp-8). Drilling depths for the St. Peter Sandstone are approximately 1,600 feet in the west near Trapp field and 7,500 feet in the east near the border of Kentucky and West Virginia.

TABLE Osp-1		Irvine-Furnace Consolidated KY	Trapp KY	Crooked Creek KY	Holly Creek Consolidated KY	Hargett KY	Stephens KY
BASIC RESERVOIR DATA	POOL NUMBER	1601029 365 STPR	1601997 365 STPR	1600507 365 STPR	1600977 365 STPR	1600887 365 STPR	1601894 365 STPR
	DISCOVERED	1947	1962	1984	1957	1967	1970
	DEPTH TO TOP RESERVOIR	2,527	1,598	1,670	3,787	1,797	4,634
	AGE OF RESERVOIR	Ordovician	Ordovician	Ordovician	Ordovician	Ordovician	Ordovician
	FORMATION	St. Peter Sandstone	St. Peter Sandstone	St. Peter Sandstone	St. Peter Sandstone	St. Peter Sandstone	St. Peter Sandstone
	PRODUCING RESERVOIR	St. Peter Sandstone	St. Peter Sandstone	St. Peter Sandstone	St. Peter Sandstone	St. Peter Sandstone	St. Peter Sandstone
	LITHOLOGY	sandstone	sandstone	sandstone	sandstone	sandstone	sandstone
	TRAP TYPE	structural	structural	structural	structural	structural	structural
	DEPOSITIONAL ENVIRONMENT	marine-shoreline	marine-shoreline	marine-shoreline	marine-shoreline	marine-shoreline	marine-shoreline
	DISCOVERY WELL IP (Mcf)	8,500	2,500	10	622		5,300
	DRIVE MECHANISM	water	water	water			
	NO. PRODUCING WELLS	0	0	0	0	0	0
	NO. ABANDONED WELLS	16	14	2	1	1	1
	AREA (acreage)	880	1,000	40	20	20	20
	OLDEST FORMATION PENETRATED	Knox	Copper Ridge	St. Peter Sandstone	Copper Ridge	Knox	Cambrian
	EXPECTED HETEROGENEITY DUE TO:	structure diagenesis	structure diagenesis	structure diagenesis	structure diagenesis	structure diagenesis	structure diagenesis
RESERVOIR PARAMETERS	AVERAGE PAY THICKNESS (ft.)	20	23	15	10		14
	AVERAGE COMPLETION THICKNESS (ft.)	23	40	18	10	13	34
	AVERAGE POROSITY--LOG (%)	10	13	11			7
	MINIMUM POROSITY--LOG (%)	8	7	8			6
	MAXIMUM POROSITY--LOG (%)	12	19	14			8
	NO. DATA POINTS	1	9	2			1
	POROSITY FEET						
	RESERVOIR TEMPERATURE (°F)		81				97
	INITIAL RESERVOIR PRESSURE (psi)	780	600	640			
	PRODUCING INTERVAL DEPTHS (ft.)	2,200-2,657	1,436-1,664	1,664-1,674	3,787-3,797	1,797-1,810	4,634-4,646 4,712-4,734
	PRESENT RESERVOIR PRESSURE (psi) / DATE	100/1960	250/1986	640/1984			
FLUID & GAS PROPERTIES	Rw (Ωm)						
	GAS GRAVITY (g/cc)	0.8325	0.626				
	GAS SATURATION (%)		59				53
	WATER SATURATION (%)		41				47
	COMMINGLED	no	no	no			no
	ASSOCIATED OR NONASSOCIATED	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated
	Btu/scf	765	955				1,017
VOLUMETRIC DATA	STATUS (producing, abandoned, storage)	abandoned	abandoned	abandoned	abandoned	abandoned	abandoned
	ORIGINAL GAS IN PLACE (Mcf)	2,400,000	1,700,000				
	ORIGINAL GAS RESERVES (Mcf)	1,900,000	1,400,000				
	PRODUCTION YEARS	1947-1960	1962-1974				
	REPORTED CUMULATIVE PRODUCTION (Mcf)	1,800,000	400,000				
	NO. WELLS REPORTED						
	ESTIMATED CUMULATIVE PRODUCTION (Mcf)						
	REMAINING GAS IN PLACE (Mcf)/DATE	600,000/ 1993	1,300,000/ 1993				
	REMAINING GAS RESERVES (Mcf)/DATE	100,000/ 1993	1,000,000/ 1993				
	RECOVERY FACTOR (%)	79	82				
	INITIAL OPEN FLOW (Mcf/d)						
	FINAL OPEN FLOW (Mcf/d)	7,818	1,399	15	622		5,300

Structure influenced deposition during Cambrian through Middle Ordovician time in eastern Kentucky, western West Virginia, and southern Ohio. Structurally dominant features controlling sand deposition and gas entrapment in the resulting reservoirs are the Kentucky River and Irvine-Paint Creek fault zones (Figure Osp-8). These fault zones in the Rome trough were episodically active from Late Precambrian time through the end of the Paleozoic. Regional stratigraphic thickening of the Cambrian section on the downthrown side of these major faults suggests a type of growth faulting, related to the tensional rifting of the Rome trough. The moderate thickening observed in the Middle Ordovician section may be a result of reactivation of subsidence along the major fault zones. Silberman (1972) did a detailed study of the Woodward fault along the northern boundary of the Rome trough in Elliott and Carter counties, Kentucky. He suggested penecontemporaneous or post-Knox movement as a controlling factor in the deposition of an abnormal thickness of St. Peter Sandstone.

The Waverly arch (Figure Osp-3) also influenced depositional patterns of the St. Peter Sandstone in eastern Kentucky. Cable and Beardsley (1984) constructed a series of regional isopach maps that indicate the Waverly arch, as depicted by Woodward (1961), primarily influenced the deposition of the Early Ordovician Beekmantown Group. However, this arch appears to have migrated across the region from east to west, beginning in the Early Cambrian and continuing until the Middle Ordovician. The migrating arch resulted in thinning or absence of St. Peter Sandstone near the arch axis, and thick deposition on the flanks. Rejuvenated fault activity along the Kentucky River fault zone accentuated depositional subsidence (Cable and Beardsley, 1984).

TABLE Osp-2	Irvine-Furnace Consolidated KY	Trapp KY
AVERAGE POROSITY--CORE (%)	8	12
MINIMUM POROSITY--CORE (%)	4	7
MAXIMUM POROSITY--CORE (%)	12	19
NO. DATA POINTS	1	2
AVERAGE PERMEABILITY (md)	14	14.1

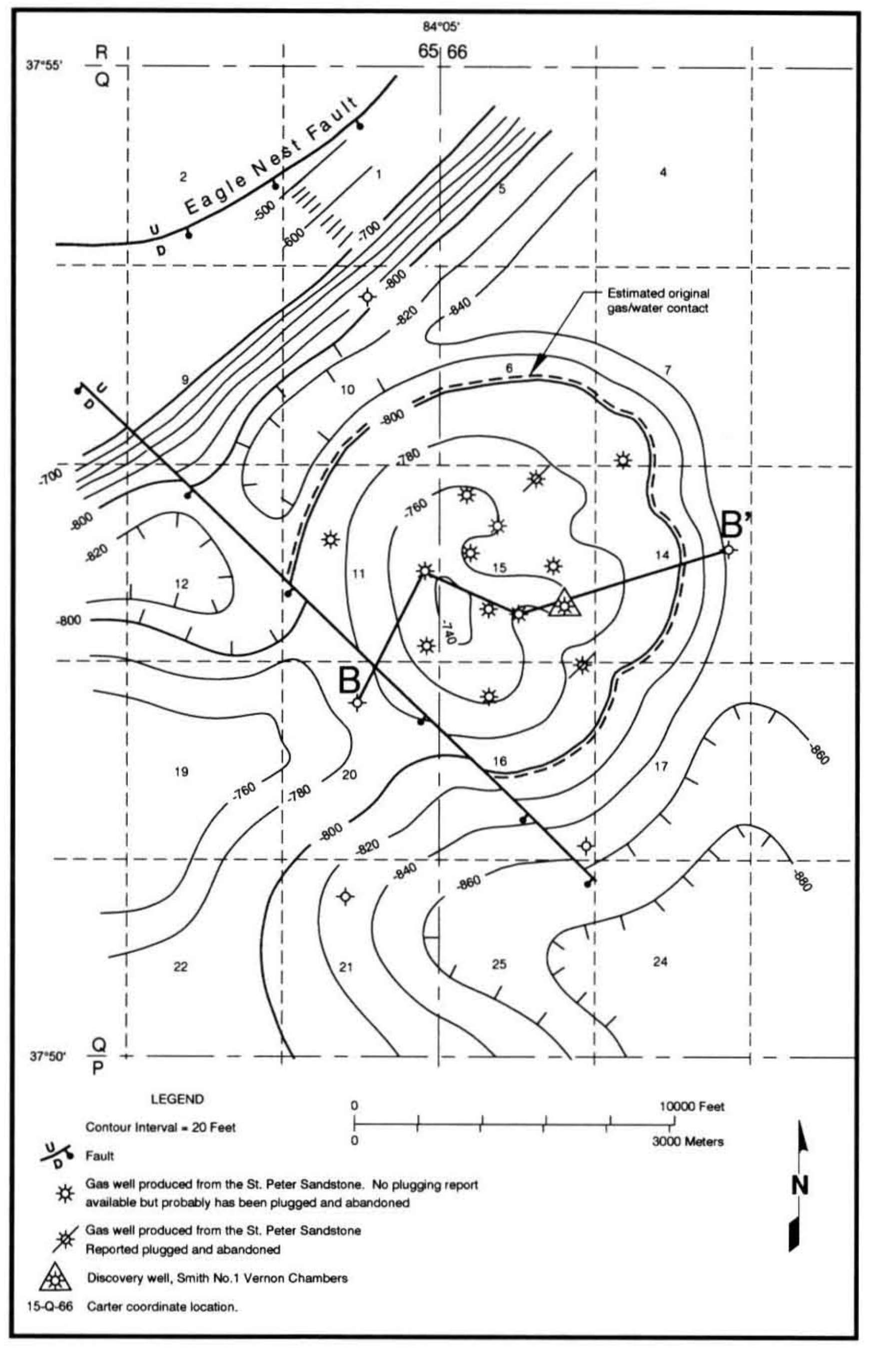


Figure Osp-9. Structure map of the Trapp field, Clark County, Kentucky, contoured on top of the St. Peter Sandstone. Contour interval = 20 feet. Datum is sea level. Line of cross section B-B' (Figure Osp-10) is also shown.

Reservoir

Typical trap types in the St. Peter Sandstone include faulted anticlines, domal anticlines, and possibly fault traps. These localized structural features formed as a result of differential uplift of basement blocks along the Kentucky River and Irvine-Paint Creek fault zones. The seal for gas entrapment is provided by the overlying Wells Creek Dolomite, which has low porosity and permeability. The source rock for gas in the St. Peter Sandstone may be the Devonian Ohio Shale, although organic-rich Ordovician shales should not be overlooked as potential source rocks. Ryder and others (1991) identified the Middle and Upper Ordovician Antes Shale as the most probable source for 15 Cambrian and Ordovician oil samples from Ohio. Cole and others (1987) concluded that the Upper Ordovician Point Pleasant Formation was the probable source of oil for some Cambrian, Ordovician, and Silurian reservoirs in Ohio. Migration of gas may have occurred along the Knox unconformity and along the major fault zones of the Rome trough.

The average depth to the top of the reservoirs (Tables Osp-1, Osp-2) in the St. Peter Sandstone is 2,669 feet and ranges from 1,598 to 4,634 feet. Average pay thickness is 15 feet and ranges from 10 to 23 feet. Completion intervals average 23 feet and range from 10 to 40 feet. Average final open flow is 3,031 Mcfg/d and ranges from 10 to 20,000 Mcfg/d. Three of the St. Peter Sandstone gas reservoirs studied are underpressured, with a pressure gradient of about 0.344 psi/foot. However, the Monitor Petroleum No. 1 Cecil Ison in the Stephens field, Elliott County, Kentucky, had shut-in pressure of 1,998 psi from a drill stem test interval of 4,620 to 4,694 feet (J.D. Silberman, written commun., 1994). The pressure gradient for this well is 0.426 psi/foot, indicating near normal pressure. The maximum initial shut-in pressure reported from the three other St. Peter Sandstone reservoirs was 780 psi at 2,639 feet, and the minimum was 600 psi at 1,694 feet. The average initial shut-in pressure for these fields is 673 psi at 2,005 feet. Gas analyses from several fields, including the Irvine-Furnace Consolidated and Trapp fields, indicate high concentrations of carbon dioxide and nitrogen, which lowers the Btu value of the gas.

In most of the St. Peter Sandstone gas fields, reservoir porosity is dominantly intergranular, with heterogeneity caused by reduction in grain sizes near the upper and lower contacts, variation in the volume of dolomite cementation, and minor occurrences of shale clasts. However, secondary fracture porosity occurs and is important in the St. Peter Sandstone reservoir at Stephens field in Elliott County, Kentucky. When exploring for gas in the St. Peter Sandstone, consideration must be given to potential enhancement of reservoir porosity due to fracturing caused by post depositional faulting. The St. Peter Sandstone has an average log porosity of 10 percent and ranges from 6 to 19 percent. Horizontal permeability averages 14.1 md and ranges from 1 to 160 md, based on three core analyses. Reservoir drive is a combination of gas expansion and partial water drive.

Completion practices since 1962 include acidizing and sand-water fracturing through 4.5-inch casing or open hole. Wells completed in the last 10 years utilize nitrogen foam fracturing. Completions in the 1940s and 1950s were natural or shot with nitroglycerin.

Description of Key Field

Trapp field: The Trapp field in Clark County, Kentucky, was selected to illustrate a typical St. Peter Sandstone gas accumulation, because it has more geophysical logs and cores than any of the other fields. The field was discovered in 1962 and has produced 0.4 bcfg from 14 wells, at an average depth of 1,598 feet. Net pay thickness averages 23 feet. Porosity averages 13 percent and ranges from 7 to 19 percent. Gas analyses indicate 88.25 percent methane, 1.66 percent ethane, 5.96 percent nitrogen, 2.96 percent carbon dioxide, 0.15 percent hydrogen sulfide, and 1.02 percent miscellaneous heavy hydrocarbons. The Btu value of the gas is 955, and specific gravity is 0.626.

The Trapp field is a faulted domal anticline situated on the downthrown side of the Eagle Nest fault, which forms a portion of the Kentucky River fault zone (Figure Osp-9). Surface mapping reveals the presence of a small anticlinal feature designated as the Mina dome on the Hedges (Black, 1975) and Palmer (Simmons, 1967) geologic quadrangle maps. A structure map contoured on top of the St. Peter Sandstone indicates about 60 feet of closure in the subsurface (Figure Osp-9). A small, vertical, normal fault on the southwestern side of the structural closure is mapped at the surface and in the subsurface. Structural cross section B-B' (Figure Osp-10) illustrates the structural rollover; the two structurally highest wells (Melcher No. 1 Sara Goolman and Melcher No. 2 Vernon Chambers) are gas productive and the flanking wells are nonproductive. Changes in gamma-ray character of the wells in cross section B-B' indicate some stratigraphic variability. Unpublished sample studies reveal zones of increased shaliness and increased dolomite cementation in the intervals of high gamma-ray readings. The original gas/water contact is interpreted to be about -800 to -810 feet subsea. Wells that penetrated the St. Peter Sandstone below the gas/water contact either produced water or were nonproductive due to low porosity caused by increased grain cementation. An isopach map of the net feet of gas pay is shown in Figure Osp-11.

Only one geophysical log is available for the Irvine-Furnace Consolidated field in Estill and Powell counties, Kentucky. A regional structure map (Figure Osp-12) depicts the trap at the Irvine-Furnace Consolidated field to be a faulted anticline on the downthrown side of the Irvine-Paint Creek fault zone. A small graben separates the Irvine-Furnace Consolidated field from the Irvine-Paint Creek fault zone. A decline curve for the original Furnace field (Figure Osp-13) indicates a 10-year producing life for the field, with an initial shut-in pressure of 740 psi and a near-abandonment pressure of 180 psi.

Resources and Reserves

Reservoir and production data from the Irvine-Furnace Consolidated and Trapp fields were used to make estimates of resources and reserves. Original gas-in-place for these two fields combined is estimated to be 4.1 bcf, based on volumetric calculations. Original reserves are estimated to be 3.3 bcf. Based on limited production data, estimated remaining reserves are 1.1 bcf. Most of the calculated remaining reserves are in the Trapp field. A word of caution is in order, because the actual cumulative production for the Trapp field could be significantly higher than the last known figure of 0.4 bcf reported in 1974.

Future resources for the St. Peter Sandstone are estimated to be 10 to 32 bcf of gas over the next 40 years, based on historical drilling results and volumetric estimates. Since 1947, exploration drilling in eastern Kentucky has resulted in the discovery of only two significant St. Peter Sandstone gas fields: Trapp and Irvine-Furnace Consolidated fields. Approximately 144 wells have been drilled through the base of the St. Peter Sandstone in the 20-county area considered to be prospective in eastern Kentucky. The resulting success ratio is 1.4 percent. Several cases were examined with a range of success ratios from 1 to 10 percent. An average annual drilling rate of four wildcat wells per year for the next 40 years was assumed, based on the historical average annual drilling rate for 1947 to 1991. Each new field discovered was assigned ultimate reserves of 2 bcfg, based on the average size of the Trapp and Irvine-Furnace Consolidated fields. A low case was selected that is more optimistic (success ratio of 3 percent) than historical drilling results, based on the assumption that many of the early wildcat wells may not have been valid St. Peter Sandstone prospects. The high case was calculated using a success ratio of 10 percent and assumed that some of the future exploration would employ new technology, which could possibly reduce the number of dry holes. These numbers are highly speculative and are based on very limited data from the St. Peter Sandstone play area in eastern Kentucky only.

Future Trends

The most promising areas for future exploration in the St. Peter Sandstone should be in regions where major fault trends coincide with areas of thick sandstone development, and where the reported Btu value of the gas is high, such as Elliott, Lawrence, Johnson, and Martin counties, Kentucky, and Mingo, Wayne, and Cabell counties, West Virginia. The St. Peter Sandstone gas play trends northeastward beyond these counties into deeper portions of the Appalachian basin. The future limit of the play in a northeasterly direction will be determined by the economics of deep drilling depths (greater than 10,000 feet) and sparse well control.

The southwestern limit of the St. Peter Sandstone gas play is defined by the depositional extent of the prospective reservoir facies. The porous St. Peter Sandstone undergoes a lateral facies change into the nonporous Wells Creek Dolomite near the western end of the Kentucky River and Irvine-Paint Creek fault zones. Unfortunately, the high concentrations of carbon dioxide and nitrogen gas are of economic concern in established producing areas such as Estill, Powell, and Clark counties, Kentucky. However, these low-Btu gases may have value as a resource for other uses, such as secondary recovery in oil fields (for example, gas from the Irvine-Furnace Consolidated field was injected into oil reservoirs in Big Sinking field, Estill County, Kentucky).

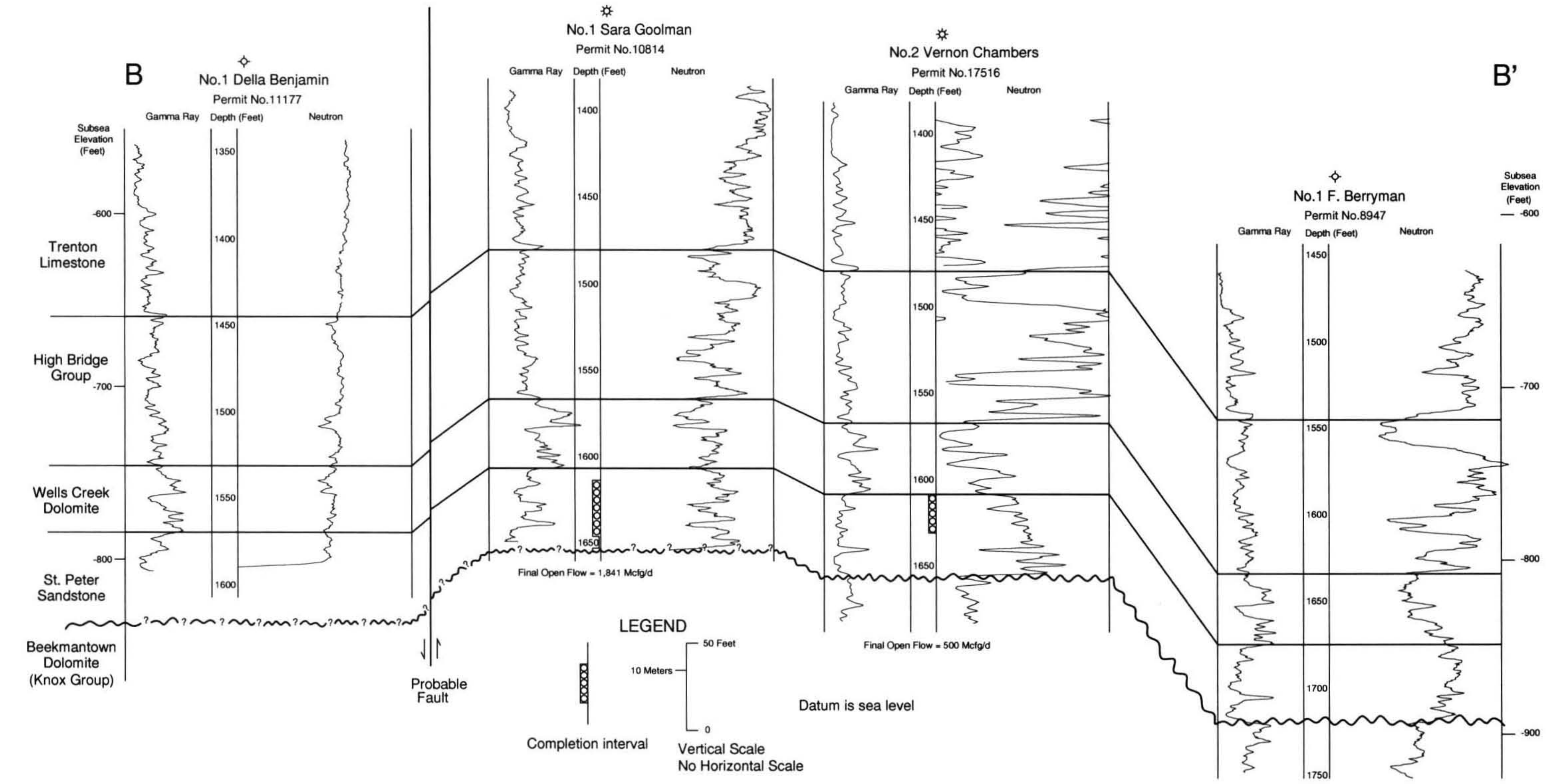


Figure Osp-10. Structural cross section B-B', across the Trapp field, Clark County, Kentucky. Completion intervals for the two gas productive wells (No. 1 Sara Goolman and No. 2 Vernon Chambers) are shown. Line of cross section is shown in Figure Osp-9.

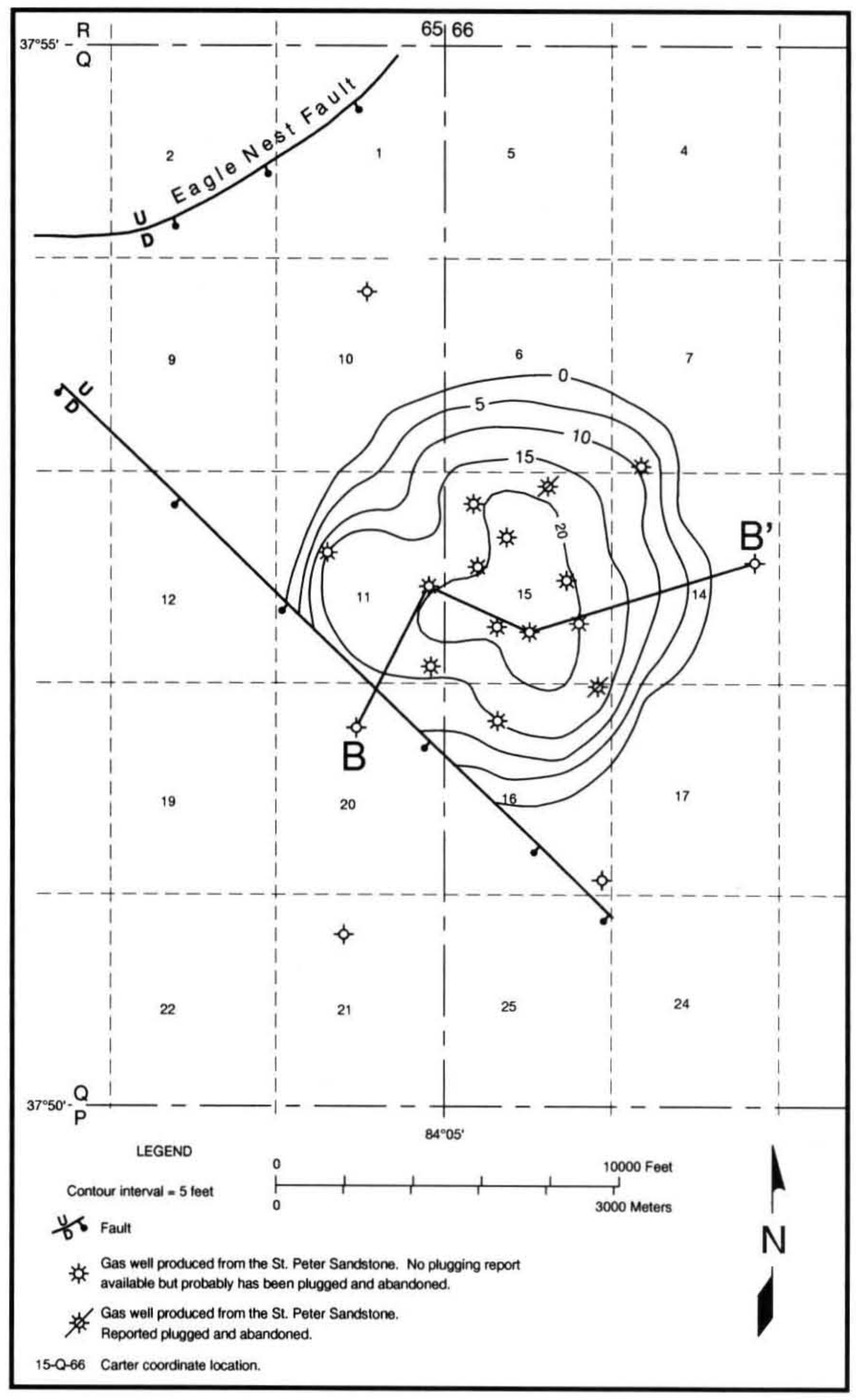


Figure Osp-11. Isopach map of St. Peter Sandstone at the Trapp field, Clark County, Kentucky showing net feet of pay with porosity greater than 9 percent, and estimated water saturation less than 55 percent.

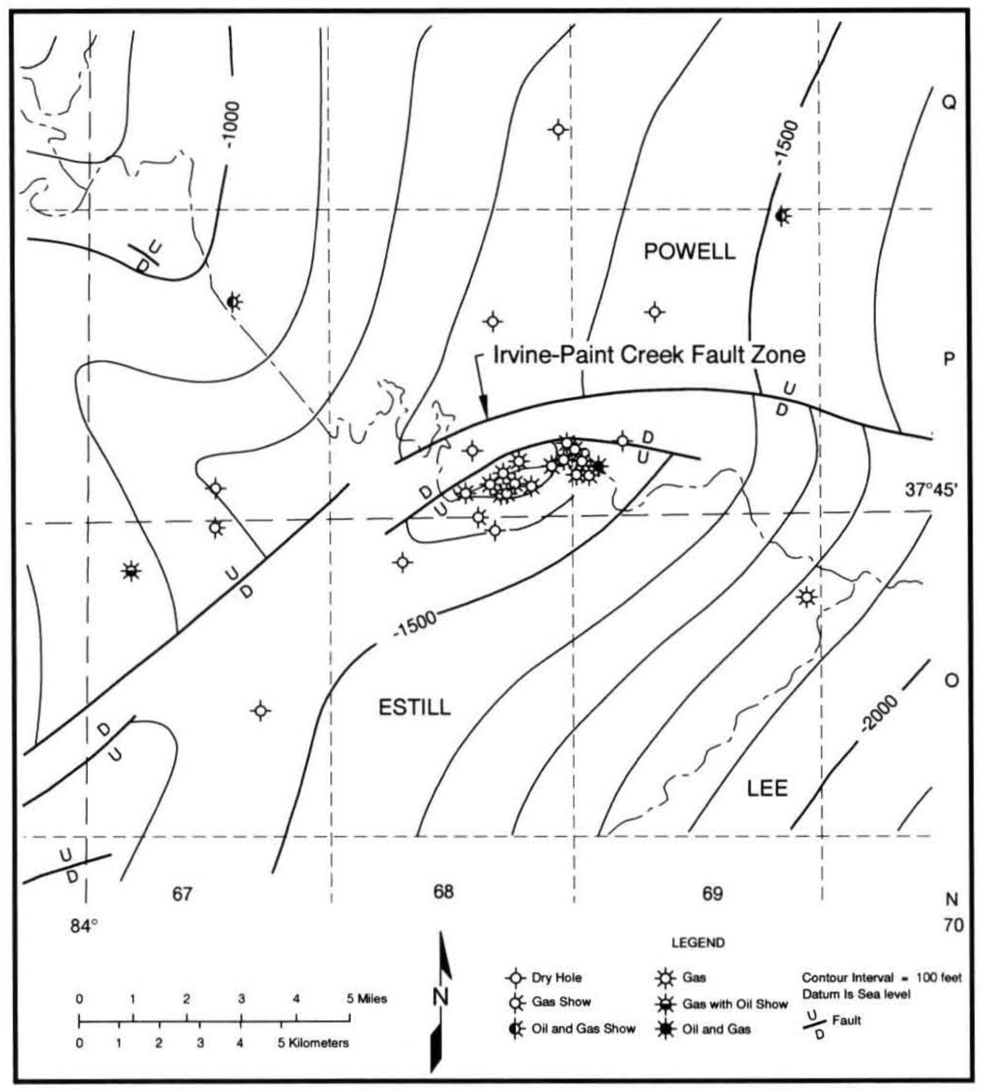


Figure Osp-12. Structure map of the Irvine-Furnace Consolidated field, Estill and Powell counties, Kentucky, contoured on top of the Knox Group. Modified from McGuire and Howell (1963).

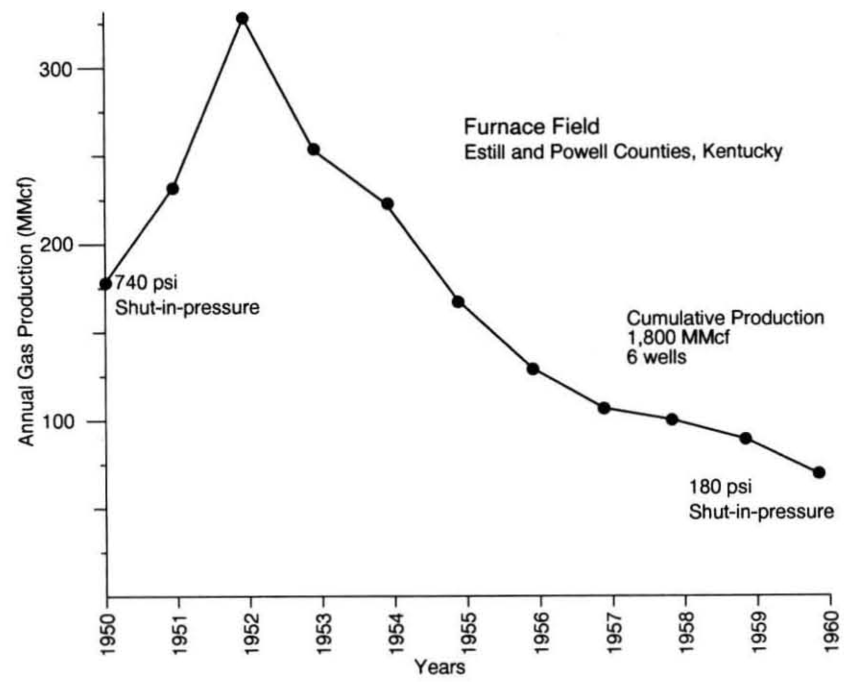


Figure Osp-13. Decline curve for St. Peter Sandstone gas production at the Furnace field (renamed Irvine-Furnace Consolidated), Estill and Powell counties, Kentucky. Modified from McGuire and Howell (1963).

PLAY COk: CAMBRIAN-ORDOVICIAN KNOX GROUP UNCONFORMITY PLAY

by Mark T. Baranoski and Ronald A. Riley, Ohio Division of Geological Survey; and Mark E. Wolfe, Ohio Division of Oil and Gas

Location

Productive gas pools and fields in the Cambrian-Ordovician Knox Group play occur in narrow to broad linear trends from northern Tennessee to south-central Kentucky, through central and northern Ohio, and extend in very localized areas of northwestern Pennsylvania and western New York (Figures COk-1, COk-2, COk-3). Knox hydrocarbon development and exploration is concentrated in Morrow and Coshocton counties of north-central and eastern Ohio and, to a lesser extent, Clinton and Clay counties in south-central and eastern Kentucky (Figure COk-2).

The Knox play consists of two major variations that are defined by and prospected for using seismic reflection data: paleotopographic reservoirs, which dominate the trends in Ohio; and fractured reservoirs, which dominate the trends in Kentucky and Tennessee. Structure appears to be important in the Kentucky-Tennessee area and in relatively unexplored areas east of the main producing trends. Other variations of the play, based largely on trapping mechanisms, can be identified within the Knox Group and include low-relief structural closures, faults, and updip stratigraphic truncation at the Knox unconformity.

Production History

The production history for Knox gas consists of three phases: pre-1960s; 1960s Morrow County, Ohio, boom; and post-1960s period. Before 1961, Knox production was obtained from fractured dolomite. In most cases, prospecting was not sophisticated. Drilling was random and near existing production or on shallow structures. Knox gas production was first established in 1919 in Marion County, Ohio, from the Caledonia field. First production in Kentucky occurred in Clinton County, Kentucky, in 1941 from the Concord Consolidated field (Figure COk-2). In Chautauqua County, New York, production from the Theresa Formation (partial Knox equivalent) was found in 1949 in a one-well pool within the giant Lakeshore field (Figure COk-2). Minor drilling for Knox production took place in Clay County, Kentucky, during the 1950s. The first significant Knox gas production in Ohio occurred from the Wiser Oil Company, No. 1-A Smith well (Medina 1143), drilled in the Hinckley field (Figure COk-2; Tables COk-1, COk-2) as a Precambrian test in 1959. This discovery had an initial daily production of 1.2 MMcfg from the Copper Ridge Dolomite. Cumulative production from this one-well pool by the end of 1992 was 1.16 bcfg.

In the early 1960s, the Knox remnant play as it is now known was discovered using geophysical techniques (W. Shafer, oral commun., 1994). In 1961, the discovery of gas and oil by the United Producing Company, No. 1 Orrie Myers well (Morrow 10), which had a reported initial daily production of 200 barrels of oil and a gas-oil ratio (GOR) of 300 cubic feet of gas per stock tank barrel (cfg/STB), led to the extensive development of the Morrow Consolidated field in Morrow County, Ohio (Figure COk-2). A combination of low gas price, high hydrogen sulfide content, and a lack of state-mandated conservation measures until 1965 caused the majority of the produced gas to be flared. Gas production was downplayed during early development of this field because of a demand for oil production. Since 1959, the Morrow Consolidated field has produced more than 35 bcfg from approximately 580 gas or combination wells, including an estimated 20 bcf of flared gas and 10 bcf of gas processed to extract butane and propane at a plant in Edison, Ohio, from 1964 to 1969.

The Morrow County, Ohio, boom resulted in the utilization of gravity and seismic reflection data during the 1960s on a widespread scale in Ohio during the prospecting for Knox hydrocarbons (Shafer, 1994). This new technology changed the way operators in the basin would look for Knox production. The excellent production found in Morrow County led to several wildcat discoveries in southern Kentucky, northern and eastern Ohio, and northwestern Pennsylvania during the 1960s (W. Shafer, oral commun., 1994).

Knox production was established in Pickett County, Tennessee, in 1963 at the Static Consolidated field (Figure COk-2). A Theresa sandstone discovery was made in Wyoming County, New York, in 1963. In Pennsylvania, the Transamerica Petroleum, No. 1 Scull well (Crawford 20094) was drilled in 1964 in Spring Township, Crawford County, and produced from the upper sandy member of the Gatesburg Formation (Rose Run Sandstone equivalent). This one-well Scull pool (Figure COk-2) had an IP of 7 MMcfg/d. Also in 1964 in Crawford County, the upper sandy member of the Gatesburg Formation produced gas in the Beaver Center pool (Figure COk-2) from the Transamerica Petroleum, No. 1 Voorhees well (Crawford 20119). In 1965 in Clark Township, Holmes County, Ohio, the Kin-Ark, No. 1 Erb well (Holmes 1328) was completed as a new field discovery in the Rose Run Sandstone. However, it would not be until the early 1980s that the significance of the Erb discovery would become known, leading to development of the Baltic field and current active drilling for Rose Run production (Figure COk-2). In 1966, seismic prospecting by Sun Oil Corporation in Erie County, Ohio, resulted in the discovery of hydrocarbons in the Krysik sandstone near the base of the Knox Dolomite in the Birmingham-Erie field (Janssens, 1973) (Figure COk-2).

Knox hydrocarbon exploration and development continued into the 1970s at a slower pace throughout the basin. In Clinton County, Kentucky, new Knox production continued in 1975 with the discovery of the Albany Consolidated field (Figure COk-2). Beekmantown gas production was discovered in 1975 in the Minard Run pool in McKean County, Pennsylvania (Figure COk-2). Knox production was discovered in 1974 in Fentress County, Tennessee, in the Glenoby field (Figure COk-2).

The 1980s marked the beginning of the current phase of exploration and development for the Knox play. Recognition of improved seismic acquisition and

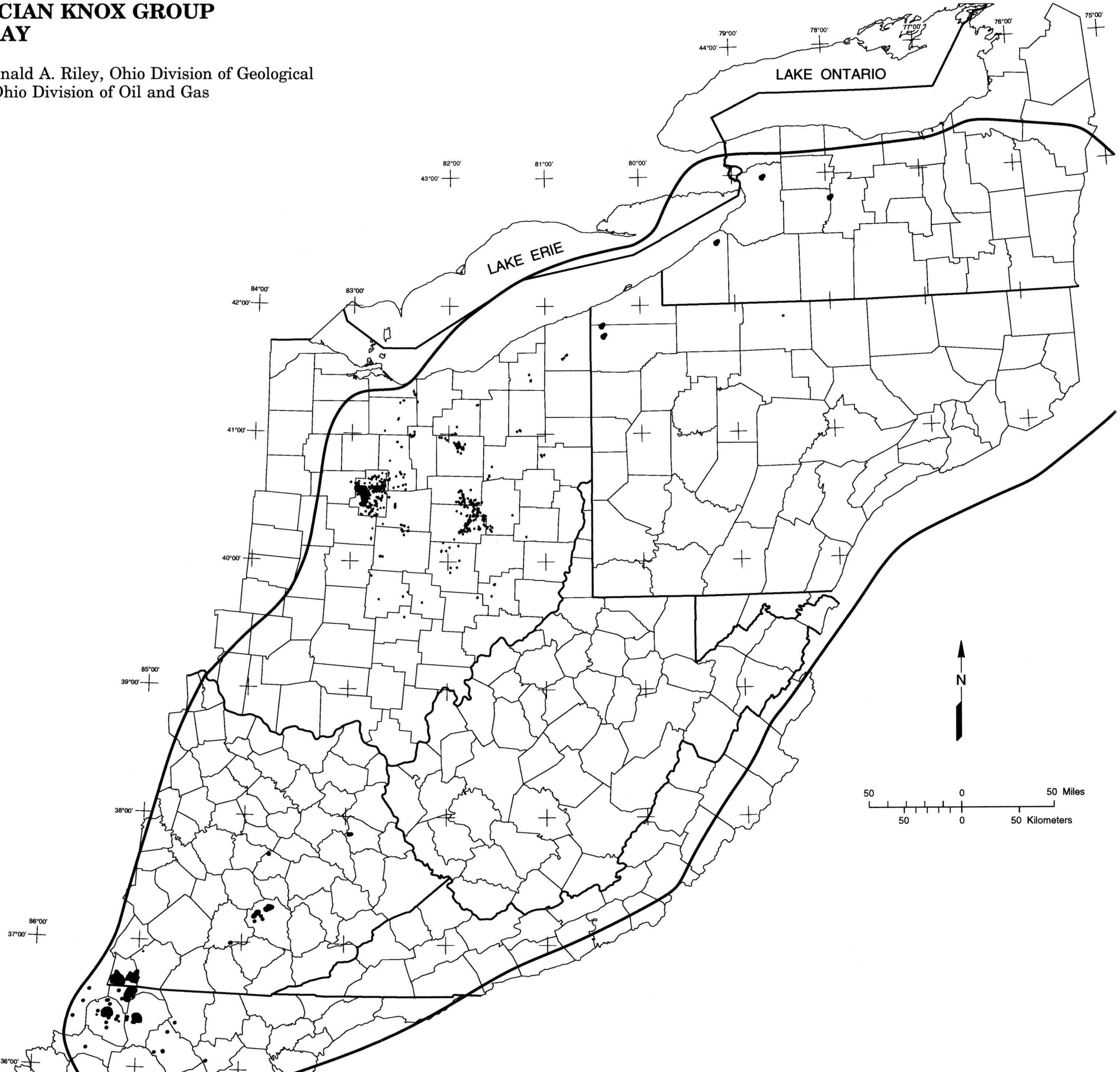


Figure COk-1. Outline of the Cambrian-Ordovician Knox Group unconformity play within the Appalachian basin. Dots represent individual gas wells; areas where dots have merged represent fields or pools. For eastern extent of play boundary, see Figure COk-23.

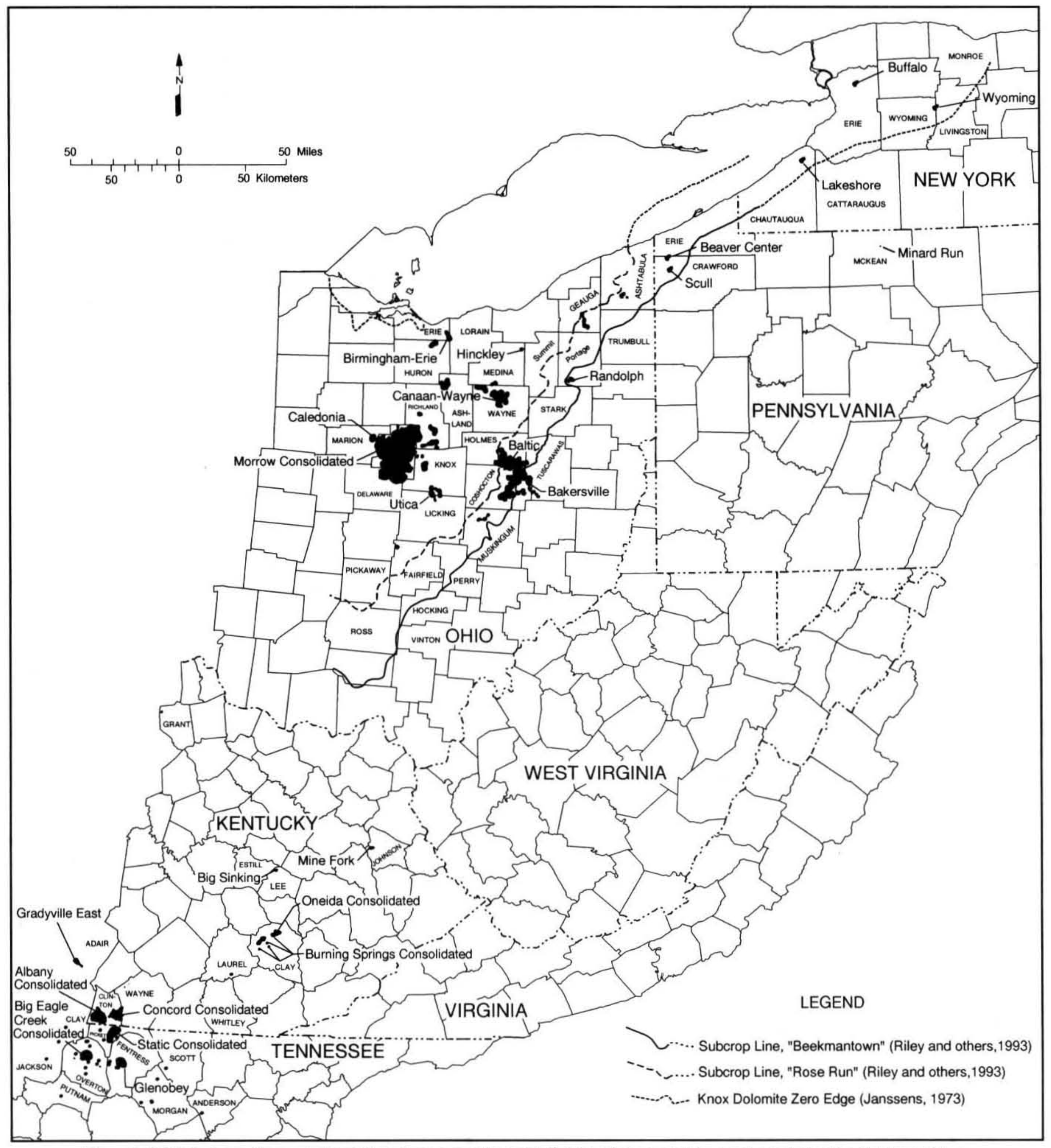


Figure COk-2. Location of significant gas pools and fields discussed in text or listed in Table COk-1.

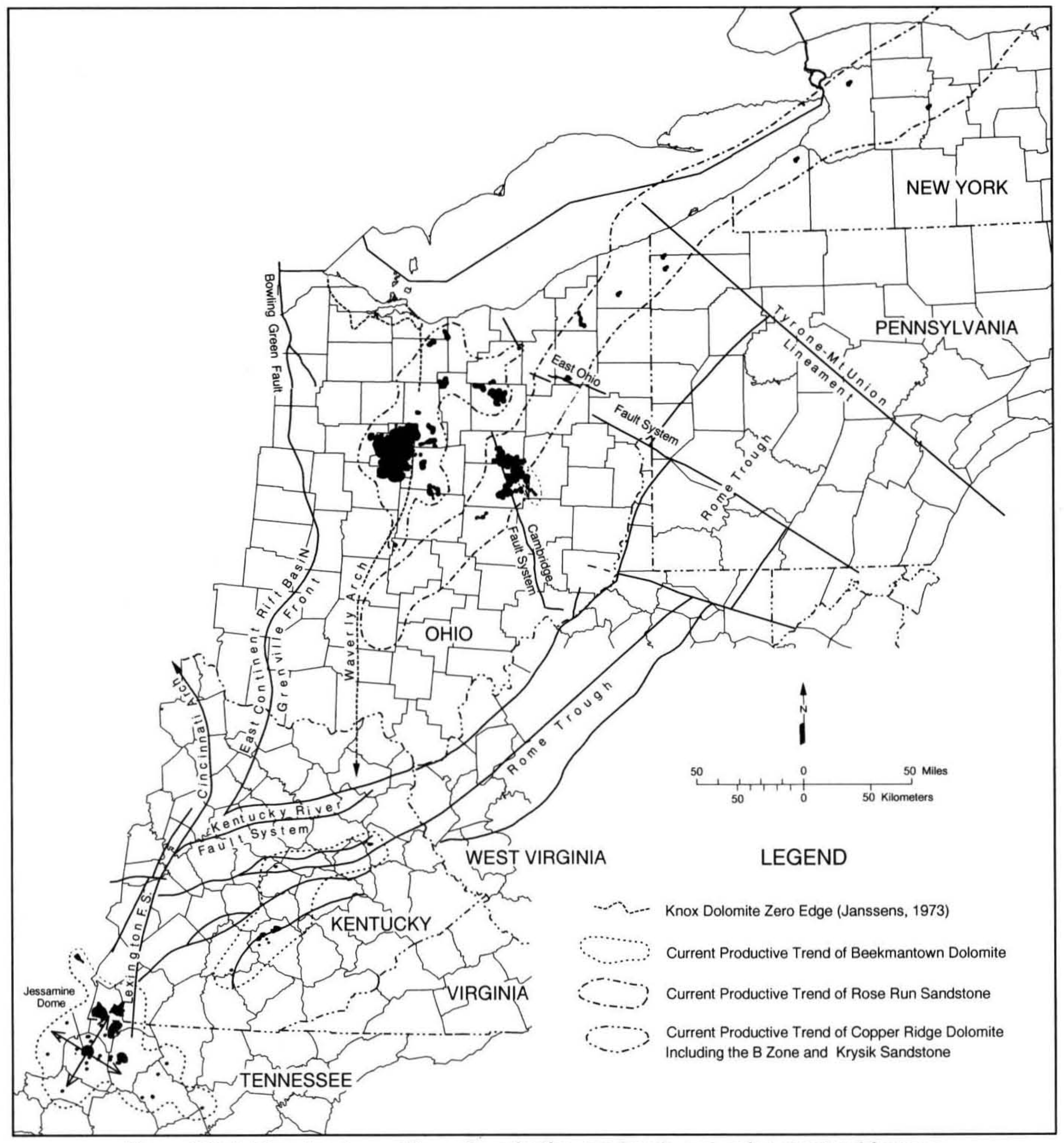


Figure COk-3. Map showing outlines of productive gas trends and major structural features.

processing and the need to drill deeper to find reserves led to the development of the Rose Run Sandstone in the Baltic field of Holmes and Coshocton counties, Ohio, and the Beekmantown Dolomite in the Bakersville field of Coshocton County, Ohio (Figure COk-2). Drilling for Knox production outside of Ohio during this phase continued in Clay, Clinton, Estill, Johnson, and Whitley counties, Kentucky, and Overton and Pickett counties, Tennessee (Figure COk-2). An extensive drilling program during the 1980s by Power Gas Company in the Wyoming field of New York resulted in the development of a thin sandstone unit in the Theresa Formation. Production has been approximately 500 MMcf in the Wyoming field from 1991 to 1993. In 1984, a significant show was found in the Rose Run Sandstone in Lee County, Kentucky, in the Big Sinking field (Figure COk-2). The Rose Run was perforated, squeezed off, and never put on line for production. The initial open flow measured for this well was 1.6 MMcfg.

Knox drilling during the 1990s continues to develop Rose Run Sandstone production along the trend (Figures COk-2, COk-3). Production to the east of the Rose Run trend has been found in seismically defined structures. The 1990 discovery of B zone production in the Utica field of Knox and Licking counties, Ohio, has added a new structural variation to the play (Figure COk-2). Based upon estimated proven Knox gas reserves of 179 bcf (Table COk-3) and assuming that approximately 80 percent of the gas has been depleted, the estimated cumulative gas production for all Knox gas fields is 143 bcf.

Stratigraphy

Cambrian and Ordovician rocks of the Knox Group in the Appalachian basin have been studied for more than 150 years, resulting in numerous stratigraphic names. The varied Upper Cambrian and Lower Ordovician stratigraphic nomenclature of the Appalachian basin is illustrated in a regional correlation chart (Figure COk-4). Summaries of previous work can be found in Calvert (1962) and Janssens (1973) for Ohio; Wagner (1966) for Pennsylvania; McGuire and Howell (1963) for Kentucky; Flagler (1966) and Rickard (1973) for New York; and Pfeil and Read (1980), Read (1980; 1989), Markello and Read (1981; 1982), and Mussman and Read (1986) in Virginia. More recent work for the Appalachian basin region is that of Harris (1975), Ryder (1991; 1992a; 1992b; 1994), Ryder, Harris, and Repetski (1992), and Riley and others (1993).

The Knox unconformity developed during a change from passive to convergent margin of the Laurentian plate during Early Ordovician time (Scotese and McKerrow, 1991). This plate movement initiated major changes in sea level, tectonism, and depositional environments (Mussman and Read, 1986; Read, 1989). By the early Middle Ordovician, much of the southern continental shelf of Laurentia was emergent, resulting in a widespread erosional surface, the Knox unconformity, that can be recognized throughout most of the present Appalachians (Mussman and Read, 1986).

Regional thickness of the Knox Group and equivalent rocks in the Appalachian basin ranges from 0 feet in extreme north-central Ohio to more than 7,000 feet in central Maryland (Figure COk-5). Two prominent regional features are evident on the Knox isopach map (Figure COk-5): a broad thin area between the zero edge in northern Ohio to 1,500 feet isopach in northeastern Kentucky; and an area of northeast-southwest thick and thin trends in central Pennsylvania, western Maryland, and Virginia ranging in thickness from 3,000 to 7,000 feet.

The broad area of relatively thin Knox in central Ohio and eastern Kentucky is largely the result of erosion that formed the Knox unconformity. This broad area is the Waverly arch (Figure COk-3). Knox units beneath the Knox unconformity thin onto the Waverly arch and suggest control by basement faulting (Ryder, 1992a; Baranoski, 1993). The thicker Knox sequence to the east probably extended further east than the Valley and Ridge and represents deposits in the rapidly subsiding asymmetric portion of the basin.

Producing units in the Knox Group (Knox Dolomite of Janssens, 1973) unconformity play are subdivided into the following, in descending stratigraphic order: Beekmantown Dolomite (Clarke and Schuchert, 1899); Rose Run Sandstone (Freeman, 1949); upper sandy member of the Gatesburg Formation (Butts, 1918); Theresa Formation (Cushing, 1908); Copper Ridge Dolomite (drillers' "Trempealeau" dolomite) (Ulrich, 1911); stray sandstones in the upper Copper Ridge Dolomite; and the B zone (Calvert, 1963) and Krysik sandstone (Janssens, 1973) of the lower Copper Ridge Dolomite (Figure COk-4).

In Ohio, west of the Rome trough, the Beekmantown Group of Ryder (1992a) is represented by two units separated by the Knox unconformity: the upper unit is the Wells Creek Formation, and the lower is the Beekmantown Dolomite of Janssens' (1973) Knox Dolomite. The Beekmantown Dolomite of the Knox Dolomite is equivalent to the lower dolomite unit of Ryder's (1992a) Beekmantown Group (Figure COk-4). The upper unit above the Knox unconformity is the Wells Creek Formation, as used by Stith (1979), and is laterally equivalent to a middle sandstone and the upper anhydritic dolomite of Ryder's (1992a) Beekmantown Group. The Ohio Beekmantown Dolomite thins westward from more than 600 feet in eastern Ohio to where it is absent on the northern portion of the Waverly arch (Figure COk-3) by erosional truncation at the Knox unconformity (Janssens, 1973). Work by Shearrow (1987) and Riley and others (1993) indicates that the Beekmantown thins across the Waverly arch in south-central Ohio, and thickens to the west and southwest (Figure COk-6).

In the Rome trough in Somerset County, Pennsylvania (Figure COk-3), the Beekmantown Group consists of a predominantly dolomite sequence that reaches a thickness of approximately 3,000 feet in the Amoco, No. 1 Svetz well (Somerset 20045) (Ryder, Harris, and Repetski, 1992). This sequence conformably overlies the upper sandy member of the Gatesburg Formation (Rose Run Sandstone equivalent) and consists of the following units, in descending stratigraphic order, as defined by Wagner (1966): the Bellefonte Dolomite; the Nittany Dolomite; and the Larke Dolomite and its equivalent, the Stonehenge Limestone (Figure COk-4). The Mines Member of the Gatesburg in Pennsylvania is a dolomite partially equivalent to the Beekmantown of Ohio. In the Rome trough in West Virginia, the Beekmantown Group consists of three units: a lower dolomite unit, a middle sandstone unit, and an upper anhydritic dolomite unit (Ryder, 1992a). East of the Rome trough in West Virginia, the Beekmantown Group lacks these well-defined units and consists of an undifferentiated dolomite. The lower unnamed unit of the Beekmantown Group thickens eastward at the expense of overlying units to approximately 2,150 feet at the Allegheny structural front (Ryder, 1992a). In west-central New York, the Tribes Hill Formation is partially equivalent to the Beekmantown Group. West of the Rome trough in the Ohio-West Virginia hinge zone of Ryder (1992a), the Beekmantown Group thins to approximately 1,100 feet. Lateral equivalents to the Beekmantown are termed Mascot Dolomite, Kingsport Formation, and Chepultepec Dolomite in southern Kentucky (Harris, 1969), Tennessee (Harris, 1969), and Virginia (Butts, 1940); and the Bellefonte Dolomite, Nittany Dolomite, and Stonehenge-Larke formations in central and eastern Pennsylvania and western Maryland (Patchen and others, 1985a; Milici and de Witt, 1988) (Figure COk-4).

The Rose Run Sandstone is the only laterally persistent sandstone within the Knox. Janssens (1973) extended the use of this term from Kentucky into Ohio. This sandstone interval can be correlated in the subsurface from eastern Ohio, where it subcrops beneath the Knox unconformity, to northeast Kentucky, into western West Virginia, Pennsylvania (upper sandy member of the Gatesburg Formation equivalent), and extends into New York as part of the Theresa Formation (Figure COk-4). Lithologically, it consists of a sequence of porous quartz arenites to subarkoses, interbedded with thin lenses of nonporous dolomite. Atha (1981) and Riley and others (1993) indicated that in Ohio the sandstone-to-carbonate ratio of the Rose Run interval appears to decrease to the east, southeast, and west of the Waverly arch (Figure COk-3).

As a result of exploratory drilling below the Rose Run Sandstone in Holmes County, Ohio, hydrocarbon production has been reported from stray sandstones in the upper Copper Ridge between the B zone and the overlying Rose Run Sandstone. These sandstones correlate in part to an unnamed sandstone in the Copper Ridge in the National Gas and Oil Corporation No. 3-A Reiss well (Coshocton 6379) (Figure COk-7). Lithologically, they consist of fine-grained, white quartz arenites to subarkoses. Isopach maps show these stray sandstone lenses to be narrow in areal extent and trend in a northwest-to-southeast direction (Riley, 1992). The linear depositional pattern of the sandstone lenses has been interpreted to be controlled by the Cambridge fault system (Riley and others, 1993).

The Copper Ridge Dolomite in Ohio is a microcrystalline to medium crystalline gray to brown dolomicrite that is pelletal and oolitic in part and contains abundant digitate stromatolites. Algal stromatolites also are present in the Copper Ridge in Tennessee. In Ohio, there are minor silty, glauconitic, argillaceous dolomicrite and silty shale interbeds (Janssens, 1973; Ryder, 1994). The Copper Ridge Dolomite in Ohio initially was dolomitized in a near-surface seawater-meteoric water mixing environment in a karstic terrain (Petrie, 1982). The Copper Ridge Dolomite and other Knox carbonates appear to have undergone several episodes of dolomitization (Anderson, 1991; Riley and others, 1993). The Conococheague Formation of Tennessee and Virginia is a lateral equivalent of the Copper Ridge Dolomite (Figure COk-4).

In north-central Ohio, a mappable, silty, glauconitic unit named the B zone by Calvert (1963) has been used by drillers to separate the upper and lower Copper Ridge Dolomite (Figure COk-8). Coogan and Maki (1988) termed this unit the Steam Corners Member of the Knox Dolomite, and in addition to Calvert (1962; 1963) and Janssens (1973), recognized the utility of this unit for correlation in certain areas of Ohio. In northeastern Ohio, however, the presence of this unit has not yet been established. Correlation is also difficult in southern and extreme eastern Ohio and the adjacent states because the easily recognized clastic sediments of the zone are absent. The B zone is recognized in Knox and Licking counties in central Ohio where it has recent production from exploratory wells.

The B zone occurs as an extensive elongate pod trending from north- to south-central Ohio. The thickness of the unit ranges from 0 to 100 feet, increasing in thickness towards the south. The thickness, however, is variable because of local facies changes where the amount of clastics is exceeded by carbonates. Lithologically, the B zone is an upward-coarsening sequence of interbedded, bioturbated, dolomitic siltstones and dolomicrites that are sandy and glauconitic in part (Ryder, 1994). Locally, the B zone is sandy at its westernmost extent in western Ohio.

The Krysik sandstone was named by drillers after the discovery well, the Sun Oil, No. 1 Krysik-Wakefield (Erie 11), in the Birmingham-Erie field in Erie County, Ohio (Figure COk-8). This well was completed in 1965 following detailed seismic exploration (Janssens, 1973). The Krysik is an angular to subangular, fine- to medium-grained, white to clear quartzose sandstone that is glauconitic in part. Coogan and Maki (1988) noted that the B zone and the Krysik sandstone of drillers' usage have an areal distribution similar to that of Janssens' (1973) older Kerbel Formation. They considered the Krysik sandstone a facies change within the basal part of the B zone and that both units constitute their Steam Corners Member. It is not certain whether or not the B zone is stratigraphically equivalent to the Krysik sandstone or possibly the Krysik is an older unit representing an earlier period of clastic deposition.

The age of the Knox Group is Late Cambrian and Early Ordovician. The Cambrian-Ordovician boundary within the Knox Group or Knox Dolomite of Janssens (1973) in Ohio is not clearly defined (Figure COk-4). The Rose Run Sandstone and its equivalents have been assigned a Late Cambrian age in Pennsylvania, West Virginia, and Ohio (Ryder, 1992a), whereas in Kentucky the Rose Run Sandstone is thought to be Early Ordovician in age (McGuire and Howell, 1963).

Deposition of the Knox units has been attributed by various authors to represent a peritidal to shallow subtidal marine environment (Atha, 1981; Mussman and Read, 1986; Anderson, 1991; Enterline, 1991; Gooding, 1992; Ryder, 1992a; 1992b; Riley and others, 1993). The Knox is part of a heterogeneous assemblage of interbedded siliciclastic and carbonate facies deposited on a carbonate shelf, which Ginsburg (1982) referred to as the "Great American Bank." This bank contained a complex mosaic of interdependent subenvironments in which depositional processes imprinted distinctive physical, diagenetic, and biogenic features on the rocks.

Hardie (1986), Read (1989), and Osleger and Read (1991) interpreted the vertical stacking of various peritidal carbonate facies to be the result of shelfwide cyclical sea-level changes (Borer and Harris, 1991). Subtidal carbonate facies in the section occur within upward-shallowing sequences deposited in a shelf lagoon environment (Demicco, 1985; Read, 1989). Lowstand deposits of siliciclastic sediments such as the Rose Run Sandstone were transported onto the peritidal platform and reworked during subsequent sea-level rises (Read, 1989). Detailed correlations by Riley and others (1993) in densely drilled producing areas of eastern Ohio corroborate this hypothesis. Ryder (1994) interpreted the B zone in western Morrow County, Ohio, to have been deposited at the distal edge of a prograding sheet sandstone on a low-energy marine shelf.

Structure

The regional structural contour map of the Knox Group (Figure COk-9) indicates that the unit plunges basinward at a rather even, low gradient eastward and southeastward in the northern half of the basin. In the southern half, the slope of the Knox is southeastward becoming southward and is broken by a large-scale structure, the east- to northeast-trending Rome trough. The Kentucky River, East Ohio, and Cambridge fault systems, and Waverly arch are the primary structural features known to affect Knox gas production in the Appalachian basin (Figure COk-3, Cok-9). Minor unnamed structural features such as localized basement faults and small-scale folds have enhanced Knox production on a local basis, as is the case with the Utica field in Ohio (Figures COk-2, COk-10, COk-11). Major large-scale structural features in the basin such as the Rome trough are largely untested (Figures COk-3, COk-9).

Locally, subtle anticlinal traps play a role in gas production from the Knox play. Open fractures also enhance this largely stratigraphic play. In Kentucky and Tennessee, the reservoir is the Beekmantown Dolomite and is dominated by tectonically controlled fractures and linear trends that are often associated with paleotopographic highs. Petroleum accumulations appear to be related to paleolineaments near the top of the Knox. These lineaments indicate a dominant fracture system trending N 20° W, N 20° E, and N 60° E that also can be recognized on high-altitude, color-infrared imagery (Anderson, 1991). A relationship between paleolineaments and alignment of paleokarst features is evident. Significant relief on the Knox unconformity and large-scale solution-collapse features indicate that the southern portion of the basin may have been subjected to a greater degree of karsting than the northern portion. In south-central Kentucky and eastern Tennessee, paleotopographic relief is on the order of 300 to 400 feet (Harris, 1969; Anderson, 1991).

A relationship between basement faults and Knox paleotopographic highs has been proposed as a controlling factor to Rose Run production in eastern Ohio (Coogan and Lesser, 1991; Riley and others, 1993). Based upon mapping in Coshocton County, Ohio, Coogan and Lesser (1991) suggested that the Knox is broken into individual structural blocks bounded by two dominant fault systems: northwest-southeast and northeast-southwest. Wells in a high structural position appear to have the best Knox production. Shafer (1994) proposed that pre-existing basement features affected Copper Ridge gas and oil accumulation in Morrow County, Ohio.

TABLE COk-1	Static Consolidated TN	Big Eagle Consolidated TN	Glenobey TN	Albany Consolidated KY	Burning Springs Consolidated KY	Oneida Consolidated KY	Mine Fork KY	Hinckley OH	Wayne-Canaan OH
BASIC RESERVOIR DATA									
POOL NUMBER	410137	410133	410049	1601142368	1600320368	1601461368	1601319372	341030350	341690421
DISCOVERED	1963	1982	1974	1975	1984	1985	1986	1959	1960
DEPTH TO TOP RESERVOIR	1,600		2,000	1,400	3,170	3,540	5,640	5,820	5,500
AGE OF RESERVOIR				Lower Ordovician	Lower Ordovician	Lower Ordovician	Lower Ordovician	Upper Cambrian	Upper Cambrian
FORMATION	Knox	Knox	Knox	Knox	Knox	Knox	Copper Ridge	Knox	Knox
PRODUCING RESERVOIR	Knox	Knox	Knox	Knox	Beekmantown	Beekmantown	Copper Ridge	Copper Ridge	Copper Ridge
LITHOLOGY	dolomite	dolomite	dolomite	dolomite	dolomite	dolomite	dolomite	dolomite	dolomite
TRAP TYPE				stratigraphic structural	stratigraphic structural	stratigraphic structural	structural	structural	structural
DEPOSITIONAL ENVIRONMENT	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine
DISCOVERY WELL IP (Mcf)				150	20	700	361	1,200	419
DRIVE MECHANISM	solution gas	solution gas		gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	solution gas water
NO. PRODUCING WELLS	6	8	8	36	24	11	2	1	25
NO. ABANDONED WELLS				5	3	0	0	0	9
AREA (acreage)				3,369	1,873	725	248	153	1,301
OLDEST FORMATION PENETRATED	Knox	Knox	Knox	Knox	Knox	Knox	Rome	Precambrian	Rome
EXPECTED HETEROGENEITY DUE TO:				fracture diagenesis	fracture	fracture	fracture	structural	structural
RESERVOIR PARAMETERS									
AVERAGE PAY THICKNESS (ft.)				6	33	42	27	20	16
AVERAGE COMPLETION THICKNESS (ft.)				52	54	79	208	15	17
AVERAGE POROSITY–LOG (%)				9	8	9	4	8	9
MINIMUM POROSITY–LOG (%)				4	4	4	2	3	9
MAXIMUM POROSITY–LOG (%)				12	16	15	15	14	12
NO. DATA POINTS				4	10	9	2	1	8
POROSITY FEET				54	264	378	108	160	144
RESERVOIR TEMPERATURE (°F)					85	93	100	110	114
INITIAL RESERVOIR PRESSURE (psi)	300	230	300		240	1,100	725	2,100	2,000
PRODUCING INTERVAL DEPTHS (ft.)	1,600-1,900		2,000-2,300	1,400-1,920	3,170-3,870	3,540-3,880	5,640-5,740	5,820-5,860	5,500-5,800
PRESENT RESERVOIR PRESSURE (psi) / DATE					350/1987		700/1985		880/1990
FLUID & GAS PROPERTIES									
Rw (Ωm)					0.06	0.06	0.05	0.035	0.035
GAS GRAVITY (g/cc)								0.63	
GAS SATURATION (%)					59	33	77	65	70
WATER SATURATION (%)					41	67	23	31	26
COMMINGLED								no	yes
ASSOCIATED OR NONASSOCIATED	associated	associated	associated	nonassociated	associated	associated	associated	nonassociated	associated
Btu/scf								1,211	
VOLUMETRIC DATA									
STATUS (producing, abandoned, storage)				producing	producing	producing	producing	producing	producing
ORIGINAL GAS IN PLACE (Mcf)				2,300,000	6,700,000	3,400,000	2,500,000	1,350,000	7,650,000
ORIGINAL GAS RESERVES (Mcf)				1,900,000	5,200,000	2,800,000	2,100,000	1,215,000	6,120,000
PRODUCTION YEARS								1959-1992	1961-1992
REPORTED CUMULATIVE PRODUCTION (Mcf)					290,000	10,000		1,160,000	3,620,000
NO. WELLS REPORTED					3	1		1	20
ESTIMATED CUMULATIVE PRODUCTION (Mcf)					290,000	10,000		1,200,000	5,100,000
REMAINING GAS IN PLACE (Mcf)/YEAR								150,000	2,550,000
REMAINING GAS RESERVES (Mcf)/YEAR								15,000/1993	1,020,000/1993
RECOVERY FACTOR (%)								80	80
INITIAL OPEN FLOW (Mcf/d)								192	144
FINAL OPEN FLOW (Mcf/d)	180	110	160	131	202	879	216	1,200	523

TABLE COk-1 (continued)	Utica OH	Birmingham-Erie OH	Bakersville OH	Baltic OH	Randolph OH	Morrow Consolidated OH	Scull PA	Beaver Center PA	Minard Run PA	Buffalo NY	Wyoming NY	Lakeshore NY
BASIC RESERVOIR DATA												
POOL NUMBER	340890537	340430953	340310967	340310948	341330969	341170974	37039	37039	37083	310029	310121	310013
DISCOVERED	1990	1966	1980	1965	1990	1959	1964	1964	1975	1923	1963	1949
DEPTH TO TOP RESERVOIR	4,100	3,800	6,720	6,010	7,030	3,000	6,300	6,010	10,010	3,420	5,250	4,410
AGE OF RESERVOIR	Upper Cambrian	Upper Cambrian	Lower Ordovician	Upper Cambrian	Upper Cambrian	Upper Cambrian	Upper Cambrian	Upper Cambrian	Upper Cambrian	Upper Cambrian	Upper Cambrian	Upper Cambrian
FORMATION	Knox	Knox	Knox	Knox	Knox	Knox	Gatesburg	Gatesburg	Little Falls	Theresa	Theresa	Theresa
PRODUCING RESERVOIR	Copper Ridge Knox	Krysik	Beekmantown	Rose Run	Rose Run	Copper Ridge	Upper Sandy	Upper Sandy	Little Falls	Theresa	Theresa	Theresa
LITHOLOGY	siltstone dolomite	sandstone	dolomite	sandstone	sandstone	dolomite	sandstone	sandstone	dolomite	sandstone	sandstone	sandstone
TRAP TYPE	structural	structural	stratigraphic structural	stratigraphic structural	stratigraphic structural	stratigraphic	stratigraphic structural	stratigraphic structural		stratigraphic	stratigraphic	stratigraphic
DEPOSITIONAL ENVIRONMENT	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine	shallow marine
DISCOVERY WELL IP (Mcf)	390		1,000	2,100	150	265	7,000	1,640	500	680	250	200
DRIVE MECHANISM	solution gas water	solution gas water	solution gas water	solution gas water	solution gas water	solution gas water	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion	gas expansion
NO. PRODUCING WELLS	19	8	33	122	4	340	0	0	1	1	4	1
NO. ABANDONED WELLS	2	1	0	9	0	241	1	1	0	1	6	0
AREA (acreage)	459	290	1,300	5,172	160	9,708	70	58	84	40	500	40
OLDEST FORMATION PENETRATED	Precambrian	Precambrian	Copper Ridge	Rome	Copper Ridge	Mount Simon	Gatesburg	Gatesburg	Little Falls	Theresa	Precambrian	Theresa
EXPECTED HETEROGENEITY DUE TO:	structural	structural	diagenesis deposition	diagenesis deposition	fracture diagenesis	diagenesis	fracture structural	fracture structural		diagenesis	diagenesis	diagenesis
RESERVOIR PARAMETERS												
AVERAGE PAY THICKNESS (ft.)	14	14	10	40	30	14	10	15	120	4	100	10
AVERAGE COMPLETION THICKNESS (ft.)	24	12	18	22	28	18	3	13		4	30	10
AVERAGE POROSITY–LOG (%)	6	11	15	8	8	9	10	10	10			
MINIMUM POROSITY–LOG (%)	2	12	2	3	3	4	4	6	4			
MAXIMUM POROSITY–LOG (%)	12	17	22	15	12	18	20	18	16			
NO. DATA POINTS	14	5	10	10	4	30	1	1	1			
POROSITY FEET	84	150	150	320	240	126	30	150	1,200			
RESERVOIR TEMPERATURE (°F)	101	93	130	126	140	98		88	172			
INITIAL RESERVOIR PRESSURE (psi)	1,260	1,500	2,200	2,200	2,200	1,280	2,150	2,200	3,000	1100	1,600	
PRODUCING INTERVAL DEPTHS (ft.)	4,100-4,500	3,800-3,900	6,720-7,380	6,010-6,770	7,030-7,160	3,000-4,200	6,300-6,310	6,010-6,025	10,010-10,230	3,416-3,420	5,250-5,400	4,410-4,500
PRESENT RESERVOIR PRESSURE (psi) / DATE						800/1992						
FLUID & GAS PROPERTIES												
Rw (Ωm)	0.04	0.04	0.035	0.035	0.035	0.04						
GAS GRAVITY (g/cc)	0.67					0.62				0.59		
GAS SATURATION (%)			60	60	67	63						
WATER SATURATION (%)		30	40	40	30	25	24	28				
COMMINGLED	yes	yes	no	no	no	yes	no	no				
ASSOCIATED OR NONASSOCIATED	associated	associated	associated	associated	associated	associated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated	nonassociated
Btu/scf	1,150			1,089		1,062				1,006		
VOLUMETRIC DATA												
STATUS (producing, abandoned, storage)	producing	producing	producing	producing	producing	producing	shut-in	abandoned	producing	abandoned	producing	producing
ORIGINAL GAS IN PLACE (Mcf)	1,840,000	1,380,000	24,750,000	77,000,000	2,200,000	52,000,000	400,000	70,000				
ORIGINAL GAS RESERVES (Mcf)	1,470,000	900,000	19,800,000	50,000,000	1,400,000	42,000,000						
PRODUCTION YEARS	1990-1992	1966-1992	1980-1992	1965-1992	1990-1992	1959-1992	1964-1965	1964-1965	1975-1992		1991-1993	
REPORTED CUMULATIVE PRODUCTION (Mcf)	390,000	530,000	8,000,000	20,000,000	425,000	35,000,000	190,000	70,000	19,202		500,000	
NO. WELLS REPORTED	7	6	28	113	4			1	1			
ESTIMATED CUMULATIVE PRODUCTION (Mcf)	1,260,000	900,000	11,500,000	26,200,000	500,000		190,000	70,000	19,202	<50,000	1,000,000	<50,000
REMAINING GAS IN PLACE (Mcf)/YEAR	580,000	480,000	13,250,000	50,800,000	1,700,000	17,000,000						
REMAINING GAS RESERVES (Mcf)/YEAR	210,000/1993	0/1993	8,300,000/1993	23,800,000/1993	900,000/1993	7,000,000						
RECOVERY FACTOR (%)	80	65	80	65	65	80						
INITIAL OPEN FLOW (Mcf/d)	152	180	80	490		390	7,000		500			75
FINAL OPEN FLOW (Mcf/d)	215	70	380	280	270	355	2,590	1,640		680	250	

Reservoir

In terms of migration, hydrocarbon entrapment, and reservoir performance (porosity and permeability), the paleotopography, its exposure, and resulting karst processes on the Knox unconformity are the most important geologic factors influencing gas production in the Knox carbonates (Dolly and Busch, 1972; Janssens, 1973; Mussman and others, 1988; Anderson, 1991; Gooding, 1992; Riley and others, 1993). Porosity development in carbonates is strongly related to dolomitization, predominantly in the form of solution-enlarged fractures and vugs near the Knox unconformity. Porosity in the Knox sandstone units is directly related to mineralogic composition of detrital grains, cementing agents, and diagenesis (Riley and others, 1993). During the Paleozoic burial process, compaction and loading continued and fractured the Knox carbonates. Deep basinal brines following the fractures caused additional dolomitization and dissolution of these units (Mussman and others, 1988).

Primary trapping mechanisms for Knox units include paleotopographic highs (erosional remnants), vuggy porosity zones, faults and associated fractures, stratigraphic updip truncations against the Knox unconformity, and basement-related structures (Figure COk-12). Channel sandstone traps, structural closures, and small anticlinal noses are less common. Reservoir rocks consist dominantly of either dolomite or sandstone. Siltstones of the B zone typically do not have as high a reservoir quality as the more porous sandstones and vuggy dolomites of the Knox.

Seismic reflection data are extremely useful in locating reservoirs for these exploration targets. Seismic reflection anomalies in the form of amplitude and frequency variations occur at or near the Knox unconformity in productive areas (Riley and others, 1993; Shafer, 1994). In most instances, productive wells on the seismic anomaly correlate to a Knox paleotopographic high where the Wells Creek Formation is thin or absent. Seals for these paleotopographic high reservoirs are the overlying Black River Group, Wells Creek Formation, Beekmantown Dolomite, or Copper Ridge Dolomite. Lateral seals against small offset faults and open joints and fractures are provided by impermeable dolomite (Riley and others, 1993).

In New York, Pennsylvania, Ohio, and West Virginia, source rocks for Knox hydrocarbons are the uppermost Middle and Upper Ordovician Utica Shale and equivalent units (Cole and others, 1987; Wallace and Roen, 1989; Laughrey, 1989; Ryder, Burruss, and Hatch, 1992). It has been suggested (without geochemical evidence) that locally the Wells Creek Formation may have been the source of hydrocarbons in the Knox (Dolly and Busch, 1972; Petrie, 1982; Ryder, Harris, and Repetski, 1992). The Upper Devonian Chattanooga Shale is the source rock for Knox hydrocarbons in the Cumberland saddle region in south-central Kentucky (Rheams and Neathery, 1984; Ryder, 1987). The Middle Ordovician Blockhouse Shale of eastern Tennessee is a graptolitic, dark-gray, calcareous shale that ranges in thickness from 150 to 950 feet (Neuman, 1955), and may have been a potential source rock in the eastern part of the basin (J. Roen, oral commun., 1994). Peak generation of hydrocarbons probably occurred during Pennsylvanian and Permian time, when thick accumulations of clastics overlaid the Ordovician- and Devonian-age source rocks (Ryder, 1987). However, in eastern Tennessee the lack of correlation of Knox oil shows with Alleghenian structures suggests that generation and migration occurred prior to the Pennsylvanian-Permian orogeny (Haynes and Kesler, 1989). Figure COk-13 illustrates the general relationship of the thermal alteration represented by the conodont alteration index (CAI) to the eastern limits of Knox oil and gas production. A CAI of about 1.5 is the upper thermal limit of oil generation. The upper limit for dry gas has a CAI of 4 to 4.5. Except for the Cumberland saddle region, it generally has been assumed that oil and gas migrated from deep within the Appalachian basin and travelled westward and downward through the stratigraphic section along fracture zones, unconformities, and fold belts (Cole and others, 1987; Ryder, Harris, and Repetski, 1992).

Sandstones and carbonates are the dominant reservoirs in the Knox. Depth to the Rose Run Sandstone along the main producing trend in Ohio (Figure COk-3) deepens to the east and southeast and ranges from 2,500 feet below surface in south-central Ohio to 7,000 feet below surface in north-central Ohio (Table COk-1). Average depth is 6,400 feet below surface. Thickness of pay ranges from 20 to 60 feet and averages 40 feet. Rock pressures range from 1,500 to 2,400 psi and average 2,200 psi. Initial open flows range from 10 Mcfg/d to 3 MMcfg/d and average 500 Mcfg/d. Final open flows range from 10 Mcfg/d to 2.1 MMcfg/d and average 300 Mcfg/d. The localized occurrence of the Krysik sandstone in the Birmingham-Erie field in north-central Ohio (Figure COk-2) ranges from 3,800 to 3,900 feet below surface with an average depth of 3,850 feet below surface (Table COk-1). Average pay thickness is 14 feet and average rock pressure is 1,500 psi. Final open flows average 180 Mcfg/d. B zone production is localized in the Utica field in central Ohio (Figure COk-2), and ranges in depth from 4,200 to 4,500 feet with an average of 4,300 feet (Table COk-1). Average pay thickness is 14 feet and average rock pressure is 1,260 psi. Initial open flows average 152 Mcfg/d and final open flows average 215 Mcfg/d..

Carbonate-producing trends are more irregular than sandstone trends, and average depth to pay ranges from 1,000 feet in the western part of the basin in northern Tennessee to 10,000 feet in the eastern part of the basin in north-central Pennsylvania. Principal Beekmantown production occurs in northern Tennessee, south-central Kentucky, and eastern Ohio (Figures COk-2, COk-3). Depths in northern Tennessee and south-central Kentucky range from approximately 1,000 to 4,000 feet below surface and average 2,500 feet below surface. Pay thickness for the key Beekmantown fields in south-central Kentucky ranges from 6 to 42 feet and averages 23 feet (Table COk-1). Reported rock

TABLE COk-2	Hinckley OH	Birmingham-Erie OH	Bakersville OH	Baltic OH	Morrow Consolidated OH
AVERAGE POROSITY–CORE (%)	8	14	15	8	8
MINIMUM POROSITY–CORE (%)	2	12	2	3	3
MAXIMUM POROSITY–CORE (%)	13	20	22	15	16
NO. DATA POINTS	1	6	3	2	6
AVERAGE PERMEABILITY (md)	0.5	56	5	4.6	7

Table COk-3. Proven Knox reserves.

Lithology	Number of wells	Estimated cumulative production per well	Recovery factor (%)	Total estimated drainage area for all wells	Original gas in place	Gas reserves	Average Life of well
Sandstone	155	400 MMcfg	65	6,200 acres	95 bcf	62 bcf	15 to 20 years
Carbonates	973	120 MMcfg	80	33,800 acres	146 bcf	117 bcf	5 to 15 years

Table COk-4. Undiscovered Knox resources (sandstones and carbonates combined).

Trend type	Gross area in acres	Estimated net productive area in acres	Estimated gas recovery per acre	Estimated recoverable gas resources	Probability of recovery (%)
Probable	36,800,000	160,000	5 MMcfg	800 bcf	95
Possible	33,900,000	165,000	10 MMcfg	1,570 bcf	4
Speculative	32,900,000	170,000	15 MMcfg	2,470 bcf	1

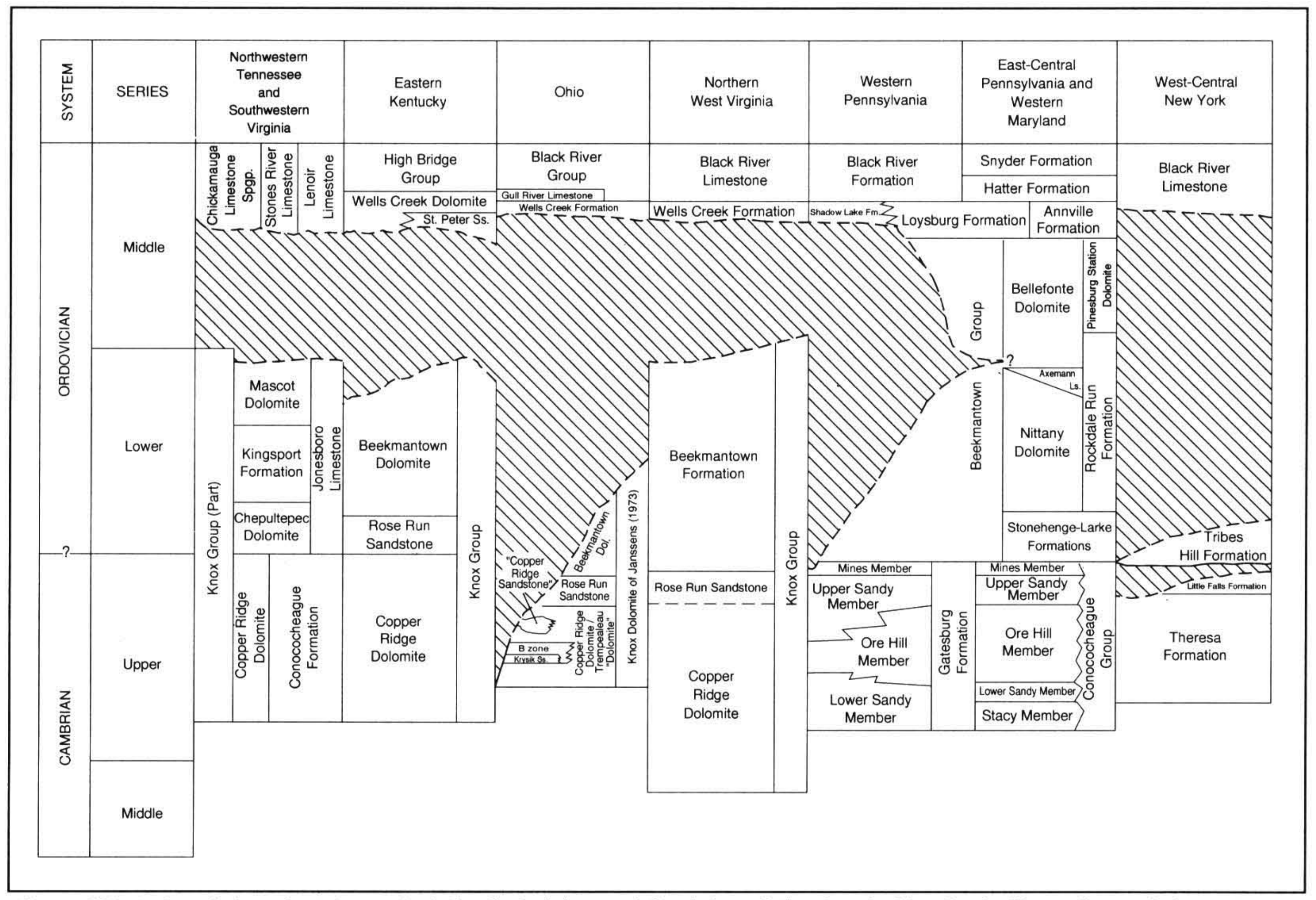


Figure COk-4. Correlation chart for part of the Ordovician and Cambrian of the Appalachian basin illustrating variations of Knox nomenclature. Modified from Janssens (1973), Patchen and others (1985a), Milici and de Witt (1988), and Riley and others (1993).

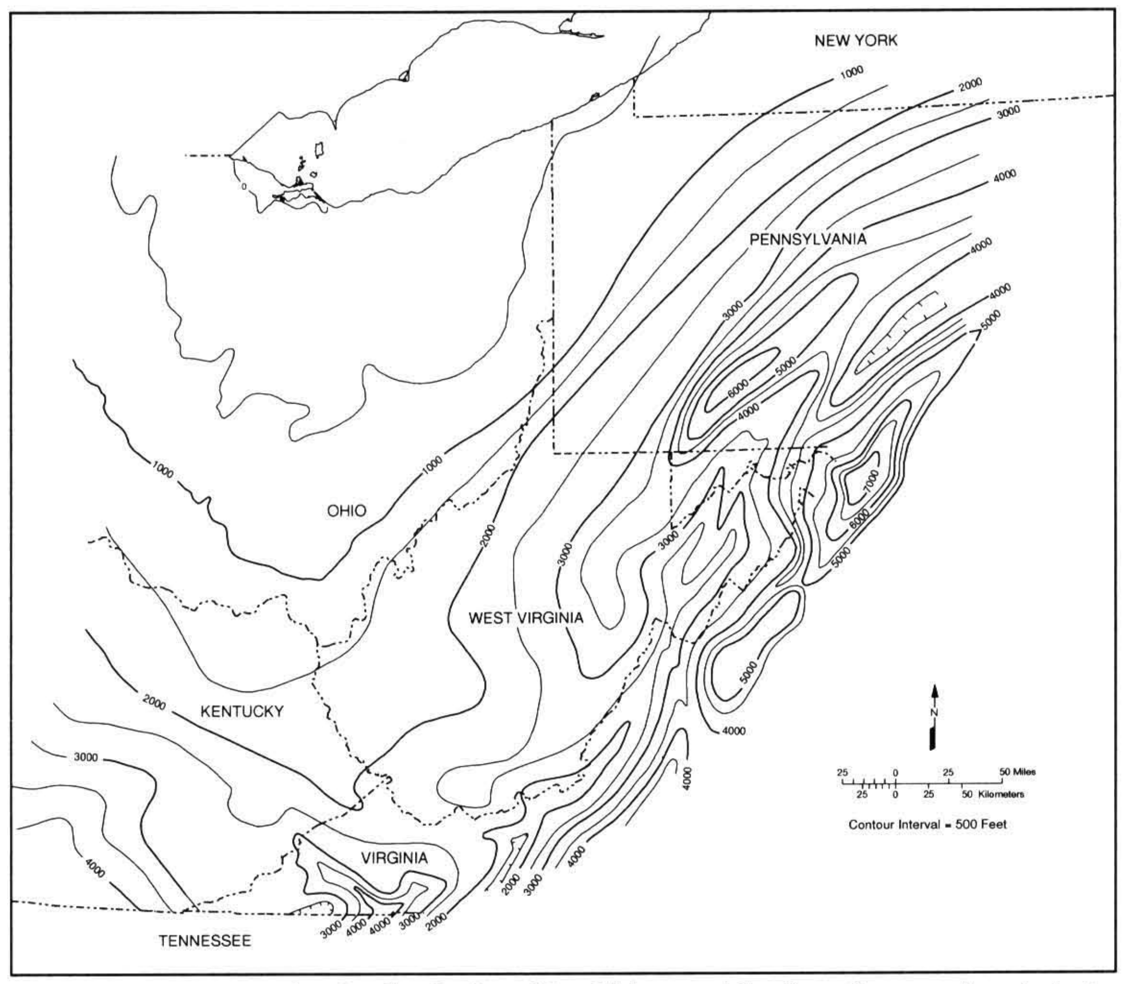


Figure COk-5. Map showing the distribution of the thickness of the Knox Group and equivalents in the central Appalachian basin and adjacent Cincinnati arch. Modified from Janssens (1973), Chen (1977), and Drahovzal and others (1992) .

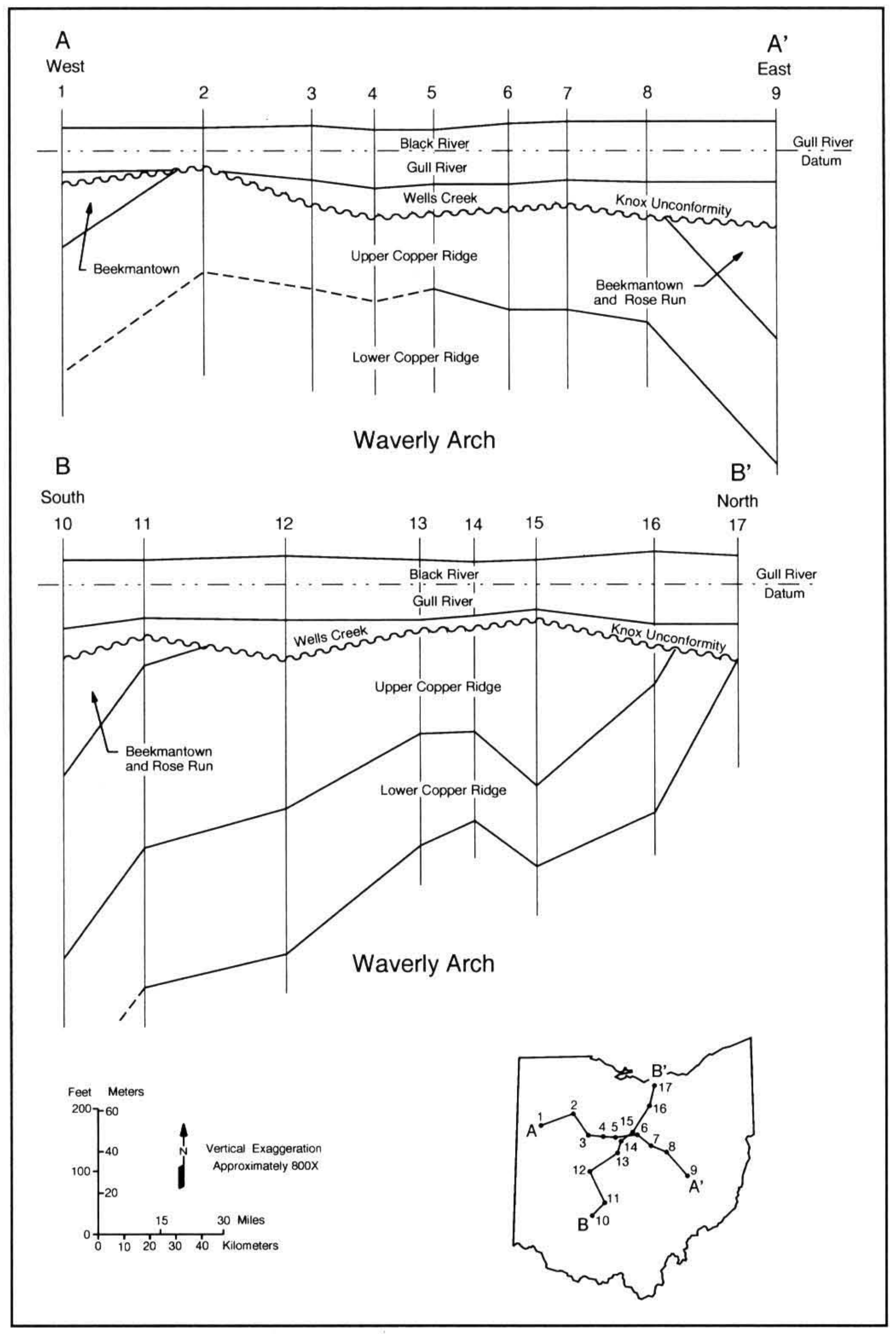


Figure COk-6. Regional cross sections A-A' and B-B' of the Upper Cambrian and Middle Ordovician on the Gull River limestone datum in central Ohio demonstrating the Knox unconformity and Waverly arch. Modified from Dolly and Busch (1972).

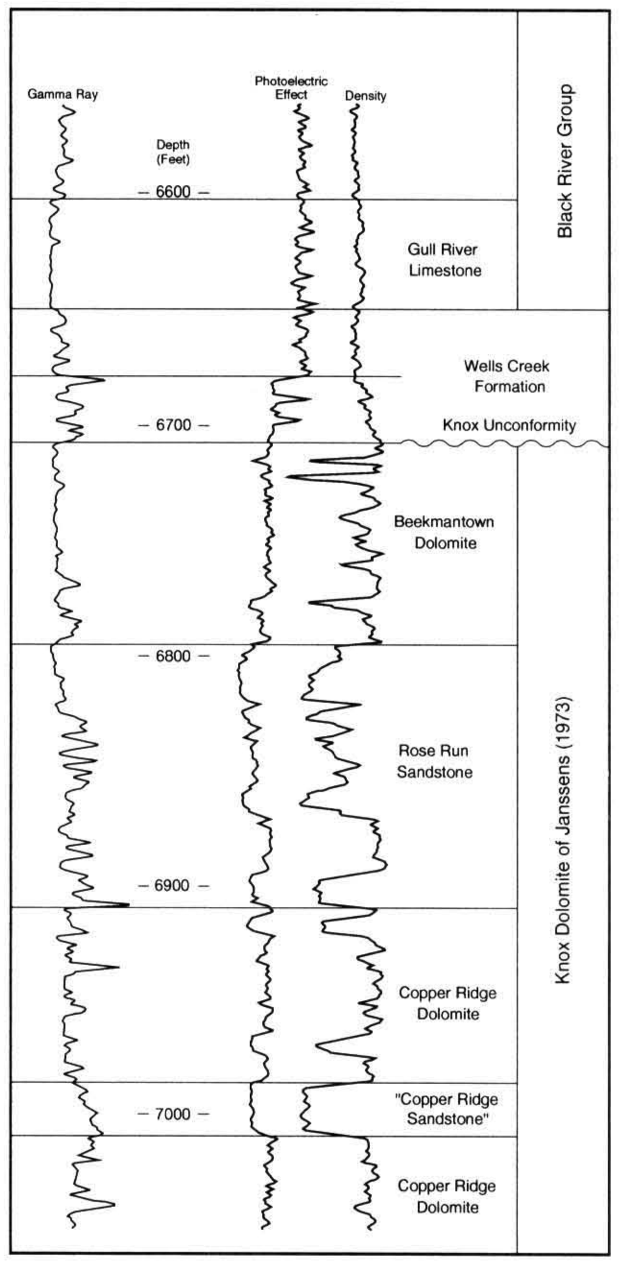


Figure COk-7. Type log showing the Knox Dolomite subdivisions, including the Beekmantown Dolomite, Rose Run Sandstone, Copper Ridge Dolomite, and "Copper Ridge sandstone" in the National Gas and Oil Company No. 3-A Reiss well (Coshocton 6379) in Coshocton County, Ohio.

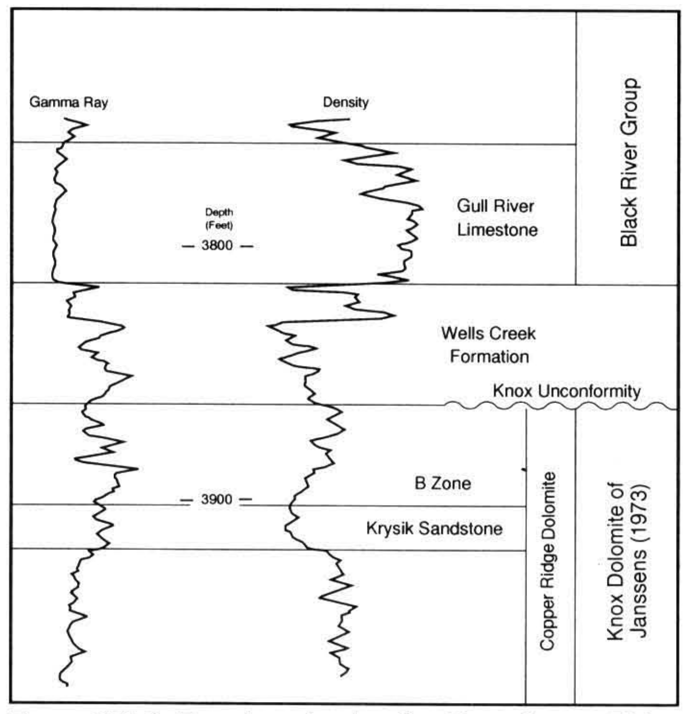


Figure COk-8. Type log showing the Knox Copper Ridge Dolomite subdivisions, including the B zone and Krysik sandstone in the Sun Oil Company No. 1 Krysik-Wakefield et. al. unit (Erie 11) in Erie County, Ohio.

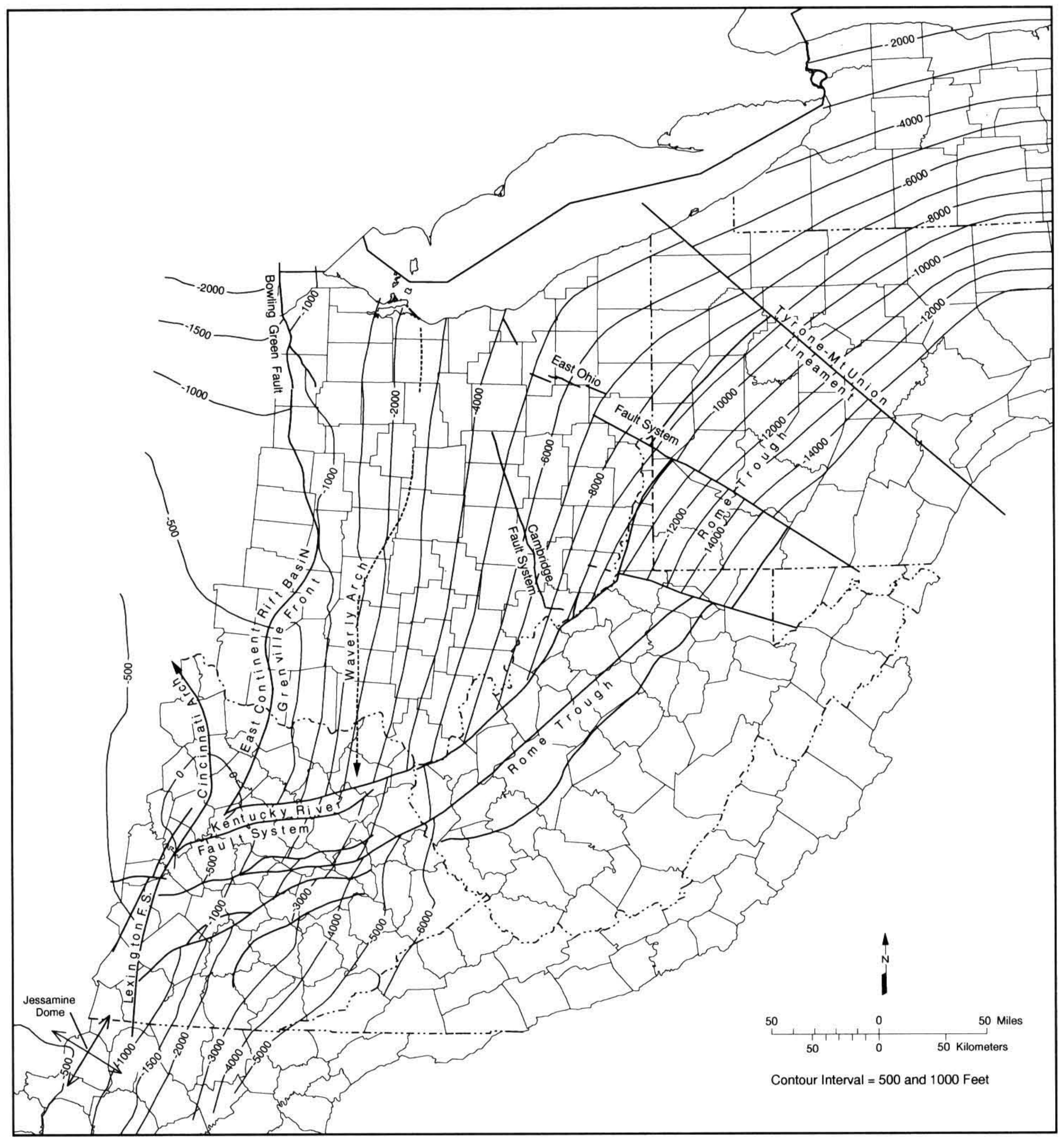


Figure COk-9. Structure map on the top of the Knox unconformity in the Appalachian basin and adjacent Cincinnati arch. Modified from Janssens (1973), Harris (1975), Drahovzal and others (1992), and Riley and others (1993). Contour interval is variable relative to sea level.

pressures for these key fields range from 245 to 420 psi and average 340 psi. Final open flows range from 131 to 879 Mcfg/d and average 420 Mcfg/d. In Ohio, Beekmantown production is concentrated in the Bakersville field where depths range from 6,720 to 7,380 feet below surface and average 6,900 feet below surface (Table COk-1). Average pay thickness is 10 feet and average rock pressure is 2,200 psi. Average initial open flows are 80 Mcfg/d and average final open flows are 380 Mcfg/d. Copper Ridge production is concentrated primarily in central Ohio, with the Morrow Consolidated field accounting for the majority of production (Figure COk-2). In the Morrow Consolidated field, depth to pay ranges from 3,000 to 4,200 feet below surface and averages 3,500 feet below surface (Table COk-1). Average pay thickness is 14 feet and average rock pressure is 1,080 psi. Average initial open flows are 390 Mcfg/d and average final open flows are 355 Mcfg/d.

Heterogeneity of Knox carbonate and sandstone reservoirs results from a complex interplay of depositional processes and structural, stratigraphic, and diagenetic features. Heterogeneity also results from lateral and vertical porosity zonation in reservoirs having predominantly interconnected vuggy to pinpoint porosity. The association of karstic-related vuggy porosity with linear fault trends in the Knox of south-central Kentucky is described by Anderson (1991). Vuggy porosities in Knox carbonate reservoirs range from 2 to 25 percent and average 10 percent. Porosity types occurring within Rose Run Sandstone reservoirs that affect heterogeneity include intergranular, oversized from dissolution, moldic, intraconstituent, and fracture (Riley and others, 1993). Secondary porosity in the sandstones ranges from 3 to 20 percent and averages 9 percent. Permeability for Rose Run Sandstone reservoirs ranges from 0.01 to 198 md, averaging 5 md. Locally, subtle structural folds and faults resulted in compartmentalization within reservoirs. Fracture porosity is associated with faulting and folding, but may be partially to completely replaced by mineralization.

Production decline curves for Ohio wells exhibit three reservoir variations: Beekmantown Dolomite, Rose Run Sandstone, and Copper Ridge Dolomite (Figure COk-14). The Beekmantown production is exclusively from the Bakersville field of Ohio, and shows the greatest average cumulative gas at 680 MMcf after 10 years. The Rose Run Sandstone average cumulative gas after 10 years is 400 MMcf. The Copper Ridge Dolomite average cumulative gas production after 10 years is estimated at 170 MMcfg.

Completion strategies commonly include natural production from open hole to acidizing through perforated casing. In some instances, the reservoirs are fractured using oil. Drive mechanisms may be solution gas, gas cap, or water.

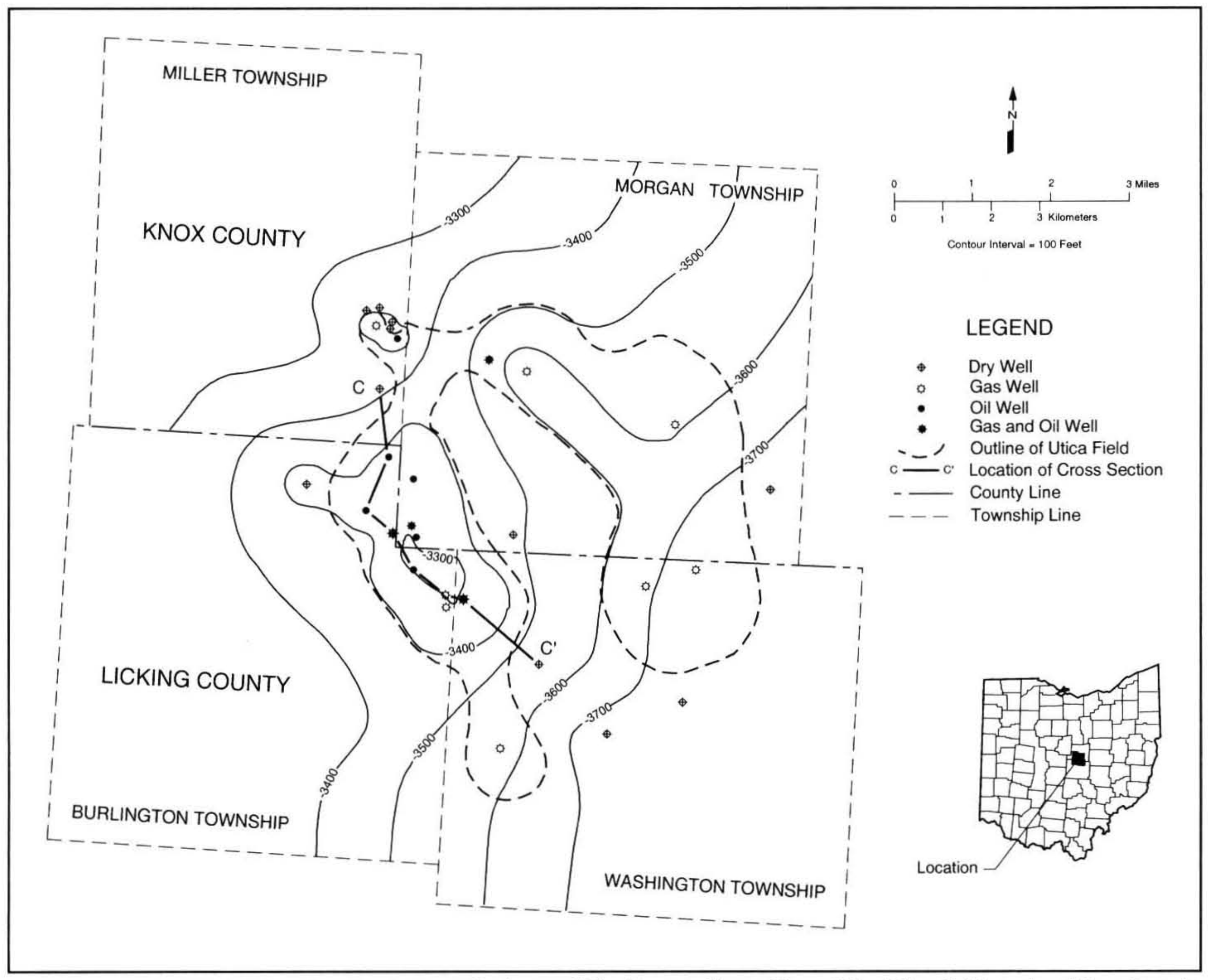


Figure COk-10. Map showing the structure on the base of the B zone, the outline of the Utica field, and well locations in Knox and Licking counties, Ohio. Location of cross section C-C' (Figure COk-11) is also shown.

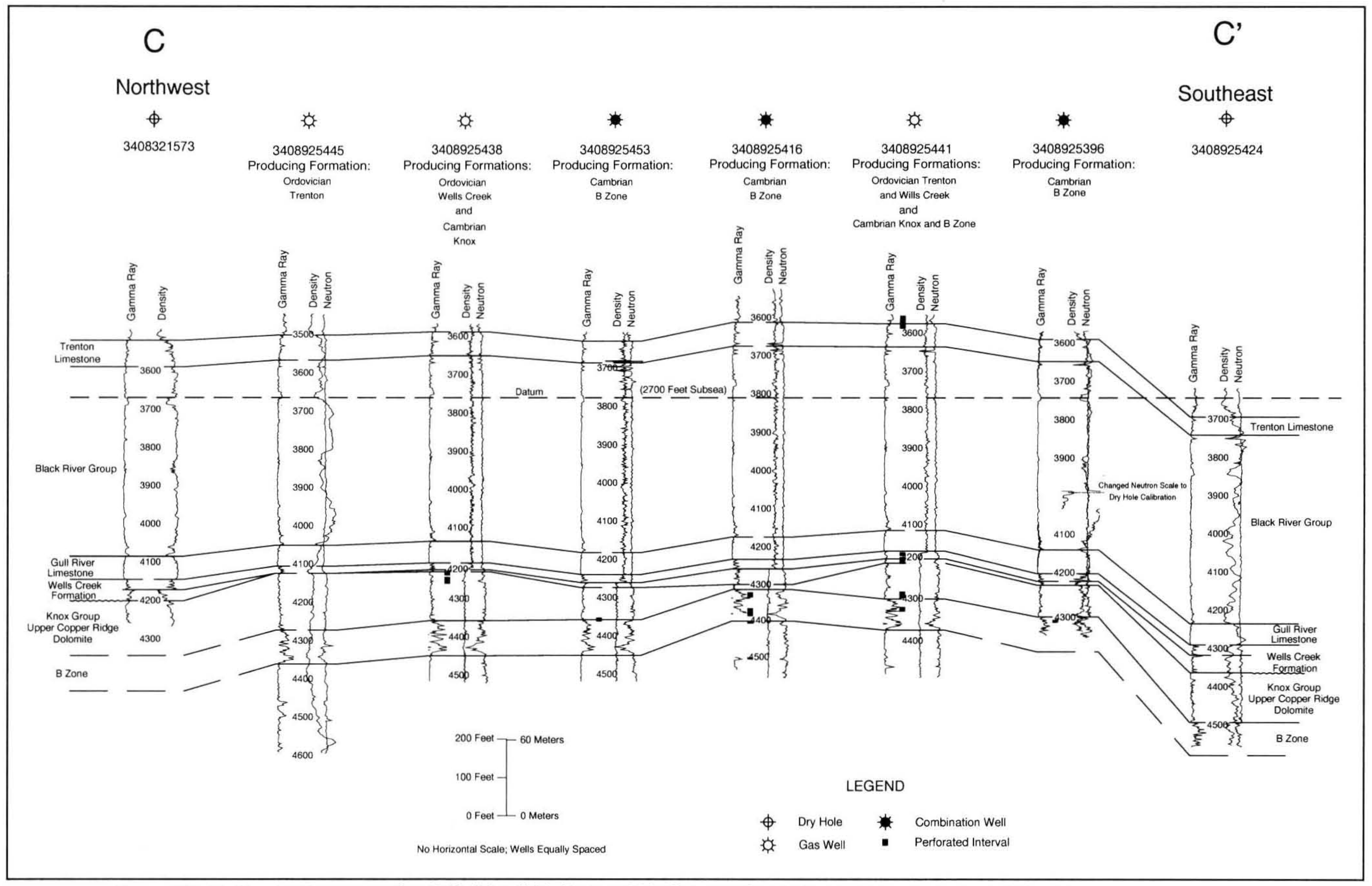


Figure COk-11. Structural cross section C-C', Utica field, Knox and Licking counties, Ohio. Location of cross section is shown in Figure COk-10.

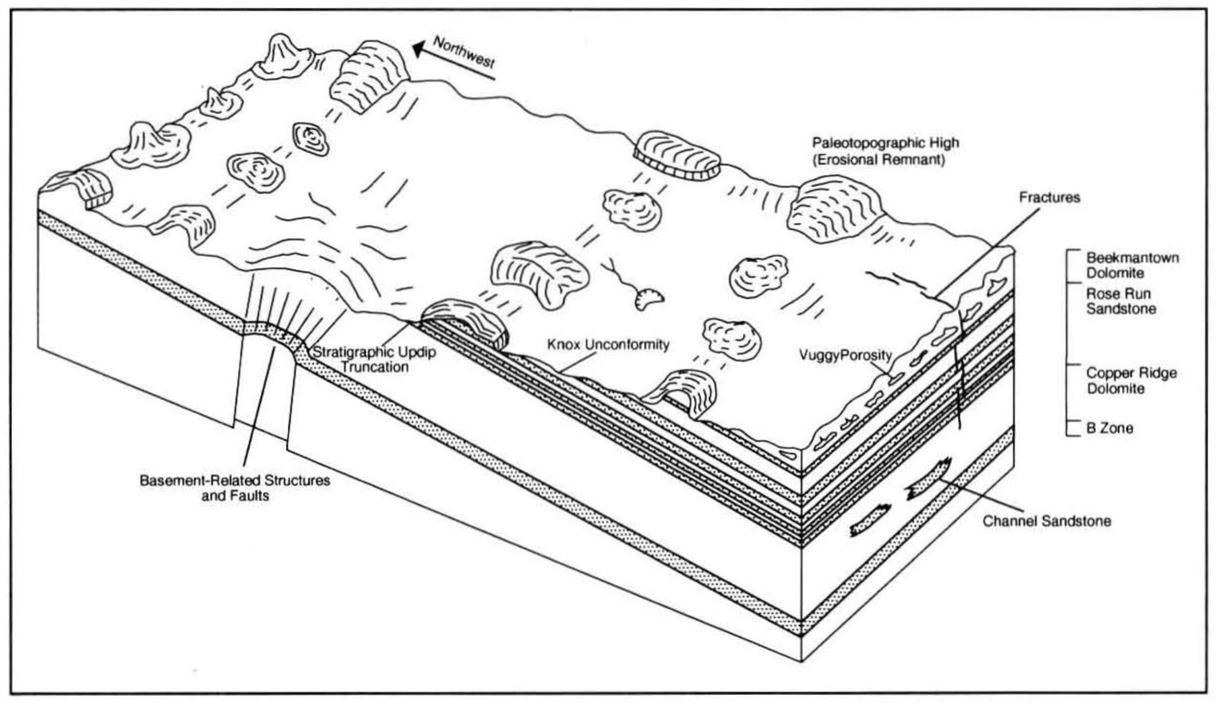


Figure COk-12. Block diagram illustrating trapping mechanisms for the Knox unconformity play.

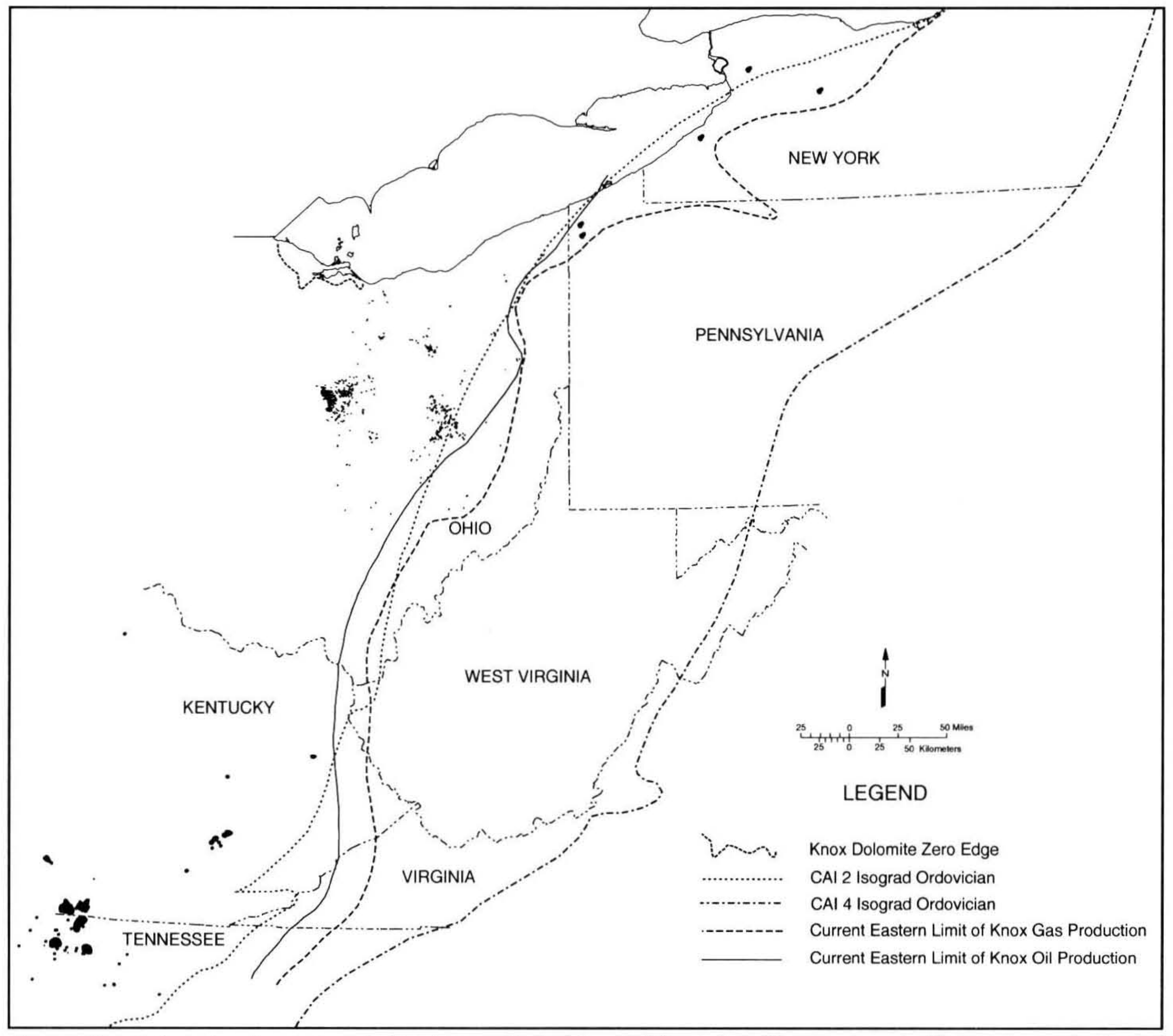


Figure COk-13. Map showing eastern limits of Lower Ordovician and Cambrian oil and gas production, and conodont color alteration isograds (CAI) for Ordovician carbonates in the Appalachian basin. Modified from Harris and others (1978).

Description of Key Fields

Key fields have been chosen based on significant geologic and production data, and geographic distribution of the major Knox producing horizons. A paucity of data from the northern and southern regions of the basin prevents an adequate evaluation for these areas. Thus, key fields for these regions will be discussed in a general fashion under northern and southern miscellaneous fields.

Birmingham-Erie field: The Birmingham-Erie field in Erie County, Ohio (Figure COk-2), discovered in 1966, is structurally controlled and produces from the Krysik sandstone. More than 40 feet of closure has been mapped in this field on the top of the Knox Dolomite (Janssens, 1973) with the structure extending upward into the overlying Middle Devonian Delaware Limestone (Janssens, 1968). Field statistics (Tables COk-1, COk-2) indicate the Krysik is a very good Knox sandstone reservoir with wells averaging 100 MMcfg and 250 million barrels of oil cumulative production. This field is also important because it illustrates excellent exploration potential where the Krysik sandstone reservoir is developed in northern Ohio. Partial water drive and excellent reservoir characteristics continue to allow secondary recovery operations in 1993 at the Birmingham-Erie field.

Morrow Consolidated field: The Morrow Consolidated field in Morrow County, Ohio, is an example of widespread hydrocarbon production from paleotopographic highs (erosional remnants) of the Copper Ridge Dolomite (Figures COk-15, COk-16) (Dolly and Busch, 1972). Trapping mechanisms are primarily from erosional remnants beneath the Knox unconformity and, to a lesser extent, from structural closure, anticlinal nosing, and fracturing. On the basis of seismic reflection data, subsurface mapping, and cross sections, these paleotopographic highs typically are 5- to 20-acre circular to elongate anomalies. Productive wells are generally characterized by depositional thinning of the Wells Creek Formation and possible draping of the overlying Black River Group. Figure COk-17 illustrates breakup of the Gull River and Wells Creek reflectors, thus defining the location of an erosional remnant. It is not a typical Morrow Consolidated trap in that the area has been faulted at a later time, as seen by structurally low Trenton and Precambrian reflectors (Figure COk-17).

The Copper Ridge Dolomite reservoir contains good to very well-developed interconnected vuggy to pinpoint porosity throughout most of the field. Original reservoir pressure was 1,080 psi, compared to a bubble point pressure (the point at which gas first begins to come out of solution) of 1,045 psi from fluid analysis (Sutton, 1965). Initial open flows and final open flows for the Copper Ridge reservoir are generally less than those of the Beekmantown in the Bakersville field and the Rose Run in the Baltic field (Table COk-1).

Heterogeneity is predominantly a result of highly variable porosity and permeability and is thought to be controlled by karstic processes and later diagenesis at or near the Knox unconformity. Porosity and permeability is also quite variable (Table COk-1).

Initial GOR is approximately 300 cf/bbl, and cumulative GOR averages 550 cf/bbl (Figure COk-18). Sutton's (1965) data suggested a solution gas drive because of the initially undersaturated conditions of the reservoir and GOR histories. Slider (1964), using typical assumed reservoir characteristics, showed production effects on the reservoir if other drive types such as water are assumed. Examination of data during this study suggests that the water drive mechanism may dominate later in the production history of Copper Ridge Dolomite producers in Morrow County. The production history demonstrates an essentially straight-line relationship between bottom-hole pressure and cumulative production.

Decline curves showing gas production typically are characterized by initial rapid decline during the first two years, followed by a gradual decline (Figure COk-14). Many wells produced for more than 25 years, although this data was not available for the average decline curve. An average Copper Ridge well in Morrow County, Ohio, produces gas and oil for a 10- to 15-year period (Shafer, 1994).

Baltic field: The Baltic field is located in portions of Holmes, Coshocton, and Tuscarawas counties, Ohio (Figure COk-19), and produces primarily from the Rose Run Sandstone. Production also occurs from the Mississippian Berea Sandstone, Silurian "Clinton" sandstone, and Beekmantown Dolomite. The Rose Run Sandstone averages 110 feet thick, and consists of a sequence of up to four or five porous sandstone lenses interbedded with less permeable, nonporous dolomite. These sandstone lenses commonly can be correlated reliably for a distance of 20 miles or greater.

Production is predominantly from erosional remnants beneath the Knox unconformity and, to a lesser extent, from up-dip pinchouts, structural closure, anticlinal nosing, and fracturing. Many of the productive remnants are located along the Rose Run Sandstone subcrop trend as seen in the Baltic field (Figure COk-19). As with the Morrow Consolidated field, seismic reflection data are an important tool in recognizing erosional remnants. These remnants are subtle features averaging 30 to 40 feet in relief, although some exceed 90 feet, and typically are 80 acres or less in areal extent. Erosional remnants may be capped with Beekmantown Dolomite and contain a thin or absent section of Wells Creek

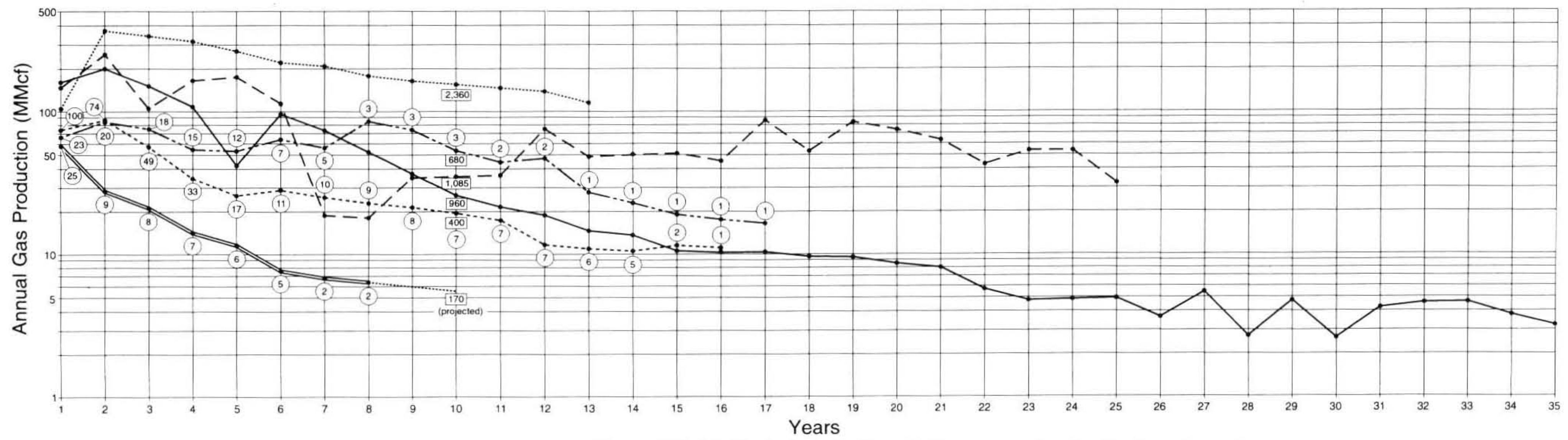


Figure COk-14. Nested production decline curves for the Beekmantown Dolomite, Rose Run Sandstone, and Copper Ridge Dolomite in Ohio based on well averages. The Beekmantown Dolomite data represents the Bakersville field. The Rose Run Sandstone and Copper Ridge Dolomite data represents all wells considered economic. Wells with less than an average of 10 MMcfg yearly cumulative production were considered uneconomic and not included. The paucity of the Copper Ridge data is due in part to the lack of reported production. For comparison, decline curves are included for the most significant Beekmantown well (National Gas and Oil, No. 1 Mizer, Coshocton 3893), Rose Run well (Buckeye Oil, No. 1 Erb, Holmes 1328), and Copper Ridge well (Wiser Oil Company, No. 1-A Smith, Medina 1143). Data from these wells were not included in the average decline curves. Data are from Janssens (1992), Ohio Division of Oil and Gas, and Columbia Natural Resources.

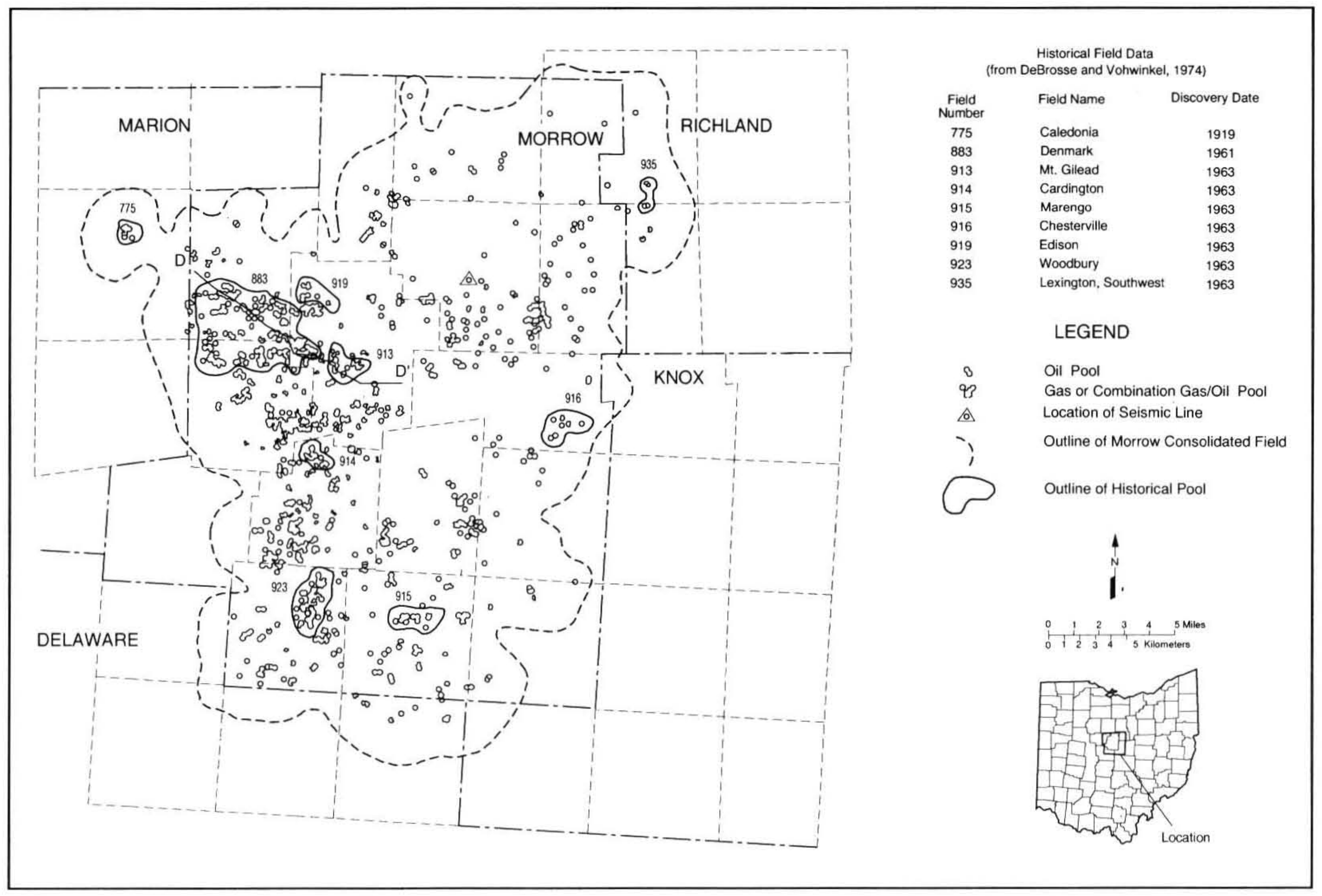


Figure COk-15. Map showing the field outline and historical pools for Morrow Consolidated field, Morrow County, Ohio. Modified from DeBrosse and Vohwinkel (1974). Location of cross section D-D' (Figure COk-16) is also shown.

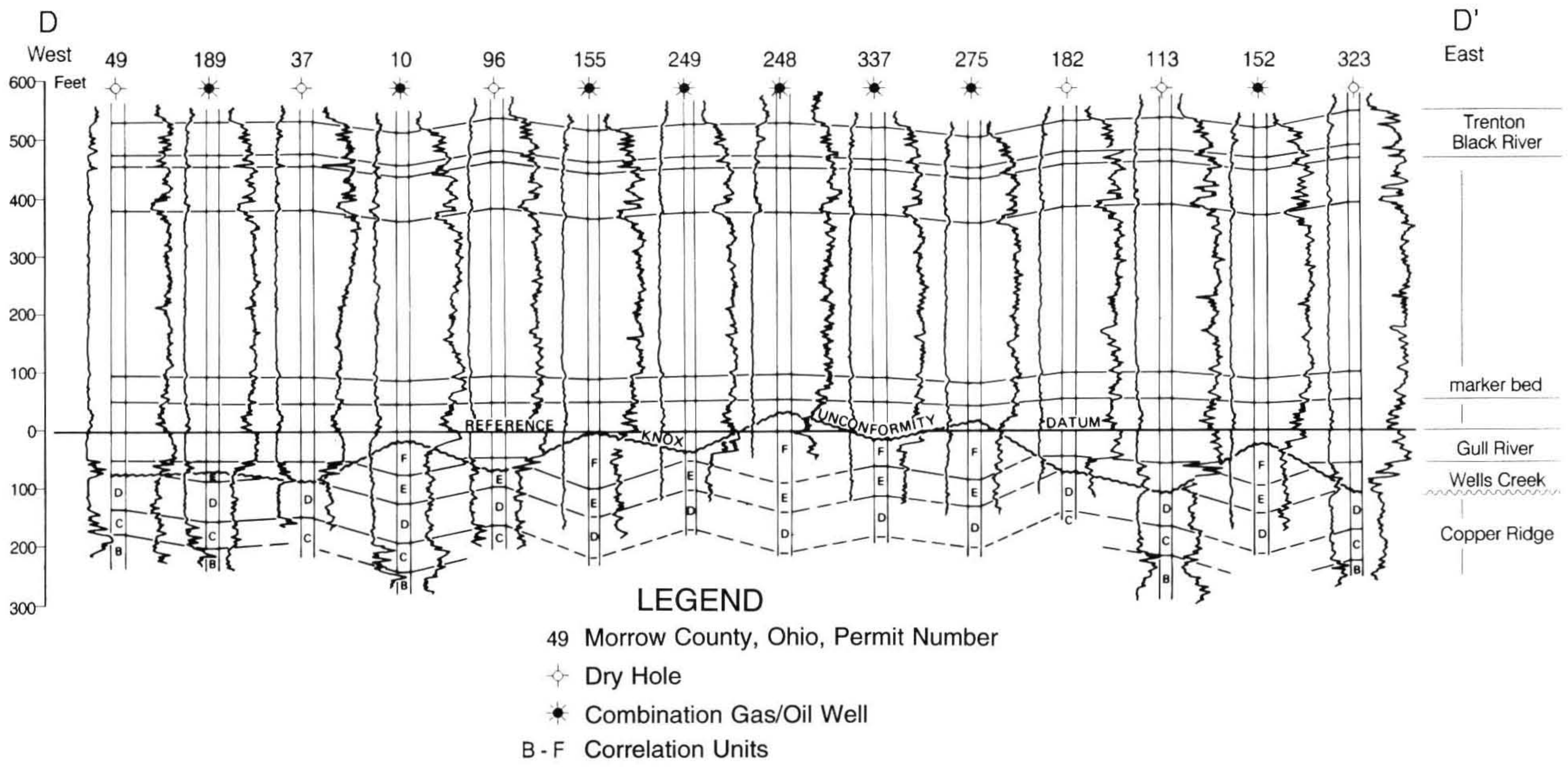


Figure COk-16. Stratigraphic cross section D-D', Morrow Consolidated field, Morrow County, Ohio. Datum is on top of the Gull River limestone. Modified from Dolly and Busch (1972). The cross section illustrates the paleotopographic trap typical of the Knox play. Location of cross section is shown in Figure COk-15.

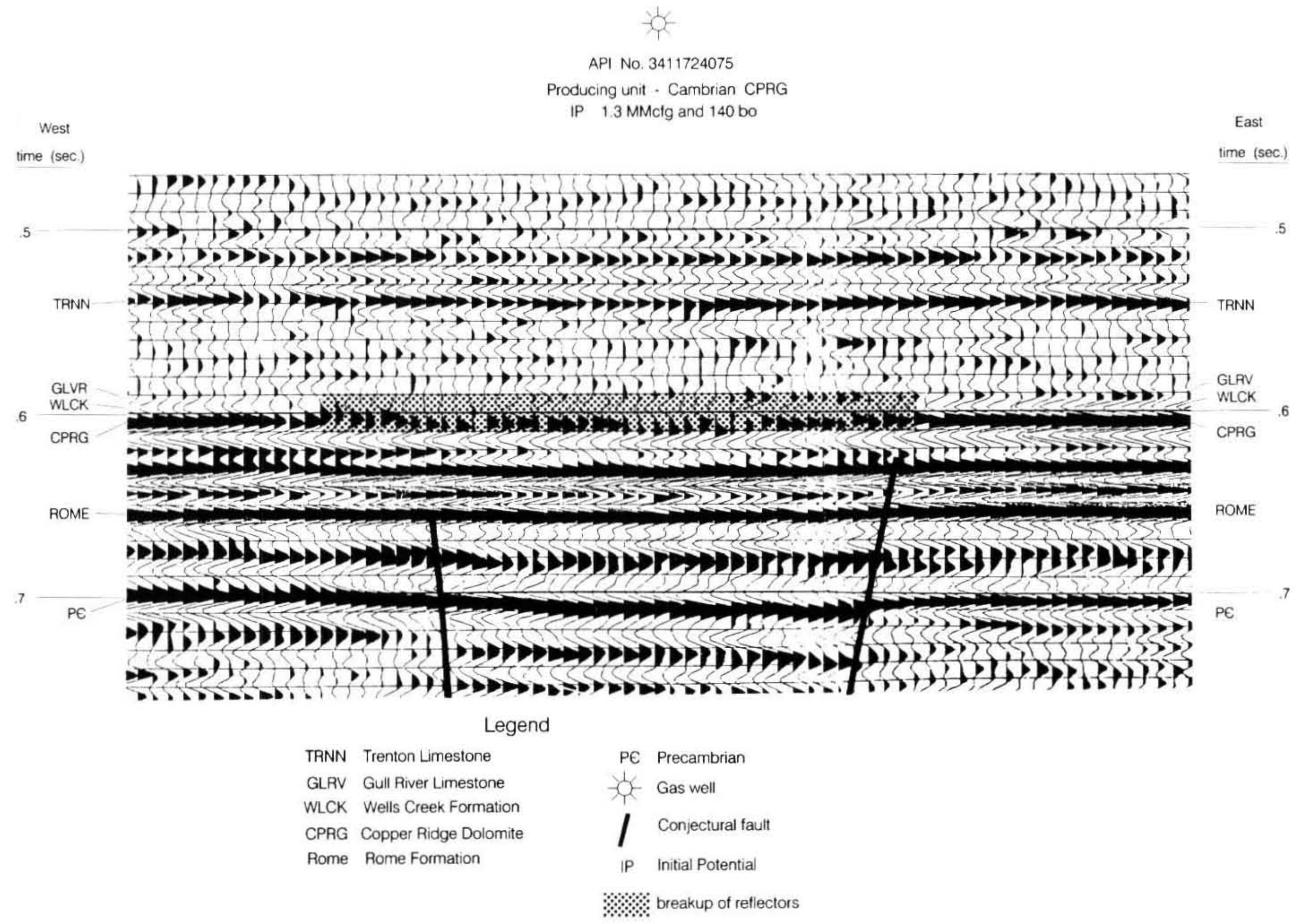


Figure COk-17. Seismic section display from Morrow County: dynamite source, 110 feet group interval, 30-fold, migration. Note breakup of the Wells Creek reflector that defines paleoremnant and conjectural basement faulting that bounds the breakup of the reflectors.

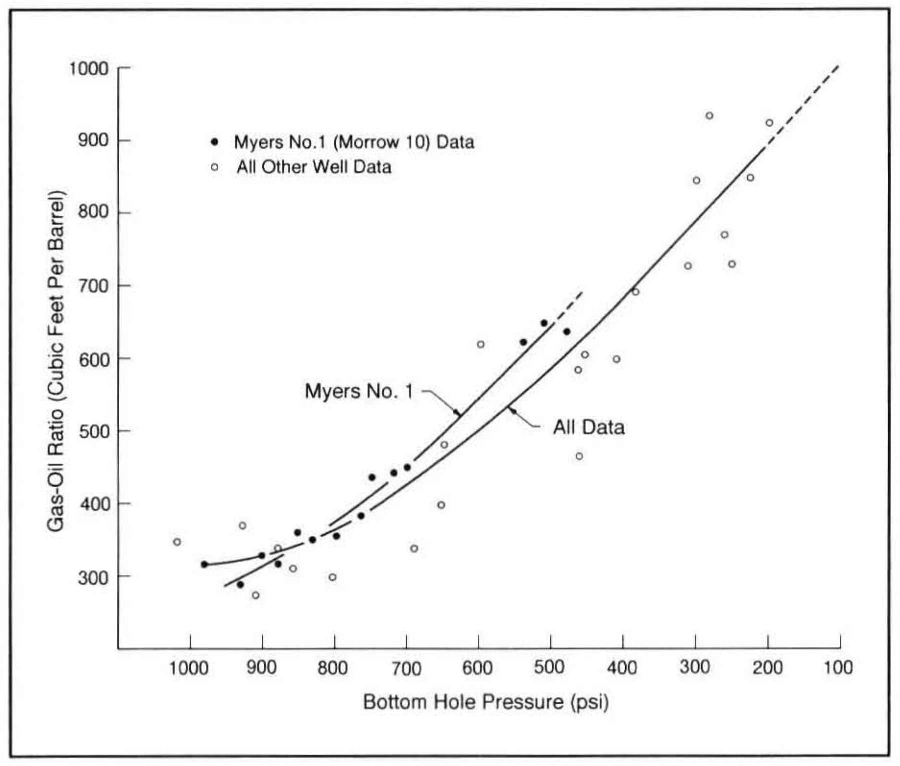


Figure COk-18. Graph showing gas-oil ratio (GOR) relative to bottom hole pressure in the Morrow Consolidated field, Morrow County, Ohio. From Sutton (1965).

Formation (Figure COk-20). In some cases, detailed subsurface mapping and seismic reflection data (Figure COk-21) show Knox paleotopographic highs to be positioned beneath structurally high features in the Ordovician Trenton Limestone, and are commonly as high as the Silurian Packer Shell of drillers' terminology (Riley, 1993). It is not known whether this effect is caused by draping of sediments, structural reactivation, or both.

Reservoir quality in terms of porosity, permeability, and pay thickness for the Rose Run Sandstone is generally greater in comparison to most Knox reservoirs throughout the basin. High initial open flows, rock pressures, pay thicknesses, and cumulative production continue to expand this trend as a result of active drilling.

Heterogeneity is predominantly controlled by depositional and diagenetic changes resulting in porosity and permeability variations. Porosities in the sandstone range from 4 to 14 percent and average 8 percent. Permeabilities vary widely from 0.01 to 198 md, averaging 4 md. Drive mechanisms may be solution gas, gas cap, or water. Wells are generally completed open hole or acidized through perforated casing.

Compared to the average Copper Ridge Dolomite well in the Morrow Consolidated field, the Rose Run Sandstone of the Baltic field has higher gas production with a lower decline rate (Figure COk-14). Production for an average Rose Run Sandstone well begins at approximately 72 MMcfg for the first year. Decline of the average well is fairly rapid during the first four years and is followed by a gradual decline over the life of the well. Some Rose Run Sandstone wells are plugged back to the "Clinton" within five years; however, the average well production life should extend past 15 years. The Kin-Ark, No. 1 Erb, an exceptional well, has produced steadily for 25 years with a cumulative gas production of 1.96 bcf.

Bakersville field: The Bakersville field is located in eastern Coshocton and western Tuscarawas counties, Ohio (Figure COk-22). Hydrocarbon production occurs primarily in Beekmantown Dolomite paleoremnants from zones of well-developed pinpoint and massive vuggy porosity that are bounded by less porous, impermeable dolomite. These porosity zones can be correlated in some areas across 6 miles or more using geophysical logs (Riley and others, 1993). Gas production also occurs in the "Clinton" sandstone and Wells Creek Formation.

Some of these Beekmantown Dolomite paleoremnants may be structurally controlled by reactivated basement faults (Coogan and Lesser, 1991; Riley and others, 1993). Subtle structural closure, anticlinal nosing, and fracturing may affect production locally.

Many of the productive remnants are located along the Rose Run Sandstone subcrop trend (Figure COk-2). Paleotopographic highs, which are the dominant trapping mechanism, are similar in size to the Rose Run Sandstone reservoirs discussed above. Similar to the Morrow Consolidated and Baltic fields, production occurs predominantly from erosional remnants beneath the Knox unconformity. The structure on the Knox unconformity (Figure COk-22) illustrates the irregular nature of this surface, which is a result of paleotopography and possibly structural deformation.

Reservoir statistics in Table COk-1 indicate that the Beekmantown in the Bakersville field is comparable to that of the Copper Ridge in the Morrow Consolidated field. This reservoir is especially sought after where it overlaps the Rose Run Sandstone production at the Baltic field (Figure COk-2). Similar to the Rose Run Sandstone reservoir, the high initial open flows, rock pressures, and pay thicknesses of the Beekmantown continue to expand this trend in Coshocton and Tuscarawas counties, Ohio. Drive mechanisms may be solution gas, gas cap, or water.

The Beekmantown Dolomite of the Bakersville field exhibits the highest gas producing rates of any reported Knox producing unit in the Appalachian basin. Average production for the first year is similar to the Rose Run Sandstone at approximately 69 MMcfg (Figure COk-14). The Beekmantown Dolomite decline rate is much lower, however, and declines less rapidly than both the Rose Run Sandstone and Copper Ridge Dolomite. The higher sustained rates of the Beekmantown Dolomite gas production in the Bakersville field compared to the Copper Ridge Dolomite in the Morrow Consolidated field may be a result of higher porosities and permeabilities, a larger drainage area per well, and wider well spacing. The immaturity of this field precludes the determination of the production life expectancy; however, the Stone Resources, No. 1 Mizer well has produced steadily for more than 13 years (Figure COk-14). A very gradual decline rate indicates production may extend up to 30 years. This is one of the best Knox gas wells in the Appalachian basin, with more than 2.7 bcfg produced during the first 12 years.

Northern miscellaneous fields: The Wyoming field of Wyoming County, New York (Figure COk-2), is an example of localized sandstone production from the Theresa Formation. The field was developed based on a 1963 sandstone

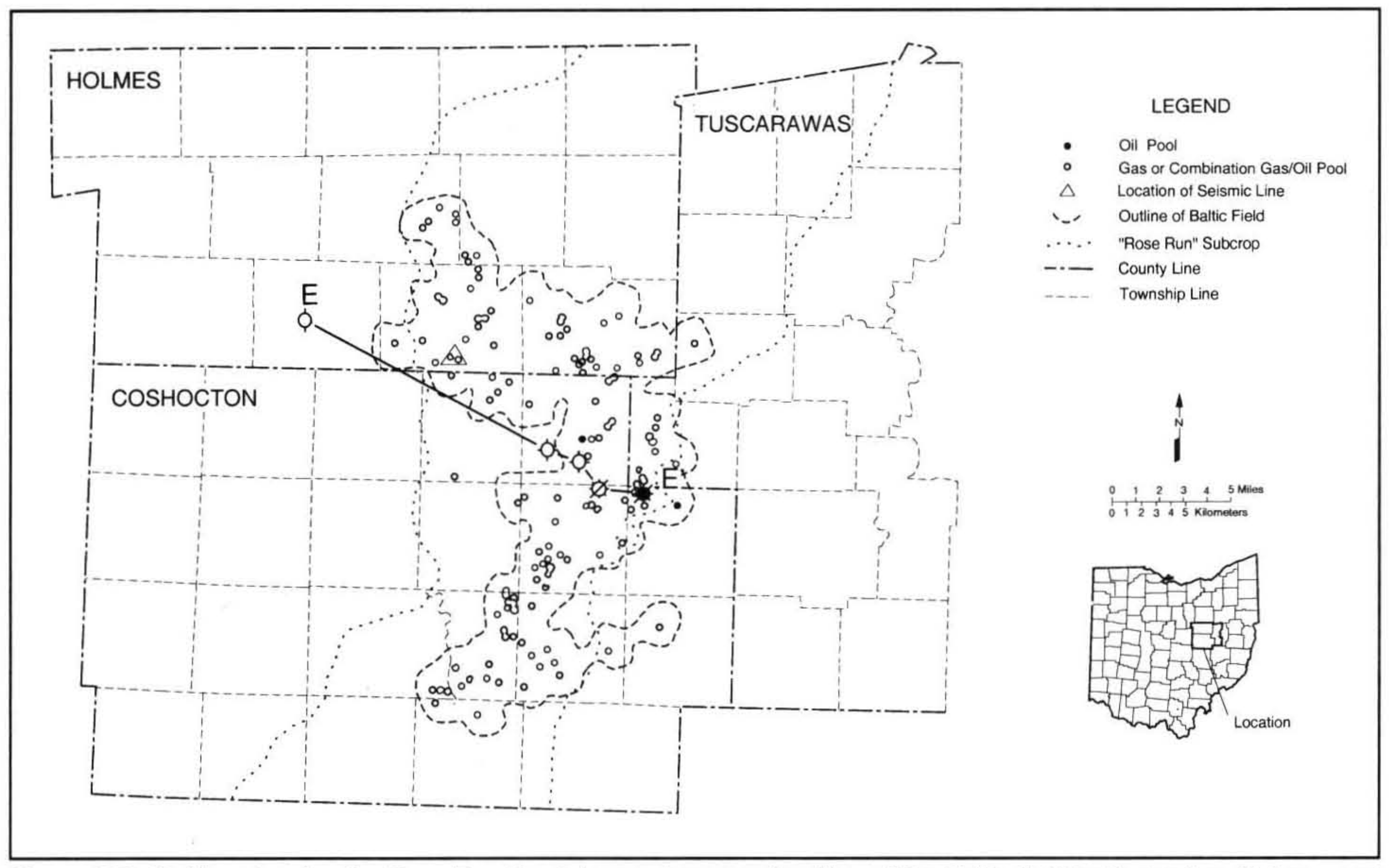


Figure COk-19. Map showing the Rose Run Sandstone subcrop and outline of the Baltic field in Coshocton, Holmes, and Tuscarawas counties, Ohio. Location of cross section E-E' (Figure COk-20) is also shown.

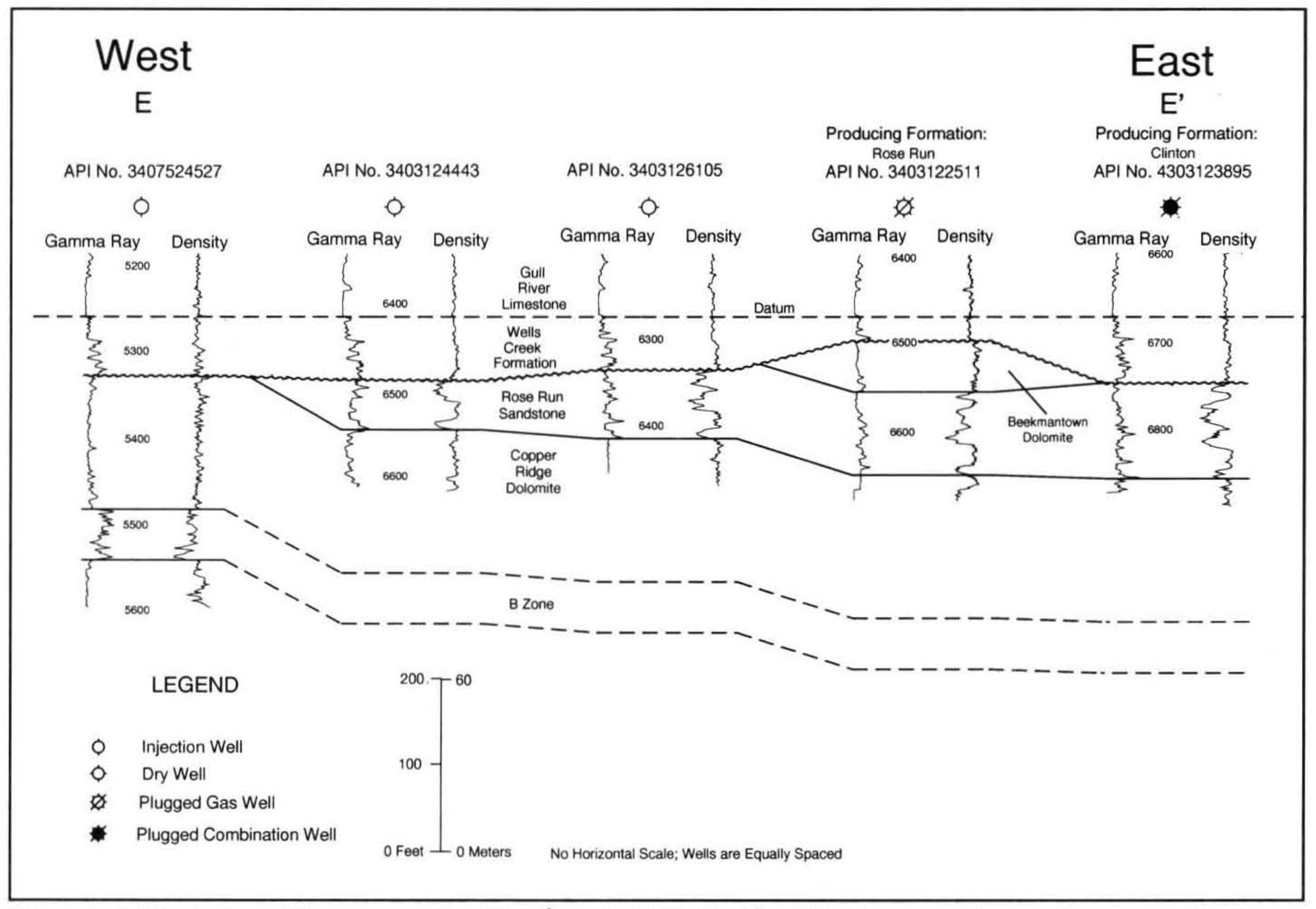


Figure COk-20. Stratigraphic cross section E-E' over the Baltic field in Ohio illustrating Knox paleotopography. Datum is the top of the Wells Creek Formation. Location of cross section is shown in Figure COk-19.

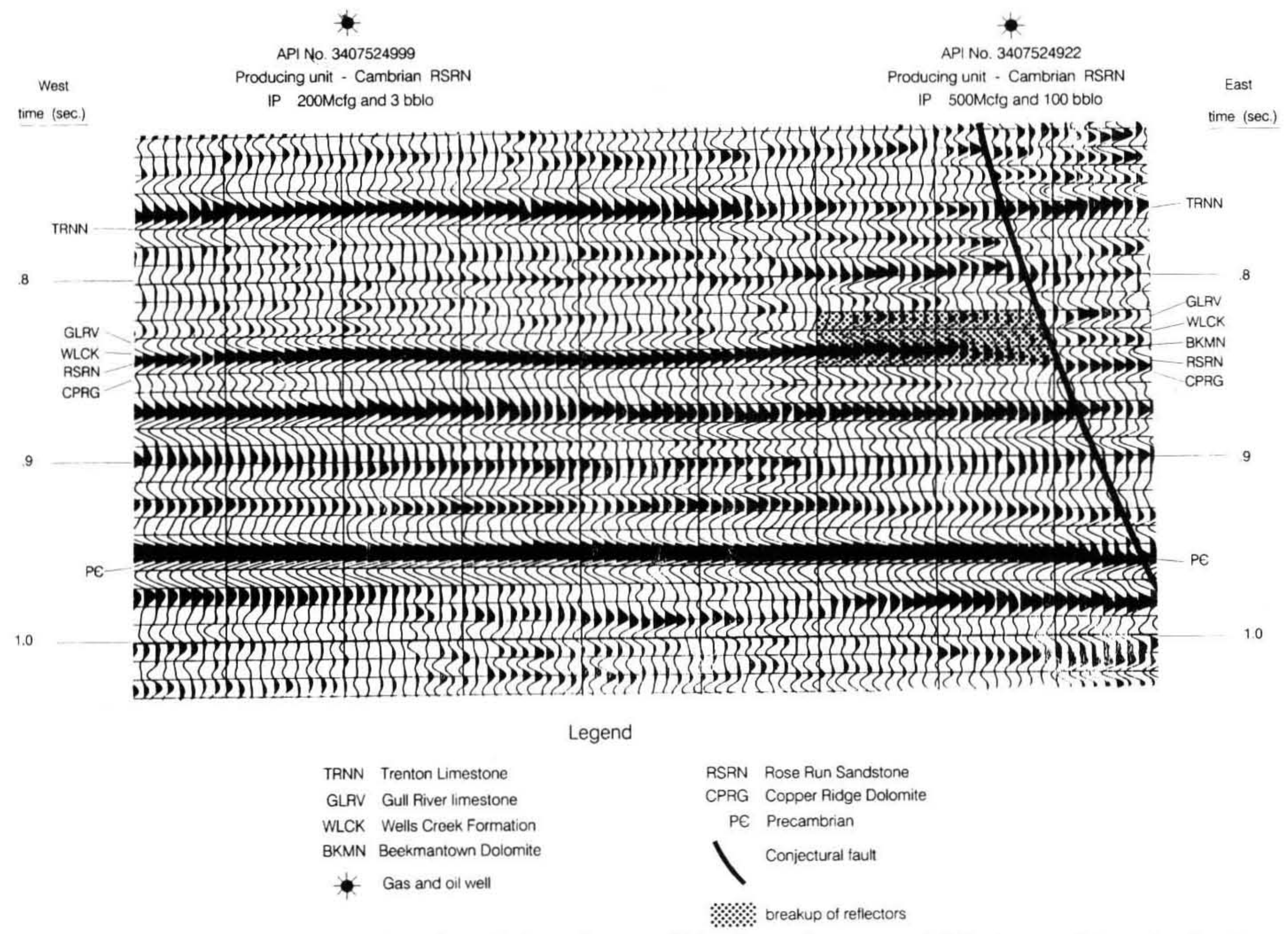


Figure COk-21. Seismic section display from Holmes County, Ohio: dynamite source, 110 feet group interval, migration. Note poorly developed Gull River and Wells Creek reflectors defining the position of producing paleoremnants.

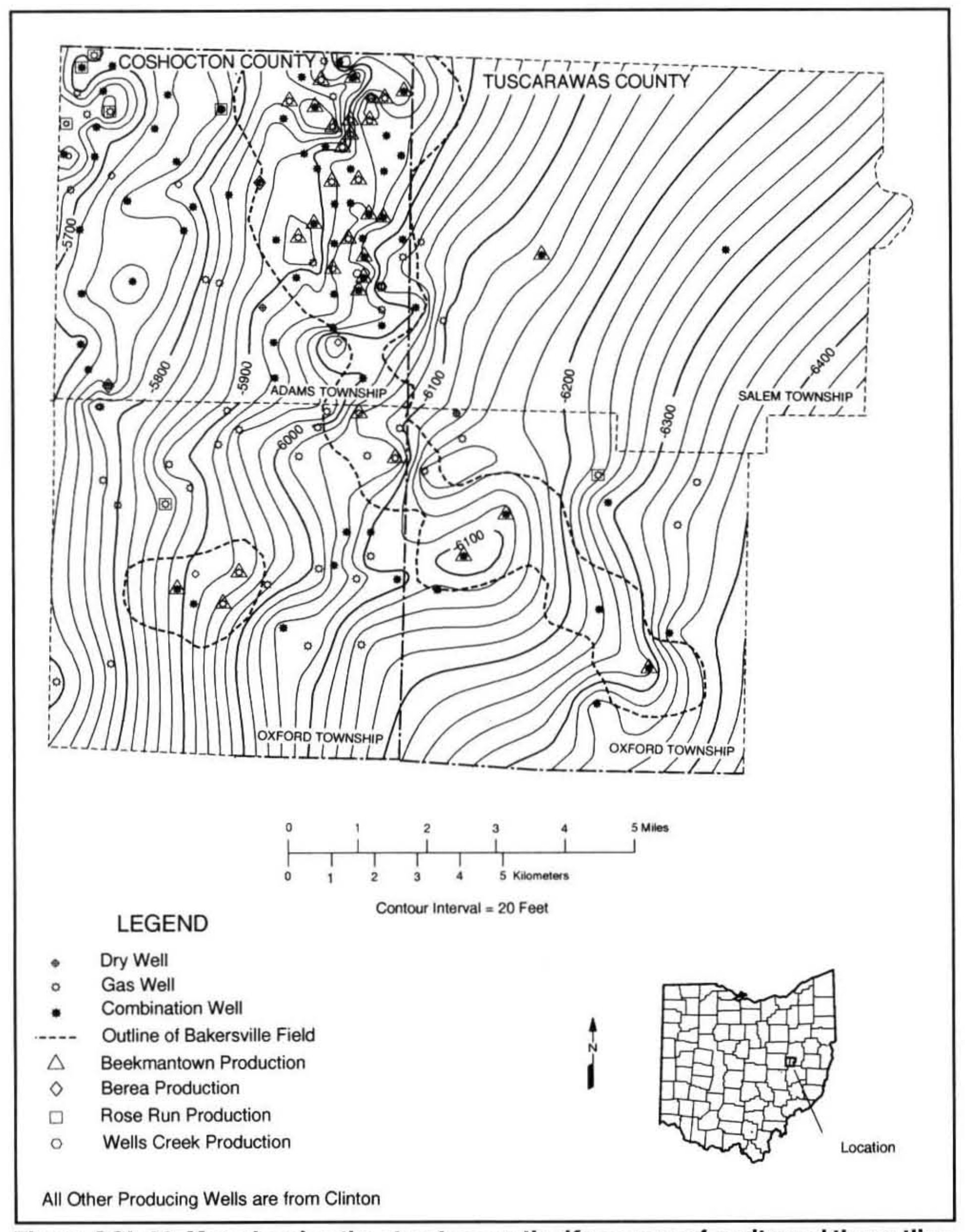


Figure COk-22. Map showing the structure on the Knox unconformity and the outline of the Bakersville field in Coshocton and Tuscarawas counties, Ohio.

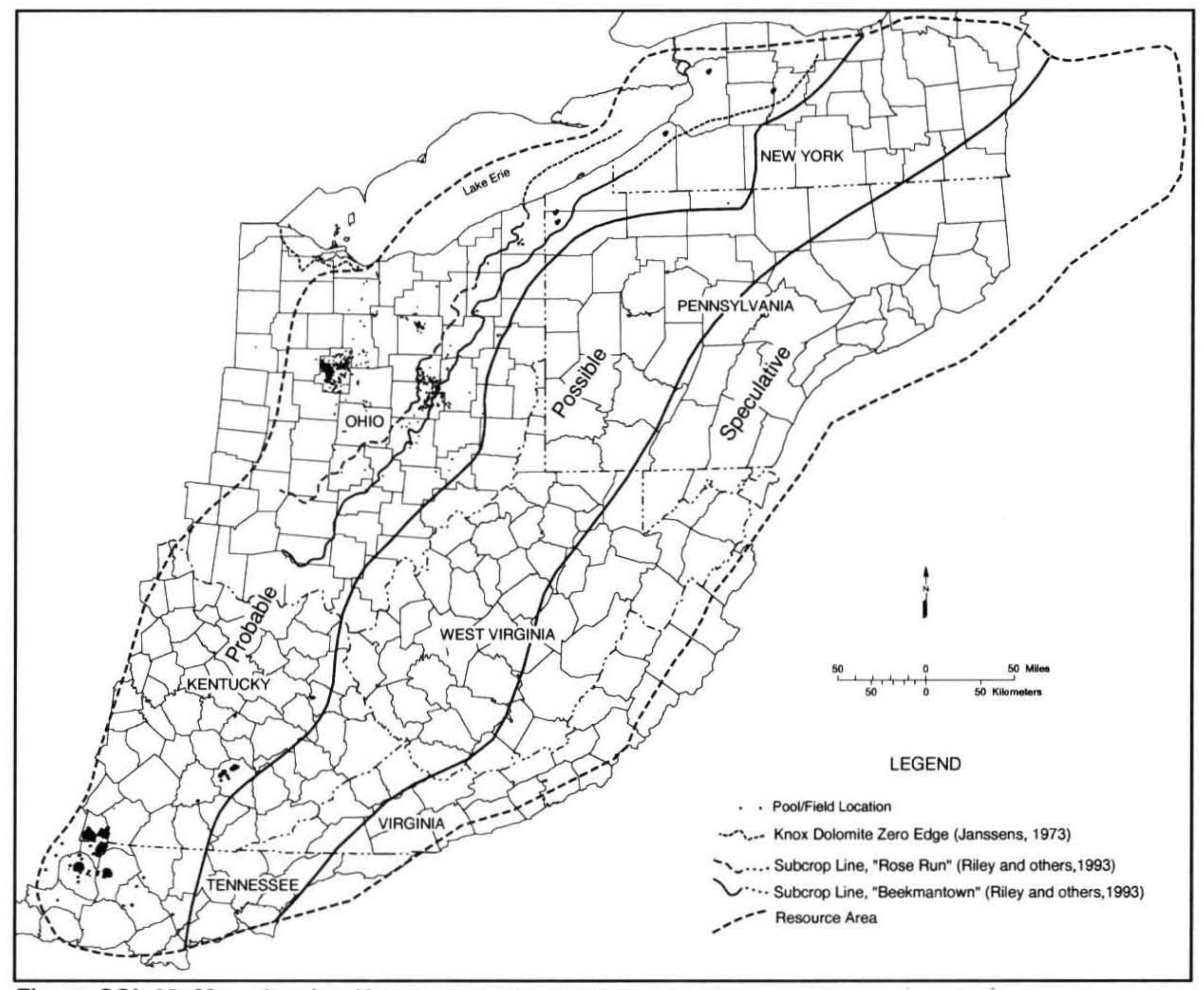


Figure COk-23. Map showing Knox gas pools and fields, including probable, possible, and speculative resource trends corresponding to Tables COk-3 and COk-4. The proven reserves of Table COk-3 are represented on the map by the pools and fields, which represent the estimated acreage drainage area for the Knox reservoirs.

discovery in the Theresa. Ten wells were drilled to evaluate this area. The trap configuration and extent of the reservoir are unknown (A. Van Tyne, oral commun., 1994).

The Beaver Center and Scull pools of Crawford County, Pennsylvania, are examples of one-well pools in the upper sandy member of the Gatesburg Formation (Figure COk-2). Reservoir statistics for these pools are similar to Ohio's Rose Run reservoir. Reservoir heterogeneity and trapping of hydrocarbons is thought to be a combination of stratigraphic variations and small fault offsets (Riley and others, 1993).

Southern miscellaneous fields: Knox production in south-central Kentucky and northern Tennessee is primarily from the Beekmantown Dolomite. Dominant porosity types are fracture, vuggy, and intergranular. Fracture porosity appears to be related to paleokarst brecciation (Mussman and others, 1988). Wide variability in the hydrocarbon production from one well to another may be controlled by proximity to fracture porosity (Hamilton-Smith and others, 1990). Knox hydrocarbon production from paleotopographic highs has been documented for fields such as the Gradyville East in Adair County, Kentucky (Figure COk-2) (Perkins, 1972). Thickness maps of the Black River to Knox and the Wells Creek Formation indicate thinning over these producing Knox erosional remnants. Perkins (1972) correlated a lower porosity zone in the Beekmantown across the Gradyville East field with values ranging from 6.4 to 14.2 percent. Relatively low horizontal permeabilities of 0.7 to 1.7 md indicate a fractured reservoir.

Resources and Reserves

A total of 1,127 gas wells (155 sandstone and 973 carbonate reservoirs) for the Knox unconformity play have been used to calculate resources and reserves. Sandstones and carbonates have been separated for proven reserve estimates for two reasons: the reservoirs are significantly different, and the Rose Run Sandstone generally has a greater gas cumulative production than Knox carbonates. The producing sandstone wells occur primarily along the Rose Run trend (Figures COk-2, COk-3). Proven reserves have been estimated for the play using the Delphi method. The estimated reservoir drainage area is based on all known producing Knox wells in the basin. The pools illustrated in Figures COk-1 and COk-23 are the drainage areas used in determining the estimates. The estimated cumulative production, recovery factors, and average life of well listed in Table COk-3 are thought to be typical for an average Knox sandstone or carbonate reservoir. Except for the Beekmantown Dolomite reservoirs at the Bakersville field, Ohio, sandstone reservoirs generally have greater gas production volumes than carbonates. Estimated cumulative production for a typical Knox sandstone well is 400 MMcfg, based on the average 10-year decline curve on Figure COk-14. Estimated cumulative production for a typical Knox carbonate well is 120 MMcfg. This appears conservative when in comparison to the decline curves on Figure COk-14. However, the number is reasonable because Knox wells in southern Kentucky and northern Tennessee are generally lower-volume producers.

Undiscovered recoverable resources may be an order of magnitude greater than the relatively small 40,000-acre proven area for Knox reservoirs. Trends were identified throughout the basin and categories of undiscovered probable, possible, and speculative gas resources were assigned based on the known production history and geology of the Knox for the region using the Delphi method (Figure COk-23). Resources for these areas are considered recoverable based on current technology, exploration and drilling costs, and market conditions. Methodology was based on criteria set by the Potential Gas Agency (Potential Gas Committee, 1990) and Geomega (1983), who used similar criteria to estimate undiscovered recoverable gas resources in Pennsylvania. Sandstone and carbonate reservoirs have not been separated. Gas recovery for the probable trend was based on an estimated gas recovery for existing Knox reservoirs. Gas recovery for possible and speculative trends was increased by two- and three-fold, respectively, to reflect the potential for large structural traps in these unexplored regions. These increases were tempered by using a low probability of recovery. Once parameters for each category were determined, resources for these areas were calculated using an estimated net productive area and estimated gas recovery (Table COk-4).

Probable resources will occur in the present producing trend of Figure COk-3. The western limit of the trend is defined by the Cincinnati and Findlay arches, and the zero edge of the Knox Dolomite in northern Ohio. The eastern limit of probable resources is near the eastern limit of present production east of the Rose Run subcrop area. A trend of undiscovered possible resources may occur in lightly explored and unexplored areas east of the probable trend in the Rome trough and beneath the Appalachian plateau. East of the possible resources area, a speculative area of resources is located beneath the Valley and Ridge and Blue Ridge, based on the CAI = 5 index of Harris and others (1978).

Future Trends

The Knox play continues to have great potential in the Appalachian basin. The Beekmantown Dolomite in the Bakersville field is currently the most prolific Knox gas producer on a well-by-well basis. Large areas of the basin remain to be tested for Beekmantown production. The Rose Run sandstone reservoirs (and equivalent upper sandy member of the Gatesburg Formation and Theresa Formation) in particular are more attractive because they are more areally extensive, porous, and permeable. Large unexplored areas occur along the Rose Run subcrop belt and to the south into northern Kentucky, where significant shows recently have been reported. New Rose Run discoveries suggest that the play will be structurally controlled east of the subcrop belt. High-risk and high-potential targets in the upper and lower sandy members of the Gatesburg Formation may exist in the Rome trough in Pennsylvania and West Virginia. High-risk targets could exist in the subthrust region beneath the Valley and Ridge and Blue Ridge in areas where the hydrocarbons that have been generated from the available source rocks have been trapped and have not been allowed to escape by structural deformation or destroyed by high temperature.

Historically, most Knox wells have been drilled to the top of the pay reservoir only. Recently, however, more companies have been drilling through the entire reservoir to evaluate deeper reservoirs. Recent discoveries in Holmes County, Ohio, have been reported from stray sandstones in the Copper Ridge below the Rose Run. The sparsely drilled B zone and Krysik sandstone of the Copper Ridge Dolomite hold much potential, especially where this unit is a well-developed thick reservoir in central and north-central Ohio. Potential deeper production from the B zone and the Krysik sandstone may exist in areas of current shallow Knox production.

Knox Dolomite hydrocarbon potential exists within fractured zones along major fault trends such as the East Ohio fault system (Figure COk-3). Production from the fractured reservoirs of southern Kentucky and northern Tennessee will continue to dominate this region, although significant paleokarst and paleoremnants should not be ruled out in exploration strategy. Advanced geophysical analyses including new logging techniques, seismic modelling, attribute analyses of seismic traces, three-dimensional seismic data acquisition, gravity, and magnetics will aid in identifying Knox stratigraphic traps and paleotopographic highs.

PLAY Cpk: CAMBRIAN PRE-KNOX GROUP PLAY

by David C. Harris, Kentucky Geological Survey, and Mark T. Baranoski, Ohio Division of Geological Survey

Location

Potential clastic and carbonate natural gas reservoirs of Cambrian age that are subjacent to the Knox Group or equivalents occur throughout much of the Appalachian basin. These potential reservoir rocks are included in the Cambrian pre-Knox Group play that extends from the western margin of the Appalachian basin to the folded rocks just east of the Allegheny Front (Figure Cpk-1). Commercial production from reservoirs in these rocks is currently confined to the western part of the play in Ontario, Canada, and to the central part of the play area in Kentucky and West Virginia.

Production History

Production from the pre-Knox play in the Appalachian basin has been limited to fields at the western edge of the play in Ontario, Canada, and several single-well pools in Kentucky and West Virginia (Figure Cpk-2). The remaining activity in the play consists of approximately 57 other wells that have reported gas shows from the pre-Knox sequence (Figure Cpk-3).

The first recorded gas production from the pre-Knox interval occurred in 1948 in Hamilton-Wentworth County, Ontario, Canada, from the Rockton pool (Figure Cpk-2). This pool was non-commercial; however, commercial production was discovered in the 1960s from four fields: Gobles, discovered in 1960; Innerkip in 1961 (Table Cpk-1); Willey in 1965; and Innerkip East in 1968. Other non-commercial gas pools in Ontario include New Glasgow, Electric, and St. Patricks (Figure Cpk-2). Exploration for Cambrian reservoirs in Ontario over the last 135 years has been limited, despite drilling depths of less than 3,500 feet. Only one significant gas field, Innerkip (Table Cpk-1), and three oil fields have been discovered (Trevail, 1990). A new phase of development drilling at Innerkip during the late 1980s resulted in the discovery of additional reserves, and a 148 percent increase in production in 1989, to 464 MMcf (Trevail, 1990).

Gas production from the pre-Knox interval in the rest of the basin is unrelated to activity in Ontario, and has been confined to the Rome trough in Kentucky and West Virginia. The first commercial well was reported in 1975, with the completion of the Exxon No. 1 McCoy in Jackson County, West Virginia. An initial open flow of 9.2 MMcfg/d and sustained production of 5.6 MMcfg/d was reported from a sandstone in the Conasauga Group from 14,350 to 14,360 feet. This well produced dry gas for about six months, and had a total cumulative production of 427 MMcfg before an increasing water cut forced the well to be plugged (Lytle and others, 1977; Petzet, 1991; de Witt, 1993; Exxon, written commun., 1994). The McCoy well holds the record for deepest production in the Appalachian basin.

In 1986, a second commercial gas well was reported from the Rome trough. The Ashland No. 1 Williams well, in Johnson County, Kentucky, was completed in the Conasauga Group (Rome Formation of Kentucky) (see Figure Cpk-3). The reported initial open flow was 1.055 MMcfg/d from 6,250 to 6,350 feet in a fractured shale interval. A slight show of condensate is also mentioned on the completion report. This well was still producing in 1995, but production data are not available.

Most recently, in July 1994, the highest initial production to date from this play was reported from a well in the Rome trough in Elliott County, Kentucky. The Carson Associates No. 1 Kazee blew out and initially flowed 11 MMcfg/d from a zone in the upper Conasauga Group/Rome Formation from 6,258 to 6,270 feet. The producing zone is a fine- to medium-grained sandstone. Initial reservoir pressure was 2,708 psi. This well was producing approximately 500 Mcfg/d at a flowing pressure of 710 psi in mid-1995. The field has been named the Homer pool (Figure Cpk-2) by operators, and several development wells were planned for 1995.

Cumulative pre-Knox gas production in Ontario at the end of 1981 was 4.51 bcf, 89 percent of which was produced from Innerkip, Willey, and Gobles fields (Bailey Geological Services Ltd. and Cochrane, 1984). Innerkip field alone had produced 3.9 bcf at the end of 1989 (Trevail, 1990). By 1994, after additional development drilling, approximately 9.5 bcf had been produced from Innerkip field (P. Mitchell, Denbridge Gas Corp., oral commun., 1994). Innerkip East had only one producing well in 1981, which produced 18.41 MMcfg in that year (Bailey Geological Services Ltd. and Cochrane, 1984). Cumulative production from Innerkip East through 1981 was 187.1 MMcfg. Cumulative production data for the Rome trough wells are only available for the Exxon No. 1 McCoy well. Estimated cumulative production from the pre-Knox interval in the whole basin is 12 bcfg in 1995.

At least 57 wells drilled in the Appalachian basin have reported gas shows from the pre-Knox interval (Figure Cpk-3). In deeper parts of the basin, hydrocarbon shows date back to 1947, when gas and oil shows were reported from the Rome Formation in the South Central No. 1 Hall well in Powell County, Kentucky (Figure Cpk-3) (McGuire and Howell, 1963; Weaver and McGuire, 1977). A well in Boyd County, Kentucky, in the Rome trough, the Inland No. 529 White, was completed as a Rome oil producer in 1967, but also produced about 90 Mcfg/d from the same zone (Kentucky Geological Survey, unpublished data). In 1980, the Lancaster No. 1 Lee well in Garrard County, Kentucky, reportedly flowed 750 Mcfg/d from Rome Formation sandstones, but was never commercially produced.

No commercial gas production from pre-Knox rocks has occurred in Ohio, Pennsylvania, or New York, although several significant gas shows from the Rome, Potsdam, Warrior, and lower Theresa formations have been reported. At least eight wells in New York have recorded gas shows from the Potsdam Formation (Mount Simon Sandstone equivalent) (Kreidler, 1959; 1963). Most of the New York wells were drilled in the 1890s, and available data are limited (see Figure Cpk-3). Locations of 60 wells with gas shows or commercial production reported from pre-Knox units outside of Ontario are illustrated in Figure Cpk-3.

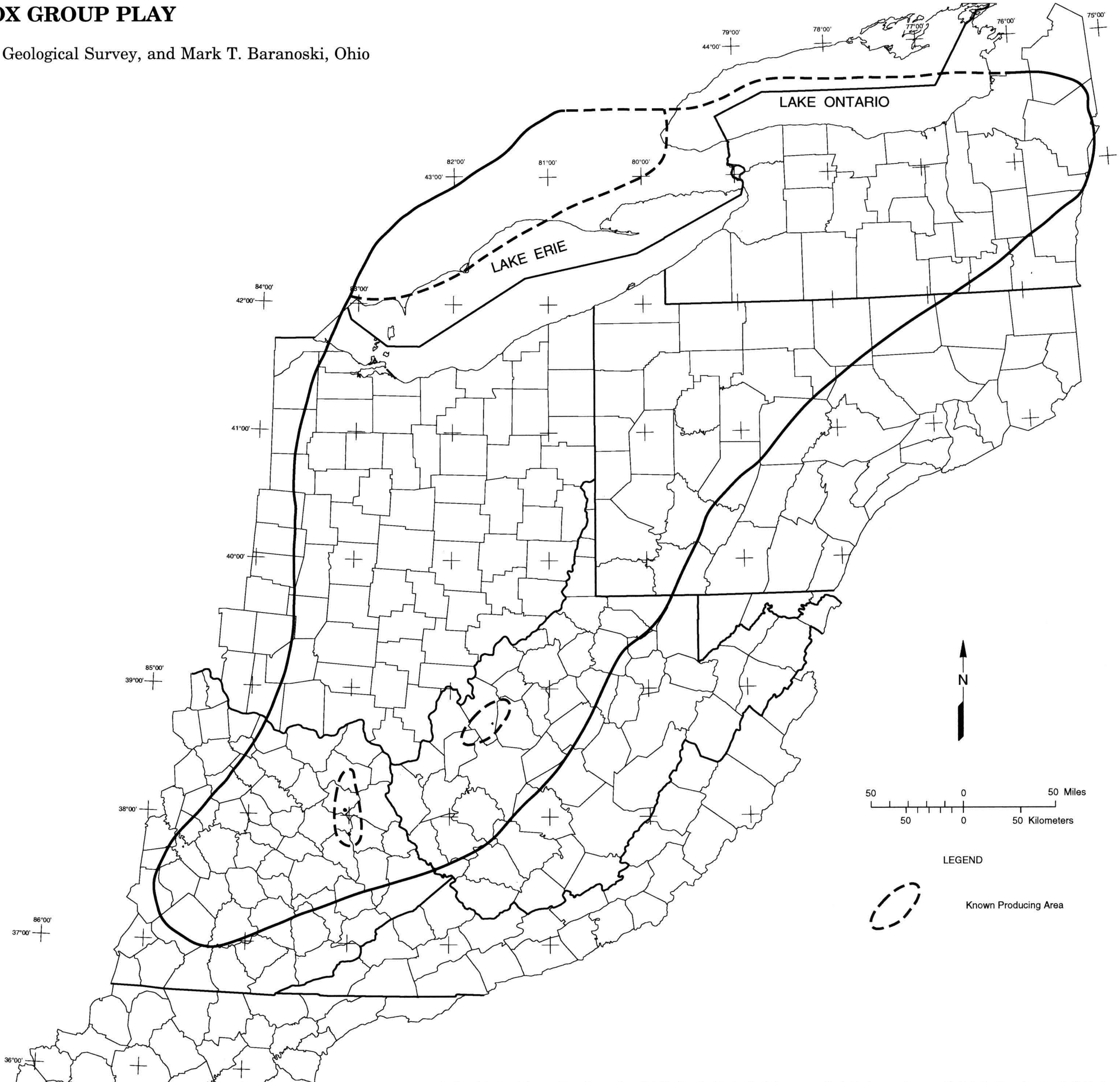


Figure Cpk-1. Outline of the Cambrian pre-Knox Group play within the Appalachian basin. Dots represent individual gas wells, except in Ontario, Canada, where individual wells are not shown. Where dashed, play boundary is inferred.

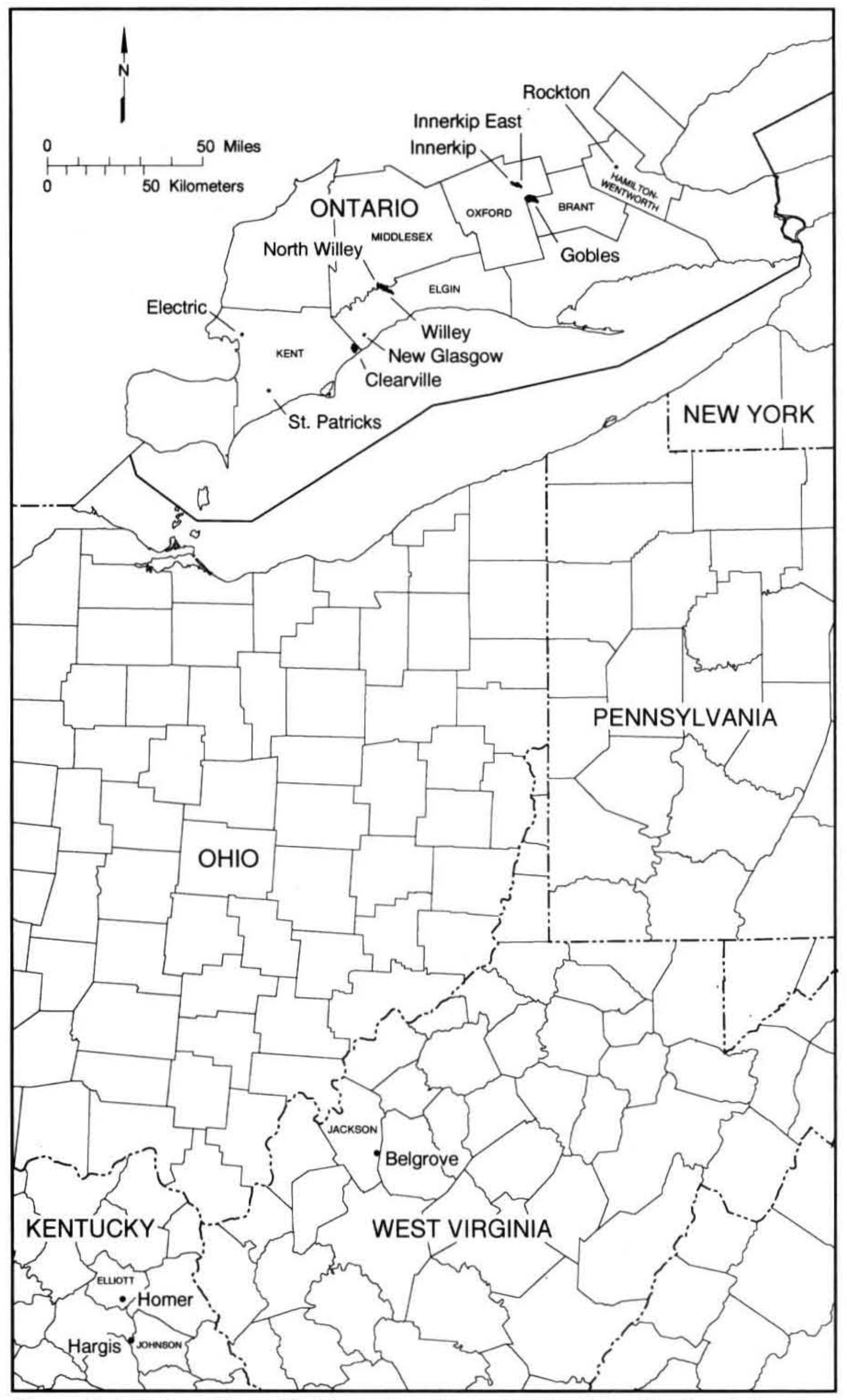


Figure Cpk-2. Location of fields and pools producing from the Cambrian pre-Knox Group play in the Appalachian basin.

Exploration of the pre-Knox play in the Rome trough has been fairly steady since the late 1950s. Until the mid-1970s prospects were generated using limited well data, surface faulting, shallow structure, and gravity and magnetic data. No commercial gas discoveries resulted during this early work. The mid-1970s saw the introduction of regional seismic data acquisition, and a new phase of deep drilling began in Kentucky and West Virginia. Since then, seismic data has been the key exploration tool, and limited commercial success was achieved. Reprocessing of older seismic data resulted in the most recent Elliott County, Kentucky, discovery. As reprocessing work and new data acquisition continues, improved seismic interpretation will lead to further success.

Stratigraphy

The stratigraphic interval of the play includes all sedimentary rocks below the Cambro-Ordovician Knox Group. Because the Knox Group is not recognized throughout the Appalachian basin, this play also includes units below the Gatesburg Formation in Pennsylvania, and the upper part of the Theresa Formation in New York. In Ontario, Canada, the Knox Group has been removed by erosion, and Cambrian units are unconformably overlain by the Middle Ordovician Shadow Lake Formation and Black River Group (Trevail, 1990). Here, the play interval will be referred to as pre-Knox, despite the absence of a formally recognized Knox Group in some areas.

The Cambrian units in the Appalachian basin have been studied in outcrop for more than 150 years, beginning with the first geological surveys of New York, Pennsylvania, and Virginia. Extension of outcrop nomenclature from different areas to the subsurface, often over hundreds of miles, has resulted in a wide variation in Cambrian stratigraphic nomenclature across the basin (Figure Cpk-4). In addition, syndepositional faulting associated with the Rome trough and other structural features has resulted in complex facies patterns and stratigraphic correlations. An excellent regional stratigraphic synthesis for the Cambrian in the Appalachian basin has been published as a series of basin-wide stratigraphic cross sections by Ryder (1991; 1992a; 1992b), Ryder, Harris, and Repetski (1992), and Ryder and others (1995a; 1995b). Stratigraphic divisions and nomenclature in this discussion will follow Ryder's usage. Figure Cpk-5, modified from Ryder (1992b), illustrates the general stratigraphic configuration of Cambrian rocks in the basin. The age of the pre-Knox Paleozoic units in the Appalachian basin ranges from Early to Late Cambrian.

Pre-Knox stratigraphy in the Appalachian basin is presented here as three sequences, each of which corresponds to a different tectonic province: a relatively stable craton in the northwest (northern Kentucky, Ohio, western Pennsylvania, western New York, and Ontario, Canada); a Cambrian-age extensional graben, the Rome trough, trending southwest-northeast from central Kentucky through West Virginia and Pennsylvania and into southern New York; and an eastern basin, lying between the Rome trough and the Allegheny structural front (Figures Cpk-5, Cpk-6) (Ryder, 1992b). The cratonic area is the stable shelf of Harris (1975). The Rome trough and eastern basin areas comprise Harris' (1975) unstable shelf province. Normal faults bounding these provinces were most active through the Middle Cambrian, and differential subsidence resulted in large variations in pre-Knox sequence thickness. The most dramatic stratigraphic thickening occurs in the Rome Formation and Conasauga Group intervals in the Rome trough. Continued reactivation of Cambrian basement faults affected stratigraphy in and around the trough throughout the Paleozoic. Cambrian units that have produced gas or are considered potentially productive below the Knox include the following formations, in descending stratigraphic order: the Kerbel Formation of Ohio; the Conasauga Group of Kentucky, Pennsylvania, West Virginia, and Virginia, and the Conasauga Formation of Ohio; the Rome Formation of Kentucky, Ohio, Pennsylvania, West Virginia, and Virginia; the Theresa/Eau Claire Formation of Ontario, the Mount Simon Sandstone of Ohio and equivalent Potsdam Formation of Pennsylvania, New York, and Ontario, Canada; and the Shady or Tomstown Dolomite and basal sandstones within the Rome trough of Kentucky, West Virginia, and Pennsylvania. The stratigraphic sequence in each tectonic province is briefly discussed below.

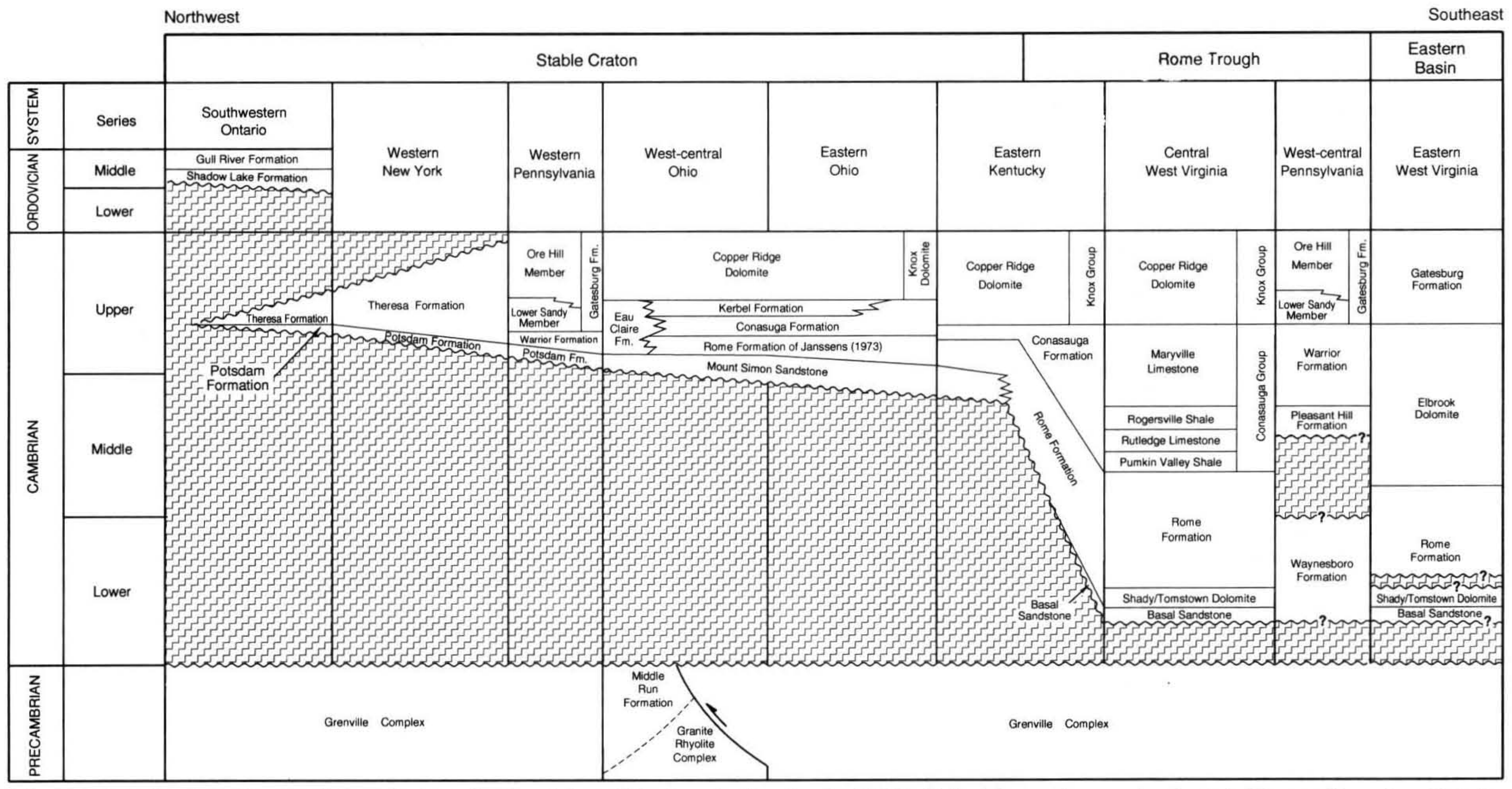


Figure Cpk-4. Stratigraphic correlation chart for the Cambrian of the Appalachian basin. Middle Ordovician rocks are also included for southwestern Ontario. Modified from Janssens (1973), Bailey Geological Services Ltd. and Cochrane (1984), Patchen and others (1985a), Milici and de Witt (1988), Ryder (1992b), Ryder, Harris, and Repetski (1992), and Riley and others (1993).

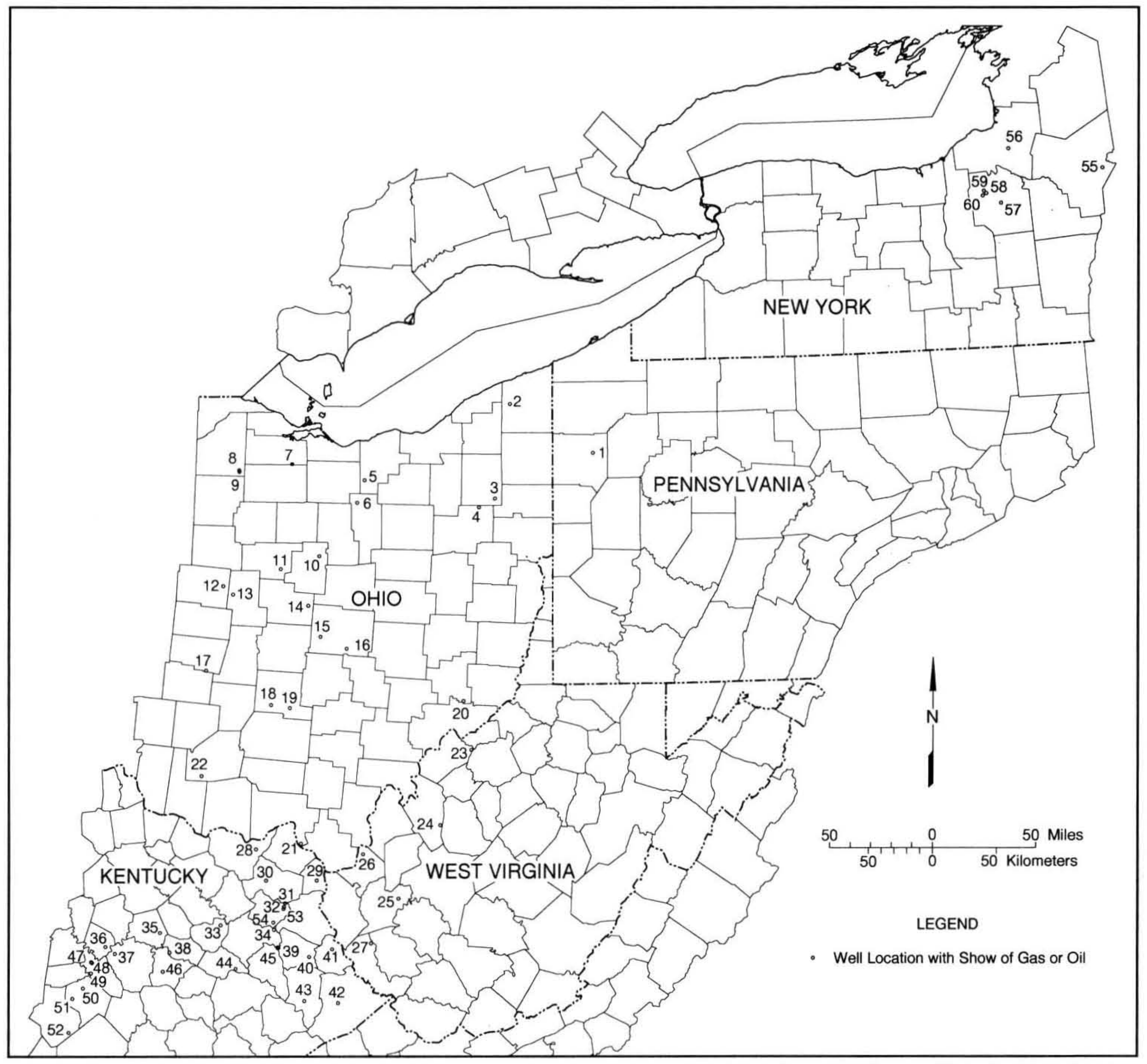


Figure Cpk-3. Map showing distribution of commercial gas production and gas shows from pre-Knox units in the Appalachian basin outside of Ontario, Canada. Well numbers refer to data listed below.

Map Number	State	County	Permit	Operator	Lease	Total Depth	Formation and Depth of Show or Production	Gauge
1	PA	Mercer	20036	Peoples Nat. Gas	Temple	9,919	Upper Cambrian sandstone at 9,580, show gas	
2	OH	Ashtabula	191	Horizon	Rhoa	6,750	Rome at 6,421, show gas	
3	OH	Portage	2860	Viking	Viking	8,797	Mount Simon at 8,506-8,712, show gas	
4	OH	Stark	4751	Kenoil	Bingham	7,725	Conasauga at 7,668-7,674, show oil and gas	50 Mcfg/d
5	OH	Lorain	795	Ohio Fuel	Burge	4,513	Kerbel at 4,469-4,473, show gas	
6	OH	Ashland	3938	Bass Energy	Fingulin	5,140	Rome at 4,830; Mount Simon at 4,930, show gas	
7	OH	Sandusky	248	Glory	Rohde	2,658	Kerbel at 2,630-2,658, show gas	
8	OH	Wood	364	Allerton	Dennis	2,290	Kerbel at 2,092, show oil	
9	OH	Wood`	366	Allerton	Tienarend	2,200	Kerbel at 2,051, show gas	
10	OH	Morrow	4043	EEI	Hickok	4,707	Rome at 4,360-4,620, show oil and gas	
11	OH	Marion	149	X-Alpha	McNamera	3,076	Conasauga at 3,040, show oil	
12	OH	Logan	91	Alerton	Robson	3,010	Rome, Mount Simon, show gas	
13	OH	Union	84	Majestic	Hutchins	2,765	Kerbel at 2,515-2,542, show gas	
14	OH	Delaware	354	Poling	Cockrell	4,860	Rome, show gas	
15	OH	Licking	5413	Clinton	Lynd	4,713	Kerbel at 4,430-4,495, show oil and gas	
16	OH	Licking	5446	Oxford	Church	5,273	Kerbel at 5,220, show gas	
17	OH	Clark	2	Friend	Mattison	4,648	Mount Simon at 3202, show gas	
18	OH	Pickaway	3	McM.-Bull.	Dunlap	3,525	Conasauga and Rome, show gas	
19	OH	Pickaway	6	Midwest	Miller	4,179	Rome at 3,949-3,958, show oil	
20	OH	Noble	1278	Amerada	Ullman	11,442	Conasauga at 10,611, gas cut water	
21	OH	Scioto	N/A	Aristech	Aristech	5,650	Rome, show gas	
22	OH	Highland	16	Oxford	Heyob	3,296	Eau Claire at 2,806-2,844	100 Mcfg/d
23	WV	Wood	351	Hope Nat. Gas	Power Oil	13,391	Mount Simon, show gas	
24	**WV**	**Jackson**	**1366**	**Exxon**	**McCoy**	**17,675**	**Conasauga at 14,358, gas completion**	**9.1 MMcfg/d**
25	WV	Lincoln	1469	Exxon	McCormick	19,124	Conasauga at 11,608, show gas	
26	WV	Cabell	537	Cyclops	Kingery	8,552	pre-Knox, show gas	
27	WV	Mingo	805	Columbia	Fee	19,537	pre-Knox, show gas	
28	KY	Lewis	N/A	Thomas	Adams	4,190	Rome, basal sandstone, show gas, oil	
29	KY	Boyd	18327	Inland Gas	White	7,676	Rome at 7,445, show gas; Rome at 7,516; 7,574; show oil and gas	15 bopd, 90 Mcfg/d
30	KY	Carter	398E9	United Fuel Gas	Stamper	5,085	basal sandstone, show gas	
31	KY	Carter	25730	Inland Gas	McDavid	9,980	Tomstown at 7,672, basal sand at 8,898, shows gas	
32	KY	Elliott	23542	Monitor Pet.	C. Ison	9,665	Rome, show gas, oil, condensate in 3 zones	
33	KY	Menifee	18101	United Fuel Gas	Brown	5,858	Rome, show gas in 8 zones	
34	KY	Morgan	24194	Monitor Pet.	F. Ison	10,012	Rome, show gas	
35	KY	Clark	25602	Widener	Glover	4,690	Rome at 4394, show gas	
36	KY	Jessamine	13950	Kin-Ark Oil	Hager	4,944	Conasuaga at 3,277, basal sandstone at 4,360, show gas	
37	KY	Madison	21905	Texaco	Perkins	6,415	Rome at 4,736, show gas	
38	KY	Powell	N/A	South Central	Hall	6,081	Rome at 5,500; 5,913, show oil and gas	15 bopd
39	**KY**	**Johnson**	**67549**	**Ashland Expl.**	**Williams**	**10,608**	**Rome at 6,250-6,350, gas/cond. completion Tomstown(?) at 10,608, show gas**	**1,055 Mcfg/d**
40	KY	Johnson	26311	U.S. Signal	Elkhorn	14,566	Rome, show gas	1,000 Mcfg/d
41	KY	Martin	870E8	United Fuel Gas	Jasper	13,172	Conasauga-Rome, 3 zones, show gas	
42	KY	Pike	24577	Signal Oil	Stratton	12,450	Rome, show gas; Tomstown, show oil	
43	KY	Floyd	27524	Signal Oil	Hall	13,000	Rome at 7,839, show gas	
44	KY	Wolfe	30520	Exxon Corp.	Banks	12,288	Rome?, show oil and gas	
45	KY	Johnson	60712	Ashland Expl.	McCarty	6,540	Rome at 6,420, show gas	411 Mcfg/d
46	KY	Estill	21865	Texaco	Tipton	6,817	pre-Knox?, show gas?	
47	KY	Garrard	38876	Lancaster Expl.	Lee	4,596	Rome at 4,536, show gas	750 Mcfg/d
48	KY	Garrard	21048	Texaco	Kirby	5,745	Rome at 4,550, show gas; basal sandstone at 4,612, show oil	
49	KY	Garrard	25811	Widener	Burdette	4,465	Rome at 4,400, show oil and gas	
50	KY	Lincoln	22948	Rome Oil & Gas	Foster	5,781	Rome, show oil and gas	
51	KY	Lincoln	N/A	California Co.	Spears	6,117	Rome at 5,080, show oil; basal sandstone at 5,703, show gas	
52	KY	Casey	34578	Cities Service	Garrett	8,251	Rome at 7,210, 7,285, 7,470, show gas	
53	KY	Elliott	67748	Ashland Expl.	Kazee	11,091	Rome at 7,186, 7,292, 8,883, show gas	
54	**KY**	**Elliott**	**85783**	**Carson Assoc.**	**Kazee**	**6,270**	**Rome at 6,258, gas completion**	**11,000 Mcfg/d**
55	NY	Oneida	N/A	unknown	Morgan	1,000+	Potsdam at 925-960, show gas	
56	NY	Onondaga	N/A	Lupher & Kline	Yost-Yenny	5,000	Potsdam at 4,810, trace gas	
57	NY	Onondaga	N/A	Empire Cement	Empire Cement	3,526+	Potsdam at 3,526, show gas	150 Mcf
58	NY	Onondaga	N/A	Empire Cement	Sherwood	3,600	Potsdam at 3,526, show gas	100 Mcf
59	NY	Onondaga	N/A	Empire Cement	Empire Cement	3,600	Potsdam at 3,526, show gas	
60	NY	Oswego	N/A	Eastern Oil Co.	Carley	2,157	Potsdam, show gas	100 Mcf

TABLE Cpk-1		Innerkip Oxford Co., Ontario
BASIC RESERVOIR DATA	POOL NUMBER	
	DISCOVERED	1961
	DEPTH TO TOP RESERVOIR	2,800
	AGE OF RESERVOIR	Upper Cambrian
	FORMATION	Potsdam/ Theresa
	PRODUCING RESERVOIR	Potsdam/ Theresa
	LITHOLOGY	sandstone
	TRAP TYPE	stratigraphic
	DEPOSITIONAL ENVIRONMENT	shallow marine
	DISCOVERY WELL IP (Mcf)	1,187
	DRIVE MECHANISM	gas expansion
	NO. PRODUCING WELLS	40
	NO. ABANDONED WELLS	37
	AREA (acreage)	4,000
	OLDEST FORMATION PENETRATED	Precambrian
	EXPECTED HETEROGENEITY DUE TO:	diagenesis deposition
RESERVOIR PARAMETERS	AVERAGE PAY THICKNESS (ft.)	11
	AVERAGE COMPLETION THICKNESS (ft.)	
	AVERAGE POROSITY–LOG (%)	9.5
	MINIMUM POROSITY–LOG (%)	3.5
	MAXIMUM POROSITY–LOG (%)	22
	NO. DATA POINTS	45
	POROSITY FEET	
	RESERVOIR TEMPERATURE (°F)	82.4
	INITIAL RESERVOIR PRESSURE (psi)	500
	PRODUCING INTERVAL DEPTHS (ft.)	2,831-2,917
	PRESENT RESERVOIR PRESSURE (psi) / DATE	300/1995
FLUID & GAS PROPERTIES	Rw (Ωm)	
	GAS GRAVITY (g/cc)	0.634
	GAS SATURATION (%)	75
	WATER SATURATION (%)	25
	COMMINGLED	no
	ASSOCIATED OR NONASSOCIATED	nonassociated
	Btu/scf	1,100
VOLUMETRIC DATA	STATUS (producing, abandoned, storage)	producing
	ORIGINAL GAS IN PLACE (Mcf)	14,300,000
	ORIGINAL GAS RESERVES (Mcf)	10,000,000
	PRODUCTION YEARS	1961-1995
	REPORTED CUMULATIVE PRODUCTION (Mcf)	9,500,000
	NO. WELLS REPORTED	
	ESTIMATED CUMULATIVE PRODUCTION (Mcf)	
	REMAINING GAS IN PLACE (Mcf)/DATE	4,800,000
	REMAINING GAS RESERVES (Mcf)/DATE	500,000
	RECOVERY FACTOR (%)	70
	INITIAL OPEN FLOW (Mcf/d)	
	FINAL OPEN FLOW (Mcf/d)	

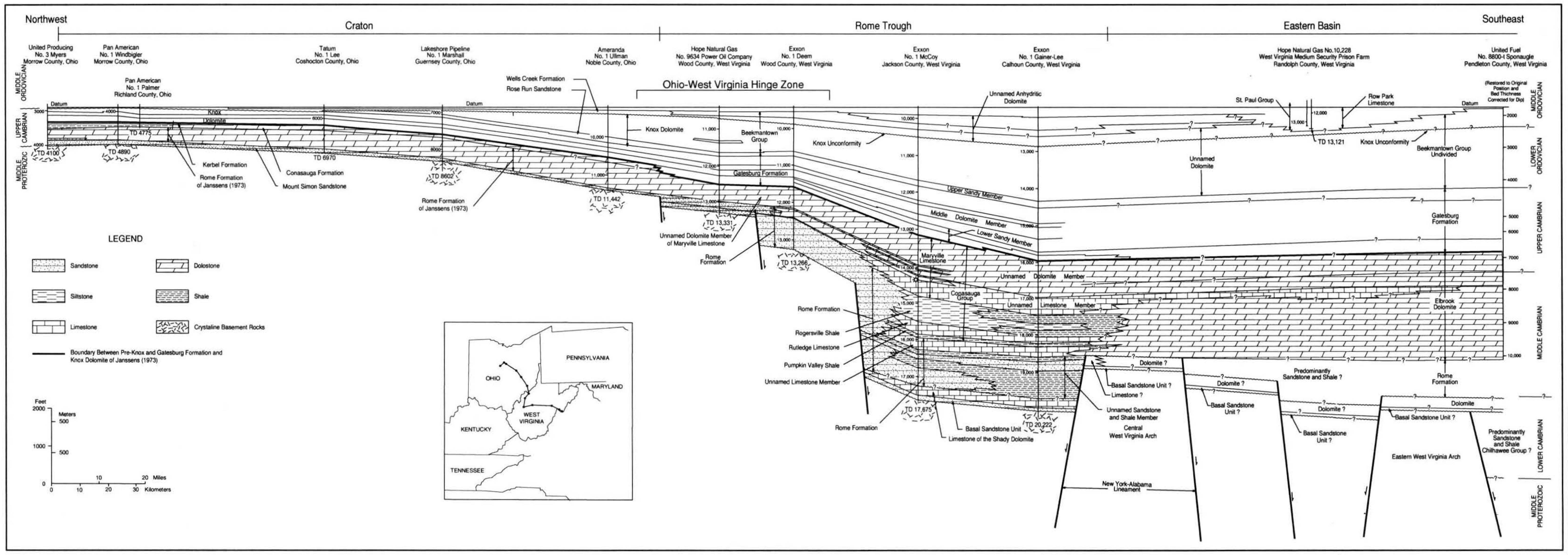


Figure Cpk-5. Stratigraphic cross section showing sedimentary units and lithologies for the pre-Knox interval in the Ohio and West Virginia portion of the Appalachian basin. Section is oriented northwest to southeast, from the craton, across the Rome trough, into the eastern part of the basin. See inset map for well locations. Bold boundary separates pre-Knox units from Knox and equivalent strata. Lithologies are shown for pre-Knox units, where known. Modified from Ryder (1992b).

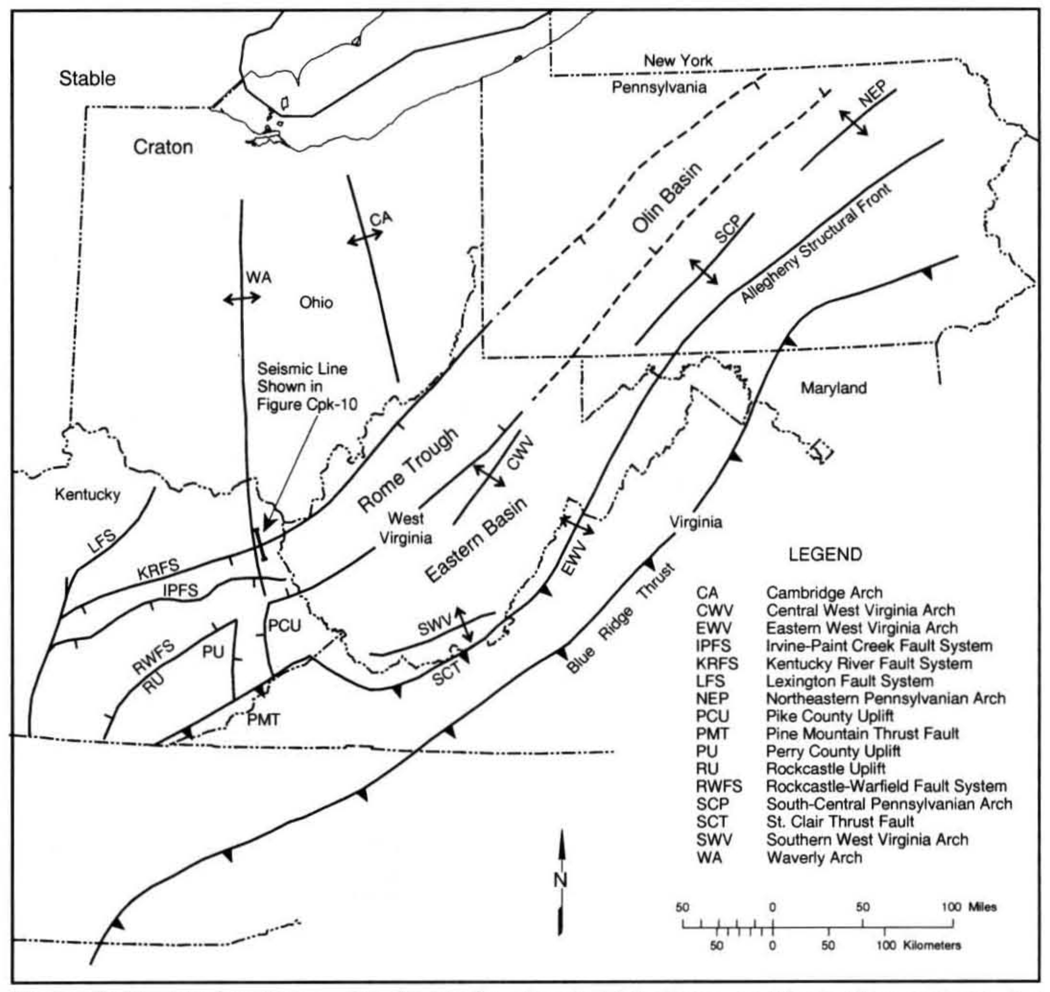


Figure Cpk-6. Regional map showing major structural features and tectonic provinces for the Cambrian pre-Knox Group play. Location of seismic line (Figure Cpk-10) is shown.

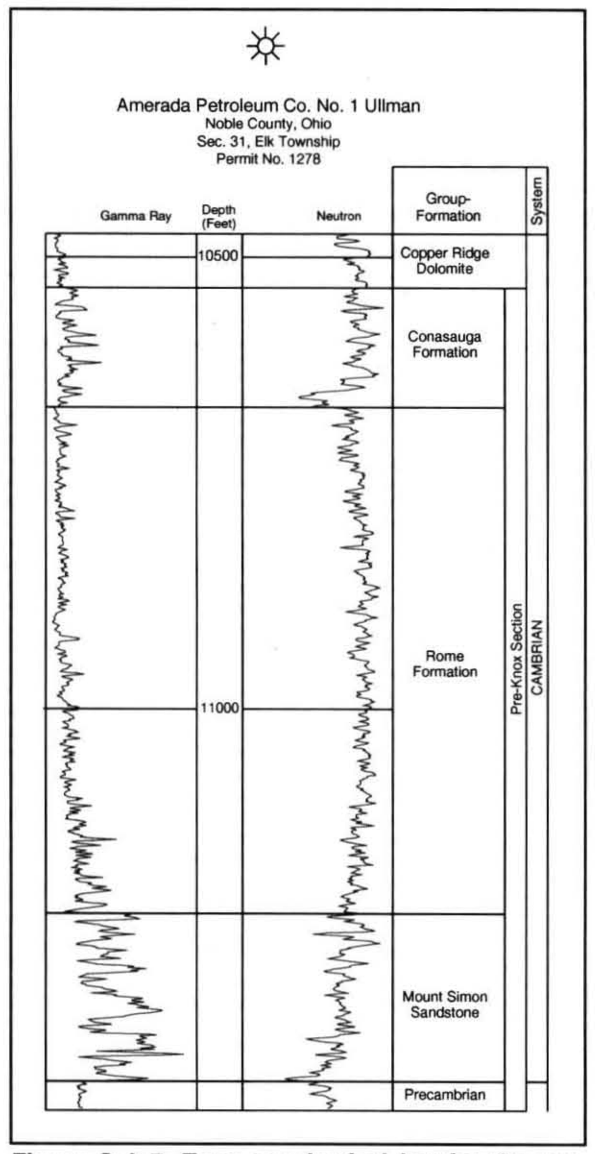
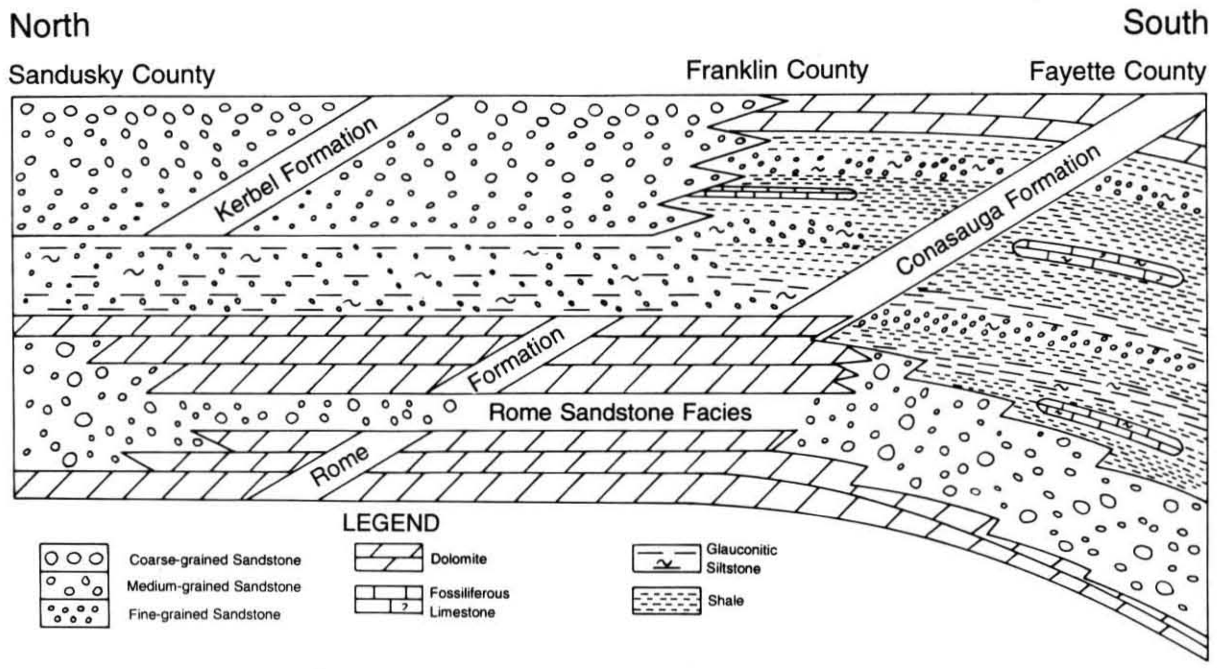


Figure Cpk-7. Type geophysical log for the pre-Knox sequence on the craton: gamma-ray-neutron logs for the Amerada No. 1 Ullman well, Noble County, Ohio. This well has a thinner pre-Knox sequence than areas to the east and southeast.



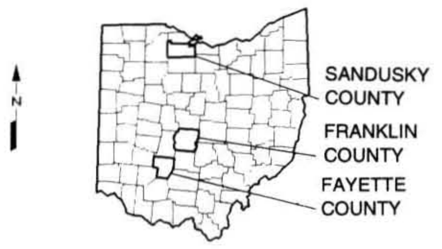


Figure Cpk-8. Schematic north-south cross section of the Kerbel and Conasauga formations, and the Rome Formation of Janssens (1973) across central Ohio. From Janssens (1973).

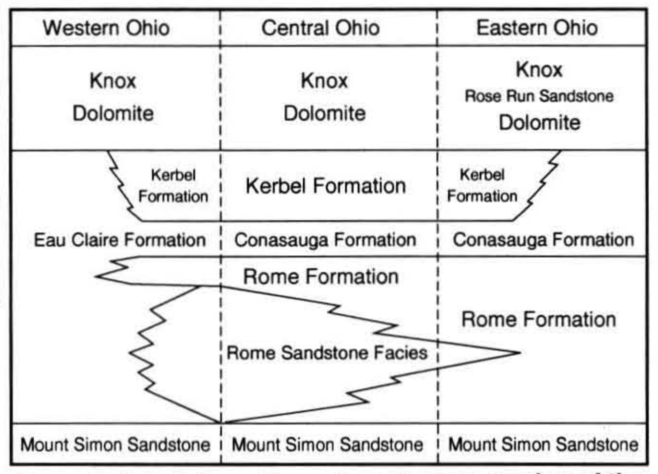


Figure Cpk-9. Schematic east-west cross section of the Eau Claire and equivalent Rome strata in Ohio. After Janssens (1973).

On the craton in Ohio and northern Kentucky, the pre-Knox interval comprises the Upper Cambrian Kerbel Formation (and the partially equivalent Eau Claire Formation), the Conasauga Formation, the Rome Formation, and the Mount Simon Sandstone (Figure Cpk-4) (McGuire and Howell, 1963; Janssens, 1973). In westernmost Pennsylvania, this sequence is roughly equivalent to the Warrior and Potsdam formations (Wagner, 1966a, 1966b; 1976; Pees and Fox, 1990; Ryder, 1992b). A type log for the cratonic sequence in eastern Ohio is shown in Figure Cpk-7.

The Kerbel Formation was defined in Ohio by Janssens (1973) as a fine- to coarse-grained sandstone that overlies the Conasauga Formation and intertongues with the Eau Claire Formation. The unit is as much as 170 feet thick, generally coarsens upward, and may grade into dolomite or dolomitic sandstone near the top. Janssens (1973) interpreted Kerbel sandstones as deltaic fan deposits, and the interbedded carbonates, shales, and sandstones of Ohio's Conasauga Formation as prodelta marine deposits. The Conasauga sandstones merge with the lower sandy member of the Gatesburg Formation in the Rome trough of West Virginia (Figure Cpk-4). Figure Cpk-8 illustrates Janssens' (1973) interpretation of the relationships between the Kerbel, Conasauga, and Rome formations of central Ohio.

The Conasauga Formation on the craton consists of red and green shales with interbedded glauconitic siltstones, very fine-grained sandstones, limestones, and dolomite (Janssens, 1973). It ranges from 40 to about 450 feet thick in Ohio. The Conasauga Formation grades conformably into the overlying Kerbel Formation or Copper Ridge Dolomite (Knox Group), and into the underlying Rome Formation of Janssens (1973).

Janssens' (1973) Rome Formation consists largely of dolomite in eastern Ohio and contains a sandstone facies in central Ohio that appears to coincide with the trend of the ancestral Waverly arch (Woodward, 1961). West of the sandstone facies, Janssens' Rome Formation changes to glauconitic sandstone, siltstone, shale, and dolomite of the Eau Claire Formation (Figure Cpk-9). The Rome Formation defined on the shelf in northeastern Kentucky by McGuire and Howell (1963) is similar to that described in Ohio by Janssens (1973).

The post-Knox unconformity truncates all the Cambrian units in southwestern Ontario, Canada, above the Theresa Formation, which probably correlates to Janssens' Rome Formation in Ohio. Unconformably overlying the Theresa Formation in Ontario is the Middle Ordovician Shadow Lake Formation (Figure Cpk-4). This unit is a bright green shale, commonly containing floating quartz sand. It is interbedded in places with argillaceous green sandstones, and red shales (Bailey Geological Services Ltd. and Cochrane, 1984). The Shadow Lake forms the top seal for most Cambrian reservoirs in Ontario.

The oldest Paleozoic sedimentary units on the craton are the Mount Simon Sandstone and correlative Potsdam Sandstone of western Pennsylvania, New York, and Ontario (Ryder, 1992a; 1992b; Ryder, Harris, and Repetski, 1992). These transgressive sandstones unconformably overlie Middle Proterozoic metamorphic (Grenville Province) and sedimentary (Middle Run Formation) rocks in Ohio and north-central and northeastern Kentucky (McGuire and Howell, 1963; Janssens, 1973; Drahovzal and others, 1992). The Mount Simon Sandstone ranges in age from latest Middle Cambrian in the southeast to early Late Cambrian in the northwest (Ryder, Harris, and Repetski, 1992). The sandstones are fine-grained to conglomeratic, and vary from clean quartz arenites to arkosic and dolomitic sandstones (Janssens, 1973; Robinson, 1982). In New York, the Potsdam Sandstone is gradational with sandstones and sandy dolomites of the Theresa Formation. Thicknesses range from 0 at the post-Knox unconformity truncation along the southern shore of Lake Ontario, to almost 1,500 feet at the Pennsylvania border (Robinson, 1982). The Mount Simon Sandstone is not recognized southeast of the northwestern boundary of the Rome trough, which is the Ohio-West Virginia hinge zone of Ryder (1992b). The Mount Simon correlates with the upper Rome Formation in the Rome trough across this fault zone (Figure Cpk-4) (Webb, 1980; Ryder, 1992b).

The cratonic units described above extend into northern Kentucky and northwestern West Virginia, but abruptly thicken across a series of extensional growth faults into a northeast-southwest-trending rift basin, the Rome trough (Figure Cpk-10) (Woodward, 1961; McGuire and Howell, 1963; Silberman, 1972; 1981; Cardwell, 1977; Harris, 1978; Webb, 1980; Sutton, 1981). This Cambrian rift basin extends from central Kentucky through West Virginia, into western Pennsylvania, where it is has also been referred to as the Olin Basin (Figure Cpk-6) (Wagner, 1976; Harper, 1989). In the Rome trough, the pre-Knox section is older and dramatically thickened, with as much as 10,000 feet of pre-Knox sediments in some areas (Harris, 1978; Webb, 1980; Ryder, Harris, and Repetski, 1992). The Rome trough may continue into southern New York, but data are sparse (Beardsley and Cable, 1983; Cable and Beardsley, 1984; Harper, 1989). Rocks as old as Early Cambrian are present within the trough, and have no equivalents to the northwest on the craton. The pre-Knox sequence within the Rome trough of Kentucky and West Virginia consists of the Conasauga Group, Rome Formation, Shady/Tomstown Dolomite, and a basal sandstone zone. Equivalent units within the trough in Pennsylvania are largely unknown due to a lack of well data, but may consist of the Warrior Formation, Pleasant Hill Limestone, and Waynesboro Formation as correlated from outcrop by Ryder, Harris, and Repetski (1992) and Ryder (1992a). The expanded Cambrian section in the Rome trough is largely conformable, and predominantly marine in origin (Ryder, 1992b). A type log for the Rome trough sequence is shown in Figure Cpk-11.

Stratigraphic correlations and nomenclature used within the Rome trough vary significantly. The greatly expanded section makes correlation with outcrop or subsurface cratonic sequences difficult. The most significant discrepancies lie in the position of the Rome Formation-Conasauga Group contact, and the recognition of the Shady/Tomstown Dolomite (Thomas, 1960; McGuire and Howell, 1963; Webb, 1980; Sutton, 1981; Cable, 1984; Allen, 1988; Donaldson and others, 1988; Ryder, 1992b; Ryder and others, 1995a). Space constraints do not allow a discussion of these problems here; Ryder's (1992b) nomenclature and stratigraphic correlations within the trough, which are illustrated in Figure Cpk-5, will be utilized. From this cross section, the lithostratigraphic basis of Ryder's correlations within the Rome trough are apparent.

The Conasauga Group consists of a 2,400- to 5,500-foot-thick sequence of shale, limestone, dolomite, and siltstone, which conformably overlies the Rome Formation in the Rome trough (Ryder, 1992b; Ryder and others, 1995b). In the subsurface of West Virginia, Ryder (1992b) recognized four of the six formations that make up the Conasauga Group in outcrop in Tennessee. These include, in descending order, the Maryville Limestone, composed of limestone, dolomite, and minor sandstone; the Rogersville Shale, consisting of shale, micritic limestone, and siltstone; the Rutledge Limestone, composed of micritic and sandy limestone and sandstone; and the Pumpkin Valley Shale, a gray shale and siltstone (Ryder, 1992b).

The Rome Formation is a 1,000- to 2,900-foot-thick sequence of sandstone, siltstone, shale, limestone, and dolomite which overlies the limestone of the Shady Dolomite (Ryder, 1992b; Ryder and others, 1995b). Sandstone beds in the upper portion of the Conasauga Group (in the middle part of the Maryville Limestone) correlate to the upper sandstone units of the Rome in the Ohio-West Virginia hinge zone and possibly to Janssens' (1973) Mount Simon Sandstone west of the Ohio-West Virginia hinge zone (Ryder, 1992b) (Figure Cpk-5). Depositional environments of the Conasauga Group and Rome Formation in cores from two West Virginia wells were interpreted by Donaldson and others (1975; 1988). They described carbonate and clastic facies deposited in tidal flat, tidal

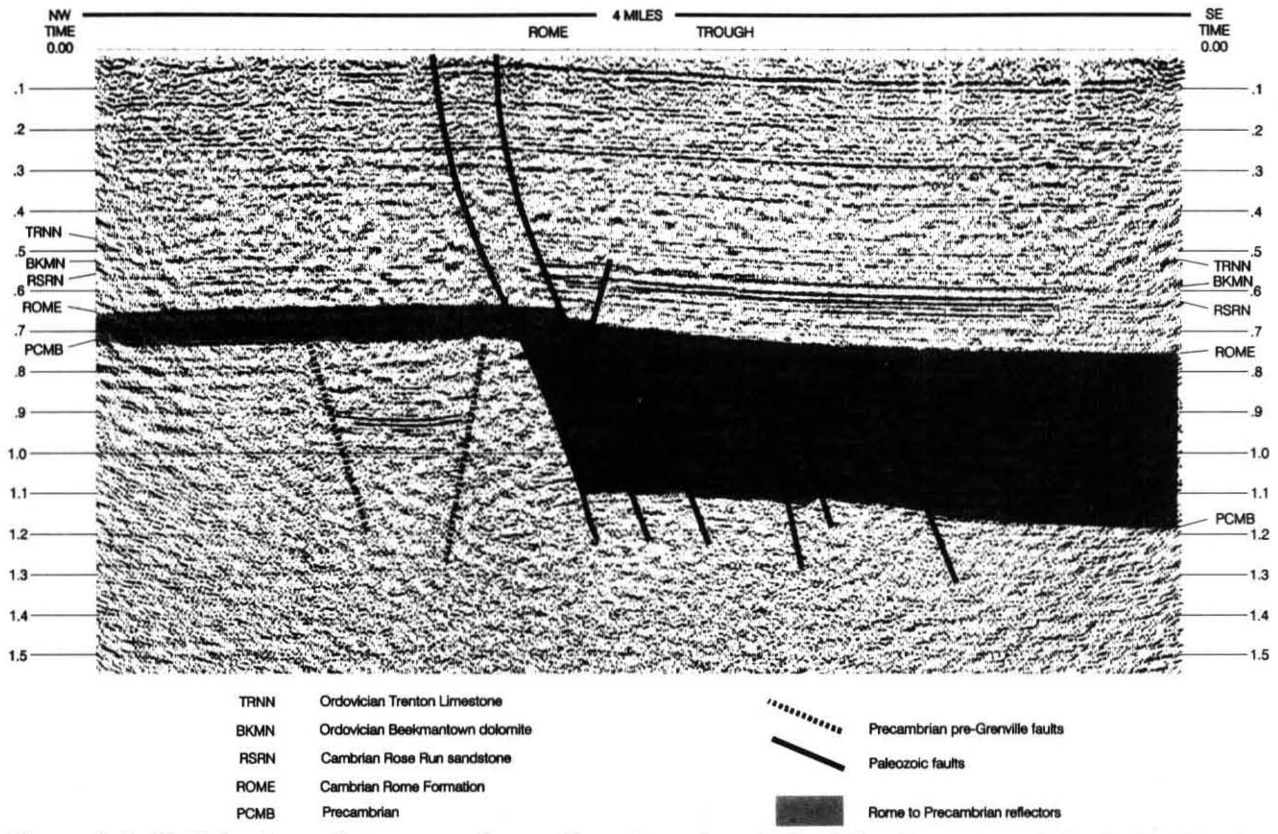


Figure Cpk-10. Seismic section across the northern boundary fault of the Rome trough in Carter County, Kentucky. Data was collected using a vibroseis source, 30-fold, migrated, with normal polarity. The Cambrian section increases in thickness to the south of the fault system, indicating growth faulting. Formation tops are indicated. Modified from Riley and others (1993).

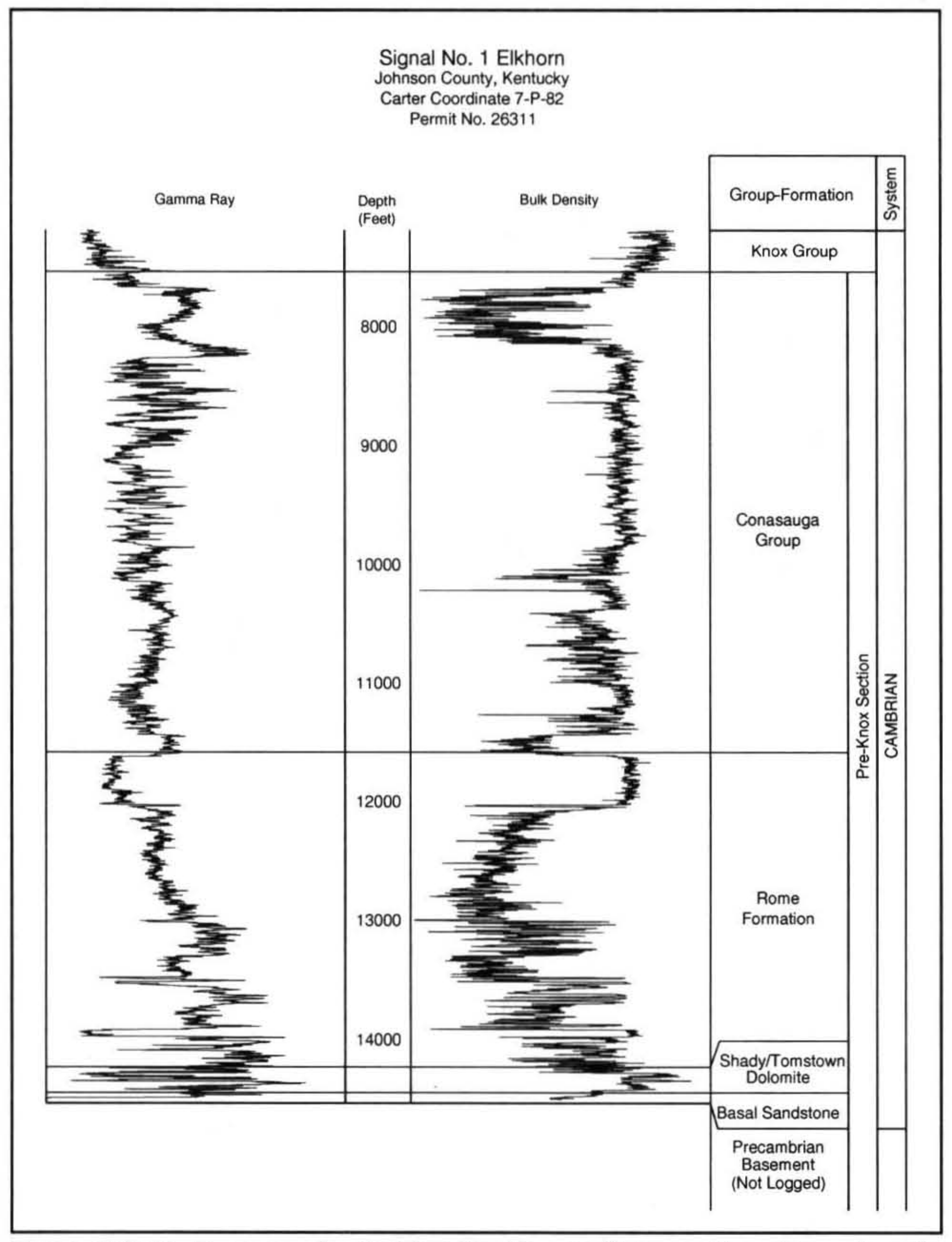


Figure Cpk-11. Type geophysical log for the pre-Knox section, Rome trough: gamma-ray/bulk density log for the Signal No. 1 Elkhorn well, Johnson County, Kentucky. This well has an expanded pre-Knox section. Stratigraphic correlations from Ryder and others (1995b).

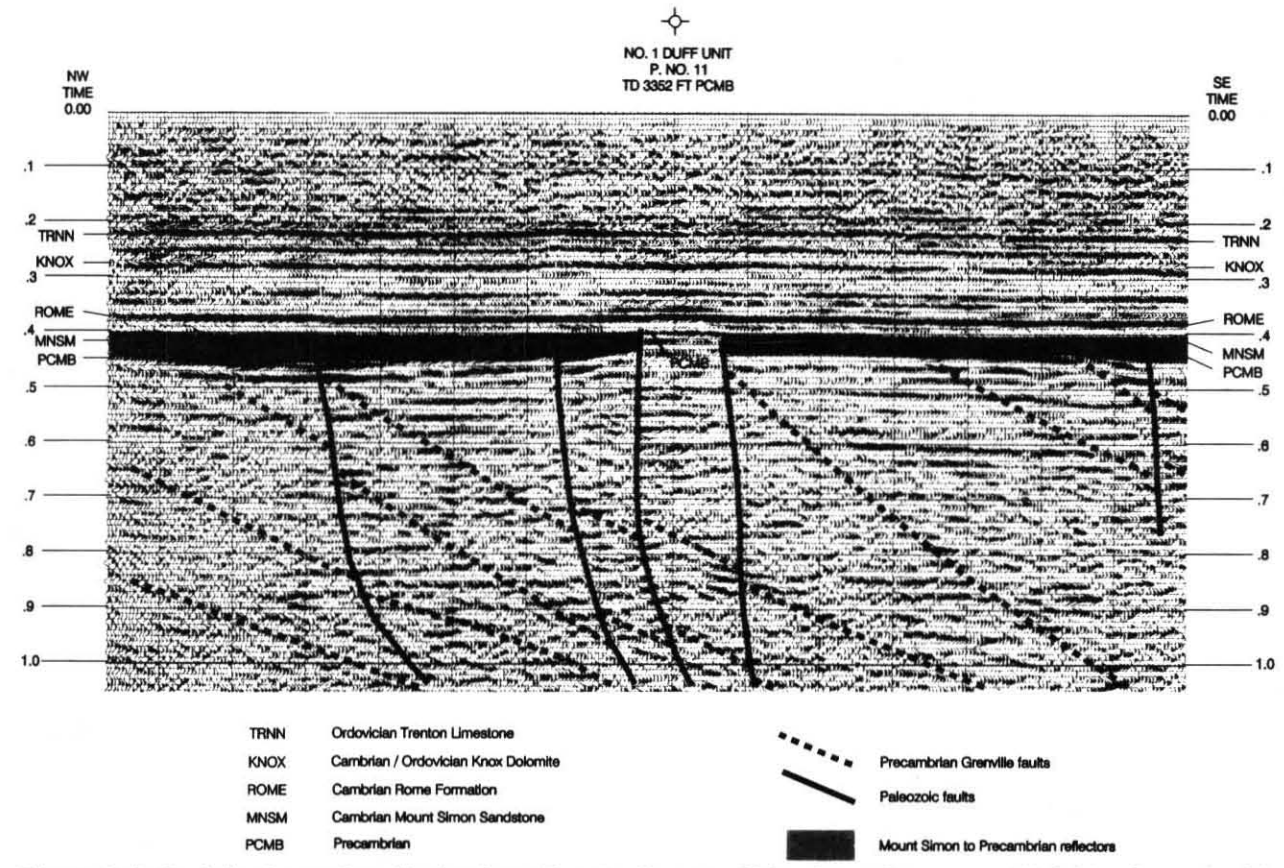


Figure Cpk-12. Seismic section display from Fayette County, Ohio: dynamite source, 12-fold, migrated, with normal polarity. Note thick Mount Simon Sandstone adjacent to Precambrian basement paleotopographic high at the Duff well. Modified from Riley and others (1993).

channel, and shallow subtidal marine environments.

Confined to the Rome trough and the block-faulted terrain to the southeast is the Shady/Tomstown Dolomite. This unit underlies the Rome Formation and overlies a basal sandstone (McGuire and Howell, 1963; Ryder, 1992b). The Shady/Tomstown Dolomite interval consists of limestone in some areas, and was considered by Ryder (1992b) to be Early Cambrian in age.

The oldest sedimentary unit in the Rome trough of Kentucky and West Virginia is a sandstone, informally named the "basal" sandstone, which unconformably overlies Middle Proterozoic crystalline basement rocks (McGuire and Howell, 1963; Webb, 1980; Sutton, 1981). This sandstone unit varies from 20 to 650 feet thick and is commonly arkosic. Previously, this basal sandstone in the Rome trough was correlated with the Mount Simon Sandstone on the craton (McGuire and Howell, 1963). The Mount Simon appears to be a much younger unit, and probably correlates with the uppermost part of the Rome Formation in the trough (Ryder, 1992b) (Figure Cpk-5).

East and southeast of the Rome trough, pre-Knox units become thinner across several basement fault blocks, but remain much thicker than in areas on the craton northwest of the trough (Beardsley and Cable, 1983; Ryder, 1991; Thomas, 1991; Ryder, 1992a; 1992b; Ryder, Harris, and Repetski, 1992). The area between the Rome trough and the Allegheny structural front probably is underlain by a series of horsts and grabens formed by faulting along inferred basement normal faults (Figure Cpk-5). The pre-Knox stratigraphic section southeast of the Rome trough becomes carbonate-dominated, as clastics of the Conasauga Group and Rome Formation thin and grade laterally into dolomites of the Elbrook Dolomite in West Virginia (Ryder, 1992b) (Figure Cpk-5). The Shady Dolomite and basal sandstone section is present throughout most of the eastern area. In northern West Virginia, the section includes the Elbrook and Waynesboro formations, Shady/Tomstown Dolomite, and basal sandstone (Ryder, 1991). In east-central Pennsylvania, the section consists of the Warrior Formation, Pleasant Hill Limestone, Waynesboro Formation, Shady/Tomstown Dolomite, and a basal sandstone (Ryder, Harris, and Repetski, 1992).

In summary, the pre-Knox interval in the Appalachian basin represents an overall transgressive depositional sequence, with progressively younger rocks deposited in a northwesterly direction (Thomas, 1991). The sequence is almost entirely shallow marine in origin, and is composed of a complex package of sandstones, siltstones, carbonates, and shales. Much of the Rome Formation consists of thinly-bedded, heterolithic intervals. Carbonates are more well-developed in the Conasauga Formation/Group, but also occur in the upper part of the Rome Formation. Deposition within the Rome trough was influenced by faulting and more rapid subsidence than surrounding areas, resulting in an expanded interval with the potential for fault-related and other types of hydrocarbon traps to occur.

Structure

Regional structure of the Cambrian pre-Knox play can also be defined in terms of the three areas discussed above: the western stable cratonic platform, the Rome trough, and the eastern basin area (Figure Cpk-6). Structure is an important component in much of the play area because of its direct influence on trapping, and because of possible syndepositional influence on reservoir character, particularly in the Rome trough. Structural influence exists in the Canadian fields, but to a minor extent relative to the Rome trough and other areas in the central part of the basin. Major structural elements in the play are shown in Figure Cpk-6.

Strata of the stable cratonic platform are characterized by a regional east to southeast dip toward the central Appalachian basin. This area, which includes Ontario, Canada, western New York, western Pennsylvania, Ohio, and northern Kentucky, has been affected by relatively small-scale basement faulting, and associated gentle folds and faults in overlying strata. Faults and positive structures that may define structural closures in pre-Knox strata include the Waverly arch (Woodward, 1961), the Cambridge arch (Riley and others, 1993; Root, 1993), the Algonquin arch in Ontario (Pounder, 1967; Bailey Geological Services Ltd. and Cochrane, 1984), and the Lexington fault system in north-central Kentucky (Black and others, 1981) (Figure Cpk-6). Reactivation of pre-existing Proterozoic faults associated with the Grenville Province (Black and others, 1981; Beardsley and Cable, 1983; Baranoski, 1993) cut overlying Cambrian sediments, forming the Lexington and Kentucky River fault systems in Kentucky. Structural traps, stratigraphic traps, and unusually thick reservoir units may be associated with these basement controlled faults (Figure Cpk-12). Subtle folds and small basement faults play a minor role in gas production from the Cambrian in Ontario.

The Rome trough is the most significant structure affecting pre-Knox rocks in the Appalachian basin. The trough, first recognized by Woodward (1961), is bounded in Kentucky by the Kentucky River fault system and Irvine-Paint Creek fault system to the north, and the Rockcastle/Warfield fault system to the south (Figures Cpk-6, Cpk-10) (McGuire and Howell, 1963; Ammerman and Keller, 1979; Webb, 1980; Silberman, 1981; Cable and Beardsley, 1984). The southern-bounding fault system is more discontinuous than the northern zone, and is defined by prominences, recesses, and subtle arches, as well as major fault segments. The Rome trough extends through western West Virginia and Pennsylvania, and possibly into south-central New York (Wagner, 1976; Cardwell, 1977; Shumaker, 1986b; Harper, 1989) (Figure Cpk-6). The Rome trough has been interpreted as a failed Cambrian continental rift basin, developing approximately 250 miles cratonward of the central area of Iapetan rifting (Harris, 1978; Ammerman and Keller, 1979; Beardsley and Cable, 1983; Keller and others, 1983; Shumaker, 1986b; 1987; Thomas, 1991; Walker and others, 1991). Maximum subsidence within the trough occurred during the Middle Cambrian based on paleontological data and thickness of the Rome Formation (Webb, 1980). Cambrian depocenters are located along the northern rift margin in Kentucky and the southern margin in West Virginia, indicating that the rift is characterized by half-graben structures of alternate polarity. Within the trough, Cambrian gas production is related to structural closures and fracturing. Fracture porosity is commonly associated with reactivated basement faults that cut pre-Knox rocks.

The area southeast and east of the Rome trough (eastern basin area) remained structurally higher, and separated the trough from the Iapetan spreading-center farther east (Beardsley and Cable, 1983; Thomas, 1991). Recurrent basement faulting within this area formed broad structures in overlying Cambrian rocks. Positive structures associated with these fault blocks include the Perry, Pike, and Rockcastle uplifts in Kentucky, the central, southern, and eastern West Virginia arches, and the south-central and northeastern Pennsylvania arches (Figures Cpk-5, Cpk-6) (Ammerman and Keller, 1979; Sutton, 1981; Kulander and Dean, 1986; Black, 1989; Ryder, 1991; 1992a; 1992b; Ryder, Harris, and Repetski, 1992).

Reservoir

Limited gas production from pre-Knox rocks makes interpretation of characteristic trap types difficult. A wide variety of structural, stratigraphic, and combination trapping mechanisms are probably available in the play. In Ontario, where Knox Group equivalent rocks have been eroded, pre-Knox reservoirs occur as unconformity truncation traps below the post-Knox (Middle Ordovician) unconformity, and as fault closures. In deeper portions of the Appalachian basin, potential traps include anticlinal structures, fault closures, and stratigraphic pinchouts. The known complexity of stratigraphy and structure in the sparsely explored pre-Knox section allows a wide variety of potential trapping mechanisms and reservoir types. Potential reservoirs include clastic and carbonate rocks containing both intergranular, vuggy, and fracture porosity. Seismic reflection data is the primary tool used by most operators to locate prospective traps in this play.

Gas production in Ontario has been attributed to both stratigraphic and minor structural trapping. The Gobles and Innerkip fields are stratigraphic traps, resulting from erosional truncation of a sandy dolostone at the post-Knox unconformity on the flank of the Algonquin arch (Sanford, 1968; Bailey Geological Services Ltd. and Cochrane, 1984; Powell and others, 1984). The Willey and Clearville fields have been attributed to both structural and stratigraphic trapping (Pounder, 1964; 1967; Bailey Geological Services Ltd. and Cochrane, 1984; Powell and others, 1984). Specific trapping mechanisms include fault-related traps, truncation by the post-Knox unconformity, and small anticlinal noses.

Structural traps are the primary target in and around the Rome trough, where basement-controlled normal faults influenced deposition and created potential structural traps during initial rifting and later reactivation. Three commercial gas wells have been reported in the Rome trough portion of the basin, and all of these accumulations are structurally influenced. The Ashland No. 1 Williams well in Johnson County, Kentucky (Figure Cpk-3), was completed in a fractured shale interval in the Conasauga Group (Rome Formation of Kentucky). This well is near the Irvine-Paint Creek fault zone in the Rome trough, and fracturing is thought to be related to proximity to this fault. The Exxon No. 1 McCoy well in Jackson County, West Virginia, produced for about six months from the Belgrove field, a probable fault-related four-way closure in the Rome trough. Data are limited for the recent Carson Associates No. 1 Kazee well in Elliott County, Kentucky, but it appears to be a fault block trap.

Source rocks for hydrocarbons present in pre-Knox reservoirs vary with the play area. Studies of oil produced from Cambrian reservoirs in Ontario have shown distinctive geochemical characteristics that correspond to source rock samples from the Upper Ordovician Collingwood Formation (Powell and others, 1984). Studies by Cole and others (1987) also found that oils from Knox reservoirs in Ohio were most likely sourced from the equivalent Upper Ordovician Point Pleasant Formation. Assuming that gas and oil in Ontario have a common origin, hydrocarbons from the Upper Ordovician source presumably migrated updip and down section along the post-Knox unconformity into pre-Knox reservoirs.

Potential source rocks for pre-Knox hydrocarbons in deeper parts of the basin in Kentucky, New York, Pennsylvania, Ohio, and West Virginia are less well constrained. Stratigraphic separation of the pre-Knox interval from the Knox unconformity makes it difficult to invoke Upper Ordovician shales as a likely source in these areas. Oil produced from the Rome-Conasauga interval in eastern Kentucky is distinguished by high gravity (41 to 54° API), unlike mostly lower-gravity oils derived from post-Knox source rocks. This suggests that both oil and gas in pre-Knox reservoirs were generated from pre-Knox or other unknown source rocks at higher thermal maturities. Ryder, Burruss, and Hatch (1991) reported geochemical analyses of 22 shale samples from the Rome and Conasauga interval in three wells in the Rome trough of West Virginia and an outcrop section in Tennessee. Total organic carbon values of these samples range from 0.05 to 0.59 percent, and are considered to have low to marginal source potential (Ryder, Burruss, and Hatch, 1991). They also calculated production indices for samples with total organic carbon values greater than 0.5 percent using pyrolytic yields (S_1 and S_2). Average production indices values for the pre-Knox samples range from 0.4 to 0.6, indicating that the interval sampled is in the gas generation window. It is possible that richer Cambrian source rocks occur elsewhere in the basin, and have undergone relatively high thermal activity, generating the characteristic gas, condensate, and high-gravity oil found in pre-Knox reservoirs.

Ontario reservoir rocks consist of either sandy dolostone or sandstone (Figure Cpk-13). The most complete reservoir data available for southwestern Ontario are from the Innerkip and Innerkip East fields (Bailey Geological Services Ltd. and Cochrane, 1984; P. Mitchell, Denbridge Gas Corp., oral commun., 1994). These data are summarized in Table Cpk-1. These fields produce primarily gas, although there is minor associated oil production from Innerkip. Gas expansion is thought to be the primary reservoir drive mechanism. The producing interval is at a depth of 2,800 to 3,000 feet. Pay thickness averages 11 feet, and the reservoir was initially underpressured at 500 psi. Forty gas wells have been completed in Innerkip through 1994. Older wells in Ontario were typically acidized, but more recent wells have been hydraulically fractured to enhance production.

Reservoir heterogeneity in Ontario is generally moderate. Sandstones and dolostones were uniformly deposited on the flank of the Algonquin arch (Trevail, 1990), but lateral facies changes occur as the result of tidal channel development and fill (P. Mitchell, Denbridge Gas Corp., oral commun., 1994). Variations in porosity result from carbonate cementation and secondary dissolution of feldspars and ooids. Average porosity for Innerkip field is 9.5 percent. Permeability in this field averages 1 md. Pressure decline data from Innerkip also indicate a low permeability reservoir (Bailey Geological Services Ltd. and Cochrane, 1984).

Potential reservoir facies in the Rome trough consist of sandstones, carbonates, and fractured shales. Sandstones and fractured shales have been responsible for most of the production to date, but the dolostone intervals of the Conasauga Group and Shady/Tomstown Dolomite may have reservoir potential. Reservoir parameters in the Rome trough are based on only three commercial wells, and thus should not be considered characteristic or inclusive. Depth to pay ranges from 6,250 to 14,350 feet below surface. Average depth to pay is 8,953 feet below surface. Thickness of pay ranges from 10 to 100 feet and averages 41 feet. Rock pressure ranges from 2,708 to 11,710 psi and averages 6,139 psi. Initial open flow data available for two wells, the Exxon No. 1 McCoy and the Carson No. 1 Kazee, were 9.2 and 11 MMcfg/d, respectively. Final open flows for the Ashland No. 1 Williams and the Exxon No. 1 McCoy were 1.055 and 9.1 MMcfg/d, respectively, with an average of 5.1 MMcfg/d. Although a final open flow of 9.1 MMcfg/d was reported for the Exxon No. 1 McCoy well, production data indicates a settled production rate of 5.6 MMcfg/d. Drive mechanisms may be solution gas, gas expansion, or water. Completion strategies range from acid fracturing of open hole intervals to acidizing through perforated casing.

In the Rome trough, reservoir heterogeneity results from a complex interplay of depositional processes and syndepositional faulting. Production to date is exclusively limited to single-well pools, so an accurate evaluation of heterogeneity within a reservoir is not possible. Fracture porosity is associated with faulting and folding, and may be partially or completely healed by mineralization in some areas. The basal sandstone (and the younger Mount Simon Sandstone on the craton) are transgressive deposits, and commonly have good porosity and permeability. They range from fine- to coarse-grained, are moderately to well-sorted, and are commonly friable. Rome Formation sandstones have poorer reservoir characteristics, but are quite variable and difficult to predict. These sandstones are typically fine- to very fine-grained, micaceous, and glauconitic. Coarser-grained facies may occur in proximity to major border faults. Porosity data for the three commercial pre-Knox wells in the Rome trough is limited. The Ashland No. 1 Williams well produces from a fractured shale, and the borehole is washed out over this interval, causing the porosity logs to be invalid (Figure Cpk-14). The Exxon No. 1 McCoy produced for about six months from a 10-foot

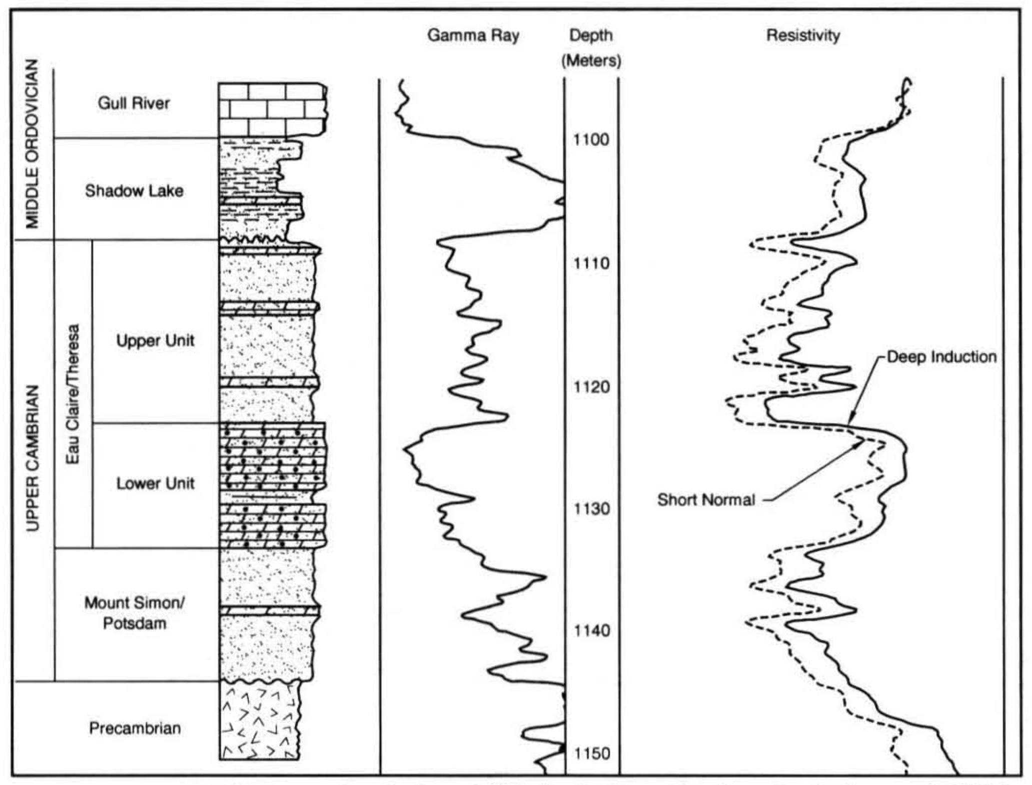


Figure Cpk-13. Typical geophysical and lithologic logs for the Cambrian and Middle Ordovician of southwestern Ontario, Canada. These data are from the Ontario Geological Survey 82-3 Yarmouth 3-9-I stratigraphic borehole. Depth scale is in meters. Lithologic patterns are the same as in Figure Cpk-5, with oolitic intervals indicated by dots. Modified from Trevail (1990).

Table Cpk-2. Analyses of commercial-quality gases from Cambrian reservoirs in the Rome trough, Appalachian basin.

Gas (Mole Percent)	Ashland No. 1 Williams Johnson County, KY Conasauga/Rome: 6,250-6,350 Feet	Exxon No. 1 McCoy Jackson County, WV Conasauga: 14,350-14,360 Feet
Methane	81	97
Ethane	9	2
Propane	4	<1
N-Butane	1	<0.1
I-Butane	<1	<0.1
Pentanes	<1	<0.1
Nitrogen	2	1
H_2S	0	0
CO_2	1	0
Total	99	100
Btu	1,175	1,022

Table Cpk-3. Analyses of low-Btu, high-nitrogen gases from Cambrian reservoirs in the western Rome trough. Unpublished data from the U.S. Bureau of Mines natural gas database.

Gas (Mole Percent)	Texaco No. 1 Kirby Garrard County, KY Conasauga/Rome		Widener No. 1 Burdette Garrard County, KY Conasauga/Rome: 4,450 Feet	Oxford Heyob Highland County, OH Eau Claire: 2,810 Feet
	4,546 Feet (Avg. of 3 Samples)	4,574 Feet		
Methane	13.9	14.5	19.3	60.23
Ethane	2.1	2.2	04.5	3.14
Propane	0.6	0.6	00.7	1.43
N-Butane	0.3	0.3	00.5	0.46
I-Butane	0.0	0.0	00.3	0.14
N-Pentane	0.2	0.4	00.2	0.15
I-Pentane	0.0	0.0	00.1	0.06
C-Pentane	<0.05	<0.05	<0.05	NA
Hexane-PL	0.2	0.2	00.1	0.1
Nitrogen	80.4	79.3	70.7	32.64
Oxygen	0.1	0.1	00.0	NA
Argon	0.4	0.4	00.5	NA
Hydrogen	0.1	0.1	00.0	NA
H_2S	0.0	0.0	00.0	NA
CO_2	0.1	<0.05	01.8	1.63
Helium	1.62	1.81	01.32	NA
TOTAL	**100.02%**	**99.91%**	**100.02%**	**99.98%**
Gravity	0.916	0.911	0.912	0.750
Free Air	0	0	0	NA
Btu	227	240	339	723

Table Cpk-4. Gas resource estimates for the Cambrian pre-Knox play in the Appalachian basin.

Resource Area	Gross Area (Acres)	Estimated Productive to Gross Area Ratio	Extimated Net Productive Area (Acres)	Estimated Gas Recovery per Acre	Estimated Recoverable Gas Resources
A	46,000,000	0.002	92,000	5.0 MMcfg	460 bcf
B	21,700,000	0.001	21,700	2.5 MMcfg	54 bcf
C	41,700,000	0.005	20,850	1.0 MMcfg	21 bcf

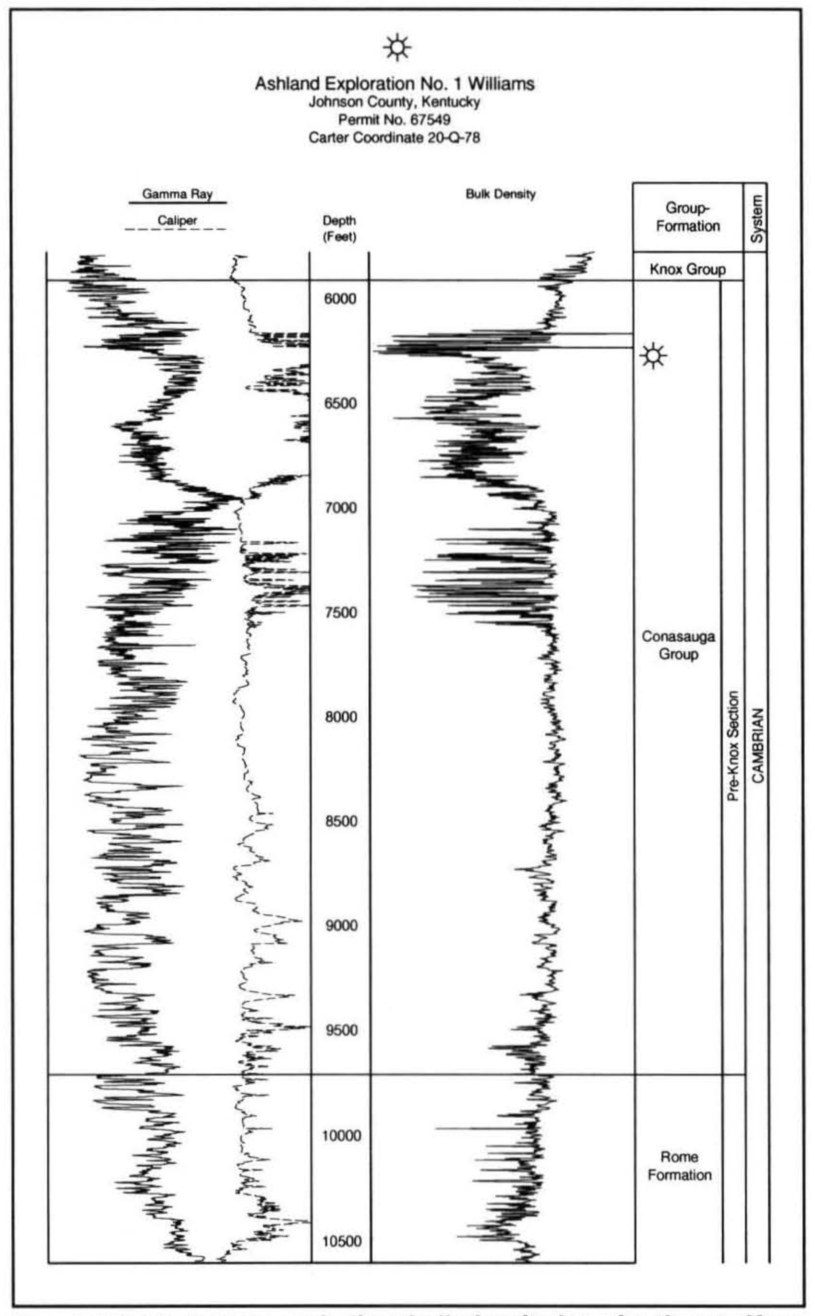


Figure Cpk-14. Gamma-ray/caliper-bulk density logs for the pre-Knox interval in the Ashland No. 1 Williams well, Johnson County, Kentucky. This well initially produced 1.055 MMcfg/d from 6,250 to 6,350 feet in the Conasauga Group (see gas symbol). Reservoir rock is a fractured shale (note severe borehole washout on caliper log). Stratigraphic correlations based on Ryder (1992b).

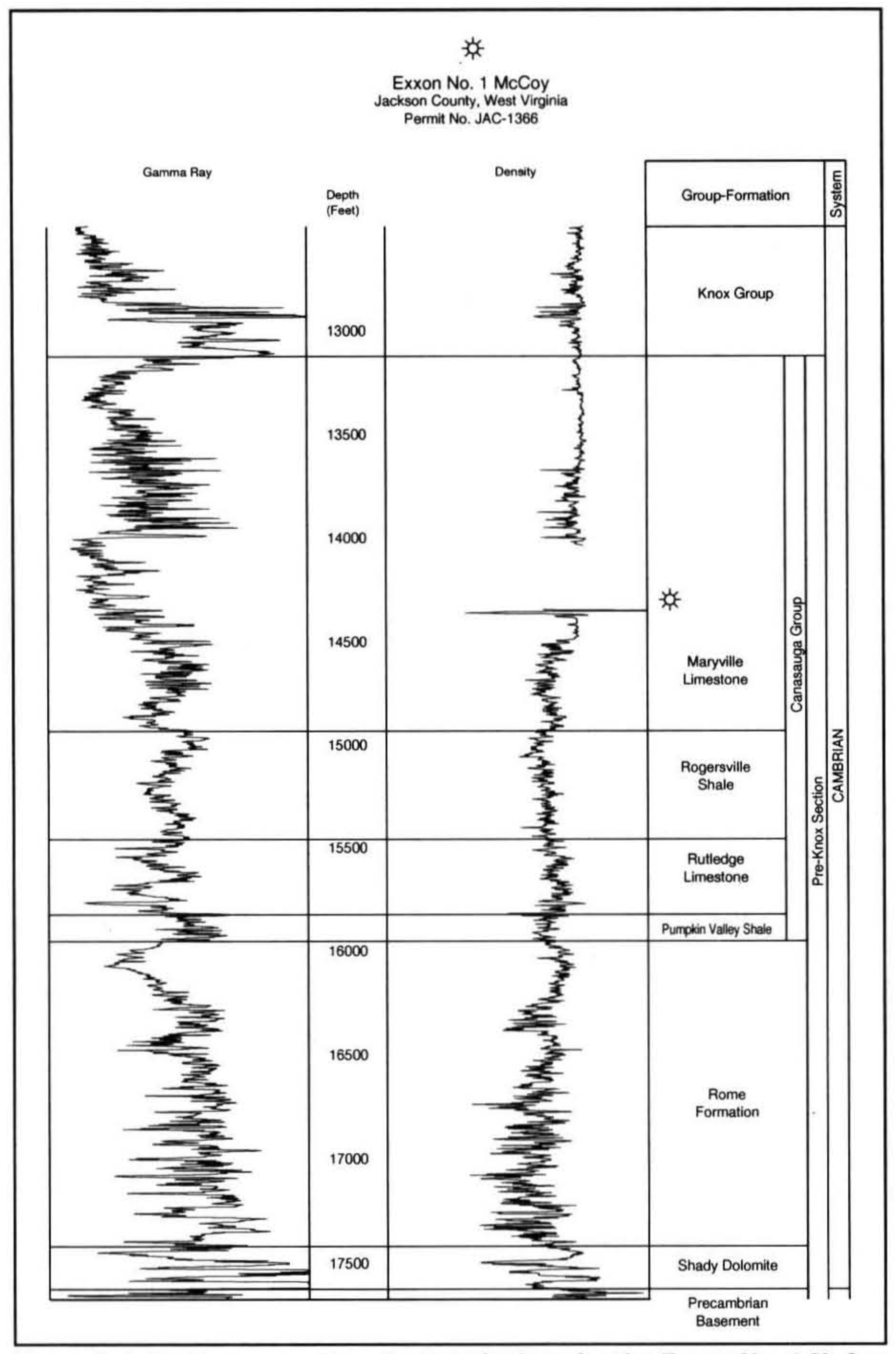


Figure Cpk-15. Gamma-ray/density porosity logs for the Exxon No. 1 McCoy well, Jackson County, West Virginia. This well produced at a settled rate of 5.6 MMcfg/d from 14,350 to 14,360 feet for about six months. Reservoir is a porous sandstone in the Conasauga Group. Stratigraphic correlations are from Ryder (1992b).

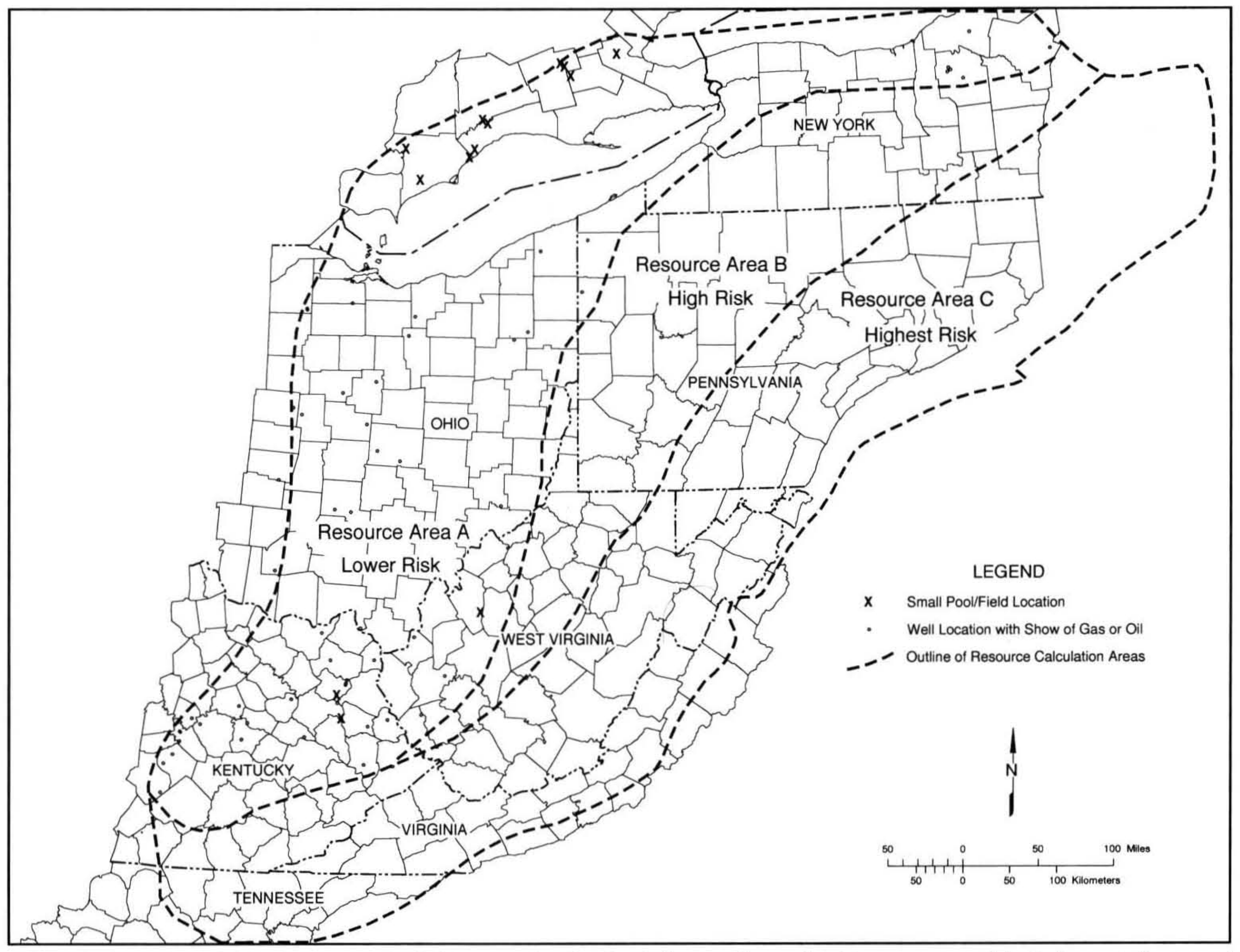


Figure Cpk-16. Map of risked reserve calculation areas for the Cambrian pre-Knox play. Resource area A includes gas shows and production to date. Area B lacks shows, but covers the sparsely drilled part of the Rome trough. Resource area C has the highest risk of commercial gas due to burial depth and thermal maturity. Gas resources calculated from these areas are shown in Table Cpk-4.

porous sandstone in the Conasauga Group (Figure Cpk-15). Average log porosity in this zone is 11 percent, ranging from 3 to 15 percent. Logs from the Carson Associates No. 1 Kazee well are confidential at this time.

Gas analyses for two of the commercial wells in the Rome trough are shown in Table Cpk-2. The Exxon No. 1 McCoy gas analysis indicates an almost pure methane composition, while the Ashland No. 1 Williams gas has heavier components, consistent with reports of some produced condensate. Gas from both wells have Btu values of more than 1,000 (Table Cpk-2). At least two wells in the western part of the Rome trough in Kentucky and one well on the craton in Highland County, Ohio, have encountered significant shows of low-Btu, non-combustible gas. Two of the wells are located in Garrard County, Kentucky, and tested gas from the Rome Formation with an average methane content of 15 percent and an average nitrogen content of 78 percent (Table Cpk-3). These wells were of interest as a possible source of helium, which averaged an unusually high 1.6 percent of the gas. Gas analyzed from the Highland County, Ohio, well was lower in nitrogen (32.6 percent) and higher in methane (60.2 percent) than the Kentucky wells, but was still non-commercial (Table Cpk-3). Helium content of gas from the Ohio well was not available. The origin of these high nitrogen gases is not known, but Garrard County, Kentucky, and Highland County, Ohio, are both located near the Grenville front, a major tectonic suture between the Precambrian Grenville Province and the Keweenawan(?) East Continent Rift Basin (Drahovzal and others, 1992). A deep basement origin for part of this low-Btu gas is possible. The risk of low-Btu gas appears confined to the western Rome trough/Grenville front area, since gas produced farther east in the trough (Johnson and Elliott counties, Kentucky, and Jackson County, West Virginia) is of commercial quality (Table Cpk-2).

Resources and Reserves

The variety of reservoir and trap types included in this play, as well as the very limited commercial production to date, make calculation of gas resources and reserves in most of the play area extremely speculative. Gas resources in the play area are best known for southwestern Ontario due to its long history of gas production and more mature stage of exploration. In Ontario, Bailey Geological Services Ltd. and Cochrane (1984) calculated total proven gas reserves of 16.6 bcf as of 1981. Gross undiscovered resources, using data from both pinchout and structural fields, were calculated to be 152.1 bcf, and potential recovery was 810.7 Mcf per acre-foot. Insufficient data is available to calculate proven reserves outside of Ontario, Canada.

There are essentially no production data on which to base more precisely determined resources; therefore, undiscovered resource calculations for the pre-Knox interval in the rest of the basin are speculative. The basin is divided into three resource calculation areas based on relative risk and estimated gas recoveries (Figure Cpk-16; Table Cpk-4). The lowest risk area (area A in Figure Cpk-16) includes all areas that have reported shows or commercial production from the pre-Knox interval. This area includes the stable craton in parts of southwestern Ontario, Ohio, Pennsylvania, New York, and Kentucky, and the western and southern parts of the Rome trough in West Virginia and Kentucky. A deeper, higher risk area (area B in Figure Cpk-16) consists of the eastern and northeastern parts of the Rome trough in West Virginia, Pennsylvania, and New York, where drilling is very sparse and no shows have been reported. The third area (area C in Figure Cpk-16) is thought to contain the highest risk of commercial gas production. It consists of the deepest parts of the basin, east and southeast of the Rome trough. Using these three areas, potential undiscovered resources were estimated. The gross acreage of each area was calculated, and a net productive area was estimated for each using ratios that reflect the relative exploration risk (Table Cpk-4). Using estimates of gas recovery per acre for reservoirs of similar age and depth from Geomega Inc. (1983), estimated recoverable gas resources were calculated (see Table Cpk-4).

Future Trends

The pre-Knox interval in the Appalachian basin has potential for future gas production. The section has been sparsely drilled, and thick untested intervals remain in parts of the Rome trough and eastern deep basin areas. Viable structural and stratigraphic prospects are possible in many areas. Fault closures and fracture zones associated with the Rome trough remain the highest priority targets. In addition, stratigraphic traps within the Rome trough, although of higher risk, are potential reservoirs. Sandstones (including turbidite fans) (Drahovzal, 1994) and carbonates in the Conasauga, Rome, and Shady intervals are possible reservoirs in the trough. In Ontario, structures downdip from the mature unconformity truncation play may prove to be prospective. On the craton in Ohio, western Pennsylvania, and New York, subtle stratigraphic and structural anomalies that appear on seismic profiles should be tested. The eastern deep basin, east of the Rome trough is poorly-drilled in the pre-Knox interval. Reservoirs in this deep area are largely unknown, but are likely to be of moderate to poor quality. Potential source rocks may be low in organic matter. Additional geochemical work and structural analyses are warranted.

Successful exploration in this play will require additional geological interpretation. Organic geochemistry studies should be expanded to determine hydrocarbon sources and maturity profiles. Depositional models should be refined with available well and seismic data to allow prediction of favorable reservoir fairways. A better understanding of the structural history of the eastern deep basin and Rome trough, using seismic data, is crucial for recognizing traps and their relative sequence of formation. The relative timing of trap formation and hydrocarbon migration, derived from geochemical and subsidence studies, should be resolved.

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