Geology of the Eau Claire Formation and Conasauga Group in Part of Kentucky and Analysis of Their Suitability as Caprocks for Deeper CO2 Sequestration

Ralph E. Bandy III

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GEOLOGY OF THE EAU CLAIRE FORMATION AND CONASAUGA GROUP IN PART OF KENTUCKY AND ANALYSIS OF THEIR SUITABILITY AS CAPROCKS FOR DEEPER CO2 SEQUESTRATION

Ralph E. Bandy III
University of Kentucky, ralph.bandy@uky.edu

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SEQUESTRATION

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THESIS

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A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science
in the Department of Earth and Environmental Sciences at the University of Kentucky

By

Ralph Edward Bandy III

Lexington, Kentucky

Director: Dr. Stephen F. Greb, Kentucky Geological Survey

Lexington, Kentucky

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ABSTRACT OF THESIS

GEOLOGY OF THE EAU CLAIRE FORMATION AND CONASAUGA GROUP IN PART OF
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SEQUESTRATION

Carbon sequestration, or carbon capture and storage (CCS), is the process of capturing anthropogenically generated CO$_2$, transporting the CO$_2$ to an injection site, and then injecting the CO$_2$ into suitable reservoirs for long-term storage, or sequestration. Integral to the successful sequestration of CO$_2$ is an understanding of the confining intervals (seals) above potential reservoirs. The purpose of this thesis research was to perform a detailed geological study of the Eau Claire Formation and equivalent parts of the Conasauga Group in part of the Ohio River Valley region in order to better evaluate its suitability as a confining interval for the underlying Mount Simon Sandstone and basal sandstone equivalents. Detailed correlations of subsurface data using available geophysical logs, cores, and cuttings are used to correlate facies between the Eau Claire Formation in western and central Kentucky and the Conasauga Group in eastern Kentucky and neighboring areas. Additional information on the confining potential of the Eau Claire and Conasauga formations were obtained through porosity evaluation and XRF analyses in combination with available geochemical and permeability data, which are keyed to the correlations.

KEYWORDS: carbon sequestration, confining interval, Maynardsville Formation, Nolichucky Shale, Maryville Formation

Ralph Edward Bandy III
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By

Ralph Edward Bandy III

Dr. Stephen F. Greb
_____
Director of Thesis

Dr. Alan E. Fryar
_____
Director of Graduate Studies

12/14/2012
_____

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Acknowledgements

This thesis would not be possible without support. Funding and support for research was provided through the Kentucky Geological Survey from a grant by the Battelle Memorial Institute and the U.S. Department of Energy (U.S. DOE/NETL award DE-FE0001034 and Ohio Department of Development grant agreement CDO/D-10-03). I would like to thank the Department of Earth and Environmental Sciences for providing me with a teaching assistantship to fund my graduate education these last two years and Dr. Alan Fryar for giving me the opportunity to come to graduate school. I would like to thank my advisor, Dr. Stephen Greb, for accepting me as his student, and for all of his wisdom, guidance, and never-ending patience. Many thanks to my committee members, Dr. Christopher Romanek, Dr. Frank Ettensohn, and Dr. Cortland Eble for their mentorship. Thanks to Dr. Suvankar Chakraborty. I would also like to thank the Kentucky Geologic Survey and its entire staff for providing work space, PETRA software, and a fantastic learning environment for students. Many thanks to Dave Harris for his instruction and encouragement and teaching me about limestones. Thanks to Dr. John Hickman and Brandon Nuttall for their patience and instruction with PETRA. Thanks to Jason Backus and Andrea Conner for teaching me about TOC analysis. Thanks to Mike Ellis for technical support with computer problems. Many thanks also to Patrick Gooding, Ray Daniel, and Ryan Pinkston at the Kentucky Geological Survey's core repository. Thanks also to Greg Schumacher at the Ohio Geological Survey's core repository and Dr. Mark Baranoski at the Ohio Geological Survey. Thanks to Pete Idstein in the Geology Department. Thanks to all of my friends for their unconditional support. I would especially like to thank my parents for always encouraging me to go to graduate school, for always being there for me, believing in me and for all of their love and support, and for setting such a good example for me. Most importantly, I would like to thank my wonderful wife, Ashley. Without her patience, love, and support, I would not have made it.

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CHAPTER 1: INTRODUCTION

Background

With ever-increasing energy needs and use of fossil fuels, anthropogenically generated volumes of carbon dioxide (CO_2) are rising rapidly. If atmospheric concentrations of CO_2 continue to increase at present rates, a change in global climate could result (e.g., Houghton and others, 1990; Le Treut and others, 2007). Because some geologic reservoirs have held petroleum resources, water, and even CO_2 for millions of years, these same reservoirs could store captured anthropogenic CO_2, preventing it from escaping into Earth's atmosphere (Reichle and others, 1999; Beecy and others, 2002). Geologic sequestration or storage involves the capture of CO_2 at the surface and injection of that CO_2 into subsurface reservoirs (U.S. Department of Energy, 1999, 2004, 2005). Integral to the successful sequestration of CO_2 is an understanding of the confining intervals (seals) above potential reservoirs.

Significant research has been ongoing in the United States for more than ten years to evaluate the potential for future geologic sequestration of carbon dioxide. In the Midwest, two U.S. Department of Energy regional partnerships have been investigating the carbon-storage potential of the region. The Midwest Regional Carbon Sequestration Partnership (MRCSP) is examining the potential for geologic sequestration along the Cincinnati Arch and northern Appalachian Basin eastward to the Atlantic coast (western Indiana, eastern Kentucky, Maryland, Michigan, New Jersey, New York, Ohio, Pennsylvania, and West Virginia (Wickstrom and others, 2005; Battelle, 2011, 2012). The Midwest Geological Carbon Sequestration Consortium (MGSC) is examining potential CO_2-storage options in the Illinois Basin (western Indiana, western Kentucky, and Illinois) (Frailey and others, 2005). Several state cooperative partnerships have

also been investigating carbon-storage potential, including the Kentucky Carbon Sequestration

Consortium (e.g., Greb and Solis, 2009).

Results of Phase I and II research from the MRCSP and MGSC partnerships have shown

that the largest potential reservoir for carbon storage in both regions is the Cambrian Mount

Simon Sandstone and its basal sandstone equivalents (Frailey and others, 2005; Wickstrom and

others, 2005). Because of the results from the Phase I research of the U.S. D.O.E. partnerships,

the Mount Simon has become the target for several Phase 2, small-scale, CO2-injection tests

(Battelle, 2011). Another U.S. D.O.E.-sponsored research program, the Simulation Framework

for Regional Geologic CO_2 Storage Infrastructure along the Arches Province of the Midwest

United States, is using the results from data collected in Phase 1 and Phase 2 research and

additional data compiled for the project to model large-scale injections into the Middle

Cambrian Mount Simon Sandstone at selected locations around the Midwest (NETL, 2011).

Modeling is up-scaling data from known injection wells in the region with data collected during

the small-scale, Phase II, CO_2-demonstration tests in order to determine the long-term feasibility

of carbon storage in different areas.

Critical to modeling and regional use of this reservoir for future carbon storage, brine

injection, or waste injection, is a geologic understanding of the vertical and lateral composition

of the confining interval (caprocks, seals) above the Mount Simon Sandstone. In western

Kentucky and the Illinois Basin, the confining interval immediately above the sandstone is the

Upper Cambrian Eau Claire Formation. In eastern Kentucky, and the northern Appalachian

Basin, the confining interval is the upper part of the Conasauga Group (Maynardsville

Limestone, Nolichucky Shale, and Maryville Limestone). Although data have been collected on

these capping units, and the Conasauga Group is known to be laterally equivalent with the Eau

Claire Formation, little research has documented the detailed lateral and vertical variability in this important confining interval in many areas.

Purpose

The purpose of this thesis research was to perform a detailed geological study of the Eau Claire Formation and equivalent parts of the Conasauga Group in part of the Ohio River Valley region in order to better evaluate its suitability as a confining interval for the underlying Mount Simon Sandstone and basal sandstone equivalents. Detailed correlations of subsurface data using available geophysical logs, cores, and cuttings are used to correlate facies between the Eau Claire Formation in western and central Kentucky and the Conasauga Group in eastern Kentucky and neighboring areas. Additional information on the confining potential of the Eau Claire and Conasauga Formations were obtained through porosity evaluation and X-ray fluorescence (XRF) analyses, in combination with available geochemical and permeability data, which are keyed to the correlations.

Carbon Storage

Carbon sequestration, or carbon capture and storage (CCS), is the process of capturing anthropogenically generated CO_2, transporting the CO_2 to an injection site, and then injecting the CO_2 into suitable reservoirs for long-term storage, or sequestration. There are many options for possible sequestration into geologic formations including using abandoned or depleted oil and gas fields, deep saline reservoirs, deep unmineable coal beds, and basalts (U.S. Department of Energy, 1999, 2004, 2005). Of the various options, saline reservoirs have by far the greatest potential to store large volumes (possibly millions of tons per year) of CO_2 within the Midcontinent U.S. (Reichle and others, 1999; Wickstrom and others, 2005; U.S. DOE, 2004, 2005). Saline reservoirs are rock units bearing saline brine. Because they hold brine, they have

porosity and permeability. Deep saline reservoirs with adequate permeability are considered

good candidates for CO_2 sequestration, because they are already used for disposal of industrial

brines and wastes, they do not hold oil and gas resources, and they are sometimes widespread,

so that they may be near to CO_2 sources (Reichle and others 1999; U.S. DOE, 2004; 2005).

Mount Simon Sandstone

The Mount Simon Sandstone is an important saline reservoir for future carbon

sequestration in Kentucky. The Mount Simon in eastern Kentucky could potentially hold as

much as 47.8 billion short tons (43.36 billion metric tons) of CO_2 (Wickstrom and others, 2005).

In western Kentucky, the Mount Simon could possibly store 154 billion short tons (140 billion

metric tons) of CO_2 (Frailey and others, 2005). The sandstone was the target for one of the

MRCSP's Phase II, CO_2-storage demonstration wells at Duke Energy's East Bend site in Boone

County, Kentucky (Batelle, 2011). The sandstone is also the target reservoir for the MGSC's

Phase III, industrial-scale CO_2-storage demonstration in central Illinois (Wickstrom and others,

2005). The regional significance of this reservoir, and its potential importance in northern

Kentucky, where it underlies the Ohio River industrial corridor, is the reason its caprocks were

chosen for investigation in this study.

Caprock, Seal, and Confining Interval

A crucial component of an acceptable reservoir is the caprock that lies above it. The

terms caprock, seal, and confining interval refer to impermeable rock above a reservoir that act

to cap, seal, or confine the gas or fluid already in the reservoir, or injected into the reservoir,

and prevent it from migrating out of the reservoir. The primary cap, seal, or confining interval is

the rock unit or zone of rock units immediately above or lateral to the reservoir. Downey and

others (1984) indicated that reservoir seals need (1) low permeability, (2) sizeable thickness, (3)

lateral continuity, (4) relative homogeneity, and (5) lack fractures. In oil and gas reservoirs,

adequate confinement is generally implied by the fact that the oil or gas is trapped by the

overlying rock units. For injection wells in saline reservoirs, however, confining characteristics

need to be demonstrated. Aside from the immediate cap or confining interval, a secondary or

ultimate confining interval is locally demonstrated for underground injection. Secondary or

ultimate confining intervals are shallower rock units or rock intervals that will act as a secondary

seal if for some reason the primary seal is breached (e.g., Wickstrom and others, 2005). Depth of

the reservoir and overlying caprock, permeability of the caprock, and the mechanical integrity of

the cap-rock are important variables to consider in any injection reservoir (Reichle and others,

1999; Bach and Adams, 2003). For effective CO_2 storage, the confining interval must also exhibit

mineralogy that will not be degraded by interaction with CO_2 or acidity produced by CO_2

(Wickstrom and others, 2005; Neufelder, 2011). To qualify as an acceptable confining interval, a

formation must be impermeable, it must be consistently thick, and must be laterally continuous

across the extent of the reservoir (e.g., Selley, 1998). Because all subsurface injections are

regulated by the government, these characteristics need to be adequately demonstrated before

any injection can be permitted. Optimal storage reservoirs should also have structural closure;

however, structural closure may not be possible for CO_2 storage because of the large volumes of

CO_2 that would need to be injected. Structural closure is not evaluated in this study, and more

work needs to be done in that area for future carbon-storage evaluation.

Characteristics of Injected CO_2

CO$_2$ injected into a saline reservoir for carbon storage would likely be injected as a

super-critical or dense-phase fluid to maximize pore-volume space. In its dense phase, CO_2

takes up 250 to 300 times less space per unit volume than in its gaseous phase (e.g., U.S. DOE).

This volume change is a favorable characteristic for carbon storage in deep saline reservoirs, especially when industrial-scale sequestration is considered. Many power plants produce 10,000 tons of CO_2 a day, and a million tons or more may need to be removed annually (U.S. DOE). As a super-critical fluid, CO_2 will behave both as a liquid and a gas. CO_2 reaches a super-critical state when surrounding pressure reaches 7.38 MPa (1070 psi) and a temperature of 31.1^0C (88.0^0F) (e.g., Bachu, 2003). In much of Kentucky and the Midcontinent U.S., these pressures and temperatures are reached between 2,500 and 2,900 ft depth (Frailey and others, 2005; Greb and Harris, 2009; Wickstrom and others, 2005).

Injected CO_2 will be more buoyant than the saline fluids in the storage reservoir (Wickstrom and others, 2005). Once CO_2 rises to the ceiling of the reservoir and meets the impermeable caprock, the CO_2 will then spread laterally along the seal as dip or structural features permit (e.g., Bentham and Kirby, 2005). For this reason, a contiguous and impermeable seal is imperative for keeping CO_2 successfully sequestered within the reservoir. Understanding lateral and vertical changes in porosity, permeability, mineralogy, and other mechanical characteristics of the Eau Claire Formation and Conasauga Group is critical for evaluating the suitability of CO_2 storage in the Mount Simon Sandstone. These same properties are also critical for evaluating the Mount Simon Sandstone and equivalents for its suitability for future waste or brine injection. Herein, porosity, permeability and mineralogy related to lateral and vertical variation of lithofaces in the Eau Claire Formation, and the laterally equivalent Conasauaga Group, are investigated.

Study Area

The Ohio River Valley has many CO_2 and industrial sources. The Ohio River Valley corridor is home to many population centers, manufacturing facilities, and power-producing

plants. Because power plants require large volumes of water to operate, the valley will continue

to be an area where future power plants will be built. Because of its economic importance, the

valley was the site for three recent, Phase 2, CO_2-storage demonstration tests (Wickstrom and

others, 2005; Battelle, 2012). The Mount Simon Sandstone and laterally equivalent basal

sandstones underlie many of these CO_2-producing sources and could be used as a reservoir to

house sequestered CO_2. The study area is limited to the region above the Mount Simon

Sandstone reservoir in Kentucky, which is north of the Rome Trough, and northeast of the

Rough Creek Graben in Kentucky (Fig. 1.1). Southeastern Indiana and southwestern Ohio are

also included in the study area to aid in correlations and extrapolation of data in northern

Kentucky.
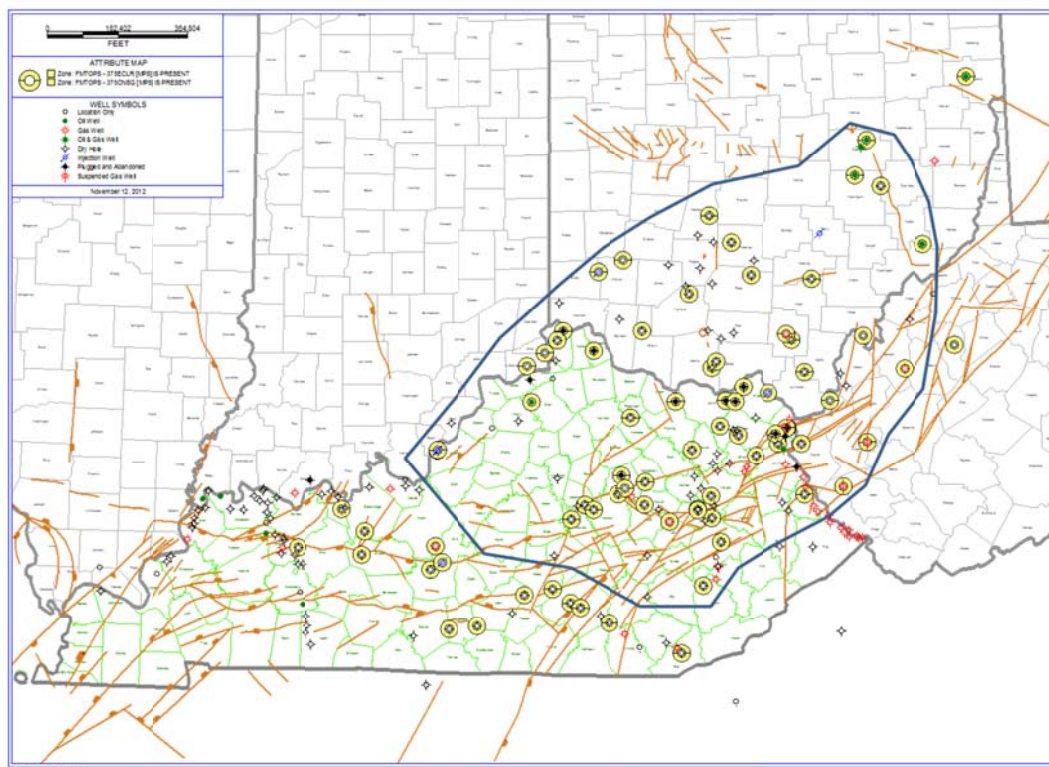
Figure 1.1. Map showing the location of the study area (enclosed polygon) and wells used in the study.

Geologic Setting

Tectonic Features

The major tectonic features within the study area are the Rome Trough, Rough Creek Graben, Grenville Front, and their associated faults (Fig. 1.2). It is important to understand the formation and history of these tectonic features, as they may influence the deposition and structure of all sedimentary rock above and around them.
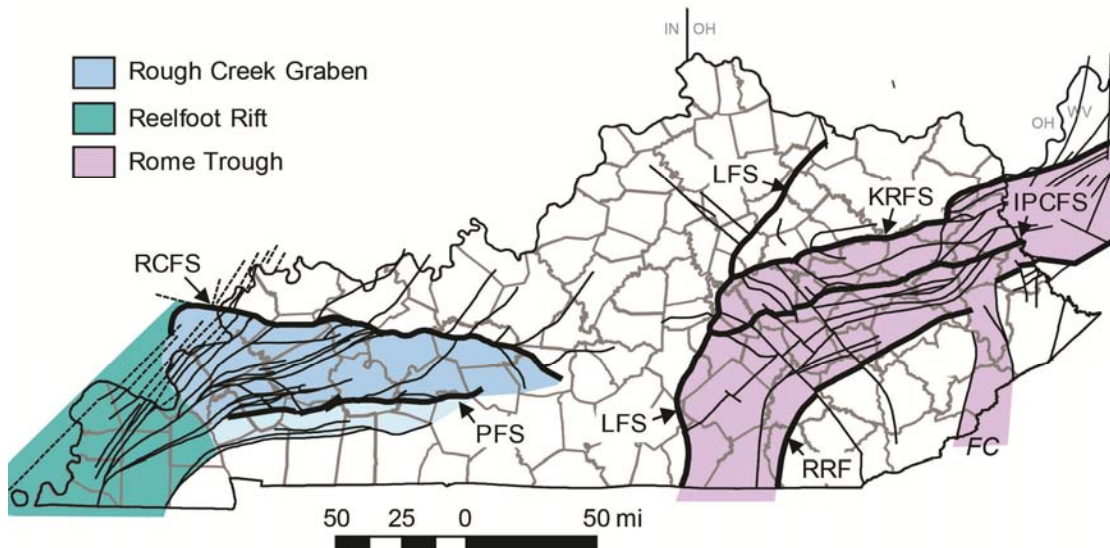
Figure 1.2. Map showing major tectonic structures in the region. RCFS=Rough Creek Fault System, PFS=Pennyrile Fault System, LFS=Lexington Fault System, KRFS= Kentucky River Fault System. Black lines are faults. From Greb and Solis (2009).

<u>*Rome Trough*</u>

The Rome Trough is an extensional graben which is filled with thick Lower to Late Cambrian strata (Woodward, 1961; McGuire and Howell, 1963; Drahovzal and Noger, 1995). The Rome Trough extends from northern Tennessee, northeastward through eastern Kentucky, into West Virginia and southwestern Pennsylvania (Fig. 1.2). The majority of faulting along the

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margins of the Rome Trough are high-angle normal faults (White, 2002; Hickman, 2004). The

Kentucky River Fault System is the northern boundary of the Rome Trough in Kentucky (KRFS in

Fig. 1.2). Structural relief within the deepest part of the trough in Kentucky (along the northern

edge) is 13,000 ft (Hickman, 2004). The Lexington River Fault System is the western boundary of

the Rome Trough (LFS in Fig. 1.2). The Rome Trough is part of the eastern North American

interior rift system and is believed to have formed in concert with the opening of the Iapetus-

Theic Ocean during the Early Cambrian (Harris, 1978; Thomas, 1991).

Grenville Front

The Grenville Front is the north to south-trending boundary between the Grenville

Precambrian Province in the east, with the Eastern Granite-Rhyolite Province in the west (e.g.,

Lidiak and others, 1966). Both of these surfaces are collectively referred to as "Basement"

relative to overlying sedimentary strata. In Kentucky, the Grenville Front separates Grenville

basement from Precambrian Middle Run metasediments (Fig. 1.3), which accumulated in a rift

basin above the Granite-Rhyolite basement, west of the front (Drahovzal and others, 1992). The

Lexington Fault System (LFS in Fig. 1.2) is developed above the front and approximates the trend

of the front at the surface. Faulting and subsequent metamorphism is believed to range from

0.880 to 1.1 Ga (Lidiak and others, 1966; Hoppe and others, 1983; Keller and others, 1983; Van

Schmus and Hinze, 1985; Lucius and Von Frese, 1988; Drahovzal and others, 1992; Wickstrom

and others, 2005).
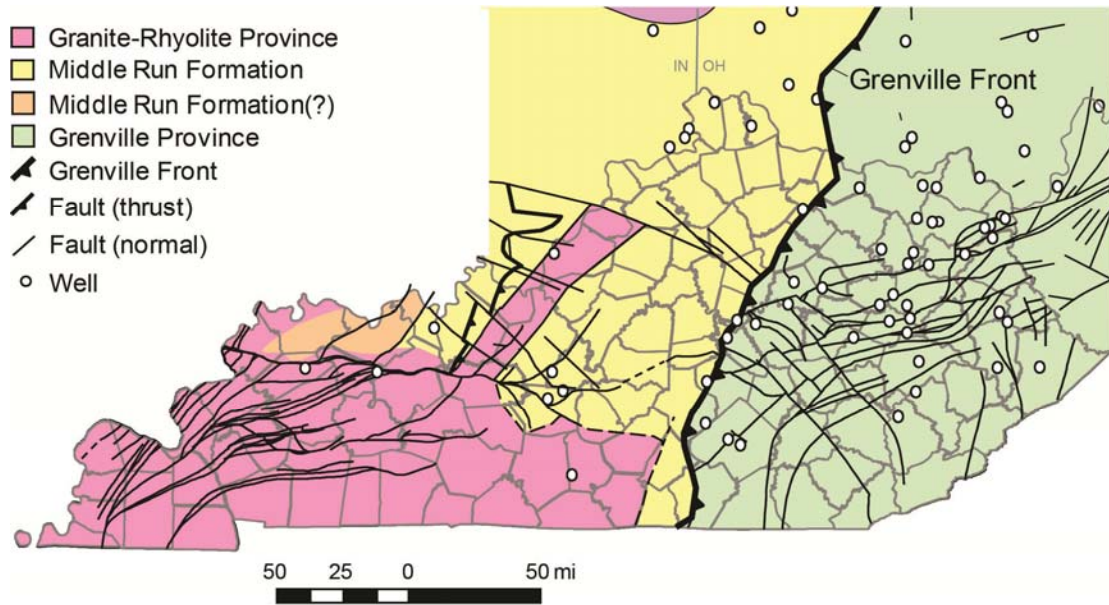
Figure 1.3. Precambrian geology in Kentucky. GF=Grenville Front. From Greb and Solis (2009).

Rough Creek Graben

In western Kentucky, the Rough Creek Graben trends east-west from central Kentucky into southernmost Illinois toward the Mississippi River Valley (Fig. 1.2). The Rough Creek Graben, like the Rome Trough, is a complex graben structure. The northern boundary of the graben is the Rough Creek and Shawneetown Fault Systems (RCFS in Fig. 1.2). The southern boundary is the Pennyrile Fault System (PFS in Fig. 1.2). It, also like the Rome Trough, created significant accommodation space for Early to Late Cambrian sediments (Ervin and McGinnis, 1975; Nelson and Zhang, 1991; Thomas, 1991; Johnson and others 1994; Marshak and Paulsen, 1996, Hickman, 2011). The fact that both the Rough Creek Graben and the Rome Trough are filled with sediment of similar ages, indicates they are likely similar in age (Hickman, 2011). The Rough Creek Graben (Fig. 1.2) is located in the extreme western edge of the study area for this

research (Fig. 1.1), and most of the data that will be used in this thesis are located outside of the Rough Creek Graben.

Stratigraphy

The study interval is the confining interval above the Mount Simon Sandstone in Kentucky, which is the Eau Claire Formation in the west and parts of the Conasauga Group in the east (Fig. 1.4). Drillers have used both terms interchangeably across a wide area [and in older wells used the term, Rome Formation, which is now restricted to older strata in the Rome Trough (Harris and others, 2004)]. The overlap of the areas in which the terms Eau Claire and Conasauga were used, caused Greb and Solis (2009) to pick a somewhat arbitrary boundary between the two units along the Grenville Front (Fig. 1.5). A better understanding of the boundary between these two units and of lithologic transitions between units is one of the goals of this thesis.
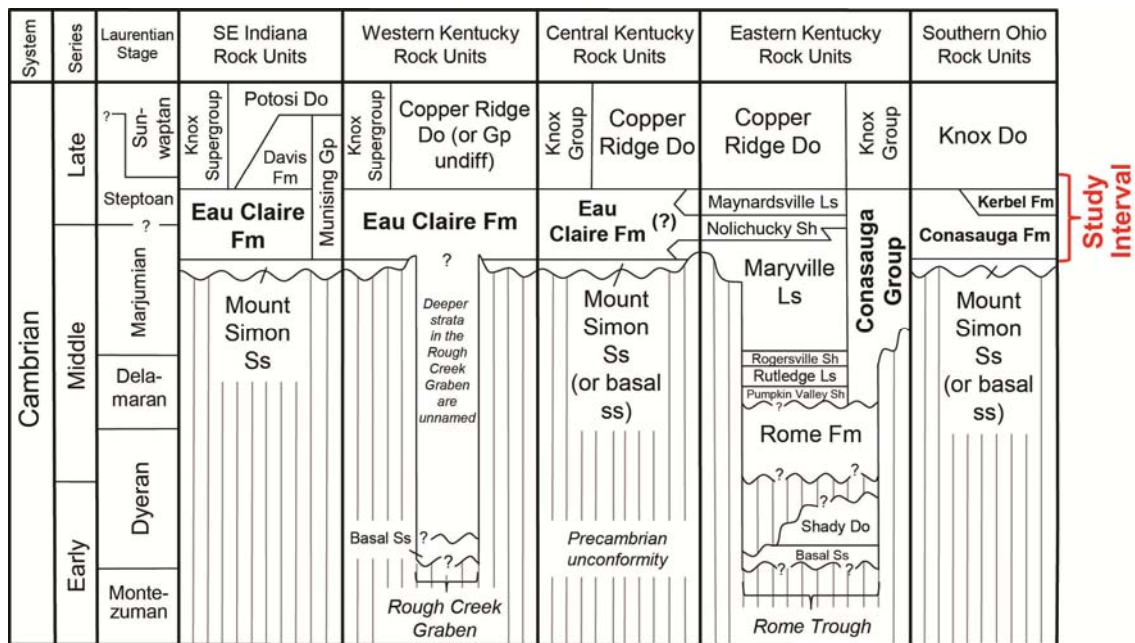
Figure 1.4. Regional stratigraphy of the study interval across Kentucky. From Greb and Solis (2009).
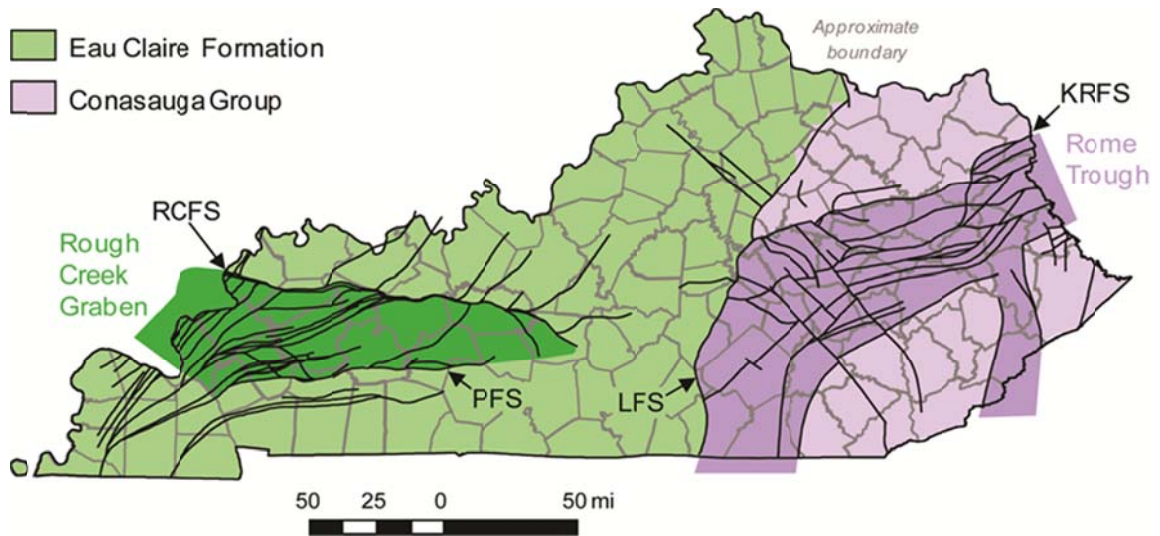
Figure 1.5. Distribution of the Eau Claire Formation and Conasauga Group in Kentucky. From Greb and Solis (2009).

Eau Claire Formation

The Eau Claire Formation was named and first identified from an outcrop of shaly sandstone near Eau Claire, Wisconsin (Walcott, 1914). The Eau Claire Formation is late Middle to Late Cambrian (Dresbachian) in age (Avila 1981; Palmer, 1982; Shaver and others 1986; Babcock, 1994). The Eau Claire is overlain by the Knox Group or Supergroup in the Illinois Basin in the western and central portions of the study area (Fig. 1.4). In Indiana, the Knox is divided into several formations. The Davis Formation is the base of the Knox and upper contact with the Eau Claire Formation (Shaver and others, 1970; Becker and others, 1978; Wickstrom and others, 2005).

The Eau Claire is 300-ft thick in western Illinois and thickens to more than 1000 ft in southeastern Illinois and southwestern Indiana (Gutstadt, 1958). In Kentucky, the Eau Claire Formation ranges from 350- to 2,760-ft thick (Greb and Solis, 2009). The thickest known interval

of Eau Claire, more than 14,000 ft, occurs in the Rough Creek Graben in Western Kentucky (Greb and Solis, 2009; Hickman, 2011), but this is because the sedimentary fill in the Rome Trough has not been stratigraphically subdivided as has been done in the Rome Trough. In Indiana, Illinois, and Kentucky, the Eau Claire is dominated by shale. The thickness and shaly character of the Eau Claire Formation are characteristics that give it good caprock potential.

Regionally, the Eau Claire Formation is lithologically variable, although shale dominated. Shales range from green, to maroon, to black in color and are variably micaceous and glauconitic (Gutstadt, 1958; Becker and others, 1978; Frailey and others, 2005; Wickstrom and others, 2005; Neufelder, 2011). Aside from shale, the Eau Claire also contains siltstones, sandstones, dolomites, and limestones. Sandstones and siltstones can be variably feldspathic, dolomitic, and glauconitic (Gudstadt 1958; Becker and others, 1978, Shaver and others, 1986; Catacosinos and Daniels, 1991). Micropores in the shale are filled with diagenetic feldspar, dolomite cement, quartz cement, and clay minerals (Wickstrom and others, 2005; Neufelder, 2011). Limestone and dolomite can occur at the top of the Eau Claire Formation in parts of western Kentucky. These carbonates may be equivalent to the Davis Limestone (part of the Knox Group) in Indiana, although the Davis is not a formal unit in Kentucky (Fig. 1.4).

Conasauga Group

The Conasauga Group was named by Hayes (1892), as the Conasauga Shale, found in the Conasauga Valley in northwestern Georgia (Hayes, 1892). Rodgers (1953) identified shales of the Conasauga Group in eastern Tennessee, alternating with carbonates. The unit was later extended into the subsurface of eastern Kentucky and Ohio. The Conasauga Group has more lithologic diversity than the Eau Claire Formation. The upper units are Late Cambrian (Ferungian) in age, and the lower units in the Rome Trough are possibly Early Cambrian in age

(Markello and Read, 1984; Glumac and Walker, 2000). The lower units are confined to the

Rome Trough (Harris and others, 2004). The upper units extend beyond the trough (Fig. 1.6).

The three units within the Conasauga Group that overlie the units confined to the Rome Trough,

also overlie the Mount Simon Sandstone in northeastern Kentucky beyond the trough. The

upper Conasauga units are the Maryville Limestone, Nolichucky Shale, and Maynardville

Limestone in ascending order (Wickstrom and others, 2005; Harris and others, 2004).

The Conasauga Group consists of interbedded shales, sandstones, limestones, and

dolostones (Ryder, 1992; Ryder and others 1996, 1997). Local sandstone horizons studied in

Ohio are typically white to light-gray and pinkish-gray in color. Sandstones are from fine- to
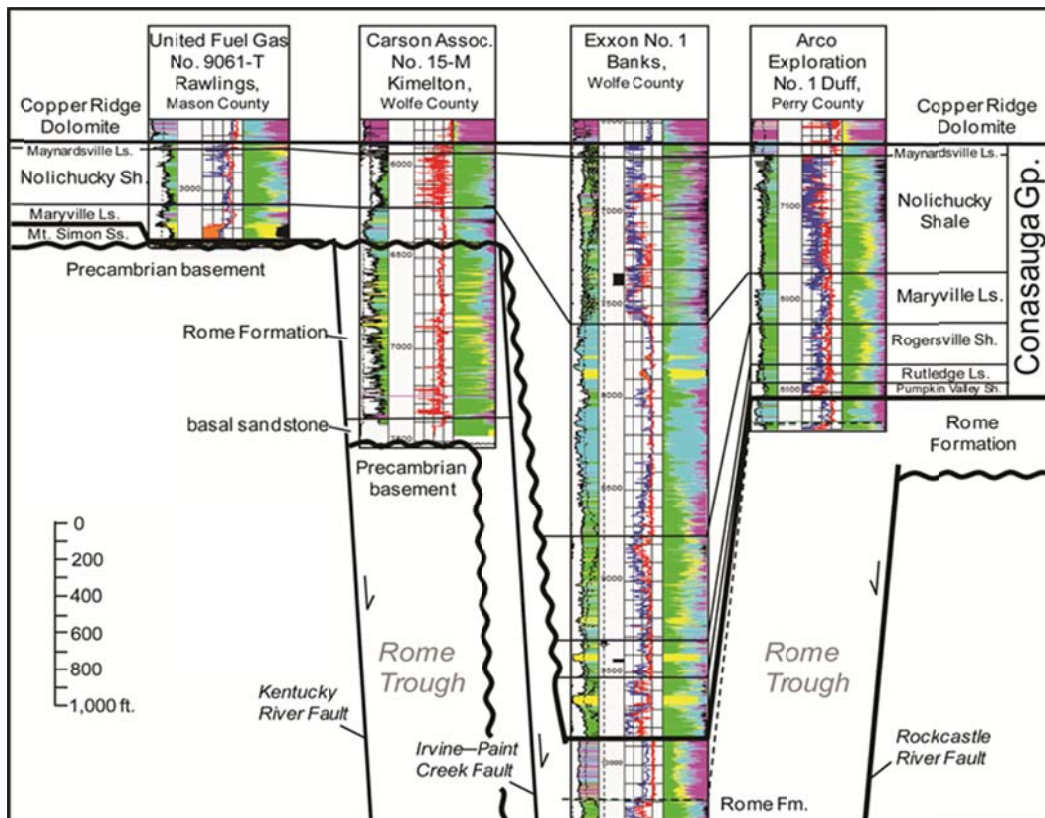
Figure 1.6. Cross section across the Rome Trough showing stratigraphy and distribution of units in the Conasauga Group units within and beyond the Rome Trough (from Greb and Solis, 2009; modified from Harris and others, 2004).

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medium-grained, moderately to well-sorted, and grains are sub-rounded to angular (Wickstrom and others, 2005). Authigenic and primary feldspar, glauconite, and bioturbated zones within the sandstones are common (Wickstrom and others, 2005). Limestones of the Conasauga Group thicken eastward and southward into the Rome Trough (Fig. 1.6). Dolostones within the Conasauga Group are light-to medium- gray or pinkish- gray in color. They can be cryptocrystalline, microcrystalline, medium crystalline, and arenaceous. Thin interbeds of grey to black shale have also been noted in Conasauga carbonates. Frosted quartz grains, selenite-filled vugs, dolomite crystals, pelloids, ooids, pyrite, and thin beds of glauconite, and apatite are present (Wickstrom and others, 2005).

Understanding lateral and vertical variability in rock types and porosity within the Conasauga Group will be important for evaluating the potential of this unit to be an adequate confining unit for deeper CO_2 sequestration. Formations in the lower Conasauga Group, which are confined to the Rome Trough and do not overly the Mount Simon Sandstone, were not included in this study.

Kerbel Formation

The Kerbel Formation was named by Janssens (1973), and is included within the Conasauga Group in Ohio (Fig. 1.4). The Kerbel Sandstone is stratigraphically at the base of the Knox Group, and possibly at the top of the Conasauga Group in northern Kentucky (Banjade, 2011). This term is not used in Kentucky, but unnamed sandstones have been encountered locally in the Maryville Limestone (slightly older than the Kerbel in northern Ohio) within the Conasauga Group (Harris and others, 2004).

In Ohio, the Kerbel Formation is interpreted to have been deposited by a prograding delta (Janssens, 1973) or a tidal environment (Donaldson and others, 1975). Baranoski (2007)

noted a series of sandstones in Ohio between what was traditionally called the Kerbel and Mount Simon sandstones. He proposed replacing the term "Kerbel" and including all of these sand bodies in a new formation called the Sandusky Formation. The Sandusky Formation would interfinger with the Conasauga Formation or Group to the east and Eau Claire Formation to the west. The Sandusky Formation has not been formalized in Ohio.

Mount Simon Sandstone and Equivalents

The Mount Simon Sandstone was named by E. O. Ulrich for outcrops on Mount Simon, in Eau Claire, Wisconsin (Walcott, 1914). The Mount Simon is the largest potential reservoir for CO_2 sequestration within the study area. It unconformably caps the Precambrian surface across much of the Midwest. The sandstone is conformably overlain by the Eau Claire Formation in the west, and by the upper part of the Conasauga Group, generally the Maryville Formation, in eastern Kentucky (Fig. 1.4).

The Mount Simon is restricted to the area north of the Rough Creek Graben in western Kentucky, and north of the Rome Trough in eastern Kentucky (Fig. 1.7; Greb and Solis, 2009). Sandstone units also occur in the Rome Trough (in fact, there is a basal sand above the Precambrian in the trough), but based on limited seismic reflection data and deep- well control, they are not connected to the Mount Simon regional aquifer, are generally thousands of feet deeper, and are much older than the Mount Simon Sandstone (Greb and Solis, 2009; Harris and others, 2004).

Basal sandstones in northeastern Kentucky and southern Ohio are sandstones above the Precambrian unconformity and below the Conasauga Group, but they are more feldspathic or shaly than the typical Mount Simon to the west. For regional mapping purposes, the Mount Simon, basal, and Potsdam sandstones (of the northern Appalachian basin) are commonly

mapped together (Wickstrom and others, 2005). A better understanding of the lateral transition between the Mount Simon and Basal Sandstone would aid in future use of this reservoir for carbon storage.

Grain sizes in the Mount Simon Sandstone range from fine to coarse, and the grains are moderately to well- sorted. The Mount Simon is primarily a quartz arenite that may sometimes be arkosic (especially toward its base). The sandstone is interbedded with sandy to silty shales that are red, green, gray, or black in color. Shales locally occur in the uppermost part of the unit (Wickstrom and others, 2005).
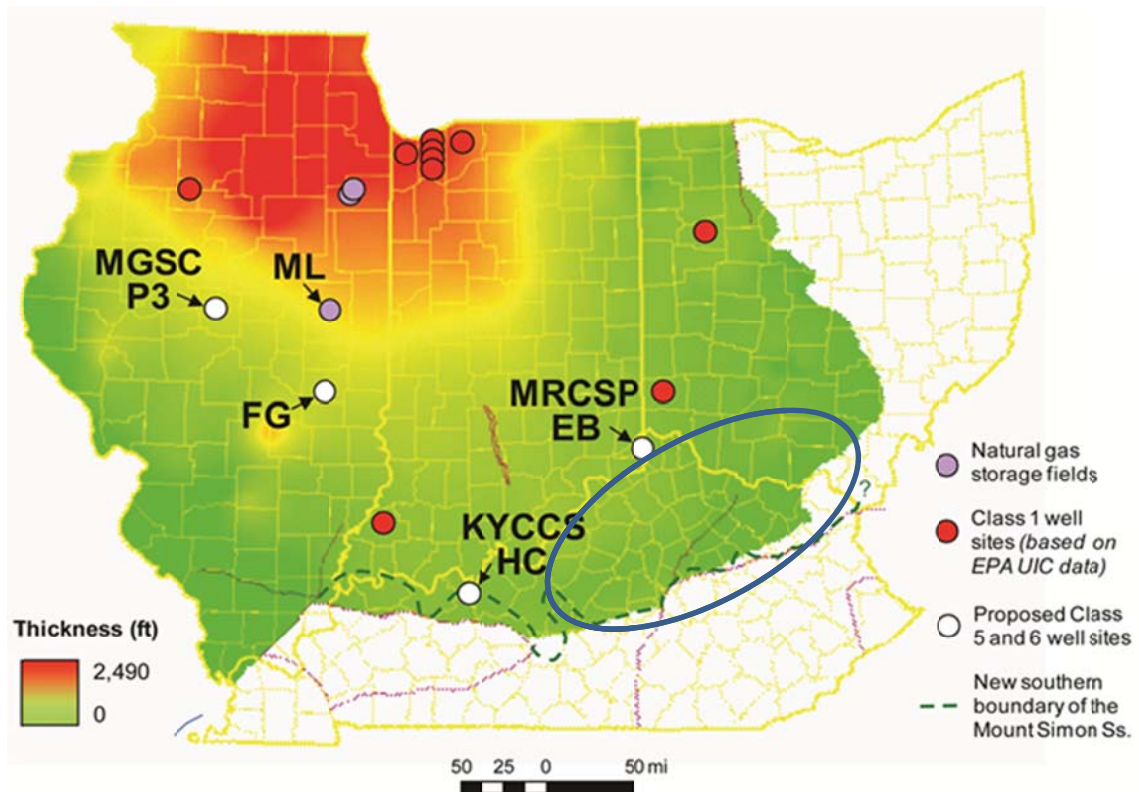
Figure 1.7. Regional isopach map of the Mount Simon Sandstone Formation, showing a recently revised southern margin in Kentucky (dashed line) and known injection wells (from Greb and Solis, 2009). Circled region constitutes the study area for thesis. See Fig. 1.1 for detailed map of thesis area.

__Collaboration with Ongoing CO$_2$ Investigations__

Data and test analyses on the Eau Claire Formation and Conasauga Group have recently been collected from a series of demonstration wells by U.S. Department of Energy (DOE)-funded carbon- storage projects. Some of those data and results from those studies are available for use and comparison in this study (e.g., Neufelder, 2011; Zhang and Scherer, 2012). This thesis research was partly supported by the Simulation Framework for Regional Geologic CO$_2$ Storage Infrastructure along Arches Province of Midwestern U.S. project. This project is DOE-funded and managed by Battelle in Columbus, Ohio. The project involves computer-modeling industrial-scale CO$_2$ injections at multiple sites along and near the Cincinnati Arch to determine the feasibility of long-term injection in the Mount Simon Sandstone reservoir. A better understanding of the confining intervals above the Mount Simon Sandstone is critical to future modeling and implementation of carbon storage in this unit.

CHAPTER 2: METHODS

Introduction

Several methods were used to evaluate the Eau Claire Formation and Conasauga Group across the study area. This chapter provides a summary of each method used, why it was used, and what data it contributed to the overall evaluation of the geology and confining characteristics of the Eau Claire Formation and Conasauga Group.

Cross Sections

Seven detailed cross sections were created with 35 wells, using available geophysical log data in PETRA® software. PETRA® is a data management and analysis package used by the petroleum industry for subsurface investigations. Twenty-three wells in Kentucky penetrate the Mount Simon Sandstone and potential overlying confining intervals north of the Rough Creek Graben and Rome Trough in Kentucky (Fig. 1.1). Fifteen additional wells are located in southern Indiana and Ohio. Forty-five more wells penetrate the Conasauga Group south of the extent of the Mount Simon Sandstone. Down-hole geophysical logs from these wells were used for regional correlation. Lithologies were interpreted from log signatures to examine the spatial variability in rock types within the potential confining interval. Three sections were correlated along regional strike trending southwest to northeast, and four sections were correlated along regional dip trending northwest to southeast. These cross sections helped to better determine and understand the lateral relationships between the Eau Claire Formation and Conasauga Group. The study interval was divided into seven units based on vertical changes in geophysical-log signatures.

Structure and Isopach Maps

Nine structure maps and nine isopach maps were constructed in PETRA® to show thickness and structure of the interval subdivisions and gross thickness and structure of the entire interval. Maps were compared with each other and known structures to test for trends and relationships. Regional structure is also important to document for intervals within the Eau Claire-Conasauga interval relative to its use as a confining interval for carbon storage in the underlying Mount Simon Sandstone, since injected CO_2 would tend to rise until it meets the cap rock, and then should expand laterally updip. Understanding the regional highs and lows, and the dip of the cap rock aid in determining where sequestered CO_2 might migrate. More precise mapping (seismic and other data) is needed for determining small structural closure or site-specific structural features.

Core Descriptions

Approximately 1,130 ft of total core were described and photographed from four wells across the study area to better understand the geology of the Eau Claire/Conasauga interval and for comparison with down-hole geophysical-log signatures (Table 2.1). These were the (1) Battelle No. 1 Duke Energy well, in Boone County, Kentucky; (2) the DuPont No. 1 WAD fee well in Jefferson County, Kentucky; (3) the ODNR DGS 2627 American Aggregates well, in Warren County, Ohio; and (4) the USS Chemical U.S. Steel No. 1 well, in Scioto County, Ohio. Ohio cores were examined at the Ohio Geological Survey's core facility in Columbus, Ohio. The Kentucky cores were examined at the Kentucky Geological Survey's core repository in Lexington, Kentucky. Both Ohio wells had core for the entire Eau Claire/Conasauga interval. The Kentucky wells only had core for a small portion of the Eau Claire interval. Lithology, grain size, bedding, fracturing, mineralization, and paleontology were observed and recorded from each core. The

Table 2.1. Core examined for this study.

Core Description Wells							
Well Name	UWI Number	County	State	Top depth (ft)	Bottom Depth (ft)	Thickness (ft)	Interval
DuPont No. 1 WAD FEE	16111000010000	Jefferson	KY	4408.4	4459.6	51.2	Davis Limestone
DuPont No. 1 WAD FEE	16111000010000	Jefferson	KY	4842	4871.71	29.71	Eau Claire
BATTELLE 1 DUKE ENERGY	16015000050000	Boone	KY	2825	2857.61	32.61	Eau Claire
ODNR DGS 2627 AMERICAN AGGREGATES	3416562627	Warren	OH	2640	3250	610	Conasauga
USS CHEM./US STEEL 1 USS CHEMICALS	3414570212	Scioto	OH	4984.1	5390.9	406.8	Conasauga

core was photographed to document major lithotypes, along with unusual structural and bedding characteristics of the rock.

Thin Sections

Thin sections were made from two Kentucky cores; the DuPont No. 1 WAD fee well in Jefferson County, and the Battelle No. 1 Duke Energy well at East Bend in Boone County. A total of 15 thin sections were made and described. Ten thin sections were taken from the DuPont core, and five thin sections were taken from the East Bend core. Samples were sent to an outside laboratory (Wagner Petrographic) for thin section production. Standard, 24 x 26 mm slides were impregnated with blue epoxy, and were vacuum impregnated to optimize the visibility of pore spaces within the samples. Slides were taken from samples representative of major lithologies in the core, special and unusual features that might affect the local sealing characteristics of the zone, and features that might help to interpret original depositional environments.

Cuttings Descriptions

To supplement the sparse distribution of available core, cuttings were described for the Eau Claire/Conasauga interval in six wells, all in Kentucky (Table 2.2). Cuttings are the chips of

subsurface rock strata collected during drilling. In general, cuttings are collected at ten-foot

intervals. They are not as useful as core for describing details of bedding and lithology and can

sometimes represent mixtures of rock from higher in the borehole. In the absence of core,

however, cuttings provide useful information on mean rock type and mineralogy. Cuttings were

described at the Kentucky Geological Survey's core repository with a petrographic microscope at

100x magnification. Wells were chosen based on availability and location across the study area.

Cuttings were described with the purpose of looking for variations in lithology across the study

Table 2.2. Wells with cutting samples, depths of samples studied, and correlative sample
intervals examined in this investigation.

Cuttings Well List						
Well	UWI Number	County	State	Top Depth (ft)	Bottom Depth (ft)	Unit within Eau Claire
Ashland 1 Wilson	16037000070000	Campbell	KY	2900	2910	Unit 4
Ashland 1 Wilson	16037000070000	Campbell	KY	3000	3010	Unit 5
Ashland 1 Wilson	16037000070000	Campbell	KY	3100	3110	Unit 6
Ashland 1 Wilson	16037000070000	Campbell	KY	3200	3210	Mount Simon
Ashland 1 Wilson	16037000070000	Campbell	KY	3150	3160	Unit 6/ Unit 7
BATTELLE 1 DUKE ENERGY	16015000050000	Boone	KY	2800	2810	Unit 3
BATTELLE 1 DUKE ENERGY	16015000050000	Boone	KY	2850	2860	Unit 3
BATTELLE 1 DUKE ENERGY	16015000050000	Boone	KY	2900	2910	Unit 3
BATTELLE 1 DUKE ENERGY	16015000050000	Boone	KY	2950	2960	Unit 4
BATTELLE 1 DUKE ENERGY	16015000050000	Boone	KY	2970	2980	Unit 4
BATTELLE 1 DUKE ENERGY	16015000050000	Boone	KY	2990	3000	Unit 4
BATTELLE 1 DUKE ENERGY	16015000050000	Boone	KY	3050	3060	Unit 5
BATTELLE 1 DUKE ENERGY	16015000050000	Boone	KY	3100	3110	Unit 5
BATTELLE 1 DUKE ENERGY	16015000050000	Boone	KY	3140	3150	Unit 6
BATTELLE 1 DUKE ENERGY	16015000050000	Boone	KY	3200	3210	Unit 7
Monitor Petroleum	16175001450000	Morgan	KY	5560	5570	Unit 3
Monitor Petroleum	16175001450000	Morgan	KY	5700	5710	Unit 3 A
Monitor Petroleum	16175001450000	Morgan	KY	5800	5810	Unit 4
Thomas 1 Adams	12442	Lewis	KY	4015	4020	Unit 6
Thomas 1 Adams	12442	Lewis	KY	4050	4055	Unit 6
Thomas 1 Adams	12442	Lewis	KY	4085	4090	Unit 6
Thomas 1 Adams	12442	Lewis	KY	4095	4100	Unit 6
Ashland Oil and Refining	16043000800000	Carter	KY	5090	5100	Unit 5
Ashland Oil and Refining	16043000800000	Carter	KY	5140	5150	Unit 6
Ashland Oil and Refining	16043000800000	Carter	KY	5185	5190	Mount Simon
Ashland Oil and Refining	16043000800000	Carter	KY	5200	5210	Mount Simon
UFG 9061T RAWLINGS	16161000290000	Mason	KY	2850	2860	Unit 3
UFG 9061T RAWLINGS	16161000290000	Mason	KY	2900	2910	unit 3 A
UFG 9061T RAWLINGS	16161000290000	Mason	KY	3050	3060	Unit 4
UFG 9061T RAWLINGS	16161000290000	Mason	KY	3120	3130	Unit 5
UFG 9061T RAWLINGS	16161000290000	Mason	KY	3160	3170	Unit 5 / Unit 6 Boundary
UFG 9061T RAWLINGS	16161000290000	Mason	KY	3240	3250	Unit 6 / Unit 7 Boundary
UFG 9061T RAWLINGS	16161000290000	Mason	KY	3300	3305	Mount Simon

area, both vertically and horizontally, and for comparison with down-hole geophysical well signatures. Special focus was placed on the amount of dolomitized versus limestone material in the Conasauga Group, as well as the presence of any quartz sand.

Porosity and Permeability

Study of the porosity and permeability of the Eau Claire Formation and Conasauga Group interval are important for understanding its suitability as a potential confining interval. An acceptable caprock must serve as an impermeable barrier above the underlying reservoir. Porosity is the percentage of pore space available within a unit. Permeability is the level of connectivity between pore-space and how well a fluid is able to move through the unit (Schlumberger Oil Field Glossary, 2012). Permeability is more critical to caprock evaluation but requires core samples and analyses. Porosity can be determined from density logs and from core samples and analyses.

Permeability data from previous studies were available for the DuPont No. 1 WAD fee well, the Battelle No. 1 Duke Energy (East Bend) well, and the USS Chem./US Steel No. 1 USS Chemicals (Aristech) well. These data were placed within the stratigraphic subdivisions of this report to better evaluate vertical and lateral permeability relative to lithology and correlations.

Total Organic Carbon

Aside from acting as physical barriers to the vertical migration of CO_2, if shales have sufficient organic content, they may actually adsorb CO_2 onto their matrix (Nuttall and others 2005), making them an even better caprock. Harris and others (2004) noted that the Conasauga Group locally contains dark shales, which may have significant total organic carbon. For this thesis, six shale samples from the Eau Claire Formation and Conasauga Group were analyzed for total organic carbon (TOC) from core in the DuPont No. 1 WAD fee well and Battelle No. 1 Duke

Energy (East Bend) well, to determine if adsorption might be possible in part of the confining interval. TOC samples were taken from shales in core that appeared to be darkest in color, which are most likely to have the highest organic content.

X-Ray Fluorescence

Analysis by X-ray fluorescence (XRF) was used to assess the elemental makeup of the units. X-Ray fluorescence works by bombarding a sample with X-rays, exciting electrons to a higher orbital from atoms that make up the sample. The fluorescence of the sample is then measured as excited atoms fall back to their original orbitals. Results reveal elemental makeup in parts per million (ppm). X-ray fluorescence is advantageous because it is non-destructive to the sample.

During the initial part of the study, CIMAREX Oil and Gas Production Company allowed the use of a Thermo Scientific Niton XL3 portable XRF device for this thesis. The handheld instrument is designed to collect field data on the chemical composition of materials (Fig. 2.1). This type of x-ray fluorescence data is different than standard lab analyses, in which samples are analyzed on a stationary analyzer in a laboratory setting with documented calibration to standards. The portable devices, however, are used in a wide variety of applications where a mobile device is beneficial. These devices are not widely used in geology, but the opportunity allowed for experimentation of the device on core and cuttings. Samples were collected using standard protocols and safety guidelines for the device to determine if use of this type of device might provide useful information for correlation and base-line elemental composition of the shale for more-detailed future analyses in the study interval.

XRF data were collected from cuttings and core samples in four wells in the study area; Core samples were analyzed from the DuPont No. 1 WAD fee well in Jefferson County, and the

Battelle No. 1 Duke Energy well in Boone County. Cuttings samples were analyzed from these wells and from the Ford No. 1 Conner well in Boone County, and the Ashland No. 1 Wilson well in Campbell County, Kentucky. Although cuttings represent mixing of an interval and can be contaminated from admixtures of up-hole rock material, they are all that is available for collecting rock data where there are few cores.

For core samples, the device was held directly on core, measuring a site on the core roughly one inch in diameter. For core, samples were collected at 1- to 2- ft spacing. The trigger was depressed for 75 seconds to collect readings on major element oxides and trace elements from each collection site on the core. Information was stored into the instrument and then downloaded to a laptop computer in a Microsoft Excel spreadsheet. For cuttings, representative samples were collected from 10- to 20-ft-interval sample bags on file in the Kentucky Geological Survey well sample library. When measuring cuttings, the handheld device was installed into a docking station platform, connected to a laptop computer with installed software for the device. Cuttings were prepared by pouring a sample into a disposable, plastic sample cup, approximately 1 inch in diameter, by ½ inch high, with a clear film bottom and placing it into the measurement chamber. The device was then activated by the laptop computer to begin sampling, and data was collected for 75 seconds per sample. Results were downloaded to the laptop computer in raw ppm values in Microsoft Excel format. The device was calibrated to a standard at the beginning of the day, but not for each collection run.

To check for accuracy between the hand-held XRF device and traditional laboratory analyses, data collected from the Battelle No. 1 Duke Energy well core with the hand-held device were compared with major oxide data analyzed from the core using standard laboratory

Figure 2.1. A Thermo Scientific Niton XL3 portable XRF device was used to analyze shale chemistry in the core. Data on major, minor, and trace elements were collected.

methods with a mass spectrometer (Neufelder, 2011) at the same depths in the core.

Comparison between datasets and results of XRF analysis are presented in the next chapter.

Stable Isotopes

Stable-isotope analysis is the process of measuring stable-isotopic ratios with a sample against a known standard. An attempt was made to evaluate shale samples from core for carbon and nitrogen stable- isotopic ratios to possibly aid in stratigraphic correlations, and to better understand depositional facies. Samples as large as 30 mg were run using an elemental analyzer coupled with a mass spectrometer at the University of Kentucky Department of Earth and Environmental Sciences stable isotope laboratory. Results yielded peaks too low to be reliable, as samples did not contain enough of the isotopes to get a good reading. Future workers may try to lower the helium dilution in an attempt to achieve a meaningful peak.

CHAPTER 3: RESULTS

Cross Sections

Seven cross sections were correlated across the study area. Three sections were correlated along regional strike, and four sections along regional dip (Fig. 3.1). The cross sections are the central data set for this thesis work. The sections show in detail how the Eau Claire Formation interfingers eastward with the Conasauga Group. The datum in all sections is the base of the Knox Group. For the purposes of this study, the Eau Claire/Conasauga interval was divided into seven units based on geophysical-log signatures (Fig. 3.2). Sharp changes in gamma and porosity (density, neutron, and resistivity) log signatures reflecting changes in lithology were used for correlation, rather than relying on the existing nomenclature that is more
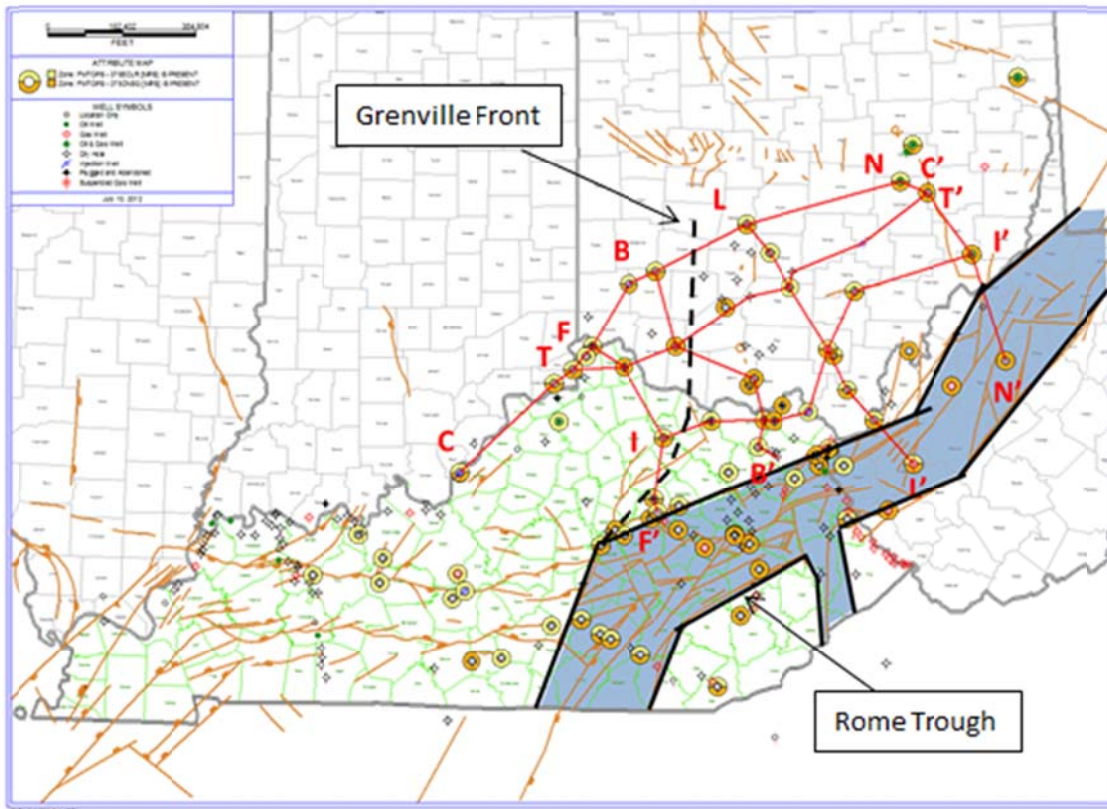
Figure 3.1. Locations of cross sections. Dashed line is Grenville Front. Shaded region is Rome Trough.

27
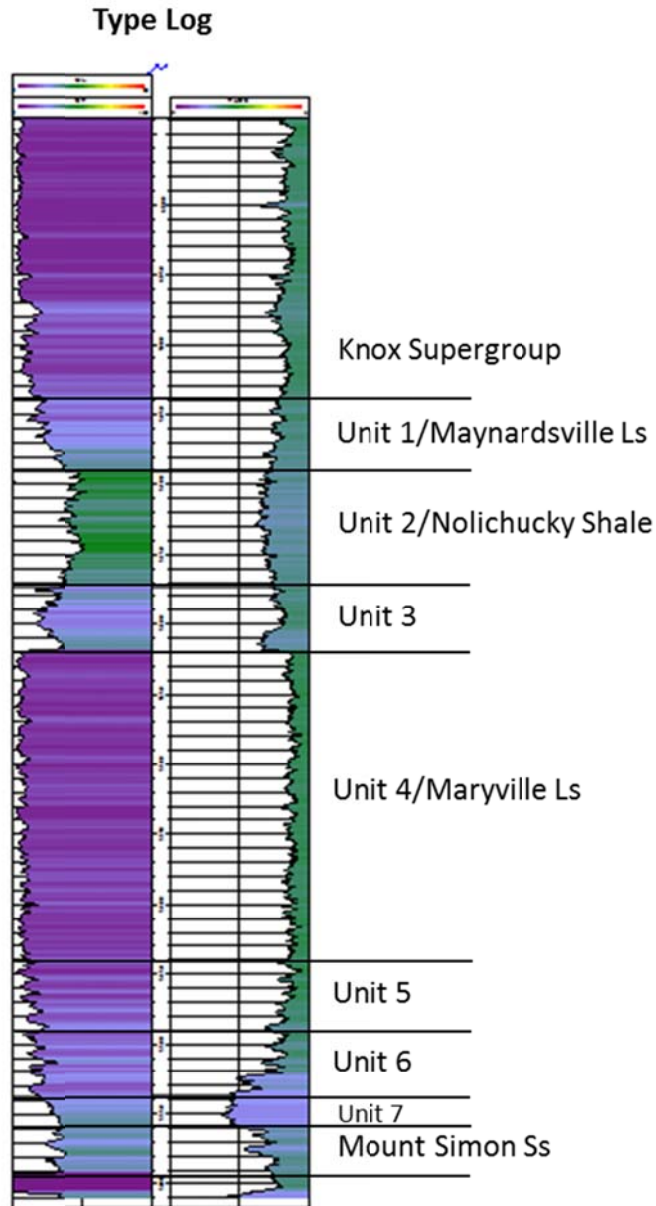
Figure 3.2. Example logs of the Eau Claire/Conasauga interval to show representative subdivisions used in the thesis. This well is the U.S. Chem/U.S. Steel No. 1 well in Scioto County, Ohio.

is more generalized, and sometimes crosscut unit boundaries. All of the wells had gamma-ray logs. Neutron, bulk-density, and resistivity logs were locally available. Units are numbered and described from the top to the base of the study interval.

Cross Section Subdivisions

<u>Unit 1</u>

Unit 1 is the uppermost subdivision in the study interval. It is mostly equivalent to the Maynardsville Limestone of the Conasauga Group to the east. The top of Unit 1 is the base of dolomites in the overlying Knox Group (Fig.3.2). This top is sharp in some logs and gradational in others. The base of Unit 1 is the base of the lowest carbonate in the interval, or the top of thick, underlying shale (Fig. 3.2). This underlying shale is the Nolichucky Shale of the Conasauga Group in the east. The base of unit 1 is generally picked at a laterally consistent vertical change in the gamma and porosity (density or neutron) logs from shale to limestone. Unit 1 is traceable across much of the region. On the eastern edge of the study area, the Conasauga Group consists of thick carbonates, and the base of Unit 1 cannot be accurately determined, so is not correlated in that area.

<u>Unit 2</u>

Unit 2 is mostly shale with some interbedded siltstone and limestone. The upper boundary is placed at the base of the lowest significant carbonate in Unit 1 (Fig. 3.2; base of the Maynardsville Limestone in the east). The base of Unit 2 is the top of a thick carbonate in Unit 3, which may have a sharp or gradational contact (Fig. 3.2). The middle part of the unit contains laterally persistent high-gamma shale. The base of the high-gamma shale is possibly a maximum flooding surface. Zones of slightly calcareous siltstones are interbedded regionally, and thicken eastward. Unit 2 is traceable across the entire extent of the study area, especially the middle high-gamma part of the unit. The high-gamma zone can be readily correlated westward into the upper part of the Eau Claire Formation in the Illinois Basin. Unit 2 is mostly equivalent to the Nolichucky Shale of the Conasauga Group in the eastern region of the study area. However, the

base of the Nolichucky is variably picked in the subsurface, especially westward where the

Maryville Limestone thins. To the west where Conasauga terminology is applied, Unit 2 only

comprises the upper part of what would normally be defined as the Nolichucky Shale (see cross

sections C-C', I-I', F-F', L-L', and B-B' for example). Similarly, the base of Unit 2 is the top of the

Maryville Limestone (Conasauga Group) in the eastern part of the study area, but the top of the

Maryville sequentially drops eastward, below the base of Unit 2.

Core showing Unit 2 was available from two wells within the study area. The first was

the ODNR DGS 2627 American Aggregates, in Warren County, Ohio. The second was the USS

Chem/US Steel No. 1 USS Chemical (Aristech) well in Scioto County, Ohio. These are described

in the Core Descriptions section.

Unit 3

Unit 3 consists of limestone, calcareous siltstone, and shale. The top of Unit 3 is

approximately the base of the Nolichucky Shale and Unit 2 to the east (Fig. 3.2). In the central

and eastern parts of the study interval the top of Unit 3 correlates to a flooding surface above a

fining upward interval at the base of Unit 2 (cross sections C-C' and I-I' for example). The base

of Unit 3 is drawn at a shale break in the thick Maryville carbonates to the east. The cross

sections show that the thick Maryville Limestone in the east consists of a series of stacked

carbonates (300- to 650-ft thick) separated by thin shale or density-log breaks. These breaks in

log signature can be traced laterally into thickening wedges of shales and siltstones. Three of

these breaks were used to define units within the interval. Unit 3 is the uppermost of these

stacked carbonate units.

The base of Unit 3 is also a possible flooding surface. Westward from where Unit 3 is a

thick carbonate, it grades into shales and siltstones and appears to consist of multiple

coarsening-upward intervals (possible parasequences), which are limestone-rich at the top, and shaly at their base. Unit 3 was divided into Units 3 and 3A where two distinct log profiles could be distinguished. Unit 3A has a lower density signature.

Core showing Unit 3 was available in three wells. The wells are (1) ODNR DGS 2627 American Aggregates in Warren County, Ohio; (2) Battelle No. 1 Duke Energy well, in Boone County, Kentucky ; and (3) the USS Chem/US Steel No. 1 USS Chemical well, Scioto County, Ohio (Aristech well). Core descriptions are summarized in the Core Descriptions section. Cuttings for Unit 3 were examined in three wells. (1) The Battelle No. 1 well, (2) the Monitor Petroleum No. 1 Stacy Heirs well in Morgan County, Kentucky, and (3) the UFG 9061 T Rawlings well in Mason County, Kentucky. Summaries of cutting analyses are described in the Cuttings Descriptions section.

Unit 4

Unit 4 consists of limestone, calcareous siltstone, and shale. Some limestones may be dolomitic (based on density-log signatures), especially in lower parts of the unit. The top of Unit 4 in the eastern part of the study area is picked at the top of a thick carbonate (usually limestone). In many areas this would be equivalent to the top of the Maryville Limestone of the Conasauga Group (Fig. 3.2). In some areas, Unit 4 represents a distinct tongue of the Maryville Limestone. The top is traced laterally westward to the top of a silty carbonate or siltstone. Unit 4 grades from carbonates in the east to siltstones and shales westward. Unit 4 becomes much more homogenous and silty westward (see cross section C-C' for example). The upper contact of Unit 4 is likely a marine flooding surface. Carbonates in Unit 4 extend further west than the carbonates in Unit 3. Unit 4 was divided into Units 4A and 4B where two distinct tongues or coarsening-upward intervals could be distinguished.

Two wells with core that showed Unit 4 were available for study in the study area. The

first was the Warren County well, and the other, the Scioto County (Aristech) well. Core

descriptions are summarized in the Core Descriptions section. Cuttings for Unit 4 were

examined in four wells. These were (1) the Ashland No. 1 Wilson well in Campbell County,

Kentucky; (2) the Battelle No. 1 Duke well; (3) the Morgan County well; and (4) the Mason

County well. Summaries of cutting analyses are described in the Cuttings Descriptions section.

Unit 5

Unit 5 consists of limestone, dolomite, sandy dolomite, calcareous siltstone, thin

sandstones, and shale. The top of Unit 5 is another distinct break in carbonate signatures in the

eastern part of the study area (not well-developed in Fig. 3.2). The top is a thick, low-gamma

carbonate in the middle part of the study area, and its apparent lateral equivalents are silty

carbonates or siltstones to the west. The base of Unit 5 is the base of the thick, low-gamma

carbonate in the eastern and middle parts of the study area (Fig. 3.2) and its lateral equivalent

westward. Unit 5 is composed of mixed lithologies. Unit 5 grades from calcareous silts in

extreme western sections of the study area, to a prominent carbonate in the middle and eastern

parts of the study area (see cross sections C-C' and I-I' for example). In some areas, Unit 5

represents a distinct tongue of the Maryville Limestone. Density-log signatures indicate the

carbonate is limestone across much of the study area, but becomes dolomitic in the lower half,

especially toward the east. In some areas where it is dolomitic, it may contain sandy zones and

sandstone stringers. Unit 5 was divided into Units 5A and 5B where two distinct tongues or

coarsening-upward intervals could be distinguished.

Core was available for Unit 5 in two wells in the study area. The first was the Warren

County well, and the other was the DuPont No. 1 WAD fee well, in Jefferson County, Kentucky.

Core descriptions are summarized in the Core Descriptions section. Cuttings were examined in

three wells across the study area. These were (1) the Battelle No. 1 well, (2) the Ashland Oil and

Refining well in Carter County, Kentucky, and (3) the Mason County well. Summaries of cutting

analyses are described in the Cuttings Descriptions section. In particular, intervals were chosen

which looked as if they might contain sandstones based on log signatures.

Unit 6

Unit 6 consists of limestone, dolomite, sandy dolomite, calcareous siltstone, thin

sandstones, and shale. In the eastern portion of the study area, Unit 6 is composed of shalier

carbonates (higher gamma) or interbedded thin carbonate and shales and calcareous siltstones

than Unit 5 (Fig. 3.2). The top of Unit 6 is the base of a low-gamma carbonate within the

Maryville Limestone to the east and laterally correlative westward. The base of Unit 6 is the

base of the carbonate interval (Units 4 through 6) across much of the eastern study area,

overlying a shalier and sandier interval in Unit 7 below (Fig. 3.2). Shales are included in the

lower sections of Unit 6 in the eastern and middle sections of the study area. The contact

between the top of Unit 6, and the base of Unit 5 is often sharp, although where carbonates in

Unit 5 grade into siltstones and shales westward, the boundary is less distinct. In the eastern

part of the study area, Unit 6 may be sandy in places, and carbonates may be dolomitic (based

on density log signatures and some cuttings). The unit is subdivided into Units 6A and 6B locally

where there were distinctive changes from clastic-dominated to carbonate-dominated log

signatures in the unit (see cross sections C-C', and I-I' for example).

Core for Unit 6 was available in the Warren County well. Core descriptions are

summarized in the Core Descriptions section. Cuttings within Unit 6 were observed in five wells

across the study area. These were (1) the Campbell County well; (2) the Battelle No. 1 well; (3)

the Thomas No. 1 Adams well in Lewis County, Kentucky; (4) the Carter County well; and (5) the Mason County well. Special attention was focused on intervals of cuttings with possible sandstones or sandy carbonates on density logs to determine if there was actually sandstone in the interval. Summaries of cutting analyses are described in the Cuttings Descriptions section.

Unit 7

Unit 7 was identified to highlight a relatively high-gamma section above the Mount Simon Sandstone at the base of what is mapped as Maryville Limestone in the eastern part of the study area (Fig. 3.2). Unit 7 has variable lithology and consists of sandy to silty shale, siltstone, sandstone, limestone, and dolomite. The top of Unit 7 is the base of a carbonate or siltstone in Unit 6 or 6B. The base of Unit 7 is the top of the traditional Mount Simon Sandstone top or "Basal" sandstone (Fig. 3.2). Unit 7 grades upward into the base of the Maryville Limestone, Conasauga Group (eastern part of Unit 6) in the extreme eastern regions of the study area where it is no longer traceable as a distinct unit (see cross sections C-C', I-I', B-B', L-L', and F-F' for example). Subunits 7A and 7B were used for correlative purposes to separate locally distinctive parts of Unit 7.

Core for Unit 7 was available in the Warren County well. Core descriptions are summarized in the Core Descriptions section. Cuttings were observed in three wells across the study area. These were the Campbell County well, the Battelle No. 1 well, and the Mason County well. Summaries of cutting analyses are described in the Cuttings Descriptions section.

Mount Simon Sandstone or Basal Sandstone

The Mount Simon Sandstone is composed of sandstones, siltstones, and shales immediately capping the Precambrian unconformity surface. Eastward in the Appalachian

Basin, the Ohio Geological Survey uses the term "Basal sandstone" rather than Mount Simon

Sandstone for sandstones directly above Precambrian granitic rocks. This eastern sandstone is

often redder and possibly more arkosic than the typical Mount Simon Sandstone of the Illinois

Basin. The change occurs near the Grenville Front, which is sometimes used as an arbitrary

boundary between the two sandstones (Greb and Solis, 2009). The top of the Mount Simon

Sandstone is the base of the study interval.

Cross Section Summaries

Cross section locations are shown in Figure 3.1. All sections are drawn at equal well

spacing to highlight correlations between wells. True spacing can be seen in Figure 3.1. All cross

sections are hung on the base of the Knox Group. Dominant lithologies are color-coded in each

section according to the legend in Figure 3.3. This legend is shown as a separate figure since

there was not enough room on some sections for a readable legend.

Limestone and Dolomite	Dolomites, Sandstones, and shales.
Shales and Siltstones	Basal Sands, Siltstones and Shales
Silty Shales and Siltstones, and limestones	Mount Simon Sandstone
Limestone with Dolomite	
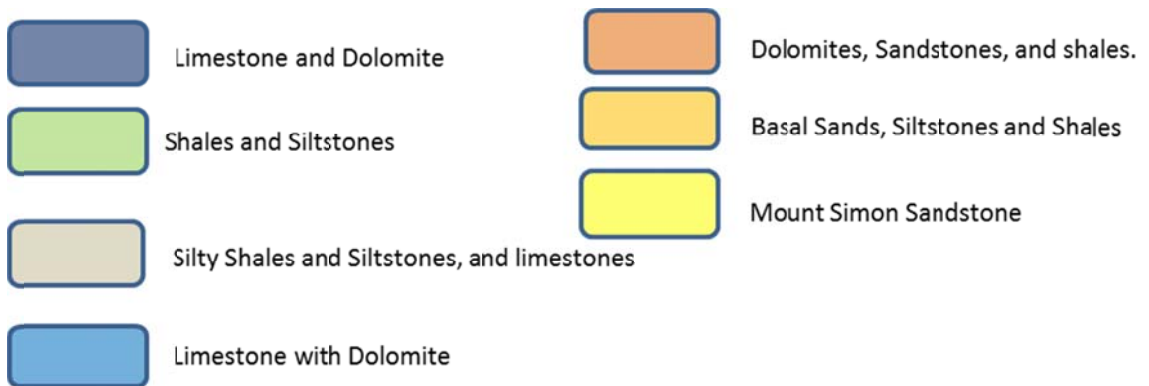
Figure 3.3. Legend for dominant lithologies shown in cross sections

Cross Section C-C'

The first cross section (Fig. 3.4) runs along strike, following the Kentucky/Indiana border, from through northern Kentucky, then northeastward into south-central Ohio (Fig. 3.1, Table 3.1). Unit 1, the Maynardville Limestone, thins before pinching out between the Battelle No. 1 Duke Energy well and Ford No. 1 Conner well (well nos. 3 and 4 in Fig. 3.4), in the western part of the section. Unit 2 (Nolichucky Shale) is present across the entire section. Units 3, 4, and 5 are carbonates to the northeast (Maryville Limestone) that interfinger westward with shales and siltstones of the Eau Claire Formation. The transition from mostly carbonates to mostly shales occurs between the Amerada Petroleum well, and the ODNR DGS 2627 (Warren County) well (well nos. 6 and 7 in Fig. 3.4), which is across the Grenville Front. Unit 6 consists of carbonates mixed with silts and shales, and is variably sandy. Unit 6 is the base of the Maryville Limestone

Table 3.1. Table showing names and location of wells for cross section C-C'. The number assigned to each well in the table corresponds with the number above each well in the cross section (Fig. 3.4).

Cross Section C-C'			
Number	**Well**	**County**	**State**
1	DuPont No. 1 WAD fee	Jefferson	KY
2	Ashland Exploration No. 1 Sullivan	Switzerland	IN
3	Battelle No. 1 Duke Energy	Boone	KY
4	Ford No. 1 Conner	Boone	KY
5	Armco Steel No. 1 Armco	Butler	OH
6	ODNR DGS 2627 American Aggregates	Warren	OH
7	Amerada Petroleum No. 1 Hume	Madison	OH
8	RSC Energy CR400 Consolidation Coal	Muskingum	OH

Figure 3.4. Cross section C-C'. See location map (Fig. 3.1) for well locations and true distances between wells. See Figure 3.3 for explanation of color shading. GF= Grenville Front. See Table 3.1 for well names.

to the east, but grades westward with silty shales of the Eau Claire Formation. Unit 7 is also

laterally consistent across the study area. It is mostly shaly, however it may be variably sandy

and contain thin carbonates. The Mount Simon Sandstone thins westward. The greatest

thinning occurs between the Amerada Petroleum No. 1 Hume well (well no. 7 in Fig. 3.4) and the

RSC Energy CR400 Consolidation Coal well (well no. 8 in Fig. 3.4), where it pinches out.

Cross Section I-I'

Figure 3.5 is a southwest- to northeast-trending strike section (Fig. 3.1, Table 3.2). This

section shows how the Eau Claire Formation (western side of section) interfingers with the

Conasauga Group (eastern side of the section) across the central and southern part of the study

area, just north of the Rome Trough (Fig. 3.1). Unit 1 (the Maynardville Limestone) and Unit 2

(Nolichucky shale) are laterally persistent across the study area. Unit 2 is thickest in the middle

of the section, and thins in the eastern and western parts of the section. Unit 3 is also

Table 3.2. Names and location of wells for cross section I-I' (Fig. 3.5).   The number
assigned to each well in the table corresponds with the number above each well in the
cross section.

Cross Section I-I'			
Number	**Well**	**County**	**State**
1	Union Light Hear 200 Mynear	Nicholas	KY
2	UFG 9061T Rawlings	Mason	KY
3	Thomas No. 1 Adams	Lewis	KY
4	Ashland No. 1 Wolfe	Lewis	KY
5	US Chemical US Steel No. 1 USS Chemicals	Scioto	OH
6	NuCorp Energy No. 1 Trepanier	Jackson	OH
7	Dunigan, EJ No. 1 Hockman	Hocking	OH
8	Amoco 1 Ullman	Noble	OH
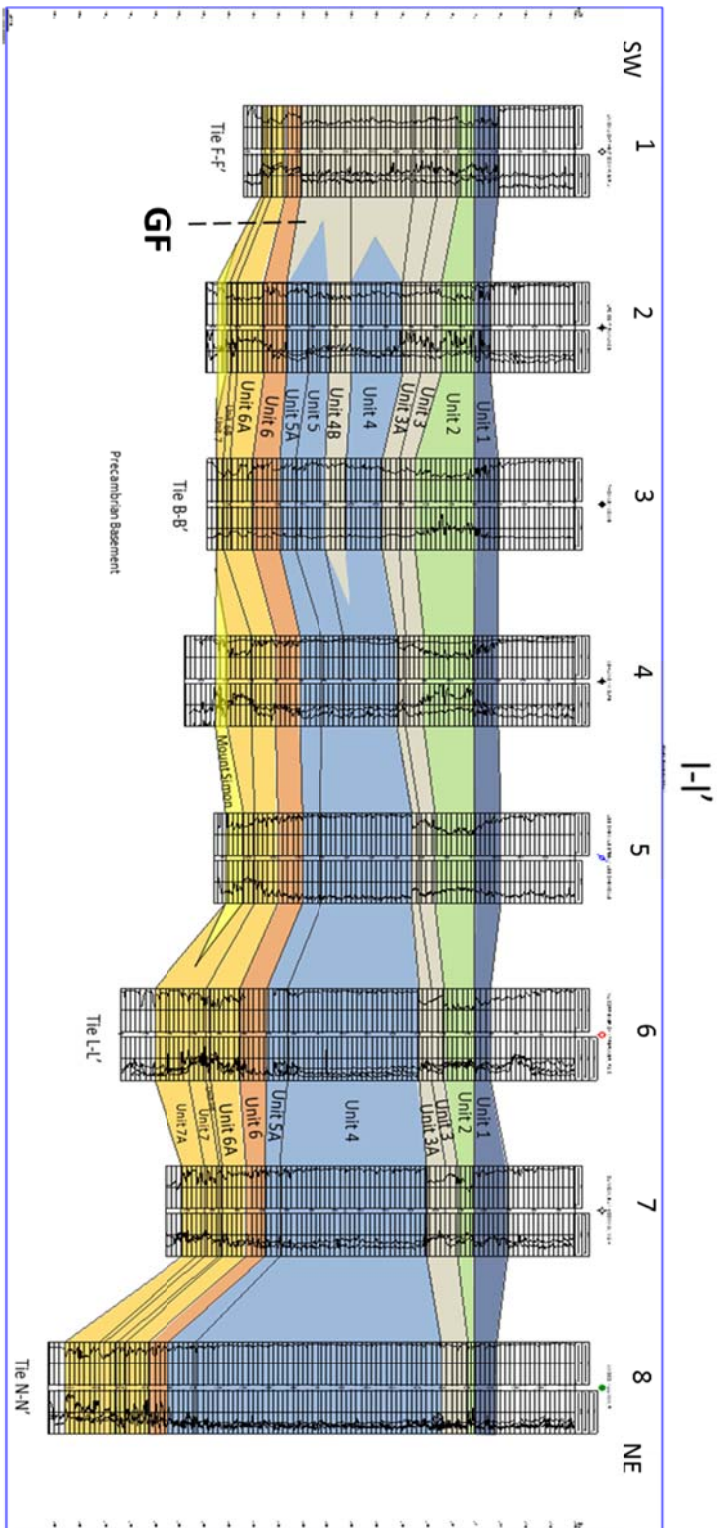
Figure 3.5. Cross section I-I'. See location map (Fig. 3.1) for well locations and true distances between wells. See Figure 3.3 for explanation of color shading. GF= Grenville Front. See Table 3.1 for well names.

continuous across the study area. Carbonates in the east grade laterally with shales and

siltstones in the extreme western part of the section, between the Union Light and Heat 200

Mynear well and the UFG 9061 T Rawlings well (nos. 1 and 2 in Fig. 3.5), which is across the

Grenville Front. Units 4 and 5 (part of Maryville Limestone) are thick carbonates in the east,

which thin and grade into clastics in the west, also between the Union Light and Heat 200

Mynear well and the UFG 9061 T Rawlings well, across the Grenville Front. Units 6 and 7 are

laterally continuous across the study area. The Mount Simon Sandstone is much thinner where

it is present, than in the previous section (Fig. 3.4).

Cross Section T-T'

This is the third strike section (Fig. 3.6, Table 3.3). As in the previous strike sections, it

shows how the Eau Claire Formation interfingers with the Conasauga Group in the central

portion of the study area. Unit 1 (Maynardville Limestone) pinches out in the westernmost area

of the section between the Battelle No. 1 Duke Energy well (well no. 1 in Fig. 3.6) and the

Table 3.3. Names and location of wells for cross section I-I' (Fig. 3.6). The number assigned to
each well in the table corresponds with the number above each well in the cross section.

Cross Section T-T'			
Number	**Well**	**County**	**State**
1	Battelle No. 1 Duke Energy	Boone	KY
2	Ashland No. 1 Wilson	Campbell	KY
3	Spencer Petroleum No. 1 Griffith	Brown	OH
4	Oxford Oil No. 1 Irvine	Ross	OH
5	Well Supervision No. 1 Immell	Ross	OH
6	Ramco Oil and Gas No. 1 Kerns	Pickaway	OH
7	Poling, R C No. 1 Rush Creek Partners	Perry	OH
8	Lakeshore Pipeline No. 1 W Marshall Comm	Guernsey	OH

Figure 3.6. Cross section T-T'. See location map (Fig. 3.1) for well locations and true distances between wells. See Figure 3.3 for explanation of color shading. See Table 3.1 for well names.

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continuous across the study area. It is mostly silty shale, but includes carbonates to the east.

Units 4 and 5 (part of the Maryville Limestone) thin into the Eau Claire Formation westward,

Ashland No. 1 Wilson well (well no. 2 in Fig. 3.6). Unit 2 (Nolichucky Shale) is present across

most of the section and thins into the Conasauga Group in the last well to the east. Unit 3 thins

in the Oxford Oil No. 1 Irvine well (well no. 4 in Fig. 3.6), near the Grenville Front. Units 6 and 7

are also continuous across the section. The Mount Simon Sandstone thins eastward as the

Precambrian basement appears to rise in elevation relative to the datum at the base of the

Knox. Basal sands to the east (non-blocky sandstone log signatures) appear to overlap the

Mount Simon Sandstone (blocky log signature) in the eastern and central areas of the section

within Unit 7 (Fig. 3.6).

Cross Section B-B'

Cross section B-B' (Fig. 3.7, Table 3.4) is a dip section (Fig. 3.1). The section highlights

changes in the study interval from northwest to southeast, across the Kentucky River Fault

System into the Rome Trough. Unit 1 (Maynardville Limestone) and Unit 2 (Nolichucky Shale)

thicken across the Kentucky River Fault System into the Rome Trough. Unit 3 extends across the

northern margin of the Rome Trough, but does not thicken as much as the units immediately

above and below it. Unit 3 consists of silty shales to the west, and shales, carbonates, and thin

sandstones or sandy carbonates in the central and eastern parts of the section. Units 4 and 5

(parts of the Maryville Limestone) grade into calcareous siltstones of the Eau Claire Formation

northwestward. The Maryville Limestone thickens significantly thicken into the Rome Trough,

but Units 4 and 5 were not correlated into the trough because the distinctive shale breaks

chosen to subdivide the units north of the trough could not be accurately picked within the

trough. Units 6 and 7 thin southward and pinch out just north of the Rome Trough, where the
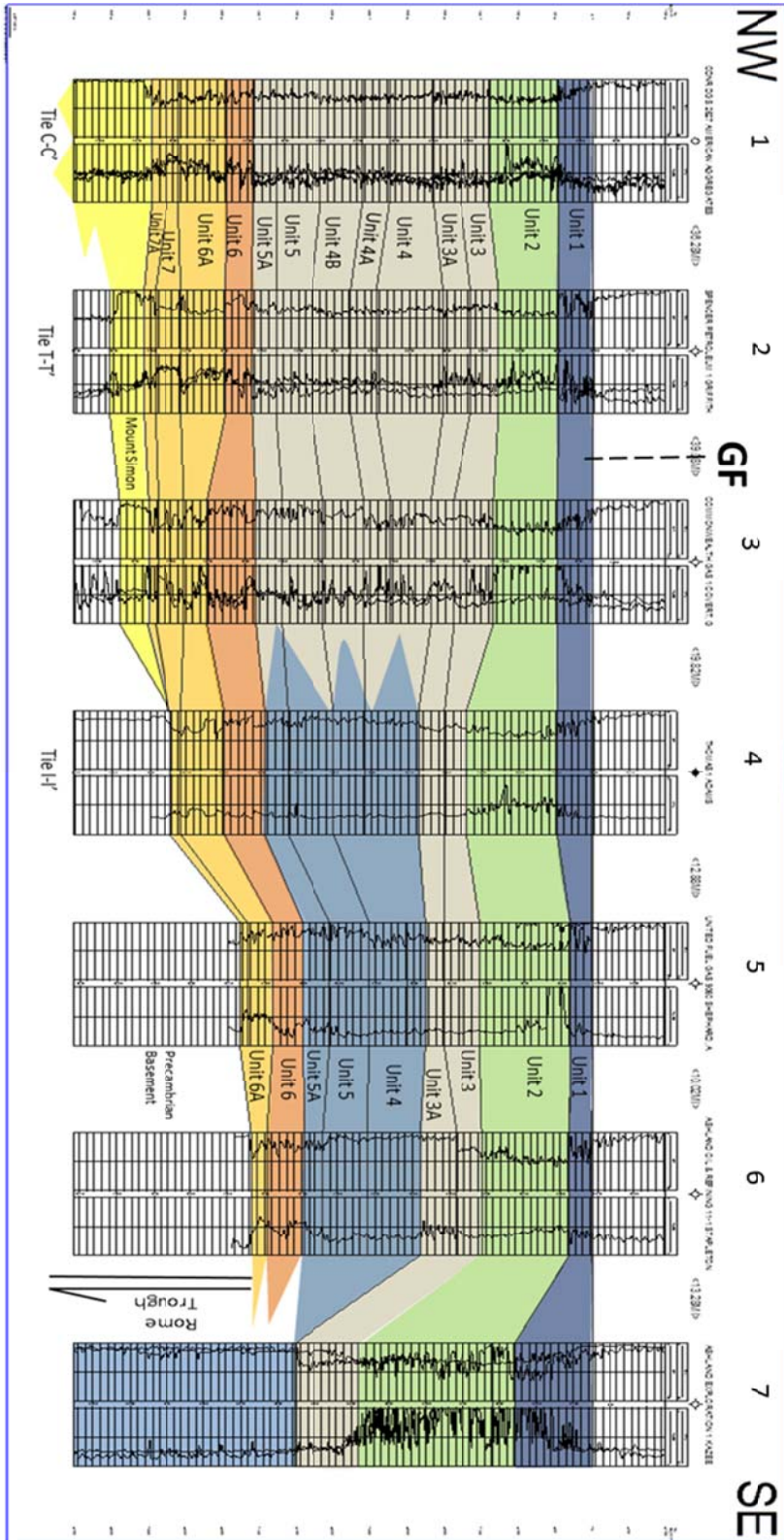
Figure 3.7. Cross section B-B'. See location map (Fig. 3.1) for well locations and true distances between wells. See Figure 3.3 for explanation of color shading. See Table 3.4 for well names.

Table 3.4. Names and location of wells for cross section B-B' (Fig. 3.7). The number assigned to each well in the table corresponds with the number above each well in the cross section.

Cross Section B-B'			
Number	Well	County	State
1	ODNR DGS 2627 American Aggregates	Warren	OH
2	Spencer Petroleum No. 1 Griffith	Brown	OH
3	Commonwealth Gas No. 1 Covert	Adams	OH
4	Thomas No. 1 Adams	Lewis	KY
5	United Fuel Gas 9060 Shephard	Lewis	KY
6	Ashland Oil and Refining 11-1 Stapleton	Carter	KY
7	Ashland Exploration No. 1 Kazee	Elliott	KY

Precambrian surface appears to rise in elevation relative to the Knox datum. The Mount Simon Sandstone pinches out even farther to the northwest. The sandstone abruptly thins between wells 1 and 2 in Figure 3.7, which is approximately along the Grenville Front. Basal sandstones are present near the lip of the trough, and appear to overlie the Mount Simon Sandstone northwestward (in Unit 7).

Cross Section F-F'

This dip section (Fig. 3.1) primarily shows the Eau Claire Formation and its distribution southeastward towards the Rome Trough (Fig. 3.8, Table 3.5). Unit 1 (Maynardsville Limestone) is present across the section, although it thins significantly northwestward. Unit 2 (Nolichucky Shale) is also present across the section, and thins significantly southeastward towards the Rome Trough. Units 3 and 4 are continuous across the section. These consist primarily of silty shales and silty carbonates, with local thin sandstones or sandy carbonates. Units 3 and 4 are equivalent to carbonates in the Maryville Limestone to the east, but thick limestones are not present in these units in this section. Unit 5 is absent from the section. Unit 6 is continuous across the section, and rests on Precambrian basement just north of the Kentucky River Fault
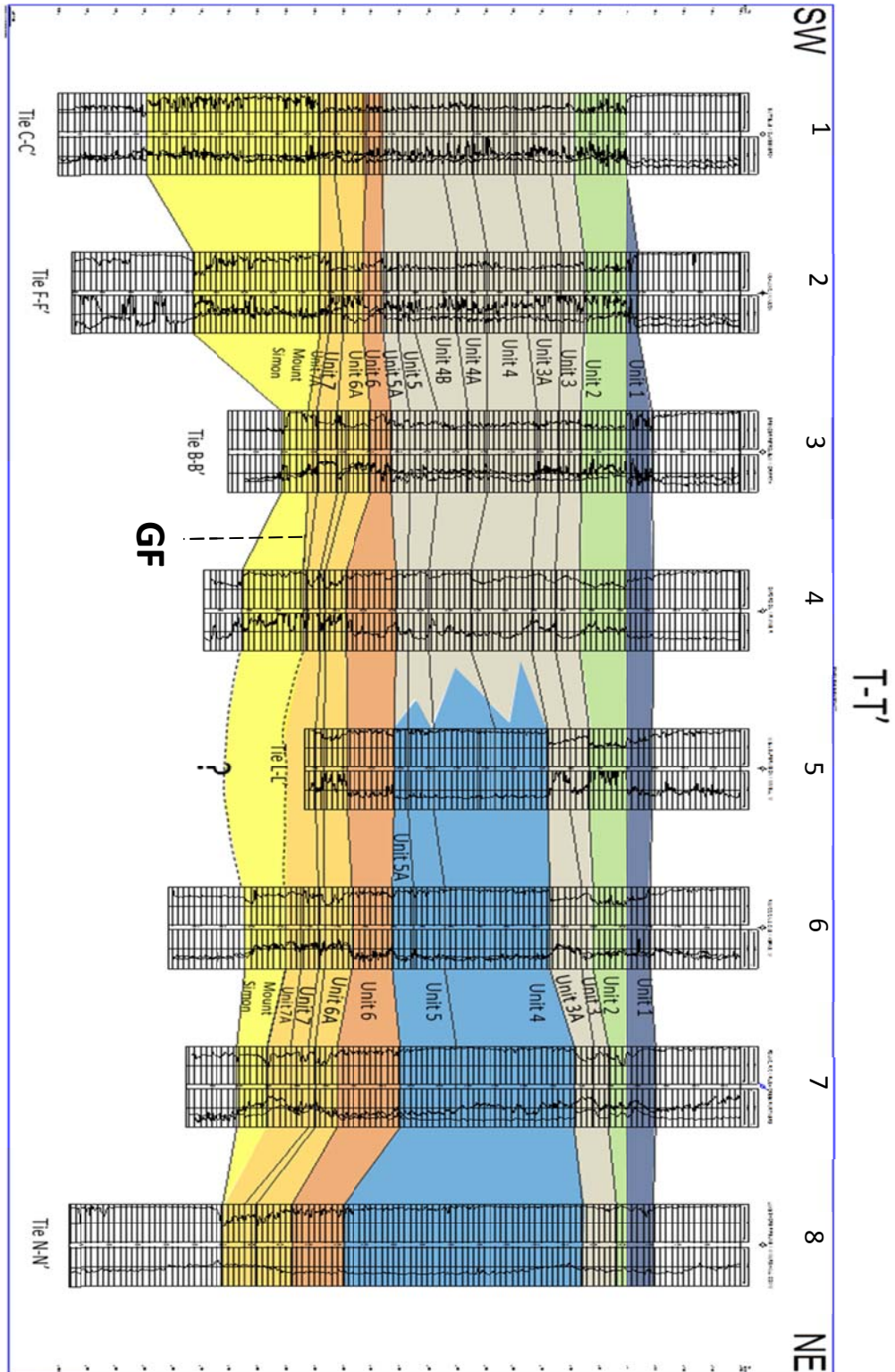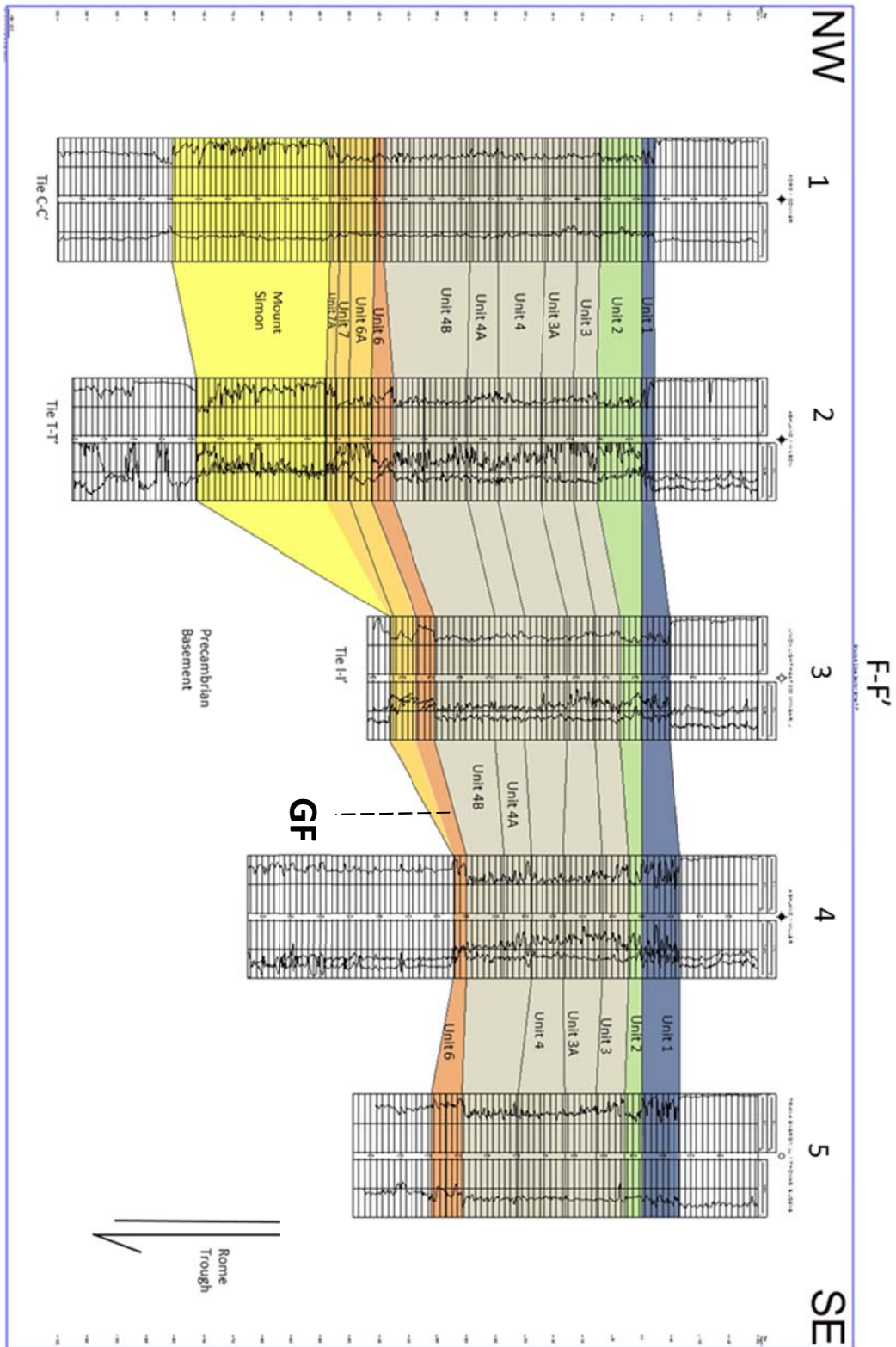
Figure 3.8. Cross section F-F'. See location map (Fig. 3.1) for well locations and true distances between wells. See Figure 3.3 for explanation of color shading. GF= Grenville Front. See Table 3.5 for well names.

Table 3.5. Names and location of wells for cross section F-F' (Fig. 3.8). The number assigned to each well in the table corresponds with the number above each well in the cross section.

Cross Section F-F'			
Number	Well	County	State
1	Ford No. 1 Conner	Boone	KY
2	Ashland No. 1 Wilson	Campbell	KY
3	Union Light and Heat 200 Mynear	Nicholas	KY
4	Ashland No. 1 Miller	Clark	KY
5	Triana Energy, LL 1 Thomas, Eugene	Clark	KY

System where the basement appears to rise in elevation (relative to a Knox datum). Unit 7 is present and thins southeastward towards the lip of the Rome Trough. Unit 7 pinches out between wells 2 and 3 in Figure 3.8, a little bit farther to the northwest.   The Mount Simon Sandstone dramatically thins and pinches out a little farther northwestward, between wells 2 and 3, which is close to the position of the Grenville Front. Possible basal sandstone equivalents (in Units 7 and 7A) above the Precambrian on the northern margin of the Rome Trough appear to drape the Mount Simon Sandstone northwestward.

Cross Section L-L'

This dip section (Fig. 3.1) shows the relationship between the easternmost fingers of the Eau Claire Formation (Fig. 3.9, Table 3.6) and carbonates of the Conasauga Group. Like the other dip sections, it shows changes across the northern margin of the Rome Trough. This dip section has more carbonate in the study interval than the sections to the west. Units 1 through 4 thicken into the Rome Trough. Units 4 and 5 (part of Maryville Limestone) thin and begin to interfinger with siltstones and shales in the northwestern-most part of the section between well nos. 2 and 3 in Figure 3.9, which is southeast of the Grenville Front. Unit 6 pinches out along

Table 3.6. Names and location of wells for cross section L-L' (Fig. 3.9). The number assigned to each well in the table corresponds with the number above each well in the cross section.

Cross Section L-L			
Number	Well	County	State
1	Amerada Petroleum No. 1 Hume	Madison	OH
2	Minuteman Exploration No. 1 Higgy	Pickaway	OH
3	Well Supervision No. 1 Immell	Ross	OH
4	Nucorp Energy No. 1 Trepanier	Jackson	OH
5	Goldberg, J Stanley No. 1 Payne	Lawrence	OH
6	Cyclopse No. 1 Kingery	Cabell	WV
7	Exxon 1 McCormick	Lincoln	WV

the northern margin of the Rome Trough. Unit 7 rests on basement from well no. 4 (Fig. 3.9) to the southeast on this apparent structural high. The Mount Simon Sandstone thins and pinches out between well nos. 2 and 4 in Figure 3.9. Well 3 does not extend into the Mount Simon Sandstone. In this section, the Mount Simon extends slightly east of the Grenville Front. A thick sandstone occurs above basement in wells 4 and 5 (Fig. 3.9). This sandstone has a different geophysical log signature from the Mount Simon Sandstone to the northwest. It likely represents a "basal" sandstone, which may or may not be equivalent to Unit 7 northwestward. Well no. 3 does not extend deep enough to determine the lateral relationship between these two units.
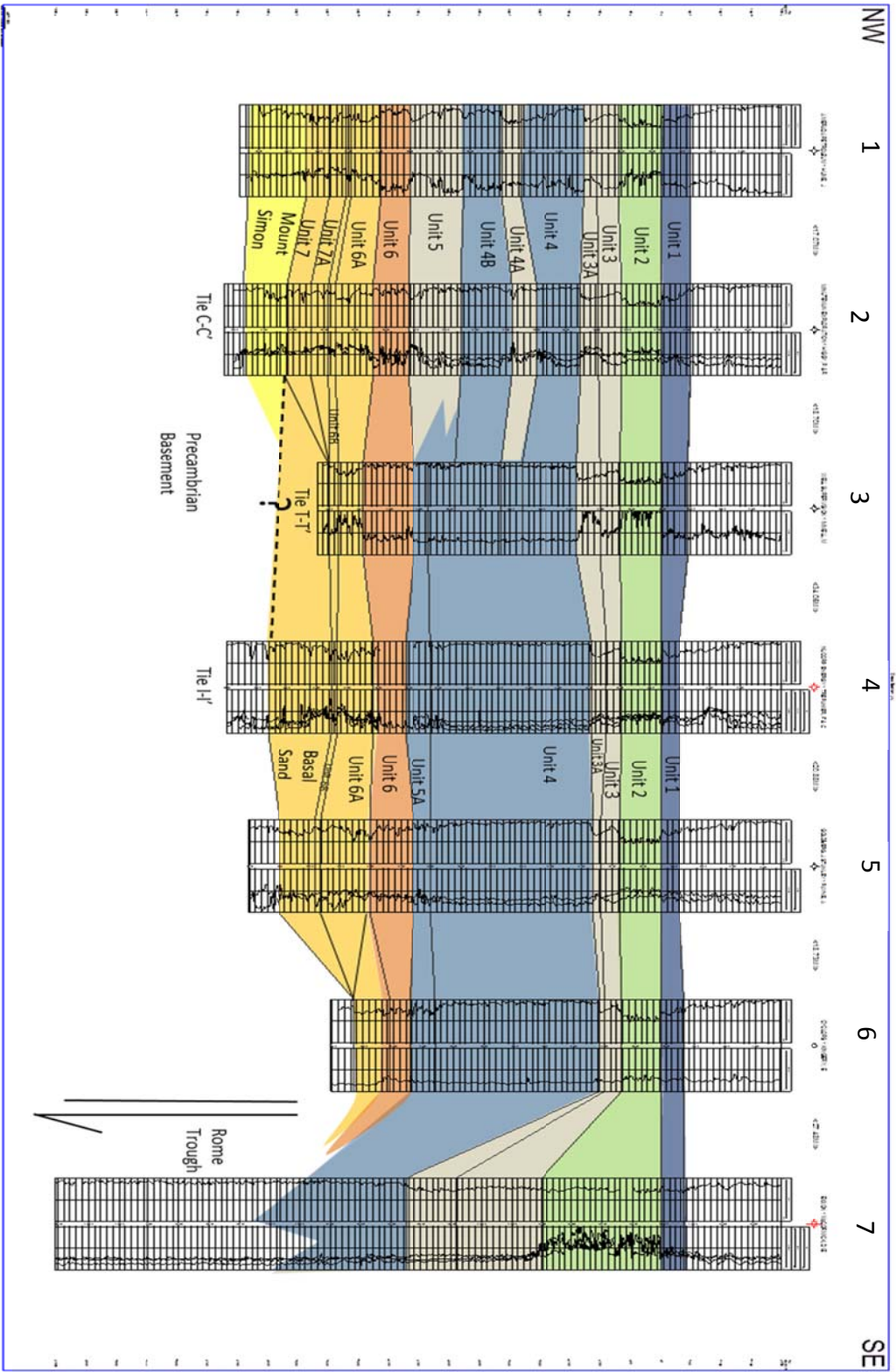
Structure Maps

Structure maps were made for the top of the Mount Simon/Basal sandstone interval (Fig. 3.10), and each unit within the Eau Claire/Conasauga interval (Figs. 3.11-3.17). Structures were mapped to show the subsurface topography and dip of each unit. The structure maps are all similar. Most show a structural high in the middle and north/middle part of the study area, which roughly corresponds to an area west of the Grenville Front. Structural lows correspond to areas in the Rough Creek Graben in western Kentucky and in the eastern Rome Trough in West Virginia. Strata dip eastward into the post-Cambrian Appalachian Basin, and westward into the Post-Cambrian Illinois Basin.
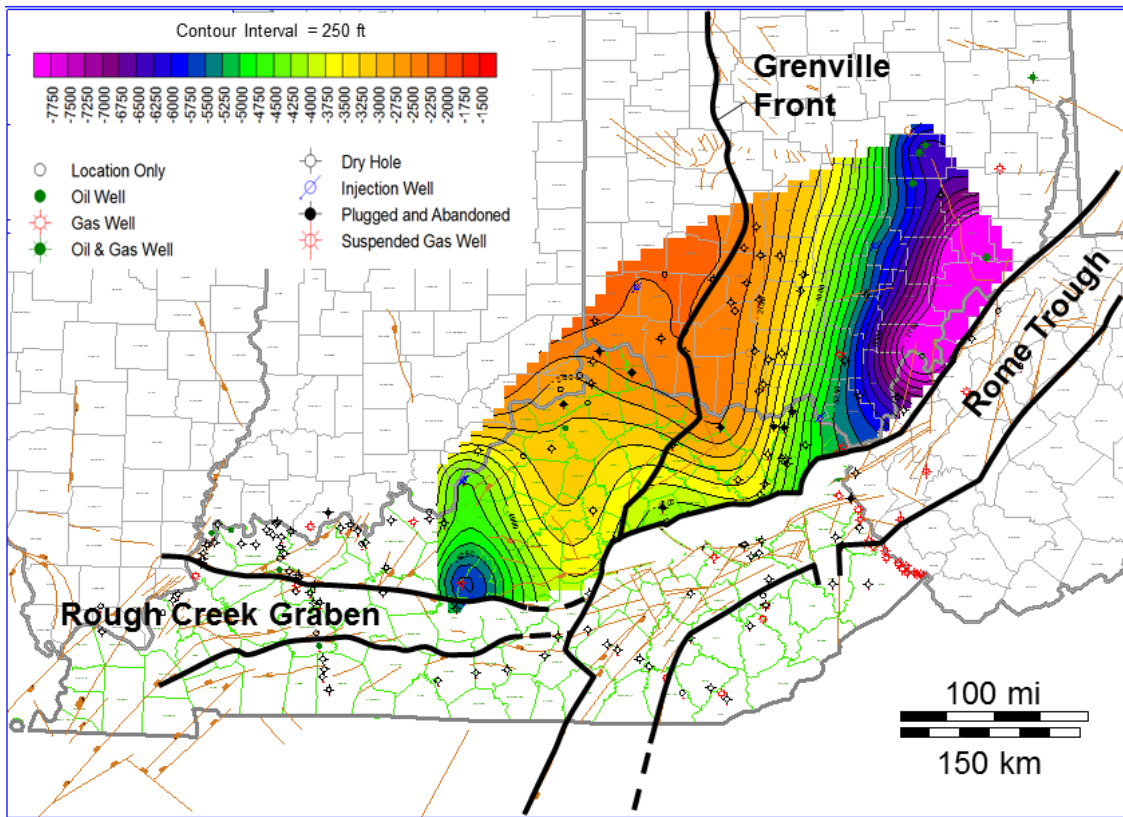
Figure 3.10. Top of Mount Simon Sandstone structure. A mask covers some of the well data and faults south of the Kentucky River Fault System in the Rome Trough where Petra extrapolated structure from north of the faults.
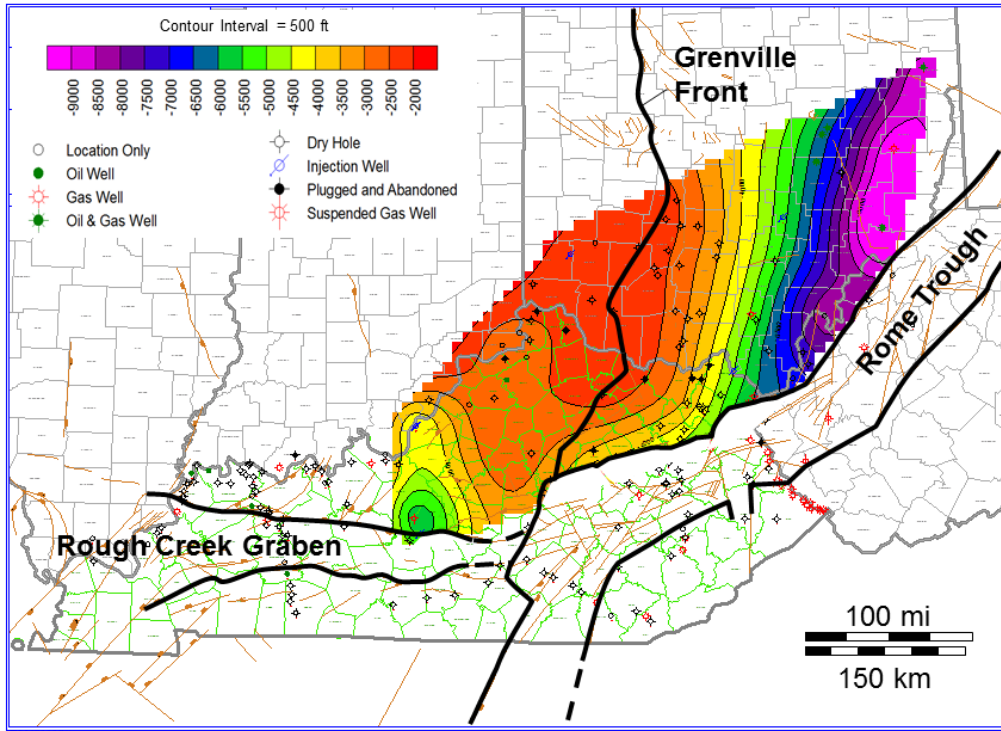
Figure 3.11. Top of Unit 7 structure. A mask covers some of the well data and faults in the Rome Trough where Petra extrapolated structure from north of the faults.
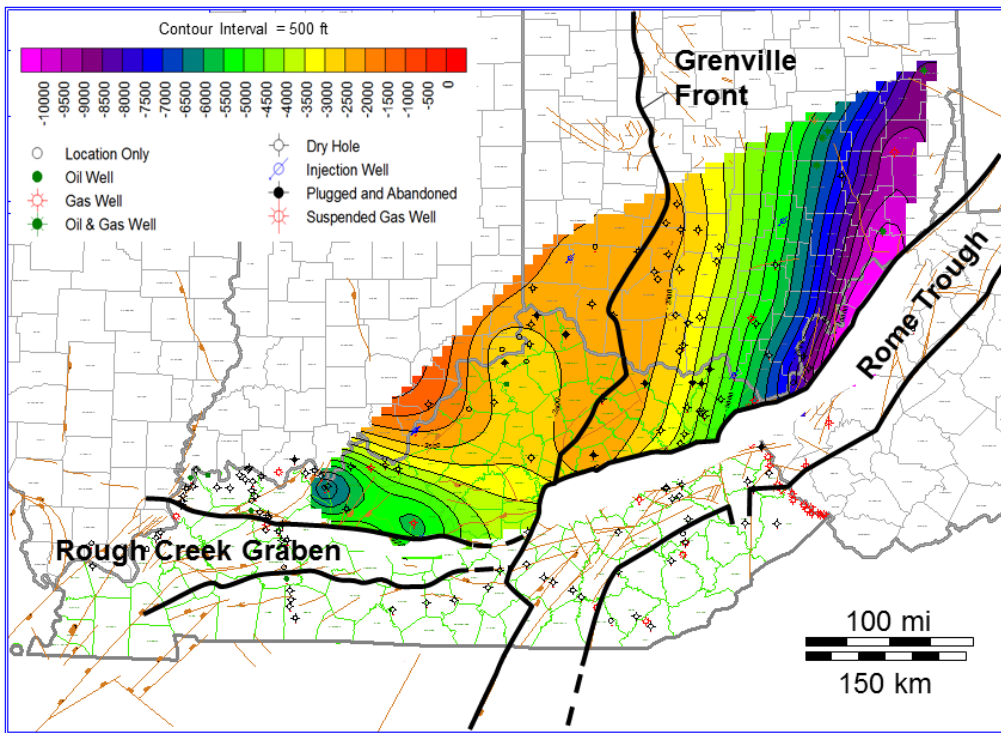
Figure 3.12. Top of Unit 6 structure. A mask covers some of the well data and faults in the Rome Trough where Petra extrapolated structure from north of the faults.
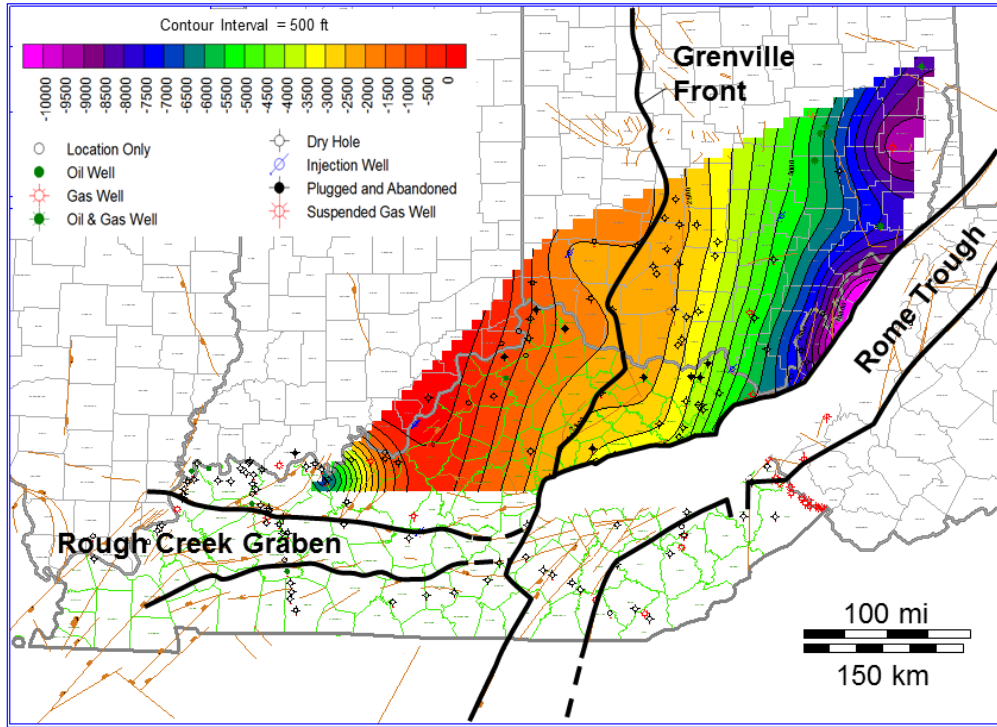
Figure 3.13. Top of Unit 5 structure. A mask covers some of the well data and faults in the Rome Trough where Petra extrapolated structure from north of the faults.
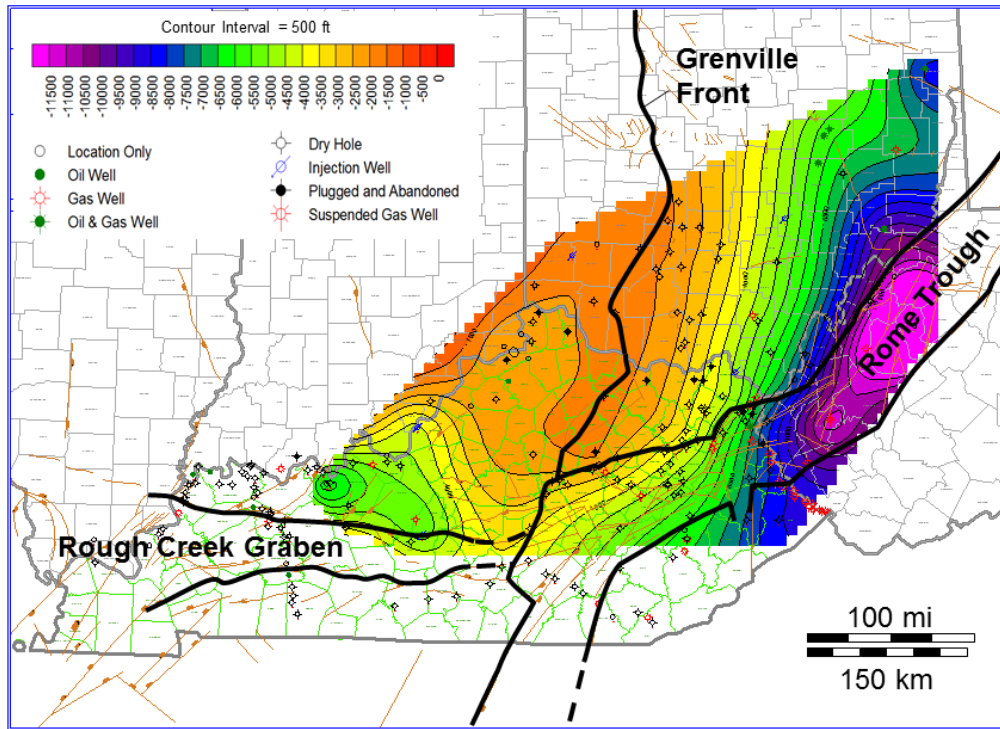
Figure 3.14. Top of Unit 4 structure. The top of Unit 4/base of Unit 3 was correlated into the Rome Trough.

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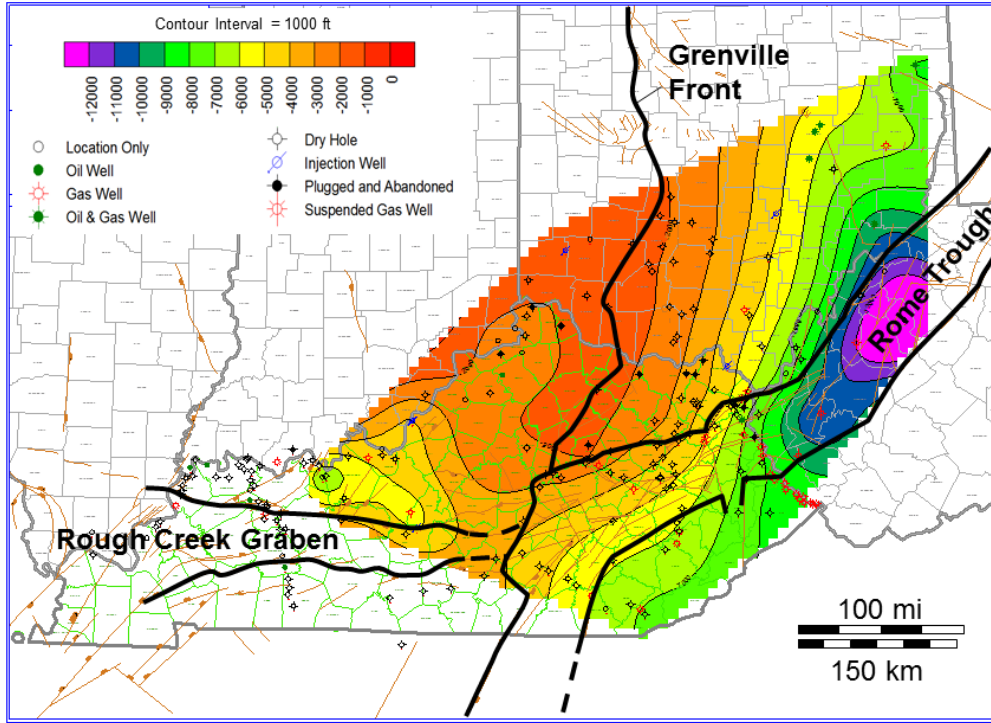
Figure 3.15. Top of Unit 3 structure. The top of Unit 3 was correlated into the Rome Trough.
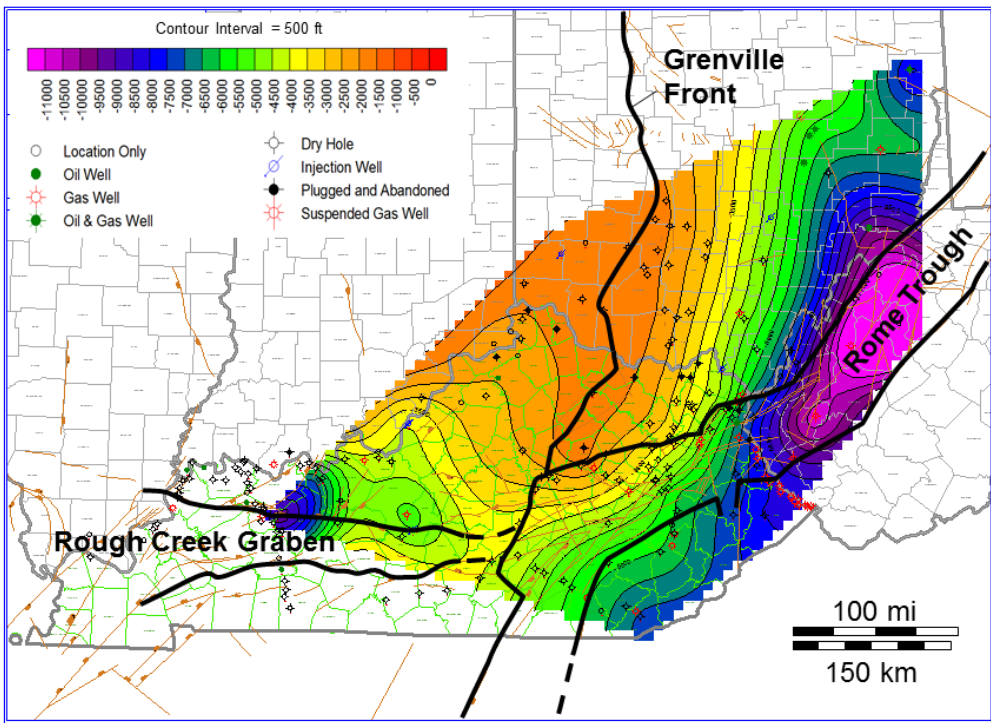
Figure 3.16. Top of Unit 2 (approximately top of the Nolichucky Shale) structure. The top of Unit 2 was correlated into the Rome Trough.
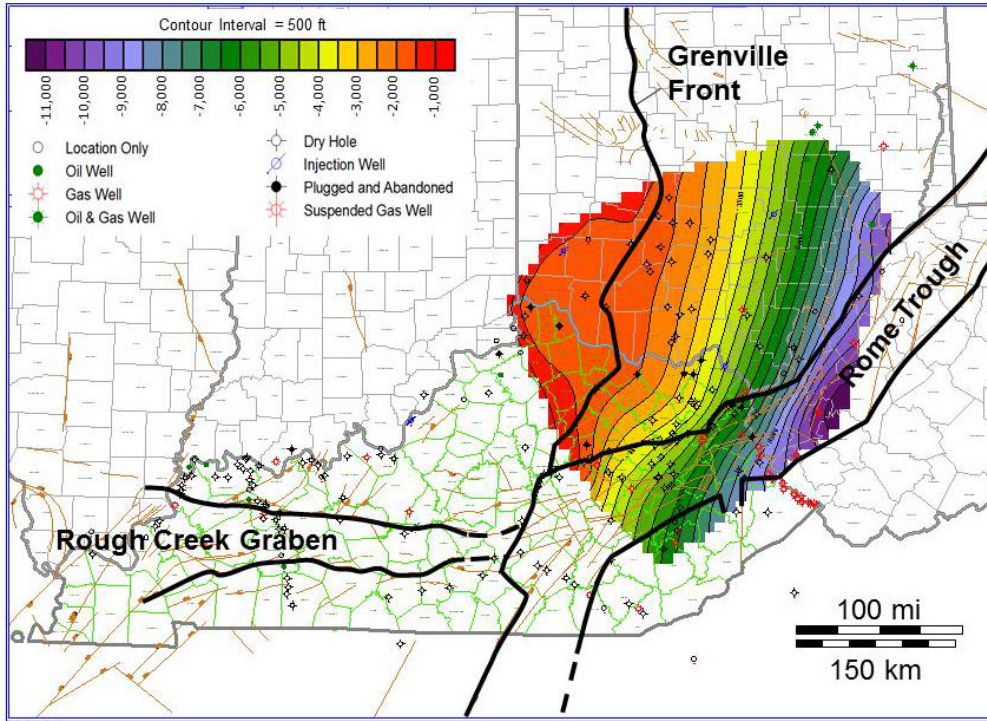
Figure 3.17. Top of Unit 1 structure (top of the Maynardsville Limestone). Unit 1 was correlated into the Rome Trough. Unit 1 pinches out beneath the Knox Group in the western part of the study area.
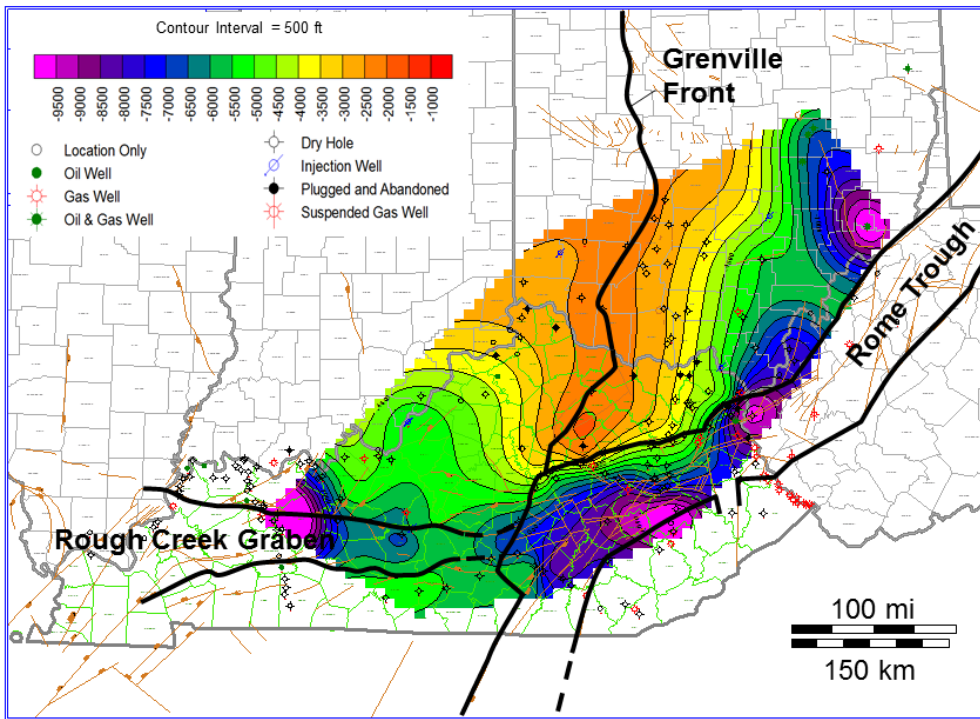
Figure 3.18. Top of Eau Claire/Conasauga interval.

Isopach Maps

Isopach maps were created for each major unit within the Eau Claire/Conasauga interval in order to demonstrate regional thickness trends. Sub-units were not mapped as they served to aid in correlations only. Units 4 through 7 were only mapped north of the Rome Trough faults because they could not be correlated with confidence into the trough. These units, however, continue and likely thicken into the Rome Trough (see Fig. 1.6).

The Mount Simon Sandstone thins to the south and east, and terminates near the northern lip of the Rome Trough (Fig. 3.19). Unit 7 exhibits relatively uniform thickness across the study area, though it thickens slightly in the northeast (Fig. 3.20). Unit 6 is similar with two thick regions to the northeast and southwest (Fig. 3.21). Unit 5 thickens northeastward (Fig. 3.22). North of the faults, Unit 4 thickens eastward (Fig. 3.23). Units 1 through 3 were mapped across the Rome Trough and all units thicken into the trough (Figs. 3.24, 3.35, 3.26). Unit 3 thickens the most, and Unit 1 the least. North of the trough, Units 2 and 3 are thickest to the west and thin to northeast. Unit 1 is more uniform in thickness than some of the other units, although a slight thickening trend can be seen eastward (Fig. 3.26). Unit 1 pinches out westward beneath the Knox Dolomite and likely thins more gradually west towards the pinchout than is shown by available data.

In general, the carbonate-dominated parts of the study interval (Units 1, 4, and 5) thicken eastward, and the upper clastic-dominated intervals (Units 2 and 3) thicken westward. Several units also exhibit NW–SE-oriented thickness trends north of the Rome Trough.
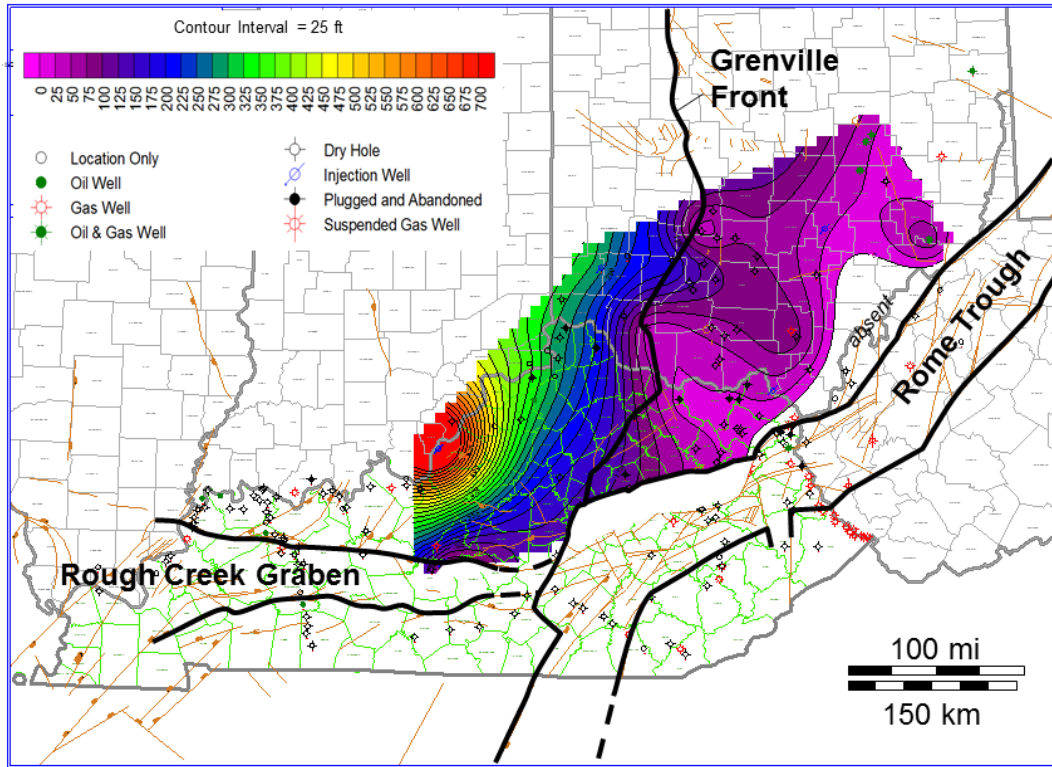
Figure 3.19. Mount Simon Sandstone isopach.
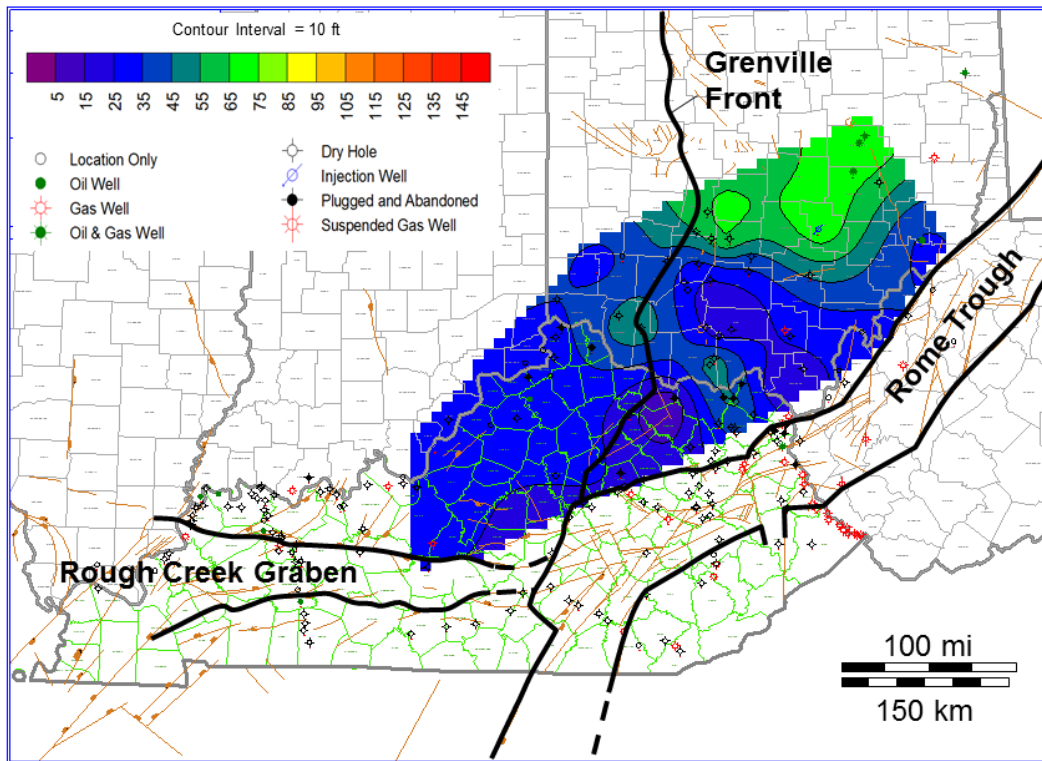
Figure 3.20. Unit 7 isopach. Unit 7 was not correlated into the Rome Trough.
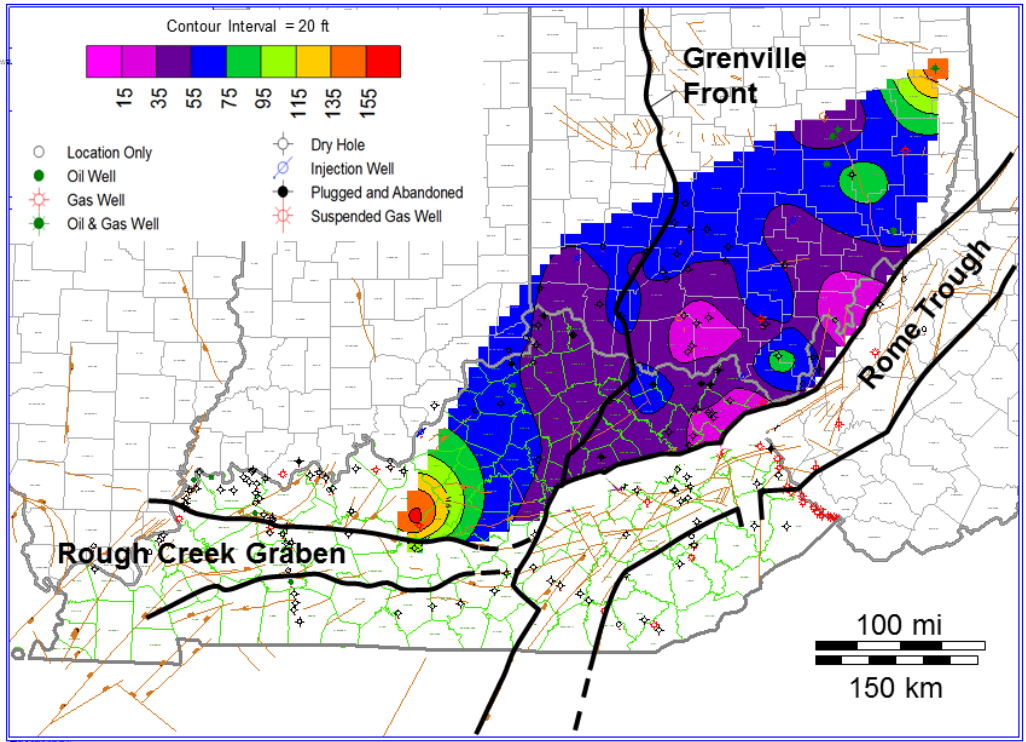
Figure 3.21. Unit 6 isopach. Unit 6 was not correlated into the Rome Trough.
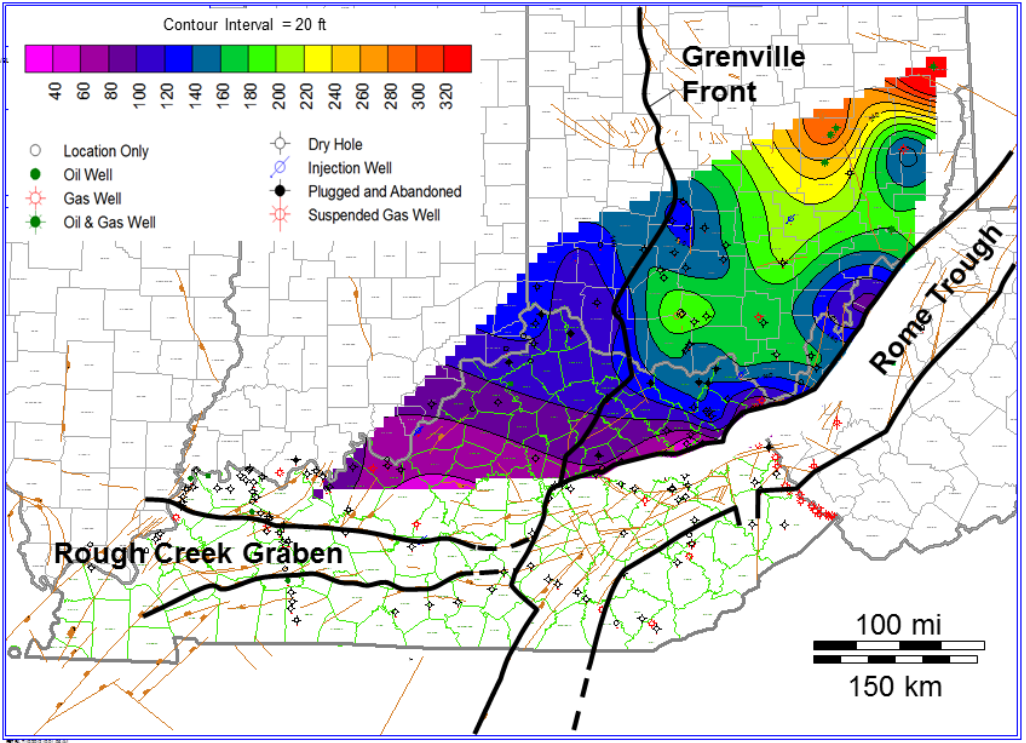
Figure 3.22. Unit 5 isopach. Unit 5 extends and likely thickens into the Rome Trough but was not correlated into the trough.
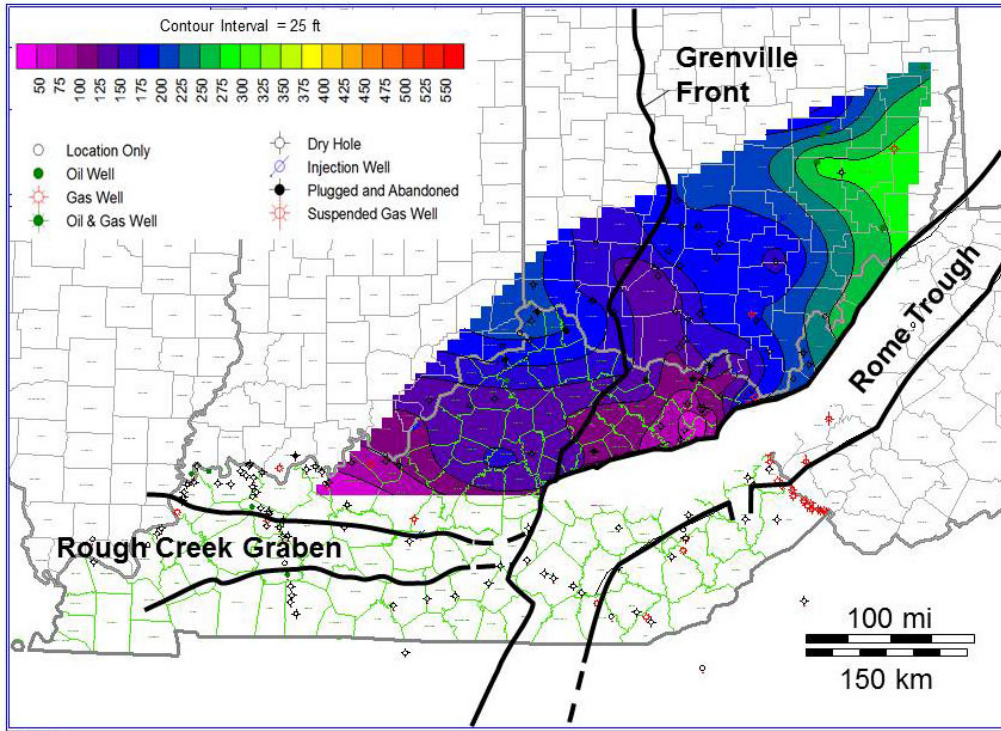
Figure 3.23. Unit 4 isopach. Unit 4 extends and likely thickens into the Rome Trough but was not correlated into the trough.
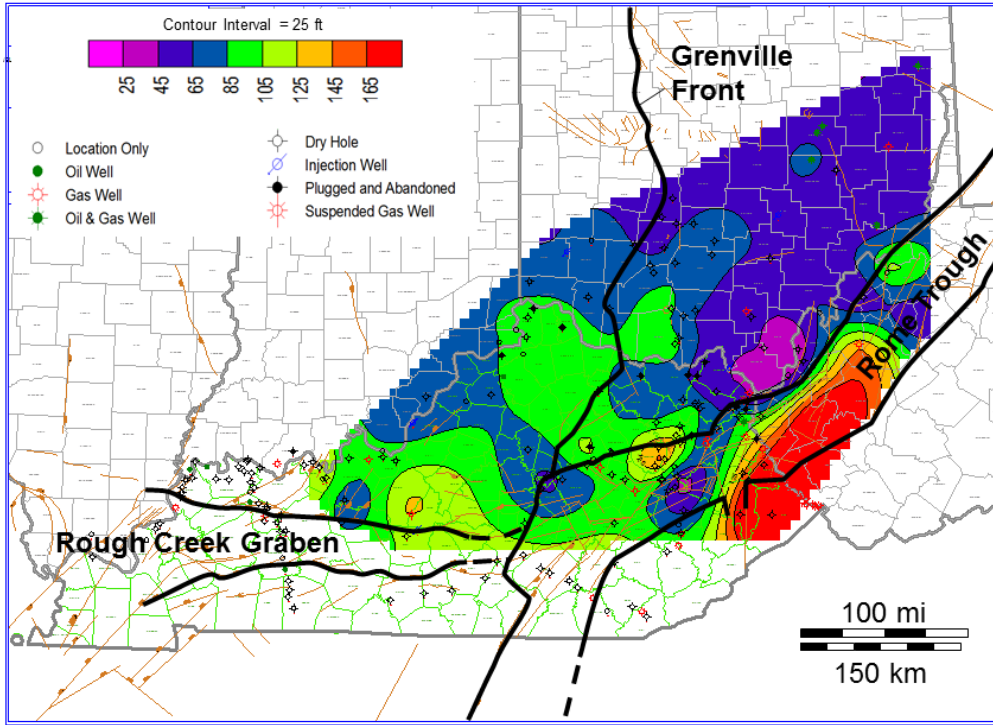
Figure 3.24. Unit 3 isopach. Unit 3 was correlated into the Rome Trough.
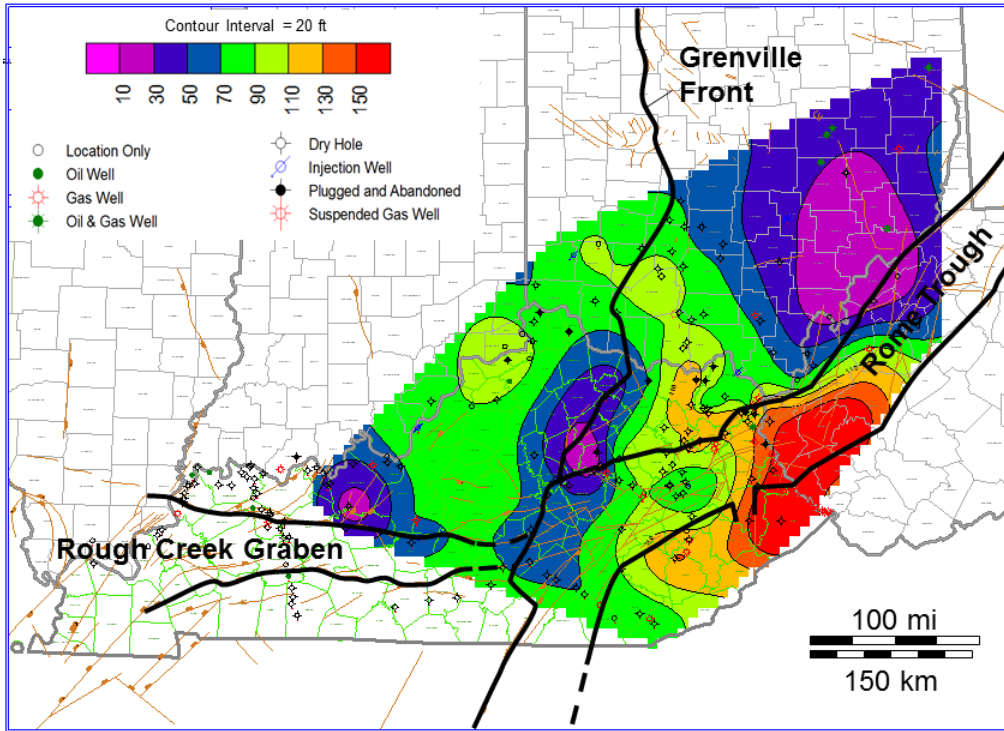
Figure 3.25. Unit 2 isopach. Unit 2 was correlated into the Rome Trough.
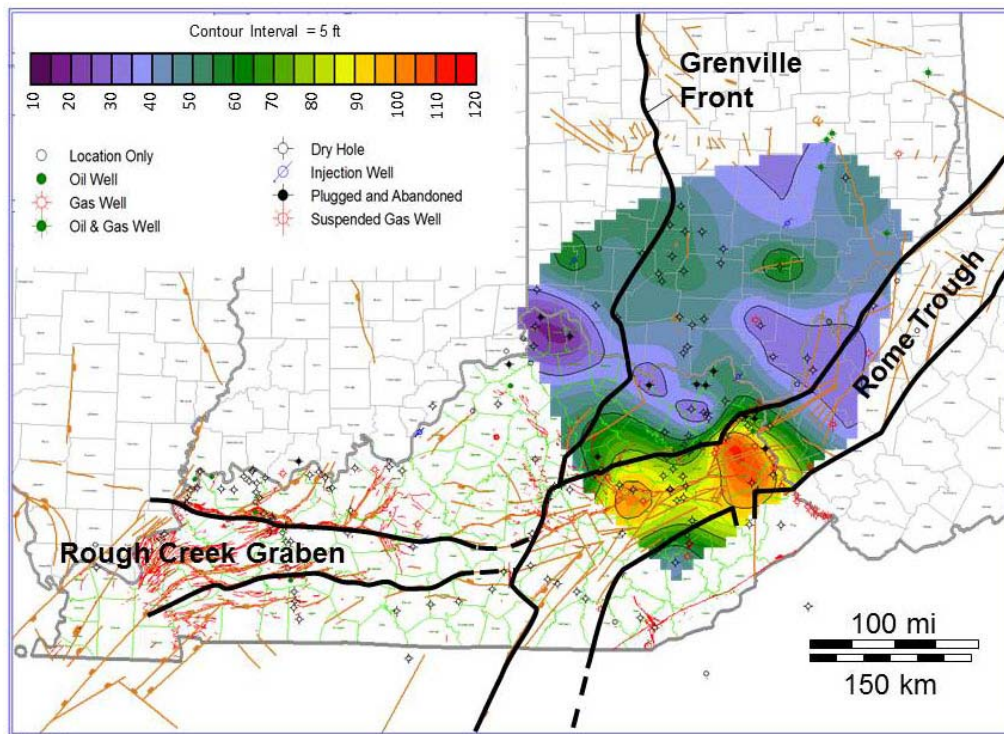
Figure 3.26. Unit 1 isopach. Unit 1 was correlated into the Rome Trough. Unit 1 pinches out or is truncated beneath the Knox Group to the west.

Core Descriptions

Core were examined from four wells to better understand the geology of the Eau Claire/Conasauga interval and for comparison with down-hole geophysical log signatures (Fig. 3.28). These were the Battelle No. 1 Duke Energy well, in Boone County, Kentucky; the DuPont No. 1 WAD fee well in Jefferson County, Kentucky; the ODNR DGS 2627 American Aggregates well, in Warren County, Ohio; and the USS Chemical/U.S. Steel 1 well, in Scioto County, Ohio. Ohio cores were examined at the Ohio Geological Survey's core facility in Columbus, Ohio. The Kentucky cores were examined at the Kentucky Geological Survey's core repository in Lexington, Kentucky.
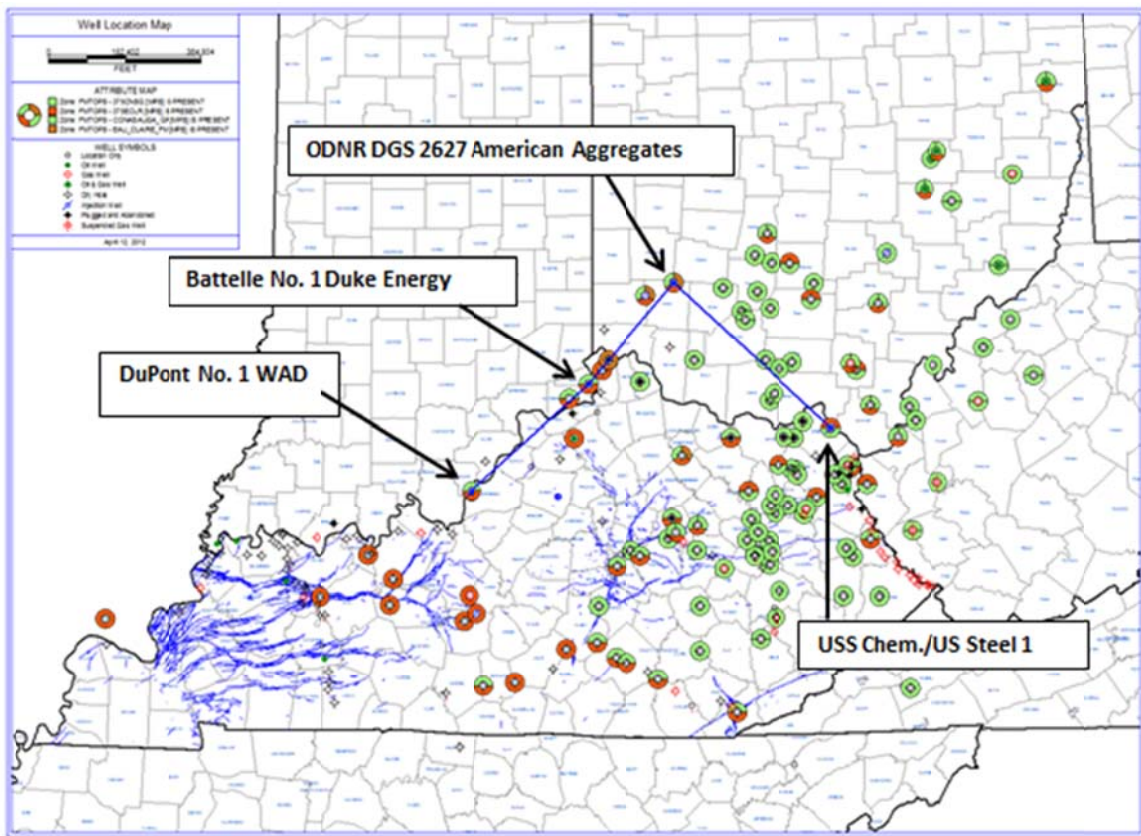
Figure 3.27. Location of cores examined for the study.
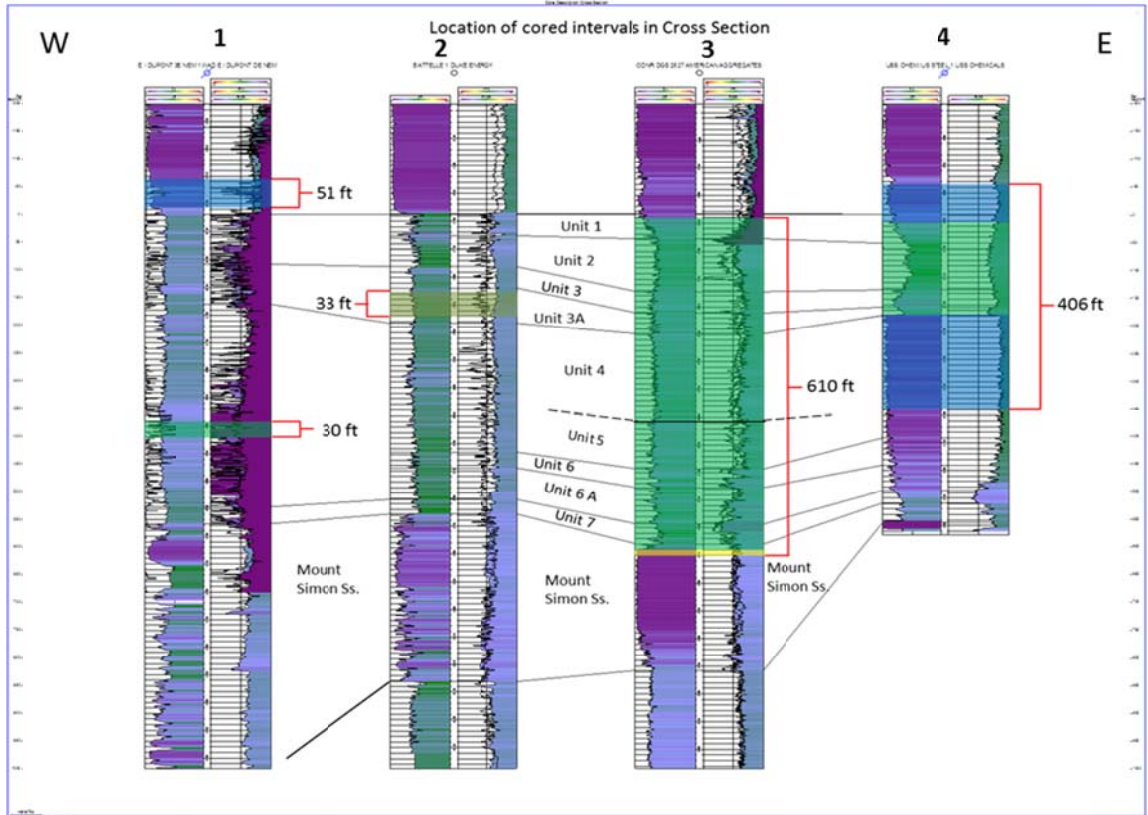
Figure 3.28. Cross section showing depths of available core (shaded and red brackets) within each well relative to unit subdivisions in this report. Wells are positioned from west to east. Wells from left to right are (1) DuPont No. 1 WAD fee well , (2) Battelle No. 1 Duke Energy well, (3)ODNR DGS 2627 American Aggregates well, and (4) U.S. Chem/U.S. Steel No. 1 well. Well locations are shown in Figure 3.28.

DuPont Well Core Descriptions

Two cored intervals from the DuPont No. 1 WAD fee well were studied. The first is at the base of the Knox Group, above Unit 1, in a unit labeled as the Davis Limestone (of Indiana)*.* The cored interval is approximately 50 ft thick; from 4408.4 ft to 4459.6 ft depth. The second cored section is in in the lower part of the Eau Claire Formation, which is in Unit 4 of this report. The core is approximately 30 ft thick; from 4842 ft to 4871.71 ft. Both cores were in poor condition, which provided additional challenges for study and observation.

Unit 4-Eau Claire Formation

The core of Unit 4 consists of silty shale, siltstone, shale, interbedded siltstone and shale, and siltstone with shale (Fig. 3.29). Siltstones are light to medium grey with varying shale content. Siltstones are generally massive to finely laminated (Fig. 3.30), and often calcareous ("C" in Fig. 3.30); reacting to a 10% hydrochloric acid solution. Some of the siltstones exhibit small, vertical burrows. Silty shales are light to dark grey, often thinly bedded. Shales are medium grey, very fissile, very brittle, and burrowed (Fig. 3.31). The core have deteriorated significantly and little bedding information could be obtained. Horizontal burrows, small brachiopod shells and trilobite fragments were noted on the faces of some shale fragments.

Thin sections were made of representative lithologies from the Eau Claire shale in Unit 1. Silty shales and shales include laminated to slightly undulatory shale fabrics with muscovite, biotite, and silt-size quartz grains in a fine clay matrix, presumably consisting of feldspars and quartz (Fig. 3.32). Biotite grains are crudely oriented with the undulatory fabric. Calcareous shaly siltstones contain abundant silt-sized quartz grains in a clay-shale matrix, with minor biotite and glauconite grains (Fig. 3.33). Bioturbated siltstones contain abundant glauconite grains (Fig. 3.34).

"Davis Limestone"

A limestone capping Eau Claire shales and siltstones in the DuPont well was examined. This limestone is equivalent to the Davis Limestone of Indiana. The Davis is a formal unit in the base of the Knox Supergroup in Indiana. It is not a formal term in Kentucky. The core is examined here as an example of the basal Knox above the Eau Claire/Conasauga interval and for comparison with similar types of carbonates in the Maynardsville Limestone in the ODNR DGS 2627 and USS Chem/US Steel No. 1 cores (Fig. 3.28).
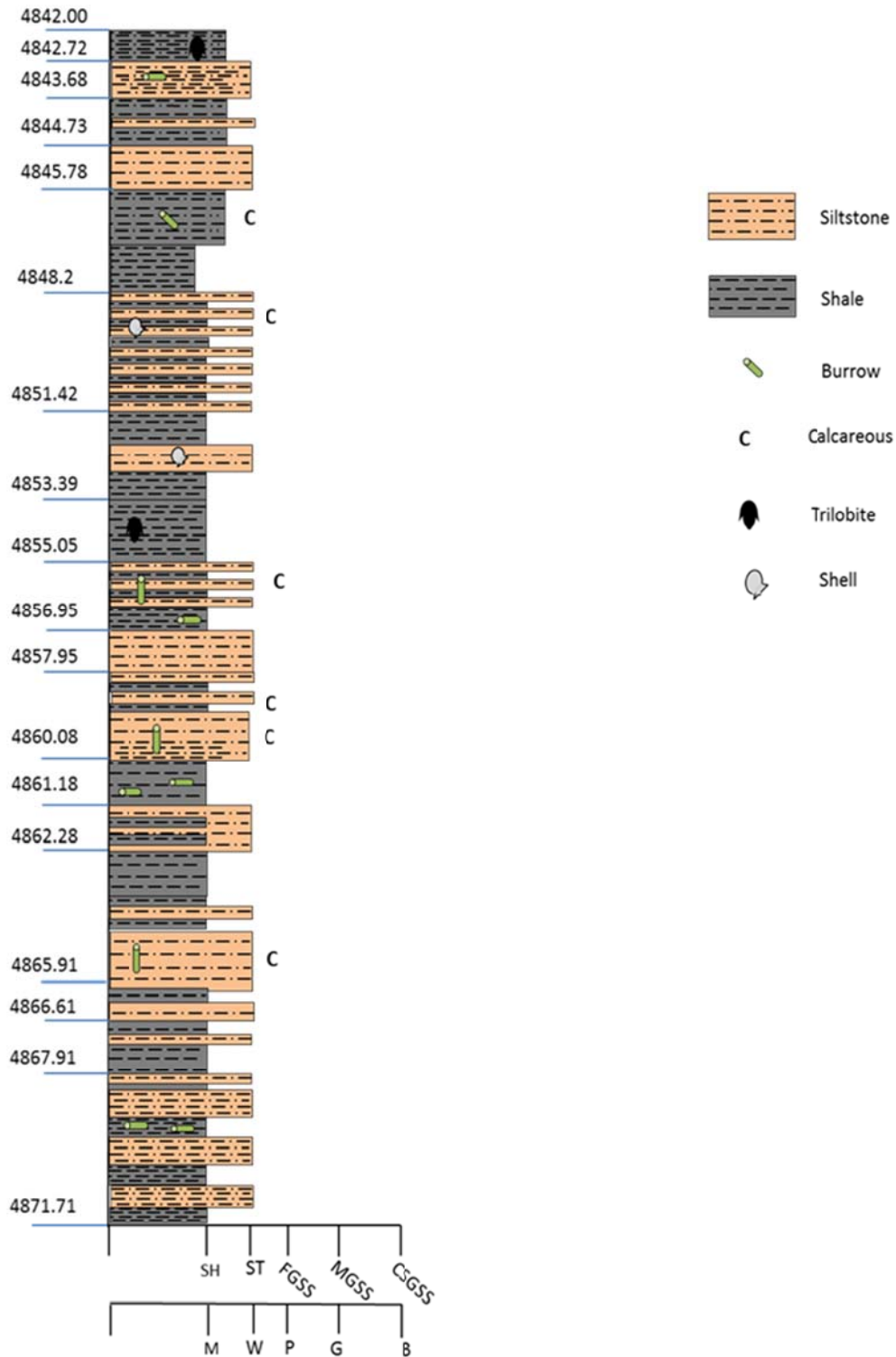
Figure 3.29. Measured section of cored interval of Eau Claire within the DuPont well. Depth in feet. SH=shale, ST=siltstone, FGSS=fine-grained sandstone, MGSS=medium-grained sandstone, CSGSS=coarse-grained sandstone, M=mudstone, W=wackestone, P=packstone, G=grainstone, B=boundstone.

Figure 3.30. Laminated siltstone in Unit 4 in the DuPont No. 1 WAD fee well. Core width is four inches.

Figure 3.31. Typical brittle, broken shale in Unit 4 in the DuPont No. 1 WAD fee well. Core width is four inches.
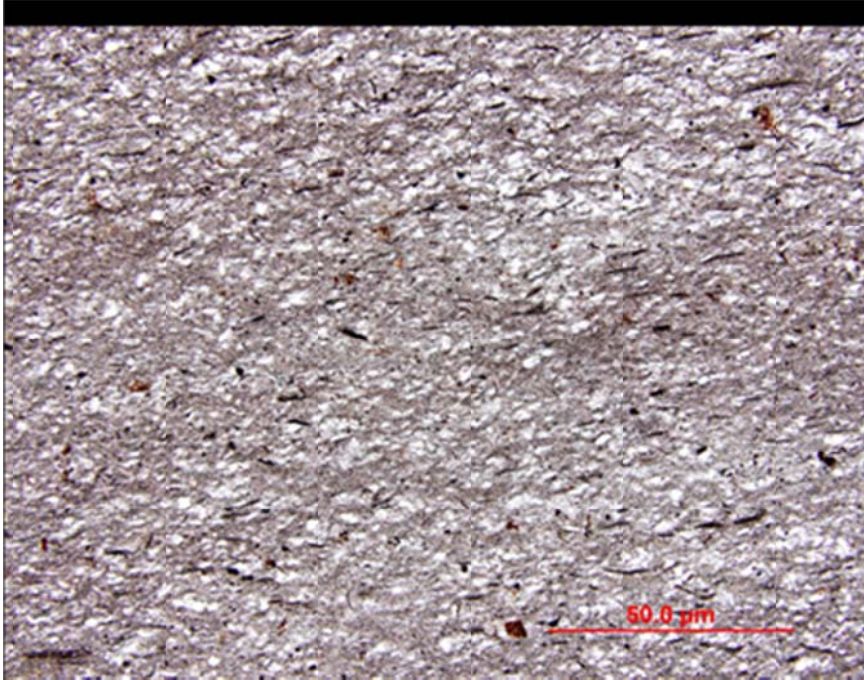
Figure 3.32. Photomicrograph of silty shale from 4854 ft deep in Unit 1. Note crude lamination, but slightly undulatory fabric. Biotite grains are brown to brown black. 100x magnification without cross polars.
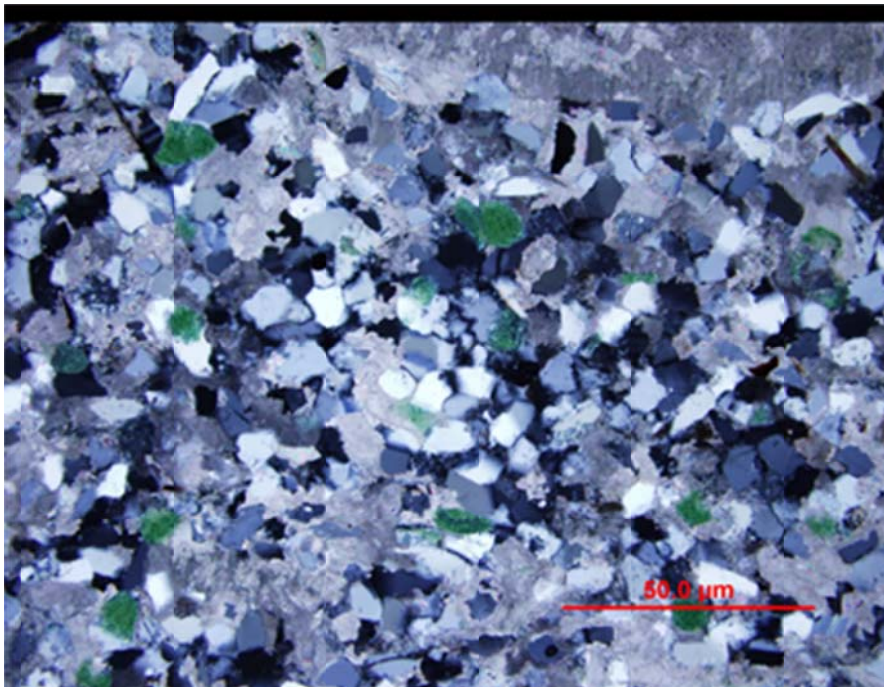
Figure 3.33. Photomicrograph of calcareous, slightly shaly siltstone from 4855 ft deep in Unit 1. Glauconite granules (green) are present. 100x magnification with cross polars.

DUP-4859-2

200 µm

Figure 3.34. Photomicrograph of bioturbated siltstone from 4859 ft deep in Unit 1. Note abundant glauconite grains. 20x magnification with cross polars.

The Davis core in the DuPont well consists of oolitic grainstones, wackestones, and boundstones. Oolitic grainstones are abundant in the upper part of the core and thrombolites are prominent in the lower part of the core (Fig. 3.35).

Thrombolite boundstones are light to medium grey, and display the unlaminated, clotted texture typical of thrombolites (Fig. 3.36A). Sparse, thin styolites were found throughout the dolomite and limestone (Fig. 3.36B). Some of the clotted textures are irregular to relatively horizontal, others show significant up-building (Fig. 3.36C). A thrombolite in part of the core had a sharp vertical contact.

Oolitic grainstones are light grey, with sparse, thin styolites, and sparse cryptalgal clasts. Grainstones are laminated to thin bedded (Fig. 3.36D). Some ooids were dissolved, leaving variable porosity. In the middle part of the core, ooid wackestones are thin and overly scour
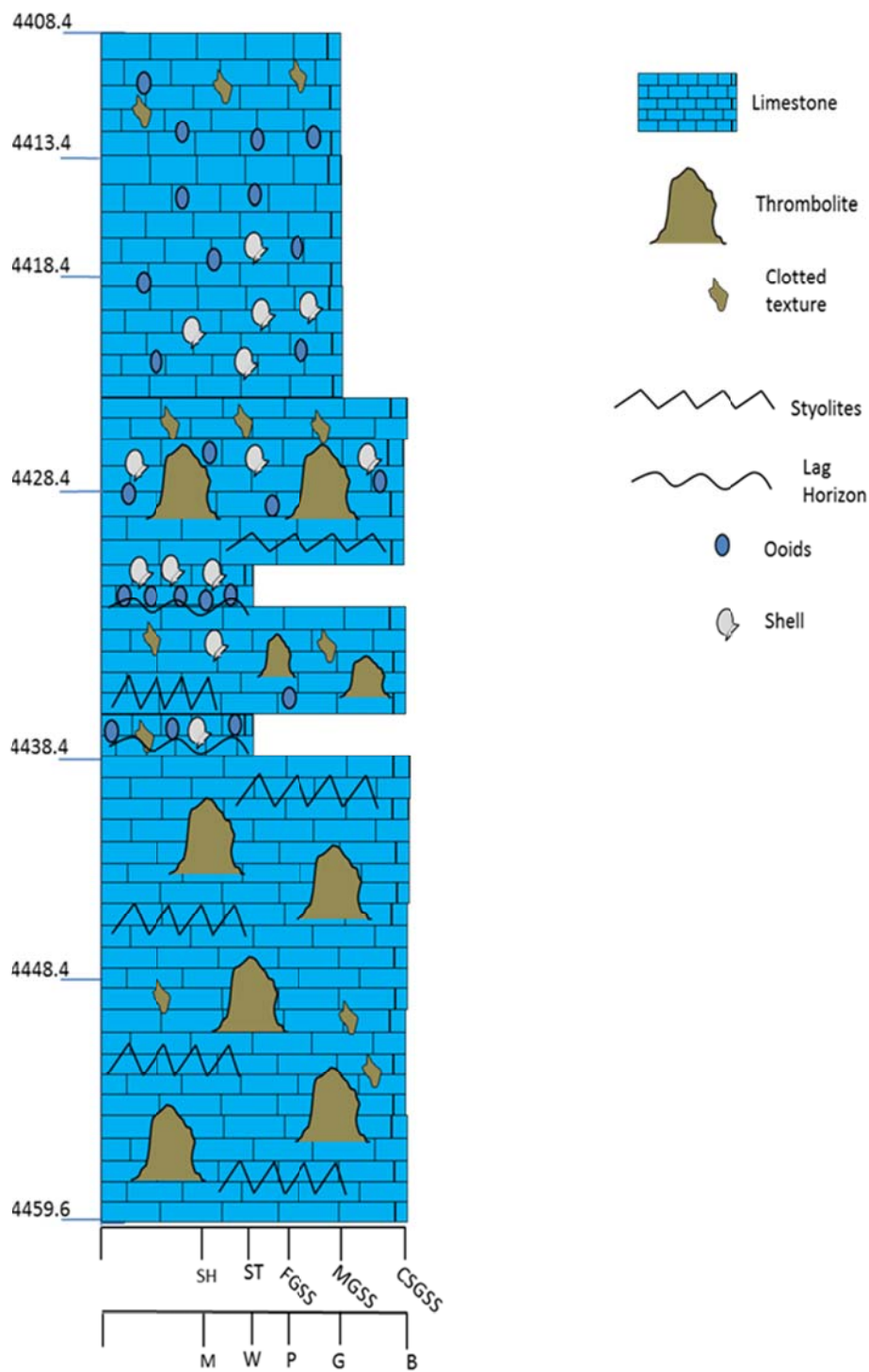
Figure 3.35. Measured section of cored interval of the Davis Limestone in the DuPont No. 1 WAD fee well. Depth in feet. SH=shale, ST=siltstone, FGSS=fine-grained sandstone, MGSS=medium-grained sandstone, CSGSS=coarse-grained sandstone, M=mudstone, W=wackestone, P=packstone, G=grainstone, B=boundstone.
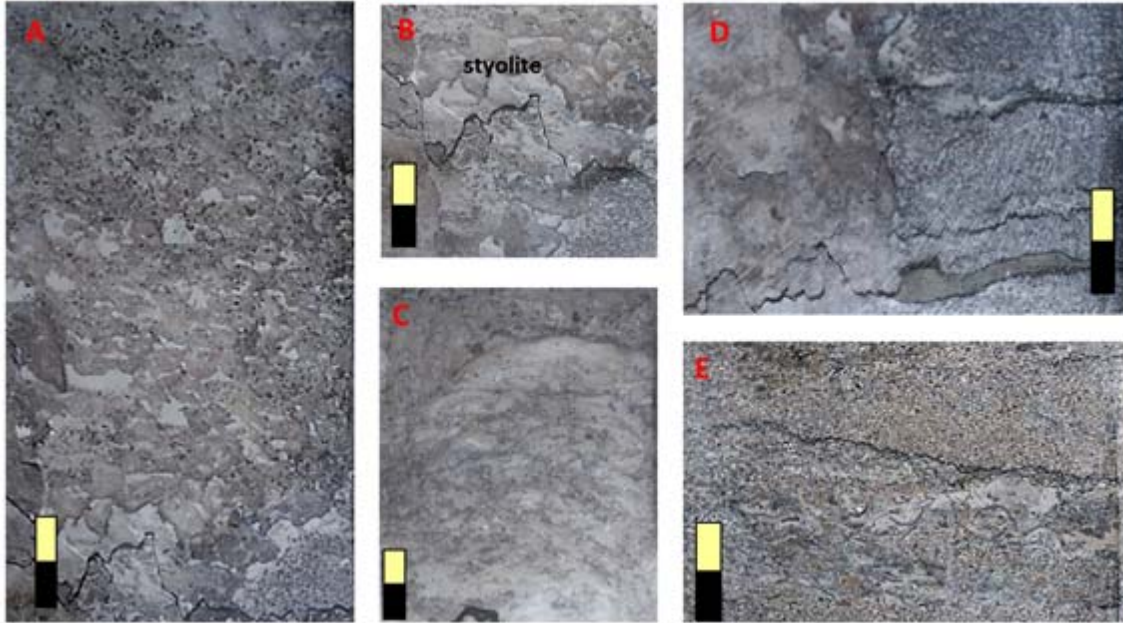
Figure 3.36. Typical features of the "Davis" carbonate in the DuPont well. (A-D) Thrombolites with clotted texture. (B) Styolite in thrombolite. (C) Up-building or mounded texture. (D) Sharp, vertical contact between thrombolite and laminated ooid grainstone. (E) Sharp-based shell debris lags with oolites. Scale bars = 2 cm.

surfaces composed of shell debris grainstones (Fig. 3.36E). Wackestones are light to medium grey in color, with abundant fossil shell and thrombolitic fragments. Sparse, light brown cherty bands are present.

In thin sections, ooids are dispersed in coarsely crystalline, intergranular calcareous cement (Fig. 3.37). Ooids exhibit a radial fabric, however, concentric laminations are still visible in their outer parts. Many of the small- and medium-sized ooids are replaced by ferrous carbonates (blue staining in Fig. 3.37) and dolomite. Small dolomite rhombs can be seen in some of the replacement fillings. Intergranular voids occur in some of the replaced ooids. Minor voids also occur in intergranular cement.
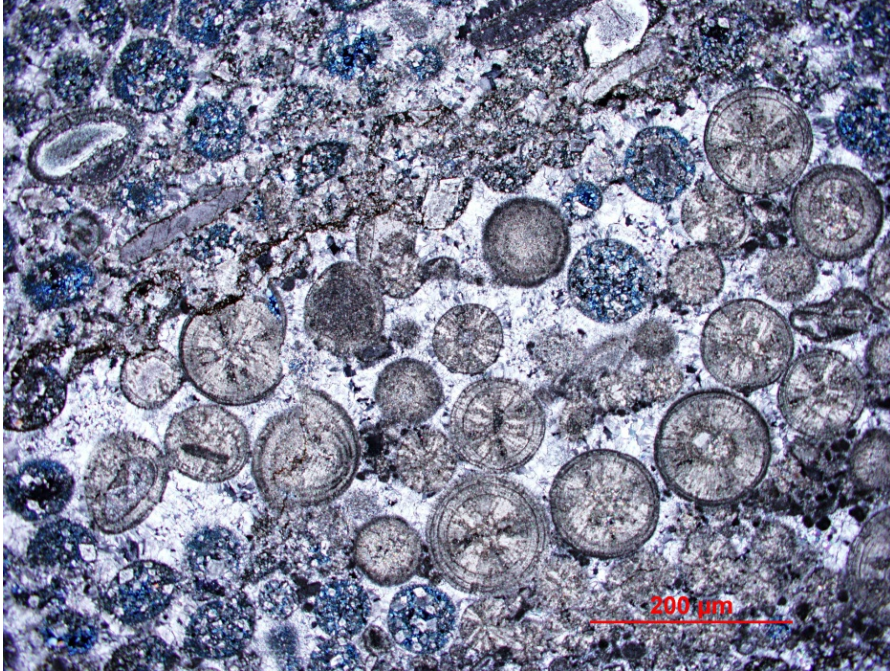
Figure 3.37. Photomicrograph of ooid grainstone in the Davis Limestone from 4412 ft deep. Ferroan carbonates are stained blue. Note replacement of some ooids by ferroan carbonates and dolomite. 20 X magnification with cross polars.
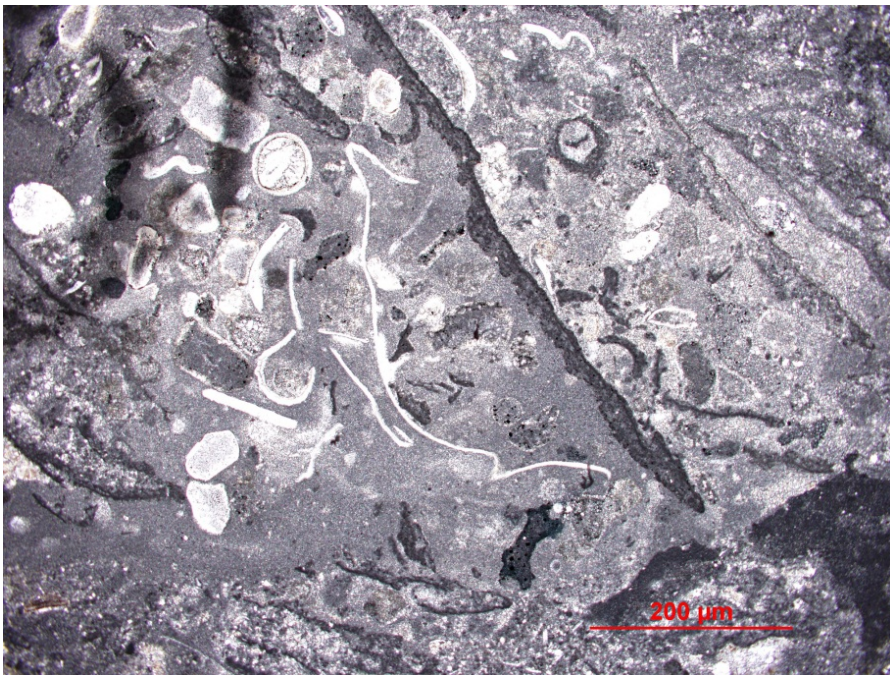
Figure 3.38. Photomicrograph of thrombolite boundstone in the Davis Limestone from 4437 ft deep. Note patchy distribution of fine carbonates and large trilobite fragment. The long, tubular structure in the lower right is possibly a burrow. 20 X magnification with cross polars.
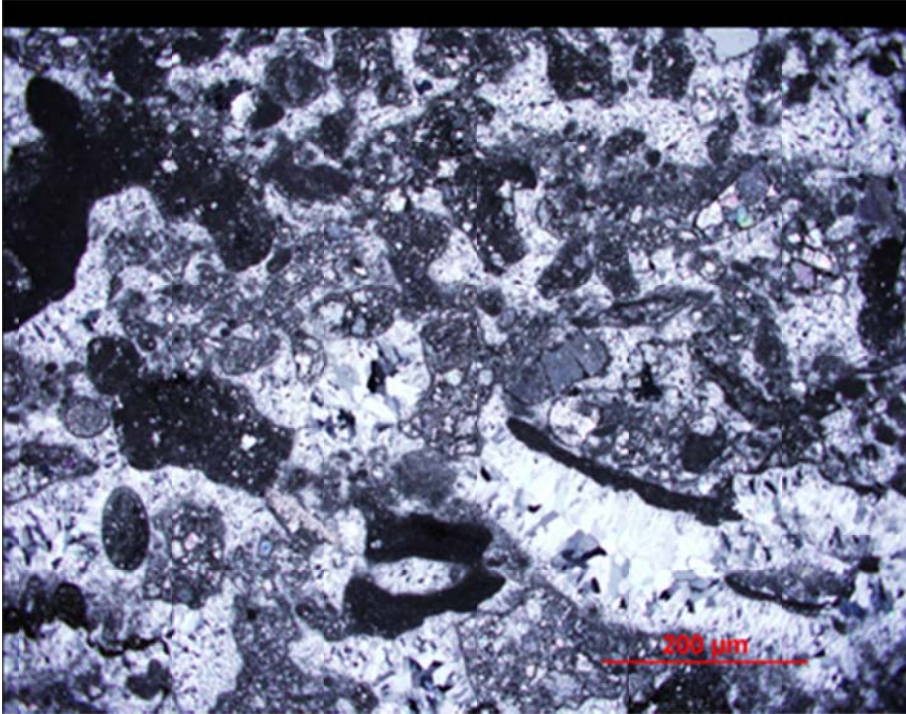
Figure 3.39. Photomicrograph of thrombolite boundstone in the Davis Limestone from 4447 ft deep. Note patchy distribution of fine dolomitized carbonates, some of which are elongate and slightly sinuous, as could occur in burrows. 20 X magnification with cross polars.

Microscopic analyses of thrombolitic boundstones show they consist of very fine, patchy, dolomitized crypt-algal clay-sized and silt-sized material with minor ooids and fossil fragments, including brachiopods, trilobites (Fig. 3.38), and possible echinoderms(?). Burrowing may be responsible for some of the patchy, clotted appearance as several patches are elongate to slightly sinuous (Figs. 3.38, 3.39). Some patches are filled with fine to silt in a clayey matix or calcareous cement. Others are filled by crystalline calcite cement, and others by dolomite cement. Ooid grains in the thrombolites are commonly replaced by dolomite cement.

Battelle-East Bend Well Core Descriptions

Thirty-two feet of the Eau Claire was cored in the Battelle No. 1 Duke Energy (East Bend) well, from depths of approximately 2825 ft to 2857 ft (Fig. 3.40). This interval is all within Unit 3 of this investigation, and is composed largely of silty shale and siltstones (Fig. 3.41 A-D).

 Shales are medium to light gray and are lighter colored where interbedded with siltstone. Shaly intervals tend to be fissile (Fig. 3.41A). Intervals with interbedded or interlaminated siltstones are less fissile. Thin siltstone interbeds are light grey and horizontal to wavy (Fig. 3.41B).

Small burrows are often filled with silt-sized material and may appear contorted from compaction (arrows in Fig. 3.41B). Sparse, low-angle to vertical slickensides occur throughout the shale. Fossils are uncommon in the shale, but include trilobite fragments (Fig. 3.41A) and whole "lingulid" brachiopods (Fig. 3.41B).

Siltstones are light grey and fine grained, finely laminated, massive, and structure-less (Figs. 3.41 C-D). Some contain contorted lamination or soft-sediment deformation. Many are slightly calcareous, and react moderately to a 10% hydrochloric acid solution. Siltstones are slightly micaceous, and exhibit small, sparse shell and trilobite fragments, and sparse vertical and horizontal burrows.   A few fractures in siltstones were filled with calcite, and have been compressed, deforming the original fracture plane. Individual siltstone beds can be as much as one ft thick. Bedding contacts at the base of the siltstones are mostly sharp, but some show gradational transitions from shale to silty shale. Sharp contacts sometimes exhibit load structures or soft-sediment deformation (Fig. 3.41D).

| | | SH | ST | FGSS | MGSS | CSGSS |
| | | M | W | P | G | B |

Legend:

Siltstone

Shale

Missing core

Core wrapped in aluminum foil by previous workers.

Burrow

C — Calcareous

Trilobite / trilobite fragments

Shell / shell fragments

Vertical Fracture

Filled Fracture

Depth markers: 2825.03, 2827.46, 2829.55, 2830.85, 2832.54, 2833.46, 2834.42, 2835.74, 2837.26, 2838.18, 2839.83, 2841.27, 2842.90, 2844.05, 2844.99, 2845.82, 2846.75, 2847.79, 2848.54, 2849.70, 2850.85, 2852.49, 2853.44, 2856.12, 2857.61

e

Figure 3.41. Typical features of the Eau Claire Formation in the DuPont No. 1 well core. (A) laminated shale, and (B-D) interlaminated and interbedded siltstone and shale in the Battelle No. 1 Duke Energy core. Bedding may be flat to undulatory. (B) Tiny burrows occur beneath siltstones (arrows). In (C) shale, siltstone, and a thin bioclastic and calcareous siltstone or silty carbonate are in sharp contact. Siltstones can have sharp bases (B, D), but often have undulatory contacts or are deformed (D). Scale in cm.
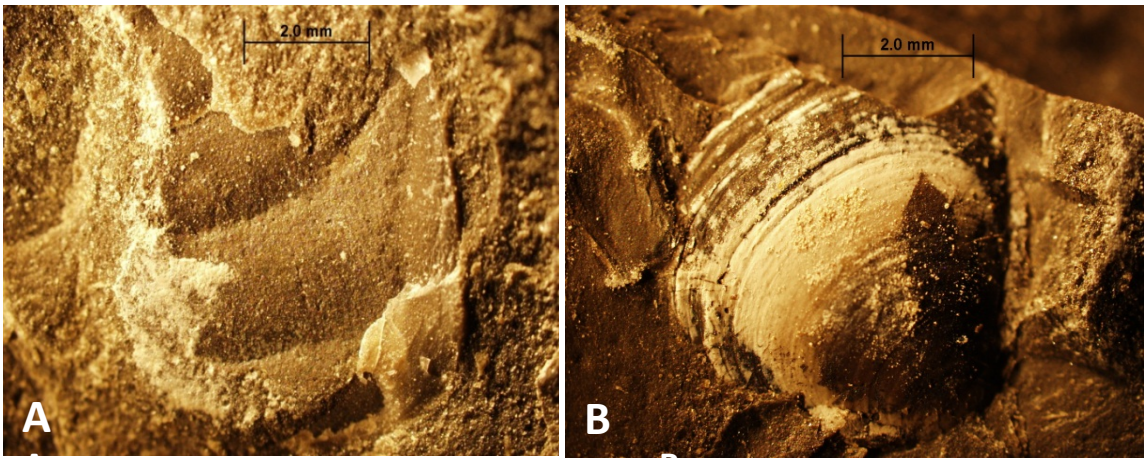
Figure 3.42. Marine fossils in the DuPont No. 1 well core. (A) Trilobite fragment in shale matrix at 2827.7 feet deep. (B) Fossil "lingulid" brachiopod shell in shale matrix at 2825.8 feet deep.

In Figure 3.41D, a siltstone is sharply and vertically juxtaposed against a shale, and thin bioclastic siltstone or grainstone with tiny shell fragments. The contact of the siltstone with the surrounding lithologies is contorted.

Thin sections were made from representative lithologies in Unit 3. Silty shales have laminated to slightly irregular fabric, which may indicate burrowing (Fig. 3.43). Shales contain minor biotite and muscovite, rare small carbonate clasts (?), and fine calcareous cements. Thinly interbedded shaly siltstone and shale contain abundant silt-sized quartz grains with calcareous cement, small shell (brachiopod) fragments and sparse glauconite (green) fragments (Fig. 3. 44). Clay-sized material occurs along stylolites (Fig. 3.44). Slightly calcareous, silty shales have a clay-shale matrix with small, silt-sized quartz grains, dispersed elongate opaque (black) grains (which may be biotite, pyrite or organic matter) and brachiopod shell fragments (Fig. 3.45).

ODNR DGS 2627 American Aggregates Well

The ODNR DGS 2627 American Aggregates well is located in Warren County, Ohio (Fig. 3.46). The entire study interval (610 ft) was cored in this well (Fig. 3.46). The core is significantly longer than the previous cores, and contains a more diverse suite of lithologies. Units 1 and 2 of this study are dominated by dolomite and limestone. Silty shales also occur Unit 2. Part of the shaly interval in Unit 2 (Fig. 3.28) was not recovered. Siltstone and shales in the middle part of the interval are part of Unit 3. Unit 4 includes a sandstone and similar lithologies as Unit 3. Unit 5 includes the lower part of the interbedded siltstones and shales. Units 6 and 7 are sandstone in this well. The lower sandstone is gradational with the underlying Mount Simon Sandstone. Each of the units is summarized in the following pages.

Figure 3.43. Photomicrograph of silty shale from 2839 ft deep from Unit 1. Biotites are dark brown. Note vertically aligned biotites and finer matrix in center of the photomicrograph, which may represent a burrow. 100x magnification with cross polars.
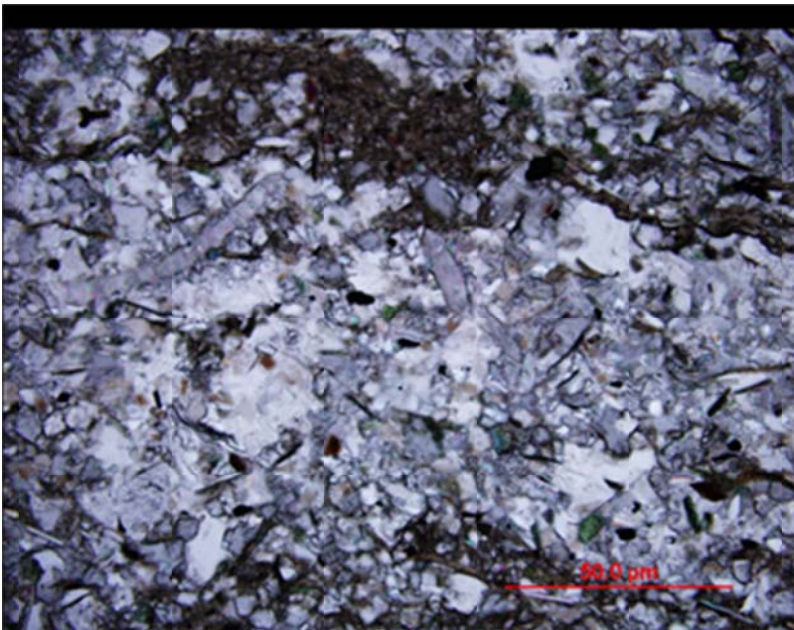
Figure 3.44. Photomicrograph of thinly interbedded shaly siltstone and shale from 2837 ft deep in Unit 1. Note shell fragments (elongate with vertical ribbing) sparse glauconite (green) fragments, and dark brown to black clay-sized material along stylolite at top middle of view. 100X magnification with cross polars.
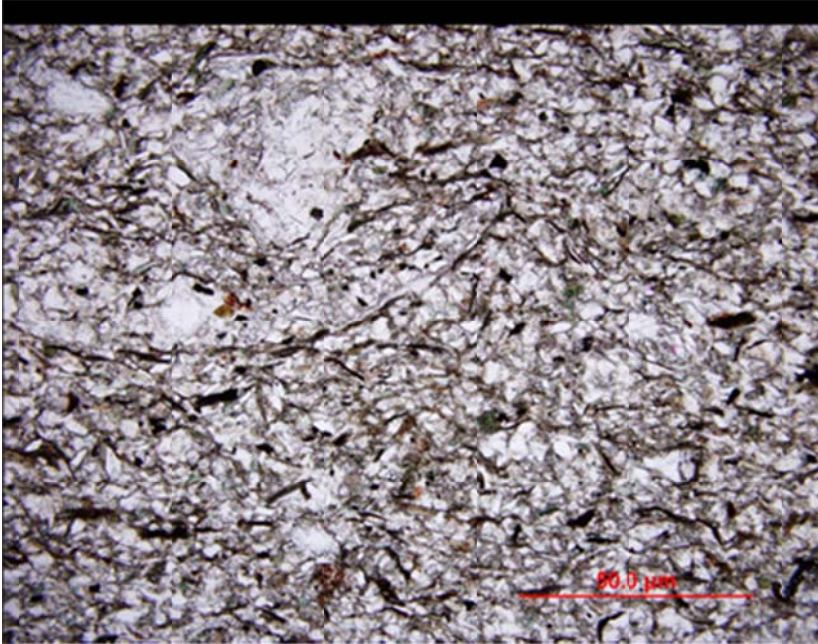
Figure 3.45. Photomicrograph of calcareous shaly siltstone from 2846 ft deep in Unit 1. Large shell fragment visible in left, upper middle of view. Brown to black elongate fragments are biotite. 100x magnification without cross polars.

Unit 1

Unit 1 in log correlations (Fig. 3.28) corresponds to depths of 2637.5 to 2679.0 ft in the core (Fig. 3.47); an interval of 41.5 ft thick. This is the Maynardsville Limestone interval. It consists of (a) interbedded carbonates and shale (Fig. 3.47), including coarse crystalline dolomite with silty shale bands, (b) dolomite with silty shale bands, (c) coarse crystalline dolomite, (d) dolomite with shale laminations, (e) nodular dolomite interbedded with shale, (f) sandy dolomite with shale laminations, (g) flat-pebble conglomerates, and (h) limestone interbedded with shale. Dolomites are variably silty, sandy, crystalline, and oolitic. Many dolomites are finely laminated Bedding is horizontal, wavy, and slightly convoluted. Sparse vertical burrowing is noted, along with silty, wispy, very thin shale laminations. Sparse, small fossil shell fragments and shale rip- up clasts occur above sharp contacts between carbonates and underlying shales.

75
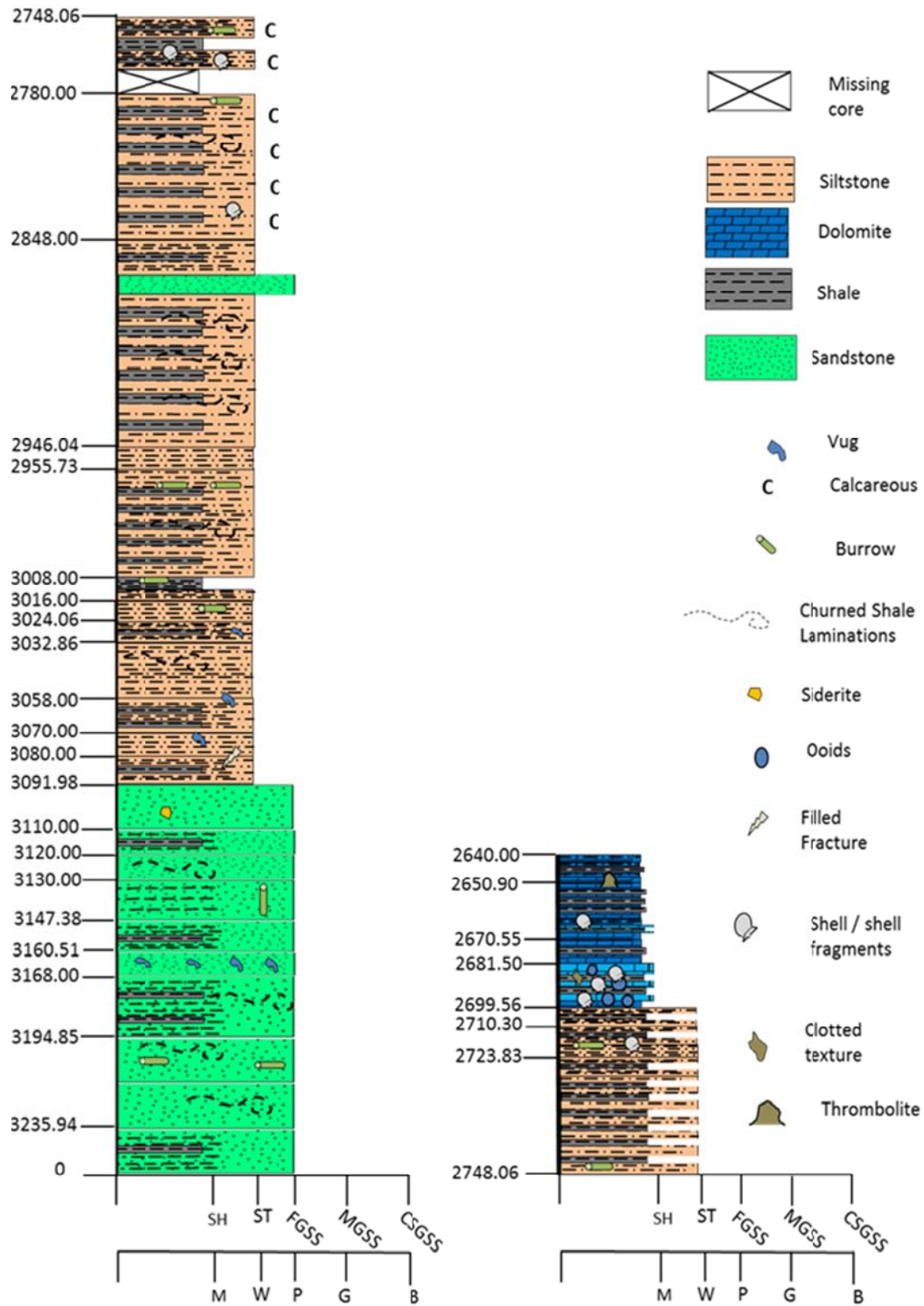
Figure 3.46. Measured section of cored interval of Conasauga Group in the Warren County well. Top of core in right-hand column. Depth in feet. SH=shale, ST=siltstone, FGSS=fine-grained sandstone, MGSS=medium-grained sandstone, CSGSS=coarse-grained sandstone, M=mudsstone, W=wackestone, P=packstone, G=grainstone, B=boundstone.

Figure 3.47. Unit 1 dolomites and interbedded shaly dolomites and shales in the Warren County well at depths of 2670 to 2680 ft deep. Top is upper left in photograph.

Some dolomites exhibited a clotted texture, signifying possible thrombolites (as in the Davis Limestone in the DuPont well), or possibly stromatolites.

Flat-pebble conglomerates occur at several horizons, from 2653.52-2654.47, 2657.82-2658.25, 2662.1-2662.45, 2667.75-2668.1, and 2679.22 to 2679.47 ft. Clasts in the conglomerates are grey to dark grey and composed of fine-grained limestone or laminated dolomite (Fig. 3.48-3.49). One of the conglomerates occurred with small black, fossil shell fragments. A flat-pebble conglomerate at 2668.5-2668.88 was mixed with oolitic limestone.

Figure 3.48. Sharp-based flat-pebble conglomerate above laminated dolomitic limestone, interbedded with laminated dolomitic limestone and shale at 2654 ft depth. Wet and dry core halves are shown. Ruler scale in cm.
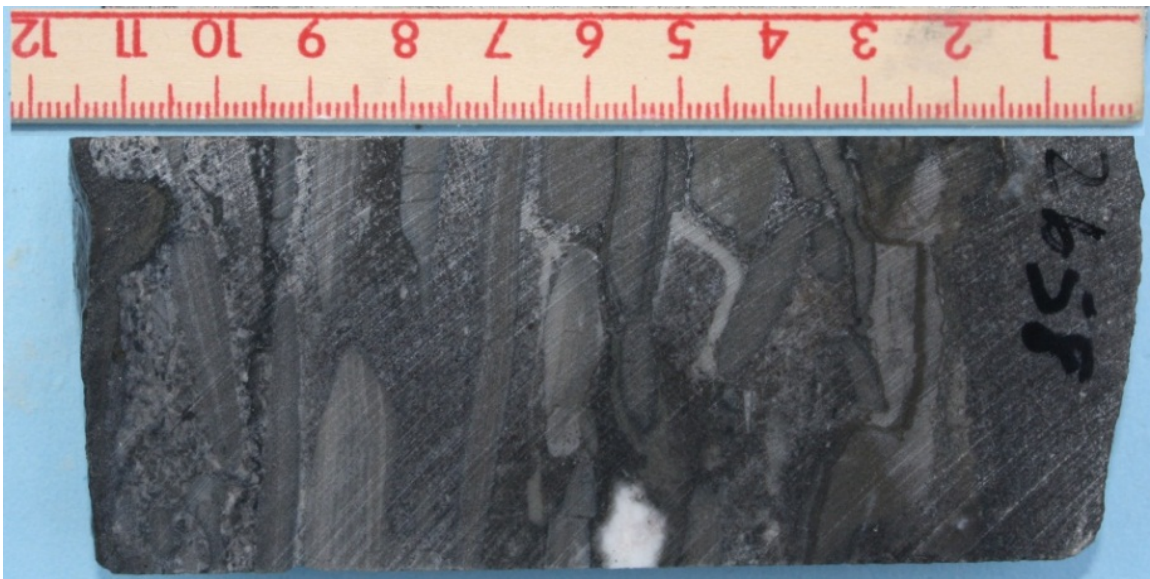
Figure 3.49. Sharp-based flat-pebble conglomerate at 2658 ft depth. Core is wet to show contrast. Note laminated dolomite clasts and white calcareous cement infilling voids between pebbles. Ruler scale in cm.

<u>*Unit 2*</u>

Unit 2 is approximately 92 feet thick in log correlations (Fig. 3.28), corresponding to the interval from 2679 ft to 2771 ft in the core (Fig. 3.46). Unit 2 consists primarily of limestone interbedded with shale (Fig. 3.50), siltstone interbedded with shale (Fig. 3.51), and calcareous siltstone with shale laminations. Unit 2 is partly equivalent to the Nolichucky Formation. Some of the more shale rich parts of the Nolichucky may be part of the missing section in this core. Unit 2 here contains a limestone- rich interval that is transitional with the overlying dolomitic carbonates in Unit 1. Some workers might pick the top of the Nolichucky Formation at the base of the limestone.

Limestones in the upper part of Unit 2 are typically dark grey to light grey in color, and were variably oolitic, with high concentrations of black ooids exhibited in clusters, especially at the top of the unit. Some black oolitic limestones were associated with flat-pebble conglomerates (Fig. 3.50). Abundant fossil shell fragments were noted above sharp bedding contacts (likely lags). Bedding was often churned.   Interbedded shales are grey, variably silty, and often very fissile (Fig. 3.51).

One thin dolomitic zone, about 1.5 feet thick, was interbedded with the limestones in Unit 2. Dolomite was light grey to grey in color, with sparse, very thin shale laminations. A zone of oolitic limestone was sandwiched between the two dolomitic beds. One thin, brown, iron rich band was noted at the top of the second dolomitic zone.

In the lower part of Unit 2, siltstones interbedded with shale were light to dark grey, to light tan in color (Fig. 3.51). Siltstones were slightly calcareous, and some horizontal burrowing was observed. Shales within the siltstones were often grey, thinly bedded, fissile, and variably
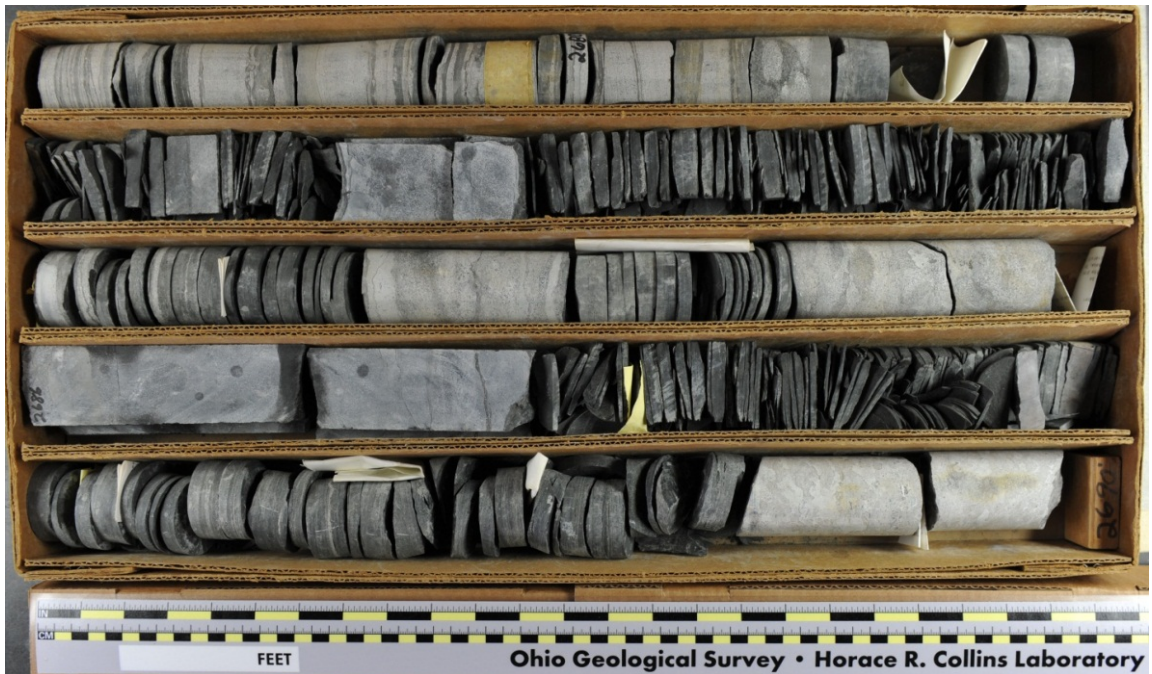
Figure 3.50. Interbedded limestone and shale core at the top of Unit 2 in the Warren County well at depths of 2680 to 2690 ft. Top is upper left in photograph. Core shown wet for bedding contrast.

Figure 3.51. Example of interbedded shale (dark) and siltstone (light) from lower in Unit 2, at depths of 2740 to 2750 ft. Top is upper left in photograph. Core shown wet to enhance bedding contrast.
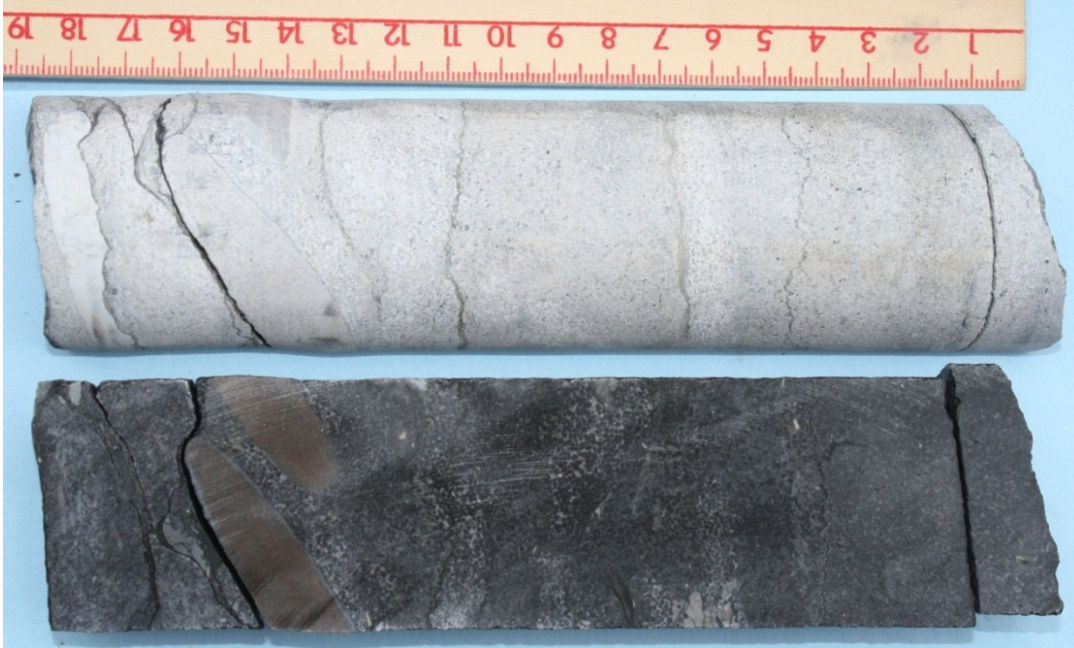
Figure 3.52. Flat pebble conglomerates (orange) in a matrix of black oolitic limestone at depth of 2695 ft. Top is to the right. Scale in cm.

silty. Sparse fossil shell fragments were noted, as were small silty pebbles in a shaly matrix above some sharp bedding contacts (Fig. 3.51).

Unit 3

Unit 3 was approximately 80 ft thick in log correlations (Fig. 3.28), which corresponds to depths of 2771 ft to 2851 ft in the core (Fig. 3.46). The uppermost part of the unit is missing in the core. Unit 3 consists entirely of calcareous siltstone with shale laminations. Siltstones were medium grey, to grey, to light tan, to brown in color, and slightly calcareous. Siltstones were interbedded with abundant, thin, medium to dark grey shales. Most contacts are sharp. Siltstones are horizontally bedded, wavy to undulatory, or contorted (Fig. 3.53). Sparse thin zones of silty, flat-pebble conglomerates in a silty, muddy matrix were common throughout the unit. One of these, at a depth of 2783 ft, consisted of pebbles more than 6 cm in length (Fig. 3.54).

Figure 3.53. Example of interbedded sitlstones and shales in Unit 3 in the Warren County well from 2800 to 2810 ft. Top is upper left in photograph. Core shown wet to enhance bedding.

Figure 3.54. Flat-pebble conglomerate comprised of large clasts, with red to pink iron (?) staining at 2783 ft. Top is to the left. Ruler scale in cm.

Shales and silty shales are common in Unit 3. Shalier intervals are fissile. Many shales, especially

near the bottom of the unit, were contorted or exhibited churned bedding.

Unit 4

Unit 4 was approximately 150 feet thick in log correlations (Fig. 3.28), which

corresponds to depths of 2851 ft to 3001 ft in the core (Fig. 3.46). The top of a sandstone bed

(Fig. 3.55) at 2860 ft might correspond better to the top of the coarsening-upward signature picked for the top of Unit 4 in the logs for this well (Fig. 3.28). Similarly, the shale break at 3008 ft depth (Fig. 3.46) corresponds better to the geophysical log break used to pick the base of Unit 4 on logs (Fig. 3.28).

Unit 4 consists of siltstones with shale laminations, siltstones, and the sandstone at the top of the unit. The sandstone from 2861 to 2870 ft is a fine- to medium-grained, quartzose, and laminated to irregularly bedded. The rest of the unit is dominated by interbedded siltstone and shale (Fig. 3.55), similar to, but overall siltier than in Unit 3. Siltstones exhibit laminations, horizontal bedding, and undulatory bedding. Many are contorted and deformed (Fig. 3.55). Some siltstones have a pinkish color, likely from iron staining. Abundant, thin, wispy shale laminations were interspersed throughout thicker siltstones in the unit. Shales, where thick enough, were fissile. Sparse, vertical burrowing through shale laminations was observed between 2,900 ft and 2,910 ft deep. Some siltstones were slightly dolomitized and displayed sparse, very small vugs, especially between 2,900 ft and 2,920 ft deep (Fig. 3.46).

Unit 5

Unit 5 was approximately 91 ft thick in log correlations (Fig. 3.28), which corresponds to depths from 3001 ft to 3092 ft in the core (Fig. 3.46). Unit 5 consisted of siltstones and shales. Variations of siltstone and shale, as in overlying units, including siltstone with shale laminations, silty shale, siltstone, and siltstone with shale laminations (Fig. 3.57). As in Unit 4 (Fig. 3.56) some of the siltstones are pink in color, suggesting iron staining. Some horizontal burrowing was observed at shale/siltstone contacts. Clean shales were very fissile. Bedding is commonly churned and contorted. Isolated vugs were present in dolomitic zones of some siltstone beds

Figure 3.55. Interbedded sandstone, siltstone and shale at the top of Unit 4, in the Warren County well from depths of 2860 to 2870 ft. Top is upper left in photograph. Each core row is two ft long.
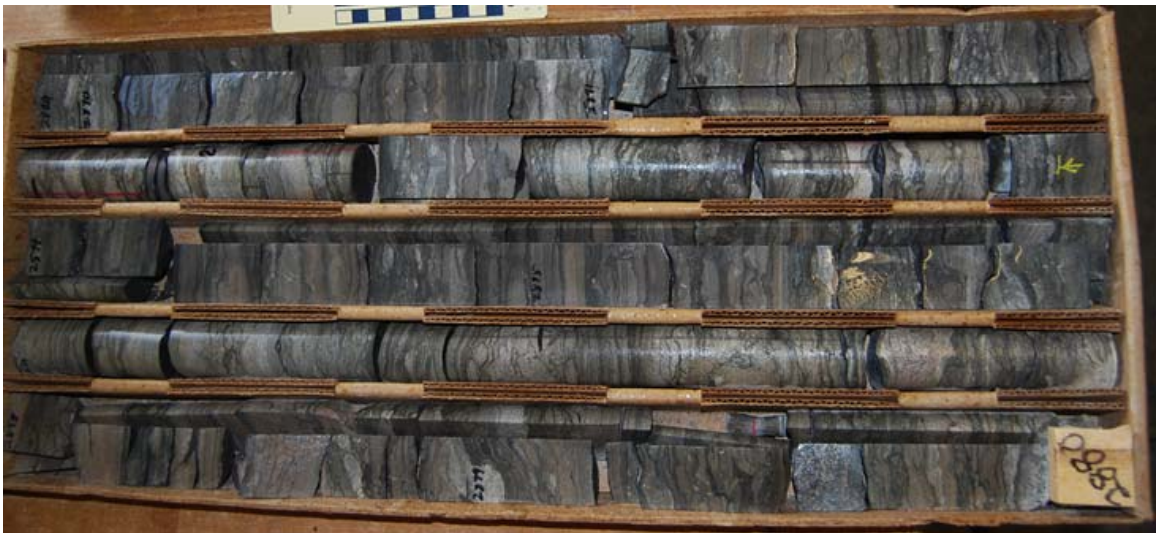
Figure 3.56. Interbedded siltstone and shale in Unit 4, in the Warren County well from depths of 2870 to 2880 ft. Top is upper left in photo. Scale in cm. Core shown wet to enhance bedding. Note pink color in some siltstones.

Figure 3.57. Interbedded siltstones and shales in Unit 5 from 3030 to 3040 ft. Top is upper left in photo. Scale in cm. Core shown wet to enhance bedding. Note pink color in some siltstones.

Figure 3.58. Small, isolated vug in gray contorted, partially dolomitic, siltstone at depth of 3079.5 ft. Scale bar is 1 cm. Top is upper left in photo.

Figure 3.59. Sandstone and interbedded shale in Unit 6 from 3130 to 3140 ft. Top is upper left in photo. Scale in cm. Core shown wet to enhance bedding contrast. Note pink color in some sandstones.

Figure 3.60. Contorted bedding and deformed vertical burrow at 3122 ft in Unit 6. Top is upper left in photo. Scale bar is 1 cm. Core shown wet to enhance bedding contrast.

Figure 3.61. Interlaminated sandstones and shales with abundant burrowing in Unit 6 at 3140 ft Top is upper left in photo. Scale bar= 1 cm. Core shown wet to enhance bedding contrast.

Unit 6

Unit 6 was approximately 100 ft thick in log correlations (Fig. 3.28), which corresponds to depths from 3092 ft to 3192 ft in the core (Fig. 3.46). In the Warren County well, Unit 6 consists of sandstone, sandstone with shale laminations, and interbedded sandstone and shales.

Sandstones were grey to light tan, and pink, medium to coarse grained, thinly bedded to laminated (Fig. 3.59). Some sandstones contained abundant black grains, interpreted to be glauconite. Sandstones are commonly bioturbated (Figs. 3.59-3.61). Bioturbation is more distinct where beds are interlaminated with shale.

Unit 7

Unit 7 was approximately 40 ft thick in log correlations (Fig. 3.28), which corresponds to depths from 3192 ft to 3232 ft in the core (Fig. 3.46). In this well, Units 6 and 7 are gradational. Unit 7 appears shaly in some wells on downhole geophysical logs, but is dominated by sandstone in the Warren County well (Fig. 3.46). This is a very good example of the variability of the lithologies both vertically and laterally within the Eau Claire/Conasauga interval across the study area. Sandstones in this unit are pink, tan and light to medium grey, and fine to medium grained. Sandstones are laminated to crossbedded (Fig. 3.62). Several intervals have less shale interlaminations than the overlying unit. Many small vugs and pores were noted in one massive (structure-less) section, approximately 1.5 ft thick.
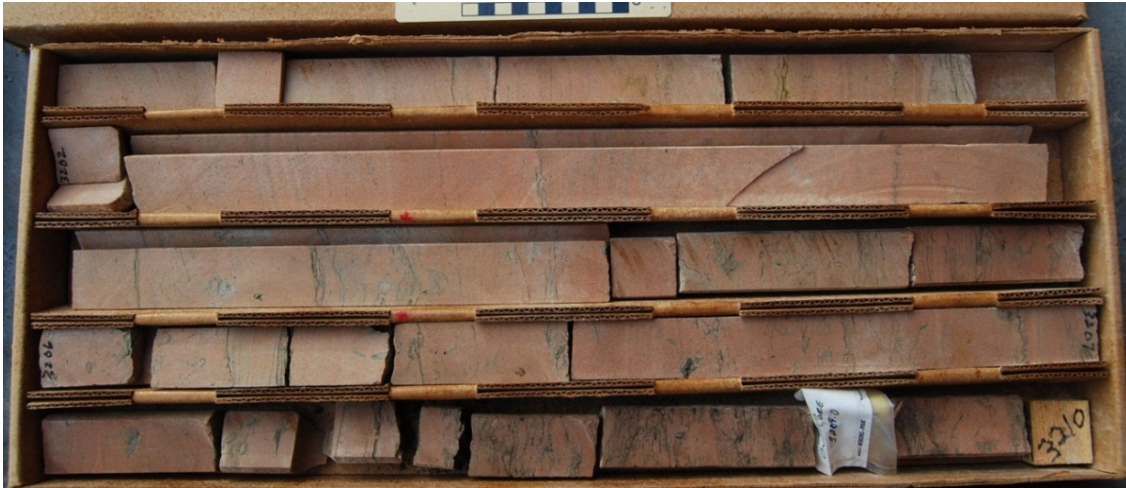
Figure 3.62. Pink sandstone with thin shale laminations in Unit 7 from 3200 to 3210 in the Warren County well. This unit is transitional with the underlying Mount Simon Sandstone. Top is upper left in photo. Scale in cm. Core shown wet to enhance bedding contrast.

Contorted and churned bedding is common, similar to Unit 6. In some cases, this is possibly from bioturbation, but it is generally less distinct than the burrows in the interlaminated shales and sandstones of Unit 6.

The base of the sandstone appears gradational with what appears to be the Mount Simon Sandstone on geophysical logs. Some previous workers have picked the top of the Mount Simon as the base of the Maryville Limestone equivalent, which would be the base of Unit 6 in this study.

USS CHEM./US STEEL No. 1 USS CHEMICALS Well

The USS Chem. /US Steel No. 1 USS Chemicals well is located in Scioto County, Ohio (Fig. 3.28). This well was originally drilled by Aristech Corporation. This well was cored through most of the study interval from the top of the Conasauga Group, down into the upper part of Unit 4. Conasauga Group nomenclature is used in this well. Approximately 406 feet of core was

described and photographed; from 4984.1 ft to 5390.9 ft deep. The core was previously described by Mark Baranoski (2001) of the Ohio Geological Survey, and Baranoski's descriptions were used for comparison in this study.

Base of Knox Group

The lower part of the Knox Group was examined to compare with the Davis Limestone in the DuPont well and underlying Conasauga Group dolomites in this well. The lower 66 ft of the Knox Dolomite (equals the Copper Ridge Formation of the Knox Group in Kentucky) was examined, from 4984 to 5044 ft. Core consisted of medium grey dolomite with sparse shale interbeds and styolites throughout. Dolomites were commonly crystalline. Where original textures were preserved, some dolomite exhibited a clotted texture, possibly thrombolitic. Zones of ooids were also observed. Clotted texture and ooids were also observed at a similar stratigraphic level in the ODNR (Warren County) and DuPont No. 1 WAD fee wells.

Unit 1

Unit 1 was approximately 46 ft thick in log correlations (Fig. 3.28), corresponding to the interval from 5044 ft to 5090 ft in the core (Fig. 3.64). The unit is approximately equivalent to the Maynardsville Limestone. Baranoski (2011) picked the top of the Maynardsville slightly higher than the correlation of Unit 1 used in the present work, (at 5024 ft, at the top of a nodular dolomite in the core). Unit 1 dolomites are gray to tan, nodular to laminated, with abundant thin shale bands. Interlaminated shales are dark grey, fissile, and dolomitic. Shales contain abundant fossil graptolites (Fig. 3.65), lingulid brachiopod fragments (Fig. 3.66), and trilobite fragments (Fig. 3.67). Siltstones were grey with interbedded to interlaminated shale.

Aristech Well Stratigraphic Column
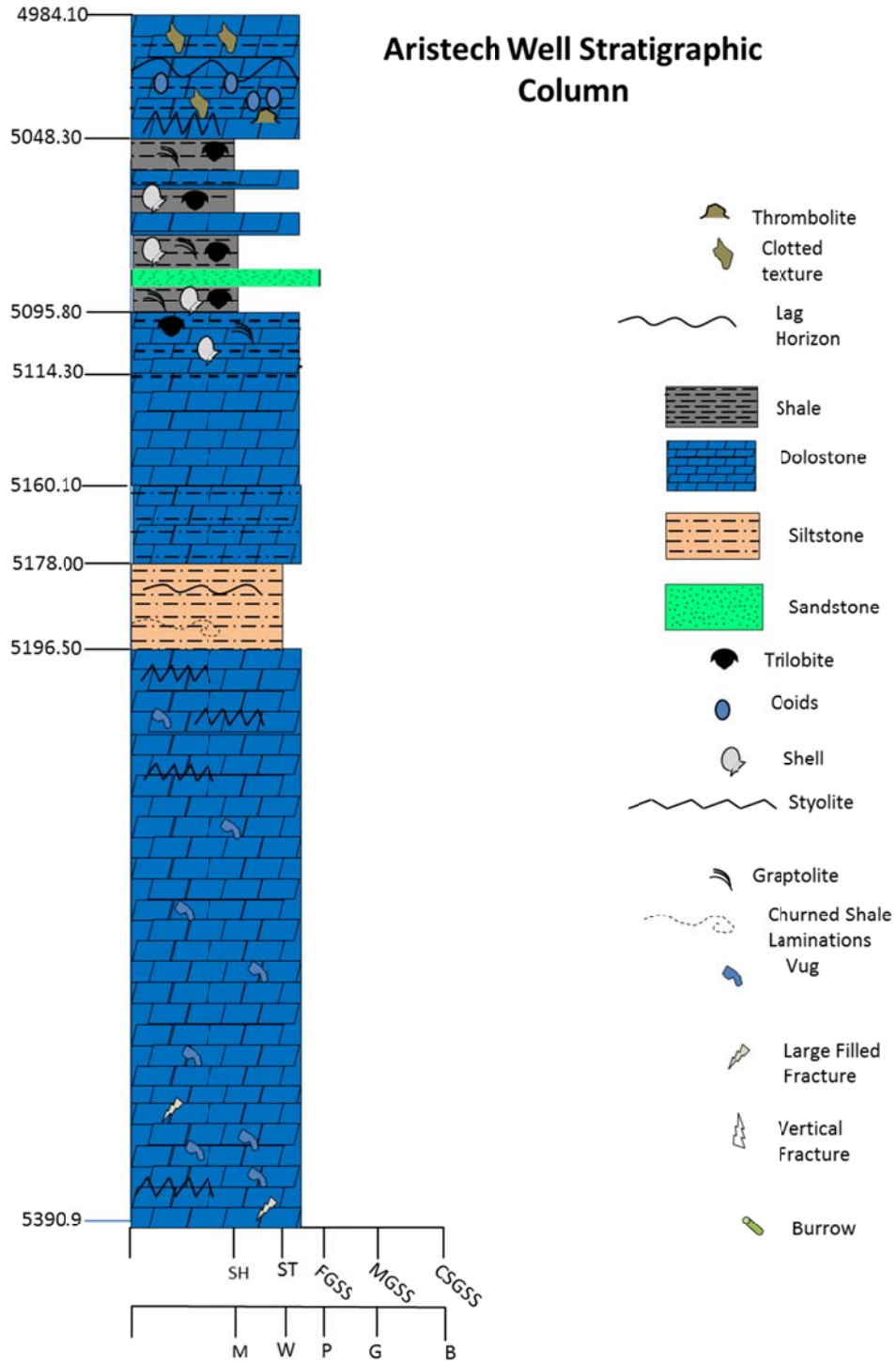
Figure 3.64. Interbedded laminated to nodular dolomites and shales in Unit 1 from 5048.3 to approximately 5058 ft. Top is upper right in this photograph. Core in middle of the box wet to enhance bedding contrast.

Figure 3.65. Graptolite fragments in lower part of Unit 1 shale at 5062.50 ft deep.

Figure 3.66. Intact lingulid brachiopod shell in lower part of Unit 1 shale at 5064.8 ft deep.

Figure 3.67. Trilobite cephalon fragment in lower part of Unit 1 shale at 5071.20 ft deep

Unit 2

Unit 2 is approximately 82 feet thick on logs (Fig. 3.28) and corresponds to depths of 5090 to 5172 ft in the core (Fig. 3.63). Unit 2 is approximately the top of a very shaly gamma response in the log for this well. Baranoski (2001) picked the base of the Maynardsville Formation/top of the Nolichucky Formation higher at the base of a thick carbonate bed, at

5064 ft. The interval between 5090 and 5064 is gradational between overlying carbonates and underlying shales. Unit 2 consists of shale and dolomite (Fig. 3.68). Shales are light grey to dark gray, and interbedded with dolomite. Dolomites were grey, often crystalline, and thick. Dolomites that were not crystalline, were often silty, and commonly exhibited zones of small, black grains interpreted to be glauconite. Shales contained fossil trilobites, brachiopods, and graptolites (Fig. 3.69).

Unit 3

Unit 3 is approximately 46 ft thick in logs (Fig. 3.28), and corresponds to depths of 5172 to 5218 ft in the core (Fig. 3.63). The top of Unit 3 on logs was picked at the uppermost apparent thick dolomite in an overall fining-upward interval from the underlying thick carbonates of the Maryville Limestone into the overlying shales of the Nolichucky Formation. Unit 3 consists of interbedded dolomite, sandy dolomite, shale, and siltstone. Dolomites were similar to the overlying unit, but overall in thicker beds. At least one bed was sandy; some others were crystalline, with abundant small vugs.

Unit 4

The top of Unit 4 on logs (Fig. 3.29) corresponds to a depth of 5218 ft in the core (Fig. 3.63). The log pick was made at the top of sharp gamma excursion and a change from blocky (consistent) dolomite density below, to more variable above. Baranoski (2001) picked the official top of the Maryville Limestone higher at 5194 ft, at the contact between a shale and top of a thick dolomite. The interval between 5194 and 5218 is mostly gradational. Approximately 166 ft of Unit 4 (below 5218 ft) was available for observation. It is dominated by light grey to white, laminated to massive dolomite. Some beds are brecciated or churned, others are

Figure 3.68. Unit 2 shales from 5133 to 5142 ft deep. Top is upper right. Each core row is 2 feet in length. Paper slips mark position of fossils in the core.

Figure 3.69. Fossil trilobite fragments in shale from core box shown in Fig. 3.68.

crystalline, and a few are sandy. Sharp to irregular scour surfaces are common. Small styolites

and vugs occur locally. Vugs were mostly filled with saddle dolomite and gypsum or anhydrite

(Fig. 3.70). Irregular anhydrite beds or nodules occur at approximately 5347, 5376, and near the

base of the core at 5383.5 ft (Fig. 3.71).

Figure 3.70. Vuggy porosity in Unit 4 dolomite at 5235.00 ft deep. Top of core is to right.

Figure 3.71. Irregular anhydrite bed (white and light blue) in Unit 4 dolomite at 5383.5 ft .
Top of core to right.

Cuttings Descriptions

Cuttings were examined in several wells to supplement core data (Figs. 3.72, 3.73).

Cuttings provide valuable data where no other data is available. Cuttings, however, represent

an average sample across a depth interval, and mixing with material that caves into the hole

from further up the well bore cannot be ruled out. Cuttings were used to check log

interpretations of dominant lithologies for parts of the study interval. Figure 3.73 shows the

relative position of correlated units between the wells and the stratigraphic position of the

cutting samples examined. Samples were examined in positions where a bedding contact or

lithology needed to be checked. Special attention was paid to presence of sand grains in the

cuttings, since sandy carbonates are difficult to differentiate from other carbonates in some

logs, and Units 6 and 7 appear to have high gamma (shaly) signatures even when in some cases,

sandstones were present.
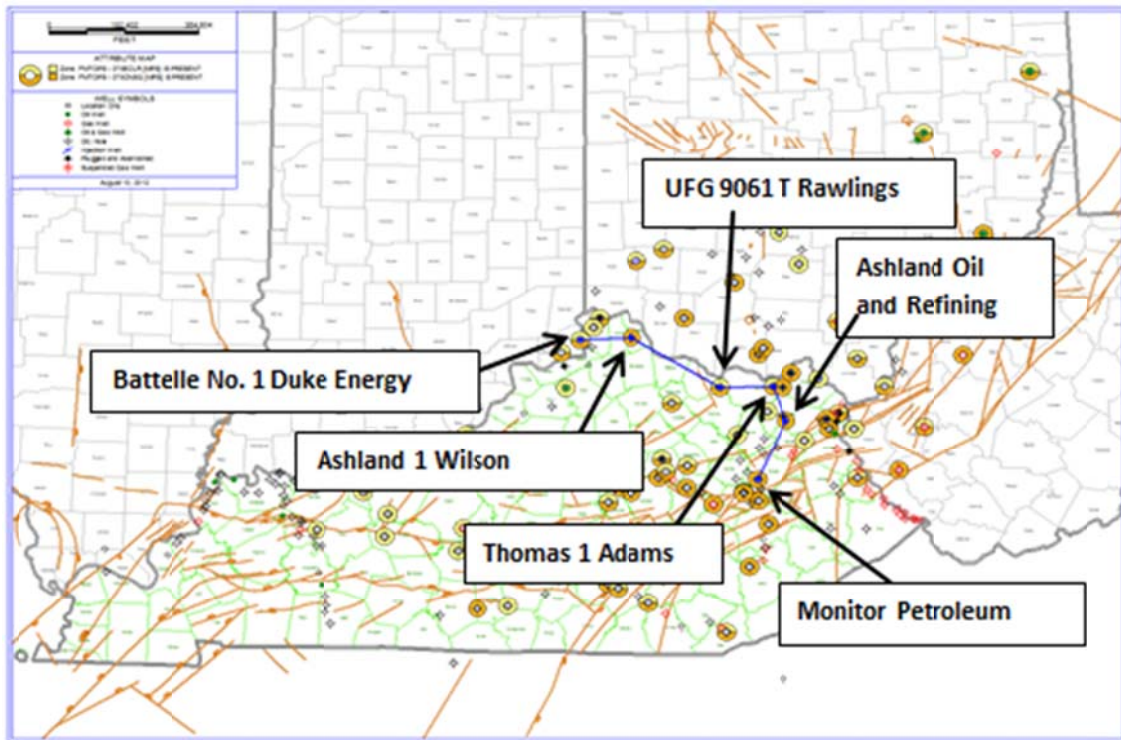
Figure 3.72. Cross section location map of wells with cuttings descriptions.
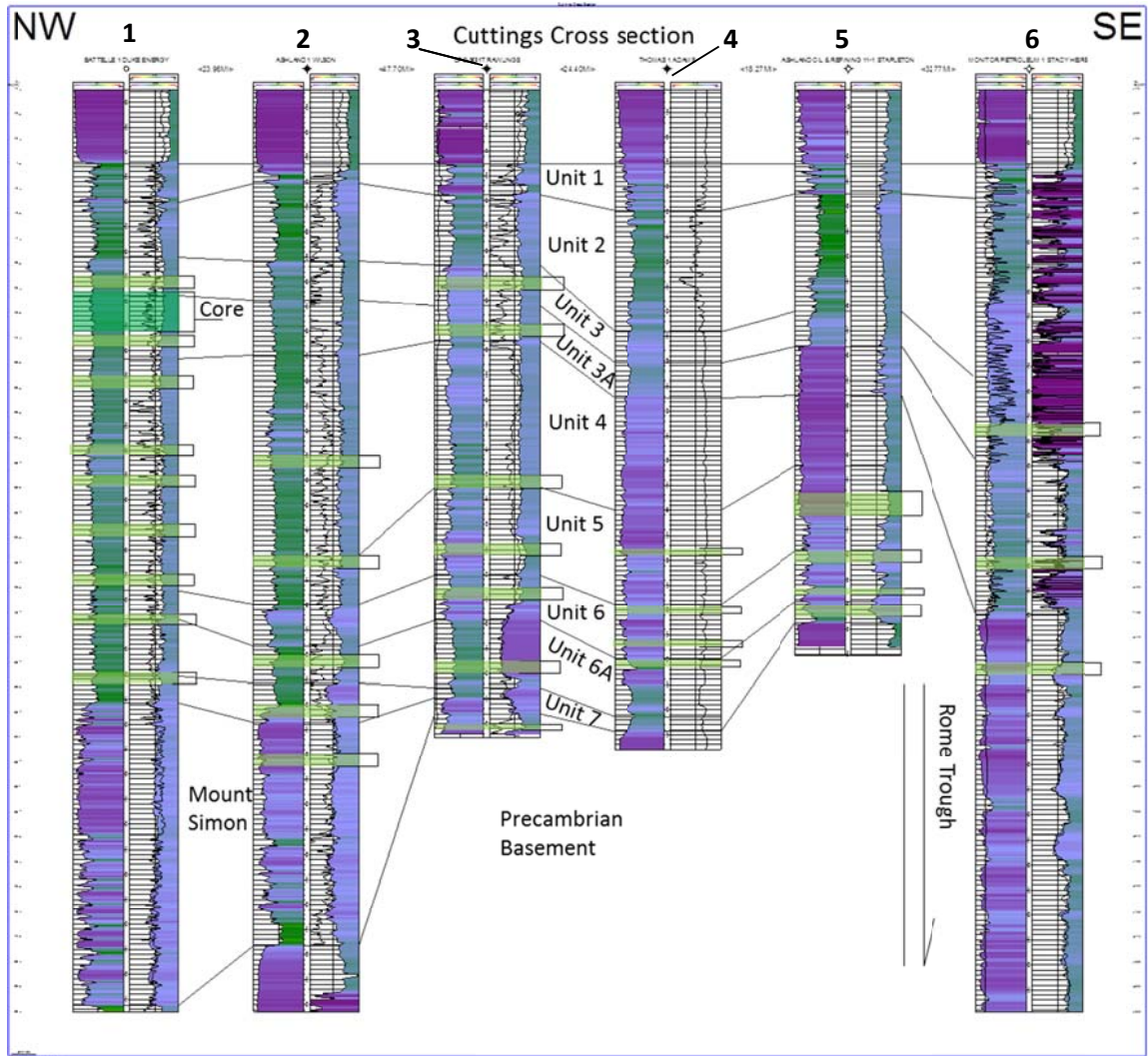
Figure 3.73. Cross section of wells in which cuttings were examined showing correlated units and intervals in which cuttings were examined (light green boxes). 1-=Battelle No. 1 Duke Energy well, 2=the Ashland No. 1 Wilson well,3= UFG 9061 T Rawlings well, 4=Thomas No. 1 Adams well, 5=Ashland Oil and Refining well, and 6= Monitor Petroleum well. Distance between wells is not to scale. See Figure 3.63 for well locations.

Battelle No. 1 Duke Energy Well

Cuttings were examined from the Battelle No. 1 well (at East Bend, Kentucky) for Unit 3, Unit 4, Unit 5, Unit 6, and Unit 7 (Fig. 3.73). Core was only available for a few intervals in this

well, so cuttings were used to check average rock types in other intervals. A summary of the cuttings analyses is shown in Figure 3.74.
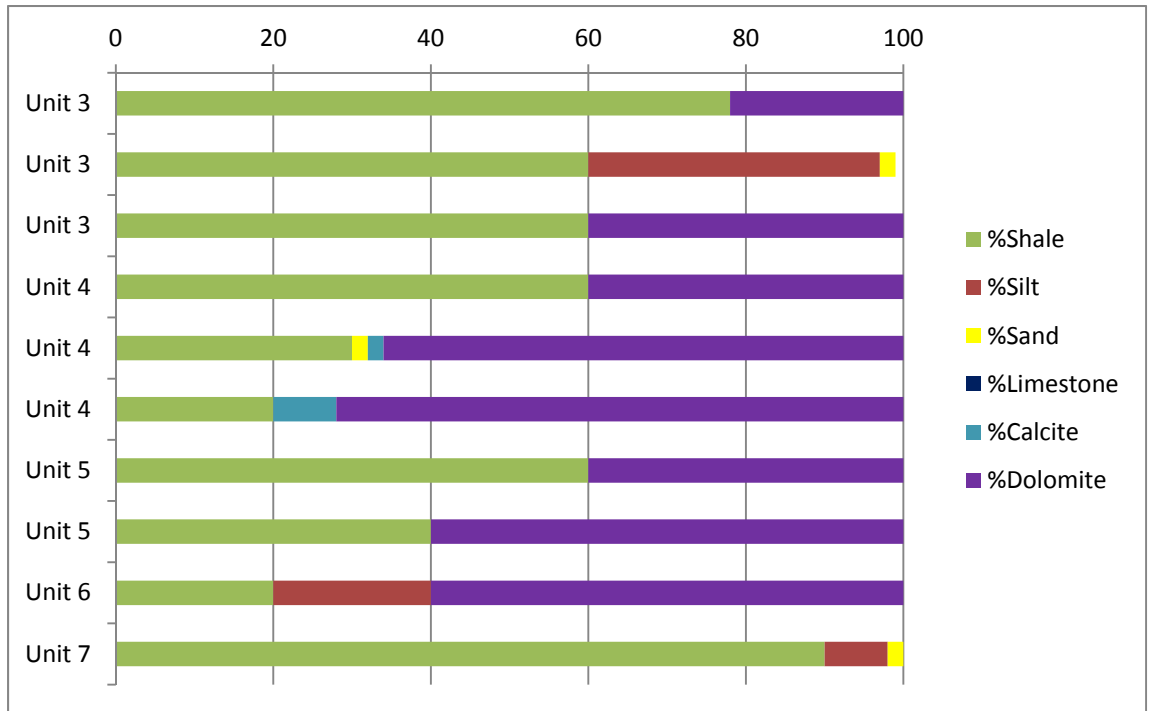
Figure 3.74. Summary of rock types in cuttings in the Battelle No. 1 Duke Energy (East Bend) well by unit.

Cuttings were examined at 2,800 to 2,810 ft, 2,850 to 2,860 ft, and 2,900 to 2,910 ft in Unit 3 (Fig. 3.74). All samples were dominated by micaceous shale. Two of the samples contained had 20 to 40% dolomite or dolomitic siltstone grains. The middle sample had more silt grains than dolomite and also had a minor amount (1-3%) of angular quartz grains.

Cuttings were examined from 2,950-2,960 ft, 2,970 to 2,980 ft, and 2990 to 3000 ft deep in Unit 4 (Fig. 3.74). In general, the percentage of shale increases upwards within the unit, while the percentage of crystalline dolomite chips decreases. The sample from 2,970 to 2,980 ft

contained chips of calcite (2%) and rounded quartz grains (2%). Calcite (8%) chips were also noted in the lower sample.

Two sample depths were examined for Unit 5 in the East Bend well, from 3,050 to 3,060 ft and 3,100 to 3,110 ft (Fig. 3.74). These samples were similar to shale-dominant samples in Units 3 and Unit 4.

One sample of cuttings was examined in both Unit 6 and 7 to see if any sandstone was present and to check the lithology of the immediate caprock above the Mount Simon Sandstone. Unit 6 was sampled from 3,140 to 3,150 ft deep (Fig. 3.74). The sample was composed of 60% crystalline dolomite, and no sandstones. The Unit 7 sample from 3,200 to 3,210 feet deep (Figs. 3.64-3.65) was almost all silty shale (90%). The remainder contained 7 to 9% silty chunks, and 1 to 3% rounded quartz grains.

Ashland No. 1 Wilson Well

Cuttings were observed in the Ashland No. 1 Wilson well (Fig. 3.73) in Unit 4, Unit 5, Unit 6, and Unit 7 (Fig. 3.75). A summary of the cuttings analyses is shown in Figure 3.75. Most of the cuttings were nearly 50% shale. More shale was observed in Unit 5 than the other units in the well. Siltstones were calcareous. Rounded quartz sand grains were in every sample. In Units 4 and 5 they were rare (1%), but Unit 6 had 10% sand grains and Unit 7 had 50% sand grains. Sandstone chips in Unit 7 were quartzose and fine-grained. Muscovite and biotite were noted in some of the sandstone chips.

Monitor Petroleum No. 1 Stacy Heirs Well

Cuttings in the Monitor Petroleum well (Fig. 3.72) were examined for Unit 3 and Unit 4 (Fig. 3.73). A summary of the cuttings analyses is shown in Figure 3.76. Two samples of cuttings

were observed for Unit 3. The first sample was from 5,560 to 5,570 feet deep. The second

sample (from Unit 3A) was from 5,700 to 5,710 ft deep. Both contained abundant shale, but the

lower sample contained significant limestone. Cuttings for Unit 4 were observed from 5,800 to
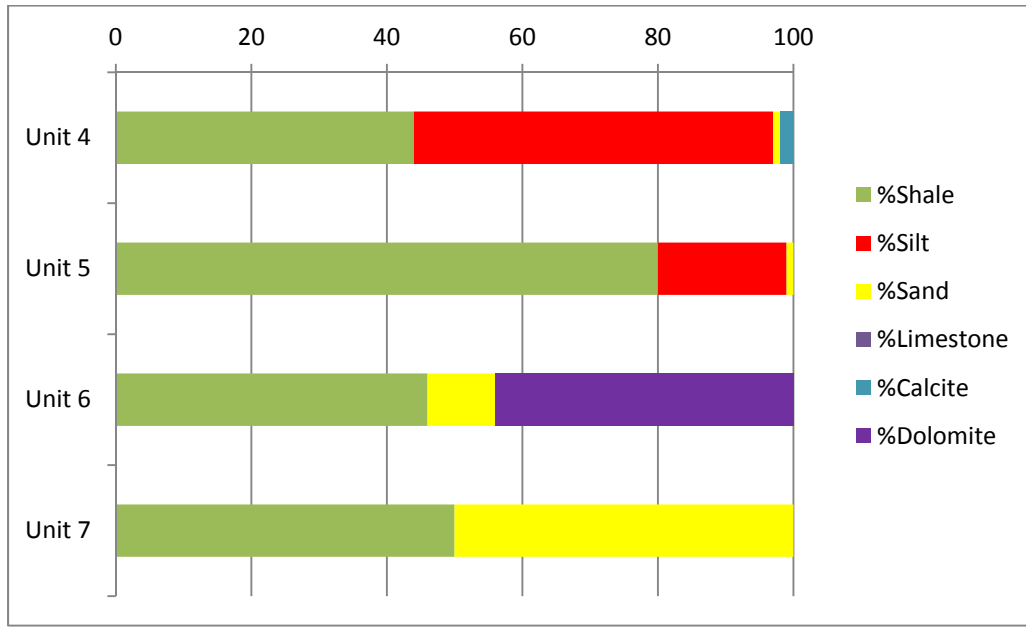
Figure 3.75. Summary of rock types in cuttings in the Ashland No. 1 Wilson well by unit.
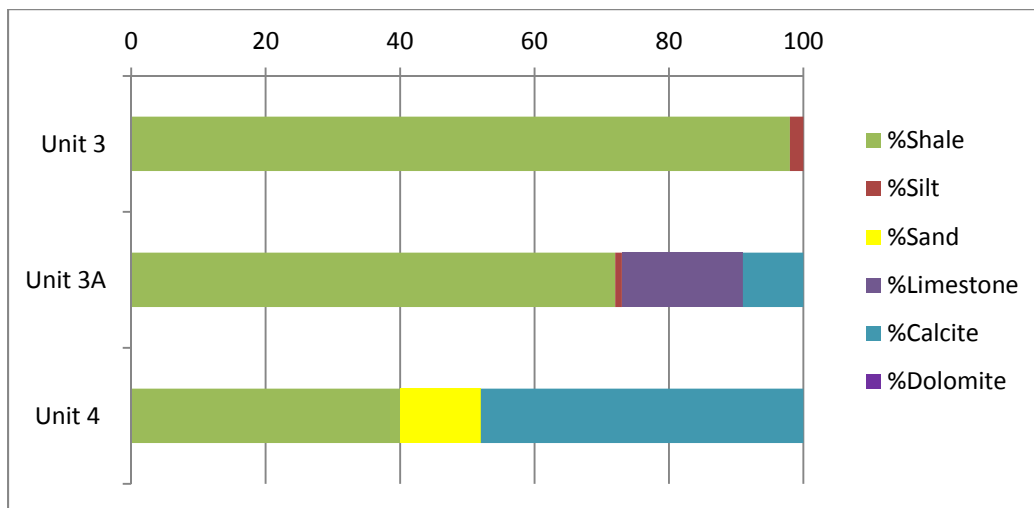
Figure 3.76. Summary of rock types in cuttings in the Monitor Petroleum No. 1 Stacey Heirs well
by unit.

5,810 feet deep. The sample was dominated (48%) by calcite chips, possibly from a limestone. Clear quartz grains comprised 12% of the sample.

Thomas No. 1 Adams Well

Cuttings were examined in the Thomas No. 1 Adams well within Unit 6 (Figs. 3.72-3.73). The purpose for focusing on Unit 6, was to identify possible sandy zones suggested in geophysical log signatures. A summary of the cuttings analyses is shown in Figure 3.77. Two samples from 4,015 to 4,020 ft (Unit 6A) and 4,050 to 4,055 ft (upper Unit 6B), contained nearly 50% sand grains. Most of the grains were clear, frosted quartz sand, but some sand grains were arkosic and pink in color. Sandstones were only minor constituents (1%) of the lower two samples from 4,085 to 4,090 ft, and 4,095 to 4,100 ft.
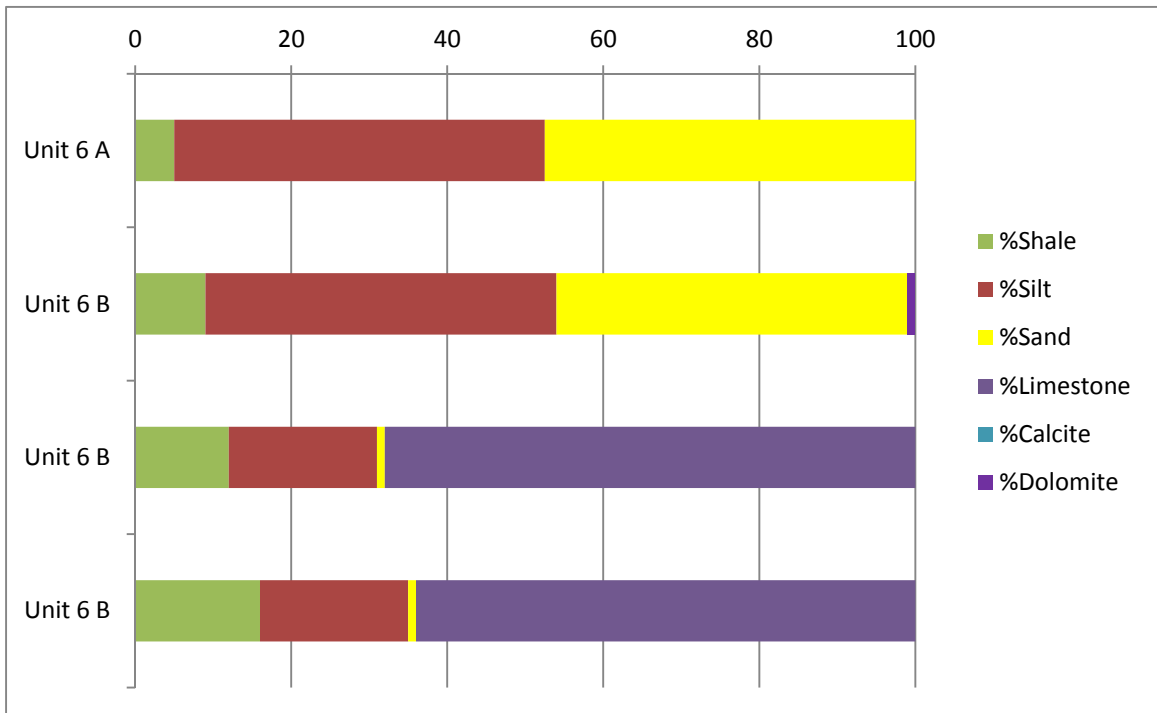
Figure 3.77. Summary of rock types in cuttings in the Thomas No. 1 Adams well by unit.

Ashland Oil and Refining No. 1 Stapleton Well

Cuttings were examined in the Ashland No. 1 Stapleton well (Fig. 3.72) for Unit 5 and Unit 6 (Fig. 3.73). A summary of the cuttings analysis is shown in Figure 3.78. The sample examined for Unit 5 was from 5,090 to 5,100 ft. Shale made up 10%, quartz sand grains were 3%, and light grey dolomite constituted the remaining 87% of the sample. Cuttings examined for Unit 6 were from 5,140 to 5,150 ft deep. Carbonates in Unit 6 appeared to be dominated by light gray limestone rather than dolomite.
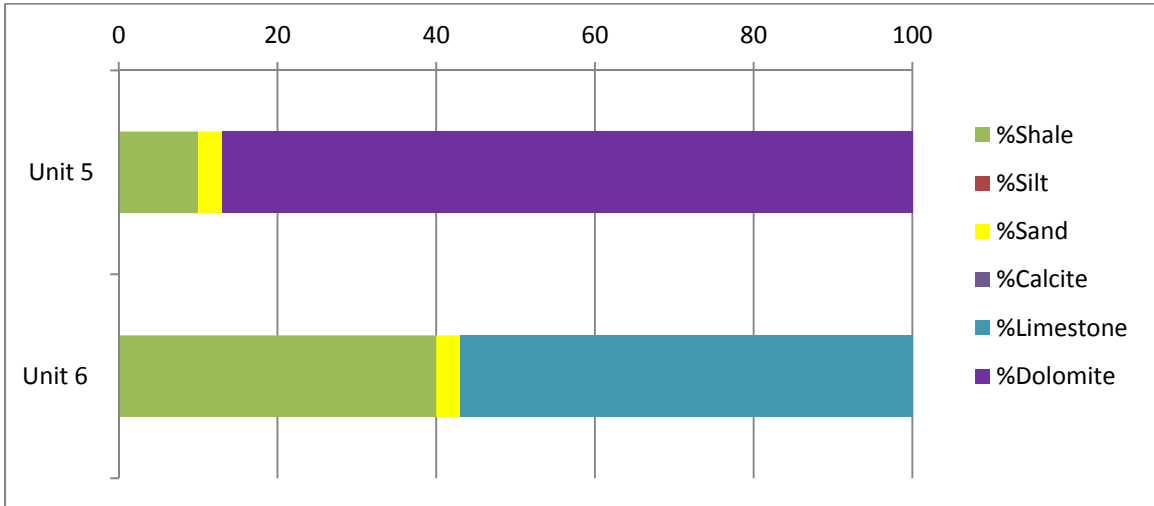
Figure 3.78. Summary of rock types in cuttings in the Ashland No. 11-1 Stapleton well by unit.

UGD 9061 T Rawlings Well

Cuttings in the UGD 9061 T Rawlings well (Fig. 3.72) were observed for Unit 3, Unit 4, Unit 5, Unit 6, Unit 7 (Fig. 3.73). A summary of the cuttings analyses is shown in Figure 3.79. Cuttings for Unit 3 were from 2,850 to 2,860 ft deep, and cuttings examined from Unit 3A were from 2,900 to 2,910 ft deep. Both were composed almost equally of dolomite and shale. Minor sand (2%) was noted in Unit 3.
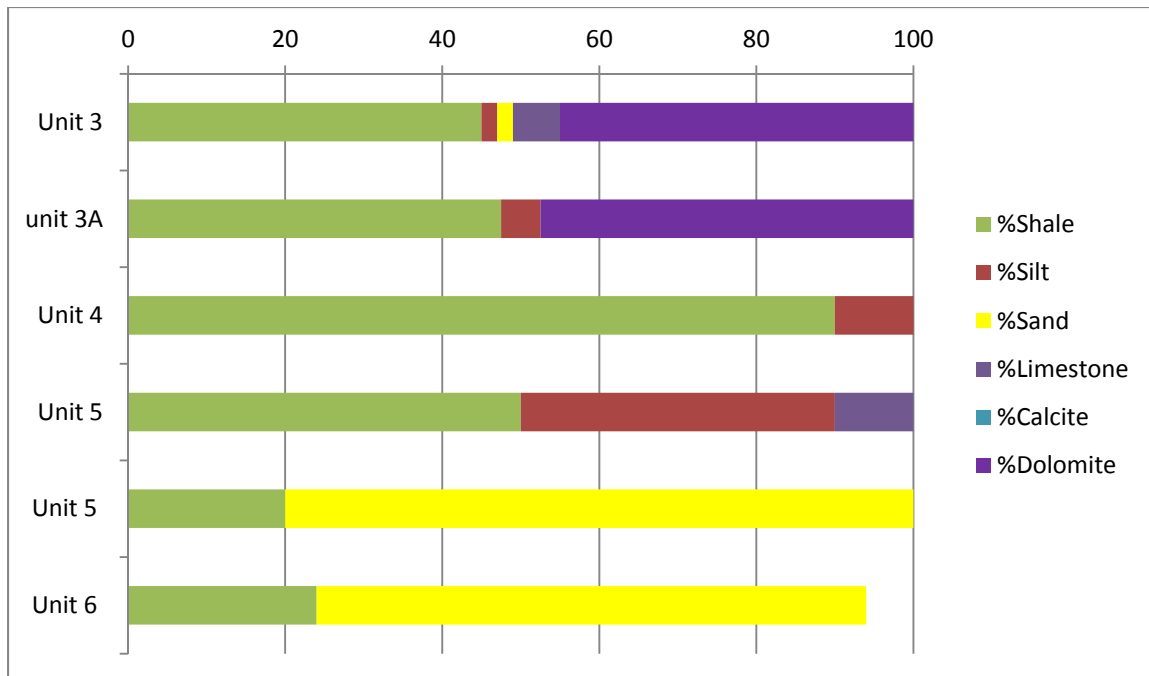
Figure 3.79. Summary of rock types in cuttings in the UGD 9061 T Rawlings well by unit.

Cuttings for Unit 4 were sampled from 3,050 to 3,060 feet, and were the most shaly of any examined from this well. Shale comprised 90% of the sample, while mixed fine grained sand and silt chips made up the remaining 10%. Cuttings for Unit 5, from 3,120 to 3,130 feet deep, and Unit 6, from 3,160 to 3,170 ft were both dominated by sandstone.

The first sample for Unit 6 was from 3,160 to 3,170 feet deep, and consisted of 80% light and 20% dark material. Dark, sandy shale with many flat, rounded chips made up 20% of the sample, while the remaining 80% of the sample was composed of fine grained, slightly peppered sandstone chunks. Two small, clear quartz sand grains were also observed. The second sample for Unit 6 crossed the boundary between the base of Unit 6, and into the top of Unit 7. The sample examined was from 3,240 to 3,250 ft deep and consisted of 70% slightly pink, fine-grained sandstone chips. Dolomite made up the remaining 6% of the sample.

Porosity and Permeability

Permeability data from previous studies was available for the DuPont No. 1 WAD fee well, the Battelle No. 1 Duke Energy (East Bend) well, and the USS Chem./US Steel No. 1 USS Chemicals (Aristech) well. These data were placed within the stratigraphic subdivisions of this report to better evaluate vertical and lateral permeability relative to lithology and correlations. Locations of wells with available data are presented in Figure 3.80. The stratigraphic position of the samples from which the permeability data came is shown in Figure 3.81, relative to the units correlated in this study. Table 3.7 shows the well, unit within the Eau Claire/Conasauga interval,
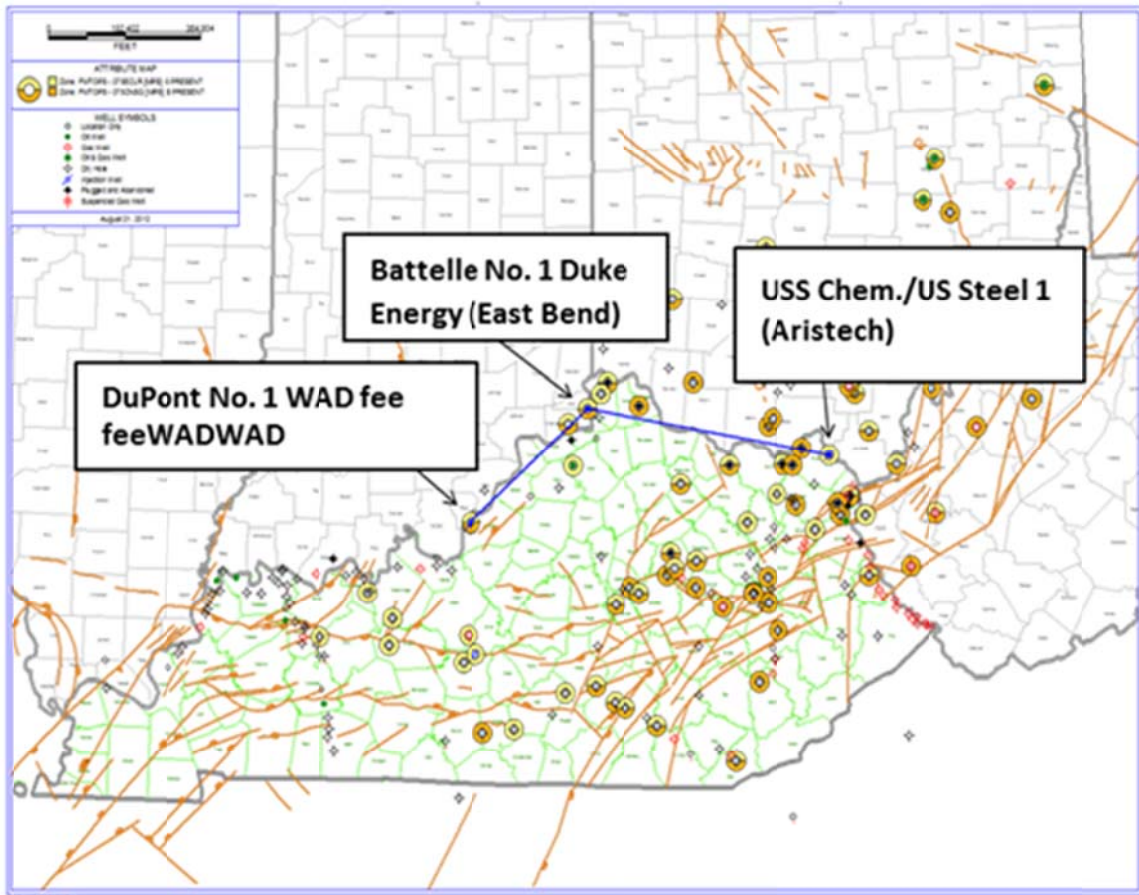
Figure 3.80. Location of wells with permeability data from the study interval.

and the permeability value in milidarcys (md) for each sample. These values are discussed in the

discussion section of this thesis.

Geochemistry

Total Organic Carbon

Six shale samples were analyzed from two wells for total organic carbon (TOC) analysis.

Samples were analyzed to determine if the shales had enough carbon to have the possibility for

adsorption of CO_2. The darkest shales within available core from the DuPont No. 1 WAD fee well

and Battelle No. 1 Duke Energy well were chosen for analyses, since these would likely have the

highest organic carbon contents. Results indicated very low TOC; below one percent in all six

samples (Table 3.8). As such, these shales will likely not have adsorptive characteristics relative

to CO_2.

X-Ray Fluorescence

Data was collected with the hand-held XRF device from several cores and cuttings. This

was an experimental methodology to see if resulting data might provide an aid in stratigraphic

correlations. Figure 3.82 shows the location of wells in which XRF data was collected. In order to

determine if results from the hand-held instrument were valid, a comparison was made with

whole-rock geochemical data previously collected by Neufelder (2011) using a lithium

metaborate/tetraborate fusion inductively coupled plasma (ICP [mass spectrometer]), from the

same cores. Figure 3.83 shows the results of the comparison for several major oxides. The

results showed similar trends of relative abundance in each case, although absolute values were

not the same.
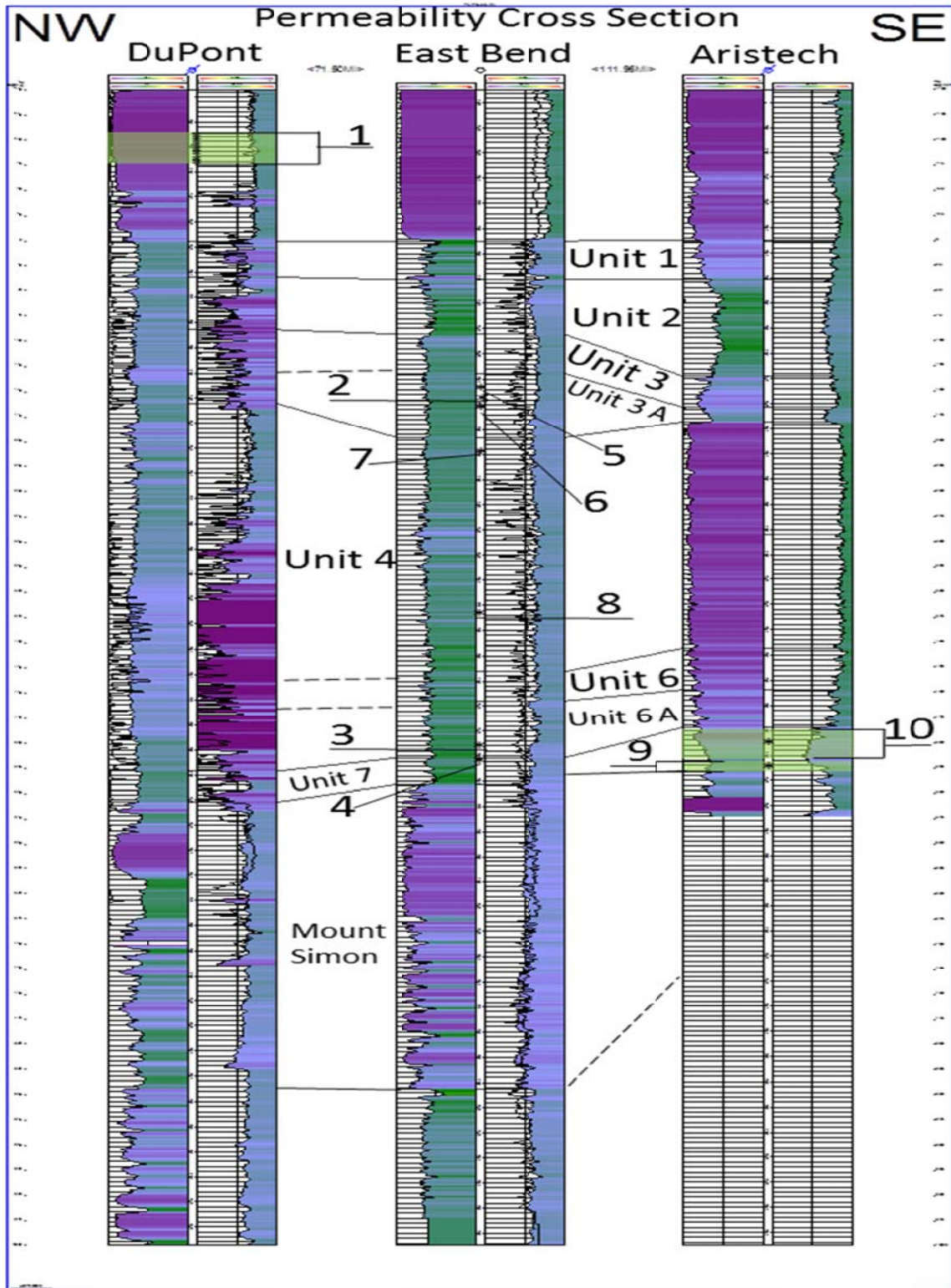
Figure 3.81. Cross section of wells with permeability data. Numbers indicate locations of permeability data within the wells. Numbers correspond with Table 3.8. Wells are arranged from west to east as shown in Figure 3.71.

Table 3.7. Depths and measured permeabilities for samples from the study interval. Numbers in the number column correspond with the sample numbers in the cross section Figure 3.72. Numbers in the unit column correspond to the study units defined in the present study. *Fractured or chipped sample. **Sample unsuitable for permeability measurement. DuPont well data from KGS online database. Battelle No. 1 Duke Energy well data from Battelle (2012). U.S. Chem/U.S. Steel No.1 well data from Baranoski (2001).

Permeability					
Number	Top Depth (ft)	Unit within Study Interval	Well	Type	Value (md)
1	4409.0-4443.1	Knox (above Unit 1)	DuPont No. 1 WAD fee	vertical	<0.1
2	2844.9	3	Battelle No. 1 Duke Energy	rotary sidewall	11.8**
3	3190	6	Battelle No. 1 Duke Energy	rotary sidewall	0.007
4	3205	7	Battelle No. 1 Duke Energy	rotary sidewall	0.003
5	2834.9	3	Battelle No. 1 Duke Energy	rotary sidewall	0.602*
6	2854.35	3	Battelle No. 1 Duke Energy	rotary sidewall	0.0004
7	2895	4	Battelle No. 1 Duke Energy	rotary sidewall	0.011*
8	3062	4	Battelle No. 1 Duke Energy	rotary sidewall	0.001*
9	5563.0-5573.0	7	U.S. Chem/U.S. Steel 1	vertical	0.4
10	5532.0-5561.0	7	U.S. Chem/U.S. Steel 1	vertical	26.8

Table 3.8. Total organic carbon results for six samples taken from core.

Well	Sample Name	Depth (ft)	TOC (%)
DuPont No. 1 WAD fee	DUPD4853.00	4853.00	0.317
DuPont No. 1 WAD fee	DUPD4858.75	4858.75	0.080
DuPont No. 1 WAD fee	DUPD4871.00	4871.00	0.150
DuPont No. 1 WAD fee	DUPD4871.71	4871.71	0.157
Battelle No. 1 Duke Energy	EBND2839.15	2839.15	0.101
Battelle No. 1 Duke Energy	EBND2855.00	2855.00	0.104
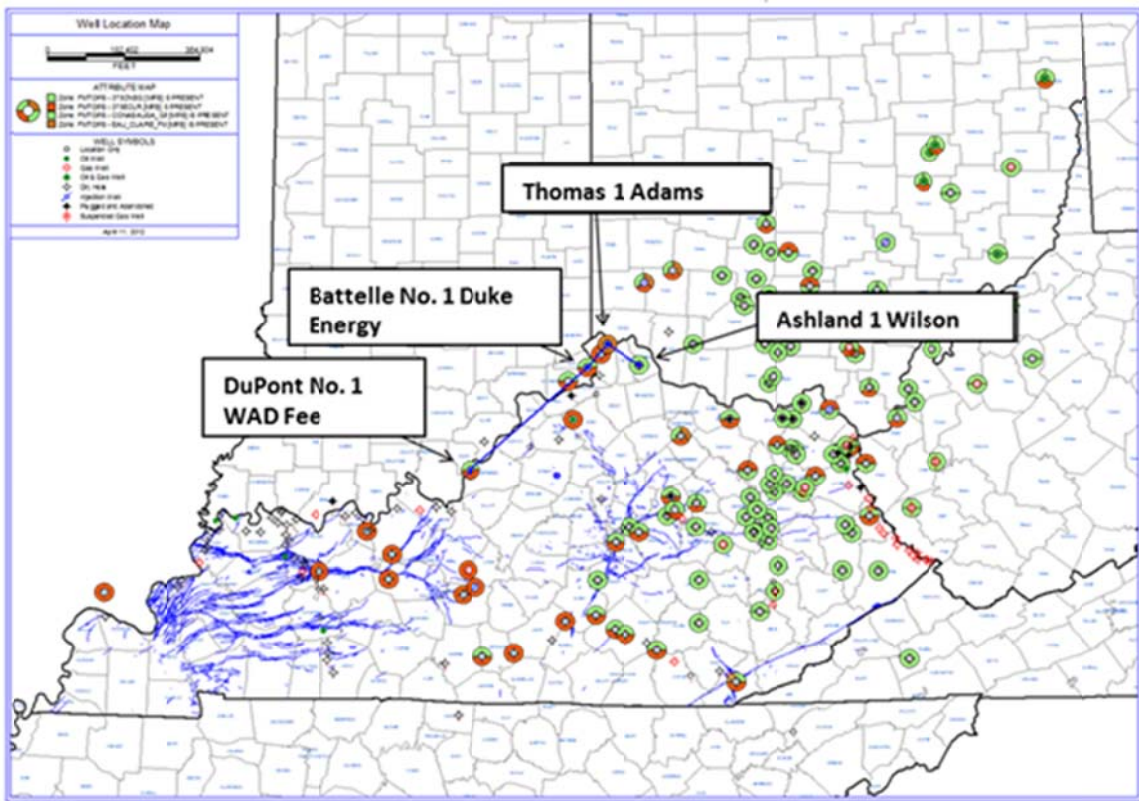
Figure 3.82. Cross section location map of wells with cuttings and core used for XRF.

These results indicate that data collected from the hand-held XRF device could be used for

qualitatively analyzing the relative occurrence of major oxides and trace elements.

In order to see if the hand-held XRF data might aid in stratigraphic correlations, data

was plotted alongside geophysical logs for comparisons. Figure 3.84 shows an example of data

collected for SiO_2 relative to stratigraphic position and log response. Concentrations tend to

increase where log signatures show more clastic-rich lithologies, as would be expected.

Concentrations also change across unit boundaries, as unit boundaries were chosen where log

signatures showed a change in lithology. Figure 3.85 shows a correlation of FeO for the same

wells. Data are more variable between wells, than for SiO_2. In general, iron decreases in the

carbonate-rich intervals. In some cases, there also appears to be changes in iron concentrations

across some of the unit boundaries.
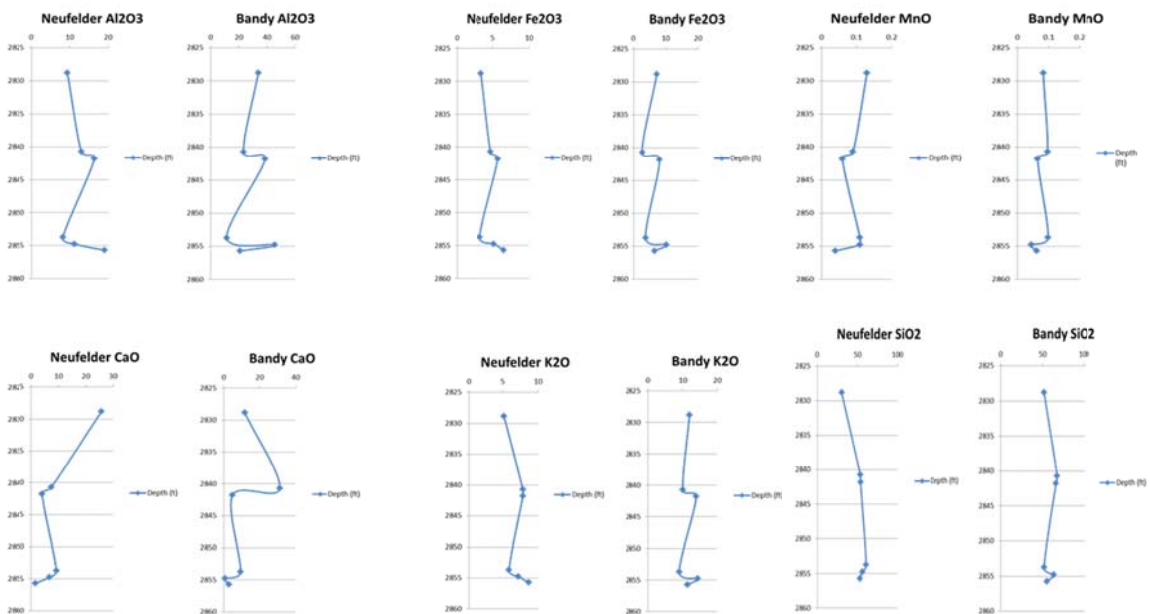
Figure 3.83. XRF data for major oxides collected with the hand-held XRF device (labeled Bandy) compared with whole rock geochemistry data collected from the same depths (labeled Neufelder; modified from Neufelder, 2011). Depth from which samples were collected in cores is labeled in ft on the Y axis and is compared to weight percent on the X axis.

Figure 3.86 shows data collected for P_2O_5 relative to stratigraphic position and log response.

This oxide was plotted because it showed distinct changes by unit between wells.

Concentrations of Phosphorus were too low to be detected in the upper sections of the well, but

in Unit 6 and Unit 7, higher concentrations were detected in all wells. Phosphorus can be

associated with uranium and thorium, which could cause the gamma curve to register higher,

making some sections look like they are shalier than they might actually be. This is likely why

the Warren County well's gamma signature (and other wells in the study area) for Unit 7 (Fig.

3.28) looks more shaly than it is in core (Figs. 46, 3.62).
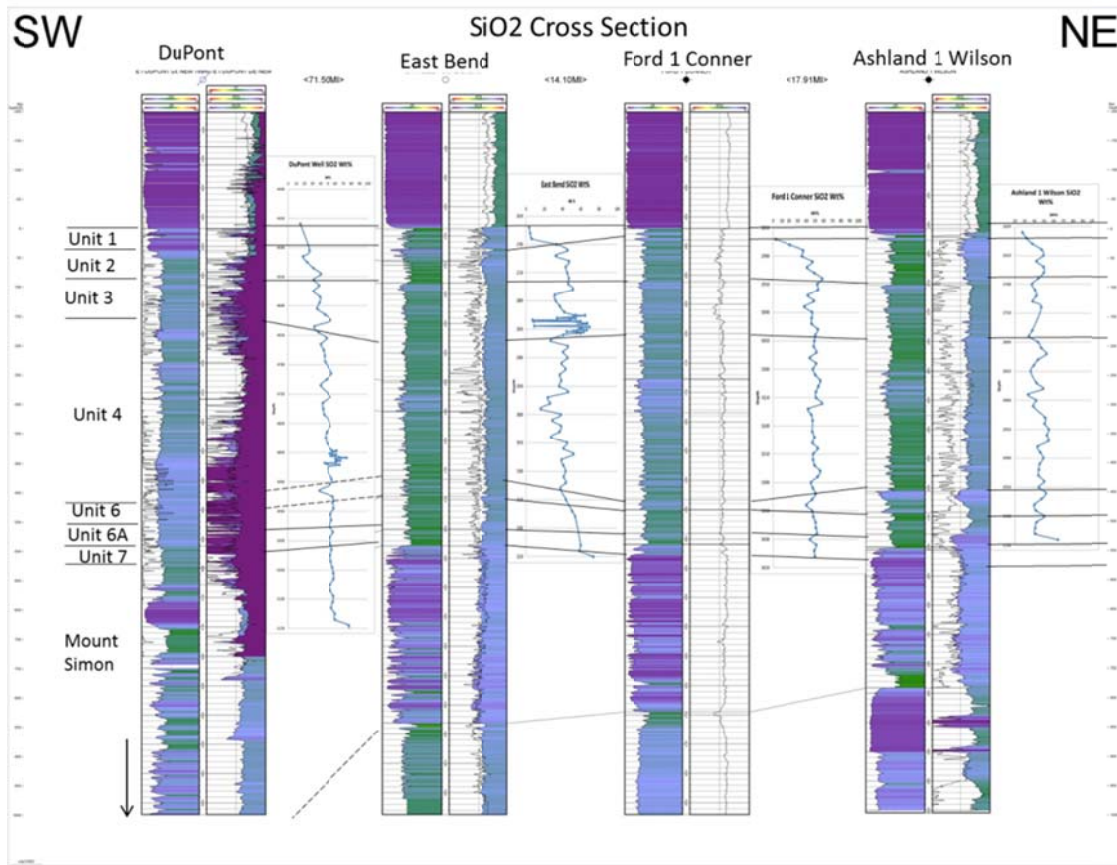
Figure 3.84. SiO$_2$ results (light blue line) plotted against geophysical log responses from west to east in the wells sampled. High concentrations to right on each chart. Unit subdivisions of the Eau Claire/Conasauga interval are also shown. The East Bend well is the Battelle No. 1 Duke Energy well.

Another way to look at the XRF results is to average the results from the samples

collected by unit for all of the wells. Figures 3.87 to 3.89 and show average weight percent of

several different oxides by unit. Calculated oxides CaO, K_2O, and Fe_2O_3 are plotted because

these could signify higher carbonate, potassium feldspar, and pyrite content respectively, which

are potentially reactive with CO_2. Previous analysis of the Eau Claire Formation suggests that

glauconite and carbonate minerals are the most potentially reactive minerals (Sposito, 2008;

Neufelder, 2011). The handheld XRF data shows where iron and calcium are most concentrated

in the cuttings sampled, which may help to guide future sampling for specific carbonate and iron

minerals. Results for the XRF data were summarized for three key intervals relative to sealing

characteristics of the study interval. Figures 3.90-3.92 show weight percent by well for CaO, K_2O,
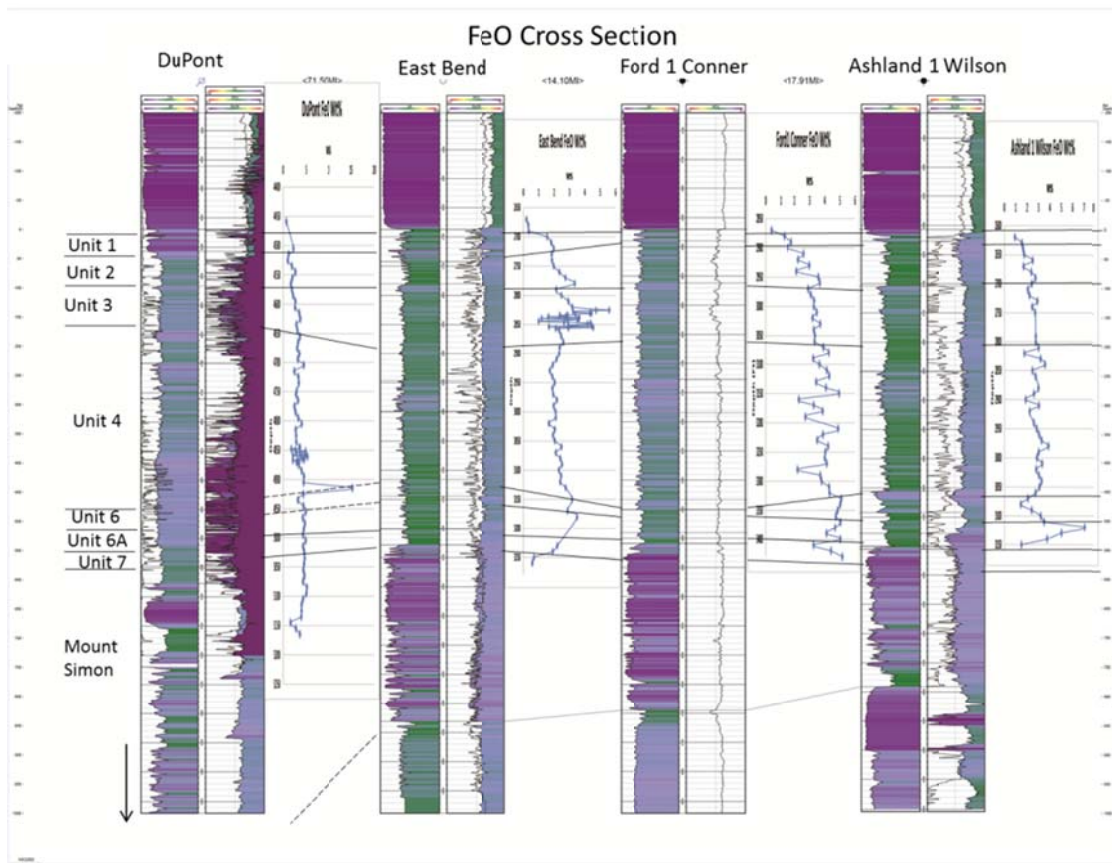
Figure 3.85. FeO results (light blue line) plotted against geophysical log responses from west to east in the wells sampled. High concentrations to right on each chart. Unit subdivisions of the Eau Claire/Conasauga interval are also shown. The East Bend well is the Battelle No. 1 Duke Energy well.
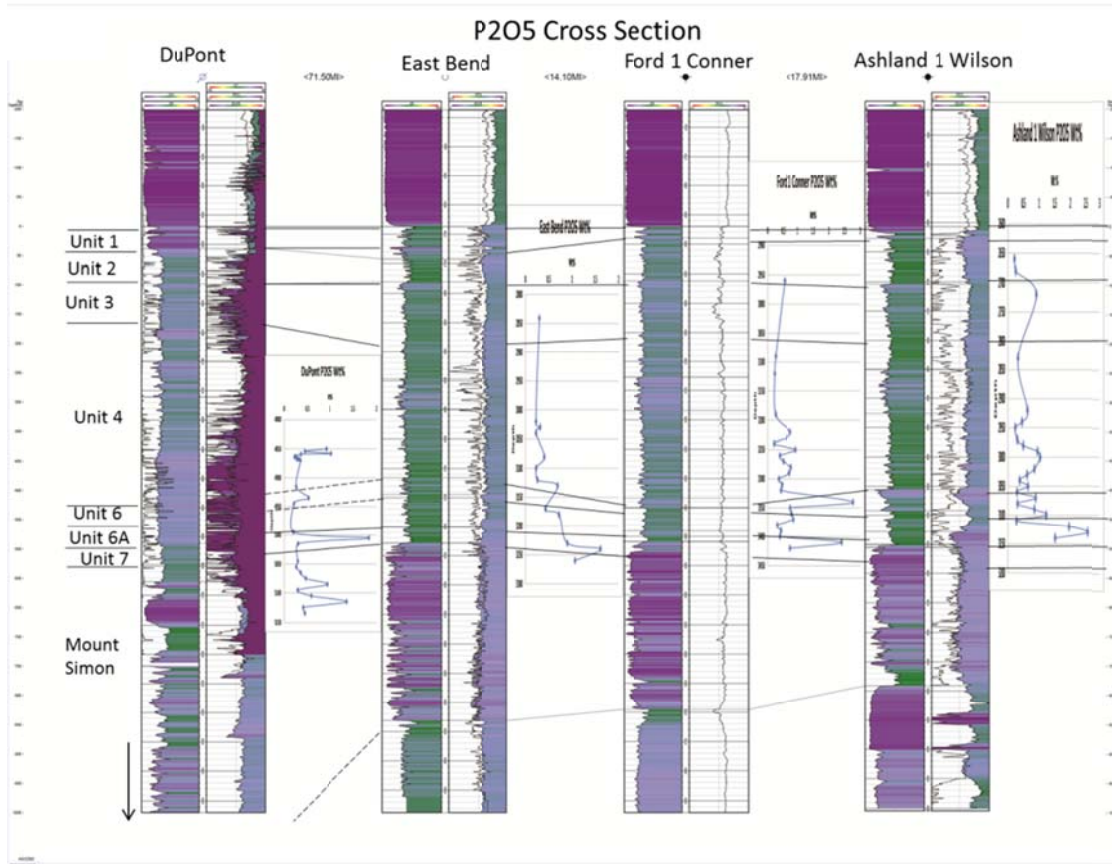
Figure 3.86. P$_2$O$_5$ results (light blue line) plotted against geophysical log responses from west to east in the wells sampled. High concentrations to right on each chart. Unit subdivisions of the Eau Claire/Conasauga interval are also shown. The East Bend well is the Battelle No. 1 Duke Energy well.

and Fe$_2$O$_3$ oxides in Unit 2 (part of the Nolichucky Shale), which is the most widespread shale in the study interval; Unit 4 (part of the Maryville Limestone), as an example of the middle of the study interval; and Unit 7, the immediate cap above Mount Simon Sandstone.

Figure 3.90 shows higher CaO concentrations in Unit 2 in the eastern part of the study area in the DuPont well, which was not expected since carbonates increase to the east in the study interval. Concentrations of K$_2$O and Fe$_2$O$_3$ did not change very much stratigraphically or laterally in the remaining wells. Figure 3.91 shows lateral changes in concentration within Unit 4
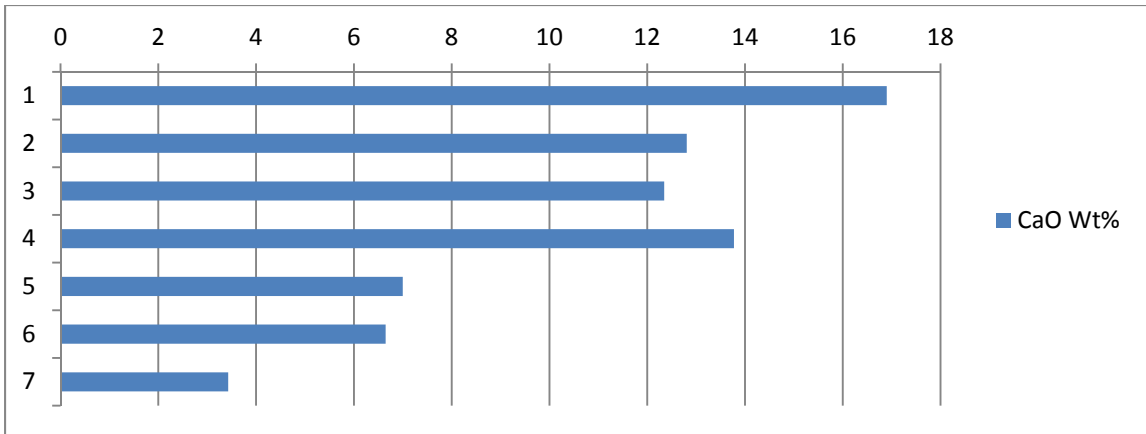
Figure 3.87. Handheld XRF results summarized by unit for the wells sampled. Y axis is weight percent CaO.
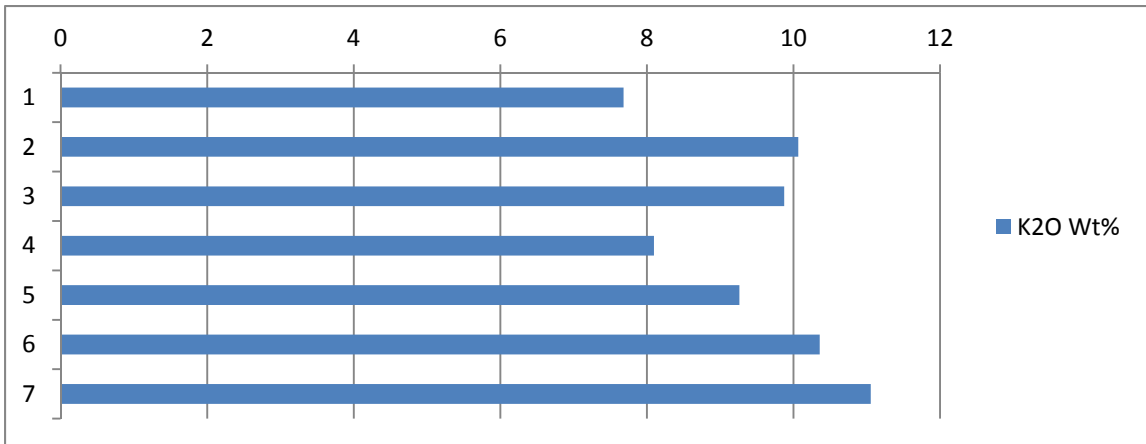
Figure 3.88. Handheld XRF results summarized by unit for the wells sampled. Y axis is weight percent K_2O.
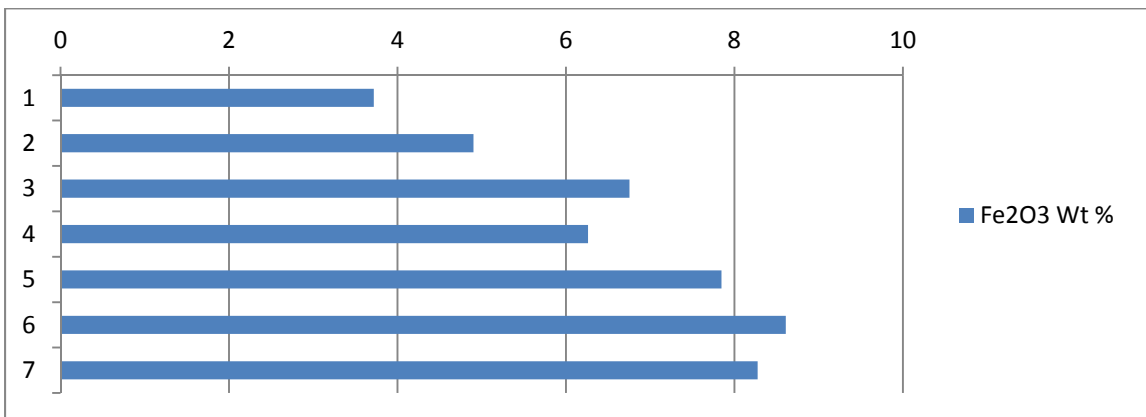
Figure 3.89. Handheld XRF results summarized by unit for the wells sampled. Y axis is weight percent Fe_2O_3.
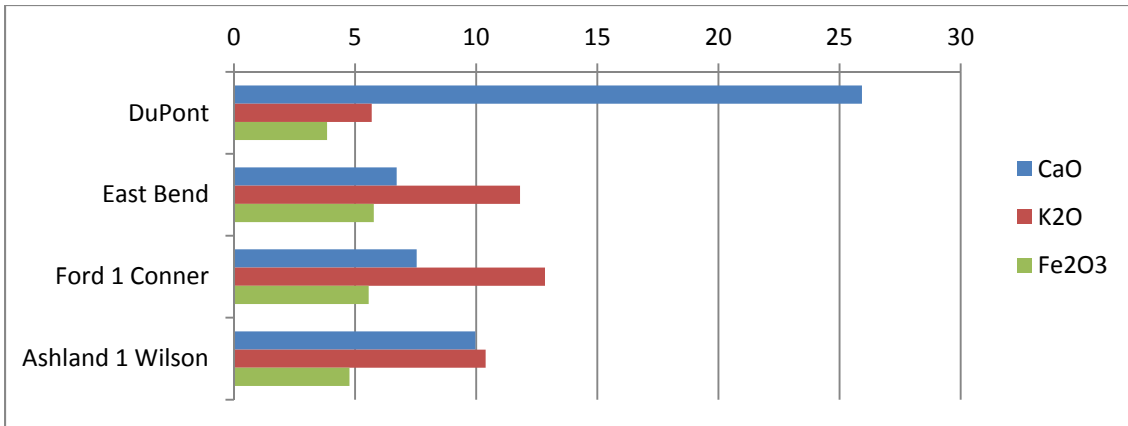
Figure 3.90. Handheld XRF results with concentrations of CaO, K_2O, and Fe_2O_3 within Unit 2 for each well. X axis in weight percent.
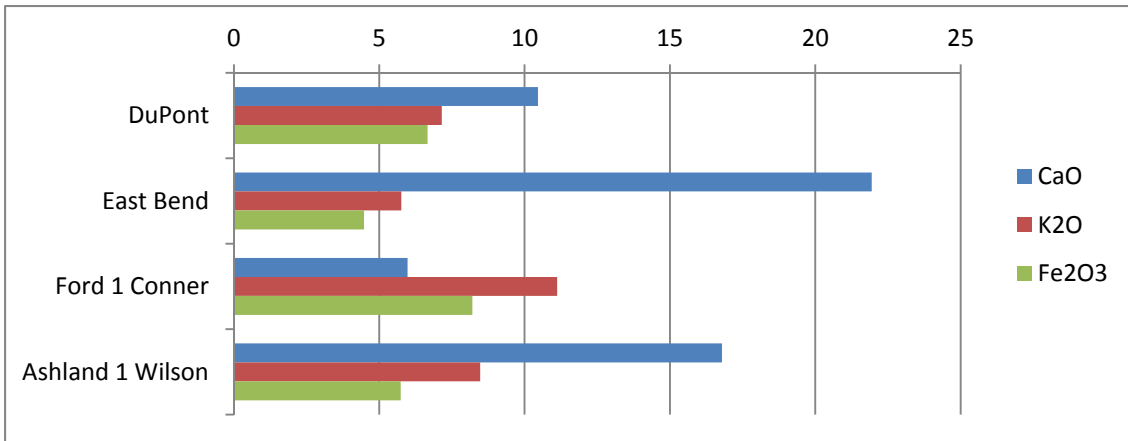
Figure 3.91. Handheld XRF results with concentrations of CaO, K_2O, and Fe_2O_3 within Unit 4 for each well. X axis in weight percent.
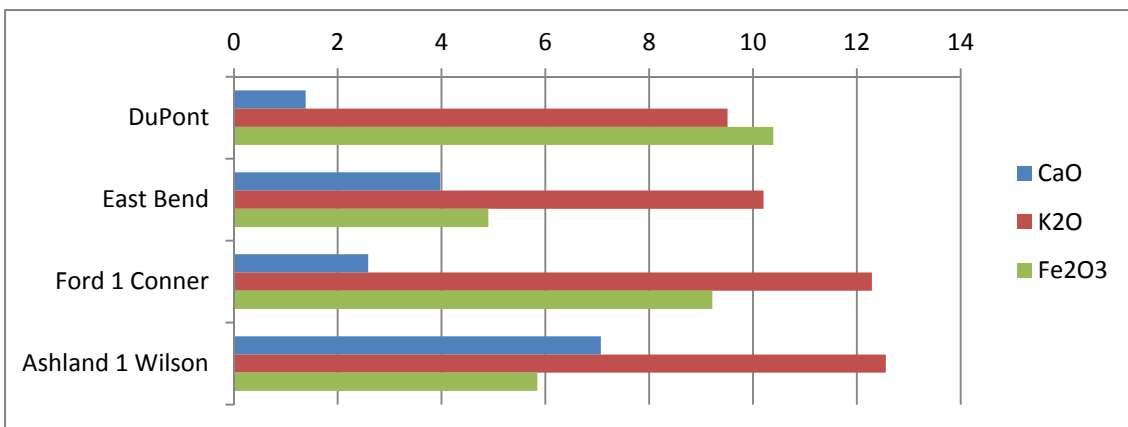
Figure 3.92. Handheld XRF results with concentrations of CaO, K_2O, and Fe_2O_3 within Unit 7 for each well. X axis in weight percent.

across the study area. Concentrations of CaO were highest in the Battelle No. 1 Duke Energy

(East Bend) and Ashland No. 1 Wilson wells in central and western Kentucky, while K_2O and

Fe_2O_3 did not change greatly (although were slightly higher in the lower units). Figure 3.92

shows lateral variation in concentration for Unit 7. Concentrations of CaO increase eastward,

which is expected as carbonates tend to increase eastward throughout the interval.

Concentrations of Fe_2O_3 show an inverse relationship and are greatest in the west and smallest

in the east. Iron concentrations are also slightly higher (5%) in Unit 7 than in Units 2 and 4.

Concentrations of K_2O did not vary across the study area much, nor did they show any distinct

vertical or lateral trends.

Overall, the hand-held XRF data shows major element and oxide variation within the

study interval (both stratigraphically and geographically). Results may help to guide future

modeling work or sampling for specific minerals of interest to CO_2 storage projects.

CHAPTER 4: DISCUSSION AND CONCLUSION

Depositional Model for the Eau Claire/Conasauga interval

The Conasauga Group was deposited as part of a thick, Cambro-Ordovician passive

margin sequence (Srinivasan and Walker, 1993). Rodgers (1953) identified three distinct phases

in Conasauga deposition. The first was a succession predominantly characterized by carbonate

lithofacies deposited to the east and southeastern sections of what was then the eastern edge

of the North American continent. The second phase was a western and northwestern

deposition of shales. The third phase was a succession in central areas between the carbonates

and shales where the shales and carbonates interbedded with each other (Rogers, 1953). The

Conasauga Group was deposited in a regional intrashelf depocenter. This depocenter consisted

of an intracratonic basin (shales) and a carbonate platform. Markello and Read (1981, 1982)

and Glumac and Walker (2000) interpreted Conasauga carbonates as carbonate platform

deposits, which graded downdip into deeper-water carbonates, and Conasauga shales in Virginia

and Tennessee.

Correlations and the subsequent cross sections created for this research support

previous   depositional models by Markello and Read (1981, 1982) and Glumac and Walker

(2000), but in a lower accommodation setting north of the Rome Trough. Also, in the study

area, the Conasauga carbonates in the east grade downdip into Eau Claire shales. Most of the

unit subdivisions used in this report are coarsening-upward (or grading upward from shales into

carbonates) in some part of the study area. In Tennessee and Virginia, intervals in the

Nolichucky Formation that coarsen upward were interpreted to be shallowing-upward cycles

(Markello and Read, 1982; Glumac and Walker, 2000). In this study interval, the upper part of

Units 2, 3, 3A, 4, 4A, 5, 6, 6A, and 7 are coarsening-upward across part of the area (e.g. Figs. 3.4,

3.8, 3.9). This suggests multiple shallowing-upward cycles and carbonate progradations, likely controlled by changes in sea level. Where carbonates interfinger with shales and silts in central portions of the study area, the coarsening-upward intervals are sharply capped by shales, which may indicate marine flooding surfaces. In times when sea level was lower, Conasauga carbonates migrated further west. When sea level was higher, Eau Claire shales migrated further east.

Sandstones are more prevalent within the lower sections of the study interval than previously noted. These sandstones could have been contributed from the Kerbel "delta" or Kerbel source area in north Ohio (Janssens, 1973). Sandstones noted in Units 3 through 7 are in the interval included in the proposed Sandusky Formation to the north in Ohio (Baranoski, 2007). Sandstone core in Unit 7 was examined in the ODNR 2627 American Aggregates well, Warren County, Ohio, and is composed of churned and bioturbated sandstone (Figs. 3.28 and 3.46), which was likely deposited as marine sands Unit 6 and 7 sands contain relatively high concentrations of phosphorous, likely phosphates, which are also marine indicators (Fig. 3.86). Sandstones in Unit 6 cores also contained glauconite, which is also a marine indicator (Boggs, 2001; Bharat, 2011).

Units 4 and 5 are similar carbonate lithologies. They make up the upper and lower portions of the Maryville Limestone in the east. The Maryville limestone thickens greatly over the Rome Trough eastward (Figs. 3.7 and 3.9) indicating substantial movement along faults within the Trough during deposition. Units 4 and 5 have two to three tongues of carbonate extending westward into the Eau Claire shales and siltstones, (Figs. 3.4, 3.5, and 3.6) to the Grenville Front. This indicates a possible depositional influence by the Grenville Front. Markello and Read (1982) interpreted Conasauga carbonates as gradually dipping down a ramp into

deeper water shales and siltstones. Cross sections for this report in Units 3, 4, and 5, (Maryville

Limestone) appear to be able to be correlated for relatively long distances (Figs. 3.4, 3.5, and

3.6). Therefore, these units most likely represent shallow dipping ramp deposits. Glauconite is

present in core, supporting marine deposition. Dolomites within Unit 4 of the Aristech well

showed clotted thrombolytic texture, as well as abundant fossil shell and trilobite fragments,

indicative of shallow marine deposition.

The top of Unit 3 is the top of the Maryville Limestone in extreme eastern sections of

the study area. Unit 3 in core from the Battelle No. 1 Duke Energy well and the ODNR DGS 2627

wells consisted of mixed clastics and carbonates, with fossil brachiopod shells and trilobite

fragments (Fig. 3.42), and flat-pebble conglomerates. Unit 3 in the U.S. Chem/U.S. Steel No. 1

well core, to the east, contained some sandstone. Sandstones were churned, from bioturbation

or higher energy deposition. Unit 3 thickens into the Rome Trough (Fig. 3.7 and 3.9) showing

continual movement of the faults within the trough during deposition, but does not show

significant thickness (e.g. Fig. 3.24), structural (Fig. 3.15), or lithologic (e.g., Fig. 3.5) change

across the Grenville Front.

Unit 2 is continuous across the entire study area, except in extreme eastern sections of

the study area where it pinches out into Conasauga carbonates. Unit 2 is the main part of the

Nolichucky Shale. The Nolichucky has previously been interpreted as deeper water shales

(Markello and Read, 1982; Glumac and Walker, 2000), which suggests flooding of the underlying

Conasauga ramp and platform. Unit 2 in core from the Warren County well (Fig. 3.46) and the

USS Chem/U.S. Steel No. 1well (Fig 3.69) contained abundant trilobite fragments, brachiopods,

and graptolites, supporting marine deposition and possibly deeper than underlying carbonates.

Unit 2 also thickens into the Rome Trough but less so than Unit 3, indicating decreased subsidence in the trough.

Unit 1 is the Maynardsville Limestone and marks a return to carbonate deposition across much of the study area. This limestone has previously been interpreted as a peritidal carbonate platform to carbonate ramp deposit (Markello and Read, 1982; Glumac and Walker, 2000). In this study, dolomites within core examined for Unit 1 or in the upper part of Unit 2 where it was transitional with Unit 1 exhibited a variety of features including thin cryptalgal laminated and nodular dolomite, flat-pebble conglomerates (eg. Fig. 3.49), oolitic limestone, and thrombolites, which all occur in shallow marine environments. Feldmann and McKenzie (1986) noted that modern thrombolites can be found in the Bahamas, in subtidal environments. Glumac and Walker (2000) placed thrombolites in agitated, shallow, subtidal ramp to platform margins and patch reefs. Unit 1 also contained ooids, which are common in shallow-marine shoal environments (e.g., Prothero and Schwab, 1996). Markello and Read (1982) place ooid shoals in the upper part of the carbonate ramp marginal to the platform. Flat-pebble conglomerates were placed near the top of subtidal succession in the Maynardsville Limestone in Tennessee (Glumac and Walker, 2000).

Unit 1 thins westward before pinching out beneath the Knox Dolomite (Fig. 3.4). The pinchout is either (1) depositional, (2) a truncation by the overlying Knox Group, or (3) could possibly represent a dolomitic transition between the Conasauga and the Knox.

Similarities Between the Maynardsville Limestone (Unit 1) and Davis Limestone (Lower Knox Group)

The Maynardsville Limestone is the uppermost Conasauga limestone in the eastern part of the study area. The Maynardsville pinches out to west beneath the Knox Group. To the west, there is a limestone above the Eau Claire Formation and beneath the Knox called the Davis Limestone in Indiana (and the DuPont No. 1 WAD fee well). The Davis in Indiana is within the lower part of Knox Group. Core examined in this thesis in the DuPont well and ODNR DGS 2627 American Aggregates well (Figs. 3.36, 3.47) are very similar to Maynardsville core in the U.S. Chem/U.S. Steel No. 1 well. Both contain abundant oolitic dolomite or dolomitic limestone and thrombolites. Thrombolites reached their peak abundance during the late Cambrian (Kennard and James, 1986), and this could just be repetition of similar facies. However, the similarity of facies might also indicate the possibility that the lower Davis of the Illinois Basin is an equivalent of the Maynardsville in the Appalachian Basin. Perhaps, dolomitization during Knox deposition is the reason for differences in present stratigraphic correlations, more than distinctly different depositional episodes. More work would be needed to test biostratigraphic correlations between the units to determine if they are actually correlative.

Caprock Suitability

To qualify as an acceptable confining interval, a formation must have (1) low permeability, (2) should be thick, (3) should be laterally continuous, (4) should be relatively homogenous, and should be (5) unfractured (Downey, 1994; Selley, 1998). The depth of the reservoir and overlying caprock, permeability of the caprock, and the mechanical integrity of the cap-rock are important variables to consider in any injection reservoir (Reichle and others, 1999; Bach and Adams, 2003). For effective CO_2 storage, the confining interval must also exhibit

mineralogy that will not be degraded by interaction with CO_2 or acidity produced by CO_2 (eg.,

Wickstrom and others, 2005; Neufelder, 2011).

This study examined lithology (lateral and vertical variability), thickness, mineralogy,

and available data on porosity, and permeability of the Eau Claire/ Conasauga interval in the

study area. From these results some preliminary assessments can be made of caprock suitability

above the underlying Mount Simon and or basal sandstone, which can be used in future

modeling projects. These results also show areas where more data is needed.

Porosity and Permeability

New porosity and permeability data were not collected in this study. However, existing

data collected from core in regional on-going carbon storage research was collected and

analyzed relative to the geologic sub-units of the Eau Claire/Conasauga interval correlated in

this study. Some modelers have determined that permeabilities of 0.01 md or less prevent

vertical leakage of CO_2 from underground storage reservoirs (e.g., White and others, 2003).

Others have suggested much smaller permeabilities may be needed. Permeabilities from 10^{-6}

to 10^{-8} darcys are cited for good caprock in the Schlumberger oilfield glossary(2012), and

permeabilities of 10^{-21} to 10^{-23} m2 [which is 10^{-12}-10^{-15} md] were cited by Deming (1994) for

pressure seals that would last for time spans of millions of years.

Preliminary modeling of the test CO_2 injection at the Battelle No. 1 Duke Energy well at

the East Bend power station in Boone County, showed that the permeabilities recorded in Eau

Claire core from the well (0.0004 to 0.602 md)(Table 3.8) were sufficient to act as a seal and the

injection test was permitted. Injection went as planned, and monitoring since the injection, has

shown no evidence of leakage from the reservoir (Battelle, 2012). As part of the Arches

modeling project (Sminchak and others, 2012), analyses of down-hole well logs, existing

permeability data in the region, and a few capillary-entry pressure data were used to define an average permeability value for regional modeling on the Cincinnati Arch (where the Eau Claire-Conasauga interval is mostly shale) of 7.6 x 10^{-5} md, which suggests the unit (where shale rich) should be a good seal. Scherer and others (2010) calculated porosities of 1.3274 x 10^{-5} md (13.274 nd), 7.124 x 10^{-6} md (7.124 nd), and 2.4011 x 10^{-5} md (24.011 nd) from samples taken from core for the Eau Claire Formation in the Battelle No. 1 Duke Energy well, using a beam-bending method.

Two values within Units 3 and Unit 7 are higher than 0.1 md. The two higher values from Unit 3 (11.8 md and 0.6 md in Table 3.8) in the Battelle No. 1 Duke Energy well were noted as fractured, chipped, or unsuitable for permeability measurement. Fractured samples are not uncommon in shale core, and could be the reason for the higher values. The two relatively high values for Unit 7 (0.4 md and 26.8 md) in the U.S. Chem/U.S. Steel No.1 well have no indication that they were fractured or damaged. They are, however, from a potentially sandy zone based on the log signature. Sandy zones in the interval might be expected to have higher permeabilities than shales.

The western part of the study interval is dominated by carbonates in the Maryville Limestone of the Conasauga Group. Although there is no permeability data for this interval, porosities on density logs are generally low when looking at available bulk density curves.

Lithology and Lateral Variability

Thick, homogenous shales and anhydrites are the rock types typically associated with low-permeability stratigraphic traps or seals in oil and gas reservoirs, although carbonates can also be effective seals (Downey and others, 1984). The Eau Claire/Conasauga interval is not a laterally continuous, thick, homogenous shale. It is shale dominant in the west, carbonate in the

east, and is mixed shale and carbonate in between. Anhydrites are noted in the Maryville Limestone in the USS Chem core but are not thick, laterally extensive beds.

Unit 7 would serve as the primary or immediate seal of an underlying Mount Simon or basal sandstone reservoir, since it is at the very base of the Eau Claire/Conasauga interval. It is laterally heterolithic and has some sandy intervals, although it looks like a low porosity unit across much of the study area. The most homogenous shale is in Unit 2, which is equivalent to the Nolichucky Shale of the Conasauga (Figure 3.4, 3.5, and 3.6).

Unit 1, Unit 3, Unit 4, Unit 5, and Unit 6 all have carbonates within them to various degrees both vertically and laterally across the study area. Carbonates increase in thickness eastward to as much as 600ft thick and constitute the dominant lithology. Observations of density porosity logs through the carbonates shows that they appear to have low porosity.

Thickness of Shales

Thicknesses of the shale portion of the Eau Claire/Conasauga interval range from approximately 300 ft to more than 500 ft in the western part of the study area. Many of these shales are silty. Unit 2 (Nolichucky Shale), has the highest gamma readings and in core from U.S. Chem/U.S. Steel No.1 and ODNR DGS 2627 well appears to be more clay rich and less silty (Fig. 3.52 and 3.53). Unit 2 ranges from approximately 30 ft to 120 ft It is the first unit with relatively uniform lithology (based on log response) over the entire interval.

Overlying the entire Eau Claire/Conasauga interval is the Knox Supergroup of carbonates, which would serve as secondary caprocks, should breached CO_2 be able to rise all the way through the entire Eau Claire/Conasauga interval. On the Cincinnati Arch, the base of the Knox is near sufficient depth (2,500 ft) to keep CO_2 in supercritical conditions. Laterally off

the arch in both directions, that depth increases (Figs. 3.4-3.9), (Greb and others, 2009). The ultimate regional seal in the region is the Upper Ordovician Maquoketa Shale to the east, off of the Arch, where it is more than 2,500 ft deep (Greb and Solis, 2009). Eastward in the Appalachian Basin, thick shales also occur in Upper Ordovician strata but data is not available to determine if they have similar low permeabilities to the Maquoketa. The next sealing unit is the Devonian shale sequence that is present on both sides of the Arch.

Mineralogy of Caprock

Mineralogy is an important component of caprock integrity, especially relative to CO_2 storage. Mineralogies, such as dolomite and calcite can be reactive with sequestered CO_2 (Frailey and others, 2005; Wickstrom and others, 2005). Caprock studies of the Eau Claire Formation in Illinois indicate that Eau Claire shale reactivity is low and limited to the caprock interface (Liu and others, 2012). Neufelder (2011) reported that minerals such as dolomite, ankerite, glauconite, calcite, chlorite, and feldspars could be reactive with sequestered CO_2 in the Eau Claire Formation. Carbonate and feldspar dissolution are possible reactive components of the shale. Hand-held XRF data collected in this study showed variation in potassium, iron, and calcium stratigraphically and geographically within the study interval (Figs. 3.87-3.92). XRF results could help guide future sampling or modeling relative to caprock mineralogy. Higher concentrations of Ca (as CaO) could mean a presence of carbonate minerals. Higher concentrations of K (as K_2O) could mean a presence of potassium feldspar, or glauconite. Higher concentrations of Fe (as FeO or Fe_2O_3) could mean the presence of pyrite or glauconite. Special focus was placed on interpreting results from Units 2, 4, and 7, as Unit 7 is the immediate caprock over the Mount Simon reservoir, Unit 2 is the thickest, most continuous shale in the study interval, and Unit 4 is representative of the interval between.

The majority of the Eau Claire Formation is shale and silty shale. XRF data (Fig. 3.84) and thin sections show it is dominated by silica (SiO_2), which should be non-reactive to CO_2. Cements in these shales, however, are variable and sometimes carbonate (Fig. 3.44), which could be reactive with sequestered CO_2. To the east, the majority of the Conasauga Group, is composed of carbonates, that are potentially reactive to CO_2 but also would be buffering to acids. Maryville carbonates are variably dolomitic. More work is needed on the mineralogy of this heterolithic interval.

Fractures and Faulting

Permeability as a function of rock type, assumes no fractures through the lithology. A fracture through an interval with low porosity and low permeability, however, will compromise the cap, allowing a pathway through the seal. Fracture analyses was not part of this study, but increased fractures are possible where syn-depositional structural influences are indicated. Faults within the Rome Trough were active during deposition of Units 3 through 7. These units thicken greatly across the trough, due to increased accommodation space created by faulting (Figs. 3.7, 3.24, 3.25, 3.26). Units 1 and 2 are more uniformly thick relative to units below them, and do not thicken as much over the trough, suggesting the faults were less active towards the end of Conasauga deposition (Fig. 3.7).

Conclusions

The purpose of this thesis research was to perform a detailed geological study of the Eau Claire Formation and equivalent parts of the Conasauga Group in part of the Ohio River Valley region in order to better evaluate its suitability as a confining interval for the underlying Mount Simon Sandstone and Basal sandstone equivalents. Detailed correlations of subsurface data using available geophysical logs, cores, and thin sections and cuttings were used to

correlate facies between the Eau Claire Formation in western and central Kentucky and the

Conasauga Group in eastern Kentucky and neighboring areas. Additional information on the

confining potential of the Eau Claire and Conasauga Formations was obtained through available

permeability data and performing XRF analyses, which were keyed to the correlations. The

following conclusions can be made based on the data in this thesis:

1. Comprehensive correlations between Conasauga Group and Eau Claire Formation were
   created in the study area. The Eau Claire/Conasauga study Interval was divided into 7
   identifiable units using available geophysical log data.

2. A new lateral relationship between the Mount Simon Sandstone and basal sands/lower
   Conasauga in Unit 7 was discovered through correlations, in that the basal sands drape
   over the Mount Simon Sandstone from the northern lip of the Rome Trough, until
   pinching out northwestward.

3. Structural controls on the study interval by the Grenville Front are interpreted for Units
   4 through 7, because of thickness and lithology changes across the Front. Carbonates of
   Units 4 and 5 are restricted to the area east of the Front.

4. Similarities between the Maynardsville Limestone of the Appalachian basin and Davis
   Limestone of the Illinois basin suggest that similar shallow-water carbonate facies were
   recurring through this interval or possibly that the part of the Davis Limestone may be a
   Maynardsville equivalent.

5. The Eau Claire Formation is generally considered to be a good caprock to the east in the
   Illinois Basin. Modeling for the Arches Simulation project found it would be a good seal
   in part of the arches province. Westward toward the Appalachian Basin, however, the
   unit is much more heterogeneous; has much more carbonate; and lacks permeability

data. More work is needed on caprock characterization of this interval in the western part of the study area.

6. XRF data was collected on several core and cuttings as an experiment on the usefulness of handheld xrf's for stratigraphic and mineralogic assessment. Results showed variation geographically across the study area, and vertically through the seven units within the Eau Claire/Conasauga interval. Although not necessarily dependable as absolute measurements, handheld XRF analysis can detect the presence or absence and comparative, relative abundance of an element, which may help future modeling and data collection.

7. TOC data were collected, but very low organic carbon concentrations were indicated.

8. More sands are present than have been previously been reported in the Eau Claire/Conasauga interval. Sands occur as distinct sandstones and as sandy carbonates. These sands are likely equivalent to what Baranoski (2011) considers the Sandusky Formation northward in Ohio. More data needs to be collected on the permeability and distribution of these sandstones.

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VITA

Ralph Edward Bandy III

Education

B.S. Geography, East Tennessee State University, 2006. B.S. Geology, East Tennessee State University, 2007.

Professional Experience

Geologist I, Marshall Miller and Associates, Kingsport, TN, Bluefield VA, 2007-2010.

Publications

Bandy, Ralph Edward III; Greb,Stephen F; and Solis, Michael P; 2012: Characterization of the Cambrian Eau Claire Formation as caprock for carbon sequestration into the Mount Simon Sandstone in Kentucky, Geological Society of America Abstracts with Programs, Vol. 43, No. 5, p. 279