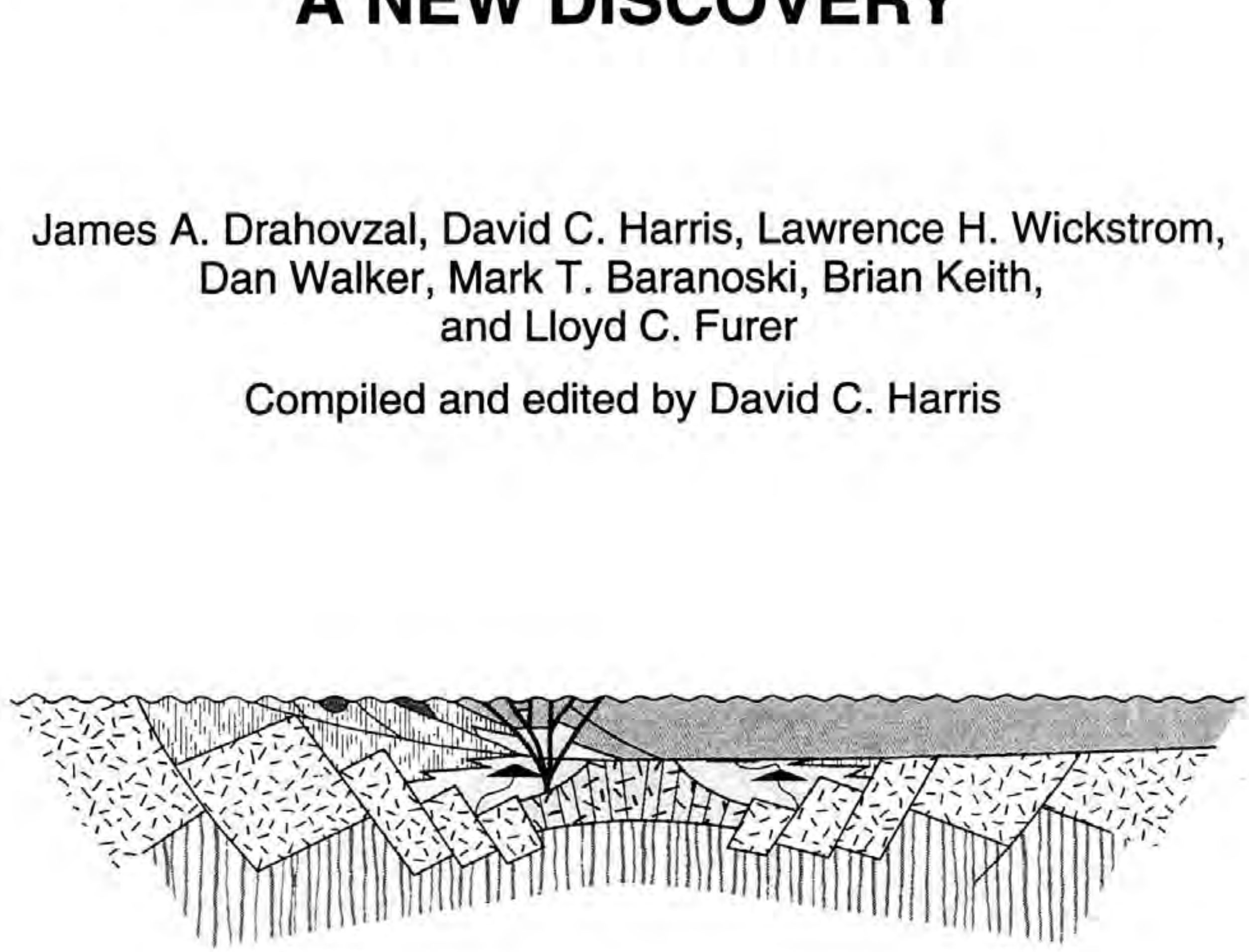
KENTUCKY GEOLOGICAL SURVEY
Donald C. Haney, State Geologist and Director
University of Kentucky, Lexington

THE EAST CONTINENT RIFT BASIN: A NEW DISCOVERY

James A. Drahovzal, David C. Harris, Lawrence H. Wickstrom,
Dan Walker, Mark T. Baranoski, Brian Keith,
and Lloyd C. Furer

Compiled and edited by David C. Harris



CINCINNATI ARCH CONSORTIUM

INDIANA GEOLOGICAL SURVEY
KENTUCKY GEOLOGICAL SURVEY
OHIO DEPARTMENT OF NATURAL RESOURCES
DIVISION OF GEOLOGICAL SURVEY

SPECIAL PUBLICATION 18
SERIES XI, 1992

PUBLISHED ALSO AS:

Indiana Geological Survey **Special Report 52**

Ohio Department of Natural Resources **Information Circular 57**
Division of Geological Survey

Prepared and published by the Kentucky Geological Survey
Lexington, Kentucky 1992

ISSN 0075-5613

KENTUCKY GEOLOGICAL SURVEY
UNIVERSITY OF KENTUCKY, LEXINGTON
Donald C. Haney, State Geologist and Director

THE EAST CONTINENT RIFT BASIN: A NEW DISCOVERY

James A. Drahovzal
David C. Harris
Lawrence H. Wickstrom
Dan Walker
Mark T. Baranoski
Brian D. Keith
Lloyd C. Furer

Compiled and edited by
David C. Harris

CINCINNATI ARCH CONSORTIUM
Indiana Geological Survey
Kentucky Geological Survey
Ohio Department of Natural Resources,
Division of Geological Survey

SPECIAL PUBLICATION 18 **SERIES XI, 1992**

CONTENTS

TABLE

ILLUSTRATIONS

Figure **Page**

THE EAST CONTINENT RIFT BASIN: A NEW DISCOVERY

James A. Drahovzal[1]

David C. Harris[1]

Lawrence H. Wickstrom[2]

Dan Walker[1]

Mark T. Baranoski[2]

Brian D. Keith[3]

Lloyd C. Furer[3]

ABSTRACT

The presence of a Precambrian sedimentary basin in the eastern Midcontinent, while suspected from geophysical evidence for years, was not proven until the Ohio Geological Survey cored lithic sandstones below the Mount Simon Sandstone in Warren County, Ohio, in 1988. This sandstone, the Middle Run Formation, was deposited in a fault-bounded basin herein named the *East Continent Rift Basin* (ECRB). Gravity and magnetic data, well samples, cores, geophysical logs, and seismic reflection data have been used to interpret the extent, origin, evolution, and economic potential of the basin.

The known distribution of the Middle Run Formation extends from Putnam County, Ohio, in the north, to Jessamine County, Kentucky, in the south, and to Fayette County, Indiana, in the west. Middle Run clastics are unconformably overlain by the Cambrian Mount Simon Sandstone in most areas. The age of the Middle Run Formation is interpreted to be Precambrian, based on its stratigraphic position and lithologic similarity with known Precambrian sandstones in the Great Lakes region. Sandstones are red-gray lithic arenites containing abundant volcanic rock fragments, and were deposited in an arid continental setting. Basalt overlies and is interbedded with Middle Run clastics in two wells. Trace-element geochemistry of these associated basalts is similar to Keweenawan continental flood basalts in the Lake Superior area.

The basin in which the Middle Run Formation was deposited is bounded on the east by the Grenville Front and on the west by normal block faulting. Gravity and magnetic data suggest that the basin is connected on the northern end with the Midcontinent Rift System (MRS) in southern Michigan. The southern boundary is poorly defined, but the basin may extend into northern Tennessee. Magnetic modeling and seismic interpretation indicate that the basin deepens eastward, reaching depths of 27,000 feet below sea level on its eastern side under the Cincinnati Arch. The sedimentary and volcanic fill is as much as 22,500 feet thick. Structural interpretations of seismic data indicate that the basin predates the Grenville Orogeny, and has been overridden in part by Grenville thrust sheets.

---

[1] Kentucky Geological Survey

[2] Ohio Department of Natural Resources, Division of Geological Survey

[3] Indiana Geological Survey

Based on the association of basalt flows with continental red beds, geophysical continuity with the MRS, block-faulted boundaries, and a pre-Grenville timing, the ECRB is interpreted to be an eastern branch of the MRS. Rifting is interpreted to be middle Proterozoic (Keweenawan) in age, but reliable dates are presently lacking. Structures associated with the ECRB were reactivated at various times during the Phanerozoic, and may have influenced Paleozoic stratigraphy. No evidence of hydrocarbon source or reservoir rocks has been found within the basin to date, although most of the basin remains undrilled.

INTRODUCTION

This report presents the results of a multi-disciplinary study of Precambrian rocks in the tri-state area of western Ohio, central Kentucky, and eastern Indiana. This research was conducted by the Cincinnati Arch Consortium (CAC), a group consisting of the Ohio, Kentucky, and Indiana Geological Surveys with funding from private industry. The primary result of this study is the definition of a previously unrecognized rift complex, which is herein named the *East Continent Rift Basin* (ECRB). The basin is a regionally extensive feature, extending from northwestern Ohio to central Kentucky, and westward across Indiana. It is interpreted to be an extension of the middle Proterozoic (Keweenawan) Midcontinent Rift System (MRS).

This initial publication summarizes the main conclusions of the project and illustrates the major features of the basin. More extensive discussion of data and interpretations resulting from the project will be published in 1993 by CAC, and will be available from each state geological survey involved in the study.

This investigation began after the discovery of an anomalous sedimentary unit in the subsurface of southwestern Ohio in 1988 (Shrake and others, 1991). An Ohio Geological Survey research borehole in Warren County (ODNR DGS No. 2627) was predicted to reach crystalline basement at a depth of approximately 3,500 feet, but instead a distinctive red sandstone was penetrated below the Cambrian Mount Simon Sandstone. This new stratigraphic unit was named the Middle Run Formation (Shrake and others, 1990; Shrake, 1991).

The discovery of the Middle Run Formation generated widespread attention, and as a result of this interest the Cincinnati Arch Consortium was formed to study the new basin. The potential for hydrocarbon source rocks or reservoirs in the basin attracted oil industry interest, and six companies funded the project (*see* Acknowledgments). The project began in September 1990 and was completed in December 1991.

PREVIOUS WORK

Regional Precambrian Geology of the Tri-State Area

Phanerozoic sedimentary rocks in the study area outlined in Figure 1 were previously thought to be entirely underlain by Proterozoic rocks of the igneous Granite-Rhyolite Province in the west (Denison and others, 1984; Bickford and others, 1986), and the metamorphic Grenville Province in the east (Bass, 1960; Lucius and Von Frese, 1988; Hoffman, 1989).

The Granite-Rhyolite Province has been mapped from western Ohio and Kentucky westward to Missouri,

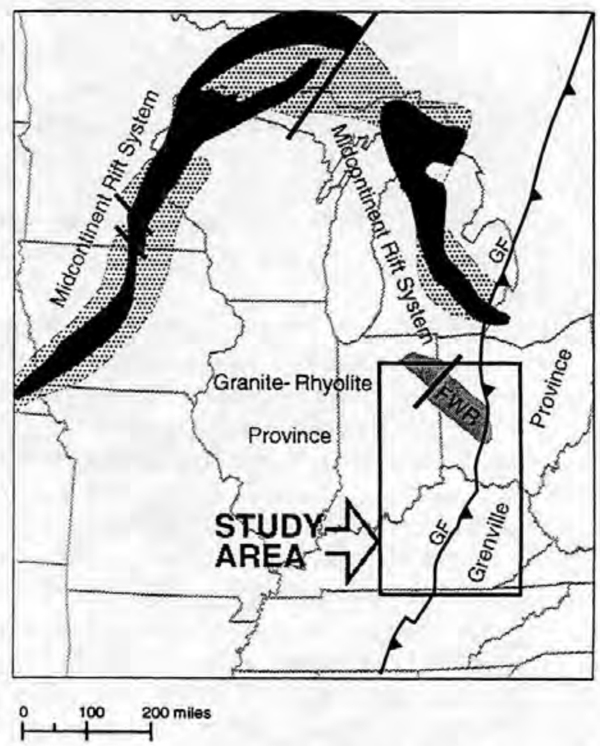


Figure 1. Index map showing relationship of Precambrian tectonic provinces and structural features in the United States Midcontinent to the study area (modified from Denison and others, 1984). FWR=Fort Wayne Rift. GF=Grenville Front.

Kansas, and Oklahoma (Denison and others, 1984). These rocks consist of rhyolite, trachyte, and fine-grained, micrographic to granophyric granite of extensional tectonic origin (Bickford and others, 1986). Radiometric dates for Granite-Rhyolite Province rocks range from 1.3 to 1.51 Ga (Hoppe and others, 1983; Bickford and others, 1986; Hoffman, 1989). The Granite-Rhyolite Province lacks significant mafic volcanic rocks, which Bickford and others (1986) attributed to shallow extensional tectonics.

The Grenville Province of the study area is an extension of the Grenville metamorphic terrane exposed in southern Canada. Rock types identified in basement wells in the study area include granite gneiss, schist, amphibolite, charnokite, and marble (Bass, 1960; McCormick, 1961; Gonterman, 1973; Keller and others, 1983; Black, 1986; Lucius and Von Frese, 1988). Grenville Province rocks have been interpreted as regionally metamorphosed igneous and sedimentary lithologies formed during a Proterozoic plate collision, the Grenville Orogeny (Moore and others, 1986; Hoffman, 1989). Subsurface Grenville rocks in the study area are significantly younger than the adjacent Granite-Rhyolite terrane, and metamorphic minerals have been radiometrically dated at 0.880 to 1.1 Ga (Lidiak and others, 1966; Keller and others, 1981; Hoppe and others, 1983; Van Schmus and Hinze, 1985; Lucius and Von Frese, 1988). In the exposed Grenville terrane in Canada, metamorphic dates of 0.920 to 1.02 Ga have been obtained from rocks nearest the front (Hoffman, 1989).

The boundary between the Grenville and Granite-Rhyolite Provinces has been interpreted by many workers on the basis of lithologic, potential field, and seismic data (Bass, 1960; Rudman and others, 1965; Muehlberger and others, 1967; Lidiak and Zietz, 1976; Denison and others, 1984; Lidiak and others, 1985; Bickford and others, 1986; Green and others, 1988; Lucius and Von Frese, 1988; Culotta and others, 1990). This boundary, the Grenville Front, runs north-south through the study area (Figs. 1–3). It is not a true metamorphic front, but rather a structural contact (Green and others, 1988; Hoffman, 1989).

Gravity Studies

The study area shown in Figure 1 encompasses several distinct features visible on gravity and magnetic anomaly maps (Figs. 2–3). Of particular relevance to this study is a chain of positive gravity anomalies that extends from southwestern Michigan to north-central Tennessee (Fig. 2). This gravity feature was named the East Continent Gravity High (ECGH) by Bryan (1975), and has also been interpreted by Mayhew and others (1982) and Keller and others (1983). The ECGH crosses the Grenville Front in western Ohio and continues east of and parallel to the front through Kentucky into Tennessee. In Michigan, the ECGH is roughly parallel to the Mid-Michigan Gravity High (Fig. 2) (Hinze and others, 1975; Dickas, 1986), and includes the Fort Wayne Rift (Fig. 2) of McPhee (1983) in northeastern Indiana and central-western Ohio. Bryan (1975) interpreted the ECGH as a possible rift zone, but the presence of a rift in this area was first suggested by Rudman and others (1965). Others have since proposed the existence of a rift zone, primarily on the basis of gravity and magnetic data, but also on the basis of seismic and lithologic data (Keller and others, 1975, 1981, 1982, 1983; Halls, 1978; Mayhew and others, 1982; Green, 1983, Fig. 1; Cable and Beardsley, 1984; Denison and others, 1984; Preziosi, 1985; Couch, 1986; Gordon and Hempton, 1986; Shumaker, 1986; Lucius and Von Frese, 1988; Pratt and others, 1989; Ullom, 1989). These rift models for the ECGH associate gravity highs with blocks of presumed mafic igneous rocks (Keller and others, 1982; Couch, 1986; Lucius and Von Frese, 1988; Ullom, 1989). Gravity modeling by these authors supports the presence of deeply rooted, dense rock in the upper basement. This mafic material is thought to represent the volcanic core of a Proterozoic rift zone. Another feature of significance on the gravity map is the Kentucky-Ohio Trough (Fig. 2), defined by Black (1986) as a late Precambrian/Cambrian basin. This linear negative gravity anomaly roughly parallels the ECGH in southwestern Ohio and central Kentucky. Similar unnamed gravity lows parallel both the Grenville Front in northwestern Ohio and the MMGH in southern Michigan.

Magnetic Studies

Distinct magnetic anomalies are also present within the study area. Magnetic anomaly patterns are largely controlled by lithologic changes, and along with drill hole and seismic data, have been used to interpret the position of the Grenville Front and rift-related volcanics in the study area. The Grenville Front (GF on Fig. 3) has been defined on the basis of a distinct north-south-trending line of high-amplitude magnetic anomalies extending from eastern Michigan through western Ohio into central Kentucky and Tennessee (Lidiak and Zietz, 1976; Mayhew and others, 1982; Denison and others, 1984; Lidiak and others, 1985). This magnetic interpretation agrees fairly well with mapped metamorphic basement lithologies (Bass, 1960; Keller and others, 1982; Lucius and Von Frese, 1988).

Magnetic anomalies coincide with some of the positive gravity anomalies, indicating deep-rooted bodies of mafic composition, possibly emplaced during rifting

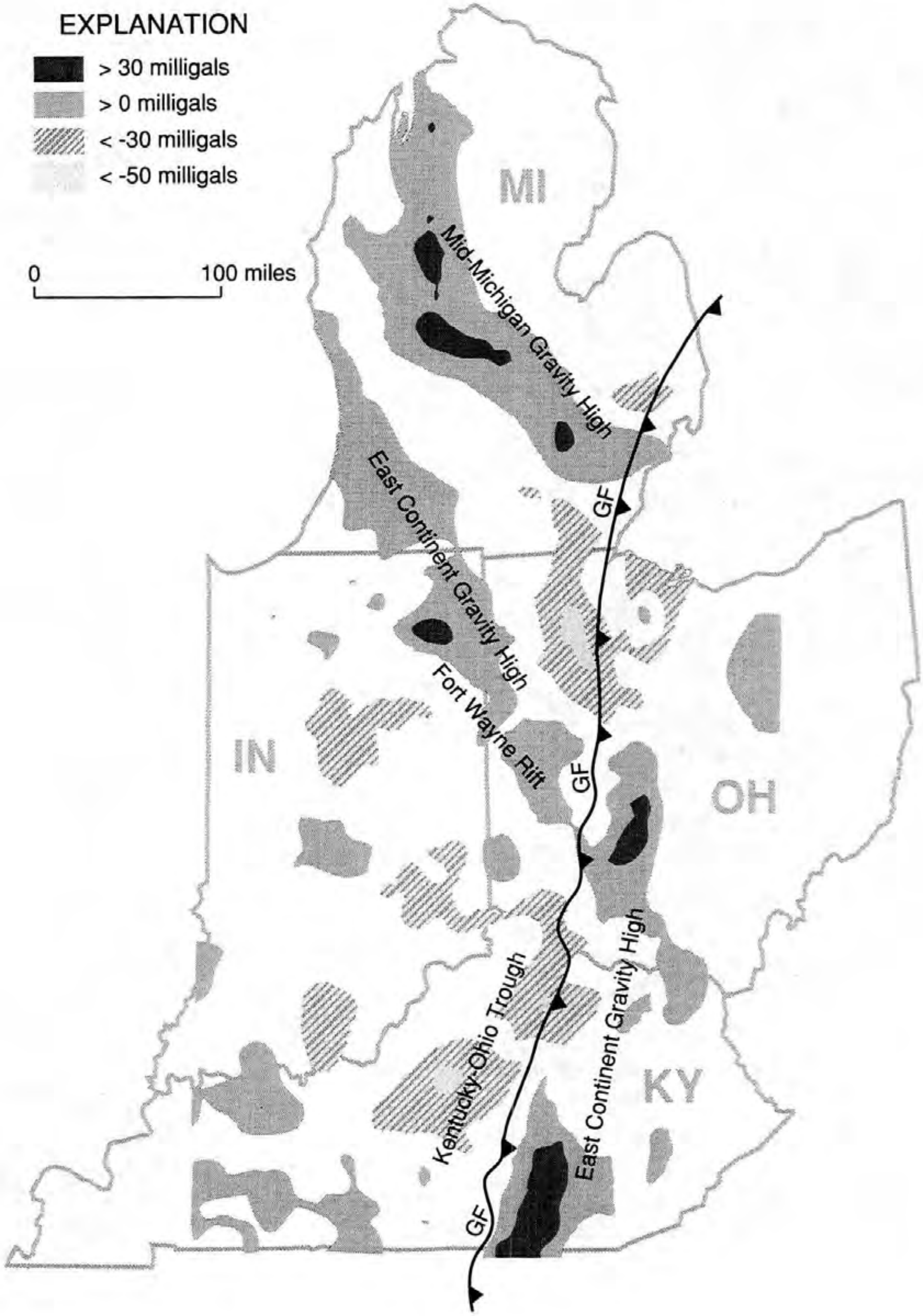


Figure 2. Regional isostatic residual gravity anomaly map of the east-central United States. Major positive and negative gravity anomalies are shaded (modified from Jachens and others, 1985). GF=Grenville Front.

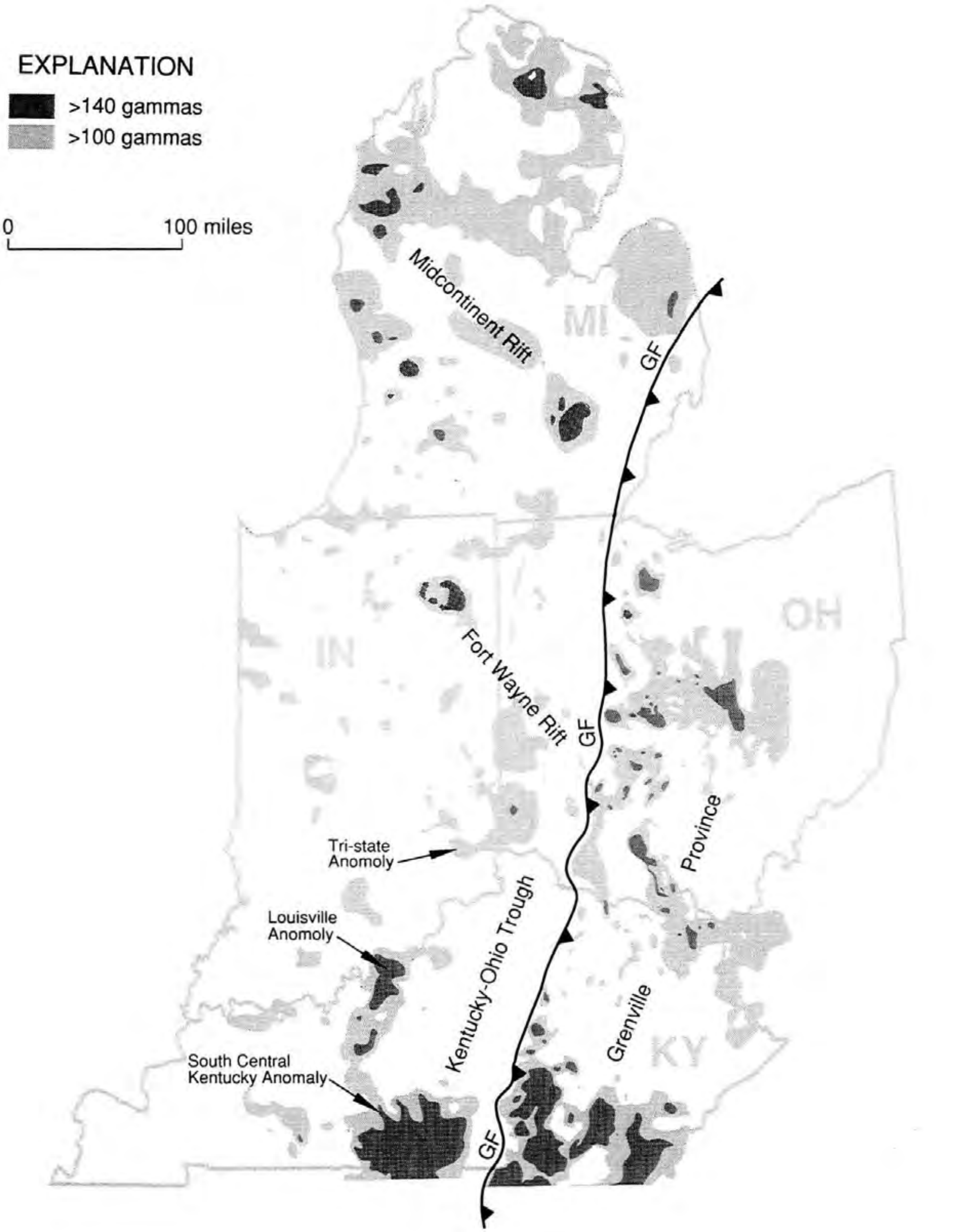


Figure 3. Regional magnetic anomaly map of the east-central United States. Positive magnetic anomalies are shaded (modified from Zietz, 1983). GF=Grenville Front.

(Keller and others, 1982, 1983; Mayhew and others, 1982; Denison and others, 1984; Lidiak and others, 1985). Mafic volcanic basement lithologies have been found associated with some of these anomalies, particularly in wells in the west-central Ohio area, and in northeastern Indiana (Fort Wayne Rift) (Denison and others, 1984; Lucius and Von Frese, 1988).

The magnetic signature of the ECGH becomes less distinct east of the Grenville Front. This fact has been used to infer a pre-Grenville timing for rifting, with rift-associated volcanics subsequently metamorphosed during the Grenville Orogeny. Metamorphism of basalts has been used to explain the origin of amphibolites in basement wells east of the Grenville Front in Ohio and Kentucky (Bass, written communication, 1970; Keller and others, 1982; Lidiak and others, 1985).

BASIN MODELS AND HYPOTHESES

The presence of a pre-Mount Simon basin in the study area has been suggested for a number of years. Wasson (1932) discussed the "red sandstones and shales" overlying possibly Keweenawan "arkose and dolomite" in an Ohio well. Pre-Mount Simon sediments have also been reported in regional Precambrian geology studies, but were never integrated into a regional model (e.g., Denison and others, 1984; Lidiak and others, 1985; Black, 1986). The discovery of a thick redbed sequence below the Mount Simon Sandstone in Warren County, Ohio, provided new data to test previous models that were based primarily on gravity and magnetic signatures. The Warren County well and subsequent seismic data acquired across the well location proved the existence of a major sedimentary basin, but its origin remained speculative (Shrake and others, 1990). The complexity of Proterozoic geology in the tri-state area allowed a variety of working hypotheses to be proposed for the new basin. These included (1) a rift basin, perhaps associated with Proterozoic or Early Cambrian extension, (2) a Grenville foreland basin, or (3) a polyphase basin with two or more phases of development (Potter and Carlton, 1991; Potter, 1989; Wolfe and others, 1989; Drahovzal, 1990; Drahovzal and others, 1990; Shrake and others, 1990).

Four types of data have been used to test these models: (1) stratigraphy and composition of the basin fill, (2) geochemistry and petrology of associated basalts, (3) regional gravity and magnetic data, and (4) structural relationships interpreted from seismic reflection and well data. Interpretation of these data is summarized in the remainder of this report.

DISCUSSION

Stratigraphy of the Middle Run Formation

The 1,922 feet of pre-Mount Simon clastics that were cored in the ODNR DGS No. 2627 borehole are the type section for a new stratigraphic unit, the Middle Run Formation, defined by Shrake and others (1990). The Middle Run Formation in the type section is remarkably homogeneous, consisting of red to gray, fine- to medium-grained, thickly bedded lithic sandstones. It is estimated to contain less than 10 percent red siltstones and shales.

Throughout most of the study area, the Middle Run Formation is unconformably overlain by the Cambrian Mount Simon Sandstone (Fig. 4). This unconformable relationship is supported by the presence of a conglomeratic sandstone at the base of the Mount Simon that contains clasts of reworked Middle Run sandstone. Seismic data from Warren County, Ohio, show a prominent angular relationship between the east-dipping Middle Run interval and the flat-lying Paleozoic section (Shrake and others, 1990; Shrake, 1991). In addition, lithic sandstones of the Middle Run Formation are compositionally and diagenetically distinct from quartzarenites of the Mount Simon.

Two wells in Kentucky contain basalt associated with Middle Run clastics (Fig. 5). Basalt overlies the Middle Run in one well, and is interbedded with clastics in the other. Sedimentary or crystalline rocks underlying the Middle Run Formation have not been penetrated to date by drilling. Within the basin, the thickness of the Middle Run Formation and associated volcanic rocks can only be interpreted from seismic or magnetic data. Seismic data from Warren County, Ohio, suggest that a basalt-dominated sequence may underlie the Middle Run Formation. This interval is characterized by seismic reflectors with high amplitude and good continuity lying below an acoustically transparent Middle Run interval (*see* ODNR-1-88 line *in* Shrake and others, 1990). The highly reflective interval is similar in appearance to the "layered Proterozoic" of Pratt and others (1989, 1992), and possibly represents interbedded volcanics and clastics.

Regional Distribution of the Middle Run Formation

After pre-Mount Simon clastics were recognized in Warren County, other basement wells in the tri-state area were re-examined for possible correlative sandstones. Intervals of pre-Mount Simon clastics were recognized in seven additional wells, and correlated with

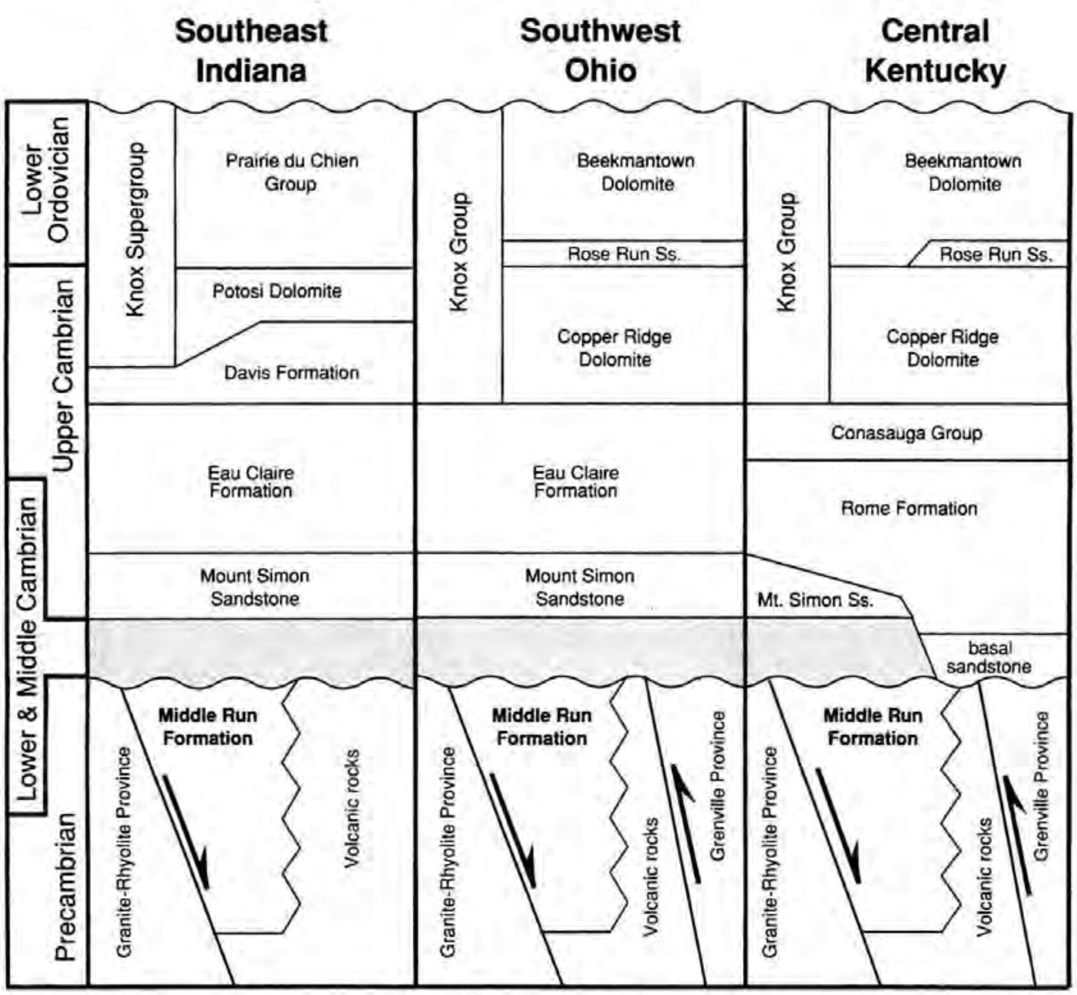


Figure 4. Pre-Knox unconformity stratigraphic correlation chart for southeastern Indiana, southwestern Ohio, and central Kentucky. Post-Precambrian unconformity between the Mount Simon Sandstone and the Middle Run Formation is indicated. No vertical or horizontal scale implied.

the Middle Run (Potter, 1989; Shrake, 1991; Shrake and others, 1991).

Another seven Middle Run localities have been identified in this study. Pre-Mount Simon sediments encountered in these wells are correlated with the Middle Run Formation on the basis of lithologic similarity and their pre-Mount Simon stratigraphic position. Previously, the pre-Mount Simon interval in these wells had been mistakenly identified as crystalline basement. These Middle Run correlations are entirely lithostratigraphic. No reliable chronostratigraphic data for the pre-Mount Simon interval are currently available to aid in correlation.

To date, 15 wells have penetrated Middle Run Formation clastics (Fig. 5). Specific information for these wells is included in Table 1. The Middle Run Formation extends from northwestern Ohio (Putnam County) to central Kentucky (Jessamine County) (Fig. 5). Wells in Fayette and Switzerland Counties, Indiana, define the known western limit of the Middle Run Formation.

Depositional Setting and Provenance

The Middle Run Formation consists of thick- to massively bedded, red to gray, fine- to medium-grained sandstones with minor red siltstones and shales. The red color of the sandstones results from both hematite grain coatings and abundant lithic grains of rhyolite. Red siltstones and shales are present in the Ohio DGS No. 2627 core (Warren County, Ohio), but comprise less than 10 percent of the interval. Sedimentary structures include large-scale crossbedding, and less abundant ripple crossbedding. Fining-upward depositional sequences are present in parts of the cored interval. Sandstones are nonporous because of intergranular compaction and cementation by hematite, quartz, feldspar, and clays.

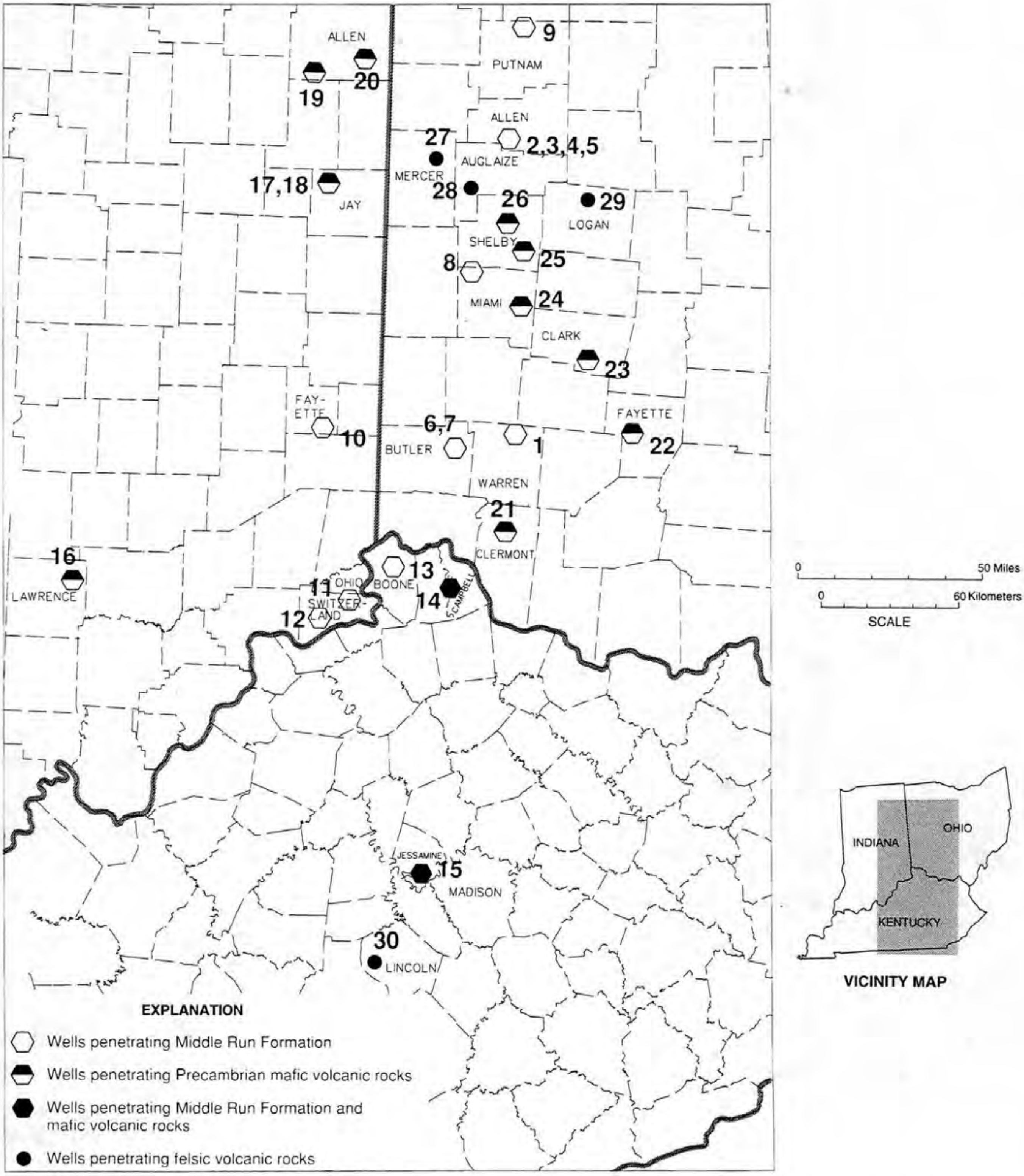


Figure 5. Map of the study area showing the location and lithology of Middle Run Formation and related intrabasinal volcanic rocks in the East Continent Rift Basin. Lithologic identifications are based on core or cutting samples from wells indicated. Well identifications and Precambrian tops and thicknesses penetrated are listed in Table 1.

Table 1.—List of Wells Penetrating Middle Run Formation, and Associated Mafic and Felsic Volcanics Within the East Continent Rift Basin.

Map Number	*Well Name*	*County, State*	*Precambrian Top (Subsea)*	*Precambrian Thickness Penetrated*	*Rock Type*
1	ODNR DGS No. 2627	Warren Co., Ohio	–2,433'	1,922'	lithic arenite
2	SOHIO No. 1 Vistron	Allen Co., Ohio	–2,261'	1'	lithic arenite
3	SOHIO No. 2 Vistron	Allen Co., Ohio	–2,290'	27'	lithic arenite
4	SOHIO No. 3 Vistron	Allen Co., Ohio	–2,282'	32'	lithic arenite
5	BP Chemicals No. 4 Fee	Allen Co., Ohio	–2,279'	147'	lithic arenite
6	Armco Steel No. 1 Fee	Butler Co., Ohio	–2,570'	61'	lithic arenite
7	Armco Steel No. 2 Fee	Butler Co., Ohio	–2,557'	57'	lithic arenite
8	Sun Oil No. 1 Levering	Miami Co., Ohio	–2,288'	130'	lithic arenite
9	Ohio Oil No. 1 Barlage	Putnam Co., Ohio	–2,628'	9'	lithic arenite
10	Gulf Oil No. 1 Scott	Fayette Co., Ind.	–2,971'	25'	lithic arenite
11	Ashland Oil No. 1 Collins	Switzerland Co., Ind.	–3,062'	58'	lithic arenite
12	Ashland Oil No. 1 Eichler	Switzerland Co., Ind.	–3,246'	111'	lithic arenite
13	Ford No. 1 Conner	Boone Co., Ky.	–2,807'	371'	lithic arenite
14	Ashland Oil No. 1 Wilson	Campbell Co., Ky.	–2,745'	58'	lithic arenite, basalt
15	Texaco No. 1 Sherrer	Jessamine Co., Ky.	–2,326'	2,008'	lithic arenite, basalt
16	Farm Bureau No. 1 Brown	Lawrence Co., Ind.	–5,850'	156'	basalt
17	Farm Bureau No. 1 Binegar	Jay Co., Ind.	–2,384'	62'	basalt
18	Pet. Dev. No. 1 Binegar	Jay Co., Ind.	–2,403'	44'	basalt
19	Tecumseh No. 1 Gibson	Allen Co., Ind.	–2,654'	41'	basalt
20	NIPSCO No. 1 Leuenberger	Allen Co., Ind.	–2,687'	188'	basalt
21	Continental No. 1 Wykoff	Clermont Co., Ohio	–2,485'	134'	basalt, andesite
22	Kewanee No. 1 Barnes	Fayette Co., Ohio	–2,288'	78'	basalt, troctolite
23	Friend No. 1 Mattison	Clark Co., Ohio	–2,279'	1,281'	basalt, rhyolite
24	NAP No. 1 Walker	Miami Co., Ohio	–2,218'	257'	basalt, gabbro
25	Sun No. 1 Nelson	Shelby Co., Ohio	–2,134'	91'	basalt, gabbro
26	Gump No. 1 Fogt	Shelby Co., Ohio	–2,261'	62'	basalt
27	Harner No. 1 Yewey	Mercer Co., Ohio	–2,263'	35'	rhyolite*
28	West Ohio No. 1 Hoelscher	Auglaize Co., Ohio	–2,144'	27'	rhyolite
29	Ohio Oil No. 1 Johns	Logan Co., Ohio	–2,062'	109'	rhyolite
30	California No. 1 Spears	Lincoln Co., Ky.	–4,609'	357'	rhyolite

* Data from Lucius and Von Frese, 1988.

Twenty-one thin sections of Middle Run sandstone from three cored wells were point-counted to provide compositional data for provenance interpretation. After normalizing framework grain counts to 100 percent, most samples were classified as lithic arenites, using the sandstone classification of Pettijohn and others (1972). Middle Run sandstones averaged 42 percent quartz, 22 percent total feldspar, and 36 percent total rock fragments. Monocrystalline quartz is much more abundant than polycrystalline quartz. Feldspars consist predominantly of K-feldspar (mainly orthoclase), and sodic plagioclase is less abundant. Rock fragments (lithics) comprise a substantial percentage of Middle Run sandstones. Volcanic rock fragments are the predominant rock fragment type, and consist of finely crystalline felsic grains (rhyolite and trachyte), but mafic volcanics grains (basalt and andesite) are also present in minor amounts. Sedimentary rock fragments consist of hematite-cemented sandstone and red silty shale. Rare foliated rock fragments of possible metamorphic origin were also observed, consisting of either low-grade micaceous schists or volcanic rock fragments that were diagenetically altered *in situ*. These metamorphic(?) rock fragments were counted as a separate class, but did not exceed 7 percent of the lithic fraction.

The fine to medium grain size, the lack of coarse conglomerates, and generally good sorting and rounding of Middle Run sandstones all suggest deposition in an environment distal from source areas. Hematite grain coatings support an arid alluvial depositional environment, and fining-upward sequences within the Warren County core suggest a fluvial channel-fill deposition for the sandstones. Based on preliminary examination of the Warren County core, the Middle Run is tentatively interpreted as a distal alluvial fan or braid plain deposit. Either depositional setting is consistent with deposition in a rift basin, but this interpretation is based on a single core, and may not characterize the Middle Run Formation in other areas.

The abundance of monocrystalline quartz, feldspar, and volcanic rock fragments suggests that granitic, gneissic, or volcanic terranes could have been sources for the Middle Run (Dickinson, 1985). The source of volcanic rock fragments in Middle Run sandstones was probably a mixture of intrabasinal and extrabasinal extrusive rocks. Rotated blocks of Granite-Rhyolite Province rocks probably were the source of much of the volcanic and plutonic fraction. Penecontemporaneous mafic and felsic extrusives also occur *within* the basin, and contributed some of the Middle Run lithic fraction. Mafic rock fragments are not abundant, so this intrabasinal contribution was relatively minor. Precambrian rocks presently east of the basin are high-grade metamorphics of the Grenville Province. These rocks are not a likely source because of the scarcity of metamorphic rock fragments. These compositional data suggest that the Grenville Orogeny postdated the basin fill.

DISTRIBUTION AND GEOCHEMISTRY OF MAFIC VOLCANICS

Mafic volcanic rocks are associated with the Middle Run Formation in two wells in Kentucky, the Ashland Wilson No. 1 (Campbell County) and the Texaco Sherrer No. 1 (Jessamine County) (Fig. 5). Basalt occurs at the top of the Precambrian sequence in the Sherrer well, and overlies the Middle Run Formation. Basalts are interbedded with Middle Run clastics in the Wilson well. A well in Lawrence County, Indiana (the Farm Bureau Brown No. 1; 16 in Fig. 5; *see* Greenberg and Vitaliano, 1962), penetrated more than 150 feet of basalt flows below the Mount Simon Sandstone, but no clastics were found. Other wells in western Ohio and northeastern Indiana bottomed in intermediate to mafic volcanics, and occur along the trend of the ECGH (Fig. 5). No Middle Run clastics occur in these wells, but the mafics may represent a volcanic trend adjacent to sedimentary subbasins within the rift.

Extrusive flows of felsic composition (rhyolites, trachytes) also occur in parts of the basin (Fig. 5). An example is the California Spears No. 1 well in Lincoln County, Kentucky (No. 30 in Fig. 5). Trachyte flows and thin arkosic sandstone were cored in this well (Bass, written communication, 1969), but no Middle Run clastics were found. These felsic extrusives may be analogous to rhyolitic flows in the North Shore Volcanic Group of Minnesota (Green, 1989).

Core samples of basalt from the Lawrence County, Indiana, well and cuttings from the two Kentucky wells were analyzed geochemically in an attempt to constrain their tectonic affinity. Abundances of major, minor, and trace elements for 35 samples were determined by X-ray fluorescence (XRF) and induced coupled plasma (ICP) analysis.

Many of the ECRB basalts have amygdaloidal textures, and most are alkalic in composition. Concentrations of large-ion lithophile (LIL) trace elements (Cs, Rb, Sr, Ba, Zr, Th, Ta, U) in these rocks appear unaffected by diagenetic alteration. The distribution of LIL elements in ECRB basalts is characteristic of documented Tertiary continental flood basalts (Wilson, 1989). Flood basalts occur in cratonic rift zones, and are geochemically distinct from mid-ocean ridge and related basalts. Geochemistry of basalts from the three wells analyzed in this study is similar to some Keweenawan basalts from the Midcontinent Rift System in the Lake Superior region (Basaltic Volcanic Study Project, 1981), suggesting that these basalts are compatible with a continental rift origin, and implying a possible association with the Midcontinent Rift System in the Great Lakes area.

AGE OF THE EAST CONTINENT RIFT BASIN

Age dates for rocks within the basin are scarce, and those available are somewhat problematic. A quartz trachyte flow in the basin from the California Spears No. 1 well, Lincoln County, Kentucky (No. 30 in Fig. 5), has been dated at 1.02 Ga (Bass, written communication, 1969), which is consistent with the timing of Keweenawan rifting in the central United States (Halls, 1978; Van Schmus and Hinze, 1985; Dickas, 1986). Rudman and others (1965) reported an isotopic date for basement rock in the Ford Conner No. 1 well, Boone County, Kentucky (No. 13 in Fig. 5), of 1.0 Ga. At the time of the analysis, the basement cuttings from this well were thought to be crystalline rock. They are now known to be Middle Run Formation, and the date was apparently obtained from sandstone. No sample information is available in Rudman and others (1965), and it is difficult to reconcile this date in light of the new lithologic interpretation. In the unlikely event that intrabasinal lithic fragments (basalt) were sampled, it may be a reasonable date. However, if detrital feldspars were used, the age should represent extrabasinal sediment source areas. In either case, diagenetic alteration may have contaminated the original composition.

Further information on the age of the rift comes from gabbros, basalts, and felsic volcanics along the ECGH in western Ohio. The Ohio Oil Johns No. 1 well, Logan County, Ohio (No. 29 in Fig. 5), has felsic volcanics that have been age dated at 1.284 Ga (Lucius and Von Frese, 1988). Basalts in the Sun Nelson No. 1 well, Shelby County, Ohio (No. 25 in Fig. 5), have been dated at 1.325 Ga (Lucius and Von Frese, 1988). The ages of these igneous rocks are older than those associated with the Midcontinent Rift (generally, Middle Keweenawan or about 1.1 Ga) (Halls, 1978; Van Schmus and Hinze, 1985; Dickas, 1986) and the 1.02 Ga age from the ECRB in Kentucky discussed above. This discrepancy suggests that the older age dates from the ECGH represent either (1) rocks formed in the early stages of a very long, 300-million-year rift evolution, which seems unreasonable, (2) igneous rocks that are an uplifted part of the Granite-Rhyolite Province that predate the ECRB fill, or (3) an error. In any event, the age of the rift is Proterozoic, and based on structural relationships to be discussed later, cannot be as young as Cambrian.

BASIN BOUNDARIES AND STRUCTURE

Although data are lacking in many areas, this study attempted to delineate the extent of the ECRB. The boundaries of the ECRB in the study area have been established by the use of well, seismic, gravity, and magnetic data. The boundaries of the ECRB are shown in detail on the map of the Precambrian crystalline basement surface (Fig. 6) and the isopach map of the rift basin fill (Fig. 7). The basin's relationship with other tectonic features in the eastern United States is illustrated in Figure 8.

Eastern Boundary

The eastern boundary of the basin is defined by well data and two seismic lines. It is coincident with the Grenville Front (Fig. 6), a distinct structural contact between metamorphic rocks to the east and ECRB lithologies to the west. In Jessamine County, Kentucky, this eastern boundary is precisely defined by well and seismic data. The Texaco Sherrer No. 1 well penetrated over 2,000 feet of Middle Run clastics, while 3.5 miles to the east, across the Kentucky River Fault System, the Texaco Wolfinbarger No. 1 well bottomed in Grenville schists and mylonites. The Kentucky River Fault System represents Paleozoic reactivation of Grenville basement faults that formed the western boundary of the Cambrian Rome Trough. Proprietary seismic data from the Jessamine and Madison County, Kentucky, area indicate that these Grenville basement structures are late Proterozoic wrench and Grenville thrust faults that were reactivated by extension primarily during Early to Middle Cambrian time (growth of the Rome Trough). Our interpretation of the seismic line (located on Fig. 6) shows east-dipping Grenville thrust structures laterally adjacent to, and overlying seismically transparent Middle Run clastic intervals (Fig. 9). This important structural relationship suggests that the ECRB and the Middle Run Formation predate, and were overthrusted by allochthonous Grenville rocks.

Farther north in Ohio, well data are not *sufficient to* closely define the eastern basin boundary, but the contact is present on COCORP regional seismic line OH-1 (located on Fig. 6). On this line the Grenville Province has been interpreted to be thrusted over Granite-Rhyolite Province rocks (Pratt and others, 1989; Culotta and others, 1990). After reprocessing the COCORP OH-1 line, we interpret the Grenville Province to be adjacent to the ECRB, and as in Kentucky, to form its eastern boundary. The overthrust relationship between the Grenville rocks and the ECRB is not clear on the reprocessed OH-1 line. We have interpreted a complex wrench-fault system at the boundary between the ECRB and the Grenville Province. Wrenching may have overprinted the Grenville boundary such that any previously existing thrust relationship is obscured. Wrench faulting cuts Grenville structures, as well as Paleozoic units, and is also present in central Kentucky (Fig. 9).

Northern Boundary

The northern limit of the ECRB is not precisely known at this time. It is likely that the basin continues to the north, connecting with the Keweenawan sedimentary basins associated with the Michigan part of the Midcontinent Rift (Fowler and Kuenzi, 1978; Sleep and Sloss, 1978; Green, 1982; Dickas, 1986). The presence of pre-Mount Simon sediments (correlated with the Middle Run Formation) north of the East Continent Gravity High in both a BP Chemical waste disposal well in Allen County, Ohio (No. 5 in Fig. 5), and the Ohio Oil Barlage

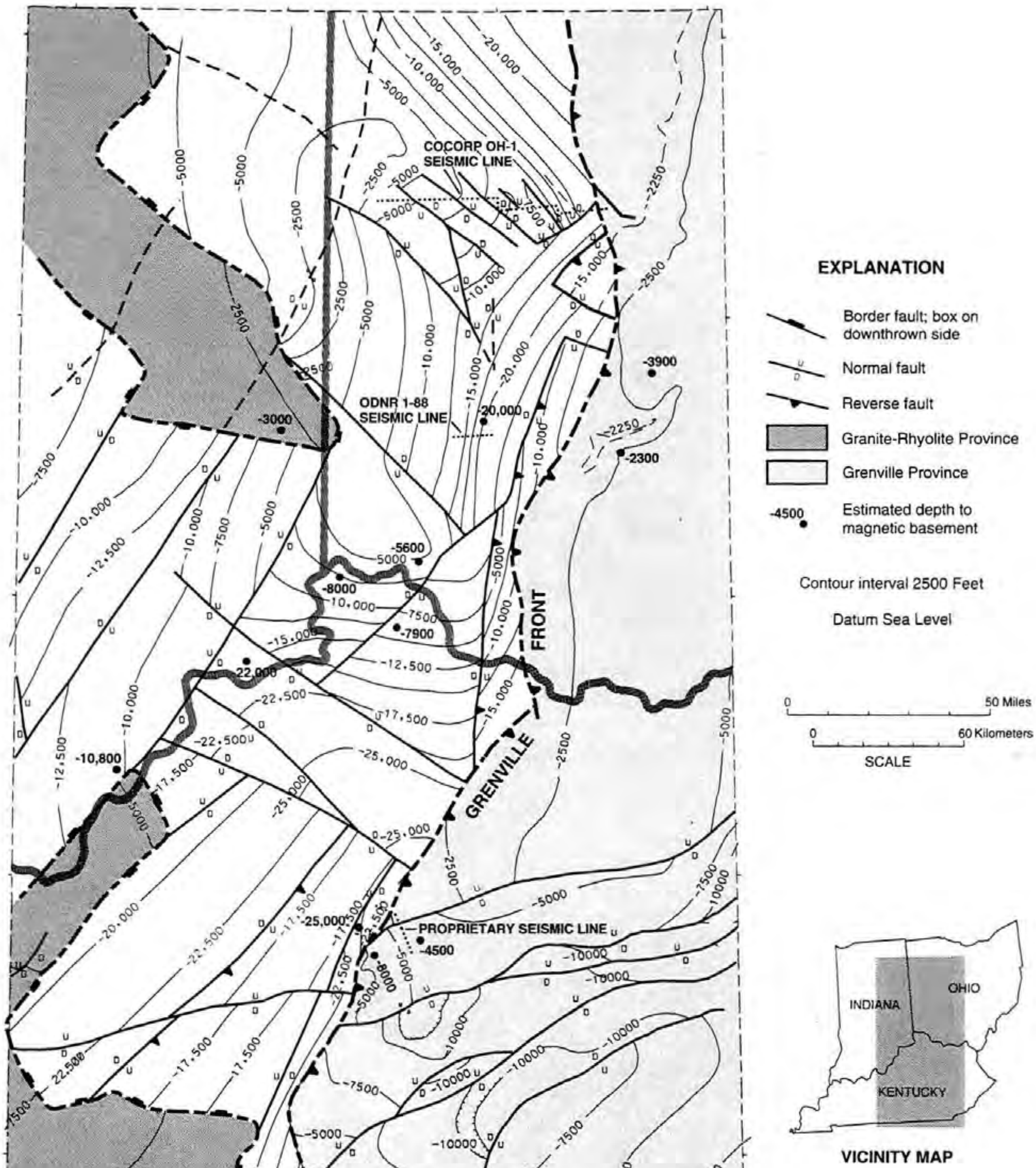


Figure 6. Structure contour map of the Precambrian crystalline basement surface. Shaded areas indicate the Grenville (metamorphic) and Granite-Rhyolite (igneous) Provinces adjacent to the ECRB, which were mapped using basement well control. Fault boundaries of the ECRB are shown by bold lines. Areas within the ECRB were mapped using a combination of magnetic anomaly trends and seismic data. Circles within the basin indicate the location of estimated depths to magnetic basement derived from magnetic anomaly data.

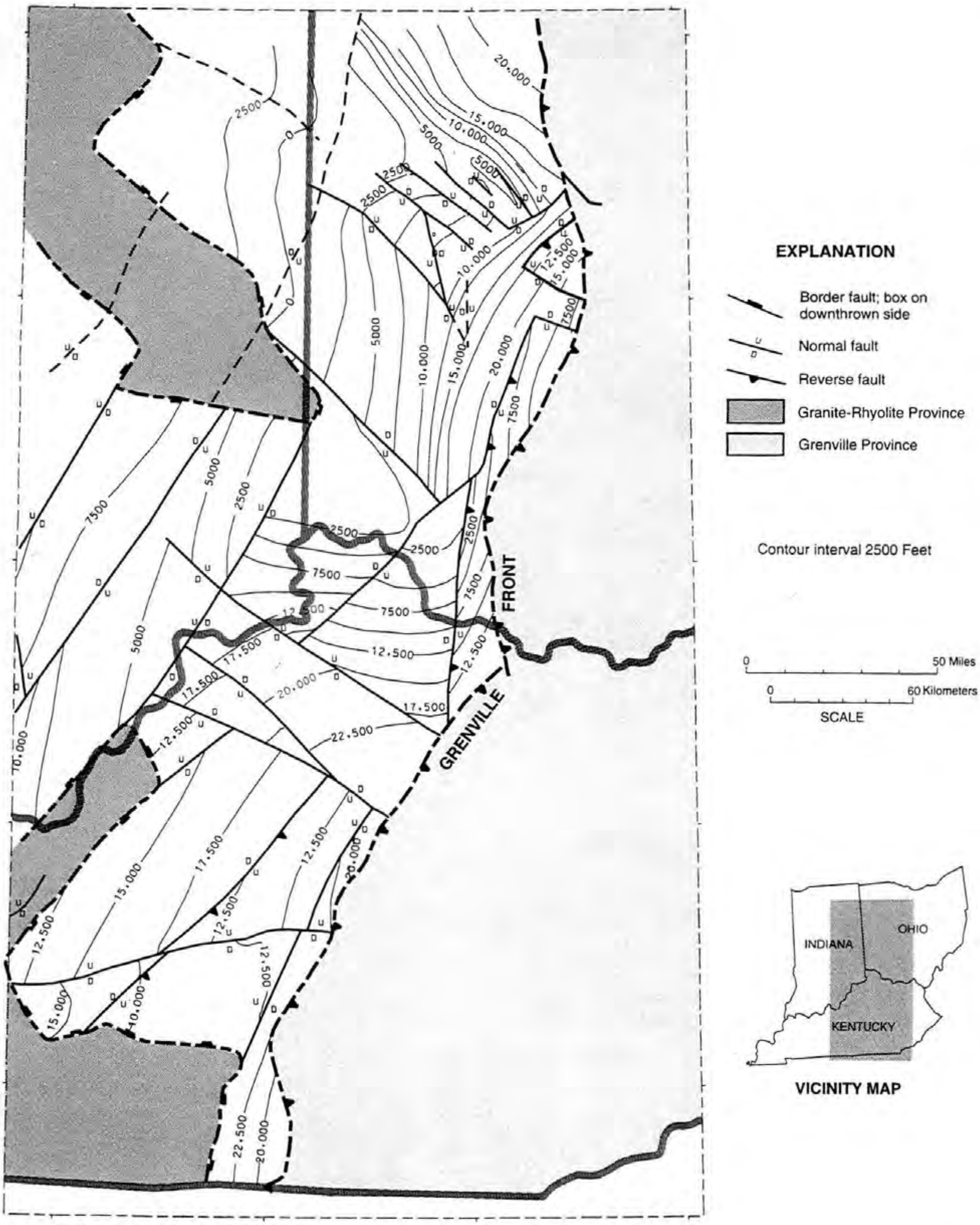


Figure 7. Isopach map of the East Continent Rift Basin fill. Thickness of the Middle Run Formation and associated volcanic rocks is shown for areas within the basin. Thickness was derived by subtracting a map of the Precambrian unconformity surface from the Precambrian crystalline basement map shown in Figure 6. ECRB sedimentary rocks thicken to the east, and are inferred to extend below overthrusted Grenville Province rocks on the eastern side of the basin.

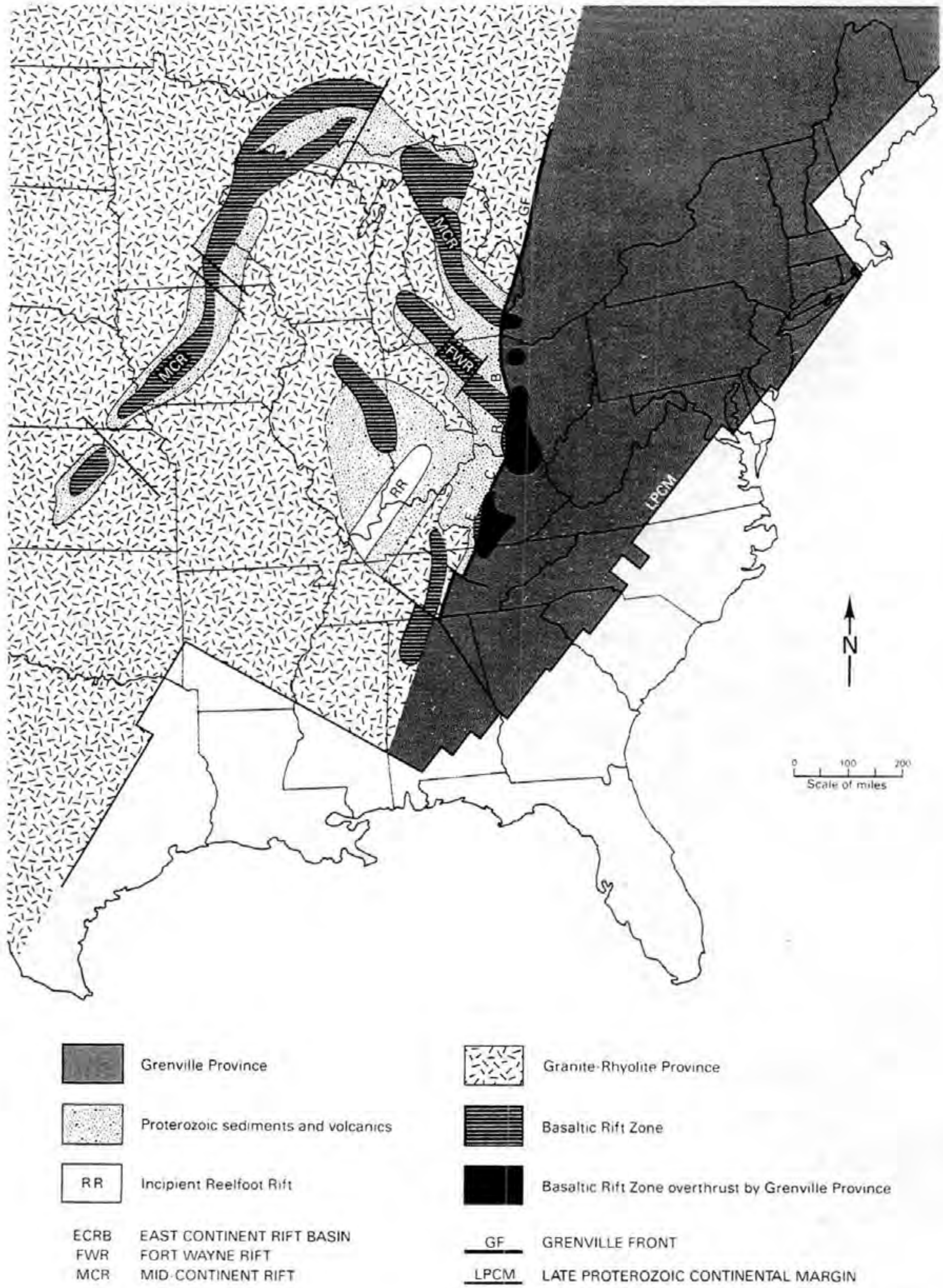


Figure 8. Regional map showing boundaries of the ECRB and relationship to other Precambrian rifts. Boundary of ECRB in Illinois is dashed where uncertain.

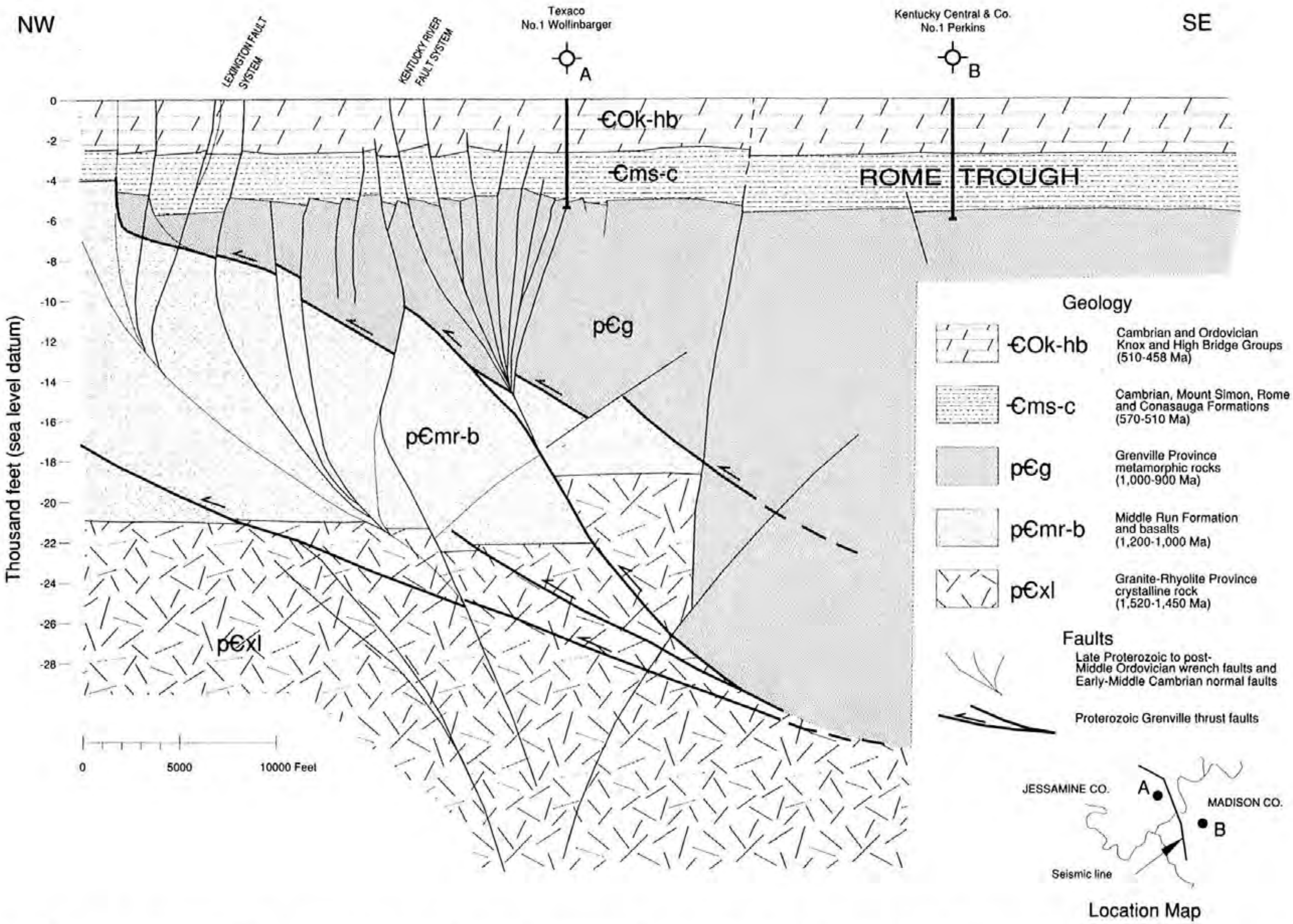


Figure 9. True-depth interpretation of proprietary seismic line in Jessamine and Madison Counties, Kentucky, showing the eastern boundary of the East Continent Rift Basin. Middle Run Formation and basalts have been overthrusted by east-dipping Grenville thrust sheets, and thus predate the Grenville Orogeny. Late Proterozoic wrench and Grenville thrust faults were reactivated in the Early to Middle Cambrian as normal faults down to the southeast, forming the western boundary of the Rome Trough.

well in Putnam County, Ohio (No. 9 in Fig. 5), is evidence of this probable connection. The continuity of the gravity and magnetic lows of these areas lends further credence to this hypothesis (Figs. 2–3). This continuity likely extends beyond Michigan to the central part of the Midcontinent Rift (Dickas, 1986), which suggests that the ECRB is an integral part of the entire Keweenawan rift system.

Southern Boundary

The boundaries of the rift on the south are poorly understood, but the basin is interpreted to narrow considerably into northern Tennessee (Fig. 8). This interpretation is based mainly on interpretation of gravity and magnetic data, and is supported by widely scattered well control. A recent interpretation by Nelson and Zhang (1991) suggests that the basin could terminate along a Grenville cross fault in northern Tennessee, but this relationship remains speculative.

Western Boundary

Delineation of the western boundary of the ECRB is hampered by a lack of available seismic data and scarce well control. The basin is bounded on the west by the Granite-Rhyolite Province, as constrained by granites penetrated in several wells in Indiana (Rudman and others, 1965; Lidiak and others, 1966). The basin extends as far west as Lawrence County, Indiana, as documented by basalt flows cored in the Farm Bureau Brown No. 1 well. The basin apparently extends beyond the study area in part, and it may continue west beneath the Illinois Basin. This interpretation is supported by the presence of "layered Proterozoic" rocks noted by Pratt and others (1989, 1992). These layered Proterozoic rocks may be equivalent to the lower basaltic part of the East Continent Rift sequence. Our present understanding of the western boundary is based primarily on the interpretation of gravity and magnetic data. Abrupt gravity or magnetic gradients have been interpreted as normal extensional faults, while more gradual trends have been mapped as thinning of the Middle Run onto tilted blocks of the Granite-Rhyolite Province. Block faulting is also evident on the western part of the OH-1 seismic line.

Precambrian Crystalline Basement Structure

The top of crystalline basement has been mapped using sparse well data, magnetic gradient models, and scattered seismic data (Fig. 6). For the purposes of this map, crystalline basement is defined as pre-rift igneous rock. Volcanic rocks interpreted to be part of the rift-fill sequence are not considered crystalline basement. No wells have penetrated pre-rift crystalline basement beneath the basin-fill sequence; therefore, the mapping of this surface is highly speculative. Regional surface and subsurface faults that exhibit evidence of deep control were projected to extend to the top of crystalline basement, and brittle failure was assumed to characterize this crystalline surface. This mapped area consists of three structurally distinct regions: the top of the Grenville Province east of the Grenville Front, the top of the Granite-Rhyolite Province *below* the ECRB fill, and the top of the Granite-Rhyolite Province west of the ECRB (Fig. 6).

West of the Grenville frontal thrust, the top of crystalline basement changes lithologically, and abruptly deepens to depths as great as 27,500 feet below sea level. These basement depths are independently supported by magnetic models (Gibson, 1991) (Fig. 6) and seismic interpretation. Crystalline basement below the basin is inferred to be Granite-Rhyolite Province. The overall structure varies from a deep basin immediately adjacent to the Grenville Front (7,500 to more than 25,000 feet below sea level) to a much shallower surface in the west (2,500 to 12,500 feet below sea level). A broad, southeast-plunging arch extends southeast from an upthrown block of Granite-Rhyolite Province rock in eastern Indiana into southwestern Ohio, dividing the basin into deeper portions both to the north and south (Figs. 6–7). The Fort Wayne Rift trend defines another northwest-oriented high area in eastern Indiana and western Ohio that also separates deeper portions of the basin.

Thickness of the East Continent Rift Basin Fill

The isopach map of the ECRB shows the outline of the basin-fill sequence as currently understood (Fig. 7). The basin-fill sequence includes the Middle Run Formation, interbedded volcanic rocks, and the inferred lower basalt-dominated sequence, which may include interbedded siliciclastics. Because the map is derived from the top of the Precambrian crystalline basement and Precambrian unconformity maps, it is subject to the same data limitations and should also be considered speculative. The overall configuration is very similar to that of the top of the Precambrian crystalline basement.

The thickness of basin-fill sequence ranges from 0 at the block-faulted edges along the southern and western edges of the study area to more than 20,000 feet at several places along the leading edge of the Grenville Front. Maximum mapped thicknesses are greater than 22,500 feet in Kentucky and central Ohio. Distinct areas of thinning extend southeast of an uplifted fault block in southeastern Indiana, and across a structural high in the vicinity of the COCORP OH-1 line in Ohio, along the trend of the Fort Wayne Rift. At the northern edge of the study area, the section thickens to more than 20,000 feet. Such thicknesses are common in the flanking sedimentary basins associated with the Midcontinent Rift. A maximum thickness of more than 45,000 feet was reported in the Keweenawan Peninsula of Michigan (Bornhorst and others, 1983), while more than 32,000 feet of syn-rift sedimentary rocks occur in the Defiance Basin of Iowa (Palacas and others, 1990).

ORIGIN OF THE EAST CONTINENT RIFT BASIN

Evidence from this study shows that the basin is a Proterozoic (1.2?–1.0 Ga) rift basin that is likely a continuation of the Keweenawan Midcontinent Rift System farther to the north and west. This evidence includes the association with basalts, composition of the sedimentary fill, geographic continuity with the Midcontinent Rift, block-faulted boundaries, and tectonic relationships.

Basalts and Other Igneous Rocks

Key evidence in support of the rift origin is the presence of continental flood basalts within the ECRB. Such basalts are associated with continental crustal stretching and the attendant emplacement of basaltic intrusions into the upper crust and flows to the surface. The association of mafic volcanic rocks and clastics precludes the possibility that the Middle Run represents sediments of a foreland basin, as basalts are not known to be associated with such basins (Allen and Homewood, 1986; Ingersol, 1988; Wilson, 1989).

The marked positive gravity anomalies of the East Continent Gravity High have been interpreted as the central mafic core of a rift zone (Keller and others, 1982, 1983). The close association of sedimentary basins with presumed mafic central cores also strongly indicates a rift origin for the basin.

Sedimentary Fill

The stratigraphy and lithology of the sedimentary fill in the ECRB also suggest a rift origin. The red lithic arenites were likely deposited as alluvial fan or distal facies equivalents in an arid continental climate. Such depositional environments are common within continental rift basins. The paucity of metamorphic rock fragments in the Middle Run Formation precludes the Grenville terrane as a source for the sediments, and suggests that the basin was not a foredeep associated with the emplacement of the Grenville allochthon.

Continuity

Physical continuity with a Keweenawan rift basin in central Michigan (part of the Midcontinent Rift System) also supports a rift interpretation. Because two wells north of the ECGH contain pre-Mount Simon lithic arenites, continuity may exist between northwestern Ohio and central Michigan (McClure Sparks No. 1–8 well, Gratiot County, Michigan) (Fowler and Kuenzi, 1978; Fowler, 1979; Catacosinos, 1981). This continuity is also suggested by gravity and magnetic signatures.

Our work also suggests that the general stratigraphy and thickness of the ECRB fill is similar to that in other parts of the Midcontinent Rift. The Midcontinent Rift fill in Michigan is characterized by an upper Keweenawan arenite sequence (Jacobsville and Freda Sandstones) that overlies a thin sequence of shale (Nonesuch Shale) and a basal conglomerate (Copper Harbor Conglomerate). Below this siliciclastic sequence is a Middle Keweenawan sequence of volcanics (Portage Lake Volcanics) (Dickas, 1986). The sequence is several tens of thousands of feet thick. Remarkably similar lithologic sequences and thicknesses are present elsewhere in the Midcontinent Rift (Catacosinos, 1981; Daniels, 1982; Dickas, 1986; Steeples, 1988; Chandler and others, 1989; Anderson, 1990). Interpretation of seismic data in the ECRB suggests a very similar thick sequence of upper siliciclastics overlying deeper volcanic rocks.

Block Faulting

Geophysical evidence for basement block faulting in and along the western edge of the basin also suggests that a rift origin is likely. Block-fault interpretations in the basement are inferred largely on the basis of sharp magnetic gradients, many of which are associated with mapped surface faulting in the Paleozoic section of Kentucky (McDowell and others, 1981), and interpreted faulting at several horizons in the subsurface of Indiana. In addition, the western part of OH-1 and other proprietary seismic data support a block-faulted western margin.

Tectonic Relationships

The overthrusted nature of the Grenville block with respect to the basin, as interpreted from seismic data in Kentucky (Fig. 9), also indicates that the basin, whatever its nature, must at least in part predate the Grenville compression. Further evidence of this age relationship is the apparent Grenville folding of basin sediments shown on the COCORP OH-1 seismic line in Ohio and an interpreted thrust fault cutting the clastic fill on ODNR-1-88 seismic line (Shrake and others, 1990).

Association of the ECRB with the Rome Trough and the Rough Creek Graben of Kentucky is precluded on the basis of structural data, the disparity in depositional settings, and inferred age differences. The western boundary fault of the Rome Trough truncates the Middle Run Formation in Jessamine County, Kentucky. The east-west-trending Rome and Rough Creek features are filled with Cambrian marine limestones, shales, and sandstones in contrast to the red lithic arenites and shales of the Middle Run Formation.

Another hypothesis on the origin of this area is that of collision-induced rifting (Gordon and Hempton, 1986). This hypothesis suggests that the rifts of the MRS and the ECRB, as well as rifts in the Grenville hinterland, formed passively as pull-apart basins related to strike-slip faulting induced by Grenville compression.

GEOLOGIC EVOLUTION OF THE EAST CONTINENT RIFT BASIN

The evidence discussed above makes a strong case that the ECRB has a continental rift origin, is genetically associated with the Midcontinent Rift, and predates the Grenville Orogeny. The hypotheses that the ECRB is related to Cambrian rifting or to Grenville foreland basin formation have been shown to be highly unlikely. A polyphase origin is possible, but based on current data, it seems unlikely.

Based on the data discussed, the geologic evolution of the ECRB can be sequentially outlined. This evolutionary sequence is illustrated in Figure 10, and is based on all data interpreted in this study.

1. *Emplacement of the Granite-Rhyolite Province*: The Granite-Rhyolite Province, whose extent to the east is unknown, was emplaced by intrusion and extrusion of igneous rocks (Fig. 10A). This event likely took place 1.5 to 1.4 Ga (Lidiak and others, 1966; Denison and others, 1984; Van Schmus and Hinze, 1985; Bickford and others, 1986).
2. *Keweenawan rifting*: Apparent extensive crustal extension in the Granite-Rhyolite Province resulted in the development of a complex of rift basins with several axes or arms of rifting. Rifting likely began with initial continental doming, normal faulting forming tilted fault blocks, deep mafic dike emplacement, and felsic volcanic activity (Fig. 10B). As extension continued, central mafic plugs were emplaced along the axes of original rifting, and basalt flows covered the surface. Clastic sediments were derived primarily from erosion of tilted fault blocks and to a minor degree from intrabasinal volcanics. Much of this sedimentation was in the form of an alluvial fan deposited in half-grabens. At about 1.0 Ga, extension waned, volcanic activity slowed, and the basin began to subside. At this point the basin became an aborted rift.
3. *Emplacement of the Grenville allochthon*: With continent-continent collision during the Grenville Orogeny, the Grenville allochthon was emplaced (Fig. 10C). This compressional event may have terminated prior extension, resulting in rift abortion. Thrusting cut the north-south part of the Keweenawan rift basin complex, possibly transporting the shallower parts of the basin to the west in allochthonous sheets and leaving only the deeper parts of the basin in the autochthonous and parautochthonous blocks. Folding also accompanied thrusting in the rift-basin sediments. Grenville foreland basin sediments were likely deposited over Keweenawan rocks at this time. The emplacement of the Grenville allochthon and development of the foreland fold and thrust belt occurred 990 to 880 Ma, based on age dates of subsurface Grenville rocks (Lidiak and others, 1966; Keller and others, 1981; Hoppe and others, 1983; Lucius and Von Frese, 1988).
4. *Late Proterozoic erosion and wrench faulting*: Subsequent to the emplacement of the Grenville rocks and before the deposition of Early Cambrian rocks, the area was deeply eroded (Fig. 10D). This erosion occurred during the late Proterozoic, and its magnitude is indicated by exhumation of high-grade metamorphic rocks in the Grenville Province at the Precambrian subcrop. The erosion is thought to have removed the foreland-basin sediments and the upper parts of the rift basin sequence. However, as shown, several downfolded remnants of foreland-basin sediments may be present west of the Grenville Front.

   In addition to erosion, extensive strike-slip faulting took place near the Grenville Front during the late Proterozoic. Wrench faulting is evident on both the reprocessed COCORP OH-1 seismic line in Ohio (Wickstrom and others, 1991) and the proprietary seismic line in central Kentucky (Fig. 9). Some of this faulting was reactivated at a later time, but the age of the erosion and the oldest wrenching can be bracketed as post-1,000 to -800 Ma and pre-570 Ma, since Cambrian rocks are not cut by many of these faults.
5. *Tectonic stability*: During the Early and Middle Cambrian, regional extension occurred. The area of the ECRB near the Grenville Front in central Kentucky remained stable, while the areas to the west and east subsided to form the Rough Creek Graben and the Rome Trough (Fig. 10E). This relative tectonic inversion apparently limited the propagation of Cambrian extensional tectonics across the region, splitting the

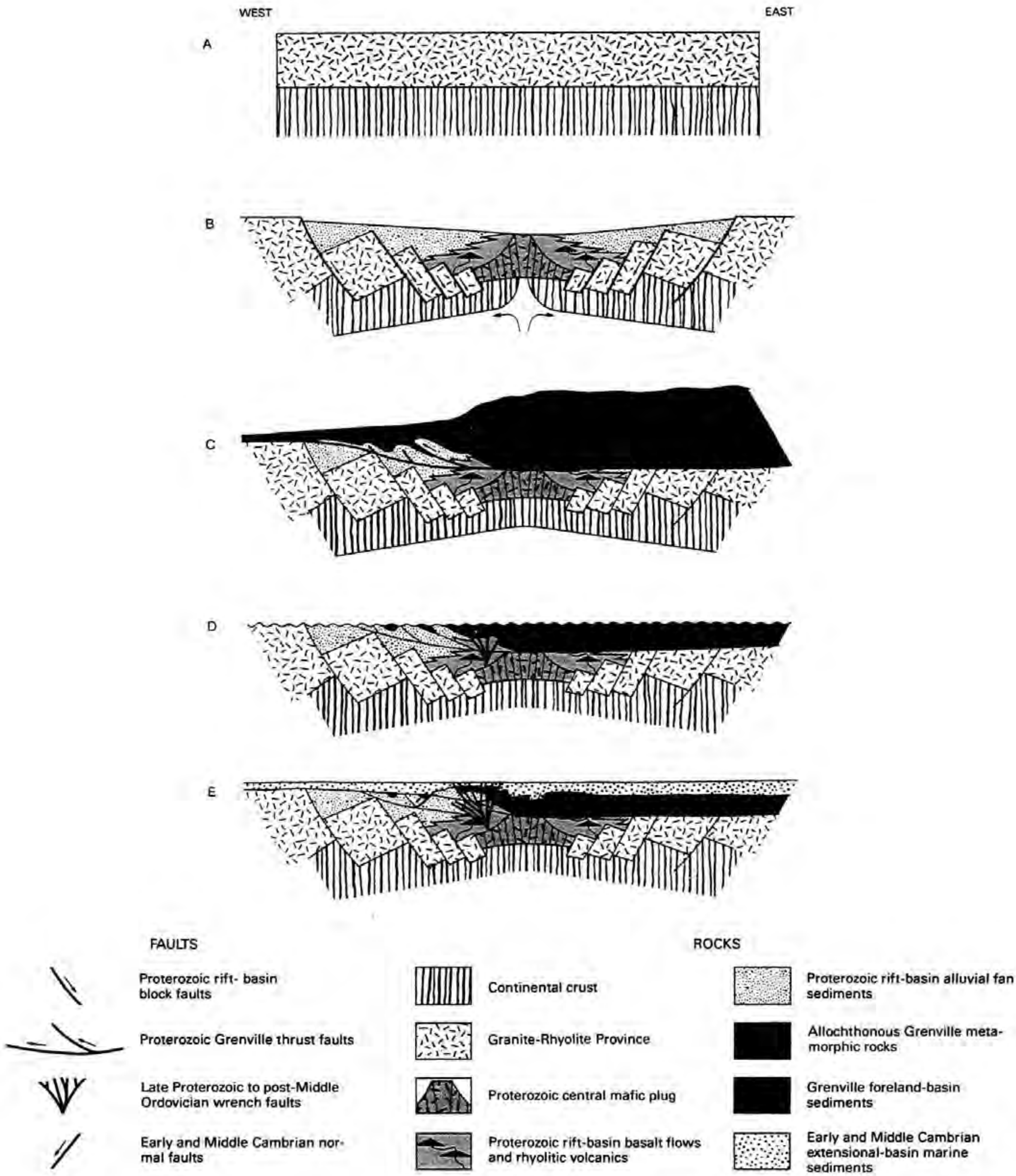


Figure 10. Evolution of the East Continent Rift Basin. A: Emplacement of the Granite-Rhyolite Province. B: Keweenawan rifting. C: Emplacement of the Grenville Allochthon. D: Late Proterozoic erosion and wrench faulting. E: Tectonic stability.

area of major subsidence into two parts. A similar stable area occurred over part of the basin in Ohio (based on the OH-1 seismic line), but the apparent extent and degree of associated Cambrian subsidence was markedly less than in Kentucky.

After the Cambrian, several periods of tectonic reactivation occurred along and near the Grenville Front on old Proterozoic faults (not illustrated on Fig. 10). In Ohio, reactivation occurred during the Cincinnatian, post-Cayugan, and possibly the Cenozoic along the Bowling Green Fault Zone (Wickstrom, 1990; Onasch and Kahle, 1991). Evidence from the reprocessed COCORP OH-1 seismic line and current bedrock mapping activities in Ohio suggests reactivated faulting during the post-Late Devonian in the Bellefontaine Outlier (Hanson, 1991; Wickstrom and others, 1992). In Kentucky, interpretation of the proprietary seismic data (Fig. 9), together with surface mapping (McDowell and others, 1981), suggests that Proterozoic faults have experienced several periods of renewed tectonic activity along the Kentucky River Fault System. In addition to the major Cambrian reactivation, post-Ordovician activity (including possibly the Early Mississippian) occurred along the system. Later tectonic adjustment also occurrred along parts of this fault system during the post-Pliocene (VanArsdale and Sergeant, 1987, 1992). The coincidence of the ECRB with the axis of the Cincinnati Arch suggests that the basin and its associated faults have had an influence on the location of this regional positive feature.

ECONOMIC SIGNIFICANCE

This work has primarily defined the structural and stratigraphic framework of the ECRB. Evaluating its economic potential was not a main objective, but a few observations regarding hydrocarbon and mineral potential are included.

Existing data from the ECRB are minimal, and a vast area and stratigraphic interval remain unsampled. The genetically related Midcontinent Rift System contains rocks with both source and reservoir potential. The Nonesuch Shale is an organic-rich lacustrine facies and has generated liquid hydrocarbons on the Keweenawan Peninsula of Michigan (e.g., Daniels and Elmore, 1988; Elmore and Daniels, 1988). The Amoco Eischeid well, drilled in the MRS in Iowa, had small shows of gas and zones of bitumen staining (Schmoker and Palacas, 1990). Some of the associated alluvial facies could form reservoirs, since porosities of up to 6 percent were found in sandstones in the Eischeid well (Schmoker and Palacas, 1990), and up to 20 percent were found in the Lake Superior region (Ojakangas, 1986). However, no rocks with organic content sufficient to have generated hydrocarbons have been found to date within the ECRB. In addition, no Middle Run sandstones with significant porosity have been penetrated. Primary porosity in Middle Run sandstones has been occluded by calcite, quartz, and feldspar cements, and by intergranular compaction. No appreciable secondary porosity has been observed in these sandstones despite their unstable mineralogy.

Perhaps the most important contribution to hydrocarbon exploration that recognition of the ECRB will have may lie in understanding and defining associated Paleozoic plays. Reactivated Precambrian structures may be significant in the development of Paleozoic structural, stratigraphic, and diagenetic traps.

The economic-mineral potential has not been explored, although sulfate and sulfide mineralization occurs above the ECRB in the Ordovician of north-central Kentucky (Anderson and others, 1982).

CONCLUSIONS

The integration of available lithologic, stratigraphic, geochemical, gravity, magnetic, structural, and seismic data has resulted in recognition of an eastern arm of the Midcontinent Rift System named the *East Continent Rift Basin.* While geologic and geophysical data are presently lacking for much of the rift basin, parts of the basin have been sampled by drilling, and imaged with reflection seismic profiles. Interpretations made on the basis of these data are summarized below:

1. An elongate, north-south-trending Precambrian rift basin is present from southeastern Michigan, through Ohio and Indiana, into central Kentucky; it may continue to the south into northern Tennessee. The basin-fill sequence lies unconformably below the Cambrian Mount Simon Sandstone.
2. The East Continent Rift Basin is filled with red continental lithic arenites, minor red siltstones and shales, and volcanics that range from mafic to felsic in composition. A lower sequence characterized by a highly reflective seismic character is interpreted to consist of interbedded extrusive flows and clastics, while an upper poorly reflective sequence is composed primarily of sedimentary rocks.
3. Gravity, magnetic, and seismic data indicate that the basin is composed of several sub-basins, some of which are as deep as –27,000 feet, and are filled with thick wedges of sedimentary and volcanic rock up to 22,500 feet in thickness.
4. The basin is bounded by the Grenville Front to the east and by normal block faults to the west. The rift

narrows to the north, but likely continues into southern Michigan. The southern boundary is not well constrained, but the basin appears to narrow into northern Tennessee.

5. Based on lithologic and stratigraphic similarities, geochemistry of associated basalts, structural style, and gravity/magnetic continuity with a known rift sequence, the basin is interpreted to be Keweenawan in age, and associated with the middle Proterozoic Midcontinent Rift System.
6. The ECRB predates the Grenville Orogeny, and the basin was subsequently overridden by allochthonous Grenville rocks. This compressional event resulted in folding and faulting of the rift-fill sequence. Post-Grenville erosion, Paleozoic inversion, and wrench faulting resulted in the present configuration of the basin.
7. Existing data for the vast areal extent and depth of the basin are minimal, but no hydrocarbon source or reservoir rocks have been found to date within the ECRB. Mineral deposits of potential economic significance have not been encountered, but basin structures may have had an influence on the distribution of overlying mineralization in some areas.
8. Structures associated with the ECRB have been reactivated during the Phanerozoic, and may have influenced Paleozoic structure, stratigraphy, diagenesis, and hydrocarbon migration and entrapment. The possible effects of ECRB fault reactivation should be considered in future Paleozoic studies.

ACKNOWLEDGMENTS

The research documented in this report resulted from the efforts of the Cincinnati Arch Consortium, composed of three state geological surveys, which unravelled the hidden geology of the Precambrian in the eastern Midcontinent. The authors would especially like to thank the following survey geologists for their contributions to the project: Doug Shrake and Jim McDonald (OGS); M. C. Noger and Brandon Nuttall (KGS). We are indebted to Dr. Manuel N. Bass for the loan of his extensive collection of Precambrian thin sections from the subsurface of the Midcontinent, and Roger Borcherding, Texaco USA, for his loan of important Middle Run thin sections.

We would also like to thank several other important contributors to the project: Drs. Charlotte Allen and Nicholas Rast of the University of Kentucky Department of Geology for their petrologic interpretation of crystalline basement samples contained in Bass's collection; Dick Gibson of Gibson Consulting, Boulder, Colorado, for his interpretations of the regional gravity and magnetic data; and Philip Towey of Philip Towey and Associates, Pittsburgh, Pennsylvania, for assistance with seismic interpretation. Lisa Van Doren (OGS) and Mike Murphy and Terry Hounshell (KGS) drafted the figures in this report.

Finally, this work would not have been possible without the financial support of AMOCO Production Co., ARKLA Exploration Co., BP Exploration, Inc., CNG Producing Co., Shell Western E and P, Inc., and United Minerals Resources, Inc.

REFERENCES CITED

Allen, P. A., and Homewood, P., eds., 1986, Foreland basins: International Association of Sedimentologists Special Paper 8, 410 p.

Anderson, R. R., 1990, Review of the Precambrian geological history of the central United States and the Midcontinent Rift System, *in* Anderson, R. R., ed., The Amoco M. G. Eischeid No. 1 deep petroleum test, Carroll County, Iowa: Iowa Department of Natural Resources Special Report 2, p. 1–25.

Anderson, W. H., Trace, R. D., and McGrain, Preston, 1982, Barite deposits of Kentucky: Kentucky Geological Survey, ser. 11, Bulletin 1, 56 p.

Basaltic Volcanic Study Project, 1981, Basaltic volcanism on the terrestrial planets: New York, Pergamon Press, 1286 p.

Bass, M. N., 1960, Grenville boundary in Ohio: Journal of Geology, v. 68, p. 673–677.

Bickford, M. E., Van Schmus, W. R., and Zietz, Isidore, 1986, Proterozoic history of the Midcontinent region of North America: Geology, v. 14, p. 492–496.

Black, D. F. B., 1986, Basement faulting in Kentucky, *in* Aldrich, M. J., and Laughlin, A. W., eds., Proceedings of the 6th International Conference on Basement Tectonics, Salt Lake City, Utah: International Basement Tectonics Association, p. 125–139.

Bornhorst, T. J., Rose, W. I., Jr., and Paces, J. B., 1983, Field guide to the geology of the Keweenawan Peninsula, Michigan: 29th Annual Institute on Lake Superior Geology, Houghton, Michigan, 116 p.

Bryan, B. K., 1975, The Greenwood Anomaly of the Cumberland Plateau: A test application of GRAVMAP, a system of computer programs for reducing and automatic contouring land gravity data: Knoxville, University of Tennessee, M.S. Thesis, 70 p.

Cable, M. S., and Beardsley, R. W., 1984, Structural controls on Late Cambrian and Early Ordovician carbonate sedimentation in eastern Kentucky: American Journal of Science, v. 284, p. 797–823.

Catacosinos, P. A., 1981, Origin and stratigraphic assessment of pre-Mount Simon clastics (Precambrian) of Michigan Basin: American Association of Petroleum Geologists Bulletin, v. 65, no. 9, p. 1617–1620.

Chandler, V. W., McSwiggen, P. L., Morey, G. B., Hinze, W. J., and Anderson, R. R., 1989, Interpretation of seismic reflection gravity, and magnetic data across middle Proterozoic Mid-continent Rift System, northwestern Wisconsin, eastern Minnesota, and central Iowa: American Association of Petroleum Geologists Bulletin, v. 73, no. 3, p. 261–275.

Couch, D. L., 1986, Seismicity and crustal structure of the East Continent Gravity High: Lexington, University of Kentucky, M.S. Thesis, 158 p.

Culotta, R. C., Pratt, T., and Oliver, J., 1990, A tale of two sutures: COCORP deep seismic surveys of the Grenville Province in the eastern U.S. Midcontinent: Geology, v. 18, p. 646–649.

Daniels, P. A., Jr., 1982, Upper Precambrian sedimentary rocks: Oronto Group, Michigan-Wisconsin, *in* Wold, R. J., and Hinze, W. F., eds., Geology and tectonics of the Lake Superior Basin: Geological Society of America Memoir 156, p. 107–133.

Daniels, P. A., Jr., and Elmore, R. D., 1988, Upper Keweenawan rift-filled sequence, Mid-continent Rift System of Michigan, *in* Daniels, P. A., Jr., and Elmore, R. D., eds., Upper Keweenawan rift-fill sequence, Mid-continent Rift System, Michigan, Michigan Basin Geological Society 1988 Fall Field Trip: Michigan Basin Geological Society, p. 1–23.

Denison, R. E., Lidiak, E. G., Bickford, M. E., and Kisvarsanyi, E. G., 1984, Geology and geochronology of Precambrian rocks in the Central Interior Region of the United States: U.S. Geological Survey Professional Paper 1241-C, 20 p.

Dickas, A. B., 1986, Comparative Precambrian stratigraphy and structure along the Mid-continent Rift: American Association of Petroleum Geologists Bulletin, v. 70, no. 3, p. 225–238.

Dickinson, W. R., 1985, Interpreting provenance relations from detrital modes of sandstones, *in* Zuffa, G. G., ed., Provenance of arenites: NATO Advanced Science Institute Series C: Mathematical and Physical Sciences: Dordrecht, Holland, D. Reidel Publishing Co., v. 148, p. 333–361.

Drahovzal, J. A., 1990, The Kentucky-Ohio Trough and its relationship to Precambrian and Cambrian basins in the eastern United States [abs.]: 21st Annual Appalachian Geology Symposium, "Appalachian Reservoir Heterogeneity," March 19–20, 1990, Morgantown, West Virginia, p. 22–23.

Drahovzal, J. A., Wickstrom, L. H., and Keith, B. D., 1990, The Kentucky-Ohio Trough and its relationship to Precambrian and Cambrian basins in the eastern United States [abs.]: Geological Society of America Abstracts with Programs, v. 22, no. 7, p. A230–231.

Elmore, R. D., and Daniels, P. A., 1988, The Nonesuch Formation: lacustrine sedimentation in a Precambrian Mid-Continent rift basin, *in* Daniels, P. A., Jr., and Elmore, Douglas, eds., Upper Keweenawan rift-fill sequence, Mid-Continent Rift System, Michigan: Michigan Basin Geological Society, 1988 Fall Field Trip: Michigan Basin Geological Society, p. 103–125.

Fowler, J. H., 1979, Analysis and interpretation of the 5,000 foot (1,538 m) red-bed sequence encountered in the Sparks *et al.* No. 1–8 (Michigan Basin deep borehole): Kalamazoo, Michigan, Western Michigan University, M.S. Thesis, 157 p.

Fowler, J. H., and Kuenzi, W. D., 1978, Keweenawan turbidites in Michigan (deep borehole red-beds); a foundered basin sequence developed during evolution of a proto-oceanic rift system: Journal of Geophysical Research, v. 83, p. 5833–5843.

Gibson, R. I., 1991, Cincinnati Arch Consortium, gravity and magnetic interpretation: Report by Gibson Consulting for Cincinnati Arch Consortium, 8 p.

Gonterman, J. R., 1973, Petrographic study of the Precambrian basement rocks of Ohio: Columbus, Ohio State University, M.S. Thesis, 139 p.

Gordon, M. B., and Hempton, M. R., 1986, Collision-induced rifting: The Grenville Orogeny and the Keweenawan Rift of North America: Tectonophysics, v. 127, p. 1–25.

Green, A. G., Milkereit, A., Davidson, A., Spencer, C., Hutchinson, D. R., Cannon, W. F., Lee, M. V., Agena, W. F., Behrendt, J. C., and Hinze, W. J., 1988, Crustal structure of the Grenville Front and adjacent terrains: Geology, v. 16, p. 788–792.

Green, J. C., 1982, Geology of Keweenawan extrusive rocks, *in* Wold, R. J., and Hinze, W. J., eds., Geology and tectonics of the Lake Superior Basin: Geological Society of America Memoir 156, p. 47–56.

Green, J. C., 1983, Geologic and geochemical evidence for the nature and development of the middle Proterozoic (Keweenawan) Midcontinent Rift of North America: Tectonophysics, v. 94, p. 413–437.

Green, J. C., 1989, Physical volcanology of mid-Proterozoic plateau lavas: The Keweenawan North Shore Volcanic Group, Minnesota: Geological Society of America Bulletin, v. 101, p. 486–500.

Greenberg, S. S., and Vitaliano, C. J., 1962, Basalt from a deep well in Lawrence County, Indiana: Journal of Geology, v. 70, p. 482–488.

Halls, H. C., 1978, The late Precambrian central North American rift system—A survey of recent geological and geophysical investigations, *in* Ramberg, I. B., and Neumann, E. R., eds., Tectonics and geophysics of continental rifts: Holland, D. Reidel Dardrecht, v. 2, p. 111–123.

Hansen, M. C., 1991, Campbell Hill—Ohio's summit: Ohio Geology, Ohio Department of Natural Resources, Division of Geological Survey, p. 1–5.

Hinze, W. J., Kellogg, R. L., and O'Hara, N. W., 1975, Geophysical studies of the basement geology of southern peninsula of Michigan: American Association of Petroleum Geologists Bulletin, v. 59, p. 1562–1584.

Hoffman, P. F., 1989, Precambrian geology and tectonic history of North America, *in* Bally, A. W., and Palmer, A. R., eds., The Geology of North America: Geological Society of America, v. A, p. 447–512.

Hoppe, W. J., Montgomery, E. W., and Van Schmus, W. R., 1983, Age and significance of Precambrian basement samples from northern Illinois and adjacent states: Journal of Geophysical Research, v. 88, p. 7270–7286.

Ingersol, R. V., 1988, Tectonics of sedimentary basins: Geological Society of America Bulletin, v. 100, p. 1704–1719.

Jachens, R. C., Simpson, R. W., Blakely, R. J., and Saltus, R. W., 1985, Isostatic residual gravity map of the United States exclusive of Alaska and Hawaii: National Geophysical Data Center, National Oceanic and Atmospheric Administration, Scale 1:2,500,000.

Keller, G. R., Ammerman, M. L., and Bland, A. E., 1981, A geophysical and tectonic study of east-central Kentucky with emphasis on the Rome Trough, *in* Luther, M. K., Proceedings of the Technical Sessions, Kentucky Oil and Gas Association Thirty-Ninth and Fortieth Annual Meetings, 1975 and 1976: Kentucky Geological Survey, ser. 11, Special Publication 4, p. 41–48.

Keller, G. R., Bland, A. E., and Greenberg, J. K., 1982, Evidence for a major Precambrian tectonic event (rifting?) in the eastern Midcontinent region, United States: Tectonics, v. 1, p. 213–223.

Keller, G. R., Bryan, B. K., Bland, A. E., and Greenberg, J. K., 1975, Possible Precambrian rifting in the southeast United States [abs.]: Transactions, American Geophysical Union, v. 56, p. 602.

Keller, G. R., Lidiak, E. G., Hinze, W. J., and Braile, L. W., 1983, The role of rifting in the tectonic development of the Mid-continent, U.S.A.: Tectonophysics, v. 94, p. 391–412.

Lidiak, E. G., Hinze, W. J., Keller, G. R., Reed, J. E., Braile, L. W., and Johnson, R. W., 1985, Geologic significance of regional gravity and magnetic anomalies in the east-central Midcontinent, *in* Hinze, W. J., ed., The utility of regional gravity and magnetic maps: Society of Exploration Geophysicists, p. 287–307.

Lidiak, E. G., Marvin, R. F., Thomas, H. H., and Bass, M. N., 1966, Geochronology of the midcontinent region, United States, part 4, Eastern Region: Journal of Geophysical Research, v. 71, p. 5427–5438.

Lidiak, E. G., and Zietz, Isidore, 1976, Interpretation of aeromagnetic anomalies between latitudes 37N and 38N in the eastern and central United States: Geological Society of America Special Paper 167, 37 p.

Lucius, J. E., and Von Frese, R. R. B., 1988, Aeromagnetic and gravity anomaly constraints on the crustal geology of Ohio: Geological Society of America Bulletin, v. 100, no. 1, p. 104–116.

Mayhew, M. A., Thomas, H. H., and Wasilewski, P. J., 1982, Satellite and surface geophysical expression of anomalous crustal structure in Kentucky and Tennessee: Earth and Planetary Science Letters, v. 58, p. 395–405.

McCormick, G. R., 1961, Petrology of Precambrian rocks of Ohio: Ohio Division of Geological Survey Report of Investigations 41, 60 p.

McDowell, R. C., Grabowski, G. J., and Moore, S. L., 1981, Geologic map of Kentucky: U.S. Geological Survey, Scale 1:250,000.

McPhee, J. P., 1983, Regional gravity analysis of the Anna, Ohio seismogenic region: West Lafayette, Indiana, Purdue University, M.S. thesis, 100 p.

Moore, J. M., Davidson, A., and Baer, A. J., eds., 1986, The Grenville Province: Geological Association of Canada Special Paper 31, 358 p.

Muehlberger, W. R., Denison, R. E., and Lidiak, E. G., 1967, Basement rocks in continental interior of United States: American Association of Petroleum Geologists Bulletin, v. 51, p. 2351–2380.

Nelson, K. D., and Zhang, J., 1991, A COCORP deep reflection profile across the buried Reelfoot Rift, south-central United States: Tectonophysics, v. 197, p. 271–293.

Ojakangas, R. W., 1986, Reservoir characteristics of the Keweenawan Supergroup, Lake Superior region, *in* Mudrey, M. G., Jr., ed., Precambrian petroleum potential, Wisconsin and Michigan: Geoscience Wisconsin, v. 11, p. 25–31.

Onasch, C. M., and Kahle, C. F., 1991, Recurrent tectonics in a cratonic setting: An example from northwestern Ohio: Geological Society of America Bulletin, v. 103, p. 1259–1269.

Palacas, J. G., Schmoker, J. W., Daws, T. A., and Pawlewicz, M. J., 1990, Petroleum source-rock assessment of middle Proterozoic (Keweenawan) sedimentary rocks, Eischeid No. 1 well, Carroll County, Iowa, *in* Anderson R. R., ed., The Amoco M.G. Eischeid No. 1 deep petroleum test, Carroll County, Iowa: Iowa Department of Natural Resources, Special Report 2, p. 119–134.

Pettijohn, F. J., Potter, P. E., and Siever, R., 1972, Sand and sandstone: New York, Springer-Verlag, 618 p.

Potter, P. E., 1989, New rift under Cincinnati Arch helps explain regional preglacial drainage: Compass, v. 67, p. 11–14.

Potter, P. E., and Carlton, R., 1991, Late Precambrian Middle Run Formation of adjacent Indiana, Kentucky, and Ohio [abs.]: Proceedings of the 22nd Annual Appalachian Petroleum Geology Symposium, Morgantown, West Virginia, p. 71–73.

Pratt, T., Culotta, R., Hauser, E., Nelson, D., Brown, L., Kaufman, S., Oliver, J., and Hinze, W., 1989, Major Proterozoic basement features of the eastern Midcontinent of North America revealed by recent COCORP profiling: Geology, v. 17, p. 505–509.

Pratt, T. L., Hauser, E. C., and Nelson, K. D., 1992, Widespread buried Precambrian layered sequences in the U.S. Mid-continent: Evidence for large Proterozoic depositional basins: American Association of Petroleum Geologists Bulletin, v. 76, no. 9, p. 1384–1401.

Preziosi, G. J., 1985, Velocity structure of the Precambrian basement in southeastern and south-central Kentucky determined from seismic refraction profiling: Lexington, University of Kentucky, M.S. Thesis, 134 p.

Rudman, A. J., Summerson, C. H., and Hinze, W. J., 1965, Geology of basement in midwestern United States: American Association of Petroleum Geologists Bulletin, v. 49, p. 894–904.

Schmoker, J. W., and Palacas, J. G., 1990, Porosity of Precambrian sandstones in lower portion of the Eischeid No. 1 well, Carroll County, Iowa, *in* Anderson R. R., ed., The Amoco M. G. Eischeid No. 1 deep petroleum test, Carroll County, Iowa: Iowa Department of Natural Resources, Special Report 2, p. 135–142.

Shrake, D. L., 1991, The Middle Run Formation: A new stratigraphic unit in the subsurface of southwestern Ohio: The Ohio Journal of Science, v. 91, no. 1, p. 49–55.

Shrake, D. L., Carlton, R. W., Wickstrom, L. H., Potter, P. E., Richard, B. H., Wolfe, P. J., and Sitler, G. W., 1991, Pre-Mount Simon Basin under the Cincinnati Arch: Geology, v. 19, p. 139–142.

Shrake, D. L., Wolfe, P. J., Richard, B. H., Swinford, E. M., Wickstrom, L. H., Potter, P. E., and Sitler, G. W., 1990, Lithologic and geophysical description of a continuously cored hole in Warren County, Ohio, including description of the Middle Run Formation (Precambrian?) and a seismic profile across core site: Ohio Geological Survey Information Circular 56, 11 p.

Shumaker, R. C., 1986, Structural development of Paleozoic continental basins of eastern North America, *in* Aldrich, M. J., and Laughlin, A. W., eds., Proceedings of the Sixth International Conference on Basement Tectonics, Salt Lake City, Utah: International Basement Tectonics Association, p. 82–95.

Sleep, N. H., and Sloss, L. L., 1978, A deep borehole in the Michigan Basin: Journal of Geophysical Research, v. 83, p. 5815–5819.

Steeples, D., 1988, Geology of the Mid-Continent Rift: Texaco No. 1 Poersch: Interstate Oil and Gas Compact Commission Committee Bulletin, v. 2, no. 2, p. 86–94.

Ullom, B. P., 1989, Crustal structure beneath the Cincinnati Arch in south-central Kentucky using magnetic, gravity and seismic reflection data: Kent, Ohio, Kent State University, M.S. Thesis, 156 p.

Van Schmus, W. R., and Hinze, W. J., 1985, The Midcontinent Rift System: Annual Review of Earth and Planetary Sciences, v. 13, p. 345–383.

VanArsdale, R. B., and Sergeant, R. E., 1987, Quaternary displacement on faults within the Kentucky River Fault System of east-central Kentucky: U.S. Nuclear Regulatory Commission NUREG/CR-4685, 36 p.; 1992, Kentucky Geological Survey, ser. 11, Reprint 34, 36 p.

Wasson, I. B., 1932, Sub-Trenton formations in Ohio: Journal of Geology, v. 40, p. 673–687.

Wickstrom, L. H., 1990, A new look at Trenton (Ordovician) structure in northwestern Ohio: Northeastern Geology, v. 12, no. 3, p. 103–113.

Wickstrom, L. H., Drahovzal, J. A., and Towey, P. E., 1992, Lower Paleozoic and shallow Proterozoic structural geology of western Ohio as interpreted from the reprocessed COCORP seismic profile [abs.]: American Association of Petroleum Geologists Bulletin, v. 76, no. 8, p. 1290.

Wilson, M., 1989, Igneous petrogenesis: London, Unwin Hyman Publishing, 466 p.

Wolfe, P. J., Richard, B. H., Shrake, D. L., Potter, P. E., and Sitler, G. W., 1989, Late Precambrian structure in southwestern Ohio [abs.]: Society of Exploration Geophysicists Expanded Abstracts with Biographies, v. 1, p. 119–121.

Zietz, Isidore, 1983, Composite magnetic anomaly map of the United States, part A: Conterminous United States: U.S. Geological Survey Map GP-960A, Scale 1:2,500,000.