Kentucky Geological Survey
James C. Cobb, State Geologist and Director
University of Kentucky, Lexington

Rough Creek Graben Consortium Final Report

John Hickman

Contract Report 55 Series XII, 2013

Our Mission

Our mission is to increase knowledge and understanding of the mineral, energy, and water resources, geologic hazards, and geology of Kentucky for the benefit of the Commonwealth and Nation.

Earth Resources—Our Common Wealth

www.uky.edu/kgs

Technical Level

General Intermediate Technical

Contents

Contents
(continued)

Figures

Figures (continued)

Plates

Plates
(continued)

Tables

Rough Creek Graben Consortium Final Report

John Hickman

Executive Summary

This research was completed by the Kentucky Geological Survey in Lexington, and was funded by a research consortium composed of 12 oil and gas exploration companies, as well as the Governor's Office of Energy Policy and the Kentucky Energy and Environment Cabinet. The 12 industry partners of the Rough Creek Graben Consortium are listed below.

Organization	Address	City	State	Zip	Phone
Chesapeake Energy	900 Pennsylvania Ave.	Charleston	WV	25302	304-353-5117
Forest Oil Corp.	707 17th St., Suite 3600	Denver	CO	80202	303-812-1798
Greensburg Oil LLC	375 Shreveport Dr.	Campbellsville	KY	42718	270-789-2886
Highway Resources	2120 E. Timberlane Dr.	Traverse City	MI	49686	231-946-2661
Kentucky Energy and Environment Cabinet	500 Mero St.	Frankfort	KY	40601	502-564-7192
Marathon Oil Co.	5555 San Felipe	Houston	TX	77056	713-296-3039
MegaWest (Kentucky Resources)	12 W. Main St.	Canfield	OH	44406	330-533-1921
MSD Energy Inc.	P.O. Box 70	Eddyville	KY	42038	270-853-7594
North Coast Energy	P.O. Box 8	Ravenswood	WV	26164	304-273-5371
Onyx International Exploration/Clipper Energy	200 S. Green St., Suite 200	Glasgow	KY	42141	270-629-5525
Sunshine Oil and Gas	12410 Hanson Rd.	Slaughters	KY	42456	270-871-0107
Triana Energy	500 Virginia St., Suite 700	Charleston	WV	25301	304-380-0100
Viking Energy LLC	425 Power St.	Bowling Green	KY	42101	270-842-9030

Goals

The goal of the Rough Creek Graben Consortium project was to evaluate the oil and gas potential of the Cambrian strata in the Rough Creek Graben and the surrounding region. In addition, this project created a data compilation and geologic framework for the more than 39,000 ft of sediment in the graben. The main purpose was not specifically to delineate drilling locations, but to increase the knowledge base and data inventory of the consortium's industry partners in order to assist in future exploration projects in the region. This intensive study of the structure, geology, and hydrocarbon system of this area yields a comprehensive and well-rounded basin model that can be used by local independents and major petroleum companies alike to achieve more successful drilling results in this region.

Data Confidentiality

As agreed in the original consortium contract, this report and all project data were held confidential to the Rough Creek Graben Consortium members for a period of 2 yr following the delivery of this report. The public release date for these data was May 1, 2012.

Study Area

Although the intent of this study was to investigate the deep petroleum potential in the Rough Creek Graben, the study area was expanded to include the surrounding region to ensure adequate coverage of the transitional areas surrounding the graben, and provide information about the coeval stratigraphy that was unaffected by this intracratonic rift system. The project area extends westward from the Cincinnati Arch in central Kentucky to the Ozark Dome in eastern Missouri, and northward from the Nashville Dome in western Tennessee to the northern end of the Mount Carmel Fault in south-central Indiana (UTM zone 16N, coordinates 3,986,800–4,350,000 m northing, 240,000–720,000 m easting).

Project Data

The final data set contains information on 1,769 wells with stratigraphic tops (with up to 60 possible tops per well), 356 wells with digitized geophysical well logs (179 with calibrated raster [scanned TIFF] logs), interpretations of 106 seismic profiles, 10 new synthetic seismograms, eight regionally mapped horizons, 20 large-scale map plates, 12 regional well-based cross sections, well-cutting microscopy and well-sample lab analyses (33 samples from 10 wells).

Summary and Major Conclusions

Extensive well-based and seismic mapping was completed, producing basinwide structural and isopach maps. Twelve new regional well-based cross sections were produced for this project. The Early Cambrian Reelfoot Arkose of Houseknecht and Weaverling (1983) was defined seismically in the Rough Creek Graben, and its depositional extent mapped in the Rough Creek Graben and northern Mississippi Valley Graben areas. A large collection of both raw and interpreted data has been compiled for the Rough Creek Graben and southern Illinois Basin area.

One of the main purposes of this research was to investigate the possibility of deep oil or gas deposits in the Cambrian strata in the Rough Creek Graben region. Unfortunately, no definitive proof was found of the existence of a hydrocarbon source rock in the pre-Knox section. All of the samples of Eau Claire Formation well cuttings that were tested for organic content with Rock-Eval[1] (see Humble Geochemical Services Division, 2001) returned very lean results (0.06 weight percent of total organic carbon). Because only a few Eau Claire or deeper wells have been drilled in the graben, the available samples of well cuttings are therefore biased toward the local geology of the northern edge of the graben. It is possible that there are organic-rich intervals of the extremely thick Eau Claire Formation in the Rough Creek Graben, but they just have not been drilled to date.

In addition to apparent low organic content, another possible risk factor for Cambrian-sourced oil exploration is that maturation models suggest that the Eau Claire Formation and deeper horizons would have been expelling oil during the Acadian and Allegh-

[1]The use of manufacturer and trademark names does not constitute an endorsement of the product by the Kentucky Geological Survey or the University of Kentucky.

enian/Ouachita Orogenies. Many of the graben-bounding faults were reactivated during these periods, increasing the risk of trap leakage along or near these fault zones.

Using all of the structural and stratigraphic interpretations for this project, four areas of possible further deep oil and gas exploration are discussed. These areas are: (1) the lower Eau Claire Formation and Reelfoot Arkose in eastern Edmonson and Hart Counties, (2) hypothesized ooid shoals along the southern boundary of the Rough Creek Graben, (3) the eastern limb of the Tolu Arch/Fluorspar Uplift in Crittenden County, Ky., and Hardin County, Ill., and (4) the Owensboro Graben of Daviess County.

Introduction

As indicated by deep drilling and geophysical data, the Mississippi Valley Graben and Rough Creek Graben, together with the Rome Trough of West Virginia and eastern Kentucky, are complex graben structures that are filled with Early to Middle Cambrian sediments (Ervin and McGinnis, 1975; Nelson and Zhang, 1991; Thomas, 1991, 1993; Johnson and others, 1994; Marshak and Paulsen, 1996). These extensional features have been interpreted by many authors as continental rift–related structures (Ervin and McGinnis, 1975; Nelson and Zhang, 1991; Thomas, 1991; Johnson and others, 1994; Thomas and Baars, 1995). The similar ages of infilling sediments suggest that the Mississippi Valley Graben, Rough Creek Graben, and Rome Trough formed at the same time. If they formed contemporaneously, then proximity suggests that they probably developed within the same tectonic environment and regional stress field. This raises the possibility that these three structures are fundamentally connected and formed part of a single continent-scale rift system that underlies the eastern United States.

The Rough Creek Graben is a deep, east–west-trending structure in western Kentucky and southernmost Illinois. It is bounded on the north by the Rough Creek and Shawneetown Fault Systems and on the south by the Pennyrile Fault System. On the west, the graben is bounded by the western edge of the Mississippi Valley Graben, at or near the Lusk Creek Fault System in southern Illinois. The exact eastern extent has not been determined; however, the graben extends eastward to at least Grayson and Edmonson Counties, Ky. The exact timing of fault initiation is unknown (the oldest strata drilled in the Rough Creek Graben are Late Cambrian in age); however, on the basis of proprietary seismic data, more than 10,000 ft of sedimentary rocks evidently lie below what has been drilled to date. On the basis of this additional thickness of sediments, Bertagne and Leising (1990) concluded that faulting began during latest Precambrian or Early Cambrian time. From those same data, Bertagne and Leising (1990) estimated a vertical basement offset of as much as 9,000 ft along the Rough Creek Fault Zone on the northern edge of the graben and around 2,000 ft of offset on the Pennyrile Fault System along the southern boundary.

The Mississippi Valley Graben (also referred to as the Reelfoot Rift) is a northeast-trending graben that borders the Rough Creek Graben on the southwest (Kolata and Nelson, 1997). The Mississippi Valley Graben was initially interpreted from gravity and magnetic surveys by Ervin and McGinnis (1975). In their interpretation, it formed as part of a failed radial-rift triple junction, with the Mississippi Valley Graben, the Rough Creek Graben, and a northwest–trending "St. Louis Arm" (inferred from gravity and magnetic surveys) as the three rift arms (Fig. 1). The axis of this structure extends from the Jackson Purchase Region of western Kentucky to east-central Arkansas, extending southward beneath the leading edge of the Ouachita allochthon. Unlike the Rome Trough and Rough Creek Graben, the Mississippi Valley Graben is strongly linear in map view, with a nearly constant width of about 40 mi (Nelson and Zhang, 1991; Kolata and Nelson, 1997). Few wells have penetrated the entire stratigraphic section in the graben, but the sediments encountered are similar in lithology and proportion to those found in the Rough Creek Graben to the east, suggesting a similar age of rifting (Early to Middle Cambrian).

Overview of Regional Stratigraphy and Tectonics

The tectonic history that is relevant to this project began at the end of the Neoproterozoic or

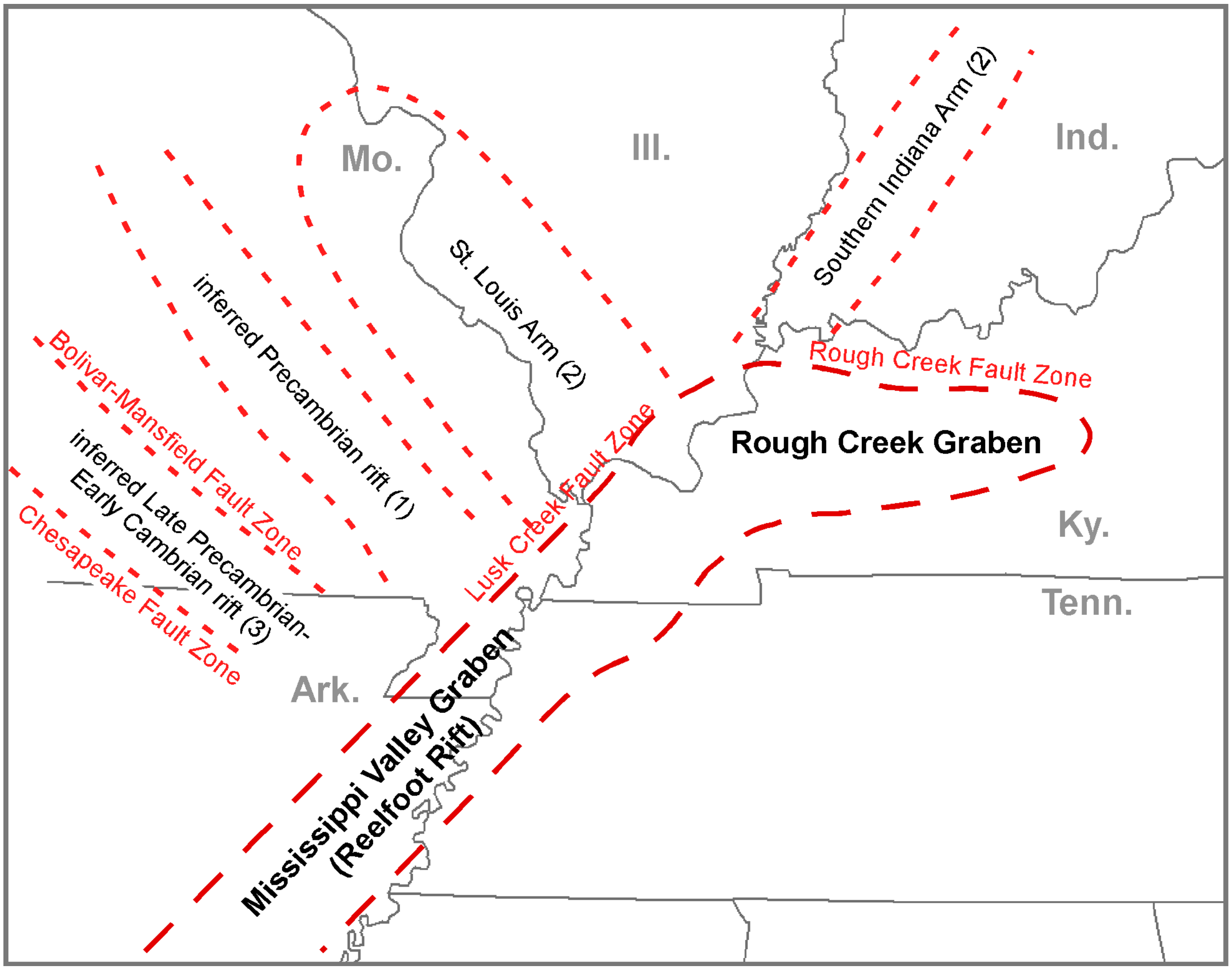

Figure 1. Interpreted Precambrian rifts in the southern Illinois Basin. Modified from American Association of Petroleum Geologists Memoir 51, © AAPG 1990 (Nelson, 1990); reprinted by permission of the AAPG whose permission is required for further use. Interpreted rift sources are Guiness and others (1982), Braile and others (1984), and Kisvarsanyi (1984).

earliest Cambrian. At that time, the supercontinent of Rodinia began to break up as the Laurentian plate started to rift from the Baltic plate (Bond and others, 1984). The southeastern edge of Laurentia developed into a passive margin as the new Iapetus Ocean was formed. Along this margin, contemporaneous with continental breakup during the Early Cambrian, numerous graben systems were formed at oblique angles to the continental margin. These grabens include the Ottawa-Bonnechere Graben in New York and southern Ontario; the Pennsylvania Aulacogen in south-central Pennsylvania; the Rome Trough in eastern Kentucky, West Virginia, and western Pennsylvania; the Rough Creek Graben of western Kentucky and southern Illinois; the Mississippi Valley Graben in eastern Arkansas, western Tennessee, and western Kentucky; and the Southern Oklahoma Aulacogen (Rankin, 1976; Braile and others, 1986; Kolata and Nelson, 1990b).

As indicated by thickness changes across the respective boundary fault systems, major subsidence and horizontal extension within the rift graben systems began at least by the Early Cambrian and had ended prior to the middle Late Cambrian Period. To accommodate these sediments, initial rifting of these linked basins began in the late Proterozoic to Early Cambrian and persisted until the early Late Cambrian (Ervin and McGinnis, 1975; Nelson and Zhang, 1991; Thomas, 1991, 1993).

Two Precambrian crystalline basement provinces and the clastic-filled East Continent Rift Basin (Drahovzal and others, 1992; Stark, 1997) lie below the Paleozoic strata in the project area. East of a boundary front that roughly follows the Cincinnati Arch through east-central Tennessee, central Kentucky, and west-central Ohio is the Grenville Province (Fig. 2).

Rocks from this province have been dated (from well samples) as middle Proterozoic, with radiometric dates (Rb/Sr, K/Ar, and zircon U/Pb) from samples of 1,060 to 890 Ma (Lidiak and others, 1966; Van Schmus and Hinze, 1985; Lucius and Von Frese, 1988). These rocks include a variety of gneisses and schists (including both metasedimentary rocks and metaigneous rocks), as well as granite, rhyolite, and anorthosite intrusions.

West of the Grenville Province lies the igneous Eastern Granite-Rhyolite Province. Although this early to middle Proterozoic province (1,500–1,420 Ma) has not been penetrated by wells drilled in the interior of the Rough Creek Graben, it has been documented by drilling to the north, south, and west of the graben (Sargent, 1990).

Over the next 350 to 450 million yr, erosion was extensive, leading to a widespread unconformity at the base of the Paleozoic section (Figs. 2–3). In the Early to Middle Cambrian, average sea level gradually rose, flooding these graben systems with thick, arkosic synrift siliciclastic sequences. The Reelfoot Arkose of the Mississippi Valley and Rough Creek Grabens, and the Rome Formation of the Rome Trough are the lithic detritus eroded from the uplifted igneous and metamorphic basement complex rocks of which these grabens were initially filled (Ammerman and Keller, 1979; Weaverling, 1987; Houseknecht, 1989).

Although few wells in the Rough Creek and Mississippi Valley Grabens have been drilled deep

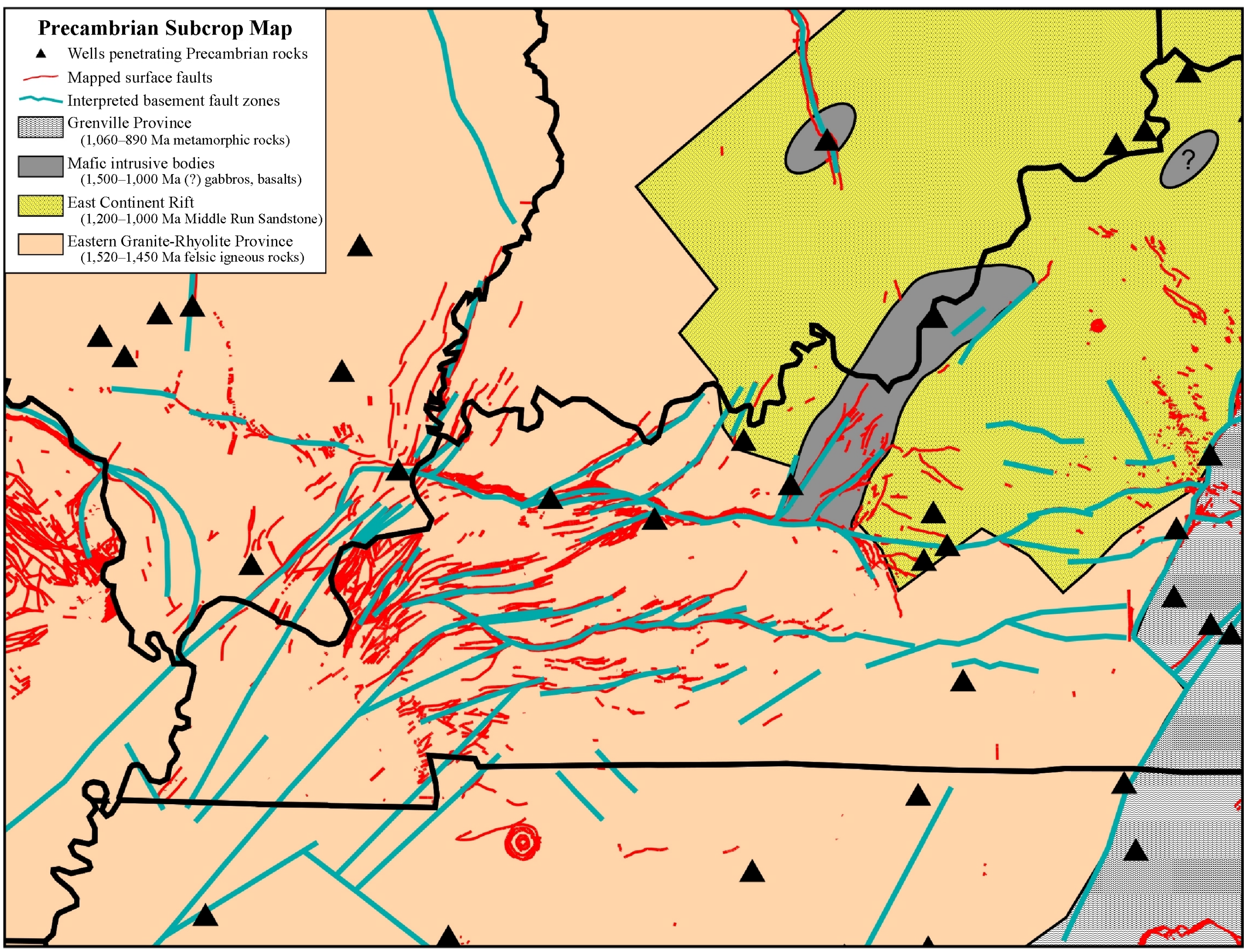

Figure 2. Generalized Precambrian subcrop map for the project area. Extents of East Continent Rift Basin modified from Drahovzal and others (1992).

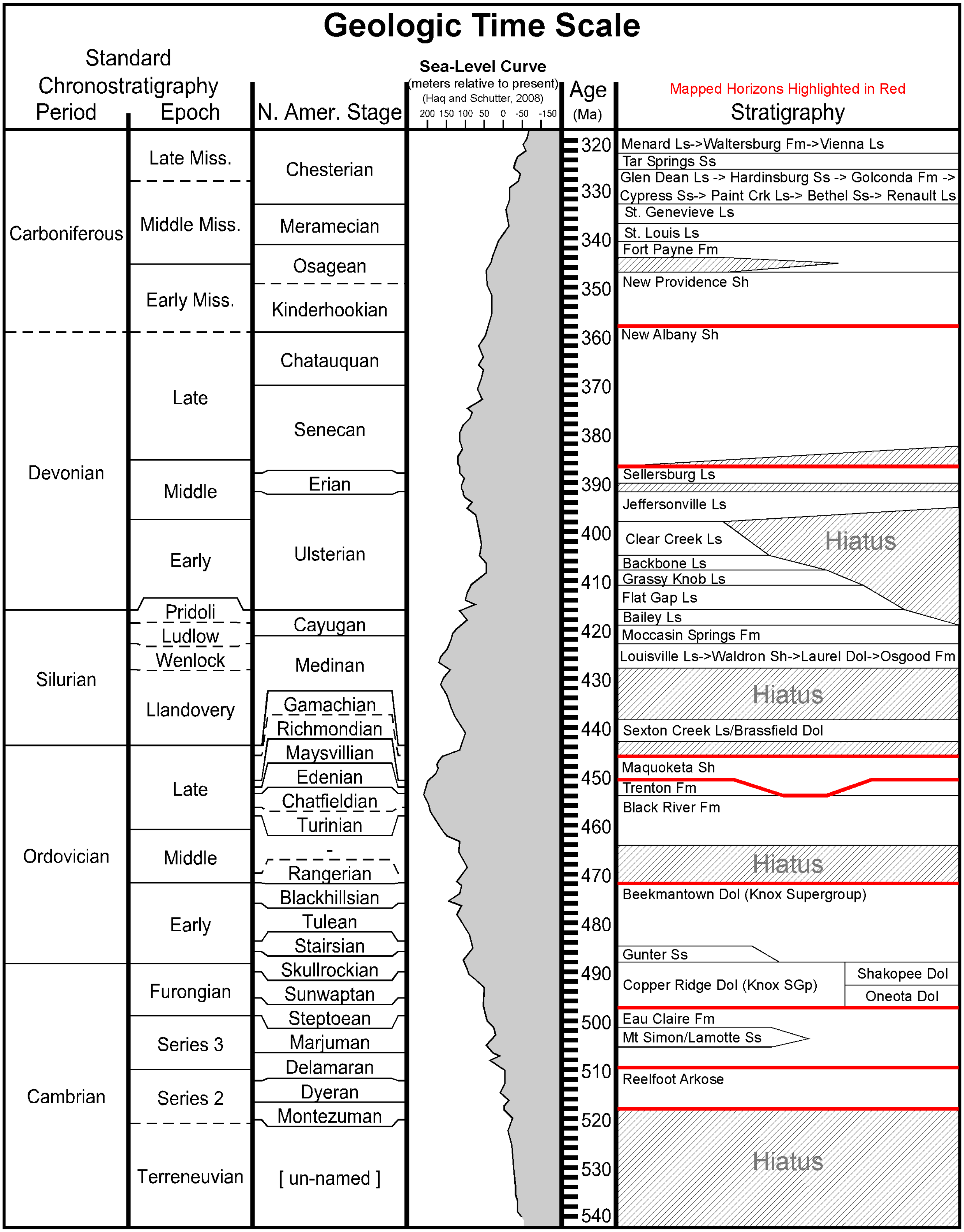

Figure 3. Time scale and stratigraphy used in the Rough Creek Graben Consortium project.

enough to penetrate the Reelfoot Arkose, proprietary reflection-seismic data suggest that this unit extends across most of the Rough Creek Graben west of Green County, and throughout the northern part of the Mississippi Valley Graben. This is a clastic fluvial fan deposit and represents the first synrift deposition in the Rough Creek Graben (Weaverling, 1987). This unit underlies the Eau Claire Formation in the graben and appears to be roughly time-equivalent to the Rome Formation of the Appalachian Basin to the east.

By the late Middle Cambrian (Shaver, 1985), regional sea level had risen to the point that the entire region was covered by a shallow sea. Sedimentation of the Eau Claire Formation in the Rough Creek and Mississippi Valley Grabens and the Conasauga Group of the Rome Trough and the Elvins and Bonneterre Formations of eastern Missouri and Arkansas consisted of low-energy marine siltstones and shales, punctuated by episodic carbonate deposition indicative of a slowly subsiding basin, with slightly elevated subsidence rates within the rift graben boundaries.

By the Late Cambrian, tectonic subsidence of the Rough Creek Graben, Mississippi Valley Graben, and Rome Trough had slowed dramatically. Sedimentation filled these grabens to the point that there was no topographic relief across these structures. Clastic deposition was replaced by a regional carbonate platform that covered much of eastern Laurentia, which lasted for more than 25 million yr (Knox Supergroup). A short but apparently intense period of regression followed, which led to the subaerial exposure and erosion of Lower Ordovician dolomites and limestones, producing a widespread regional Knox unconformity.

The Upper Cambrian to Lower Ordovician Knox Supergroup overlies the post-rift strata over the entire region (Schwalb, 1982; Shaver, 1985; Noger and Drahovzal, 2005). The Knox is a platform to passive-margin succession composed predominantly of carbonate, with minor amounts of mature, quartz-rich sandstones. Unlike the older units, there is no evidence of syndepositional faulting of the Knox strata in these grabens.

At the beginning of the Middle Ordovician, sea level rose, and a transgressive sequence was deposited consisting of near-shore, shallow-marine sandstone (St. Peter Sandstone), followed by the argillaceous limestones and dolomites of the Ancell Group (Dutchtown and Joachim Formations), and finally by the broad carbonate-bank facies of the Black River and Trenton Formations. By the Late Ordovician, however, the Taconic Orogeny that was occurring to the east in the incipient Appalachian Mountains had created sufficient foreland-basin subsidence in the Midcontinent that the region was flooded with deeper-water shale and mudstone facies of the Maquoketa Shale.

In the Early Silurian, the center of impact deformation from the Taconic Orogeny had moved northeastward to the central Appalachian region, removing much of the foreland subsidence that had occurred in the region of the project area. Reduced subsidence rates lasted through the Early Devonian and produced a lower regional sea level and led to warm-water, shallow-marine deposits of limestone and dolostone, with minor amounts of sandstone and shale. These units include the Brassfield and Laurel Dolomites, the Osgood and Moccasin Springs Formations, and the Louisville, Bailey, Flat Gap, Grassy Knob, Backbone, Clear Creek, Jeffersonville, and Sellersburg Limestones (Seale, 1981).

Foreland basin subsidence returned to the region in the Middle Devonian as a result of the Acadian Orogeny to the northeast. Extensive organic-rich deposits of prodeltaic black shales were formed on the Midcontinent during the Middle Devonian to Early Mississippian Periods. This time was coeval with the uplift and formation of the Cincinnati Arch and Nashville Dome and initial subsidence of the Illinois and Appalachian Basins. An estimated 500 ft of Devonian through Ordovician strata was removed from the Nashville Dome through erosion during this time (Stearns and Reesman, 1986). The uplift of the arches and domes adjacent to subsiding basin areas led to extensive thickening of the Devonian black shale into the Illinois and Appalachian Basins.

Throughout the Middle to Late Mississippian, progressively shallower-water sediments were deposited across the region. Following the New Albany/Ohio Shale, prograding deltaic siltstones of the Fort Payne/Borden Formations were deposited. As water depth decreased, the St. Louis and Ste. Genevieve Limestones were deposited in the Middle Mississippian. These carbonate units were then followed by alternating sandstones and limestones of the Chesterian Stage, including the Renault Limestone, Bethel Sandstone, Paint Creek Limestone, Cypress Sandstone, Golconda Formation, Hardinsburg Sandstone, Glen Dean Limestone, Tar Springs Sandstone, and Vienna Limestone.

Additional post-Mississippian tectonic events that affected the geology of this area include the compressive Alleghenian (Early Pennsylvanian) and Ouachita (Late Pennsylvanian through Permian) Orogenies, and the tensile tectonics associated with the opening of the Gulf of Mexico to the south (Triassic and Jurassic) and the Atlantic Ocean to the east (Late Jurassic to Early Cretaceous). Numerous ultramafic intrusions in the Western Kentucky Fluorspar District have been dated as Early Permian in age (Zartman and others, 1967; Kolata and Nelson, 1997). Whether this magmatic activity was related to the Ouachita compression or the later extension related to the breakup of Pangea is unknown.

The petrology and depositional environments of the post-Knox strata were not the focus of this study. For more specific depositional or petrographic analysis of Middle Ordovician and younger strata, refer to:

Knox unconformity: Sloss (1963), Skinner (1971), Mussman and Read (1986), Mussman and others (1988), Smosna and others (2005)

Everton Dolomite: Schwalb (1969a), Noger and Drahovzal (2005)

St. Peter Sandstone: Schwalb (1969a), Hoholick and others (1984)

Middle Ordovician: Freeman (1951), Cressman (1973), Cressman and Noger (1976)

Maquoketa Shale: Weir and others (1984)

Silurian: Freeman (1951), Currie and MacQuown (1981), Peterson (1981), Seale (1981), Kepferle (1986), McDowell (1986)

Early Devonian: Meents and Swann (1965)

Middle–Late Devonian: Bergstrom and Shimp (1977), Schwalb and Potter (1978), Beard (1980), Lineback (1980)

Oil and Gas Exploration History

The petroleum history of the study area began in 1856 in western Kentucky, when a plant in Breckinridge County began distilling kerosene and paraffin from cannel coals (Miller, 1919). Also that year, the first state geologist of Kentucky, David Dale Owen, described the tar sands of Edmonton County (Owen, 1857). In 1865, natural gas was discovered in Webster County (Orton, 1891), and although the operator chose not to produce it, the first oil well was drilled in western Kentucky near Calhoun in McLean County (Eyl, 1922). The first commercially produced oil well in western Kentucky was not drilled until 1912 in Hartford, Ohio County (Smith, 1968).

Deep drilling to explore pre-Knox strata in the Rough Creek Graben began in 1974 with the Texas Gas Transmission No. 1 Herman Shain well. This dry hole was drilled in west-central Grayson County, about 2.6 mi south of the Rough Creek Fault Zone, and penetrated 5,120 ft of Eau Claire Formation shales and limestones before reaching total depth.

The next year, 1975, the Exxon Minerals Co. No. 1 Jimmy Bell well was drilled in Webster County. This well was drilled into an inverted fault block (positive flower structure) in the Rough Creek Fault Zone. In the subsurface, this well cut at least two faults and reached total depth at 14,340 ft in a crystalline andesite, apparently within the footwall block. Because of the fault cuts, most or all of the Eau Claire Formation is missing from this wellbore. This well was plugged and abandoned, and no hydrocarbon shows were listed on the completion report.

In 1977, the Exxon Minerals Co. No. 1 Choice Duncan well was drilled in Webster County. The Duncan well was drilled 1.9 mi southwest (local strike of fault set about N60°W) of the Rough Creek Fault Zone. This well reached total depth at 15,200 ft after penetrating 2,690 ft of Eau Claire. No hydrocarbon shows were reported for this well, and Exxon did not drill any more deep wells in the Rough Creek Graben. This remains the deepest well drilled in the state of Kentucky.

Four years after the completion of the Duncan well, the Sun Oil Co. drilled the No. 1 Stephens, W.W. & Lillie M. well in 1981. Unlike all of the other deep wells drilled in the graben, this well was drilled away from the intensively deformed and faulted Rough Creek Fault Zone in Caldwell County. This well was also different from the other deep tests in that the entire hole was drilled with an air-rotary drill rig. Sun Oil was unable to log the entire well because of hole problems (the completion report noted caving and "junk in hole"). Whether these hole problems were a result of formation damage caused by the air-hammer bit is unknown. No shows were reported for this well, and it was plugged and abandoned.

In 1992, Conoco began their deep drilling program in the Rough Creek Graben. Three wells were drilled just south of the Rough Creek Fault Zone during the next 3 yr. The first drilled was the Conoco No. 1 Turner well in McLean County. Conoco has released to the Kentucky Geological Survey its internal petrographic report of sidewall and whole-core samples taken in this well (Mitchell, 1993). The Turner well was drilled about 1.8 mi south of the Rough Creek Fault Zone, near the intersection of the Central Fault System and the Rough Creek Fault System in easternmost McLean County. This basement test well was targeting lower Eau Claire Formation carbonate shoal facies and clastic rocks of the Reelfoot Arkose. Although some oil staining and potential residual bitumen was discovered in core, all potential reservoir zones were tight, with no oil or gas shows, and the well was plugged and abandoned.

The second Conoco well was the No. 1 Isaac Shain in west-central Grayson County, drilled in 1993. This well was drilled 1.4 mi south of the Rough Creek Fault Zone and 1.2 mi north of the earlier Texas Gas Transmission No. 1 Herman Shain well discussed above. Some minor gas shows were encountered in this well in the Silurian Decatur Dolomite and the Ordovician Trenton Limestone, but the well was plugged after the casing collapsed at 8,719 ft in the Eau Claire Formation. This well drilled through 4,651 ft of Eau Claire and possibly deeper strata, but because of the casing collapse, geophysical logs were only obtained to a depth of about 9,800 ft. Near total depth of 12,622 ft, the well penetrated what was described on the mud log as an altered (metamorphosed) granite wash and other sands. This geologic description is similar to that of the Reelfoot Arkose; however, reflection-seismic data indicate that the top of the Reelfoot at the Shain well location is at about 13,050-ft depth, 428 ft below total depth.

The final deep well Conoco drilled was the No. 4-1 Einart Dyhrkopp in Gallatin County, Ill. This well was drilled about 1.5 mi south of the surface exposure of the Rough Creek–Shawneetown Fault Zone in the northwestern corner of the Rough Creek Graben. This well also cut at least two faults and reached total depth at 14,185 ft on the footwall block (Precambrian igneous basement) after penetrating 740 ft of Eau Claire Formation and 88 ft of Reelfoot Arkose. Similarly to the results of the other two Conoco wells, this well was also dry and abandoned.

The drilling programs of Exxon and Conoco appear to have been focused on drilling fault traps updip from the deepest part of the Rough Creek Graben. This strategy maximized the thickness of sediment that the wells could theoretically drain, and added the possibility of access to numerous stacked reservoirs. Oil staining and residual bitumen indicated past hydrocarbon migration through at least parts of the Eau Claire and deeper strata, but no accumulations or significant porosity were found. The Conoco No. 1 Turner well also targeted a carbonate buildup interpreted on seismic data. An oolitic shoal deposit was penetrated in the well within the Eau Claire Formation, but very little remaining porosity was discovered.

All of these wells (with the exception of the Sun Oil No. 1 Stephens) were drilled within or in proximity to the Rough Creek Fault Zone. This complex system of intertwining faults is exposed at the surface and has been reactivated at least twice since the Cambrian. This type of geologic history would promote deformation and vertical transmissivity near the fault zone through fractures and fault breccias. That factor may be a major contributor to the lack of success in these drilling programs. These vertical pathways would allow previously migrated hydrocarbons to leak from the reservoir, as well as allow mineral-saturated fluids to migrate. Rising fluids would undergo a drop in both pressure and temperature, which would lead to precipitation of minerals and porosity destruction. From all accounts, very little porosity was found in any of the Exxon or Conoco wells below the Knox Supergroup, and secondary quartz, calcite, or dolomite fills all fractures and pore spaces.

Data and Methods

Well Data

The maps of the Rough Creek Graben Consortium, which are described below, are the result of incorporating numerous types of data into a single, comprehensive interpretation. The project started with compiling location and header information (API, well name, total depth, latitude/longitude coordinates, etc.) for 8,072 wells across the Illinois Basin and adjacent regions (Fig. 4). Using available geophysical well logs, drillers' logs, and core or cutting descriptions, stratigraphic tops were picked for the major mapped horizons, as well as several secondary-level tops useful for local correlations. Interpreted stratigraphic tops information was used from a total of 1,764 wells (Fig. 5, Plate 1), including 489 wells with Early Ordovician and older tops. A total of 403 wells has at least one digital geophysical well-log curve (LAS), and an additional 175 wells have at least one calibrated raster log image.

Seismic Data

The 66 reflection-seismic data used in this project have been compiled from numerous sources over the past 20 yr or more. With the exception of the KGS data that surround the KGS No. 1 Blan CO_2 research well from Hancock County, all of the data used had been donated to or purchased for KGS and are in "permanent loan" agreements that allow for internal research but no distribution, reproduction, or sale of the data. The Blan data were acquired by KGS as part of its ongoing CO_2 sequestration research, and KGS has full rights to that data set.

The majority of the donated data came from eight original owners. These data sets are currently available for purchase from seismic vendors. Although KGS is not at liberty to distribute the data, a subjective review of the data sets is permissible. The following are my opinions and are intended to inform, not to recommend or dissuade the purchase of any specific data. Shorter lines, lines not available for sale, or those of poor quality are not reviewed.

Compagnie Générale de Géophysique. Three 40- to 45-mile-long CGG lines were used. All three are north-south lines across the eastern part of the Rough Creek Graben. The quality of these migrated, vibrator-source lines is very good. At least two other regional lines were originally recorded as part of this set, but were unavailable to KGS. These other lines are assumed to be of the same quality as those reviewed here.

Conoco. Five Conoco lines were used for this project. Line lengths range from 5 to 30 mi and are all along the northern border of the Rough Creek Graben. The quality of these data is average to good. It appears that some of the lines may have been overprocessed (poor migration?), leading to a wispy appearance, which can make the identification of fault terminations difficult. Nonmigrated versions of these data may not have this issue, but are not in KGS's inventory.

Deep Illinois Basin prospect, Seismic Specialists Inc. KGS has copies of nine of these seismic lines, which combine into two north-south and two northwest-southeast regional surveys across the Western Kentucky Fluorspar District and adjacent areas of southern Illinois. The data quality for these lines is good to very good. The combined line lengths for the northwest-southeast lines are more than 45 mi.

Gulf Exploration and Production. This collection is the largest in the KGS seismic inventory for western Kentucky. These are migrated, vibrator-source lines. These data were especially helpful because of the long line lengths (many more than 50 mi), which improved the signal/noise ratio for the deeper sediments and structures. Data quality ranges from good to very good.

Illinois Basin–Kentucky line, Seitel Inc. Although this data set consists of only one line, it is worth mentioning because of the very long length (85 mi) and excellent data quality. In some areas, numerous seismic reflectors are resolvable down to 4 s of two-way travel time. This line was recorded in an east-west direction just north of the axis of the Rough Creek Graben.

Mississippi River Transmission. This data set is composed of six lines that range from 5 to 14 mi long. These surveys are arranged in a crisscross pattern across the Rough Creek Fault Zone in Union County. The lines in KGS's inventory are of average quality, although this may be a result of poor quality scanning of the original paper seismic line and not an issue with the quality of the digital data.

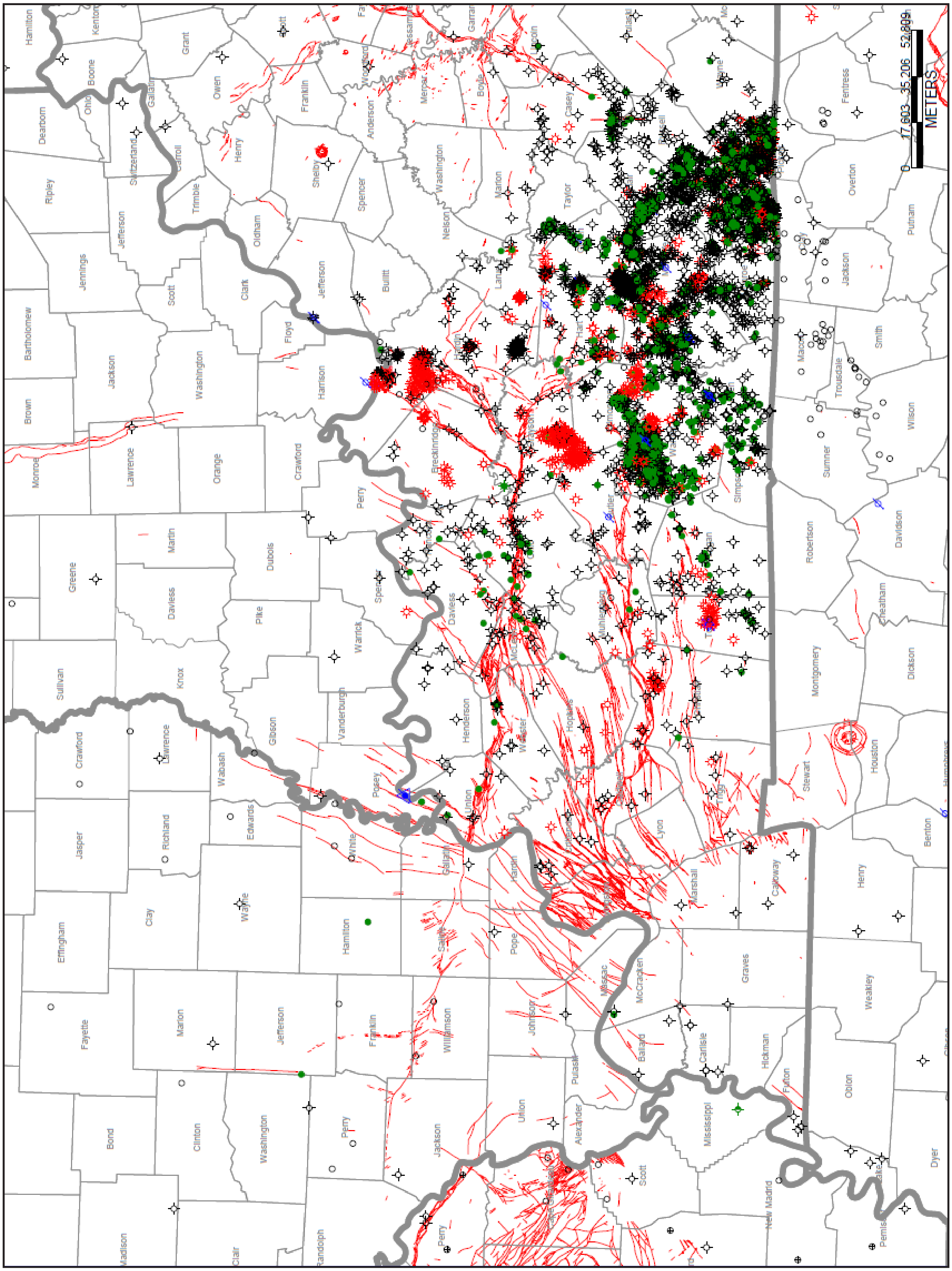

Figure 4. Locations of wells listed in the Rough Creek Graben Consortium database.

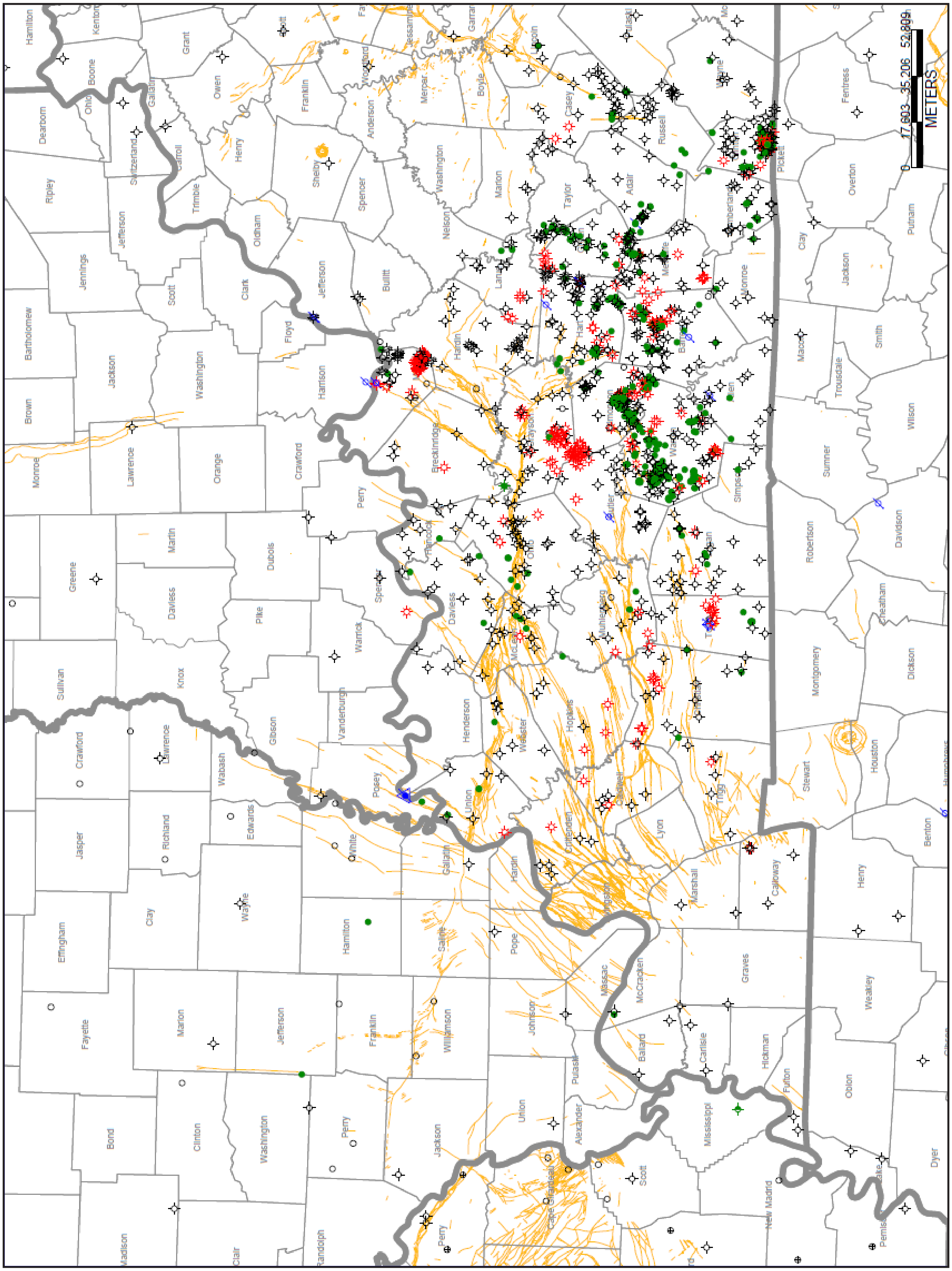

Figure 5. Locations of wells with stratigraphic tops interpretations. Mapped surface faults are marked in orange.

Texas Gas Transmission. Twelve closely spaced seismic lines in central and western Grayson County were interpreted for this project. These relatively short lines (3 to 9 mi long) are of average to good quality, but the short lengths reduce the resolution of deeper structures and horizons. As with many shorter seismic lines, the data quality drops at depths below about 2.3 s of two-way travel time.

Vastar. Six of the seven lines of this data set are from southern Indiana and the seventh is across Jefferson and Shelby Counties of Kentucky. All are entirely outside of the graben, but are mentioned here because of their good quality and as control for structural and stratigraphic interpretations away from the major fault systems in the rift system.

In addition to the previously existing seismic data used for this project, a Weatherford International vertical seismic profile from Hancock County was used to help constrain stratigraphic correlations and the time-to-depth conversions for Hancock, Breckinridge, and Ohio Counties, north of the Rough Creek Fault zone (acquired and processed by Weatherford Inc. for ongoing KGS CO_2 research).

Time Horizons. Synthetic seismograms were produced using bulk-density and sonic logs from several deep wells that are located close to one or more 2-D seismic lines in the KGS inventory. By matching seismic wavelet character and estimated travel times, these seismograms facilitated the correlation of the major stratigraphic tops onto the seismic lines (Fig. 6). These seismic tops were then interpreted as far as possible across 66 seismic lines, totaling more than 900 mi of profiles in western Kentucky, southern Indiana, southern Illinois, and northwestern Tennessee (Fig. 7).

Velocity Analysis. Using the Petra family of mapping, petrophysical, and seismic software from IHS/GeoPlus Inc., average surface-to-horizon velocities were computed using the elevations of the mapped tops from wells and the time horizons from the seismic data. This collection of average velocities calculated at well locations was then gridded to produce a continuous velocity grid surface across the study area for each mapped horizon. In areas of low data density, control points or lines were added as necessary to maintain a geologically reasonable output and minimize any edge effects created by fault or survey area discontinuities.

The two-way travel times from individual seismic shotpoints were multiplied by the velocity value from the grid (at the same X/Y coordinate as the shotpoint) to produce a depth in feet below the seismic datum at that shotpoint location. These depths were then converted into elevation values relative to mean sea level.

The method described above worked well outside of the rift grabens, where wells drilled to basement are more common and seismic horizons were shallower than 1-s two-way travel time. For the deeper horizons in the graben areas, limited well penetrations produced greater uncertainty in velocity calculations (and therefore in subsea depth calculations) using the above method. A different technique was used to produce the maps of the Reelfoot Arkose and Precambrian basement in the Rough Creek and Mississippi Valley Grabens. Interval velocities were calculated directly from reflection-seismic data to reduce possible errors in the depth and isopach calculations below the Eau Claire Formation. Using root-mean-square stacking velocities published on processed seismic profiles in a Dix equation (equation 1) layered sequence, interval velocities were calculated for seismic intervals that had been interpreted as the Eau Claire Formation and the Reelfoot Arkose. The RMS velocity is the speed of a wave through subsurface layers of different interval velocities along a specific ray path. The RMS value is the square root of the sum of the squares of each layer's velocity, divided by the number of layers, and is usually symbolized by V_{rms}. This technique aided in both depth calculations and interpretation of the lithology of deep geologic units.

$$V_{int(n)}^{2} = \frac{((V_{rms(n)}^{2} \times t_{0(n)}^{2}) - (V_{rms(n-1)}^{2} \times t_{0(n-1)}))}{(t_{0(n)} - t_{0(n-1)})} \qquad (1)$$

where n = velocity layer number (value of 1 at surface and increases downward), $V_{int(n)}$ = calculated interval velocity of layer n, $V_{rms(n)}$ = RMS stacking velocity for layer n, and $t_{0(n)}$ = two-way vertical travel time to the reflector at the top of layer n.

This method was tested at a few chosen locations near deep wells with ample data and known subsurface lithologies. When the results were

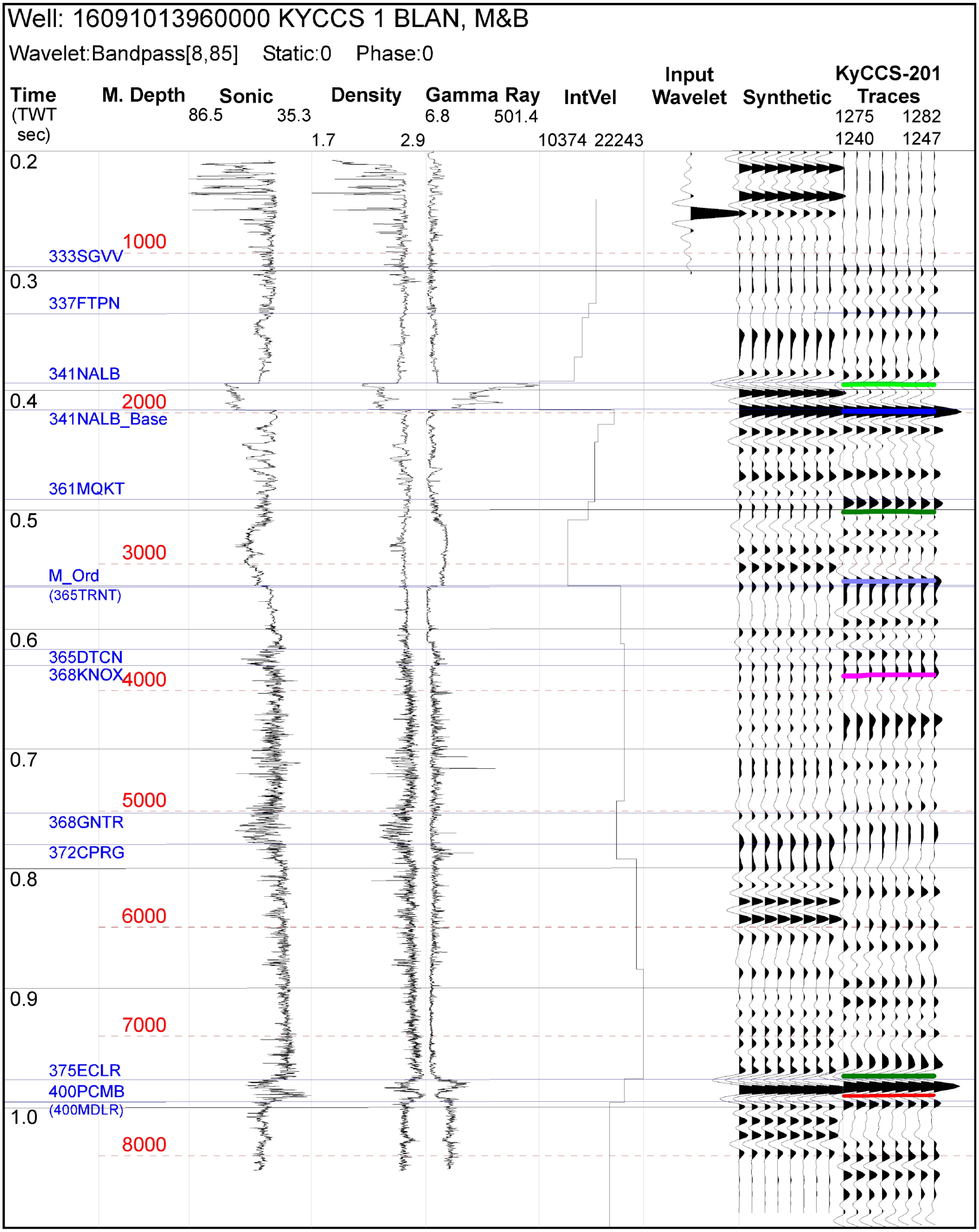

Figure 6. Synthetic seismogram for the KGS No. 1 Blan well, with extracted wavelets from the nearby L-201 seismic line.

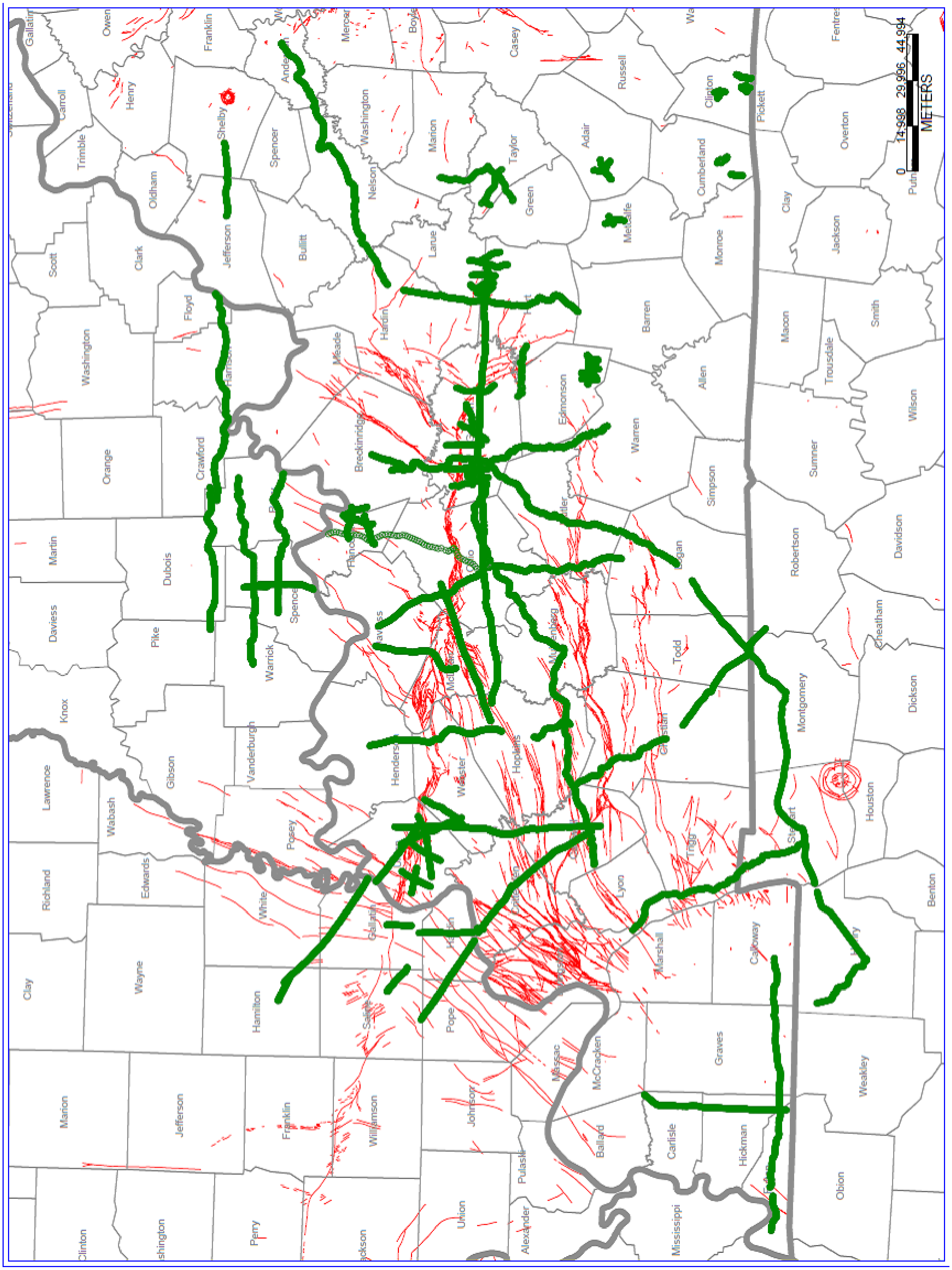

Figure 7. Locations of seismic data used in this project.

satisfactory, interval velocities were calculated for 1,151 depth ranges (in time) from 11 regional seismic lines. Depending on location, depth of resolution, etc., the input RMS velocity values for approximately every 200 shotpoints were used for the calculations. These RMS sets ranged from four to 28 layers per location (varied by area, processing company, etc.), with seven to eight layers being the most common. Using these velocities, probable lithologies have been estimated with the help of some geologic inference (no igneous rocks above the Eau Claire, zones with parts across the Knox Supergroup contain dolomite, etc.). Although this sonic-velocity method of lithologic identification is not necessarily definitive (there are overlaps in the velocity ranges of some rock types), any additional information for these deep horizons will aid in interpretations of depositional history.

These calculated velocity values for the Eau Claire Formation and what was later interpreted to be the Reelfoot Arkose were manually contoured and gridded across the deeper depositional areas. Isochronal thickness grids of the interpretations were manually produced in a similar manner. The isopach thickness of the Reelfoot Arkose was then calculated by multiplying these two gridded data sets:

$$Z\ (\text{ft}) = \Delta t\ (\text{sec}) \times V_{int}\ (\text{ft/sec}). \qquad (2)$$

The elevation (grid surface) of the base of the Eau Claire Formation in the grabens was produced by subtracting the calculated isopach thickness of the Eau Claire from the elevation of the top of the Eau Claire, which is the deepest horizon with sufficient well tops needed to constrain velocity calculations using Petra’s standard time-depth conversion method. The same process was used to calculate the isopach thickness and produce top and base elevation grids of the Reelfoot Arkose. Where the Reelfoot Arkose is present, the base of the Reelfoot is also the top of the Precambrian surface.

Areas outside of the grabens were then set to null values for the manually created deep isopach and elevation grids. After resampling to a common set of grid nodes, these grids of deep areas were merged with the appropriate elevation and isopach surfaces outside of the grabens using Petra (“Use B if A is NULL” grid equation transform) to produce continuous grid surfaces across the study area.

The estimated interval velocity values from the Dix equation process also aided in the interpretation of the Reelfoot Arkose in the Rough Creek Graben. The Reelfoot Arkose had been defined in Missouri (Weaverling, 1987; Houseknecht, 1989) and interpreted as far north and east as southern Illinois from well cuttings. A high-amplitude and laterally extensive seismic-reflector package below the Eau Claire Formation represented an as-yet-undefined formation above igneous basement but below the Eau Claire Formation in the eastern Rough Creek Graben counties of Butler, Edmonson, and Grayson. The seismic velocities within the unit, as well as the character of the horizons, were consistent with arkosic alluvial fan deposits as described by Weaverling (1987). Directly overlying Precambrian igneous basement and overlain by the Eau Claire Formation (Bonneterre Formation and Elvins Group of Missouri), the stratal position of this package is also consistent with the Reelfoot Arkose. This seismic unit was later interpreted westward, and a complete depositional area map has been interpreted from these data.

Potential Fields Data. Four public-domain potential-fields data sets were used in this study: the USGS Midcontinent magnetic surveys, Tennessee Valley Authority high-resolution aeromagnetic data, USGS isostatic residual gravity, and USGS Bouguer gravity anomaly data sets. These data were used to constrain the strikes and lateral extents of major basement faults that were interpreted to cross seismic profiles and to define major graben boundary faults where no seismic data are available.

The TVA aeromagnetic data were recorded between 1972 and 1978. These total magnetic field intensity data were later reprocessed and corrected for temporal variations in magnetic intensity by Parker Gay of Applied Geophysics Inc. of Salt Lake City, Utah. The flight-line point data were gridded into a mathematical surface using Esri ArcMap software by KGS researchers. Because of gaps between flight lines and the intention to produce a continuous surface, a grid sample size of 2.5 km was used.

The USGS aeromagnetic data were compiled from various sources to produce the “Aeromagnetic Map of East-Central United States" (Hildenbrand and others, 1981), and include some of the earlier TVA data. This total magnetic field intensity data set covers most of the Rough Creek Graben (west of Green County) and all of the Mississippi Valley Graben in the study area. Close data and no data gaps permitted a much higher-resolution grid, an 800-m cell sample size, than was possible with the TVA data. With the assistance of Dr. Dhananjay Ravat of the Department of Earth and Environmental Sciences at the University of Kentucky, reduced-to-pole and second-vertical-derivative magnetic values were calculated.

The magnitude of Earth's magnetic field at any one location can be described as the sum of three perpendicular component vectors: X (east), Y (north), and Z (vertical). At the equator, the field is near horizontal (Y > X, Z–0), whereas at the magnetic poles the magnetic flow vectors are approximately vertical (X = Y–0). The reduced-to-pole process is a mathematical transformation of the total magnetic field intensity to calculate the Z component of the field. By using only the vertical component vector, the anomalies represented in the magnetic survey are displayed so that they are directly above the anomalous structure, aiding in the resolution and definition of large subsurface fault offsets (or igneous intrusions, subsurface voids, etc.). The second-vertical-derivative magnetic survey maps are a representation of the vertical rate of change of the reduced-to-pole data. This type of display can produce erratic values for near-surface targets, but can be very useful in defining deep crustal structures and boundaries. By using these two types of data representations together, a more thorough structural interpretation of the region was possible.

The USGS gravity survey data sets originally came from the DDS-0009 data series "National Geophysical Data Grids; Gamma-Ray, Gravity, Magnetic, and Topographic Data for the Conterminous United States" (Phillips and others, 1993). Gravity surveys are labor intensive and must be performed on site as opposed to aeromagnetic data that are recorded from moving airplanes or helicopters. This tends to lead to either smaller survey areas or wider spaced data points chosen for the survey. The USGS gravity data are no exception, and the sample-size grids used to produce these map surfaces are 4,000 m on a side. Bouguer anomaly and isostatic residual anomaly calculations are derived from these data.

A Bouguer anomaly map represents recorded gravity-intensity data that have been corrected for elevation (free-air correction) and local topography (Bouguer correction); a theoretical reference field value is subtracted to produce the Bouguer anomaly map. Isostatic residual gravity-anomaly maps have had long-wavelength anomalies removed from the data (after free-air and Bouguer corrections). Long-wavelength anomalies commonly are associated with isostatic compensation of topographic or tectonic loads. Removing these anomalies can produce higher resolution of near-surface structures while suppressing the effects of the deeper crust and mantle.

Faults

Similar to features in other intracratonic rift basins, the features in the Rough Creek Graben that affect the facies and sedimentation patterns the most are the basement fault systems (Fig. 8). The Rough Creek Graben has undergone numerous tectonic events, which have produced thousands of faults. Some of these faults probably moved only once, but many more have been reactivated or inverted at least once, leading to a highly complex structural arrangement of faults. Trying to accurately map individual subsurface offsets from all of these faults is not possible because of both a lack of data for each individual fault block mapped at the surface and the immense computing power that would be needed to process such a large data set. Using too few (or no) faults, however, would lead to inaccurate and unrealistic maps. To complete this project, a more generalized fault set was needed to differentiate between regionally significant major faults and less significant minor faults.

Surface-fault locations from 7.5-minute U.S. Geological Survey geologic quadrangle maps and interpreted faults from seismic sections provided the bulk of the fault-location information. The complex array of mapped surface faults was examined for local offset magnitude and direction, as well as proximity to other faults. Local groups of minor faults with similar strike and sense of offset were assumed to have acted as a group and were simplified into a single major fault. Singular faults

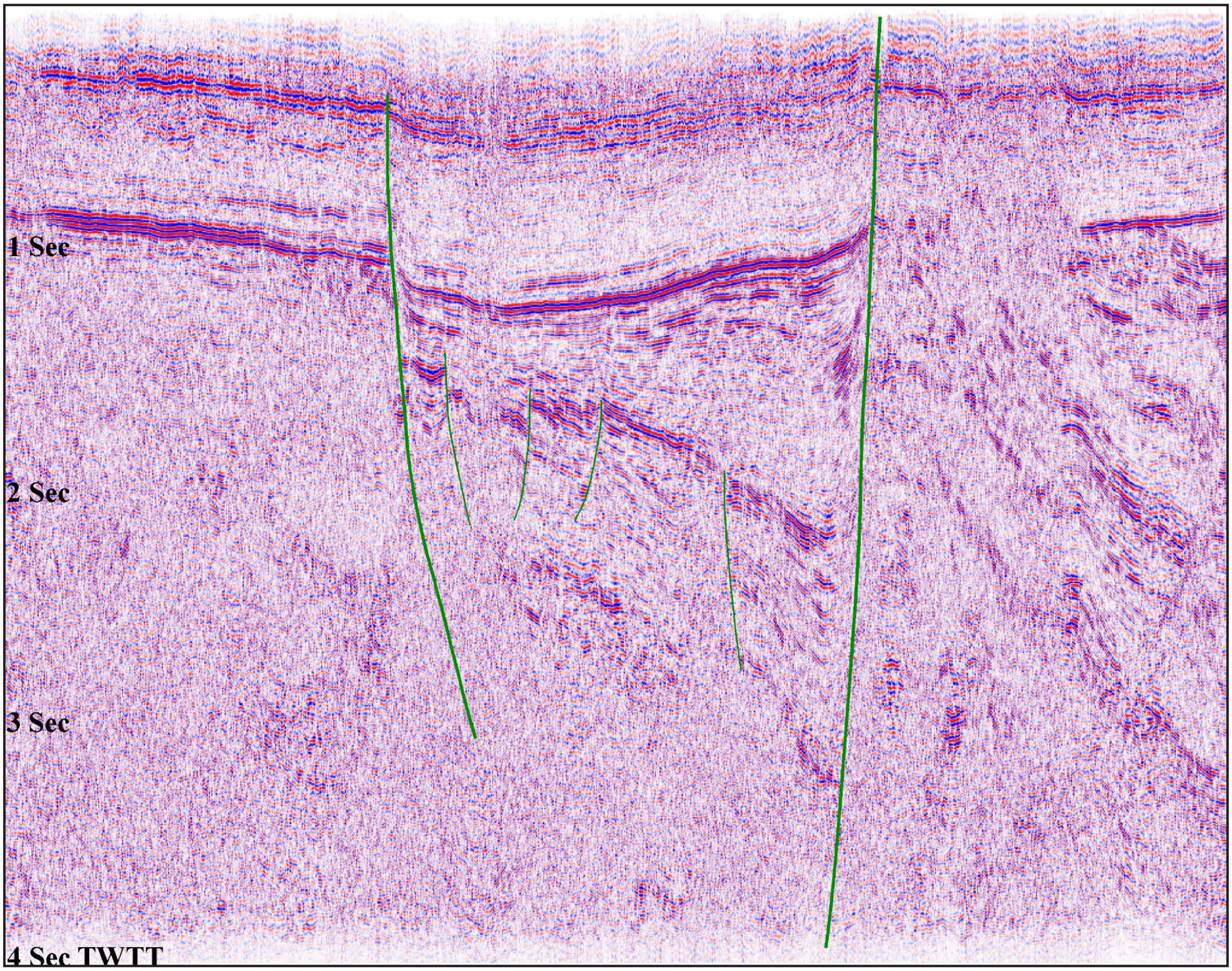

Figure 8. Simplified seismic section across the Rough Creek Graben illustrating major offsets along basement faults (in green).

with relatively small offsets (less than 100 ft) were ignored, but those with larger offsets were treated as faults.

For basement faults that do not reach the surface (and do not cross a seismic line), a combination of magnetic-intensity data, Bouguer gravity anomaly data, and the 1:24,000-scale structure-contour data from the project area were used. With these three data sets loaded into a GIS project (ArcMap), extended linear trends were searched for (across two or more 7.5-minute quadrangles) with a high rate of structural slope (Figs. 9–10).

Because of the numerous tectonic events that have reactivated the faults in the region since the Cambrian (three Appalachian orogenies, the Ouachita Orogeny, the opening of the Gulf of Mexico, and the opening of the Atlantic Ocean), these linear features on the surface are interpreted to be the result of movement along reactivated basement faults causing deformation (drape) in the cover rocks. Using aeromagnetic and gravity data to constrain (or highlight) these structural trends, fault location, and throw direction data were interpreted for these faults.

In the subsurface, a similar technique was used to separate minor from major faults resolvable on the seismic lines. Where necessary because of a lack of seismic data, geophysical potential-fields maps (Plate 2, Plate 3, and Plate 4) were used to help constrain the strike and lateral extent of faults interpreted from 2-D seismic lines. Finally, in the map compilation and gridding process, ar-

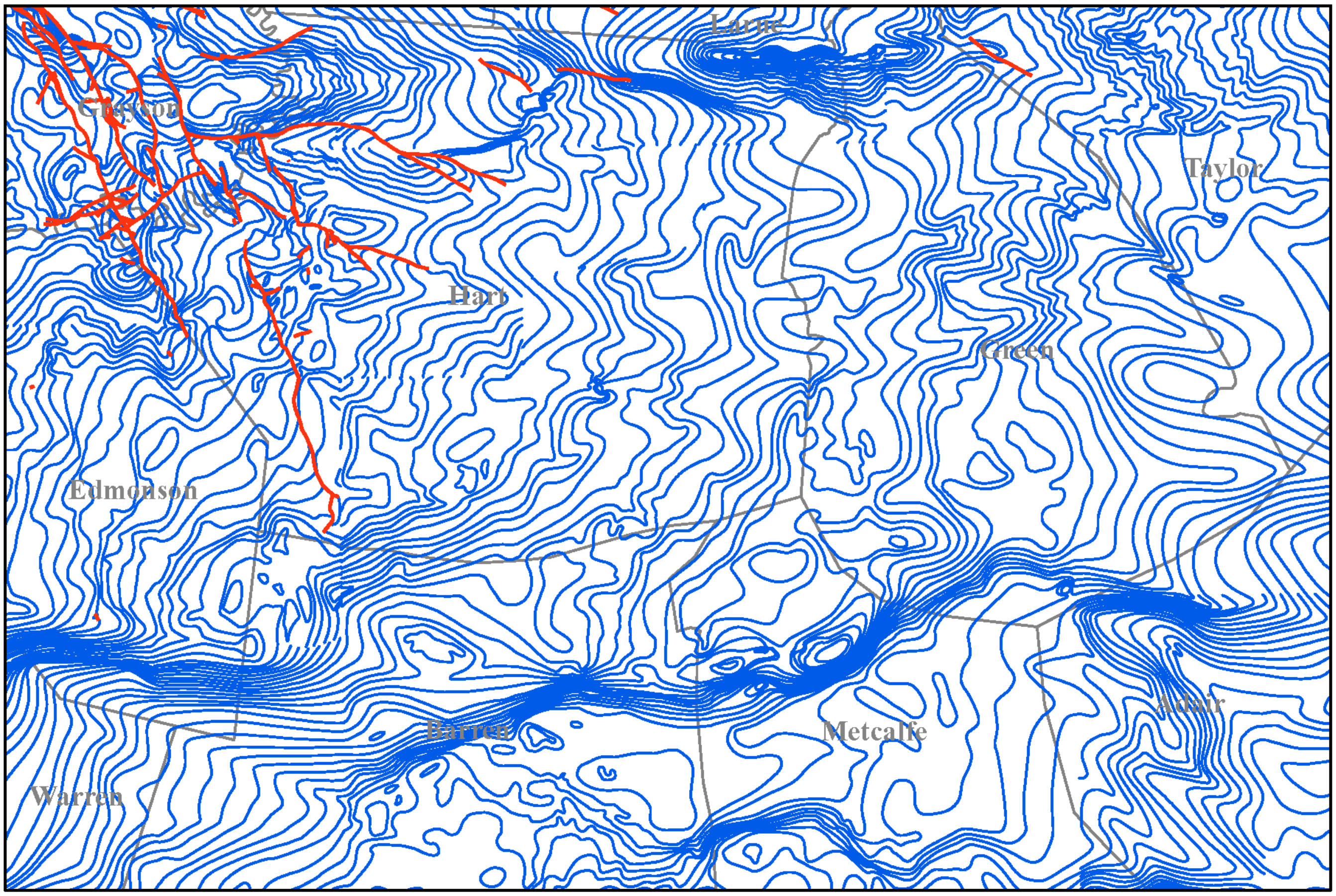

Figure 9. Mapped surface faults (red) and structure (blue contours) in west-central Kentucky.

eas with abrupt and dramatic elevation contrasts along a linear trend were also treated as major faults. These major faults were then used in the gridding process to produce fault discontinuities in the mapped surfaces. Four sets of fault cuts were used in this project: one for only the New Albany Shale interval, one for the New Albany through Knox section, one for the Eau Claire through Precambrian section, and a final set for the faults in the New Madrid Seismic Zone. Using different fault sets for different stratigraphic intervals compensated for lateral changes in fault position with depth because of fault dip. It also allowed for the removal of faults that did not penetrate (or otherwise affect) the horizon or isopach being mapped. See Plate 1 for the generalized fault trends.

Mapping Techniques

After both stratigraphic well tops and seismic horizon values had been converted into subsea elevation units, the seismic and well data point sets could be combined and treated as a single data type. Using Petra, 480.0 × 363.2 km grids across the project area (300 × 227 cells with 1,600-m sides) were created for each mapped stratigraphic horizon using all of the available data. An inverse distance-squared ($1/d^2$) weighting algorithm (the "Highly Connected Features" function in Petra) was used to produce the grid surfaces. Surface discontinuities were included along the fault-line sets described above to allow for vertical offsets of the mapped horizon. The fault lines act as barriers to the $1/d^2$ search function, removing the influence of neighboring data points across a fault line. In areas of complex faults or low data density, control elevation lines were added as necessary to maintain a geologically reasonable output and minimize any edge effects created by fault or survey-area irregularities. Fault offsets at each stratigraphic horizon were calculated from seismic time offsets where seismic data crossed a fault. Fault offsets in areas

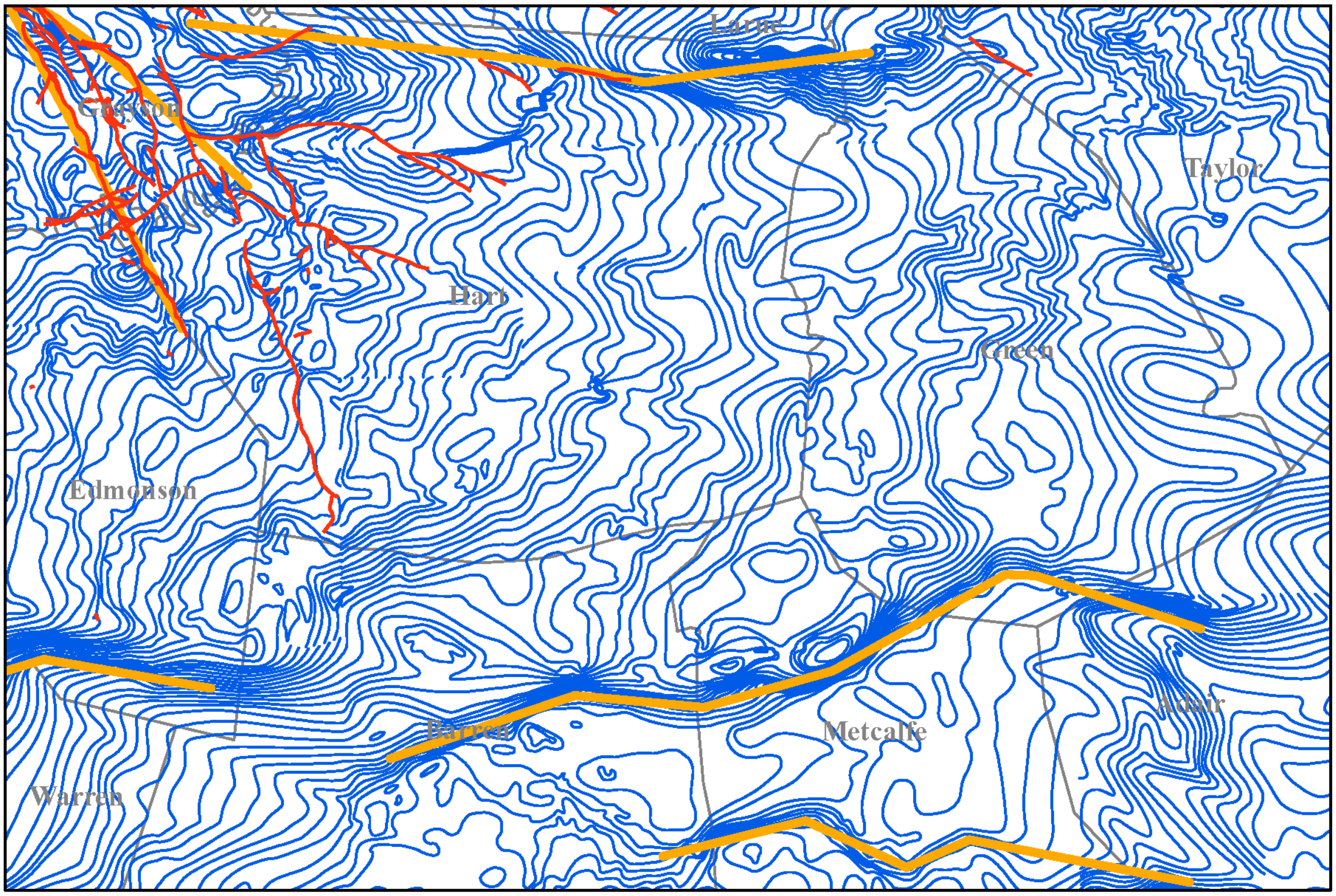

Figure 10. Mapped surface faults (red) and structures from Figure 9, with interpreted subsurface fault zones (in orange).

not coincident with seismic data were interpreted from regional structural trends. These stratigraphic horizon grids are represented in both the Rough Creek Graben Consortium Plate 5, Plate 6, Plate 7, Plate 8, Plate 9, Plate 10, Plate 11, Plate 12, Plate 13, Plate 14, Plate 15, Plate 16, Plate 17, Plate 18, and Plate 19 and in the grid profiles displayed on the Rough Creek Graben Consortium cross sections (Plate 20, Plate 21, Plate 22, Plate 23, Plate 24, Plate 25, Plate 26, Plate 27, Plate 28, Plate 29, Plate 30, and Plate 31).

Only regional stratigraphic units that are resolvable on seismic reflections were mapped. For the Ordovician through Mississippian strata, many more units were interpreted from well logs than was possible with current seismic technology. These tops are included with the well data and are displayed on the wells in the geologic cross sections. See Table 1 and Table 2 for a list of well and seismic stratigraphic tops interpreted for this project.

In addition to the traditional stratigraphic well tops described above, included in the project database are interpolated grid elevations for all of the mapped horizons (indicated by a "_G" suffix for the top name). For each well in the mapped area, the elevation value from the final mapped horizon grid cell containing that well's location was extracted and included as a well top. These interpolated values permit stratigraphic tops elevations to be estimated below the drilling depth of the well. Because each cell value is a weighted average of all Z values near or within that cell, the interpolated value may not be exactly the same as the interpreted value at the exact well position. For wells with both an interpreted and interpolated value for a stratigraphic top, the interpreted value is more accurate and should take precedence.

Table 1. Middle Silurian through Upper Mississippian stratigraphy interpreted for the Rough Creek Graben Consortium project.

Stratigraphic Code	*Description*	*Well Count*	*Source*
300PLZC	top of Paleozoic strata	36	wells only
Upper Mississippian			
332BRLW	Barlow Limestone	55	wells only
333SGVV	Ste. Genevieve Limestone	64	wells only
Lower Mississippian			
337FTPN	Fort Payne Formation	174	wells only
Upper Devonian			
341NALB	New Albany Shale	1,381	wells and seismic
341NALB_B	base of New Albany Shale	1,408	wells and seismic
Middle Devonian			
344SLBG	Sellersburg Limestone	495	wells only
344JFVL	Jeffersonville Limestone	482	wells only
344DCCK	Dutch Creek Sandstone	313	wells only
Lower Devonian			
347CCEK	Clear Creek Formation	273	wells only
347CCGK	Clear Creek/Grassy Knob undifferentiated	241	wells only
347BKBN	Backbone Limestone	28	wells only
347FLGP	Flat Gap Limestone	43	wells only
347GRKB	Grassy Knob Limestone	68	wells only
Upper Silurian			
351BILY	Bailey Limestone	204	wells only
351DCTR	Decatur Limestone	90	wells only
351LSTN	Liston Creek Limestone Member, Wabash Formation	15	wells only
351RNDL	Randol Shale	75	wells only
Middle Silurian			
355MSPG	Moccasin Springs Formation	73	wells only
355MSWA	Mississinewa Shale Member, Wabash Formation	19	wells only
355BRPT	Brownsport Formation	103	wells only
355LBLV	Lobelville Limestone	80	wells only
355BOB	Bob Limestone	83	wells only
355BCRV	Beech River Limestone	107	wells only
355DIXN	Dixon Limestone	103	wells only
355LSVL	Louisville Limestone	95	wells only
355SCLR	St. Clair Limestone	28	wells only
355LEGO	Lego Limestone	119	wells only
355WLDR	Waldron Shale	229	wells only
355LAUR	Laurel Dolomite	237	wells only

All of the maps in this report are displayed in universal transverse Mercator zone 16 north projection on the North American 1983 datum. The X and Y values for surface locations are in meters and all Z elevations are in feet relative to mean sea level.

Table 2. Precambrian through Lower Silurian stratigraphy interpreted for the Rough Creek Graben Consortium project.

Stratigraphic Code	*Description*	*Well Count*	*Source*
Lower Silurian			
357OSGD	Osgood Shale	207	wells only
357SXCK	Sexton Creek Limestone	36	wells only
357BRSF	Brassfield Dolomite	238	wells only
Upper Ordovician			
361MQKT	Maquoketa Shale	225	wells and seismic
Middle Ordovician			
M_ORD	Base of Maquoketa Shale/top Middle Ordovician (Trenton Formation or Black River Group)	410	wells and seismic
365TRNT	Trenton Formation	295	wells only
365BKRV	Black River Group	320	wells only
365PLTN	Plattin Limestone	14	wells only
365PCAV	Pencil Cave bentonite	265	wells only
365PCNC	Pecatonica Limestone	218	wells only
365JCHM	Joachim Formation	253	wells only
365DTCN	Dutchtown Formation	235	wells only
365STPR	St. Peter Sandstone	128	wells only
365EVRN	Everton Formation	66	wells only
Lower Ordovician			
368KNOX	Knox Supergroup	293	wells and seismic
368GNTR	Gunter Sandstone	50	wells only
Upper Cambrian			
372CPRG	Copper Ridge Dolomite	128	wells only
372PTSI	Potosi Dolomite	9	wells only
372ELVN	Elvins Formation	2	wells only
372DAVS	Davis Formation	42	wells only
372BNTR	Bonneterre Formation	24	wells only
Middle Cambrian			
375ECLR	Eau Claire Formation	82	wells and seismic
ECLR_LS	mid–lower Eau Claire limestone unit	12	wells only
375MTSM	Mount Simon Sandstone	30	wells only
375LMTE	Lamotte Formation, Mount Simon Sandstone equivalent	18	wells only
375SFRN	St. Francis Formation of Missouri	7	wells only
375RLFT	Reelfoot Arkose	9	wells and seismic
Precambrian			
400PCMB	Precambrian basement (Middle Run Formation, Grenville Province igneous-metamorphic rocks, or Granite-Rhyolite Province igneous rocks)	61	wells and seismic
400MDLR	Middle Run Formation (sandstone)	11	wells only
400GRVB	Grenville Province igneous-metamorphic rocks	20	wells only
400GRRY	Granite-Rhyolite Province igneous rocks	27	wells only

Map Analysis

The maps described in this section are structure-contour maps of eight major stratigraphic horizons and the isopach thicknesses between these horizons. The eight mapped surfaces are the top and base of the New Albany Shale, the top and base of the Maquoketa Shale, the top of the Knox Supergroup, the top of the Eau Claire Formation, the top of the Reelfoot Arkose, and the top of Precambrian strata. All of the data used to produce each horizon map are represented on the maps discussed in this section. The well symbols printed on each map represent only wells that penetrated that horizon for interpretation. In a similar manner, shotpoint locations along seismic lines, where an interpretation of that seismic horizon was possible, are highlighted with small gray squares to distinguish them from locations where the unit is absent or unresolvable from those data.

Structure on the Top of the New Albany Shale

The youngest and stratigraphically highest unit mapped in this project is the Devonian New Albany Shale. Because of the relatively shallow depth, this horizon has the most well penetrations and thus highest well data density of all eight mapped stratigraphic units. This black shale also has strong well-log response, especially on the three most common logs used in this region: gamma-ray, neutron-porosity, and bulk-density. Therefore, not only does this unit have the most well data, the tops data from the New Albany Shale also have the highest confidence level.

In the study area, the prominent structures of the top of the New Albany Shale are the Cincinnati Arch, the Jessamine and Nashville Domes, and the Cretaceous subcrop beneath the Mississippi Embayment. The regional shape of the Illinois Basin is roughly triangular at this level.

At the top of the New Albany, as well as in the deeper horizons, there is a dramatic difference in structural style between the eastern and western parts of the Rough Creek Graben. The general boundary between these two halves strikes northeast through northern Caldwell and Hopkins Counties, across the graben to northeastern McLean County. The western part of the graben (west of McLean County) is a highly asymmetric, north-dipping, half-graben style of structure, whereas the eastern Rough Creek Graben is only slightly asymmetric and dips to the south. The deepest points of the New Albany are around –4,600 ft in the Fairfield Basin in White County, Ill. (outside of the graben complex) and around –4,400 ft in Union County, Ky., in the northwestern corner of the Rough Creek Graben. Fault offsets of the New Albany Shale in the major graben-bounding fault zones range from less than 200 ft along the Pennyrile Fault System on the south to more than 400 ft in Union County and 500 ft in Grayson County.

The erosion beneath the Cretaceous cover of the Mississippi Embayment has removed the New Albany from all but the very northern part of the Mississippi Valley Graben. For the remaining northern area, fault offsets appear to be around 100 to 200 ft on average at this level. Outside of the grabens and away from mapped faults, the New Albany has a gently dipping upper surface, as indicated by wide contour spacing with a 200-ft contour interval.

Uplifted blocks along the Rough Creek Fault Zone in Ohio and Grayson Counties, as well as a small uplifted fault block in Caldwell County, have characteristics of traditional positive flower structures: a narrow band of faults that merge into a single plane at depth, generally associated with transpression along preexisting faults. In contrast, an uplifted area in McLean County northwest of the Conoco No. 1 Turner well is much wider but not bisected by as many faults and is locally around 600 ft higher than the upthrown side of the Rough Creek Fault Zone (Fig. 11). Another post-Devonian structure that is observable on this map is the north–northwest-striking Tolu Arch in Livingston and Crittenden Counties (Trace and Amos, 1984). This arch is associated with the nearby Hicks Dome, which has been attributed to Early Permian magmatic intrusion, as indicated by the numerous mafic dikes and sills in the region (Trace and Amos, 1984). This broad arch crosses a region near the intersection of the Mississippi Valley and Rough Creek Grabens and is characterized by numerous chaotic faults exposed at the surface. The Tolu Arch has an amplitude of just more than 1,200 ft at the top of the New Albany Shale. Similar amplitudes for this anticline are interpreted down as far as the top of the Knox Supergroup.

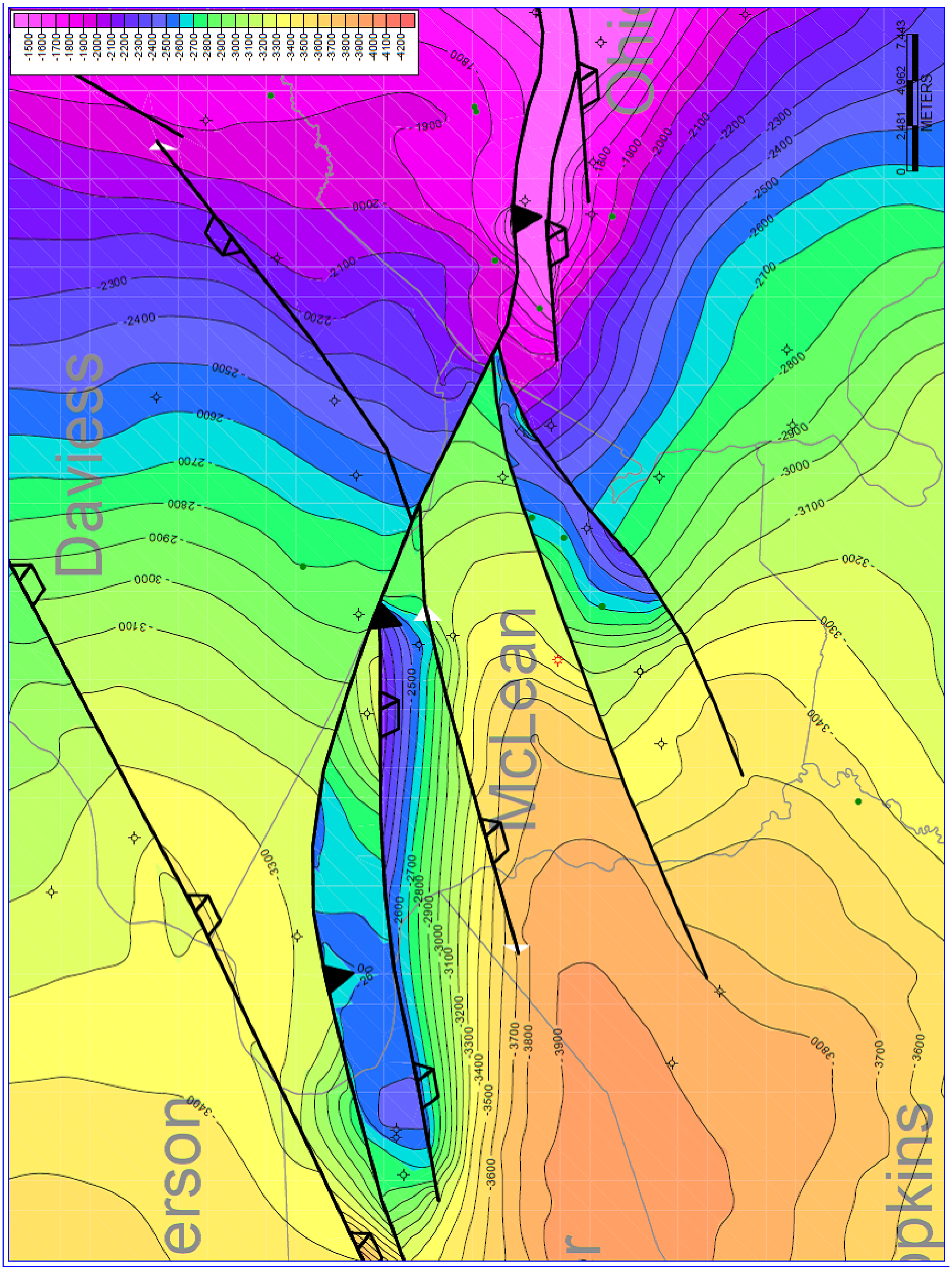

Figure 11. Structural inversion structures along the Rough Creek Fault Zone at the top of the New Albany Shale.

Other notable structures that can be seen at this level are the faults that create the DuQuoin Monocline and LaSalle Anticlinal Belt at the surface. These two roughly north-south faults in south-central Illinois constrain the downwarped region known as the Fairfield Basin (see Fig. 12).

One other fault-related structure on this map is the Muldraugh Dome in northern Meade County (McDowell, 1986). This is a relatively small uplifted structure, about 2 mi in diameter, with no mapped faults at the surface (Withington and Sable, 1969; McDowell, 1986). Freeman (1951) reported several wells penetrating an undeformed Silurian dolomite directly overlying brecciated dolomite and chert of the Lower Ordovician Knox Supergroup, indicating more than 1,550 ft of missing section. Although the cause of the Muldraugh Dome is unknown, its circular shape and the uplifted and brecciated nature of the subsurface geology implies an impact crater origin.

Thickness of the New Albany Shale

The New Albany Shale in this region thins eastward onto the Cincinnati Arch (less than 50 ft) and around the Jessamine and Nashville Domes (including some pinch-outs in localized areas). The unit thickens toward eastern Illinois and into the Rough Creek Graben (as much as 650 ft in Crittenden County). This thickening in the graben suggests either syndepositional fault movement/subsidence, or possibly fault movement just prior to deposition that produced varied topography, which the shale later filled. This thickness change is especially dramatic across many of the Rough Creek Fault Zone faults, suggesting the whole fault trend was deforming at the same time as part of a larger tectonic framework, and not just a local event affecting one or two faults.

Structure on the Base of the New Albany Shale

The New Albany Shale in the study area overlies Late Silurian to Early Devonian strata. Numerous regional and local unconformities are present from this period, so the specific formation present immediately below the New Albany at any point is highly variable across the study area. For simplicity, this stratigraphic horizon is herein referred to as the base of the New Albany Shale, regardless of the identity of the underlying strata.

Because the New Albany Shale is relatively thin, the structure of the base is very similar to that of the top of the unit, including regional dip directions and outcrop patterns. The deepest points in the study area are around –4,800 ft in the Fairfield Basin and around –4,400 ft in the Rough Creek Graben in Webster County. Graben-bounding fault offsets along the northern border are slightly less than at the top of the unit (about 450 ft of normal offset in Grayson County, around 400 ft of post-Devonian inverted offset in McLean County, and around 300 ft in Union County). Offsets along the southern border of the Rough Creek Graben and the borders of the Mississippi Valley Graben are similar to those at the top of the New Albany Shale (200 and 100–200 ft, respectively). The differences in structural asymmetry between the eastern and western parts of the Rough Creek Graben apparent at the top of the New Albany are also expressed at the base. The general shape of the eastern end of the Rough Creek Graben is more distinct from the more regional Cumberland Saddle erosional patterns. The inversion structures along the Rough Creek Fault Zone in Webster and Ohio/Grayson Counties described for the top of the New Albany Shale are also expressed at the base.

Thickness of the Interval Between the Base of the New Albany Shale and the Top of the Maquoketa Shale

This interval is composed of shallow-water carbonate and clastic units, with dolostone as the dominant lithology. It includes the entire Silurian section and, in some areas, the Early to Middle Devonian strata as well (Seale, 1981). This package thins to the south and east, resulting in numerous pinch-outs along the Cincinnati Arch. The removal of this section along the arch can make distinguishing the base of the New Albany Shale in well logs from the top of the Upper Ordovician Maquoketa Shale difficult. The thickest areas of this unit are in the Fairfield Basin (2,400 ft) and along the southeastern trend between Hardin and Hopkins Counties (average 1,800 to 2,200 ft thick) along the basinal axis of the Rough Creek Graben. In the southern Indiana and Illinois region, this section is expressed as a relatively flat, wide body with thicknesses generally more than 1,000 ft.

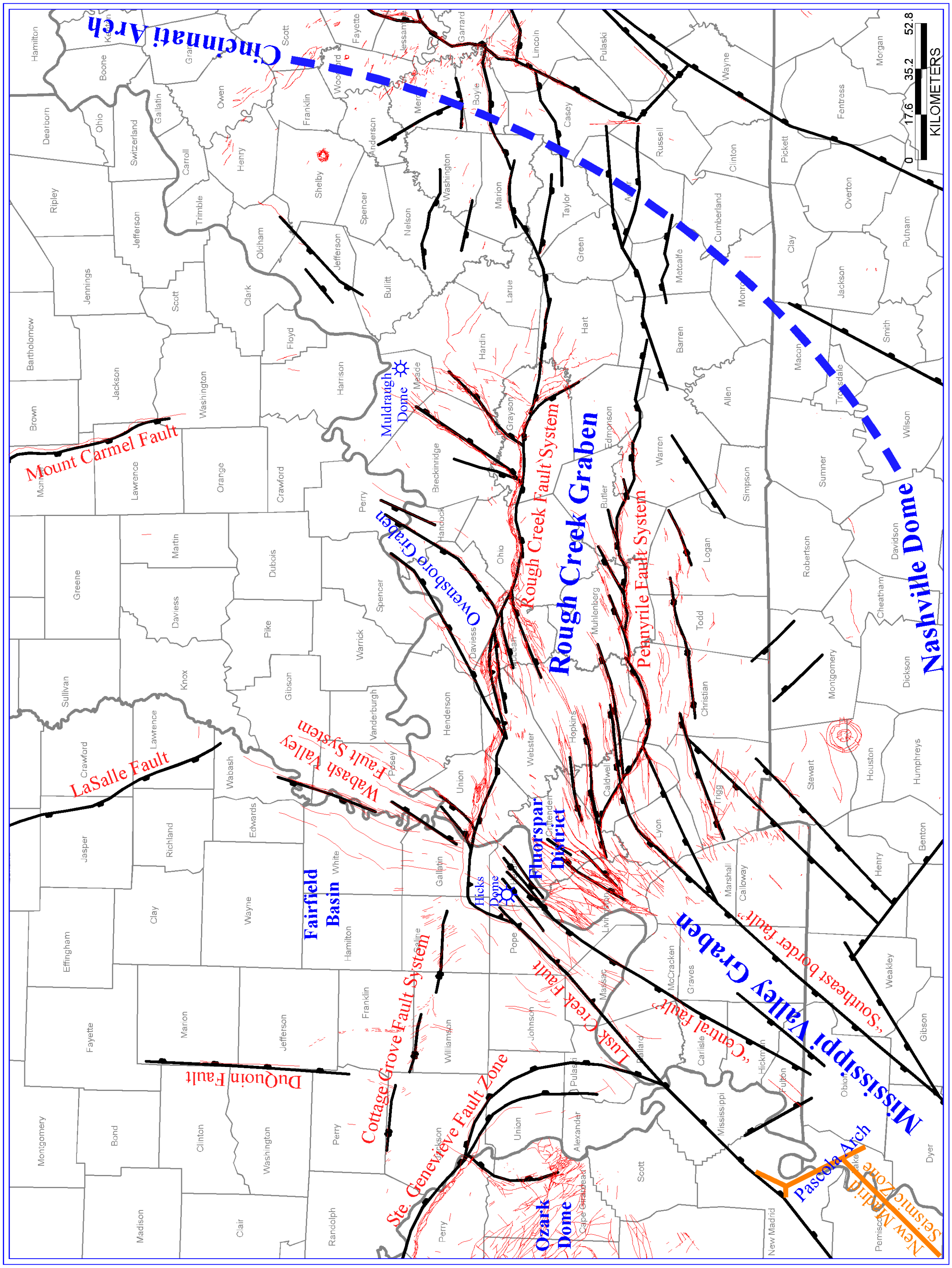

Figure 12. Major structural features in the Illinois Basin region. Interpreted basement faults in black, mapped surface faults in red, and faults associated with the New Madrid Seismic Zone in orange.

This package of strata thickens southward across the Rough Creek Fault Zone, with greater amounts of thickening observed in the eastern part of the Rough Creek Graben. A more subtle thickening can be observed in the fault-bounded Owensboro Graben (Greb, 1985) in Daviess and western Hancock Counties. There also appears to be some thickening to the northwest in the Mississippi Valley Graben, possibly from sagging over a deeper sub-basin (see below).

Structure on the Top of the Maquoketa Shale

The top of the Maquoketa Shale is also the top of the Upper Ordovician strata in this region and is composed of calcareous shales and siltstones. The unit crops out at the surface along the domes of the Cincinnati Arch, and extends down to below –6,200 ft in the Fairfield Basin and to around –6,600 ft in the Rough Creek Graben in Union County. Unlike the previously described stratigraphic packages, the deepest points in the study area are in southern Union County in the Rough Creek Graben and not in the Fairfield Basin to the north.

Offsets along the bounding faults of the Rough Creek Graben range from around 1,000 ft along the Rough Creek Fault Zone in Union County, to 800 ft in Grayson County, to 400 to 800 ft in Muhlenberg County, to close to 0 ft of cumulative offset in McLean County adjacent to the Owensboro Graben. Current interpreted offsets along the borders of the Mississippi Valley Graben are less than 200 ft. The basin axis in the Rough Creek Graben is still a linear depression at this level, extending from close to the Rough Creek Fault Zone in Union County southeastward to Hopkins County. The different structural style between the eastern and western halves of the Rough Creek Graben is apparent at this horizon, but is less pronounced than at shallower levels. The Tolu Arch, as well as the inversion structures along the Rough Creek Fault Zone, are also apparent at the top of the Maquoketa Shale.

Thickness of the Maquoketa Shale

With the exception of local thickening along some individual faults in the southwestern part of the Rough Creek Graben, the thickness distribution of the Maquoketa Shale does not appear to have been affected by regional tectonics. Overall, the Maquoketa thickens to the east-northeast. Thicknesses range from less than 300 ft in central Illinois to as much as 600 to 700 ft along the outcrop belt in central Kentucky. Other than in one isolated fault block in Lyon County, there is little apparent tectonic effect on the thickness of the Maquoketa Shale in the Mississippi Valley Graben.

Structure on the Base of the Maquoketa Shale

Similarly to the New Albany Shale discussed above, the base of the Maquoketa directly overlies more than one formation across the study area, and therefore this horizon is mapped as a base rather than the top of the geologic section below it. Across southern Illinois and west-central Kentucky, the Maquoketa conformably overlies the fossiliferous limestones of the Middle Ordovician Trenton Formation. Between these two regions is a linear zone referred to as the Sebree Trough (Kolata and others, 2001) where the Trenton is absent, and a thickened Maquoketa section directly overlies the carbonates of the Black River Group. The transition zones along the edges of the Sebree Trough can be observed in well logs, and appear to be a gradational depositional change unrelated to fault movement. This interpretation is further supported by the lack of any other regional structures that are parallel to the Sebree trend. The gradual thickening of the Maquoketa across the Sebree Trough is not directly evident at the mapped scale and contour interval.

This unit extends from where it crops out around the Inner Bluegrass and Nashville Dome down to –6,800 ft in Union County and down to –6,400 ft outside the graben in White County, Ill. Fault offsets along the Owensboro Graben in McLean and Daviess Counties are increasing at this level, making it a more prominent feature. The general basin and graben structure is very similar to the structure of the top of the Maquoketa Shale, with a pronounced Cincinnati Arch and a highly asymmetric, north-dipping half-graben-shaped basin west of the Owensboro Graben and a more U-shaped synclinal graben to the east in the Rough Creek Graben. Fault offsets at the base along the Rough Creek Graben border fault zones are around 800 ft each in Union and Grayson Counties, 200 to 400 ft along the Pennyrile Fault System, and less than 100 ft in McLean County. Interpreted fault offsets around the Mississippi Valley Graben are around 100 to 200 ft. The structurally inverted regions in the Rough Creek Fault Zone are present, but much less pronounced than across the younger strata.

Thickness of the Interval Between the Base of the Maquoketa Shale and the Top of the Knox Supergroup

This stratigraphic interval includes all of the Middle Ordovician strata in the region, including the Trenton Formation, Black River Group, Ancell Group, and Everton Formation (where present). The lithology of this unit is predominantly limestone, with only minor amounts of sandstone, shale, and dolomite. This section increases in average thickness toward the southern Illinois Basin and northern Mississippi Valley Graben. It reaches a maximum thickness of around 1,800 ft along parts of the Mississippi Valley Graben bounding faults. In the study area, the thinnest points are around 400 ft thick in the northeast and in an isolated area in central Christian County.

Locally, this unit thickens adjacent to faults on individual downthrown blocks in the Rough Creek and Mississippi Valley Grabens. Possible reactivation and structural inversion of the Lusk Creek Fault Zone is evident in a thickened section along the northwestern footwall block.

Structure on the Top of the Knox Supergroup

The top of the Cambrian-Ordovician Knox Supergroup is a regional unconformity surface that marks the top of the Sauk Sequence (Sloss, 1963). The deepest points are –8,000 ft in the Webster/Union County area and –7,700 ft outside the graben in White County, Ill. The Knox reaches its shallowest points of +200 ft along the northern Cincinnati Arch and +600 ft above sea level on the edge of the Ozark Plateau in southeastern Missouri.

Offsets along the Rough Creek Graben bounding faults range from around 1,100 to 1,200 ft along the Pennyrile Fault System in Muhlenberg and Christian Counties, 400 ft along the Rough Creek Fault Zone in Union County, 200 ft in Grayson County, to close to 0 ft of cumulative offset in McLean County, adjacent to the Owensboro Graben. Interpreted offsets along the borders of the Mississippi Valley Graben are less than 200 ft. The basin axis in the Rough Creek Graben is still a linear depression at this level, extending from close to the Rough Creek Fault Zone in Union County, southeastward to Hopkins County. The different structural style between the eastern and western halves of the Rough Creek Graben is still present, but is less pronounced than at shallower levels. This is also the deepest horizon in which the inversion structures along the Rough Creek Fault Zone are evident.

Because of the later pre-Cretaceous unconformity under the sediments of the Mississippi Embayment, the top of the Knox Supergroup is also the top of the Paleozoic section in the central and southern regions of the Mississippi Valley Graben. The amplitude of the underlying Pascola and Blytheville Arches (McKeown and others, 1990) produces a small area in the central Mississippi Valley Graben above these arches where the Knox is absent and Cretaceous sediments directly overlie the Middle to Upper Cambrian Eau Claire Formation.

Thickness of the Knox Supergroup

The Upper Cambrian to Lower Ordovician Knox Supergroup overlies the post-rift strata over the entire region (Schwalb, 1969b; Shaver, 1985; Ryder, 1992; Noger and Drahovzal, 2005). This passive margin sequence is predominantly carbonate, with minor amounts of mature, quartz-rich sandstones. In the project area, the Knox Supergroup reaches its thickest point in Carlisle County, along the northwestern border of the Mississippi Valley Graben at more than 11,500 ft. The supergroup's thinnest points are along the Blytheville and Pascola Arches, including some local pinch-outs. The Knox thickens into the Rough Creek Graben and, with the exception of the thinned Knox trend in Meade to Breckinridge Counties between the Owensboro Graben and the Locust Hill/Cave Spring Fault System (local thicknesses of 3,000 to 3,500 ft), the Knox thickens around the graben as well.

To account for the dips of fault planes and for faults that terminate in different stratigraphy, three separate fault-line sets were used to create the maps in this study. Because of the thickness of the Knox, the lateral differences in fault-cut locations from these differing fault sets led to irregular, dogtooth-shaped gridding errors or small cell gaps along some fault trends.

Structure on the Top of the Eau Claire Formation

This region of the Midcontinent has undergone numerous episodes of deformation and faulting. These various tectonic events led to different series of faults that affect different stratigraphic levels. The set of faults that affect the top of the Eau Claire Formation and the set for the top of the Knox are quite different. More basement-rooted faults are present in the Eau Claire on the southern shelf area outside of the graben complex and along the eastern end of the Rough Creek Graben. In Grayson and Ohio Counties, the faults that produced the positive flower structure and its structurally inverted block along the Rough Creek Fault Zone at the surface merge at depth, leading to a single fault plane at the Eau Claire and deeper horizons.

The structure of the top of the Eau Claire Formation has a bimodal depth distribution: The deepest elevations are in two areas in central Union County (around –14,000 ft) and in the Webster/Hopkins County area (–13,500 ft). This contrasts somewhat with the structure of the overlying Knox and younger strata, for which the deepest structure has a single linear, synclinal shape. The eastern part of the Rough Creek Graben is fairly symmetrical at this horizon, but the Rough Creek Graben west of McLean County has a muted, down-to-the-north half-graben structure. Outside of the rift graben complex, the Eau Claire in the Fairfield Basin is at –12,500 ft. The Eau Claire is highest (around –1,500 ft) along the Cincinnati Arch north of the Jessamine Dome and on the eastern edge of the Ozark Dome in southeastern Missouri.

Fault offsets at the Eau Claire level along the majority of the Rough Creek Fault Zone from Union to Grayson Counties range from 200 to 500 ft. Along the Pennyrile Fault System, offsets are around 400 ft in Butler County and increase to about 1,200 ft in northern Christian County.

At this horizon in the Mississippi Valley Graben, the deepest area is west of the large north–northeast-striking central fault, which reaches a depth close to –14,000 ft. Fault offsets along the edges of the Mississippi Valley Graben range from less than 500 ft in Graves County to more than 2,000 ft across the Lusk Creek Fault Zone along the northwestern border of the Mississippi Valley Graben. On the southwestern edge of the study area, the Blytheville and Pascola Arches, associated with the underlying New Madrid Seismic Zone (McKeown and others, 1990), are dramatic features at this stratigraphic level.

Thickness of the Eau Claire Formation

Except for two small areas in northeastern Union and southeastern Daviess Counties, where the Eau Claire Formation appears to pinch out on the northern shelf of the Rough Creek Graben, the Eau Claire Formation extends across the entire study area. Across the majority of these shelf areas outside of the major grabens, the Eau Claire has a relatively smooth undulatory character in profile; thicknesses range from 250 to 2,000 ft. The areas of least thickness lie on the northern shelf immediately adjacent to the graben in Union, Henderson, and Ohio Counties, Ky. In the Rough Creek Graben, there are two areas of relatively great thickness in Ohio and Webster Counties; the thickest point of around 10,350 ft is near the center of Ohio County. These two areas combine to form a linear zone of increased thickness that trends parallel to the strike of the Rough Creek Graben and terminates against the southeast-striking Rough Creek Fault Zone splay faults in eastern Grayson County.

In the Mississippi Valley Graben, an area of greater thickness is present in the Pascola and Blytheville Arches in New Madrid and Pemiscot Counties, Mo., and Lake County, Tenn. The fact that these arches outline the region of earthquake activity associated with the New Madrid Seismic Zone implies an interconnected origin. Using published seismic lines (Howe and Thompson, 1984; Sexton, 1988) and well data analyzed in this project, these arches were interpreted to be fault-cored anticlines formed above the New Madrid Seismic Zone faults from northeast-southwest compression. The specific age of formation for these structures is unknown, but appears to be after the Early Ordovician but before the Cretaceous, as indicated by a locally thinned and uplifted Knox section overlain by the undeformed Cretaceous sediments of the Mississippi Embayment.

Structure on the Top of the Reelfoot Arkose

The Early Cambrian Reelfoot Arkose (Weaverling, 1987; Houseknecht, 1989) does not extend across the entire study area and is confined to just the Mississippi Valley Graben and the deeper parts of the Rough Creek Graben west of Green County. The Reelfoot Arkose was also deposited adjacent to and northwest of the Mississippi Valley Graben between the Cottage Grove and Ste. Genevieve Fault Systems northwest of the Lusk Creek Fault, in a small area less than 14 mi wide. This region may have served as a conduit into the western Rough Creek Graben and northern Mississippi Valley Graben for arkosic detritus from eroding felsic granites of the uplifted Ozark Dome during the Early Cambrian (Weaverling, 1987).

The top of the Reelfoot Arkose in the Rough Creek Graben has a north-dipping, trimodal basin structure; the deepest points are in Union, Webster, and Ohio Counties (–19,500, –19,000, and –21,000 ft, respectively). The prominent, steep-sided sub-basin centered in Ohio County apparently was filled before Knox deposition, and thus produced the thickened section of Eau Claire in that area described above. In the Mississippi Valley Graben, the top of the Reelfoot is much deeper within a sub-basin graben on the northwest (downthrown) side of the large north–northeast-striking central fault, having reached a maximum depth of close to –17,800 ft in Carlisle County. The Reelfoot is shallowest at –7,500 ft in two locations in the project area. One is in southeastern Hart County, where the Reelfoot pinches out in the eastern Rough Creek Graben. The other shallow point is in Weakley County, Tenn., on the downthrown side of the northeast-striking, down-to-the-northwest normal fault that marks the local southeastern boundary of the Mississippi Valley Graben. A wide anticline that formed east of the central fault in the upper surface of the Reelfoot Arkose extends from near the Tolu Arch in Livingston County south to Graves County.

The only graben-boundary fault system crossed by the Reelfoot Arkose is the Lusk Creek Fault in Massac, Pope, and Saline Counties, Ill. Fault offsets range from 1,000 to 2,000 ft. To the south, the top of the Reelfoot rises sharply to the southwest in New Madrid and Pemiscot Counties, Mo., Lake County, Tenn., and Fulton County, Ky. This rise produces the cores of the Blytheville and Pascola Arches along the New Madrid Seismic Zone fault trends.

Thickness of the Reelfoot Arkose

In both the Mississippi Valley Graben and the Rough Creek Graben, the Reelfoot Arkose has an average calculated thickness of around 3,000 to 4,000 ft, but is as thick as 17,500 ft in localized areas in Ohio, McLean, and Muhlenberg Counties. Available data density is relatively low for the Mississippi Valley Graben area, however, and additional data may prove that thickness trends are more complex than portrayed here. The Reelfoot Arkose is bounded on most sides by faults. A few areas where the Reelfoot is interpreted to pinch out by onlap onto the Precambrian surface include the eastern Rough Creek Graben near Hart County, in Trigg and Christian Counties between the Pennyrile and Lewisburg (proposed herein) fault trends, two small areas in the Rough Creek Graben to the north of the Pennyrile Fault System, and the area between the Cottage Grove Fault Zone and the Ste. Genevieve Fault Zone at the intersection of the Mississippi Valley and Rough Creek Grabens around Pope County, Ill.

In the Mississippi Valley Graben, the Reelfoot Arkose thickens toward the northwestern border faults, in contrast to thinning toward the Pennyrile faults. Whether this thickening is a result of numerous proximal deposits in alluvial fans coming off the Ozark Dome to the west or from lateral transport and depositional filling of the increased accommodation space produced by continuous offset along the border faults within the graben, is unknown.

Structure on the Top of Precambrian Basement

Large fault offsets define the northern and western boundaries of the Rough Creek Graben. Along the southern boundary, the vertical offsets that create the basin are spread between two fault trends: the Pennyrile Fault System and an unnamed east–west-striking fault zone just south of the Pennyrile Fault System. The informal name "Lewisburg fault system" is proposed for this series of faults. The east end of the graben rises sharply to a plateau around Hart County. Along the eastern

Rough Creek Graben, the spacing of the basin's northern and southern bounding fault trends remains relatively constant across west-central Kentucky to the Lexington Fault System along the western border of the Rome Trough. The structurally high shelf areas outside the Rough Creek and Mississippi Valley Grabens are fairly smooth at the mapped 500-ft contour interval. The boundaries of the Rough Creek and Mississippi Valley Grabens appear to be more highly dissected by faults on the southeastern side than on the northwestern sides. Deformation and uplift related to later New Madrid Seismic Zone activity are evident in the extreme southwestern corner of the study area.

The lithologic makeup of the Precambrian basement in the study area at any one locality is difficult to predict. In generalized terms, this part of the Midcontinent is primarily in the Eastern Granite-Rhyolite Province of Precambrian igneous rocks (1.42–1.50 Ga) (Bickford and others, 1986; Van Schmus and others, 1996). Some subhorizontal layering is imaged within the Precambrian basement along regional 2-D seismic lines shot over the eastern part of the Rough Creek Graben (Pratt and others, 1989; Drahovzal, 1997). The most likely scenarios for this type of response would be layered clastic deposits such as the 1.0-Ga-old Middle Run sandstones (Shrake and others, 1991) in an extension of the Midcontinent Rift Basin (Drahovzal and others, 1992), or from layered volcanic deposits in the Eastern Granite-Rhyolite igneous province. Examples of both possibilities can be found in the region. The KY Operating No. 1 Riordan well in Hart County drilled into a lithic-arenite sandstone at the bottom of the well, and this was later interpreted to be part of the Middle Run Formation (Harris, 2000). In Hancock County, the KGS No. 1 Marvin Blan well drilled through 542 ft of Middle Run Sandstone before reaching total depth (Bowersox, 2013). The Middle Run is interpreted in this well as having been deposited in a low-relief, fine-grained fluvial environment.

Fifty-two miles northwest of the No. 1 Riordan well and 16 mi southeast of the No. 1 Blan well, on the basis of well cuttings analyzed by the Kentucky Geological Survey, the KY Operating No. 1 Braden well in Breckinridge County penetrated 458 ft of unnamed Precambrian rhyolitic welded tuff and basalt nonconformably below the Eau Claire at 6,045 ft (Bowersox, 2013). Unfortunately, the resolution of nearby seismic lines at that depth do not permit the regional interpretations needed to make stratigraphic correlations with these two possible layered Precambrian rock units or with any boundaries with the crystalline rhyolitic igneous rocks penetrated by basement wells drilled west of the Braden well to date.

On the top of the Precambrian surface, the Rough Creek Graben has a bimodal basin structure, with the deepest points in southern Union County (–31,000 ft) and along the McLean/Muhlenberg County border (–38,000 ft). The structure of the top of Precambrian basement in the eastern part of the Rough Creek Graben is a narrow, V-shaped basin in appearance, whereas the western Rough Creek Graben has a northward-dipping, more flat-bottomed graben structure. The structure of the northern Mississippi Valley Graben is dominated by a large central fault that strikes north-northeast and offsets the Precambrian surface down to the northwest. This fault produces the western subbasin and deepest region in the Mississippi Valley Graben at –21,000 ft.

Fault offsets are around 12,000 ft in Union County, 500 to 1,000 ft in McLean County, and as much as 16,000 ft across the Rough Creek Fault Zone in Ohio County. Along the Pennyrile Fault System, fault offsets decrease eastward from around 4,000 ft in northern Christian County to 1,000 ft in Edmonson County. Because of the structural dissimilarity of the Mississippi Valley Graben and western Rough Creek Graben to the eastern part of the Rough Creek Graben at this and shallower levels, it is possible that the fault trend at the southeastern boundary of the Mississippi Valley Graben continues farther northeast than is displayed here and crosses the Rough Creek Graben to connect to the mapped faults in Hopkins and McLean Counties along the northern side of the Rough Creek Graben.

Well-Based Cross-Section Analysis

Twelve regional well-based cross sections were produced for this project (Plate 20, Plate 21, Plate 22, Plate 23, Plate 24, Plate 25, Plate 26, Plate 27, Plate 28, Plate 29, Plate 30, and Plate 31). Deeper wells and wells with detailed log suites were preferred over shallower wells or those with limited logs. These lines were constructed to be either parallel to the Rough Creek Graben axis (strike lines) or perpendicular to it (dip lines). Because of the change in strike of the Rough Creek/Mississippi Valley rift system, the three westernmost dip lines (MV-A, -B, and -C) are rotated with respect to the rest of the dip lines (RC-D1 through -D5) so as to cross perpendicular to the axis of the Mississippi Valley Graben. See Table 3 for a list of wells used in the cross sections.

Precambrian through Lower Mississippian stratigraphic tops were picked on the basis of all available data for each well (logs, cutting descriptions, etc.). All but the most minor of well tops (mostly thin Silurian units that are indistinguishable at the printed scale) are included on the cross-section logs. To aid in structural and stratigraphic interpretation between wells, grid profiles from the Rough Creek Graben Consortium structure maps along the cross-section traces are projected onto the sections. Major faults along the lines are also drawn on the line, with interpreted offsets of the stratigraphic horizons.

The Rough Creek Graben Consortium cross sections were produced in Petra, edited in ACD Systems Canvas-11 software, and printed to Adobe PDF files. These cross sections have a 1 in. = 1,000 ft vertical scale and a 1 in. = 10,000 ft horizontal scale (10X vertical exaggeration). At this scale, most of the lines can be plotted on 36-in.-wide plotter paper.

Laboratory Sample Analysis

A total of 25 well-cutting samples from eight wells of the Middle to Upper Cambrian Eau Claire Formation were collected for this project in an attempt to locate a hypothetical deep hydrocarbon source rock in the Rough Creek Graben. In addition, eight whole-core samples from two wells in the Upper Ordovician Maquoketa Shale were also collected from wells in the Rough Creek Graben region (Fig. 13). All samples were collected at the Kentucky Geological Survey Well Sample and Core Library in Lexington. Sample depths were chosen based on gamma-ray logs, with high-API (radioactive) intervals preferentially targeted on the assumption that clay-rich mudstones are more likely to have elevated organic content. Each of the Eau Claire cutting samples was split into two sets. One set of samples underwent X-ray diffraction, X-ray fluorescence, and optical microscopy analysis at KGS. The other set was sent to Worldwide Geochemical LLC in Humble, Texas, for Rock-Eval analysis.

Well Cuttings X-Ray Diffraction and Fluorescence

X-ray diffraction and fluorescence analysis was run by the KGS laboratory to determine mineral-phase and elemental composition for the cutting samples from the Eau Claire Formation. The entire diffraction and fluorescence laboratory results are included in Table 4, but notable findings are:

- The noncarbonate fraction and component variability decrease upward in the Eau Claire Formation.
- The dolomite fraction increases upward in the Eau Claire Formation.
- Silica (SiO_2) is the dominant component in the Eau Claire Formation (average 42 percent).
- The siliciclastic component is less in the Sun No. 1 Stephens well, possibly because of its position away from graben-bounding fault zones (more distal and deeper waters than the other sampled wells).

Hydrocarbon Samples

We had hoped that oil-sample biomarker analysis would validate the presence of a source rock other than the Devonian New Albany Shale or Upper Ordovician Maquoketa Shale, such as the Upper to Middle Cambrian Eau Claire Formation (or an even deeper formation in the Rough Creek Graben). Although we intended to sample numerous producing wells to test their oils for Cambrian and Ordovician biomarkers, we have only been able to obtain one sample to date. Some wells were no longer producing from below the New Albany Shale (thus contaminating the Cambrian portion of any potential samples), and for others the operating company no longer exists, and we even had a surprising number of wells reported by companies that are now undergoing State investigations for fraudulent practices (thus calling their production amounts and reported zones into question).

Table 3. Wells used to construct Rough Creek Graben Consortium cross sections.

API/UWI	*Well Name*	*County*	*State*	*Result*	*Formation at Total Depth*	*Latitude*	*Longitude*	*GL*	*Total Depth*	*Cross Section Lines*
120592489400	Conoco Inc. 4-1Dyhrkopp, Einart	Gallatin	Ill.	dry & abandoned	400PCMB	37.682120	–88.221870	447	14,185	D1, S2
120650345000	Texaco Inc. 1 Cuppy, E.	Hamilton	Ill.	oil	400PCMB	38.026640	–88.477780	393	13,060	D1
120872028500	Texas Pacific Oil 1 Farley, B., et al.	Johnson	Ill.	dry & abandoned	400PCMB	37.341270	–88.863010	594	14,284	DB, S2
121010742500	Atlantic Richfield 77 Lewis, J.B.	Lawrence	Ill.	dry & abandoned	375MTSM	38.750350	–87.773660	500	9,261	D2, S1
121512030200	Texas Pacific 1 Streich, M.L.	Pope	Ill.	dry & abandoned	375RLFT	37.589710	–88.512790	783	14,942	DA, S2
121810010600	Humble Oil & Ref. 1 Pickel, J.F.	Union	Ill.	dry & abandoned	375MTSM	37.373810	–89.336710	424	8,492	DB, S1
121892329000	Brehm Drl. 1 Bochantin Comm.	Washington	Ill.	dry & abandoned	400PCMB	38.216110	–89.293640	458	7,338	DA, S1
121910773100	Union Oil of Cal. 1 Cisne Community	Wayne	Ill.	dry & abandoned	400PCMB	38.469160	–88.406750	504	11,614	D1, S1
121992329000	Gallagher, Victor 1 Old Ben Coal	Williamson	Ill.	unknown	368KNOX	37.852680	–89.057400	384	7,404	DA
16001016560000	Ashland Oil & Ref. Co. 1 Tarter, R.	Adair	Ky.	plugged & abandoned	375BASL	37.181755	–85.056990	850	6,677	S3
16009018160000	Ohio Kentucky Oil 1 Bailey, B.	Barren	Ky.	dry	368KNOX	37.113000	–85.855730	700	2,287	D4, S3
16015000010000	Ford, Fm. 1 Conner, Cecil	Boone	Ky.	dry & abandoned	400MDLR	39.065156	–84.685974	908	4,089	S1
16027002440000	KY Operating 1 Braden, E.D.	Breckinridge	Ky.	dry	375MTSM	37.635860	–86.486940	623	6,511	D3
16031001770000	Brown-Cliff Energ. 1 Rose, D. & D.	Butler	Ky.	dry	368KNOX	37.243610	–86.578410	512	4,470	D3, S3
16031004440000	Imco Recycling 1 International Met.	Butler	Ky.	injection	368KNOX	37.206460	–86.717210	446	6,450	S3
16033000410000	Sun Oil Co. 1 Stephens W., W., & L.	Caldwell	Ky.	dry	375ECLR	37.226410	–87.936670	563	12,965	D1, DA, S3
16035000100000	South Central Pet. 1 Cherry, P.J.	Calloway	Ky.	dry	372CPRG	36.649070	–88.372910	583	5,610	DB
16039000030000	Wafakaree Inc. 1 Davis, Marshal	Carlisle	Ky.	plugged & abandoned	365TRNT	36.947248	–88.817848	345	2,077	DB
16045000110000	Monday, Freeman 2 Monday, F.	Casey	Ky.	DG	368KNOX	37.328048	–85.033117	1,053	2,207	S2
16045002190000	Cities Service Oil A 1 Garrett	Casey	Ky.	plugged & abandoned	400PCMB	37.222509	–84.806300	1,220	8,251	S2
16047008040000	West Bay Expl. 1 Weatherford Unit	Christian	Ky.	dry	368KNOX	36.798800	–87.379920	604	3,375	DA
16055000100000	Shell Oil Co. 1 Davis, Mildred	Crittenden	Ky.	dry	368KNOX	37.437900	–88.222140	363	8,821	D1, DA
16059056760000	Lafitte Co. 13 O'Flynn, Rex A.	Daviess	Ky.	plugged & abandoned	347CCEK	37.611514	–87.118909	408	3,504	D2
16061005790000	Fair Oil Ltd. 1 Reynolds	Edmonson	Ky.	dry	372CPRG	37.240030	–86.279910	664	6,514	S3
16083000020000	Fulk Perry 1 Hayden, Charles B.	Graves	Ky.	dry	368KNOX	36.782610	–88.807270	482	3,035	DB, S3
16085003280000	Texas Gas Transmi. 1 Shain, Herman	Grayson	Ky.	dry	375ECLR	37.469340	–86.513960	692	13,551	D3, S2
16091013960000	KYCCS 1 Blan, M. & B.	Hancock	Ky.	AI	400PCMB	37.792426	–86.694177	620	8,126	D3
16099004520000	KY Operating Inc. 1 Riordan, T.D.	Hart	Ky.	dry	400MDLR	37.366300	–85.903240	684	8,019	D4, S2
16099004830000	KII Inc. 1 Brooks, J.H.	Hart	Ky.	injection	400MDLR	37.417200	–85.799340	723	8,213	D4
16111000010000	DuPont 1 WAD E.I. DuPont de Nemours	Jefferson	Ky.	injection	400PCMB	38.219270	–85.840350	452	6,011	D4
16123000090000	KY Operating 1 Sherrard, V.	Larue	Ky.	gas	400MDLR	37.533140	–85.858680	721	7,093	D4
16141003280000	The Wiser Oil Co. 1 Markham, W.O.	Logan	Ky.	dry	368KNOX	36.824940	–86.953170	625	3,613	D2
16145000020000	McCracken Exploration 2 Gibbs, David	McCracken	Ky.	plugged & abandoned	360ODVC	37.173949	–88.846685	348	3,260	DB
16149015810000	Conoco Inc. 1 Turner, Mark	McLean	Ky.	dry	400PCMB	37.515960	–87.088150	441	14,202	D2, S2
16155000230000	Caldwell, Ivo 1 Ball, J.A.	Marion	Ky.	plugged & abandoned	372CPRG	37.530567	–85.421629	596	2,918	D5

Table 3. Wells used to construct Rough Creek Graben Consortium cross sections.

API/UWI	*Well Name*	*County*	*State*	*Result*	*Formation at Total Depth*	*Latitude*	*Longitude*	*GL*	*Total Depth*	*Cross Section Lines*
16163001540000	Mercury Expl. 1 Olin Corporation	Meade	Ky.	injection	368KNOX	38.005210	–86.130790	456	3,150	D4
16169004830000	G & R Oil Co. Inc. 1 England, B.	Metcalfe	Ky.	dry	375CNSG	36.962330	–85.478920	1,072	5,500	D5
16169015230000	Benz Oil Corp. 1 Nunnally, Charles	Metcalfe	Ky.	dry	400PCMB	36.940530	–85.737580	757	6,114	D4
16177027630000	Har-Ken Oil Co. 14 Peabody Coal Co.	Muhlenberg	Ky.	dry	368BKMN	37.261510	–87.242950	513	6,700	D2, S3
16199003790000	Amerada Hess 1 Daulton, H. & M.	Pulaski	Ky.	dry	400PCMB	37.122406	–84.647908	1,043	6,722	S3
16211000050000	Beaver Dam Coal 1 Morris, C.J.	Shelby	Ky.	dry & abandoned	372CPRG	38.158360	–85.171953	763	2,075	D5
16221000010000	Reynolds & Vincen. 1 Humphries, Ira	Trigg	Ky.	gas	368KNOX	36.851080	–87.768560	475	3,998	D1
16227033080000	Pittman T.R. 1 Hunt, Jack	Warren	Ky.	dry	372CPRG	36.966840	–86.360310	540	3,959	D3
16233014790000	Exxon Minerals 1 Duncan, Choice	Webster	Ky.	dry	375ECLR	37.580080	–87.742460	524	15,200	S2
41027205440000	Arnco Oil Co. 7A Langford, W.H. & E.	Clay	Tenn.	dry	375ROME	36.488940	–85.463500	640	5,918	D4, S4
41037000080000	E.I. DuPont 1 Davidson Plant	Davidson	Tenn.	injection	400PCMB	36.277330	–86.663110	504	5,574	DA, S4
41053100010000	Big Chief Drilling 1 Taylor, H.H.	Gibson	Tenn.	dry	400PCMB	36.105850	–89.031710	381	7,175	DC
41079100010000	Gulf Oil Corp. 1A Spinks Clay Co.	Henry	Tenn.	dry	375LMTE	36.336420	–88.484220	482	10,748	DB
41085000020000	Fee 2 DuPont de Nemours	Humphreys	Tenn.	injection	400PCMB	36.043200	–87.978950	384	7,461	D1, DB, S4
41095000100000	Benz Oil Co. 1 Merritt Estate	Lake	Tenn.	dry	372CPRG	36.239850	–89.451210	275	6,021	DC, S3
41111100040000	Houghland & Hardy 2 Goad, Sam	Macon	Tenn.	dry	400PCMB	36.540520	–85.939790	750	5,050	D3, S4
41137001660000	Associated O & G Co. 1 Sells, F. & A.	Pickett	Tenn.	dry	400PCMB	36.57110	–85.041780	884	5,827	D5, S4
IN-107208	Indiana Farm Bur./TGT 2614 Brown	Lawrence	Ind.	dry & abandoned	400PCMB	38.846420	–86.315320	791	6,806	D4, S1
IN-118307	Citizens Gas 9 Lucille Rollison	Greene	Ind.	dry & abandoned	375MTSM	38.973290	–86.983960	552	6,785	D3, S1
IN-155634	Warren Oil 1 Paulin	Perry	Ind.	plugged & abandoned	368KNOX	38.241870	–86.714873	456	4,100	D3
IN-156024	Eastern Nat. Gas 1 Peabody Coal	Warrick	Ind.	dry & abandoned	368KNOX	38.151376	–87.322987	584	7,147	D2
IN-159292	Ashland Exploration 1 Sullivan	Switzerland	Ind.	dry & abandoned	400PCMB	38.816401	–85.017331	779	4,151	D5, S1
KGS-9441	Moore Oil Co. 1 Perkins, Carl	Green	Ky.	dry	375CNSG	37.226050	–85.552560	675	5,385	D5, S3
KGS-9668	Jackson Petroleum 1 Turner, R.	Green	Ky.	SWD	368KNOX	37.352500	–85.485690	605	2,150	D5, S2
MGS-007222	Strake Petr. 1 Russell	Pemiscot	Mo.	unknown	375LMTE	36.264807	–89.825915	271	4,740	DC, S2
MGS-008742	M.H. Marr 1 Barnett	Stoddard	Mo.	dry & abandoned	375LMTE	36.834944	–89.850698	300	4,585	DC, S1
MGS-008882	USBM 1 Oliver	New Madrid	Mo.	unknown	372BNTR	36.519800	–89.891100	278	3,728	DC
MGS-024204	Mammoth Prod. 1 Big Oak Farm	Mississippi	Mo.	PAOS	372CPRG	36.739600	–89.254900	294	4,909	S2

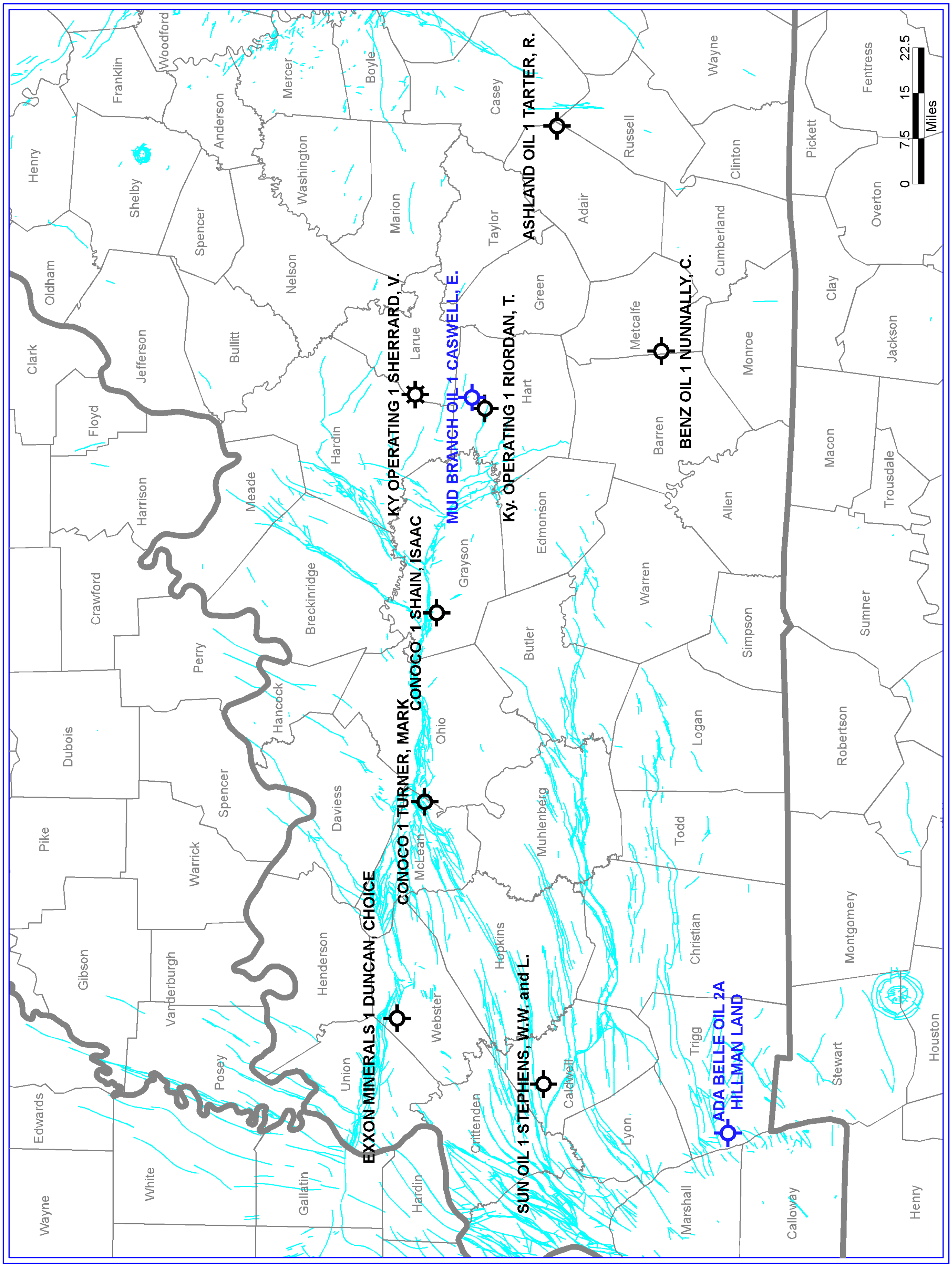

Figure 13. Locations of wells sampled for Cambrian and Ordovician hydrocarbon source potential. Black symbols indicate Eau Claire Formation cuttings were used. Blue symbols indicate 2-in.-diameter cores of the Maquoketa Shale were used.

Table 4. Summary of Rough Creek Graben Consortium laboratory results.

Sample ID	*Sample Information—Rough Creek Graben, Kentucky*							
	Call No.	*Operator*	*County*	*State*	*Formation*	*Sample Type*	*Top Depth (ft)*	*Base Depth (ft)*
RCGC-1	8475	Ashland Oil & Ref 1 Tarter, R	Adair	Kentucky	M. Cambrian Eau Claire Fm.	cuttings	5,180.0	5,220.0
RCGC-2	8475	Ashland Oil & Ref 1 Tarter, R	Adair	Kentucky	M. Cambrian Eau Claire Fm.	cuttings	5,950.0	5,990.0
RCGC-3	9193	Benz Oil 1 Nunnally, C	Metcalfe	Kentucky	M. Cambrian Eau Claire Fm.	cuttings	5,410.0	5,440.0
RCGC-4	15536	Sun Oil 1 Stephens, W&L (air rotary)	Caldwell	Kentucky	M. Cambrian Eau Claire Fm.	cuttings	12,220.0	12,280.0
RCGC-5	15536	Sun Oil 1 Stephens, W&L (air rotary)	Caldwell	Kentucky	M. Cambrian Eau Claire Fm.	cuttings	12,400.0	12,460.0
RCGC-6	15536	Sun Oil 1 Stephens, W&L (air rotary)	Caldwell	Kentucky	M. Cambrian Eau Claire Fm.	cuttings	12,540.0	12,600.0
RCGC-7	15557	Exxon Minerals 1 Duncan, C	Webster	Kentucky	M. Cambrian Eau Claire Fm.	cuttings	12,780.0	12,800.0
RCGC-8	15557	Exxon Minerals 1 Duncan, C	Webster	Kentucky	M. Cambrian Eau Claire Fm.	cuttings	13,250.0	13,300.0
RCGC-9	15557	Exxon Minerals 1 Duncan, C	Webster	Kentucky	M. Cambrian Eau Claire Fm.	cuttings	14,200.0	14,240.0
RCGC-10	15557	Exxon Minerals 1 Duncan, C	Webster	Kentucky	M. Cambrian Eau Claire Fm.	cuttings	14,820.0	14,870.0
RCGC-11	15557	Ky Operating 1 Sherrard	Larue	Kentucky	M. Cambrian Eau Claire Fm.	cuttings	6,020.0	6,050.0
RCGC-12	15557	Ky Operating 1 Sherrard	Larue	Kentucky	M. Cambrian Eau Claire Fm.	cuttings	6,240.0	6,270.0
RCGC-13	15557	Ky Operating 1 Sherrard	Larue	Kentucky	M. Cambrian Eau Claire Fm.	cuttings	6,520.0	6,550.0
RCGC-14	15758	Ky Operating 1 Riordan	Hart	Kentucky	M. Cambrian Eau Claire Fm.	cuttings	6,640.0	6,670.0
RCGC-15	15758	Ky Operating 1 Riordan	Hart	Kentucky	M. Cambrian Eau Claire Fm.	cuttings	6,960.0	7,000.0
RCGC-16	15758	Ky Operating 1 Riordan	Hart	Kentucky	M. Cambrian Eau Claire Fm.	cuttings	7,370.0	7,410.0
RCGC-17	15826	Conoco 1 Shain, I	Grayson	Kentucky	M. Cambrian Eau Claire Fm.	cuttings	8,200.0	8,240.0
RCGC-18	15826	Conoco 1 Shain, I	Grayson	Kentucky	M. Cambrian Eau Claire Fm.	cuttings	8,690.0	8,730.0
RCGC-19	15826	Conoco 1 Shain, I	Grayson	Kentucky	M. Cambrian Eau Claire Fm.	cuttings	9,120.0	9,150.0
RCGC-20	15826	Conoco 1 Shain, I	Grayson	Kentucky	M. Cambrian Eau Claire Fm.	cuttings	9,390.0	9,430.0
RCGC-21	15826	Conoco 1 Shain, I	Grayson	Kentucky	M. Cambrian Eau Claire Fm.	cuttings	9,520.0	9,570.0
RCGC-22	15831	Conoco 1 Turner, M	McLean	Kentucky	M. Cambrian Eau Claire Fm.	cuttings	10,080.0	10,120.0
RCGC-23	15831	Conoco 1 Turner, M	McLean	Kentucky	M. Cambrian Eau Claire Fm.	cuttings	10,860.0	10,890.0
RCGC-24	15831	Conoco 1 Turner, M	McLean	Kentucky	M. Cambrian Eau Claire Fm.	cuttings	11,460.0	11,500.0
RCGC-25	15831	Conoco 1 Turner, M	McLean	Kentucky	M. Cambrian Eau Claire Fm.	cuttings	12,500.0	12,510.0
RCGC-26-MQ-1	187	Mud Branch 1 Caswell (2-in. whole core)	Hart	Kentucky	U. Ordovician Maquoketa Sh.	core	1,048.3	
RCGC-27-MQ-2	187	Mud Branch 1 Caswell (2-in. whole core)	Hart	Kentucky	U. Ordovician Maquoketa Sh.	core	1,299.5	
RCGC-28-MQ-3	187	Mud Branch 1 Caswell (2-in. whole core)	Hart	Kentucky	U. Ordovician Maquoketa Sh.	core	1,429.3	
RCGC-29-MQ-4	187	Mud Branch 1 Caswell (2-in. whole core)	Hart	Kentucky	U. Ordovician Maquoketa Sh.	core	1,509.0	
RCGC-30-MQ-5	1294	Ada Belle 2A Hillman Land (2.-in. whole core)	Trigg	Kentucky	U. Ordovician Maquoketa Sh.	core	2,080.0	
RCGC-31-MQ-6	1294	Ada Belle 2A Hillman Land (2.-in. whole core)	Trigg	Kentucky	U. Ordovician Maquoketa Sh.	core	2,145.8	
RCGC-32-MQ-7	1294	Ada Belle 2A Hillman Land (2.-in. whole core)	Trigg	Kentucky	U. Ordovician Maquoketa Sh.	core	2,209.8	
RCGC-33-MQ-8	1294	Ada Belle 2A Hillman Land (2.-in. whole core)	Trigg	Kentucky	U. Ordovician Maquoketa Sh.	core	2,222.0	

Table 4. Summary of Rough Creek Graben Consortium laboratory results, continued.

Sample ID		*Primary Measurements, Humble Geochemical Laboratory*							*Interpretive Ratios*		
		Organic Richness	*Carbonate Carbon*	*Free Oil*	*Kerogen Yield*	*Organic CO_2*	*Thermal Maturity*	*% R_o Equivalent*	*Relative Hydrogen Content*	*Relative Oxygen Content*	*Kerogen*
	Median (ft)	*TOC (wt %)*	*CC (wt %)*	*S1 (mg HC/g R)*	*S2 (mg HC/g R)*	*S3 (mg CO_2/g R)*	*T_{max} (°C)*	*% R_{o-e} (from T_{max})*	*HI (mg HC/g TOC)*	*OI (mg HC/g TOC)*	*Type S2/S3*
RCGC-1	5,200.0	0.09	32.19	0.06	0.13	0.13	402.00	–999	144	144	1
RCGC-2	5,970.0	0.05	8.61	0.04	0.08	0.14	350.00	–999	160	280	1
RCGC-3	5,425.0	0.03	22.67	0.12	0.17	0.17	404.00	–999	400	567	1
RCGC-4	12,250.0	0.06	50.35	0.06	0.18	0.35	370.00	–999	300	583	1
RCGC-5	12,430.0	0.03	39.44	0.03	0.10	0.30	358.00	–999	333	1,000	0
RCGC-6	12,570.0	0.04	29.20	0.04	0.11	0.32	360.00	–999	275	800	0
RCGC-7	12,790.0	0.11	45.47	0.05	0.13	0.17	400.00	–999	118	155	1
RCGC-8	13,275.0	0.10	47.65	0.03	0.05	0.13	337.00	–999	50	130	0
RCGC-9	14,220.0	0.05	17.87	0.02	0.04	0.13	308.00	–999	80	260	0
RCGC-10	14,845.0	0.06	27.97	0.01	0.03	0.12	302.00	–999	50	200	0
RCGC-11	6,035.0	0.12	55.07	0.04	0.09	0.23	332.00	–999	75	192	0
RCGC-12	6,255.0	0.08	38.56	0.06	0.10	0.17	332.00	–999	125	213	1
RCGC-13	6,535.0	0.09	22.57	0.02	0.06	0.16	423.00	–999	67	178	0
RCGC-14	6.655.0	0.09	21.17	0.03	0.04	0.12	315.00	–999	44	133	0
RCGC-15	6,980.0	0.09	10.53	0.04	0.08	0.20	324.00	–999	89	222	0
RCGC-16	7,390.0	0.03	6.48	0.01	0.01	0.05	0.00	–999	33	167	0
RCGC-17	8,220.0	0.03	38.69	0.02	0.03	0.10	350.00	–999	100	333	0
RCGC-18	8,710.0	0.05	40.80	0.02	0.08	0.21	377.00	–999	160	420	0
RCGC-19	9,135.0	0.04	23.68	0.01	0.02	0.09	0.00	–999	50	225	0
RCGC-20	9,410.0	0.03	18.23	0.01	0.02	0.12	308.00	–999	67	400	0
RCGC-21	9,545.0	0.04	23.62	0.00	0.01	0.19	0.00	–999	25	475	0
RCGC-22	10,100.0	0.06	21.37	0.01	0.01	0.06	0.00	–999	17	100	0
RCGC-23	10,875.0	0.03	23.92	0.01	0.02	0.10	423.00	–999	67	333	0
RCGC-24	11,480.0	0.03	23.41	0.03	0.06	0.13	363.00	–999	200	433	0
RCGC-25	12,505.0	0.04	27.89	0.06	0.04	0.22	304.00	–999	100	550	0
RCGC-26-MQ-1	1,048.3	0.28	11.86	0.05	0.54	0.19	432.00	0.62	193	68	3
RCGC-27-MQ-2	1,299.5	0.21	11.04	0.03	0.31	0.19	431.00	–999	148	90	2
RCGC-28-MQ-3	1,429.3	0.51	14.04	0.10	1.69	0.19	434.00	0.65	331	37	9
RCGC-29-MQ-4	1,509.0	0.80	15.87	0.28	3.04	0.23	433.00	0.63	380	29	13
RCGC-30-MQ-5	2,080.0	0.79	24.53	0.26	2.20	0.20	442.00	0.80	278	25	11
RCGC-31-MQ-6	2,145.8	0.93	23.83	0.70	3.31	0.20	442.00	0.80	356	22	17
RCGC-32-MQ-7	2,209.8	1.63	27.21	0.66	5.84	0.22	440.00	0.76	358	13	27
RCGC-33-MQ-8	2,222.0	0.53	20.15	0.26	1.31	0.18	439.00	0.74	247	34	7

Table 4. Summary of Rough Creek Graben Consortium laboratory results.

Sample ID	*Interpretive Ratios (continued)* Carbon in Oil and Kerogen	Dead Carbon	Relative Oil Content	Production Index	*Humble Geochemical Laboratory Summary*				*KGS Laboratory Results X-Ray Fluorescence—Oxides*				
	PC (% of TOC)	*RC (% of TOC)*	*S1/TOC (mg/g)*	*S1(S1+S2) PI*	*Organic Richness*	*Thermal Maturity*	*Principal Product*	*Oil Staining*	*SiO_2 %*	*Al_2O_3 %*	*Fe_2O_3 %*	*Na_2O %*	*MgO %*
RCGC-1	18	82	67	0.32	very lean	?	minor	none	40.13	13.14	5.09	0.55	3.98
RCGC-2	20	80	80	0.33	very lean	?	minor	none	51.50	19.08	7.64	0.58	2.71
RCGC-3	66	34	400	0.50	very lean	?	minor	none	44.02	13.05	4.55	0.66	2.23
RCGC-4	33	67	100	0.25	very lean	?	minor	none	32.25	10.87	3.60	0.25	3.95
RCGC-5	36	64	100	0.23	very lean	?	minor	none	39.59	12.45	3.88	0.48	2.11
RCGC-6	31	69	100	0.27	very lean	?	minor	none	40.73	12.83	4.09	0.57	2.40
RCGC-7	14	86	45	0.28	very lean	?	minor	none	30.57	9.93	3.74	0.44	2.93
RCGC-8	7	93	30	0.38	very lean	?	minor	none	29.05	10.54	3.87	0.55	2.28
RCGC-9	10	90	40	0.33	very lean	?	minor	none	52.05	18.95	6.54	0.95	2.42
RCGC-10	6	94	17	0.25	very lean	?	minor	none	47.04	17.23	6.37	0.92	2.46
RCGC-11	9	91	33	0.31	very lean	?	minor	none	33.45	7.36	2.34	0.61	5.40
RCGC-12	17	83	75	0.38	very lean	?	minor	none	38.83	9.16	3.01	0.66	4.42
RCGC-13	7	93	22	0.25	very lean	?	minor	none	44.32	15.25	6.17	0.37	3.66
RCGC-14	6	94	33	0.43	very lean	?	minor	none	48.20	16.16	6.18	0.54	3.08
RCGC-15	11	89	44	0.33	very lean	?	minor	none	50.07	14.43	4.97	0.98	2.45
RCGC-16	6	94	33	0.50	very lean	?	minor	none	53.27	19.47	7.44	0.62	2.69
RCGC-17	14	86	67	0.40	very lean	?	minor	none	36.94	13.07	5.26	0.42	2.87
RCGC-18	17	83	40	0.20	very lean	?	minor	none	36.62	13.79	5.79	0.64	4.24
RCGC-19	6	94	25	0.33	very lean	?	minor	none	48.22	18.18	7.01	0.59	2.12
RCGC-20	8	92	33	0.33	very lean	?	minor	none	50.30	18.73	7.13	0.69	2.25
RCGC-21	2	98	0	0.00	very lean	?	minor	none	47.53	16.83	7.05	0.53	2.31
RCGC-22	3	97	17	0.50	very lean	?	minor	none	44.25	15.68	5.87	0.48	3.38
RCGC-23	8	92	33	0.33	very lean	?	minor	none	37.46	13.28	5.00	0.36	4.24
RCGC-24	25	75	100	0.33	very lean	?	minor	none	39.73	13.68	5.54	0.43	3.72
RCGC-25	21	79	150	0.60	very lean	?	minor	none	43.50	10.86	6.22	0.70	1.87
RCGC-26-MQ-1	17	83	18	0.08	very lean	?	minor	none	n/a	n/a	n/a	n/a	n/a
RCGC-27-MQ-2	13	87	14	0.09	very lean	?	minor	none	n/a	n/a	n/a	n/a	n/a
RCGC-28-MQ-3	29	71	20	0.06	lean	?	mixed	oil window?	n/a	n/a	n/a	n/a	n/a
RCGC-29-MQ-4	34	66	35	0.08	lean	?	oil	oil window?	n/a	n/a	n/a	n/a	n/a
RCGC-30-MQ-5	26	74	33	0.11	lean	?	mixed	oil window?	n/a	n/a	n/a	n/a	n/a
RCGC-31-MQ-6	36	64	75	0.17	lean	?	oil	oil window?	n/a	n/a	n/a	n/a	n/a
RCGC-32-MQ-7	33	67	40	0.10	good	?	oil	oil window?	n/a	n/a	n/a	n/a	n/a
RCGC-33-MQ-8	25	75	49	0.17	lean	?	mixed	oil window?	n/a	n/a	n/a	n/a	n/a

Table 4. Summary of Rough Creek Graben Consortium laboratory results (continued).

Sample ID	X-Ray Fluorescence—Oxides (continued)								X-Ray Fluorescence—Minor Elements							
	P_2O_6 (%)	K_2O (%)	CaO (%)	TiO_2 (%)	MnO (%)	T S (%)	T C (%)	TOC (%)	Ba (ppm)	Co (ppm)	Cr (ppm)	Cu (ppm)	La (ppm)	Mo (ppm)	Nb (ppm)	Ni (ppm)
RCGC-1	0.07	3.95	13.07	0.58	0.07	0.04	6.62	3.94	371	11	79	17	30	4	10	26
RCGC-2	0.08	4.79	2.96	0.79	0.06	0.17	3.12	2.62	438	20	101	17	40	6	11	48
RCGC-3	0.10	4.39	12.70	0.63	0.08	0.08	6.56	4.06	417	9	66	19	19	10	11	9
RCGC-4	0.07	3.38	22.47	0.44	0.05	0.08	8.52	3.62	174	5	64	10	30	3	8	16
RCGC-5	0.08	3.41	17.99	0.48	0.06	0.10	7.62	4.15	343	6	56	13	36	0	8	22
RCGC-6	0.08	3.41	16.00	0.48	0.06	0.60	6.91	0.62	451	7	60	13	36	2	9	24
RCGC-7	0.06	2.86	25.39	0.39	0.08	0.34	9.18	4.00	272	5	73	17	33	0	6	22
RCGC-8	0.05	2.27	26.93	0.43	0.05	0.54	8.35	3.23	232	5	55	20	35	0	7	25
RCGC-9	0.09	3.67	5.68	0.75	0.06	0.38	4.87	3.86	317	16	94	26	39	5	10	42
RCGC-10	0.08	3.04	9.55	0.73	0.07	0.51	5.70	3.91	321	15	84	17	34	2	9	44
RCGC-11	0.08	2.91	19.53	0.33	0.08	0.02	9.92	4.13	341	3	47	13	36	0	7	20
RCGC-12	0.09	3.15	15.61	0.40	0.07	0.02	8.26	3.97	442	7	51	20	36	0	6	24
RCGC-13	0.09	4.58	8.84	0.66	0.07	0.16	4.96	3.07	356	14	86	20	35	2	10	44
RCGC-14	0.08	5.92	6.80	0.71	0.05	0.14	4.48	3.07	415	14	93	17	32	6	10	34
RCGC-15	0.17	4.02	7.80	0.64	0.09	0.04	5.27	3.88	513	12	61	15	31	4	10	25
RCGC-16	0.07	5.07	0.79	0.81	0.04	0.28	2.29	2.29	444	21	100	26	35	8	11	49
RCGC-17	0.06	2.65	19.42	0.53	0.07	0.38	7.63	3.06	181	10	77	22	36	0	7	36
RCGC-18	0.06	2.38	16.18	0.55	0.10	0.42	7.25	3.17	193	12	92	23	36	6	7	38
RCGC-19	0.06	5.18	8.28	0.75	0.07	0.34	3.91	2.51	339	15	89	18	35	3	11	45
RCGC-20	0.06	4.26	5.90	0.77	0.07	0.47	3.93	2.82	425	17	95	24	36	3	10	50
RCGC-21	0.10	4.71	7.96	0.71	0.15	0.38	5.53	3.77	437	16	84	24	37	3	10	46
RCGC-22	0.07	4.20	9.79	0.63	0.08	0.22	5.01	2.84	323	13	89	18	34	3	9	43
RCGC-23	0.06	3.84	15.60	0.55	0.17	0.15	7.35	3.07	250	9	73	18	34	0	9	35
RCGC-24	0.09	3.39	14.63	0.63	0.13	0.20	6.69	3.34	243	10	85	29	34	4	8	35
RCGC-25	0.09	2.69	14.04	0.72	0.16	0.15	5.88	3.41	421	12	89	30	32	5	8	36
RCGC-26-MQ-1	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
RCGC-27-MQ-2	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
RCGC-28-MQ-3	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
RCGC-29-MQ-4	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
RCGC-30-MQ-5	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
RCGC-31-MQ-6	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
RCGC-32-MQ-7	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
RCGC-33-MQ-8	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

Table 4. Summary of Rough Creek Graben Consortium laboratory results (continued)

Sample ID	*X-Ray Fluorescence—Minor Elements (continued)*						*X-Ray Diffraction*			*Mineralogy*						
	Pb (ppm)	*Rb (ppm)*	*Sr (ppm)*	*Th (ppm)*	*U (ppm)*	*V (ppm)*	*Y (ppm)*	*Zn (ppm)*	*Zr (ppm)*	*Quartz*	*Calcite*	*Dolomite*	*Pyrite*	*Chlorite*	*Dickite/ Kaolinite*	*K, Al, SiO_2/Glauconite/ Microcline/Muscovite/Illite*
RCGC-1	38	103	227	8	7	24	22	195	109	X	X	X	X	X	X	X
RCGC-2	38	139	176	10	3	93	29	225	135	X	X		X		X	X
RCGC-3	30	98	148	10	15	30	21	128	121	X	X		X	X	X	X
RCGC-4	33	73	240	7	8	0	17	226	74	X	X	X	X	X	X	X
RCGC-5	32	85	240	7	6	0	20	221	129	X	X	X			X	X
RCGC-6	32	93	226	8	7	7	21	215	143	X	X	X		X		X
RCGC-7	46	64	259	6	6	0	16	269	86	X	X	X	X	X	X	X
RCGC-8	40	69	357	6	13	0	17	305	84	X	X	X	X	X	X	X
RCGC-9	38	128	212	10	6	73	28	236	151	X	X		X	X	X	X
RCGC-10	37	106	256	8	7	60	26	264	132	X	X		X	X		X
RCGC-11	33	62	208	7	10	0	17	202	145	X	X	X	X	X	X	X
RCGC-12	38	72	579	8	19	0	20	212	158	X	X	X		X	X	X
RCGC-13	41	117	252	9	9	49	25	231	130	X	X	X	X	X	X	X
RCGC-14	42	135	174	10	4	62	26	180	134	X	X	X	X	X	X	X
RCGC-15	41	124	185	10	3	50	27	124	222	X	X			X	X	X
RCGC-16	48	158	128	11	1	106	31	210	159	X	X		X	X	X	X
RCGC-17	37	69	350	6	11	5	18	458	79	X	X	X	X	X	X	X
RCGC-18	39	72	305	7	10	15	20	268	84	X	X	X	X	X	X	X
RCGC-19	39	124	164	9	4	61	26	287	104	X	X		X	X	X	X
RCGC-20	40	112	205	9	6	78	27	267	114	X	X		X	X	X	X
RCGC-21	39	107	143	8	5	59	26	246	102	X	X		X	X	X	X
RCGC-22	34	103	171	8	7	41	23	273	113	X	X	X	X	X	X	X
RCGC-23	35	96	163	8	6	13	21	273	98	X	X	X		X	X	X
RCGC-24	39	93	157	8	5	30	22	263	104	X	X	X	X	X	X	X
RCGC-25	36	73	122	7	4	54	23	227	118	X	X		X	X		X
RCGC-26-MQ-1	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	X-Ray Diffraction Mineralogy						
RCGC-27-MQ-2	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a							
RCGC-28-MQ-3	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a							
RCGC-29-MQ-4	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a							
RCGC-30-MQ-5	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a							
RCGC-31-MQ-6	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a							
RCGC-32-MQ-7	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a							
RCGC-33-MQ-8	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a							

Additional Analyses

An attempt was also made to find suitable samples for fluid inclusion analysis. The most accurate results can be made on primary or secondary inclusions in carbonates, or in silica cements in sandstones. Although it is possible to mount larger cuttings onto a microscope slide to study the fluid inclusions, the small size of the available cutting particles (medium to very fine sand-sized grains) made this impractical. Because of their size, it was also impossible to determine which nonshale grains came from a depositional environment and which from later (possibly much later) vein cementation.

Discussion

Kinematic Structural and Tectonic Analysis

For the Eau Claire Formation and older units in the Rough Creek/Mississippi Valley Graben system, very little is known about local facies patterns or depositional rates. Kinematic analysis for the Cambrian section is based on the assumptions that sediment thickness is proportional to local subsidence rates and that subsidence rates are proportional to local fault movement. To date, no Cambrian unconformities have been defined in these grabens by well or seismic data that would equate to the pre-Conasauga unconformity that is observed in the northwestern Rome Trough of Kentucky. Therefore, this stratigraphic interval is assumed to be a complete record of the deposition of that time without any major hiatuses.

Initiation of rifting in the Rough Creek Graben and adjacent Mississippi Valley Graben began in the latest Precambrian or earliest Cambrian Period (Ervin and McGinnis, 1975). Local erosion of the exposed crystalline basement rocks of the Granite-Rhyolite Province, along with minor amounts of the Precambrian Middle Run Sandstone along the Cincinnati Arch, produced the clastic sediments of the Reelfoot Arkose (Weaverling, 1987; Houseknecht, 1989). Thickness trends indicate that the boundary fault systems of the Mississippi Valley Graben and Rough Creek Graben underwent normal dip-slip movement during Reelfoot Arkose deposition, but the large central fault (Fig. 12) of the Mississippi Valley Graben did not.

Paleozoic tectonic subsidence was greatest in Ohio County, with a slightly smaller depocenter in Union County. Both of these locales are just south of the Rough Creek Fault Zone, and the thickness of Cambrian strata implies that the asymmetrical, half-graben shape of the basin formed early. The cause of these dual depocenters is unclear, but their spacing along the Rough Creek Fault Zone is similar to the spacing between the northwestern (Lusk Creek) and southeastern boundary fault systems of the Mississippi Valley Graben (although offset to the east by about 17 mi). It is possible that the intersection of these two parallel fault systems with the Rough Creek Fault Zone created regions with extensive brittle fracture and fault deformation, leading to accelerated subsidence. These deformed blocks could then have migrated eastward during the initial fast rifting period as the south and east regional blocks/plate drifted away from the north and west regional blocks/plate.

In most areas, the seismic velocity of the material immediately overlying the Reelfoot Arkose was determined to be within the range of carbonate strata, probably limestone. The high-amplitude seismic reflection at the top of the Reelfoot Arkose is also consistent with a transition from a fast, clean carbonate to a lower-velocity, coarse clastic deposit. This high-carbonate unit (exact lithology is unknown) appears not to be related to the younger oolitic shoals penetrated in the No. 1 Turner well and may be an extension of the proposed St. Francois Formation of Weaverling (1987). The St. Francois Formation was defined from a 1,044-ft-thick dolomitic limestone unit, with multiple oolite zones in the Cockrell-CNG No. 1 Carter well in St. Francis County, Ark., in the southern part of the Mississippi Valley Graben (beyond the study area of this project). The approximate age, bedding patterns resolvable on seismic profiles, and stratal position above an arkosic clastic unit all appear to be similar to the characteristics of the upper limestone unit of the Early to Middle Cambrian Rome Formation in the adjacent Rome Trough in eastern Kentucky, West Virginia, and Pennsylvania. No wells in this project area penetrate this lower Eau Claire Formation carbonate.

In the Rough Creek Graben, there is no strong, regionally extensive reflection horizon between the top of the Eau Claire and the top of the Reelfoot Arkose. This is interpreted as an indication of a gradational contact between the high-carbonate units directly above the Reelfoot Arkose and the siltstones and shales of the upper Eau Claire Formation. The lower Eau Claire carbonate units may be equivalent to the limestone units of the Middle to Late Cambrian Conasauga Group of the Appalachian Basin. Without further data, the exact age and interbasinal stratigraphic correlations of this unit cannot be determined. Because of uncertainty of the unit's age and the inability to confidently interpret the top of the carbonate unit from seismic data alone, this possible St. Francois Formation or equivalent was not mapped as part of this project. The stratigraphic well tops for the proposed St. Francois Formation from Weaverling (1987) were used for this project.

During Eau Claire Formation deposition, the smaller depocenter in southern Union County diminished in size and relative magnitude. The linear depocenter in Ohio, Grayson, and McLean Counties, however, increased in both length and depth during this time. The implications of this are that the center of deformation (zone of highest extension) migrated eastward along the northern Rough Creek Graben during the Middle to Late Cambrian. As much as 5,500 ft of thickening southward across the Rough Creek Fault Zone in Ohio County indicates the magnitude of syndepositional fault movement during this time.

The filling of the linear depocenter in Grayson and Ohio Counties stopped by the end of Eau Claire deposition. Both the structure at the top of the Eau Claire and the isopach thickness of the overlying Knox Supergroup display no linear trend in this region. Similarly, the relatively smooth isopach of the Knox indicates that the movement along the Rough Creek Fault Zone had also ended by the end of Eau Claire deposition.

Thinning of the Eau Claire over the Tolu Arch and Western Kentucky Fluorspar District indicates that the region has been uplifted relative to the surrounding area since at least the Late Cambrian, and not solely from magma intrusion during the Permian.

The Pascola and Blytheville Arches in the Mississippi Valley Graben outline the region of earthquake activity associated with the New Madrid Seismic Zone and imply an interconnected origin. Using published seismic lines (Howe and Thompson, 1984; Sexton, 1988) and well data analyzed in this project, these arches are interpreted to be fault-cored anticlines formed above the New Madrid Seismic Zone faults from northeast-southwest compression. The thickened shale and mudstone section of the Eau Claire Formation was deformed to fill the arched structure below the rigid Knox Supergroup. The specific age of formation for these structures is unknown, but appears to be after the Early Ordovician but before the Cretaceous, as indicated by a locally thinned and uplifted Knox section overlain by the undeformed Cretaceous sediments of the Mississippi Embayment.

During Knox Supergroup deposition, the area of major fault movement and extension changed from the northeastern Rough Creek Graben to the Mississippi Valley Graben. The Lusk Creek Fault Zone, which acts as the northwestern boundary of the Mississippi Valley Graben, and the central fault (Fig. 12) were active during Knox deposition, as indicated by the large thickness changes of the Knox Supergroup across these faults. Tectonic movement in the region continued to decrease during Knox time, as indicated by fewer faults displacing the top of the Knox than the base.

The Knox Supergroup and the overlying Middle Ordovician Trenton–Black River interval thicken over southern Illinois, the western part of the Rough Creek Graben, and the connected Owensboro Graben (Fig. 12). Because this gradual thickening includes areas beyond the graben-bounding faults, this may indicate sag from crustal relaxation after the cessation of rifting along this graben system. This pattern of thickening deviates around the Western Kentucky Fluorspar District (Fig. 12) in the northern part of the Mississippi Valley Graben. This uplift (or lack of subsidence) of the Western Kentucky Fluorspar District appears to have begun sometime in the Late Cambrian to Early Ordovician Period.

Thickness distribution of the Trenton and Black River Formations indicates basin subsidence continued throughout the Middle Ordovician, and may have also reactivated faults in the northern part of the Mississippi Valley Graben and southernmost Illinois. At the top of this unit, a thickened Maquoketa Shale interval appears to downcut into the Trenton Formation along a roughly north-south linear zone across the center of the Rough Creek Graben (Fig. 14). The transition zones along

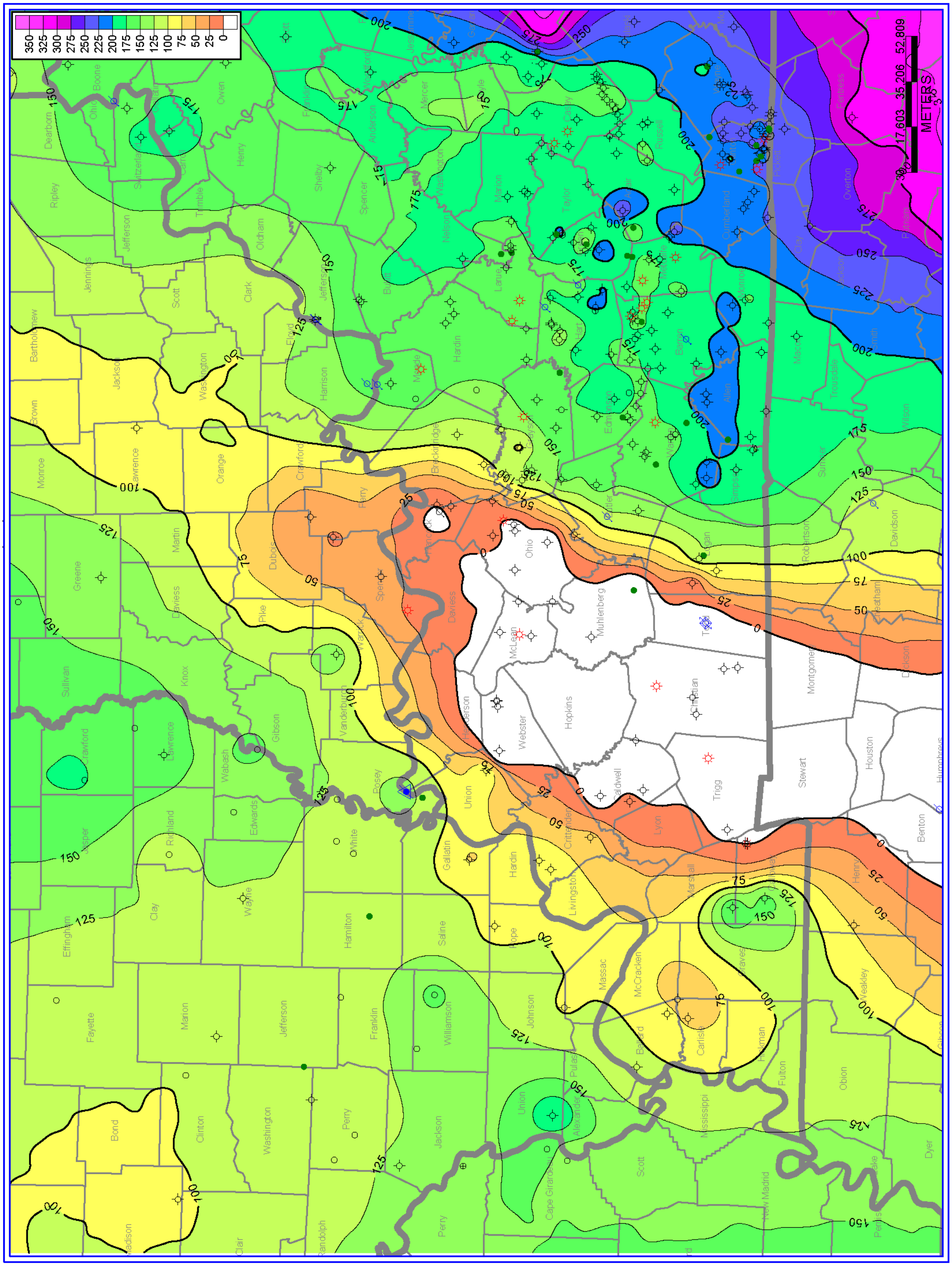

Figure 14. Thickness of the Trenton Formation (based only on well data). The Sebree Trough is the thinned region across the center of the map.

the edges of the Sebree Trough can be observed in well logs, and appear to be gradational over a few to several kilometers. Within the Sebree Trough, the missing interval of the Trenton Formation is completely replaced by the lower part of the Maquoketa Shale. Because of the lack of any other regional structures that are coincident and parallel to the Sebree Trough, and because the affected stratigraphy is limited to the Trenton Formation and Maquoketa Shale, this feature is interpreted to be depositional in origin (not structural) and is unrelated to fault movement.

By the end of Maquoketa deposition, the structural low in southern Union County had become smaller in area than the low area of the Fairfield Basin in White County, Ill. This implies that the subsidence rates prior to and during the deposition of the Maquoketa were higher in the Rough Creek Graben than in the main body of the Illinois Basin to the north. Subsidence rates after this time were greater in the Fairfield Basin, which resulted in younger units having deeper points outside the graben complex. Other than in one isolated fault block in Lyon County, there is little apparent tectonic effect on the thickness of the Maquoketa Shale in the Mississippi Valley Graben.

In the period between Maquoketa Shale and New Albany Shale deposition, the majority of subsidence in the Rough Creek Graben occurred closer to the graben axis rather than along the main border faults. During this time, the depocenter in Union County migrated southward to the area along the Crittenden/Union County border. Along the southern border of the Rough Creek Graben, the majority of subsidence (interpreted from isopach thicknesses) moved northward from the Pennyrile Fault System to the Tabb Fault System (Fig. 12) in Caldwell and Hopkins Counties. Whether these changes in subsidence patterns reflect larger-scale changes in tectonic stresses or post-rift structural progression is unknown. This thickening pattern appears to deviate around the Western Kentucky Fluorspar District, implying possible reactivated uplift or reduced subsidence of that region, similar to what is observed in the Knox Supergroup interval. However, the combined uplift interpreted during the Knox Supergroup deposition and the Silurian to Early Devonian (pre-New Albany Shale) does not equal the present-day structural offset. Because of this, it is possible that this is an inverted fault block produced by the same later (post-Mississippian) compression that caused the inverted structures along the Rough Creek Fault Zone. Whether this uplifted area and the Tolu Arch it forms is purely from fault reactivation or from magmatic underplating and intrusion, as suggested by Trace and Amos (1984), or is a combination of the two, is unknown.

The Middle Devonian to Early Mississippian New Albany Shale thickens across both the Rough Creek Fault Zone and the Pennyrile Fault System into the Rough Creek Graben. This thickening in the graben suggests either syndepositional fault movement/subsidence or possibly fault movement just prior to deposition that produced varied topography, which the shale later filled. This thickness change is especially dramatic across many of the Rough Creek Fault Zone faults, suggesting the whole fault trend was deforming at the same time as part of a larger tectonic framework, and is not just a local event affecting one or two faults.

The Middle Devonian to Early Mississippian syndepositional fault movement along the Rough Creek Fault Zone appears to have occurred predominantly east of the Owensboro Graben (Fig. 12). This may be in part a result of reduced resolution produced by the lower data density of both well tops and seismic profiles along the Rough Creek Fault Zone west of the Central faults. However, there is the possibility that the extensional tectonic forces that produced the fault offsets along the eastern Rough Creek Fault Zone also produced dextral strike-slip movement along the Central Fault System. This would have transferred the zone of fault movement southwestward across the graben toward the north-central part of the Mississippi Valley Graben. Although this area is fairly distant from the Appalachian collision zone of the Acadian Orogeny, dextral compression caused by that obliquely convergent orogeny (Ferrill and Thomas, 1988) may have reactivated the faults of the Rome Trough–Rough Creek Graben–Mississippi Valley Graben intracratonic rift. Crustal blocks south and east of this older rift system may have been translated slightly southwestward relative to the rest of the Laurentian continental crust northwest of the rift.

Regional post-Devonian deformation is indicated by uplifted Devonian and Mississippian strata within inversion structures along the Rough Creek Fault Zone and in the fault offsets observed in the outcrop patterns surrounding the Jessamine Dome in central Kentucky.

Petroleum Systems Analysis

The stratigraphic intervals with the highest probability of hydrocarbon generation in the Illinois Basin, including the Rough Creek and Mississippi Valley Grabens, are the Middle Devonian to Early Mississippian New Albany Shale, Late Ordovician Maquoketa Shale, and Middle to Late Cambrian Eau Claire Formation (Cluff and Byrnes, 1990). The results and interpretations of this project will be discussed for these source-rock intervals in stratigraphic order, from youngest to oldest.

Using the petroleum systems analysis technique described by Magoon and Dow (1994), economically viable oil and gas plays must include four essential elements and two essential processes. The essential elements are (1) an organic-rich source rock, (2) sufficient overburden rocks to allow for petroleum source-rock maturation temperatures and pressures, (3) an appropriate reservoir rock, and (4) a geologic trap or seal. The two essential processes are (1) hydrocarbon trap formation and (2) hydrocarbon generation, migration, and accumulation (trapping). In order for an oil or gas field to be created, the appropriate timing of trap formation and generation/migration of hydrocarbons must occur. Petroleum systems can also be subdivided into three types based upon whether they are known (oil or gas play that has been geochemically traced to a known source rock), speculative (source-quality rock present, but no known hydrocarbon accumulations), or hypothetical (unproven or theoretical source rock, with no known accumulations).

New Albany Shale. The Middle Devonian to Early Mississippian New Albany Shale qualifies as a known or proven petroleum system, with numerous producing oil and gas fields in the southern Illinois Basin. No additional samples of New Albany Shale were analyzed as part of the Rough Creek Graben Consortium project.

Organic Content—The New Albany Shale in southern Illinois and the Rough Creek Graben is a laminated, dark brown to black shale with minor amounts of siltstone and limestone (Macke, 1996). This shale is very organic-rich, with average total organic carbon values of 2.5 to 9 weight percent; some samples are as high as 20 weight percent (Stevenson and Dickerson, 1969; Cluff and Byrnes, 1990). This organic matter has been interpreted as type II (Fig. 15) and is capable of producing both oil and gas (Comer and others, 1994).

Overburden/Burial—Paleozoic burial history and petroleum-maturation timing calculations have been produced from wells in the Illinois Basin (Cluff and Byrnes, 1990; Kolata and Nelson, 1990a; Bethke and others, 1991; Horn and Associates, 2002; Rowan and others, 2002). For the Rough Creek Graben and adjacent Fairfield Sub-basin, rapid subsidence occurred during the Middle Cambrian and Permian Periods. In the Rough Creek Graben, syndepositional fault movements accelerated the Middle Cambrian burial relative to the nonrifted area to the north (Figs. 16 and 17, respectively). Maximum burial depths were attained during the Middle Permian, followed by relatively constant erosional exhumation until the present. Current drilling depths should be viewed as minimum burial depths because of regional post-Paleozoic erosion of around 500 to 2,000 ft of surficial geol-

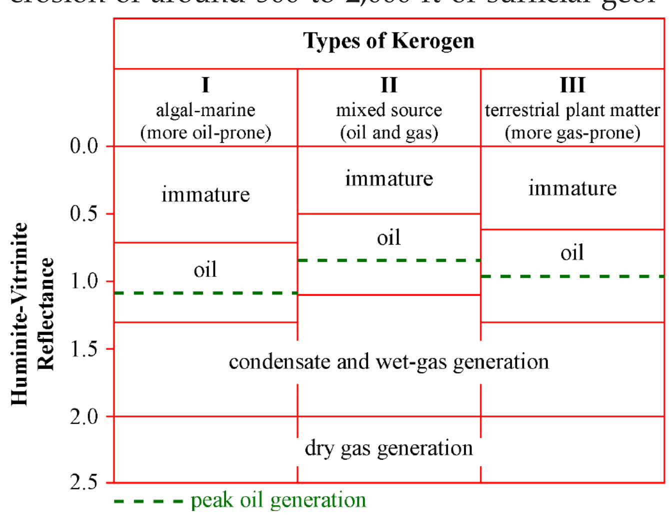

Figure 15. Vitrinite-reflectance values for various stages of hydrocarbon maturation and differing organic kerogen types. Modified from American Association of Petroleum Geologists Memoir 51, © AAPG 1990 (Cluff and Byrnes, 1990, Fig. 25-1); reprinted by permission of the AAPG whose permission is required for further use.

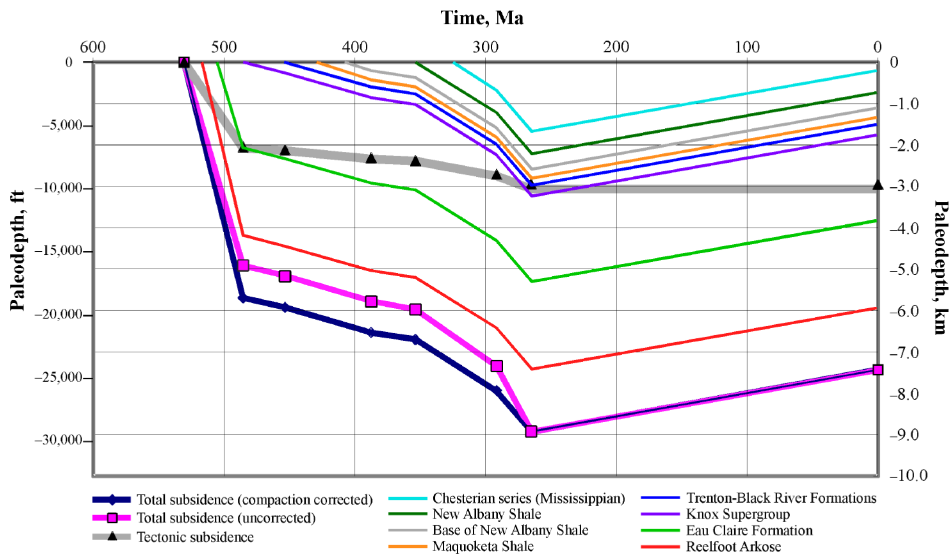

Figure 16. Calculated burial history for the Rough Creek Graben, based on the Exxon 1 Duncan well in Webster County. Modified from Modified from American Association of Petroleum Geologists Memoir 51, © AAPG 1990 (Kolata and Nelson,1990b); reprinted by permission of the AAPG whose permission is required for further use.

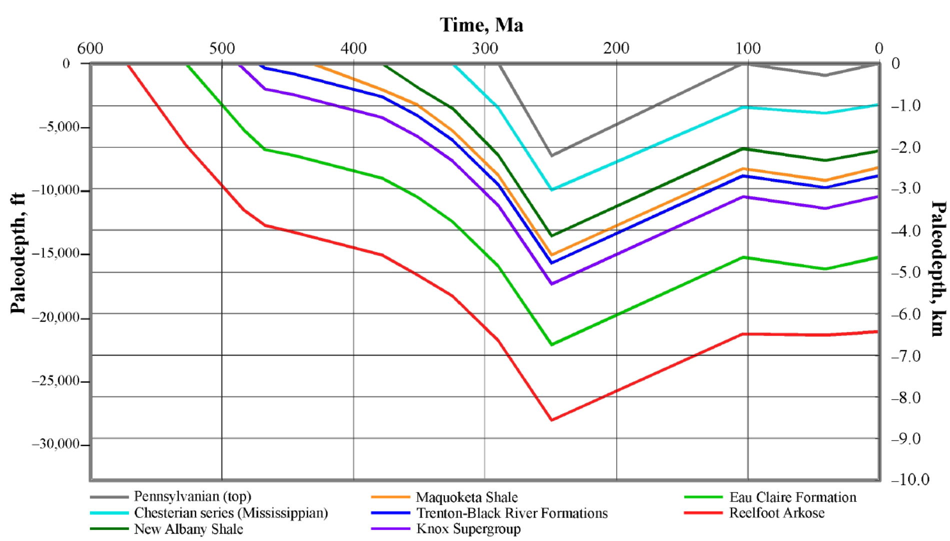

Figure 17. Calculated burial history for the Fairfield Sub-basin in southern Illinois. Includes data from the American Association of Petroleum Geologists' UDRIL Source Rock Database (Horn and Associates, 2002).

ogy (Stearns and Reesman, 1986; Andrews, 2006). Middle Mississippian and younger strata provide the overburden for New Albany hydrocarbon generation.

Hydrocarbon Generation/Migration—Vitrinite-reflectance (percent R_o) values for New Albany Shale samples from the Rough Creek Graben (Fig. 18) range from close to 0.5 percent R_o in the eastern end of the graben to 1.1 percent R_o in southeastern Illinois (Barrows and Cluff, 1984; Cluff and Byrnes, 1990). These values indicate that the New Albany Shale is currently in the immature to early oil generation stage of hydrocarbon maturation (Tissot and Welte, 1978), with the Hicks Dome area approaching peak oil generation (Cluff and Byrnes, 1990). At these maturation levels, hydrocarbon generation and migration are calculated to have begun around 300 Ma (Early Permian) near Hicks Dome (a result of the increased heat flux surrounding the area's Permian igneous intrusions), and expanded to the majority of the project study area by 250 Ma (Early Triassic).

Reservoir—Common reservoir intervals for Devonian shale–sourced hydrocarbons include Upper Mississippian to Pennsylvanian sandstone and carbonate units, with the majority of production being derived from Chesterian Series rocks. In some areas, the New Albany Shale is also believed to act as an oil source rock for the underlying Silurian and Lower Devonian strata. This scenario would require either downward migration of oil, presumably by overcoming buoyancy issues with overpressures or through long-range lateral updip migration through fractures (and not parallel to bedding planes). The New Albany Shale can also act as a self-sourced, unconventional reservoir. In these cases, the shale acts as both a source rock and as a fractured reservoir. In addition, shale-gas production may also be possible by desorbing nat-

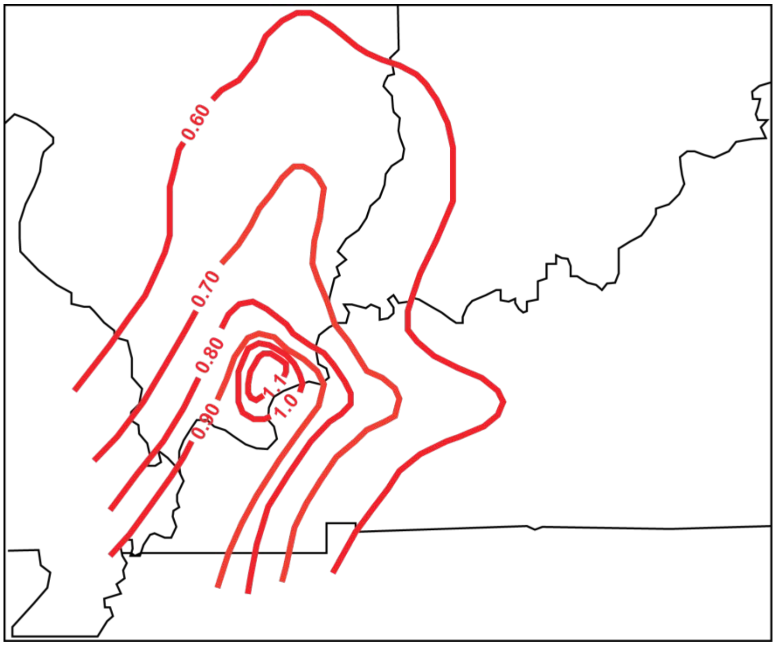

Figure 18. Predicted maturation values at the base of the New Albany Shale (percent R_o). Modified from Modified from American Association of Petroleum Geologists Memoir 51, © AAPG 1990 (Cluff and Byrnes (1990, Fig. 25-1); reprinted by permission of the AAPG whose permission is required for further use.

ural gas out of the shale matrix following reservoir depressurization (from pumping).

Trap/Seal—There are numerous potential structural and stratigraphic traps within and in the area surrounding the Rough Creek Graben. These include both primary traps (updip facies changes, stratigraphic pinch-outs, and units terminating along fault cuts) and secondary traps (angular unconformities following local exhumation or uplift, and inversion structures related to fault reactivations).

Shallow water levels, coupled with varying local sea levels caused by tectonic compression and loading during the Taconic (Silurian) and Acadian (Devonian to Early Mississippian) Orogenies resulted in complex deposits of alternating sandstones and dolomites with numerous unconformities during the Silurian to Early Devonian and can create erosional pinch-outs that can act as hydrocarbon traps if they pinch out updip. These types of traps are found along the western limb of the Cincinnati Arch and possibly on the southern limb of the Rough Creek Graben. The Late Devonian to Early Mississippian New Albany Shale acts as a seal for the Silurian to Devonian clastics and carbonates.

Maquoketa Shale. The Late Ordovician Maquoketa Shale qualifies as a hypothetical petroleum system: A known-source, organic-rich unit is present, but no produced oil or gas has been geochemically linked to the potential source rock in the southern Illinois Basin. Eight whole-core samples of Maquoketa Shale were analyzed as part of the Rough Creek Graben Consortium project.

Organic Content—The Maquoketa Shale in the Rough Creek Graben area is a dark gray to brownish black shale. Total organic carbon levels of 1 to 4 percent were reported for Illinois Basin samples by Stevenson (1971), which is sufficient to make it a hydrocarbon source. Present-day vitrinite-reflectance values for the Maquoketa were calculated to be between 0.5 and 1.5 percent R_o. This represents a maturity in the oil to wet-gas window for type I organic matter (Tissot and Welte, 1978; Cluff and Byrnes, 1990).

Eight Maquoketa Shale whole-core samples from two wells in western Kentucky were analyzed for the Rough Creek Graben Consortium project. Total organic carbon values determined through Rock-Eval pyrolysis for these samples ranged from 0.21 to 0.80 weight percent in Hart County (Mud Branch No. 1 Caswell) and 0.53 to 1.63 weight percent in Trigg County (Ada Belle No. 2A Hillman Land).

In 2009, the Kentucky Consortium for Carbon Storage drilled the KGS No. 1 Blan well in eastern Hancock County to study carbon-sequestration possibilities. During drilling, a 30-ft whole core was cut in the middle of the Maquoketa Shale section. The 11 total organic carbon values determined for that core range from 0.33 to 0.93 weight percent, within the same range as the Rough Creek Graben Consortium samples.

Overburden/Burial—Silurian through Pennsylvanian strata are the overburden rocks for the Maquoketa Shale in the Rough Creek Graben, and Silurian through Cretaceous strata are the overburden for the Maquoketa in the Mississippi

Valley Graben. The current drilling depth to the top of the Maquoketa Shale in the graben areas of this project varies from about 1,000 ft near the pre-Cretaceous subcrop in the Jackson Purchase Region of the Mississippi Valley Graben to around 7,000 ft in Union County. See Figures 16 and 17 for the calculated burial history of the Maquoketa Shale.

Hydrocarbon Generation/Migration—The current maturation level at the base of the Maquoketa Shale in the Rough Creek Graben was calculated by Cluff and Byrnes (1990) to be between 0.55 and 1.40 percent R_o (and up to 1.6 percent R_o over Hicks Dome) (Fig. 19). These vitrinite-reflectance values correspond with near-oil maturation (at 0.55 percent R_o in the eastern Rough Creek Graben) to early wet-gas generation. Most of the Maquoketa Shale in the Rough Creek Graben is therefore currently in the oil window, and probably has been since the Permian. The northern Mississippi Valley Graben is currently near the peak-oil-generation stage for the Maquoketa Shale.

Vitrinite reflectance-equivalent values (percent R_{o-e}) were calculated for this project from the Rock-Eval results of the Rough Creek Graben Consortium samples (Espitalie and others, 1977; Humble Geochemical Services Division, 2001). The percent R_{o-e} values for the Hart County well ranged from 0.62 to 0.65, just within the oil window for type II organic matter. Closer to the basin center and currently at a greater depth, the Maquoketa Shale samples from the Trigg County well had percent R_{o-e} values of 0.74 to 0.80, near the peak oil-generation level (Tissot and Welte, 1978) (Fig. 15). The Trigg County values are in agreement with those predicted by Cluff and Byrnes (1990); however, the Hart County samples had slightly greater percent R_{o-e} values than Cluff and Byrnes (1990) estimated (0.63 versus about 0.55). If the slope of percent R_o from Figure 19 is reduced to fit the 0.63 calculated from Rock-Eval T_{max} measurements, this implies that the more organic-rich layers (total organic carbon values around 1 weight percent or greater) of the Maquoketa Shale produced oil at some time in the past for almost all of the Rough Creek Graben and areas west of Daviess and Christian Counties outside of the graben. Based on the timing of hydrocarbon generation calculations of Cluff and Byrnes (1990), oil generation from the Maquoketa Shale began in 325 Ma (Early Pennsylvanian) and peaked around 175 Ma (Middle Jurassic) in the northern Mississippi Valley Graben/Hicks Dome area. The area around Hicks Dome is calculated to have entered the gas window around 275 Ma (Early Permian).

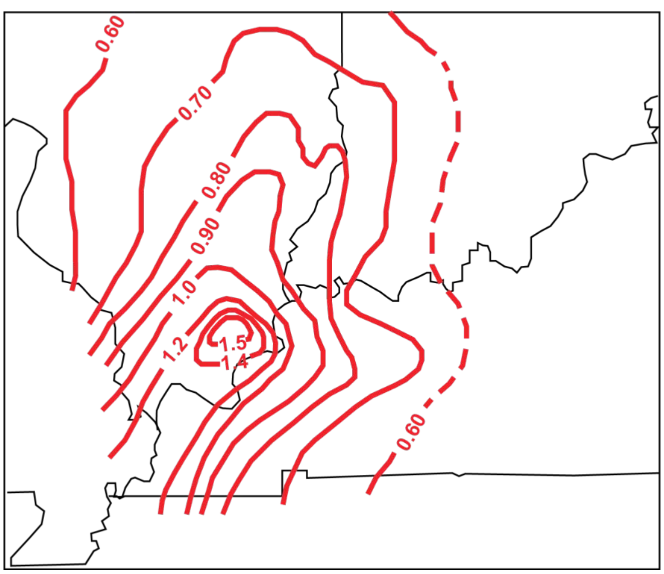

Figure 19. Predicted present-day maturation values (percent R_o) at the base of the Maquoketa Shale. Modified from American Association of Petroleum Geologists Memoir 51, © AAPG 1990 (Cluff and Byrnes (1990, Fig. 25-1); reprinted by permission of the AAPG whose permission is required for further use.

Reservoir—The most likely reservoirs for Maquoketa Shale–derived hydrocarbons are in the Silurian to Early Devonian carbonate and sandstone interval. Many of these formations contain adequate porosity, and only minimal vertical migration distances are required to charge these units. If sufficient pore pressures are achieved during or after oil or gas generation, downward migration of hydrocarbons into the Middle Ordovician Trenton Formation and Black River Group could also occur.

Another reservoir possibility for Maquoketa hydrocarbons is fault-controlled, hydrothermal dolomite bodies in the Trenton–Black River interval. In numerous locations in the Appalachian Basin in West Virginia, Pennsylvania, New York, and southern Ontario, hydrothermal fluids have apparently migrated up preexisting faults, altered the country rock into dolomite, and can result in prolific oil or gas fields. During this process, limestone dissolution increases the porosity and permeability of the Middle Ordovician carbonates. The additional heat flux from the intrusion of these hydrothermal fluids may also act as a local accelerant for hydrocarbon generation by "cooking" the surrounding strata. Although not an active oil or gas field, at least one example of similar fault-controlled hydrothermal alteration has been defined in the Rough Creek Graben region (Fig. 20).

Trap/Seal—The clay-rich New Albany Shale could act as an effective seal for the Silurian-Devonian carbonates and sandstones. On the western limb of the Cincinnati Arch in south-central Kentucky, there is an angular unconformity between the top of the Silurian section and the base of the New Albany Shale. Numerous oil fields produce from this angular unconformity. For Middle Ordovician carbonate reservoirs, the Maquoketa Shale itself may act as the seal.

For the unconventional "tectonic dolomite" reservoir model, the Maquoketa Shale would act as a vertical seal unit, whereas late mineral precipitation could effectively seal the faulted zone from lateral migration of hydrocarbons.

Eau Claire Formation. The Middle to Late Cambrian Eau Claire Formation qualifies as a speculative petroleum system: Neither an organic-rich pod of source rock from the Eau Claire nor a geochemically linked hydrocarbon sample from the Illinois Basin has been identified. Twenty-four well-cutting samples of Eau Claire Formation shales were analyzed as part of the Rough Creek Graben Consortium project.

Organic Content—Stevenson (1971) reported a 0.15 to 0.5 percent range of total organic carbon values for the Eau Claire Formation, with one well as high as 1.5 percent in Hamilton County, Ill., in the Fairfield Sub-basin. Stevenson (1971) also reported 0.4 to 0.5 percent for the Bonneterre Formation, which is equivalent to the lower Copper Ridge and upper Eau Claire of Kentucky.

Ryder and others (2005) reported total organic carbon levels of 0.19 to 0.59 percent for the Maryville Limestone in the Rome Trough in West Virginia, and 1.2 to 4.4 percent for the Rogersville Shale; both are members of the Conasauga Group. The Maryville Limestone is interpreted to be the stratigraphic equivalent of the limestone units in the middle to upper Eau Claire Formation in the Rough Creek Graben and environs.

For this project, 25 sets of shale and mudstone well cuttings from the Cambrian Eau Claire Formation were sampled from wells in the Rough Creek Graben region for chemical analysis and source-rock potential. Worldwide Geochemistry LLC performed total organic carbon, vitrinite-reflectance (percent R_o), and Rock-Eval (T_{max}) analyses on these samples. See Figure 13 for a map of wells sampled for source potential. All of the Eau Claire Formation samples tested resulted in total organic carbon values below source-rock quality (less than 0.6 percent). Total organic carbon values range from 0.03 to 0.12 weight percent, with an average of 0.06 weight percent.

Because cuttings are only available where wells have already been drilled to the Eau Claire

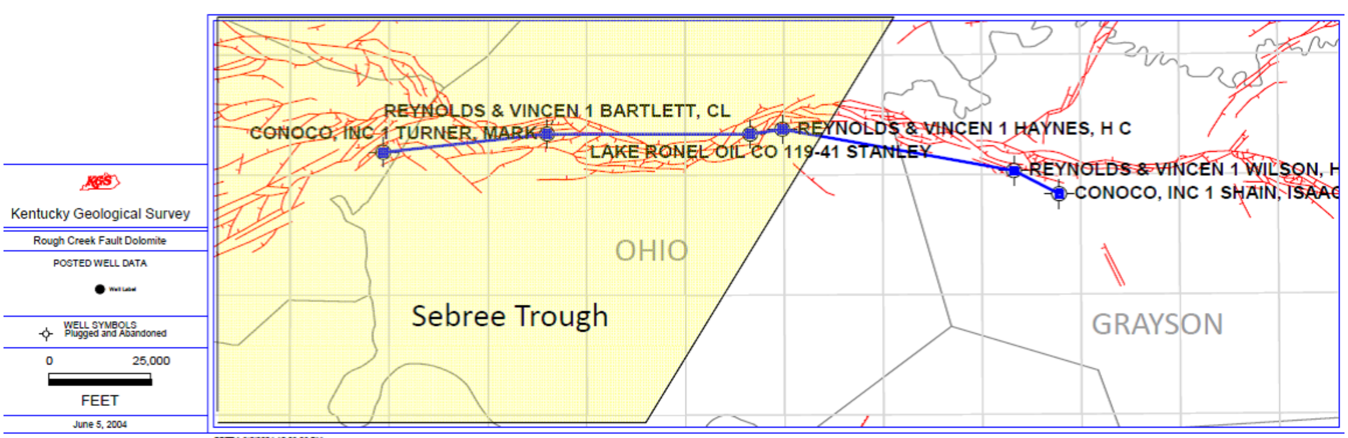

Figure 20. Detail of cross-section wells displayed in Figure 21. Modified from Harris (2004).

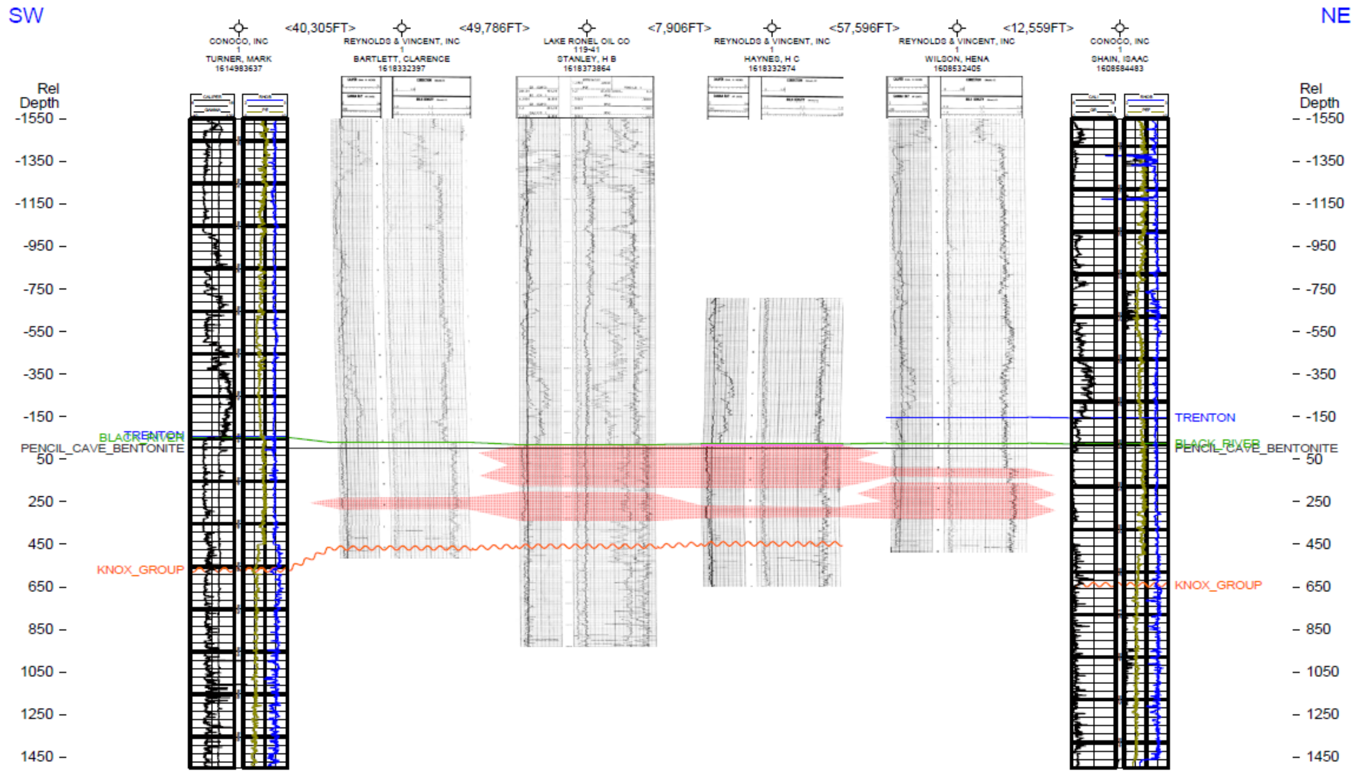

Figure 21. Well-based cross section along the Rough Creek Fault Zone that displays the effects of Sebree Trough deposition on the Trenton Formation, and the local hydrothermal alteration of Middle Ordovician Black River Group carbonates. Shaded region of Black River indicates limestone replacement by nonplanar dolomite. Modified from Harris (2004).

(and which were submitted to the State), the results only reflect those locations. Also, because testing cutting samples every 10 ft was economically unfeasible, depths with the highest gamma-ray log responses and lowest bulk-density log readings were sampled. It is possible that there are carbon-rich strata in the Eau Claire that are not in the layers with high gamma-ray log responses. The presence of petroleum staining and solid bitumen residue in the oolitic limestones of the Eau Claire Formation in the Conoco No. 1 Turner well in McLean County (Mitchell, 1993) indicates that there was petroleum migration through that oolite at some time in the past. Because of the depth of the sample and the well's location in a fault-bounded graben, lateral or downward migration from younger units is unlikely.

As kerogen is converted into petroleum in the hydrocarbon maturation process, a part of the organic-carbon content is consumed and is subsequently removed from the bulk rock composition as the oil is expelled during migration. Geochemical mass-balance analysis has estimated that this loss of measurable total organic carbon in overmature source rocks can be significant (Cooles and others, 1986; Daly and Edman, 1987; Leythaeuser and others, 1988; Rullkötter and others, 1988). Daly and Edman (1987) estimated that for type I source rocks, this total organic carbon reduction can be up to 80 percent. The Eau Claire Formation in the deeper parts of the Rough Creek Graben has an estimated vitrinite-reflectance maturity level of up to 3.5 percent R_o (Cluff and Byrnes, 1990). Prior to its (calculated) maturity in the Mississippian, the organic content of the shales in the Eau Claire Formation may have been higher. Whether this hypothetical increase in total organic carbon content would be sufficient to categorize the Eau Claire as a source rock is unknown. A slightly higher paleo-total organic carbon level, combined with the extraordinary thicknesses that the Eau Claire achieves in the graben, may have been adequate for it to produce oil. It is also possible that organic-rich units of the

Eau Claire Formation still exist today, but have not been sampled for total organic carbon analysis.

Overburden/Burial—The Eau Claire Formation is buried to depths greater than 2,000 ft across the entire project area. In the Rough Creek Graben, current lithostatic pressure and temperature calculations for the top of the Eau Claire Formation range from around 170°F at 5,800 psi (near the top of the oil production window) along the Cincinnati Arch in Casey County to around 400°F at 17,400 psi in Union County (well within the dry-gas production window).

Hydrocarbon Generation/Migration—On the basis of Lopatin analysis, Cluff and Byrnes (1990) calculated the current maturation levels at the top of the Eau Claire Formation to be between 1.2 and 3.5 percent R_o in the majority of the Rough Creek Graben (Fig. 22). Because of its age and depositional environment, the organic content of the Eau Claire Formation is assumed to be algal (type I) in origin. According to calculations by Cluff and Byrnes (1990), the Eau Claire Formation (assuming there is sufficient organic matter) in the eastern part of the Rough Creek Graben in Edmondson County would be near peak-oil generation. To the west, the Eau Claire in Hopkins and Webster Counties would be in the dry-gas generation window. The period of oil generation is calculated to have been during the Devonian through Permian Periods, with peak oil generated during the Mississippian and Pennsylvanian Periods. These calculations take into account many factors such as changes in geothermal gradients and sediment loads with time. The anomalous maturity spike (up to 5 percent R_o) centered over Hicks Dome (Fig. 22) results from estimates of additional heat flow caused from Permian volcanic intrusions. Numerous variables with unknown or uncertain values are needed to complete these analyses. Varying the estimates of past erosion (removed overburden) or volcanic heat-source parameters (timing, heat flux, etc.) could change this modeled pattern of maturity.

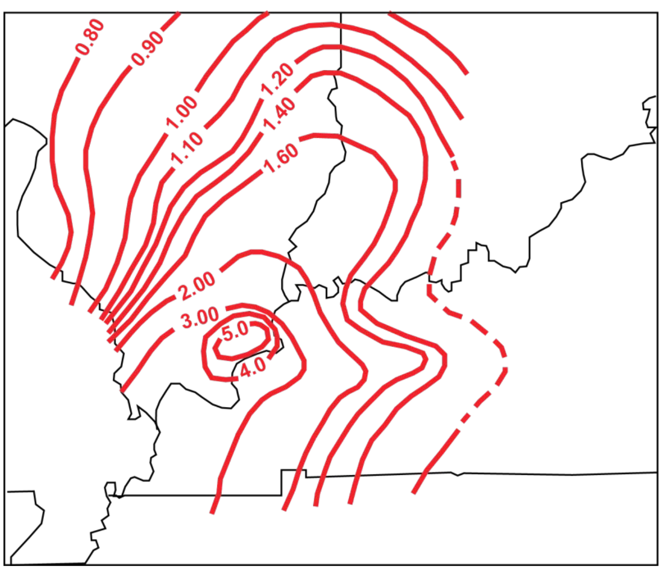

Figure 22. Predicted present-day maturity (percent R_o) at the top of the Eau Claire Formation. Modified from American Association of Petroleum Geologists Memoir 51, © AAPG 1990 (Cluff and Byrnes, 1990, Fig. 25-1); reprinted by permission of the AAPG whose permission is required for further use.

A Middle Cambrian Eau Claire–equivalent unit in the Rome Trough in West Virginia is the Rogersville Shale. Rock-Eval T_{max} values of 460 to 477°C (about 1.1 to 1.5 percent R_o) have been reported from Rogersville Shale samples (Harris and others, 2004; Ryder and others, 2005). The values correspond to the peak-oil to condensate/wet-gas generation window.

For the Rough Creek Graben Consortium project analysis, Rock-Eval T_{max} values were measured for all of the Eau Claire samples. Unfortunately, low S_2 levels (milligrams of hydrocarbon per grams of organic carbon) produced erratic results. The values calculated for the Eau Claire Formation samples should be disregarded for these data because of insufficient S_2 levels to produce accurate results. The T_{max} values calculated for the Maquoketa Shale samples appear to be correct (Fig. 23).

Once a source rock has matured to the point of expelling oil, there must be an open and secure pathway of porosity and permeability for the hydrocarbons to migrate to a trap and accumulate. Although not quite as permeable as open fractures, active shallow fault zones are far less restrictive to fluid flow than intergranular porosity. As fault zones become inactive and age, vein filling and mineralization tend to destroy available permeability and create a hydrocarbon-sealing fault. However, if the fault zone remains active, recurring movement along the fault planes in the shallow (cataclastic) zone rejuvenates the fracture and interclast porosity of the gouge zone.

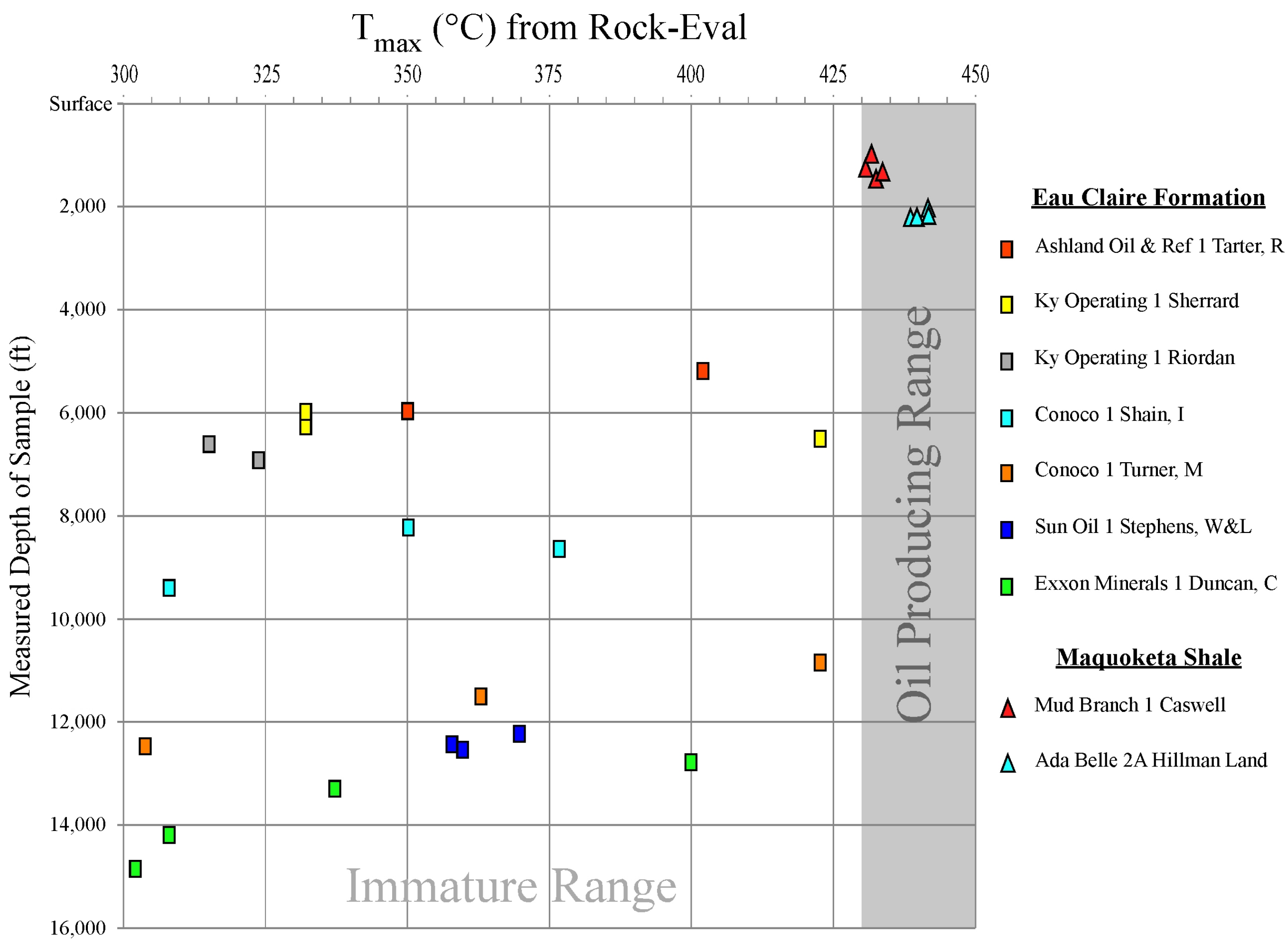

Figure 23. T_{max} values versus measured depth for Rough Creek Graben Consortium source-rock samples. T_{max} data for all Eau Claire samples are unreliable because of low S_2 values.

If current Lopatin models are correct, the Eau Claire Formation would have been maturing (assuming sufficient organic material) during three different organic cycles: the Acadian (Devonian to Early Mississippian), the Alleghenian, and the Ouachita Orogenies (Late Mississippian to Permian). There is a strong probability that any oil near the heavily reactivated Rough Creek, Shawneetown, and Cottage Grove Fault Systems during this time migrated out of the area through these active fault zones. This might help explain the failure of previous exploration attempts in that part of the graben. Accumulations of Eau Claire Formation–sourced hydrocarbons may be possible away from the northern and western graben-border fault areas that have undergone so much reactivation. In unfaulted areas, traditional updip migration through intergranular porosity would predominate.

Reservoirs—There are three probable reservoir units for hydrocarbons produced from the Eau Claire Formation: the Knox Supergroup, the Reelfoot Arkose, and within the Eau Claire itself. The thick carbonate section of the Knox Supergroup overlies the Eau Claire Formation across the entire project area. Reservoirs in the Knox would primarily be in vugular and fracture-derived porosity zones. If there are permissible pathways (through lateral or downward vertical migration), intergranular porosity in Reelfoot Arkose sandstone units could also be reservoirs of Eau Claire hydrocarbons. Finally, the shale and mudstone units of the Eau Claire could act as a source rock, whereas its interbedded limestone members (similar to the oolite drilled in the No. 1 Turner well) could act as reservoirs. The largest risk associated with the Reelfoot Arkose and Eau Claire Formation carbonates is the preservation of open porosity. These formations are now present at depths that could lead to both compaction-derived and vein-filling porosity-destruction processes.

Trap and Seal—There are numerous potential structural and stratigraphic traps within and in the area surrounding the Rough Creek Graben. These include both primary traps (updip facies changes, stratigraphic pinch-outs, and units terminating along fault cuts) and secondary traps (angular unconformities following local exhumation or uplift, and inversion structures related to fault reactivations).

Potential traps in the Knox Supergroup include areas where the lower Knox is juxtaposed against igneous basement rocks along the graben-bounding fault zones, or in porous zones in the Knox that lie below tight, low-permeability dolomite layers. Some isolated sands are often found in the Knox as well, but log responses usually suggest little open porosity. Because of the strong but inelastic nature of massive dolostone deposits, through-going, near-vertical fractures in the Knox can be common. These fractures can act as reservoirs (if properly sealed) or as trap leaks/spill points if they propagate through the local seal. Depending on location and local depositional layering, the Knox Supergroup can act as a reservoir, seal, or even as a hydrocarbon migration conduit (through open fracture systems).

The combination of the argillaceous Dutchtown and Joachim Formations and the low-porosity Black River Group carbonates have the potential of acting as a seal for the underlying Knox Supergroup. These units have the same fracturing tendency as the Knox, but to a lesser extent because of the lower dolomite content.

Because of the syntectonic deposition of the Eau Claire Formation and Reelfoot Arkose, individual units in this interval tend to both thin toward and dip away from the graben bounding faults. This appears to have been the exploration strategy of the Conoco Rough Creek Graben drilling program in the early 1990's. Also, little is known about the depositional fabric or porosity content of the carbonate units in the lower Eau Claire Formation in the graben, immediately above the top of the Reelfoot Arkose sandstones. All of the current evidence and published interpretations to date have not suggested any subaerial exposures during Eau Claire deposition, implying a lack of karstic or vugular porosity zones in the lower Eau Claire carbonates, increasing the possibility that the Eau Claire could act as a seal for the underlying Reelfoot Arkose. However, original intergranular porosity was apparently present in the high-energy ooid shoals in the middle Eau Claire penetrated in the Conoco No. 1 Turner well, so other oolitic zones may have been deposited elsewhere as well. As long as fracture or fault zones did not breach the top of the Eau Claire, the upper shaly units could act as a vertical seal for the lower units.

Untested Zones of Higher Potential for Deep Gas Production

On the basis of the results of this study, the following areas may justify further investigation in the search for deep oil and gas production opportunities in the Rough Creek Graben.

Southern Shelf Edge

The Rough Creek Graben has undergone numerous fault reactivation episodes resulting from north–south- or northwest–southeast-directed compression. The asymmetric, down-to-the-north half-graben shape of the Rough Creek Graben could result in the steep northern border of the graben acting as a buttress or backstop to these forces. The faults of the Rough Creek and Shawneetown Fault Systems in this scenario would be more prone to deformation and reactivation than those of the Pennyrile and Lewisburg Fault Systems on the southern border of the graben. The mapped patterns of surface faults in these two areas would seem to support this interpretation (fewer interweaving fault segments in the southern fault zones).

An oolitic shoal deposit was encountered in the lower Eau Claire Formation in the Conoco No. 1 Turner well in McLean County. Thin-section analysis of sidewall cores (Mitchell, 1993) suggested high original porosity; however, later mineralization had completely filled all available porosity space. If a similar shoal existed contemporaneously on the southern rim of the Rough Creek Graben (Fig. 24), this area may well have under-

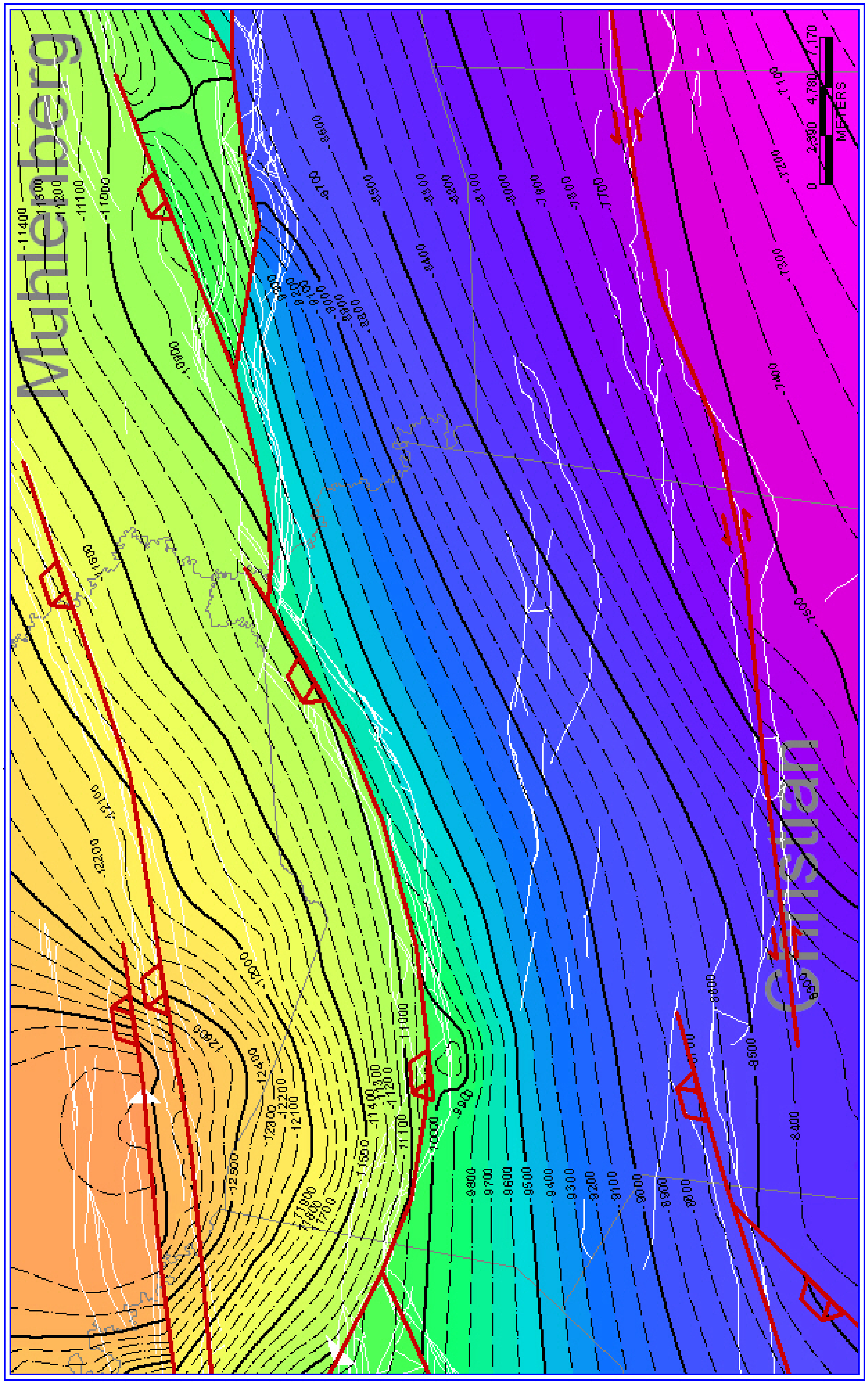

Figure 24. Southern shelf region of the Rough Creek Graben. Mapped horizon is the top of the Eau Claire Formation. Interpreted basement fault zones in dark red, mapped surface faults in white. Contour interval is 100 ft.

gone a lesser amount of deformation from fault reactivations. These deposits would also be at a shallower depth, further limiting porosity destruction from precipitation of deep, heated, mineral-rich fluids migrating through the rocks. Because of the asymmetric shape of the graben, the southern limb of the broad syncline of Eau Claire deposited in the graben would also drain a larger area than the northern limb drains. No carbonate buildups similar to what is observed near the Turner well were apparent on the few seismic profiles from this project that crossed the Pennyrile Fault System or the Lewisburg faults farther south (although vast areas along these fault zones have not been seismically surveyed).

Eastern Limb of the Tolu Arch/Fluorspar Uplift

This area in eastern Hardin County, Ill., and northeastern Crittenden County, Ky. (Fig. 25) shares many of the advantages of the southern shelf area shoals hypothesized above. The crest of the Fluorspar Uplift has been heavily faulted and contains numerous Permian volcanic intrusions,

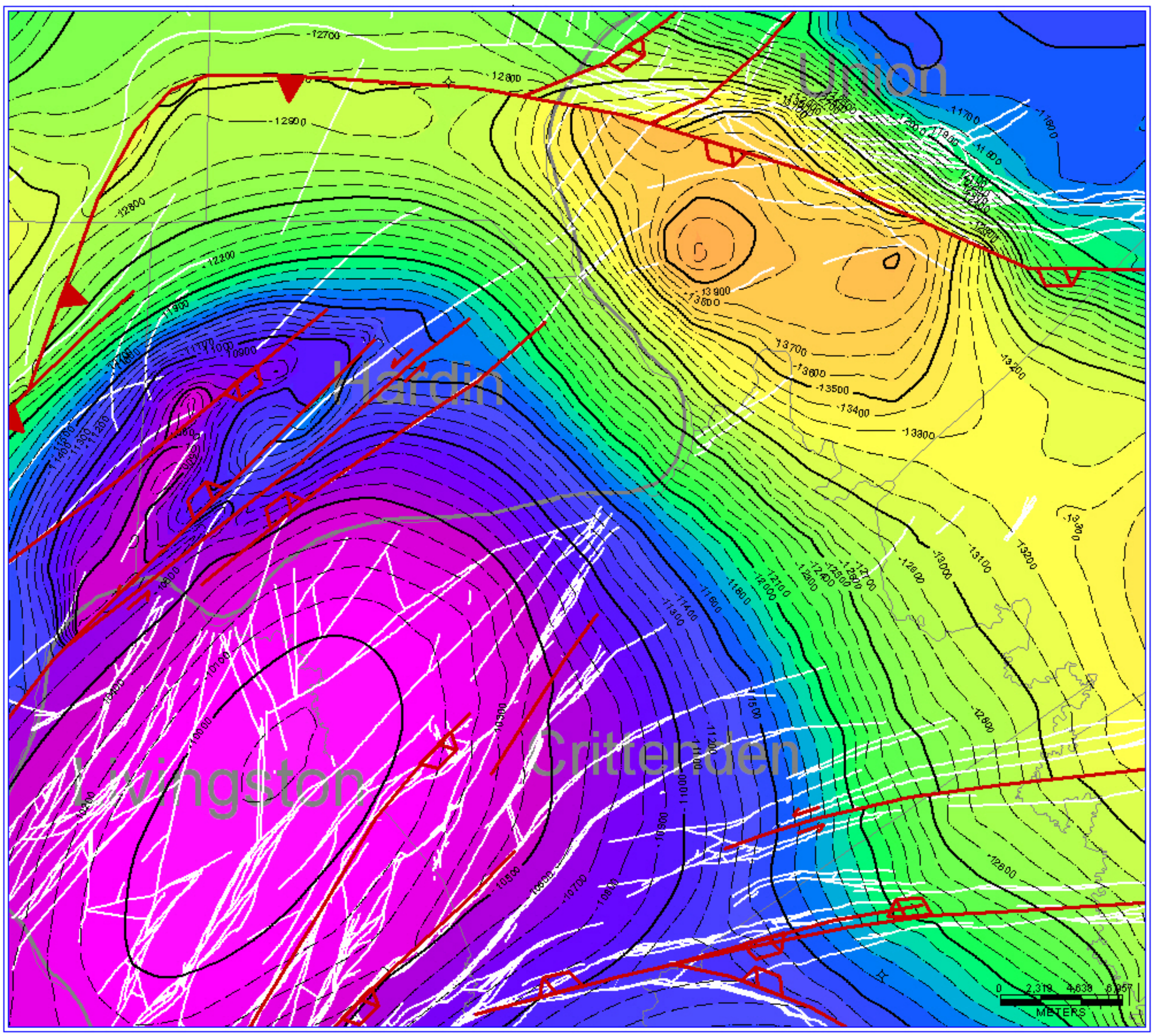

Figure 25. Detail of the Union County depocenter and Fluorspar Uplift areas. Mapped horizon is the top of the Eau Claire Formation. Interpreted basement fault zones in dark red, mapped surface faults in white. Contour interval is 100 ft.

both of which increase the risk of leaking and possibly "overcooking" of hydrocarbons from volcanic intrusion–derived heat flow. However, if stratigraphic or structural traps are on the northeast limb of this structure in Crittenden and Hardin Counties that would keep any produced oil from reaching the shattered crest, this could access approximately 600 km^2 of drainage area. Two wells listed in the Rough Creek Graben Consortium database have been drilled in this area away from faults, and both produced gas from the New Albany Shale (Equitable Resources K10002 Mast, A., and the Equitable Resources K10005 Heine Brothers wells). No wells have been drilled in this region deeper than the Upper Silurian.

Owensboro Graben Spillway

This northeast–southwest-oriented graben feature in Daviess and Hancock Counties (Fig. 26) has not been drilled deeper than the upper few feet of the Maquoketa Shale. Because of its location off of the main graben trend and situated on the northern shelf area, the strata in the graben may have been protected from later deformation in a stress shadow that was isolated from the main Rough Creek Graben tectonic motions. Because of the regional westward dip, the eastern side may have unproven hydrocarbon potential. The Eau Claire in this graben is fairly thin and so is less attractive as a local source rock (less than 1,000 ft thick, compared to more than 5,500 ft thick across the Rough Creek Fault Zone in McLean County). The Maquoketa Shale, however, has a slightly increased thickness across the graben (Sebree Trough) and might act as a local source rock.

Slope-to-Flat Transition Zone in Hart County

The top of Precambrian basement in southern Edmonton and Hart Counties changes from a steeply westward-dipping surface to a more flat geometry to the east along the axis of the Rough Creek Graben (Fig. 27). Along this same area, the Reelfoot Arkose pinches out to the east between the Precambrian basement and the base of the Eau Claire Formation. In southern Hart County, the top of the Reelfoot Arkose is shallower than 10,000 ft, suggesting that there may still be porosity in the coarse sandstones of the Reelfoot Arkose. This could have been a hydrocarbon migration pathway, if there are source-rock-quality strata in the Eau Claire Formation in the deeper parts of the graben to the west. The shales and lower carbonate units of the Eau Claire would act as a seal, trapping any migrated oil in the updip pinch-out of the Reelfoot Arkose. Carbonate shoal deposits in the lower Eau Claire may also be present near the basement slope break in Edmonson County. No wells have been drilled over the thinning Reelfoot Arkose in this area deeper than the Knox Supergroup.

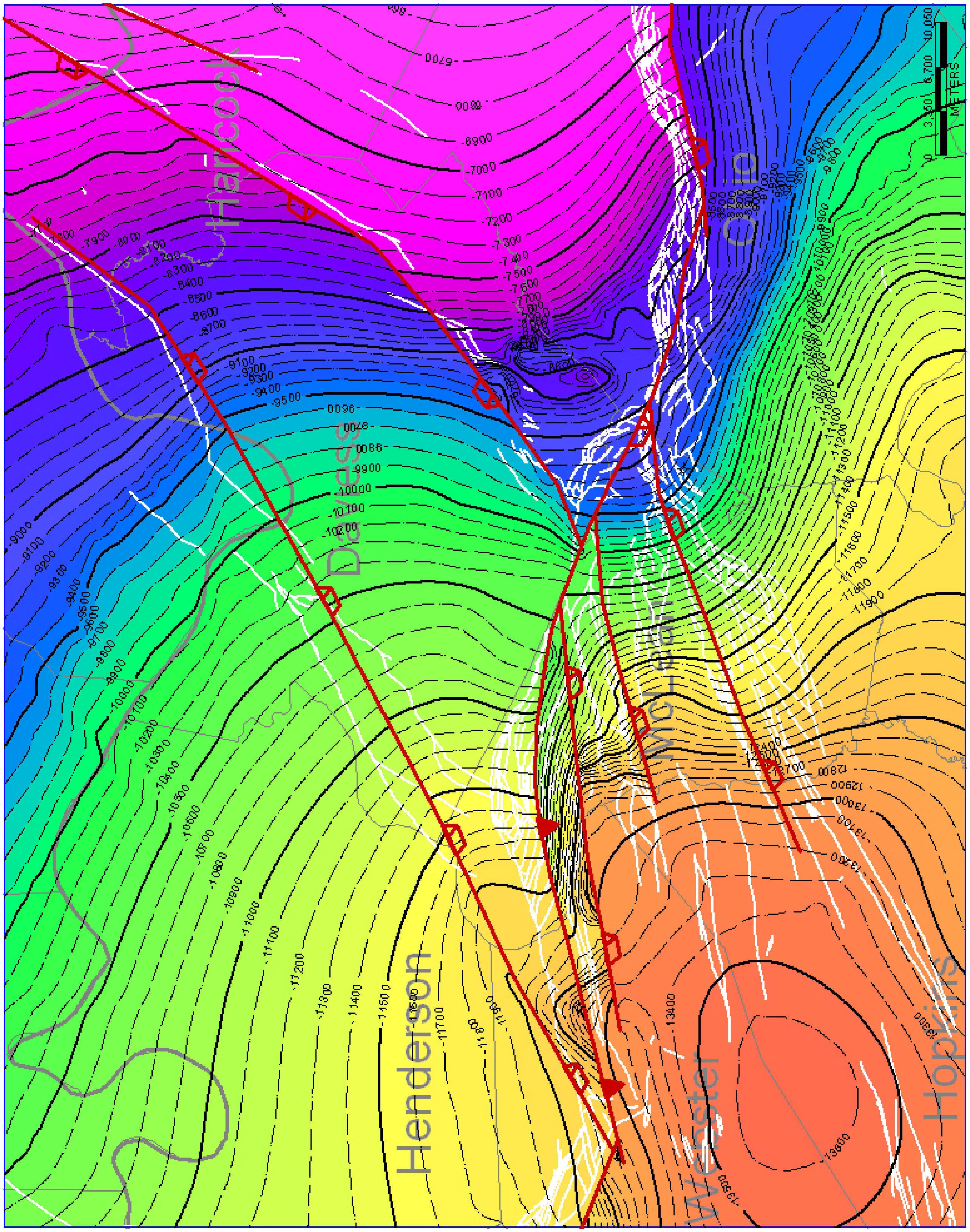

Figure 26. Detail of the Owensboro Graben area. Mapped horizon is the top of the Eau Claire Formation. Interpreted basement fault zones in dark red, mapped surface faults in white. Contour interval is 100 ft.

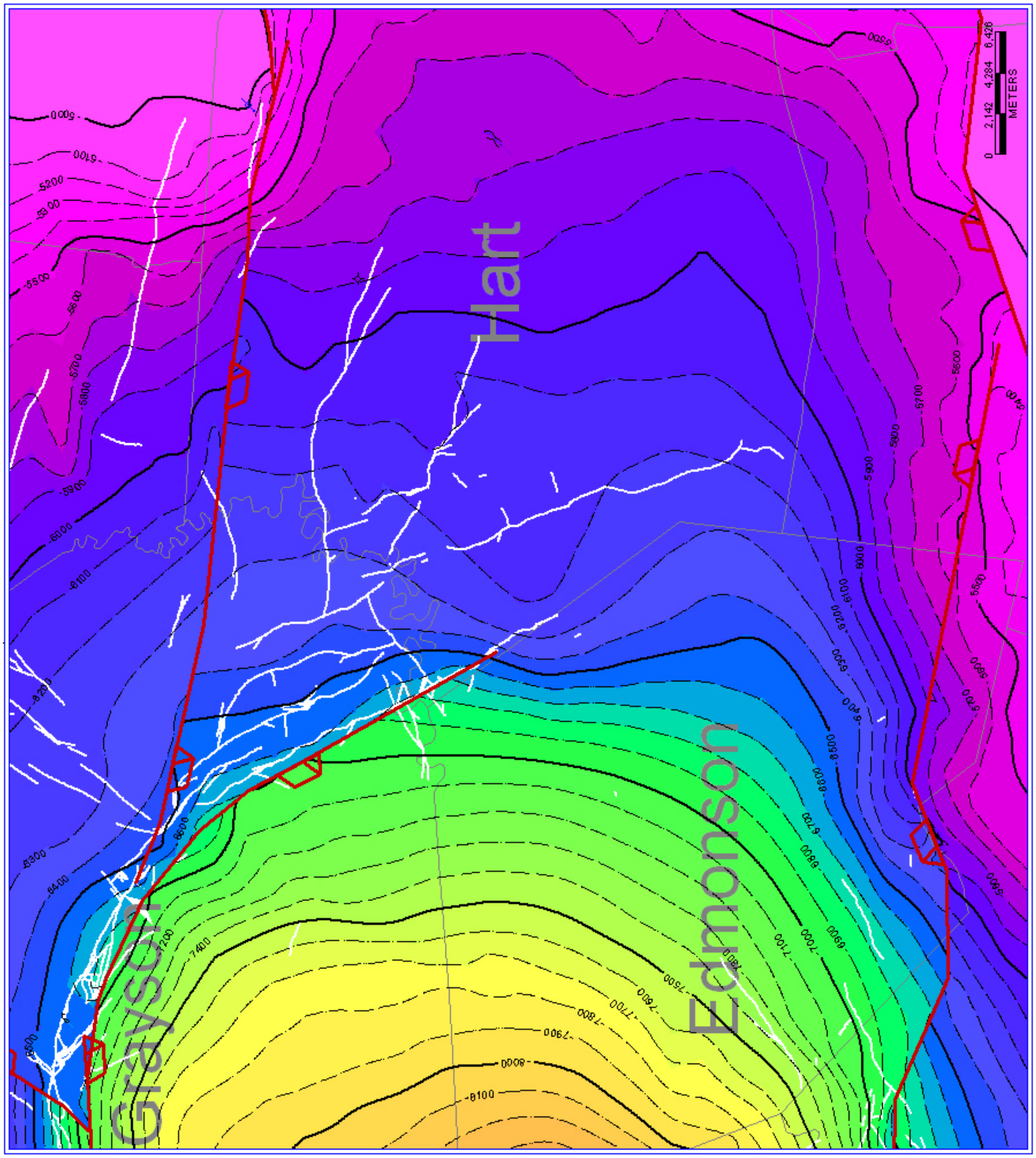

Figure 27. Detail of the Edmonson/Hart County area. Mapped horizon is the top of the Eau Claire Formation. Interpreted basement fault zones in dark red, mapped surface faults in white. Contour interval is 100 ft.

References Cited

Ammerman, M.L., and Keller, G.R., 1979, Delineation of Rome Trough in eastern Kentucky by gravity and deep drilling data: American Association of Petroleum Geologists Bulletin, v. 63, no. 3, p. 341–353.

Andrews, W.M., 2006, Geologic controls on Plio-Pleistocene drainage evolution of the Kentucky River in central Kentucky: Kentucky Geological Survey, ser. 12, Thesis 4, 216 p.

Barrows, M.H., and Cluff, R.M., 1984, New Albany Shale Group (Devonian-Mississippian) source rocks and hydrocarbon generation in the Illinois Basin, *in* Demaison, G., and Murris, R.J., eds., Petroleum geochemistry and basin evaluation: American Association of Petroleum Geologists Memoir 35, p. 111–138.

Beard, J.G., 1980, Devonian black shale study of western Kentucky: Final status report: Kentucky Geological Survey, Open File Report OF-80-02, 113 p.

Bergstrom, R.E., and Shimp, N.F., 1977, Geologic and geochemical studies of the New Albany Group in Illinois (Devonian black shale) to evaluate its characteristics as a source of hydrocarbons: Illinois State Geological Survey Annual Report, p. 40–41.

Bertagne, A.J., and Leising, T.C., 1990, Interpretation of seismic data from the Rough Creek Graben of western Kentucky and southern Illinois, *in* Leighton, M.W., Kolata, D.R., Oltz, D.F., and Eidel, J.J., eds., Interior cratonic basins: American Association of Petroleum Geologists Memoir 51, p. 199–208.

Bethke, C.M., Reed, J.D., and Oltz, D.F., 1991, Long-range petroleum migration in the Illinois Basin: American Association of Petroleum Geologists Bulletin, v. 75, no. 5, p. 925–945.

Bickford, M.E., Van Schmus, W.R., and Zietz, I., 1986, Proterozoic history of the Midcontinent region of North America: Geology, v. 14, no. 6, p. 492–496.

Bond, G.C., Nickerson, P.A., and Kominz, M.A., 1984, Breakup of a supercontinent between 625 Ma and 555 Ma: New evidence and implications for continental histories: Earth and Planetary Science Letters, v. 70, p. 325–345.

Bowersox, J.R., 2013, Evaluation of phase 2 CO_2 injection testing in the deep saline Gunter Sandstone reservoir (Cambrian-Ordovician Knox Group), Marvin Blan No. 1 well, Hancock County, Kentucky: Kentucky Geological Survey, ser. 12, Contract Report 53, 43 p.

Braile, L.W., Hinze, W.J., Keller, G.R., Lidiak, E.G., and Sexton, J.L., 1986, Tectonic development of the New Madrid Rift Complex, Mississippi Embayment, North America: Tectonophysics, v. 131, p. 1–21.

Braile, L.W., Hinze, W.J., Sexton, J.L., Keller, G.R., and Lidiak, E.G., 1984, Tectonic development of the New Madrid Seismic Zone, *in* Gori, P., Hays, W., and Nuttli, O.W., Proceedings of the Symposium on the New Madrid Seismic Zone: U.S. Geological Survey Open-File Report 84-770, p. 204–233.

Cluff, R.M., and Byrnes, A.P., 1990, Lopatin analysis of maturation and petroleum generation in the Illinois Basin, *in* Leighton, M.W., Kolata, D.R., Oltz, D.F., and Eidel, J.J., eds., Interior cratonic basins: American Association of Petroleum Geologists Memoir 51, p. 425–454.

Comer, J.B., Hamilton-Smith, T., and Frankie, W.T., 1994, Source rock potential, *in* Hasenmueller, N.R., and Comer, J.B., eds., Gas potential of the New Albany Shale (Devonian and Mississippian) in the Illinois Basin: Illinois Basin Consortium, Illinois Basin Studies 2, p. 47–54.

Cooles, G., Mackenzie, A., and Quigley, T., 1986, Calculation of petroleum masses generated and expelled from source rocks: Organic Geochemistry, v. 10, nos. 1–3, p. 235–245.

Cressman, E.R., 1973, Lithostratigraphy and depositional environments of the Lexington Limestone (Ordovician) of central Kentucky: U.S. Geological Survey Professional Paper 768, 61 p.

Cressman, E.R., and Noger, M., 1976, Tidal-flat carbonate environments in the High Bridge Group (Middle Ordovician) of central Kentucky: Kentucky Geological Survey, ser. 10, Report of Investigations 18, 15 p.

Currie, M., and MacQuown, W., 1981, Subsurface stratigraphy of the Corniferous (Silurian-Devonian) of eastern Kentucky, *in* Luther, M.K., ed., Proceedings of the technical sessions, Kentucky Oil and Gas Association forty-fifth annual meeting, June 10–12, 1981: Kentucky

Geological Survey, ser. 11, Special Publication 11, p. 1–21.

Daly, A.R., and Edman, J.D., 1987, Loss of organic-carbon from source rocks during thermal maturation [abs.]: American Association of Petroleum Geologists Bulletin, v. 71, no. 5, p. 546.

Drahovzal, J.A., 1997, Proterozoic sequences and their implications for Precambrian and Cambrian geologic evolution of western Kentucky; evidence from seismic-reflection data [abs.]: Seismological Research Letters, v. 68, no. 4, p. 553.

Drahovzal, J.A., Harris, D.C., Wickstrom, L.H., Walker, D., Baranoski, M.T., Keith, B.D., and Furer, L.C., 1992, The East Continent Rift Basin, a new discovery: Kentucky Geological Survey, ser. 11, Special Publication 18, 25 p.

Ervin, C.P., and McGinnis, L.D., 1975, Reelfoot Rift; reactivated precursor to the Mississippi Embayment: Geological Society of America Bulletin, v. 86, no. 9, p. 1287–1295.

Espitalie, J., Madec, M., Tissot, B.P., and Leplat, P., 1977, Source rock characterization method for petroleum exploration: Offshore Technology Conference, Houston, Texas, OTC 2935, 6 p.

Eyl, W.C., 1922, Special oil and gas edition map of Kentucky: An original compilation: Kentucky Geological Survey, ser. 6, scale 1 in.=4 mi.

Ferrill, B.A., and Thomas, W.A., 1988, Acadian dextral transpression and synorogenic sedimentary successions in the Appalachians: Geology, v. 16, no. 7, p. 604–608.

Freeman, L.B., 1951, Regional aspects of Silurian and Devonian stratigraphy in Kentucky: Kentucky Geological Survey, ser. 9, Bulletin 6, 575 p.

Greb, S., 1985, Structural control of sedimentation, Madisonville Paleovalley (Carboniferous), western Kentucky [abs.]: Geological Society of America Abstracts with Programs, v. 17.

Guiness, E.A., Arvidson, R.E., Strebeck, J.W., Schultz, K.J., Davies, G.F., and Leff, C.E., 1982, Identification of a Precambrian rift through Missouri by digital image processing of geophysical and geological data: Journal of Geophysical Research, v. 87, no. B10, p. 8529–8545.

Harris, D.C., 2000, Petrology and stratigraphy of the Middle Run Formation (Precambrian) in Kentucky [abs.]: American Association of Petroleum Geologists Bulletin, v. 84, no. 9, p. 1380.

Harris, D.C., 2004, Outcrop analogs and subsurface examples of tectonic dolomite in Kentucky: Understanding the Trenton Black River reservoir: Presentation to Petroleum Technology Transfer Council–Appalachian Region.

Harris, D.C., Drahovzal, J.A., Hickman, J.B., Nuttall, B.C., Baranoski, M.T., and Avary, K.L., 2004, Rome Trough Consortium final report and data distribution: Kentucky Geological Survey, Open-File Report OF-04-06, 1 CD-ROM.

Hildenbrand, T.G., Johnson, R.W.J., and Kucks, R.P., 1981, Aeromagnetic map of east-central United States: U.S. Geological Survey Geophysical Investigation Map 948, scale 1:1,000,000.

Hoholick, J.D., Metarko, T., and Potter, P.E., 1984, Regional variations of porosity and cement: St. Peter and Mount Simon Sandstones in Illinois Basin: American Association of Petroleum Geologists Bulletin, v. 68, no. 6, p. 753–764.

Horn and Associates, 2002, U-DRIL source rock database: American Association of Petroleum Geologists.

Houseknecht, D.W., 1989, Earliest Paleozoic stratigraphy and facies, Reelfoot Basin and adjacent craton, *in* Gregg, J.M., Palmer, J.R., and Kurtz, V.E., eds., Field guide to the Upper Cambrian of southeastern Missouri—Stratigraphy, sedimentology, and economic geology: University of Missouri–Rolla, Department of Geology and Geophysics, p. 25–42.

Houseknecht, D.W., and Weaverling, P.H., 1983, Early Paleozoic sedimentation in Reelfoot Rift [abs.]: American Association of Petroleum Geologists Bulletin, v. 67, no. 9, p. 1456.

Howe, J.R., and Thompson, T.L., 1984, Tectonics, sedimentation, and hydrocarbon potential of the Reelfoot Rift: Oil & Gas Journal, v. 82, no. 46, p. 179–190.

Humble Geochemical Services Division, 2001, TOC and Rock-Eval or SR analyzer interpretive guidelines: Humble Instruments & Services Inc., 15 p.

Johnson, P.R., Zietz, I., and Thomas, W.A., 1994, Possible Neoproterozoic–early Paleozoic grabens in Mississippi, Alabama, and Tennessee: Geology, v. 22, no. 1, p. 11–14.

Kepferle, R.C., 1986, Devonian and Mississippian black shales of Kentucky: Geological Society of America Centennial Field Guide, v. 6, p. 31–36.

Kisvarsanyi, E.B., 1984, Precambrian tectonic framework of Missouri as interpreted from magnetic anomaly map, *in* Contributions to Precambrian geology: Missouri Division of Geology and Land Survey, v. 14, no. B, p. 19.

Kolata, D.R., Huff, W., and Bergström, S., 2001, The Ordovician Sebree Trough: An oceanic passage to the Midcontinent United States: Geological Society of America Bulletin, v. 113, no. 8, p. 1067–1078.

Kolata, D.R., and Nelson, W.J., 1990a, Basin-forming mechanisms of the Illinois Basin, *in* Leighton, M.W., Kolata, D.R., Oltz, D.T., and Eidel, J.J., eds., Interior cratonic basins: American Association of Petroleum Geologists Memoir 51, p. 287–292.

Kolata, D.R., and Nelson, W.J., 1990b, Tectonic history of the Illinois Basin, *in* Leighton, M.W., Kolata, D.R., Oltz, D.T., and Eidel, J.J., eds., Interior cratonic basins: American Association of Petroleum Geologists Memoir 51, p. 263–285.

Kolata, D.R., and Nelson, W.J., 1997, Role of the Reelfoot Rift/Rough Creek Graben in the evolution of the Illinois Basin, *in* Ojakangas, R.W., Dickas, A.B., and Green, J.C., eds., Middle Proterozoic to Cambrian rifting, central North America: Geological Society of America Special Paper 312, p. 287–298.

Leythaeuser, D., Littke, R., Radke, M., and Schaefer, R.G., 1988, Geochemical effects of petroleum migration and expulsion from Toarcian source rocks in the Hils Syncline area, NW-Germany: Organic Geochemistry, v. 13, nos. 1–3, p. 489–502.

Lidiak, E.G., Marion, R.F., Thomas, H.H., and Bass, M.N., 1966, Geochronology of the Midcontinent region, United States; 4, Eastern area: Journal of Geophysical Research, v. 71, no. 22, p. 5427–5438.

Lineback, J.A., 1980, Coordinated study of the Devonian black shale in the Illinois Basin: Illinois, Indiana, and western Kentucky: Final report prepared by the Illinois State Geological Survey for the U.S. Department of Energy, Contract/Grant Report 1981-1, 36 p.

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

Macke, D.L., 1996, Illinois Basin Province (064), *in* Gautier, D.L., Dolton, G.L., Takahashi, I.I., and Varnes, K.L., eds., National assessment of United States oil and gas resources—Results, methodology, and supporting data: U.S. Geological Survey Digital Data Series 30, 1 CD-ROM.

Magoon, L.B., and Dow, D.W., 1994, The petroleum system, *in* Magoon, L.B., and Dow, D.W., eds., The petroleum system: From source to trap: American Association of Petroleum Geologists Memoir 60, p. 1–30.

Marshak, S., and Paulsen, T., 1996, Midcontinent U.S. fault and fold zones: A legacy of Proterozoic intracratonic extensional tectonism?: Geology, v. 24, no. 2, p. 151–154.

McDowell, R.C., ed., 1986, The geology of Kentucky—A text to accompany the geologic map of Kentucky: U.S. Geological Survey Professional Paper 1151-H, 76 p.

McKeown, F.A., Hamilton, R.M., Diehl, S.F., and Glick, E.E., 1990, Diapiric origin of the Blytheville and Pascola Arches in the Reelfoot Rift, east-central United States; relation to New Madrid seismicity: Geology, v. 18, no. 11, p. 1158–1162.

Meents, W.F., and Swann, D.H., 1965, Grand Tower Limestone (Devonian of southern Illinois): Illinois State Geological Survey Circular 389, 34 p.

Miller, A.M., 1919, The geology of Kentucky, a classified compendium of State reports and other publications with critical comment based on original investigations: Kentucky Geological Survey, ser. 5, Bulletin 2, 392 p.

Mitchell, R., 1993, Depositional interpretation and pore history of core and sidewalls from the Conoco Turner #1 well, Rough Creek Graben, Kentucky: Conoco Geoscience & Reservoir R&D, Technical Service Report.

Mussman, W., and Read, J., 1986, Sedimentology and development of a passive- to convergent-margin unconformity: Middle Ordovician

Knox unconformity, Virginia Appalachians: Geological Society of America Bulletin, v. 97, no. 3, p. 282–295.

Mussman, W.J., Montanez, I.P., and Read, J.F., 1988, Ordovician Knox paleokarst unconformity, Appalachians: Paleokarst: New York, Springer-Verlag, part II, p. 211–228.

Nelson, K.D., and Zhang, J., 1991, A COCORP deep reflection profile across the buried Reelfoot Rift, south-central United States: Tectonophysics, v. 197, nos. 2–4, p. 271–293.

Nelson, W.J., 1990, Structural styles of the Illinois Basin, *in* Leighton, M.W., Kolata, D.R., Oltz, D.T., and Eidel, J.J., eds., Interior cratonic basins: American Association of Petroleum Geologists Memoir 51, p. 209–243.

Noger, M.C., and Drahovzal, J.A., 2005, Lithostratigraphy of Precambrian and Paleozoic rocks along structural cross section KY-1, Crittenden County to Lincoln County, Kentucky: Kentucky Geological Survey, ser. 12, Report of Investigations 13, 29 p.

Orton, E., 1891, Report on the occurrence of petroleum, natural gas and asphalt rock in western Kentucky, based on examinations made in 1888 and 1889: Kentucky Geological Survey, ser. 2, v. E, 233 p.

Owen, D.D., 1857, Second report of the geological survey in Kentucky, made during the years 1856 and 1857: Kentucky Geological Survey, ser. 1, v. 1, p. 3–148.

Peterson, W.L., 1981, Lithostratigraphy of the Silurian rocks exposed on the west side of the Cincinnati Arch in Kentucky: U.S. Geological Survey Professional Paper 1151-C, 29 p.

Phillips, J., Duval, J., and Ambroziak, R., 1993, National geophysical data grids; gamma ray, gravity, magnetic, and topographic data for the conterminous United States: U.S. Geological Survey Digital Data Series 9, 1 CD-ROM.

Pratt, T.L., Culotta, R.C., 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, no. 6, p. 505–509.

Rankin, D.W., 1976, Appalachian salients and recesses; late Precambrian continental breakup and the opening of the Iapetus Ocean: Journal of Geophysical Research, v. 81, no. 32, p. 5605–5619.

Rowan, E., Goldhaber, M., and Hatch, J., 2002, Regional fluid flow as a factor in the thermal history of the Illinois Basin: Constraints from fluid inclusions and the maturity of Pennsylvanian coals: American Association of Petroleum Geologists Bulletin, v. 86, no. 2, p. 257.

Rullkötter, J., Leythaeuser, D., Horsfield, B., Littke, R., Mann, U., Müller, P., Radke, M., Schaefer, R., Schenk, H., and Schwochau, K., 1988, Organic matter maturation under the influence of a deep intrusive heat source: A natural experiment for quantitation of hydrocarbon generation and expulsion from a petroleum source rock (Toarcian shale, northern Germany): Organic Geochemistry, v. 13, nos. 4–6, p. 847–856.

Ryder, R., Harris, D., Gerome, P., Hainsworth, T., Burruss, R., Lillis, P., Jarvie, D., and Pawlewicz, M., 2005, Evidence for Cambrian petroleum source rocks in the Rome Trough of West Virginia and Kentucky, Appalachian Basin: U.S. Geological Survey Open-File Report 05-1443, 79 p.

Ryder, R.T., 1992, Stratigraphic framework of Cambrian and Ordovician rocks in the central Appalachian Basin from Morrow County, Ohio, to Pendleton County, West Virginia: U.S. Geological Survey Bulletin 1839-G, 25 p.

Sargent, M.L., 1990, Sauk Sequence: Cambrian System through Lower Ordovician Series: Part I. Illinois Basin: Stratigraphy, *in* Leighton, M.W., Kolata, D.R., Oltz, D.T., and Eidel, J.J., eds., Interior cratonic basins: American Association of Petroleum Geologists Memoir 51, p. 75–85.

Schwalb, H.R., 1969a, Deep (Cambro-Ordovician) exploration in western Kentucky, *in* Rose, W.D., ed., Proceedings of the technical sessions, Kentucky Oil and Gas Association 32nd annual meeting, June 6–7, 1968: Kentucky Geological Survey, ser. 10, Special Publication 17, p. 16–19.

Schwalb, H.R., 1969b, Paleozoic geology of the Jackson Purchase Region, Kentucky, with reference to petroleum possibilities: Kentucky Geological Survey, ser. 10, Report of Investigation 10, 40 p.

Schwalb, H.R., 1982, Paleozoic geology of the New Madrid area: U.S. Nuclear Regulatory Commission Division of Health, Siting, and Waste Management/Illinois State Geological Survey, 61 p.

Schwalb, H.R., and Potter, P.E., 1978, Structure and isopach map of the New Albany–Chattanooga–Ohio Shale (Devonian and Mississippian) in Kentucky: Western sheet: Kentucky Geological Survey, ser. 10, scale 1:250,000.

Seale, G.L., 1981, Relationship of possible Silurian reef trend to Middle Paleozoic stratigraphy and structure of the southern Illinois Basin of western Kentucky: Lexington, University of Kentucky, master's thesis, 63 p.

Sexton, J.L., 1988, Seismic reflection expression of reactivated structures in the New Madrid Rift Complex: Seismological Research Letters, v. 59, p. 141–150.

Shaver, R.H., regional coord., 1985, Midwestern Basins and Arches Region—Correlation of Stratigraphic Units of North America (COSUNA) project: American Association of Petroleum Geologists, 1 sheet.

Shrake, D.L., Carlton, R.W., Wickstrom, L.H., Potter, P.E., Richard, B.H., Wolfe, P.J., and Sitler, G.M., 1991, Pre-Mount Simon basin under the Cincinnati Arch: Geology, v. 19, no. 2, p. 139–142.

Skinner, B., 1971, A paleoaquifer and its relation to economic mineral deposits: The Lower Ordovician Kingsport Formation and Mascot Dolomite of East Tennessee: A symposium: Economic Geology, v. 66, no. 5, p. 735–743.

Sloss, L.L., 1963, Sequences in the cratonic interior of North America: Geological Society of America Bulletin, v. 74, no. 2, p. 93–114.

Smith, A.E., 1968, History of oil and gas development in western Kentucky, *in* Miller, D.N., ed., Geology and petroleum production of the Illinois Basin, a symposium: Illinois and Indiana-Kentucky Geological Societies, v. 1, p. 41–48.

Smosna, R., Bruner, K.R., and Riley, R.A., 2005, Paleokarst and reservoir porosity in the Ordovician Beekmantown Dolomite of the central Appalachian Basin: Carbonates and Evaporites, v. 20, no. 1, p. 50–63.

Stark, T.J., 1997, The East Continent Rift Complex: Evidence and conclusions: Geological Society of America Special Paper 312, p. 253–266.

Stearns, R.G., and Reesman, A.L., 1986, Cambrian to Holocene structural and burial history of Nashville Dome: American Association of Petroleum Geologists Bulletin, v. 70, no. 2, p. 143–154.

Stevenson, D.L., 1971, Organic content of Cambro-Ordovician rocks in region 9, *in* Proceedings, symposium on future petroleum potential of NPC Region 9; Illinois Basin, Cincinnati Arch, and northern part of Mississippi Embayment, 11–12 March 1971, Champaign, Illinois: Illinois State Geological Survey, Illinois Petroleum 95, p. 141.

Stevenson, D.L., and Dickerson, D.R., 1969, Organic geochemistry of the New Albany Shale in Illinois: Illinois State Geological Survey, Illinois Petroleum 90, 11 p.

Thomas, W.A., 1991, The Appalachian-Ouachita rifted margin of southeastern North America: Geological Society of America Bulletin, v. 103, no. 3, p. 415–431.

Thomas, W.A., 1993, Low-angle detachment geometry of the late Precambrian–Cambrian Appalachian-Ouachita rifted margin of southeastern North America: Geology, v. 21, no. 10, p. 921–924.

Thomas, W.A., and Baars, D.L., 1995, The Paradox transcontinental fault zone: Oklahoma Geological Survey Circular 97, p. 3–12.

Tissot, B.P., and Welte, D.H., 1978, Petroleum formation and occurrence: A new approach to oil and gas exploration: New York, Springer-Verlag, 538 p.

Trace, R.D., and Amos, D.H., 1984, Stratigraphy and structure of the Western Kentucky Fluorspar District: Contributions to the geology of Kentucky: U.S. Geological Survey Professional Paper 1151-D, 41 p.

Van Schmus, W.R., Bickford, M.E., and Turek, A., 1996, Proterozoic geology of the east-central Midcontinent basement, *in* van der Pluijm, B.A., and Catacosinos, P.A., eds., Basement and basins of eastern North America: Geological Society of America, v. 308, p. 7–23.

Van Schmus, W.R., and Hinze, W., 1985, The Midcontinent Rift System: Annual Review of Earth and Planetary Sciences, v. 13, no. 1, p. 345–383.

Weaverling, P.H., 1987, Early Paleozoic tectonic and sedimentary evolution of the Reelfoot–Rough Creek Rift System: Midcontinent, U.S.: Columbia, University of Missouri, master's thesis, 232 p.

Weir, G.W., Peterson, W.L., and Swadley, W C, 1984, Lithostratigraphy of Upper Ordovician strata exposed in Kentucky: U.S. Geological Survey Professional Paper 1151-E, 121 p.

Withington, C.F., and Sable, E.G., 1969, Geologic map of the Rock Haven quadrangle, Kentucky-Indiana, and part of the Laconia quadrangle, Kentucky: U.S. Geological Survey Geologic Quadrangle Map GQ-780, scale 1:24,000.

Zartman, R.E., Brock, M.R., Heyl, A.V., and Thomas, H.H., 1967, K-Ar and Rb-Sr ages of some alkalic intrusive rocks from central and eastern United States: American Journal of Science, v. 265, p. 848–870.