



9-25-2018

# Structural Evolution and Petroleum Potential of a Cambrian Intracratonic Rift System: Mississippi Valley Graben, Rough Creek Graben, and Rome Trough

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**Kentucky Geological Survey**  
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**Structural Evolution and  
Petroleum Potential of a Cambrian  
Intracratonic Rift System:  
Mississippi Valley Graben, Rough  
Creek Graben, and Rome Trough**

**John B. Hickman and David C. Harris**

## **Our Mission**

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### **Technical Level**



## **Statement of Benefit to Kentucky**

Structural movement in Cambrian rocks in Kentucky, deposited from 490 to 515 million years ago, may have created traps for oil and natural gas. Producing these natural resources could benefit Kentucky companies and mineral rights owners and provide tax revenue for the commonwealth.

**ISSN 0075-5591**

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# **Structural Evolution and Petroleum Potential of a Cambrian Intracratonic Rift System: Mississippi Valley Graben, Rough Creek Graben, and Rome Trough**

**John B. Hickman and David C. Harris**

## **Abstract**

Drilling and geophysical data demonstrate that the Mississippi Valley Graben, Rough Creek Graben, and Rome Trough are fault-bounded structures filled with as much as 27,000 ft of Cambrian sediments. Data including stratigraphic tops from 1,764 wells, 106 seismic profiles, aeromagnetic and gravity surveys, and mapped surface geology at a scale of 1:24,000 were used to study seven stratigraphic packages across parts of Kentucky, Ohio, Indiana, Illinois, Missouri, and Tennessee. Detailed analysis of the thickness patterns of these stratigraphic packages was used to interpret the locations and timing of movement along major fault systems in the study area.

Active rifting of the Precambrian crystalline bedrock began by the Early Cambrian and resulted in thick, sand-rich deposits of the Reelfoot Arkose in the Mississippi Valley Graben and Rough Creek Graben, and the Rome Formation in the Rome Trough. Subsidence continued in these grabens during the Middle to Late Cambrian, leading to deposition of an alternating succession of shales and carbonates (Eau Claire Formation of the Illinois Basin and Conasauga Group of the Appalachian Basin) on top of the coarse clastic Reelfoot Arkose and Rome Formation. Although the tectonic extension that formed these features ended by the Late Cambrian, fault-zone reactivation during the Taconic, Acadian, and Alleghenian Orogenies altered fault-block orientations and produced areas of basin inversion, possibly creating numerous deep structural traps for hydrocarbons sourced by the Cambrian shales of the Eau Claire Formation and Conasauga Group.

## **Introduction**

The geology and tectonic history relevant to Cambrian hydrocarbon potential in Kentucky began in the middle to late Neoproterozoic. At that time, the supercontinent Rodinia began to break up and the Laurentian Plate started to rift from the Amazonia Plate (Cawood and others, 2001; Li and others, 2008; Allen and others, 2009; Fisher and others, 2010). Southeastern Laurentia developed into a passive margin as the new Iapetus Ocean was

formed (Thomas, 1991, 2006). Along this margin and contemporaneous with continental breakup, numerous graben systems were formed inboard of the continental margin of Laurentia. These systems include the Ottawa-Bonnechere Graben in New York and southern Ontario; the Rome Trough in western Pennsylvania, West Virginia, and eastern Kentucky; the Rough Creek Graben of western Kentucky and southern Illinois; the Mississippi Valley Graben in western Kentucky, eastern Arkansas, and western Tennessee; and the Southern

Oklahoma Aulacogen (Rankin, 1976; Soderberg and Keller, 1981; Thomas, 1983, 1991, 1993, 2006; Braile and others, 1986; Kolata and Nelson, 1990).

The Mississippi Valley Graben (Reelfoot Rift), Rough Creek Graben, and Rome Trough are part of an eastern North American interior rift system that formed in conjunction with the opening of the Iapetus-Theic Ocean (Thomas, 1991; Hickman, 2011). Based upon stratal relationships viewed on seismic profiles (Drahovzal, 1996; Hickman, 2011) and the few dates derived from paleontological analysis of the sediments filling these features (Palmer, 1962), the majority of the tectonic extension and normal fault movement in these grabens occurred during the Early to Middle Cambrian Period.

### **Rome Trough**

The Rome Trough extends from northern Tennessee, northeast through central and eastern Kentucky and West Virginia, into southwestern Pennsylvania, and possibly as far north as southern New York (Woodward, 1961; McGuire and Howell, 1963; Wagner, 1976; Drahovzal and Noger, 1995; Harris and others, 2004; Patchen and others, 2006). All of the major boundaries and structures in the trough were created, either directly or indirectly, by basement-rooted faults. These faults are all high-angle normal faults (probably with minor amounts of strike-slip motion), although there is evidence of reactivated reverse motion during Appalachian tectonic compression (White, 2001). The Rome Trough overlies the late Proterozoic metamorphic basement rocks of the Grenville Allochthon (Keller and others, 1981; Drahovzal and Noger, 1995). Based upon well data, the structural relief on the top of the basement between the northern edge and the deepest part of the trough is more than 13,000 ft. Seismic data suggest that the basement relief along the southern boundary is up to 4,400 ft (White, 2001). Overall, the top of the basement in the trough is shallow in central Kentucky, and deepens eastward along strike into central West Virginia. Although not documented by drilling data, previous interpretations of seismic data (Gao and others, 2000) suggest that the basement deepens to more than 24,000 ft below sea level in Kanawha County, W.Va. The deepest basement top from well data in this region is 18,836 ft

below sea level in the Exxon No. 1 Gainer-Lee well in Calhoun County, W.Va.

The Rome Trough is bordered by several basement faults, including the Lexington Fault System to the west, the Kentucky River and Ohio River Fault Systems to the north and northwest, and the Rockcastle River Fault System and the East Margin Fault of Gao and others (2000) to the southeast (Fig. 1). The Lexington Fault System trends north-northeast from southern Casey County through Bourbon County, Ky. The Kentucky River Fault System trends roughly west-to-east through central Kentucky (Fig. 1); unlike the Lexington Fault System to the west, however, only about half of its length is exposed at the surface. Although later movement in this fault system has been interpreted (based on river terrace deposits) to be as recent as the post-Pliocene (Van Arsdale and Sergeant, 1992), the majority of vertical, down-to-the-southeast movement (which totaled at least 1,200 to 1,800 ft) occurred during the early Middle Cambrian, which corresponds to the deposition of the lower part of the Rome Formation.

The Ohio River Fault System in West Virginia is not exposed at the surface, but is visible on seismic profiles (Gao and others, 2000) and from dramatic changes in the depth to basement observed in local wells. This fault system trends northeast, approximately from the northeastern terminus of the Kentucky River Fault System near the border with Kentucky, through western West Virginia, and into southwestern Pennsylvania. Because deep wells and seismic data are scarce in western Pennsylvania north of Greene County (Kulander and Ryder, 2005), the configuration of this fault system, as well as the structure of the whole Rome Trough in this area, is poorly understood. In West Virginia, movement along this fault system was at about the same time as more than 1,000 ft of down-to-the-southeast movement along the Kentucky River Fault System during the Early to Middle Cambrian.

None of the southeastern bounding faults of the Rome Trough are exposed, although there is evidence of localized deformation in the form of surface anticlines along the Rockcastle Uplift. In Kentucky, the Rockcastle River Fault System separates the trough from the Rockcastle River and Perry County Uplifts to the south (Fig. 2). Based on stratigraphic thicknesses, movement along these

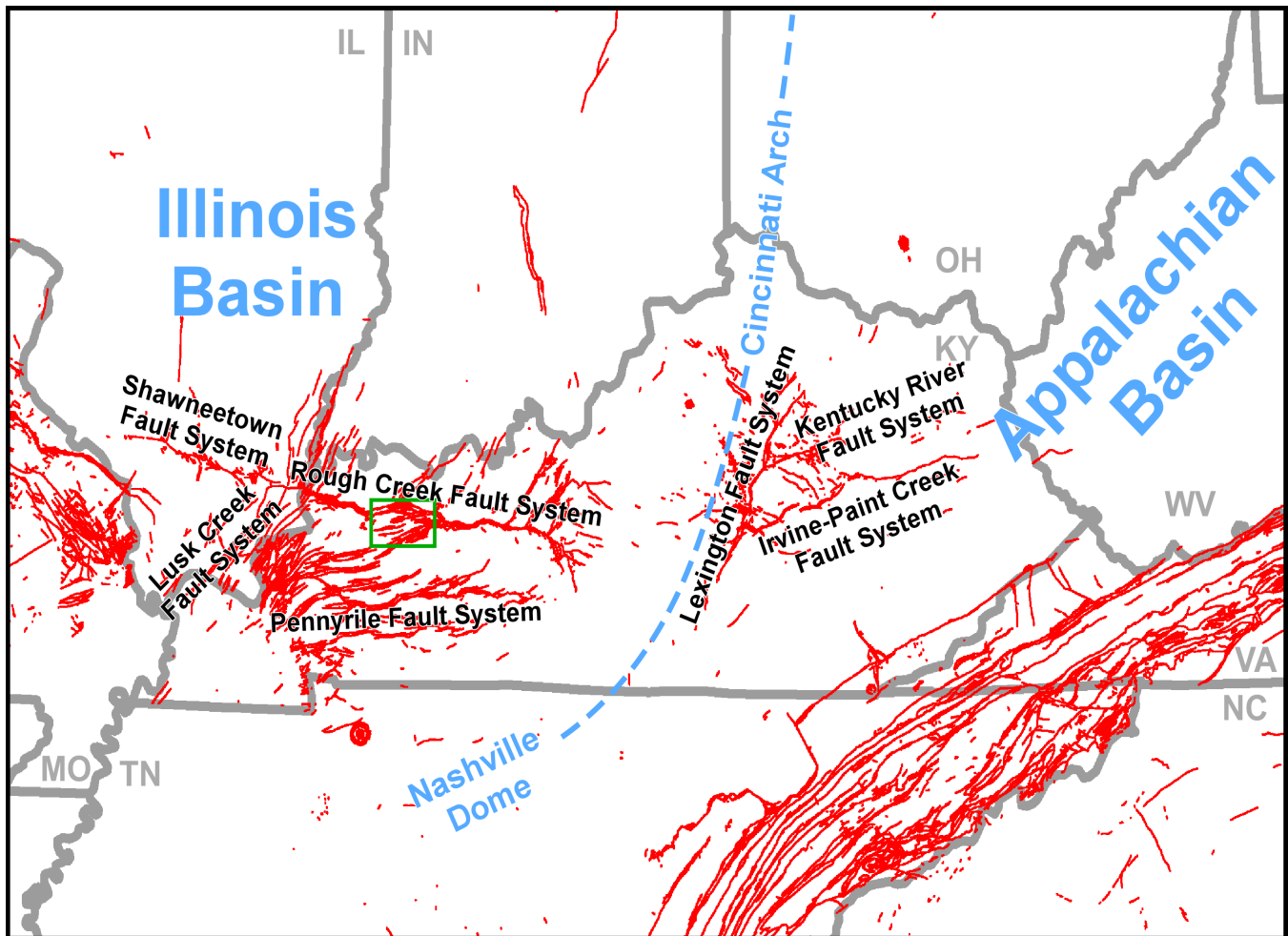


Figure 1. Surface features of the Mississippi Valley Graben–Rough Creek Graben–Rome Trough intracratonic rift system. Exposed faults are shown in dark red, and regional basins and arch axes in light blue. Green rectangle in western Kentucky notes location of map shown in Figure 5.

faults began around the same time as the fault movement in the Kentucky River Fault System, but lasted until the Late Cambrian. This corresponds to the time of deposition of the upper Rome Formation and the Conasauga Group (Fig. 3). Total vertical offset occurring through this interval across the fault system increases to the east from around 1,000 ft for the Rockcastle River Uplift to 1,800 ft or more along the Perry County Uplift to more than 3,600 ft along the Pike County Uplift (Fig. 2).

Unfortunately, no wells in West Virginia southeast of the East Margin Fault of Gao and others (2000) penetrate in-place Precambrian or Cambrian strata (below the thrust faults of the Appalachian orogenies). This makes direct measurement of basement offset across the fault impossible, but the displacement has been estimated from seismic

data to be as much as 6,500 ft (Gao and others, 2000). The age of this movement appears to be the same as that for the Rockcastle River Fault System: Early through Late Cambrian (Shady Dolomite to the top of the Conasauga Group) (Fig. 3).

Basement faults also bisect the Rome Trough's interior. In central and eastern Kentucky, the Irvine-Point Creek Fault System (Fig. 1) delineates an internal boundary between the shallower, northern section of the trough and a deeper region to the south. The strike of the Irvine-Point Creek Fault System is nearly identical to the strike of the Kentucky River Fault System, about 20 mi to the north. Both of these fault zones offset strata down to the south. The surface exposure of the Irvine-Point Creek Fault System extends east from Lincoln County to Johnson County, Ky. Subsurface



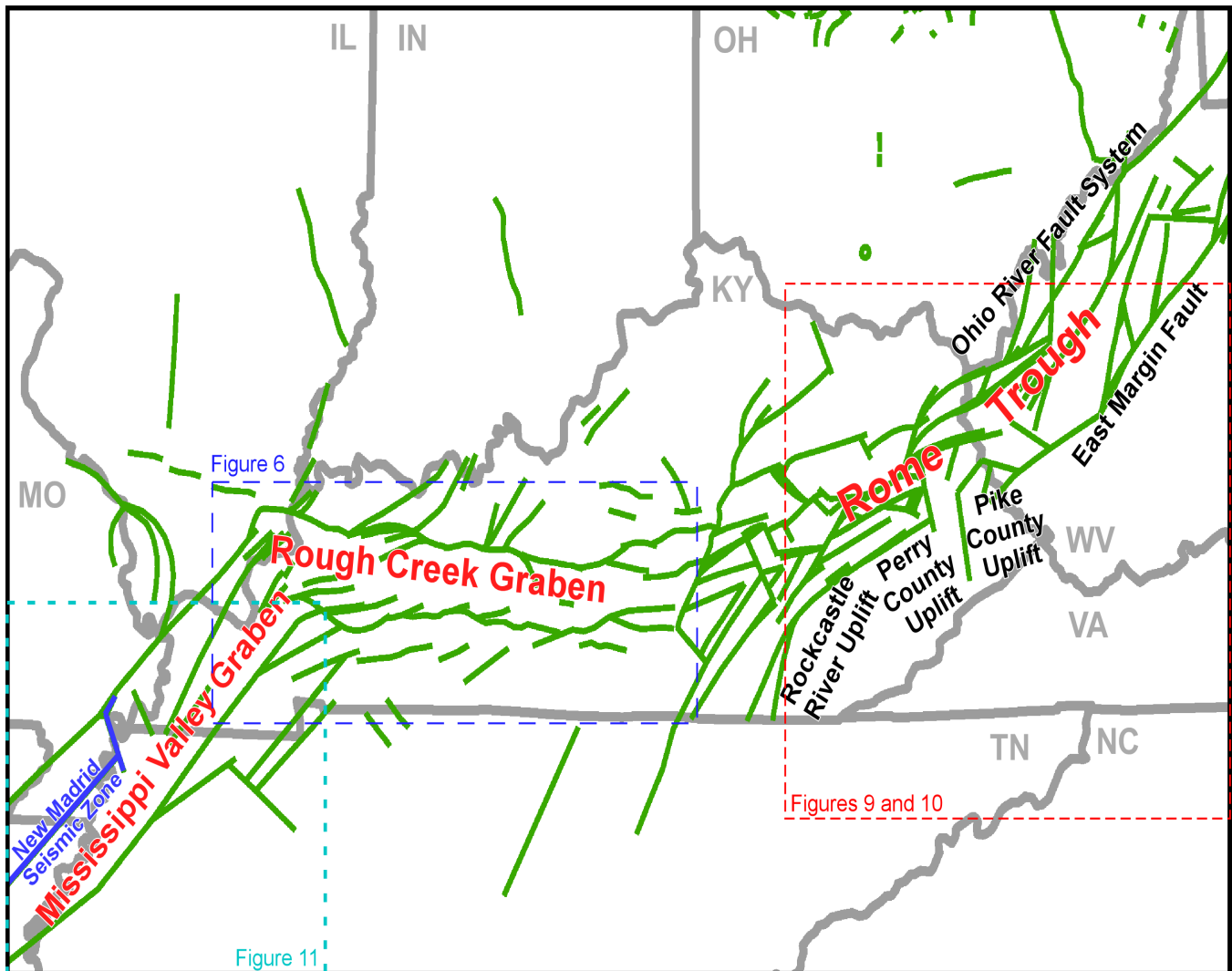


Figure 2. Subsurface features of the Mississippi Valley Graben–Rough Creek Graben–Rome Trough intracratonic rift system. Major basement fault systems are in green, and individual rift components are labeled in red. Faults of the New Madrid Seismic Zone are shown in dark blue. The location of Figure 6 is shown by the dashed dark blue rectangle; Figures 9 and 10 by the dashed red rectangle; and Figure 11 by the dotted light blue rectangle.

interpretations suggest that the shallower shelf on the northern side of the trough in Kentucky created by the Irvine–Paint Creek Fault System extends between the Lexington Fault System to the west and the Isonville Fault (Figs. 1–2) to the east (Lynch and others, 1999; Harris and others, 2004).

Stratigraphic evidence (Harris and others, 2004) indicates a transfer of displacement during the Middle Cambrian between the Kentucky River Fault System and the Irvine–Paint Creek Fault System (Fig. 1). Before then, the extension forming the northern and southern boundaries of the Rome Trough in Kentucky was being created along the Kentucky River and Rockcastle River

Fault Systems. Sometime during the deposition of the middle part of the Rome Formation, however, the movement along the Kentucky River faults stopped (or slowed dramatically) and extension began along the Irvine–Paint Creek Fault System. Movement along the Rockcastle River faults during this time appears to have continued at approximately the same rate without interruption. This tectonic movement led to the formation of the shallower Irvine–Paint Creek shelf along the northern border of the trough between the Kentucky River and Irvine–Paint Creek Fault Systems. South of this zone, the trough extends down to the full depth, similar to what occurs in West Virginia. Because

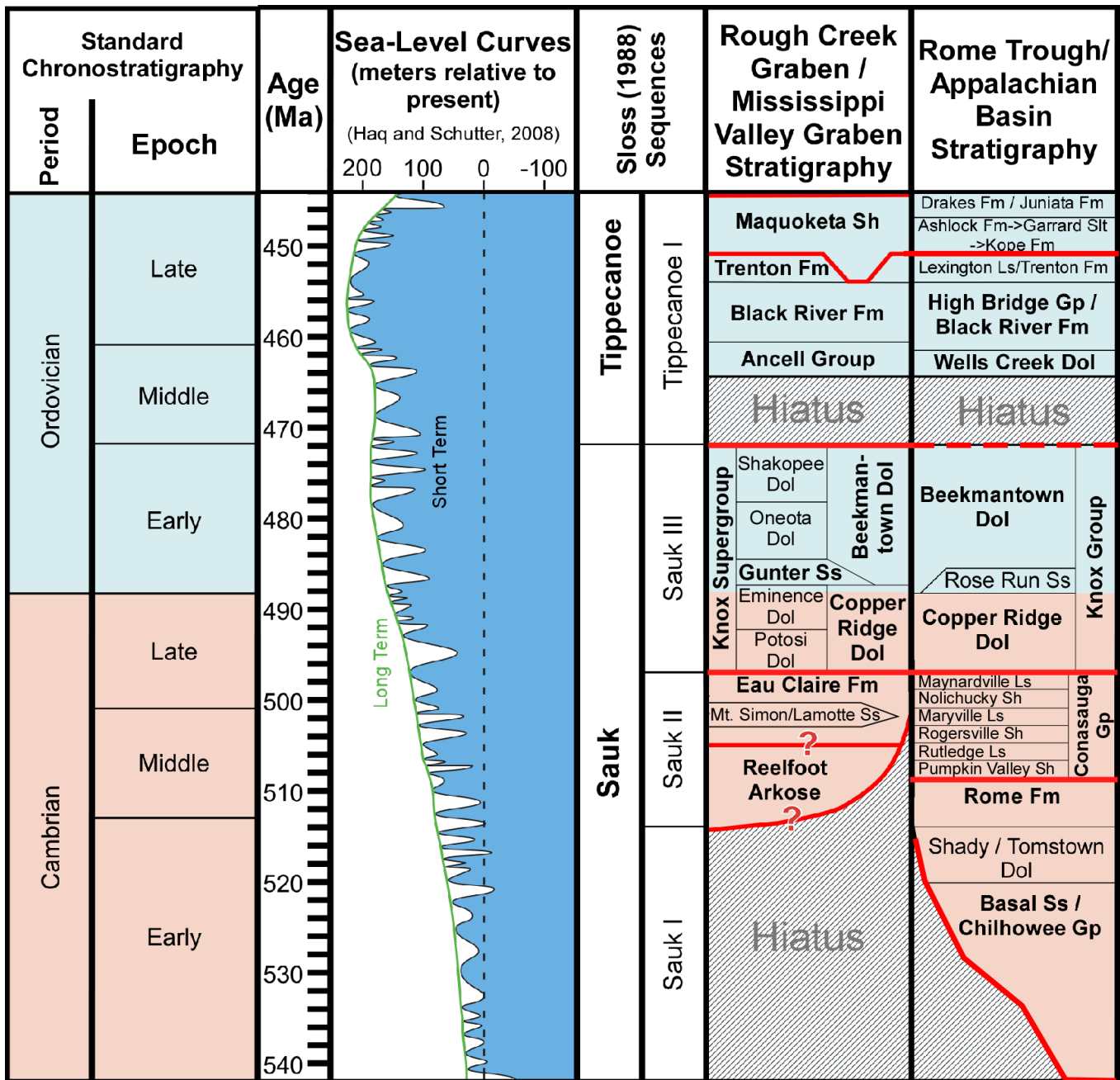


Figure 3. Geologic time scale showing both Appalachian (Rome Trough) and Illinois Basin (Mississippi Valley and Rough Creek Grabens) stratigraphy.

of this, there is a major unconformity between the Rome Formation and the Maryville Limestone of the Conasauga Group in the shallower northern area. In the deeper, southern zone in Kentucky, there is a nearly continuous record of sedimentation from the Lower Cambrian Shady Dolomite to the Middle Ordovician Knox Unconformity.

The Rome Formation and most of the Conasauga Group strata were deposited through syn-

tectonic sedimentation in the Rome Trough extensional sedimentary basin. By the time the upper parts of the Nolichucky Shale (Conasauga Group, Middle to Late Cambrian) were deposited, the majority of the fault motion that created the Rome Trough had ended. Stratigraphic thickening over the trough continued until the Middle Ordovician, however. Although minor fault reactivations may have assisted this growth to a lesser extent,

this post-rift sag basin was primarily formed from compaction of the several thousand feet of clastic sediment in the trough. The formation of the sag basin appears to have ceased by the Late Ordovician (post-Knox Unconformity).

During the Alleghenian Orogeny of the Appalachians to the east, compressional tectonic forces extended all the way into the Midcontinent. This reactivated in a reverse motion some of the normal faults that were created during the extension and formation of the Rome Trough. This fault movement produced inversion structures during the Mississippian in West Virginia (Shumaker and Wilson, 1996) and the Mississippian and Pennsylvanian Periods in Kentucky. One notable inversion structure in eastern Kentucky attributed to this fault reactivation is the Paint Creek Uplift. This local uplift, first mapped and described by Hudnall and Browning (1949), is partly the result of a reactivation of the buried Isonville Fault (Fig. 2). The deformation and upward movement of the hanging wall of this fault in the Paint Creek Uplift created the hydrocarbon trap that would later become the Homer Field, a Cambrian-sourced deep oil and gas field in southern Elliott County, Ky.

### ***Rough Creek Graben***

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 Pennyryle Fault System. On the west, the Rough Creek Graben intersects the northern terminus of the Mississippi Valley Graben, along the Lusk Creek and Shawneetown Fault Systems in southern Illinois. The exact eastern extent has not been determined, but the deepest part (deeper than 12,000 ft) extends east at least to Grayson and Edmonson Counties, Ky. Smaller faults and fold axes on strike with the Rough Creek and Pennyryle Fault Systems have been mapped at the surface eastward to near the western end of the Rome Trough, at the Lexington Fault System. These features have been interpreted as structural deformation within drape folds overlying buried basement fault systems (Hickman, 2011). If this interpretation is correct, these basement faults would act as the mechanical connection between the Rome Trough to the east and the Rough Creek Gra-

ben to the west. In cross section (Fig. 4), the Rough Creek Graben has an asymmetrical half-graben shape, with larger basement fault offsets along the northern border. Along this border in parts of Ohio and McLean Counties, Ky., the base of the Paleozoic section has been interpreted to be more than 38,000 ft deep (Hickman, 2011).

The exact timing of fault initiation is unknown (the oldest strata drilled in the Rough Creek Graben are interpreted to be latest Early Cambrian in age); however, proprietary seismic data indicate 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 Pennyryle Fault System along the southern boundary.

### ***Mississippi Valley Graben***

The Mississippi Valley Graben (the upper crustal feature created by the Reelfoot Rift) is a northeast-trending graben that borders the Rough Creek Graben to the west and southwest (Kolata and Nelson, 1997). The graben was initially interpreted from gravity and magnetic surveys by Ervin and McGinnis (1975). On the basis of an anomalous high-velocity layer at approximately 30 to 45 km depth under the axis of the graben (calculated from refraction-seismic data), Ervin and McGinnis (1975) theorized that magmatic underplating of the crust caused doming, which in turn caused tensional faults at the surface that evolved into a rift graben as the dome subsided. Nelson and Zhang (1991) used regional reflection-seismic sections (COCORP lines AR-6 in eastern Arkansas and TN-3 in western Tennessee) and well data in their analysis of the Mississippi Valley Graben. Unlike previous researchers, Nelson and Zhang (1991) proposed a passive rifting mechanism for the origin of the graben. In their model, continental breakup initiated tensional faulting and lithospheric thinning along the rift axis. On the basis of the seismic cross sections, the lateral rift extension was estimated at approximately 10 km. In their some-

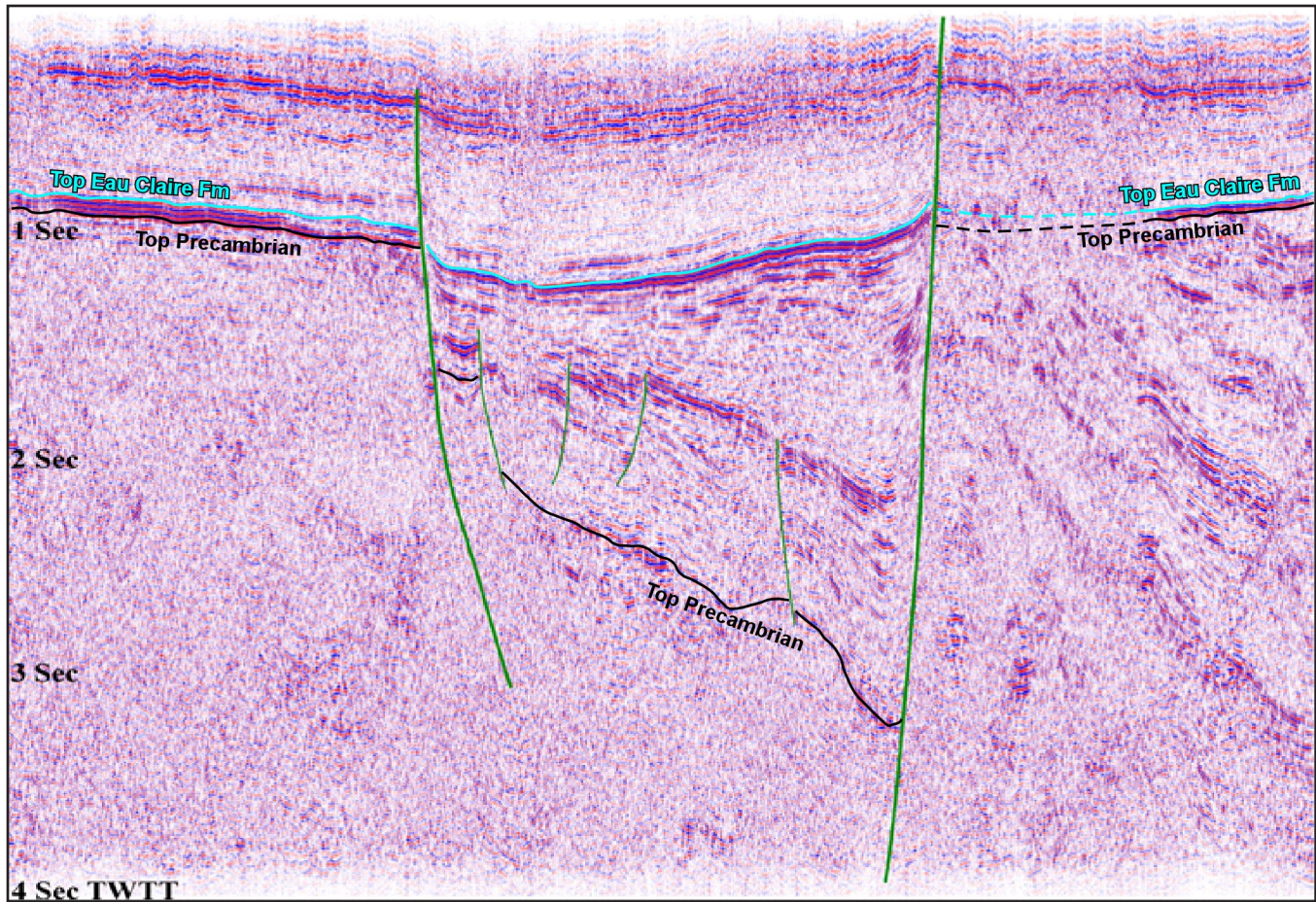


Figure 4. Simplified proprietary seismic profile across the Rough Creek Graben illustrating major offsets along basement faults (in green). Profile is approximately 100 km long, and north is to the right (Hickman, 2011).

what controversial interpretation, the location and orientation of the rift axis is related to a preexisting suture fault, formed from a northwest offset in the Grenville Front (from south-central Tennessee). This differs from the conclusion of Thomas (2006) that the Grenville Front extends southwest to the Alabama-Oklahoma Transform Fault (Thomas, 1991) in central Mississippi and curves northwest to the north of the Llano Uplift in northeastern Texas. Thomas (1991, 1993) interpreted the formation of the Mississippi Valley Graben as a product of the extensional tectonics associated with the separation of the Ouachita Rift and the associated movement along the Alabama-Oklahoma Transform. In this analysis, during the Early Cambrian, the Alabama-Oklahoma Transform connected the active Ouachita and mid-Iapetus rifting zones that led to the separation of Laurentia from Amazonia, opening the Iapetus Ocean.

The axis of the Mississippi Valley Graben extends southwest from westernmost Kentucky to east-central Arkansas and northwestern Mississippi, beneath the leading edge of the Ouachita Allochthon (Thomas, 1993). 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). Sediments penetrated by the existing deep wells 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).

## Depositional History

### *Precambrian*

Two Precambrian crystalline basement provinces (Grenville and Eastern Granite-Rhyolite) and the clastic Middle Run Formation lie below the Paleozoic strata in the study area (Bickford and oth-

ers, 1986; Potter and Carlton, 1991; Shrake, 1991; Harris, 2000). The metamorphosed rocks of the Grenville Province lie beneath the Appalachian Basin, east of the aeromagnetic and gravity lineament called the Grenville Front that roughly follows the Cincinnati Arch through east-central Tennessee, central Kentucky, and west-central Ohio.

The basement beneath the Paleozoic sediments west of the Cincinnati Arch is composed of felsic igneous rocks of the early Mesoproterozoic Eastern Granite-Rhyolite Province (Bickford and others, 1986; Pratt and others, 1989). The calculated age (U/Pb) of these rocks is  $1,470 \pm 30$  Ma (Van Schmus and others, 1996). In some parts of Indiana, Kentucky, and Ohio, the igneous rocks of the Eastern Granite-Rhyolite Province are overlain by the sandstones and conglomerates of the Middle Run Formation. Zircon analysis suggests that the Middle Run Formation is contemporaneous with the Grenville Orogeny, and is probably a foreland basin deposit of the Grenville (Hauser, 1993; Cawood and others, 2007; Bowersox and Williams, 2014).

Well samples from the Grenville Province have been dated (Rb/Sr, K/Ar, and zircon U/Pb) as middle Proterozoic; ages range from 1,060 to 890 Ma (Lidiak and others, 1966; Van Schmus and Hinze, 1985; Lucius and Von Frese, 1988). These rocks contain a variety of gneisses and schists (both metasedimentary rocks and meta-igneous rocks), as well as granite, rhyolite, and anorthosite intrusions (Ammerman and Keller, 1979).

### **Early Cambrian**

Following the collision between Laurentia and Amazonia and the subsequent emplacement of the Grenville Province (1.3–0.9 Ga) until at least the Early Cambrian, regional erosion was extensive, leading to a continent-wide unconformity at the base of the Paleozoic section (Sloss, 1988). Ocoee Supergroup synrift rocks that fill the Blue Ridge Rift of the Appalachian Basin to the east on the southeastern edge of Laurentia are latest Precambrian in age (Thomas, 1991; Walker and Driese, 1991) and mark the youngest possible date for the initiation of the breakup of Rodinia. As active rifting was ending in the Blue Ridge Rift at the beginning of the Cambrian, synrift volcanic rocks were being emplaced within the Southern Oklahoma

Fault System (Ham and others, 1964; Thomas, 1991). These diachronous rifting ages suggest that the active spreading center in southern Laurentia shifted northwest from the Blue Ridge Rift to the Ouachita Rift in southern Oklahoma and eastern Texas at the end of the Neoproterozoic Era, initiating sinistral displacement along the Alabama-Oklahoma Transform Fault (Thomas, 1991, 2006). This northwestward shift in the continental spreading center also correlates to the approximate age of the initial normal faulting that would produce the Rome Trough, Rough Creek Graben, and Mississippi Valley Graben (Hickman, 2011). As indicated by thickness changes across the respective boundary fault systems, major subsidence and horizontal extension in the Rome, Rough Creek, and Mississippi Valley Graben systems began as early as the Early Cambrian and had ended prior to the middle Late Cambrian Period (Houseknecht, 1989; Thomas, 1991, 1993; Shumaker and Wilson, 1996; Harris and others, 2004; Hickman, 2011).

In the Early–Middle Cambrian, average sea level gradually rose (Fig. 3), flooding these graben systems and leading to deposition of thick, arkosic synrift siliciclastic successions (Weaverling, 1987). The sediments that compose the Reelfoot Arkose (Mississippi Valley Graben and Rough Creek Graben) and the Rome Formation (Rome Trough) are the lithic detritus that was eroded from the uplifted igneous and metamorphic basement rocks that surround these grabens (Ammerman and Keller, 1979; Weaverling, 1987; Houseknecht, 1989; Harris and others, 2004). The Rome Formation is present below much of the southeastern United States, but is thickest (up to 3,400 ft) in the synrift section of the Rome Trough (Harris and others, 2004). The Rome Formation is absent northwest of the Rome Trough, and does not extend across the Kentucky River Fault Zone in Kentucky or the Ohio River Fault Zone in eastern Ohio and western West Virginia.

Although few wells in the Rough Creek Graben and northern Mississippi Valley Graben have been drilled deep enough to penetrate the Reelfoot Arkose, proprietary reflection-seismic data suggest that this unit is present across most of the Rough Creek Graben west of Green County, Ky., and throughout the northern part of the Mississippi Valley Graben. This is a clastic fluvial fan-type de-

posit and represents the first synrift deposition in the Rough Creek and Mississippi Valley Grabens (Weaverling, 1987). This unit has a similar lithologic composition and occupies a similar stratigraphic position as the late Early Cambrian Rome Formation in the Rome Trough to the east (Harris and others, 2004). Unlike in the Rome Trough, in the Rough Creek Graben or Mississippi Valley Graben there is no evidence of Shady Dolomite or upper Chilhowee Formation equivalent units. Different facies of time-equivalent units may be present, but no Early Cambrian fossils have been described or rocks radiometrically dated in these grabens to date.

### **Middle Cambrian**

By the late Middle Cambrian (Shaver, 1985), relative sea level across the region had risen to the point that the entire area was covered by a shallow sea. Middle-Late Cambrian deposition of the Eau Claire Formation in the Rough Creek and Mississippi Valley Grabens (Palmer, 1962; Collins and others, 1992; Collins and Bohm, 1993; Mitchell, 1993) and the Conasauga Group in the Rome Trough (Palmer, 1971; Harris and others, 2004) consisted of low-energy siltstones and shales, punctuated by episodic carbonate deposits, suggestive of a slowly subsiding basin margin.

The Conasauga Group is subdivided into six members, not all of which are present everywhere across the study area. These members (from oldest to youngest) are the Pumpkin Valley Shale, Rutledge Limestone, Rogersville Shale, Maryville Limestone, Nolichucky Shale, and Maynardville Limestone. The oldest three formations in the Conasauga Group (Pumpkin Valley Shale, Rutledge Limestone, and Rogersville Shale) are largely absent on the shallower shelf north of the Irvine-Paint Creek Fault System (Fig. 2) on the northwest side of the Rome Trough, where the Maryville Limestone unconformably overlies the Rome Formation. This unconformity is named the Pre-Conasauga Unconformity (Harris and others, 2004). The Conasauga Group overlies older rocks to the north, so that only the Maryville Limestone, Nolichucky Shale, and Maynardville Limestone are present in Ohio. The Mount Simon Sandstone is time-equivalent to the lower Maryville Limestone to the east and south. Although there are similar clastic-to-

carbonate horizons in the Eau Claire Formation of the Rough Creek and Mississippi Valley Grabens, no formal submembers have yet been defined.

### **Late Cambrian**

By the Late Cambrian, tectonic subsidence of the Rough Creek Graben, Mississippi Valley Graben, and Rome Trough had ended (Thomas, 1991, 1993; Harris and others, 2004). Sedimentation had filled these grabens to the point that no topographic or bathymetric relief remained across these structures (Harris and others, 2004). Clastic deposition was replaced by a regional carbonate platform that covered much of eastern Laurentia and lasted for more than 25 million yr (Sloss, 1988; Derby and others, 2012). The Late Cambrian–Early Ordovician Knox Supergroup overlies the synrift strata throughout the entire region (Schwalb, 1982; Shaver, 1985; Noger and Drahovzal, 2005). The Knox is a platform to passive-margin succession, composed predominantly of carbonate rocks (mostly dolomite), with minor amounts of mature, quartz-rich sandstones.

### **Tectonic Effects on Cambrian Strata in Southeastern Laurentia**

The Cambrian rift-filling sediments of the Rome Trough, Rough Creek Graben, and Mississippi Valley Graben have been subjected to numerous episodes of both near- and far-field tectonic loading and deformation. In addition to the syndepositional west-northwest to east-southeast (present-day orientation) tension during the breakup of Rodinia, the Cambrian rocks and geologic structures in this area were also exposed to far-field tectonic compression during the Taconic Orogeny (east-west beginning in the Ordovician and rotating to east-northeast to west-southwest in the Silurian), Acadian Orogeny (northwest-southeast in the Devonian to earliest Mississippian), Alleghenian Orogeny (east-west in Mississippian to Permian), and Ouachita Orogeny (south-southwest to north-northeast in the Pennsylvanian to Permian) (Hickman, 2011). These later tectonic events (especially the Alleghenian and Ouachita Orogenies) reactivated some of the rift-related basement faults with wrench or high-angle reverse fault movements. These fault movements further complicated the already complex structural array of subsurface basement faults in the rift graben system and pro-

duced localized areas of structural inversion. This is most readily observable along the south side of the Rough Creek Fault Zone in western Kentucky, where the Mississippian and Devonian strata in many hanging-wall blocks are now structurally higher than those along the footwall side of the fault system (Fig. 5).

## Exploration History

### Rome Trough

Hydrocarbon exploration in Cambrian rocks in Kentucky, West Virginia, and Ohio dates back to the 1940s, when better drilling technology allowed deeper targets to be tested. For a complete list of wells with reported Cambrian sub-Knox hydrocarbon shows, see Harris and Baranoski (1996). Improved reflection-seismic techniques in the early 1960s helped encourage deep exploration in the

late 1960s and 1970s. Numerous deep tests were drilled by several major companies and medium-size independents. Seven wells have been drilled to depths greater than 15,000 ft, with the deepest well reaching 20,222 ft (the Exxon No. 1 Gainer-Lee well, Calhoun County, W.Va.). Although most deep wells reported oil or gas shows from the Cambrian section, very few encountered commercial volumes of hydrocarbons.

The first commercial production from Cambrian sub-Knox rocks occurred during this period with the completion of the Inland Gas No. 529 White well in Boyd County, Ky., in 1967. This well is reported to have produced about 30,000 bbl of oil. In 1975, Exxon completed the No. 1 McCoy well in Jackson County, W.Va., with an initial open flow of 9.2 MMcf/day. This was the first commercial gas well in the Rome Trough, and produced a total of

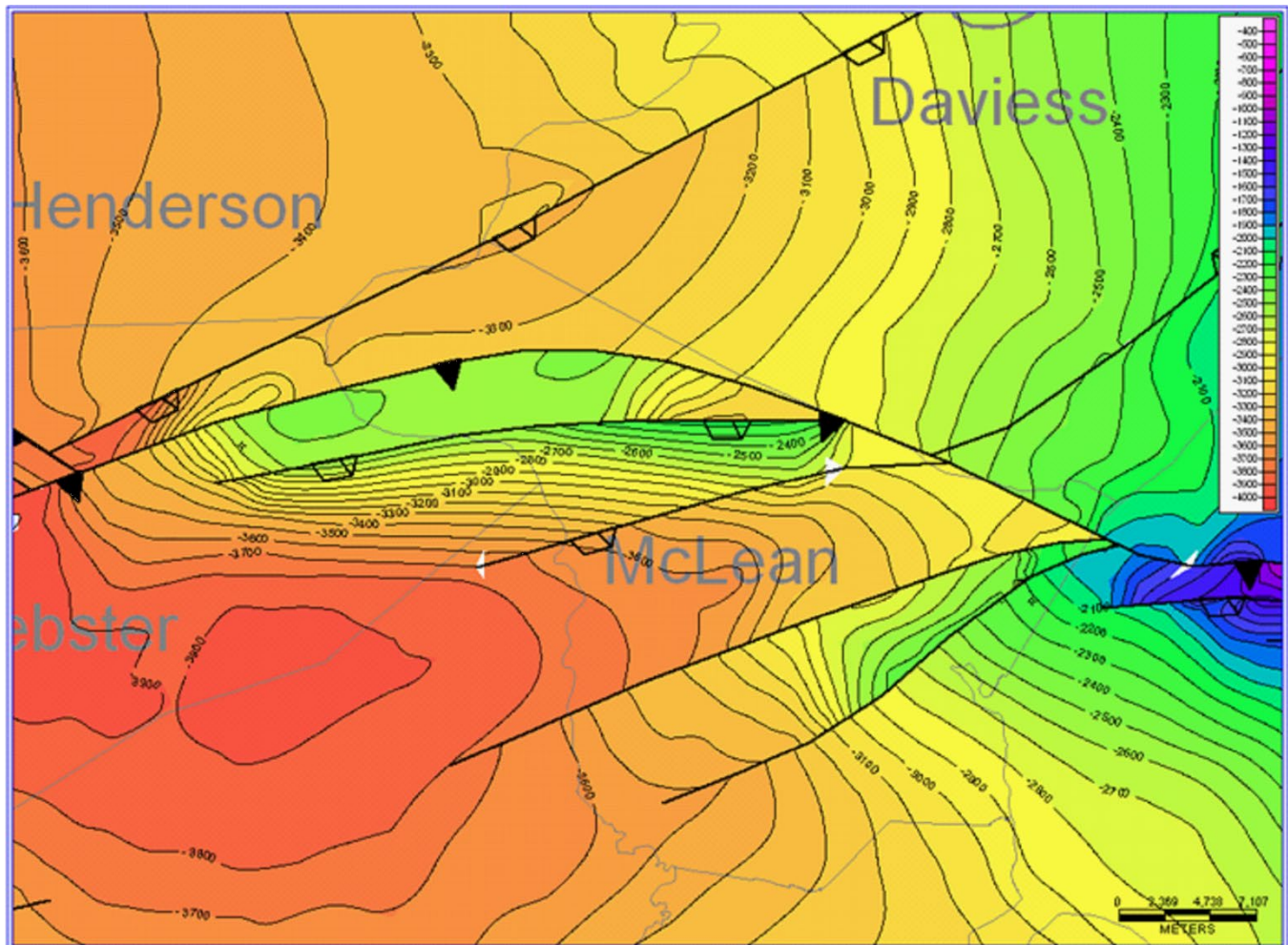


Figure 5. Structural inversion structures along the Rough Creek Fault Zone at the top of the New Albany Shale (Hickman, 2011). Contour interval is 100 ft; cooler colors are shallower and warmer colors are deeper. See Figure 1 for area location.

427 MMcf at a rate of 5.6 MMcf/day for approximately 6 mo (Harris and Baranoski, 1996). This well produced from a sandstone in the Maryville Limestone of the Conasauga Group, but was plugged after 6 mo because of increasing water production. About 10 yr later, Ashland Exploration completed a deep test in the Minefork Field in Johnson County, Ky. The Ashland No. 1 Williams well reported an initial open flow of 1.055 MMcf/day from fractured Nolichucky Shale at 6,250–6,350 ft.

In 1994, a second major phase of deep drilling to Cambrian targets in eastern Kentucky began after the discovery of gas in the Carson Associates 1 Kazez well in Elliott County, Ky. This discovery well of what was later named the Homer Field initially flowed 11 MMcf/day from a sandstone in the Maryville Limestone. This well produced at a rate of 500 Mcf/day for an unknown period. When the well was visited in 1999 for gas sampling, production had declined sufficiently for the well to be converted for use as a domestic gas supply. Since 1994, the Homer Field has been successfully developed with additional drilling. In 1998, Carson Associates made one additional gas discovery in the Rome Trough in Lawrence County, Ky. The Carson Associates 1 Ray well produces gas and condensate, also from the Maryville Limestone.

Research by the Kentucky, Ohio, and West Virginia geological surveys refined the stratigraphic framework of a Cambrian extensional basin underlying the Appalachian Basin in 2004 (Harris and others, 2004). Well-log correlations extended the Cambrian Conasauga Group north from outcrops along the Eastern Tennessee Overthrust, across parts of eastern Kentucky, and into the Rome Trough. Regional distribution of these formations and the underlying Rome Formation is controlled by extensional faults that were active during and after Conasauga deposition.

To identify the source of hydrocarbons produced from various Cambrian completions in eastern Kentucky and southern West Virginia, numerous Cambrian shale samples were analyzed from across the Rome Trough. Total organic carbon content of these shales was less than 1 percent for all samples, except for a core of Rogersville Shale from the Exxon No. 1 J.P. Smith well in Wayne County, W.Va. Shows of gas in the Rogersville interval were reported on the mud log from this well. TOC

for the Rogersville Shale in this core ranges from 1.2 to 4.4 percent, with  $T_{\max}$  values of 460 to 469°C. Six additional Rock-Eval analyses from the Smith core confirmed the original data, with TOC of 1.2 to 4.75 percent and  $T_{\max}$  of 446 to 460°C (Hickman and others, 2015). Low hydrogen indices and  $T_{\max}$  data indicate a thermal maturity in the wet gas-condensate window. The Rogersville Shale is a dark gray, fissile shale, interbedded with thin laminated and bioturbated siltstone. Hydrocarbon extracts from the Smith core (Fig. 6) are geochemically very similar to produced condensate from Elliott and Boyd Counties, Ky., and suggest the Rogersville was the source of gas and condensate in the Homer Field in Elliott County, Ky. (Ryder and others, 2005).

### ***Rough Creek and Northern Mississippi Valley Grabens***

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, Ky., 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 (Fig. 7).

In 1975, the Exxon Minerals Co. No. 1 Jimmy Bell well was drilled in Webster County, Ky. 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 in 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, Ky. The Duncan well was drilled 1.9 mi southwest (local strike of fault set approximately 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 well remains the deepest well drilled in Kentucky.



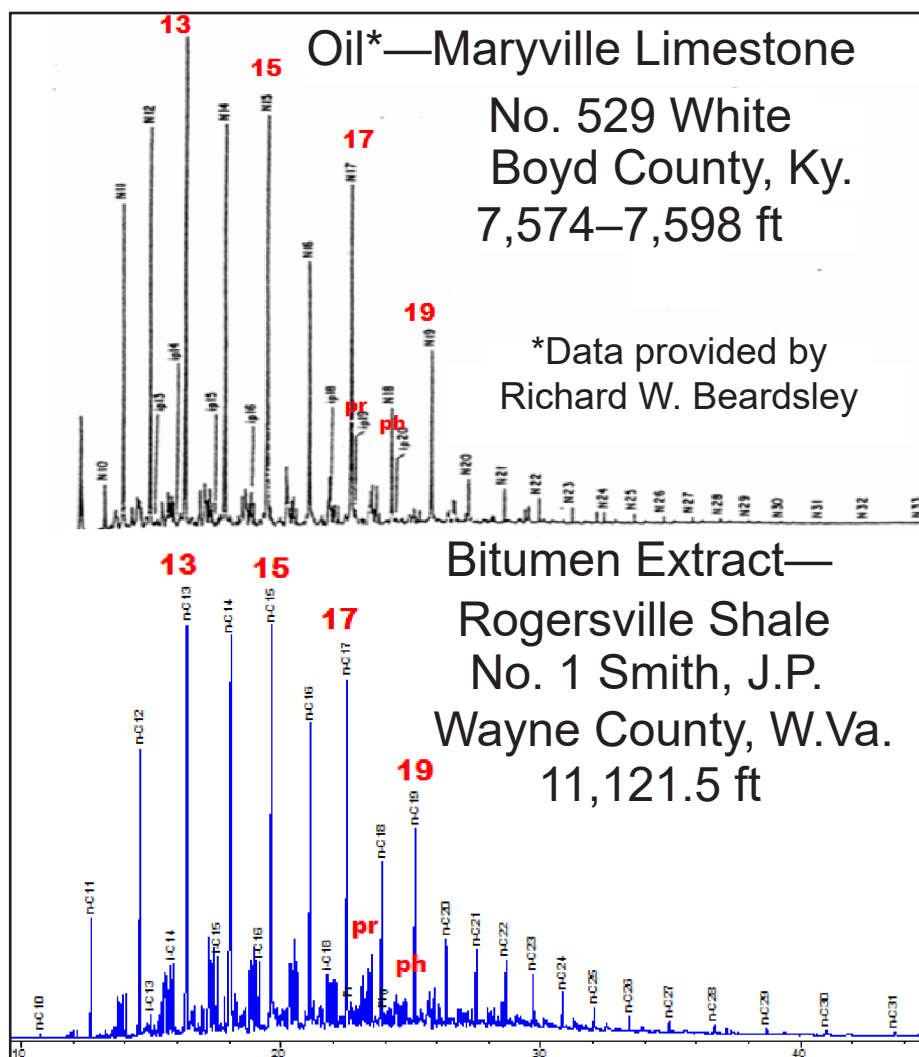


Figure 6. Comparison of gas chromatograph results from oil produced from the Conasauga Group Maryville Limestone in Boyd County, Ky. (top), with a bitumen extract from the No. 1 J.P. Smith core of the Conasauga Group Rogersville Shale (bottom) (Ryder and others, 2005).

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, Ky. This well was also different from the other deep tests in that the entire hole was drilled with an air-rotary drill rig. Sun was unable to log the entire well because of hole problems (the completion report notes 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 its 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, Ky. The Turner well was drilled about 1.8 mi south of the Rough Creek Fault Zone, near the intersection of the Central Fault System with the Rough Creek Fault System in easternmost McLean County, Ky. This basement test well targeted lower Eau Claire Formation carbonate shoal facies and clastic rocks of the Reelfoot Arkose. Although some oil staining and potential residual bitumen were discovered in core samples, all potential reservoir zones exhibited low porosity and permeability 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, Ky., 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. 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 prior to the third logging run, 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 de-

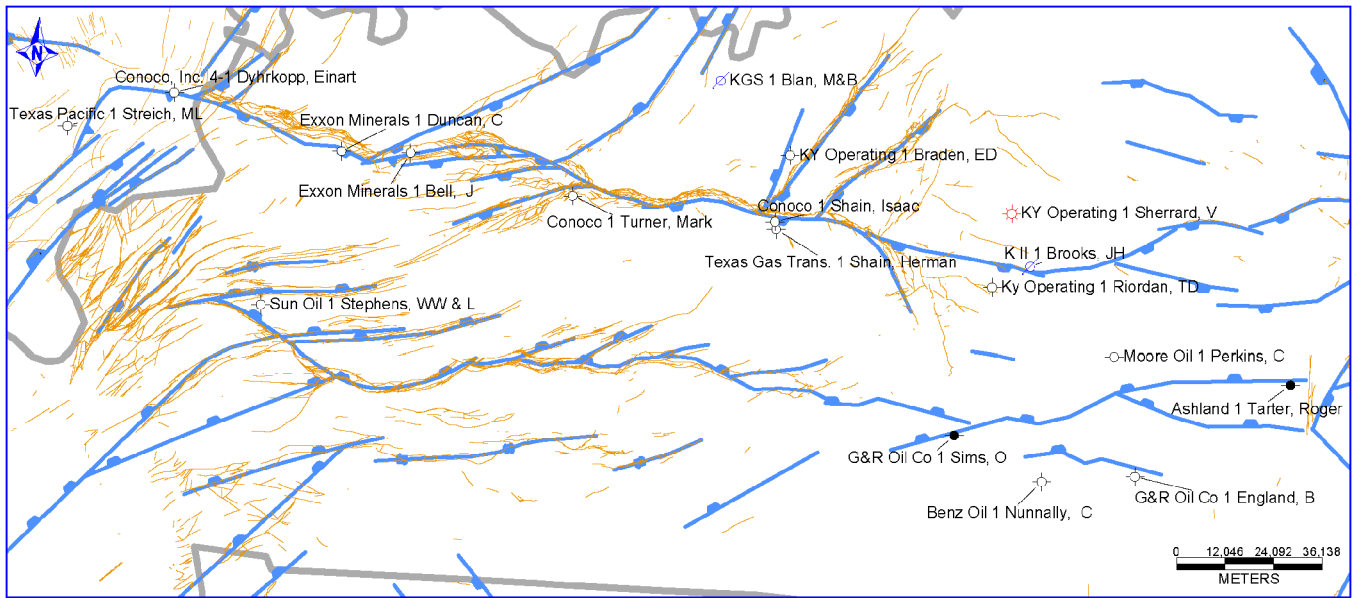


Figure 7. Deep wells in and surrounding the Rough Creek Graben. Interpreted basement fault systems are in blue (Hickman, 2011), surface faults in orange (U.S. Geological Survey data, available at [mrddata.usgs.gov/geology/state](http://mrddata.usgs.gov/geology/state)).

scription 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 Einhart Dyhrkopp well 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 in 1994. The 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 the Eau Claire Formation and 88 ft of the Reelfoot Arkose. As with the other two Conoco wells, this one was also dry and abandoned.

### Recent Exploration

Following the success of unconventional shale plays such as the Barnett and Marcellus in the early 2000s, oil and gas exploration companies began to reevaluate bypassed formations that had once been deemed unproductive using older completion techniques. Previous work (Harris and others, 2004) led to an interest in the Rogersville Shale of the Conasauga Group as a potential unconventional reservoir in addition to its role as a source rock. In early 2014, Bruin Exploration drilled the first well specifically targeting the Rogersville Shale in Law-

rence County, Ky. The official completion report for that well listed initial test rates of 19 bbl/day of oil and 115 Mcf/day of natural gas (at 200 psi back-pressure) produced from the Rogersville. After initial testing, the well was shut-in, at which time the pressure increased to 2,599 psi after 24 hours. Later in 2014, Cabot Oil and Gas drilled the No. 50 Amherst Industries Inc. well into the Rogersville Shale in Putnam County, W.Va. This well produced about 340 MMcf of gas between May 2015 and September 2017. In early 2015, Horizontal Technology Energy Inc. drilled the first horizontal well in the prospective play (No. 572360 EQT Production Co.) in Johnson County, Ky. At the time of this writing, Bruin Exploration is drilling its second Rogersville well, a horizontal test, the No. 1 Walbridge Holdings LLC, in Lawrence County, Ky. The presumed success of these wells has initiated a localized leasing boom in Lawrence, Johnson, and Magoffin Counties, Ky. Between January 2014 and June 2015, 3,863 Rogersville leases were signed in those counties (Cate, 2015).

## Source Rocks in Rift System

Thousands of vertical feet of clastic sediments were deposited in the Rome Trough–Rough Creek–Mississippi Valley rift graben system, much of it as shales or argillaceous limestones. Although every foot has obviously not been sampled, numerous

individual samples from most of the correlatable shale or shaly units have been analyzed for total organic carbon content. Although various units in the Mississippi Valley–Rough Creek–Rome Trough intracratonic rift system have produced single samples of “source grade” material, the only Cambrian unit that has repeatedly returned TOC values greater than 1 percent (minimum needed to become an effective hydrocarbon source rock) to date is the Rogersville Shale of the Conasauga Group in the Rome Trough in eastern Kentucky and southern West Virginia. A total of 37 samples of Rogersville Shale, processed and analyzed by four different laboratories, returned source-grade values of up to 4.4 percent TOC (Ryder and others, 2005; Hickman and others, 2015). Most of these samples are from the Exxon No. 1 J.P. Smith cores, but organic-rich samples from well cuttings in the Rogersville Shale were also derived from the Ashland No. 1 Williams well in Johnson County, Ky.

### **Rogersville Shale of the Conasauga Group, Rome Trough**

The Cambrian Conasauga Group extends across parts of eastern Kentucky and includes, in ascending order, the Pumpkin Valley Shale, Rutledge Limestone, Rogersville Shale, Maryville Limestone, Nolichucky Shale, and Maynardville Limestone. Most fault movement had ceased and the trough was filled by the end of Conasauga time. The trough is overlain by the Cambrian–Ordovician Knox Group, a thick, regional, carbonate platform sequence. Regional distribution of these formations and the underlying Rome Formation is controlled by extensional faults that were active during Conasauga deposition.

Stratigraphic well-log correlation of Cambrian synrift strata reveals the presence of a west-prograding carbonate ramp and distal intrashelf shale basin in the Rome Trough in eastern Kentucky. The Conasauga formations record several cycles of progradation and transgression from east to west into this basin. The full sequence of Conasauga formations is restricted to areas south of the Irvine–Paint Creek Fault. North of this fault, the Pumpkin Valley Shale, Rutledge Limestone, and Rogersville Shale are missing, and the Maryville Limestone overlies the Rome Formation. Maryville and Rutledge carbonate units thin and pinch out

to the west into an intrashelf basin in central Kentucky. The Rogersville Shale cannot be recognized in the westernmost Rome Trough (Harris and others, 2004).

In 1974, Exxon drilled its No. 1 J.P. Smith well in Wayne County, W.Va. Whole cores were taken during the drilling of this 14,625-ft-deep basement test, two of which (cores 3 and 4) were from the Rogersville (11,135–11,201 ft). These cores are mostly composed of dark gray, fissile shales with fine-grained sandstone laminae. Trilobite and lingulid brachiopod fossils are common, along with indications of burrowing and tidal currents. These features, along with the presence of glauconite, suggest that the Rogersville Shale was deposited in a near-shore, shelf to upper ramp marine environment (Harris and others, 2004). At this time, these cores from the Exxon No. 1 J.P. Smith well are the only Rogersville Shale cores available in the public domain (for more information, contact the West Virginia Geological and Economic Survey, [www.wvgs.wvnet.edu](http://www.wvgs.wvnet.edu)).

### **Source-Rock Potential of the Rogersville Shale**

In the Exxon No. 1 J.P. Smith cores, organic matter in the Rogersville Shale consists of amorphous marine algal macerals and solid bitumen (Hickman and others, 2015). Although no vitrinite is present in Cambrian rocks, bitumen reflectance ( $BR_o$ ) in the Smith cores was measured at the Kentucky Geological Survey. The calculated equivalent vitrinite reflectance ( $R_o$ ) values using the method from Jacob (1989) are 1.49–1.54, within the wet-gas generation window (Table 1). Spectral fluorescence ( $\lambda$ ) for these samples was also measured, which yielded results of 638–648 nm, or about 1.35–1.45  $R_o$  equivalent (slightly lower than  $BR_o$ , but also within the wet-gas window). Fluorescent liptodetrinite is also present, despite the depth and thermal maturity of the shale in the Exxon No. 1 J.P. Smith core.

Oil and condensate from Cambrian reservoirs in Kentucky have a unique composition that is characteristic of Ordovician (and older?) source rocks containing the alga *Gloeocapsomorpha prisca*. Gas chromatographs show that odd-carbon normal alkanes ( $C_{13}$ – $C_{19}$ ) are more abundant than even alkanes (Reed and others, 1986; Jacobson and others, 1988; Fowler, 1992; Guthrie and Pratt, 1995). This

**Table 1.** Results of bitumen reflectance and spectral fluorescence analyses from four separate core depths in the Exxon No. 1 J.P. Smith well in Wayne County, W.Va.

<b>API #4709901572</b>				
<b>Exxon #1 J.P. Smith</b>				
<b>Wayne County, W.Va.</b>				
<b>Rogersville core "discovery" well</b>				
<b>Bitumen Reflectance</b>				
Core Depth (ft, md)	11,167	11,178	11,191	11,197
Average $R_o$ Random	1.76	1.80	1.80	1.84
Maximum $R_o$ Random	2.11	2.11	2.04	2.10
Minimum $R_o$ Random	1.50	1.47	1.53	1.59
Standard Deviation	0.14	0.16	0.13	0.13
Observations/Sample	50	50	50	50
Calculated $R_o$ Equivalent ( $R_o$ random $\times$ 0.618) + 0.4 (Jacob, 1989)	1.49	1.51	1.51	1.54
Indicated $T_{max}$ from calculated $R_o$ equivalent	480	482	482	484
<b>Spectral Fluorescence</b>				
Core Depth (ft, md)	11,167	11,178	11,191	11,197
$\lambda$ Maximum	638	648	648	645
Indicated $R_o$	1.35	1.45	1.45	1.45
Indicated $T_{max}$ from $\lambda$ Maximum	473	479	479	479

odd-carbon predominance was also seen in bitumen extracted from the Rogersville Shale (Ryder and others, 2005) in the Exxon No. 1 J.P. Smith core (Fig. 6). This similarity strongly suggests correlation of the Rogersville with produced hydrocarbons, and defines a Cambrian petroleum system in the Rome Trough. No identifiable *Gloeocapsomorpha prisca* microfossils were observed in the core samples, however.

The Rogersville Shale ranges in thickness from under 100 to more than 1,100 ft (Fig. 8), and in depth from approximately 5,000 to 18,000 ft below the surface (Fig. 9). Well data and analysis of well samples (cuttings and core) indicate that the Rogersville Shale potentially has suitable thickness, mineralogy, and organic content to produce gas or liquids if fracture-stimulated to improve permeability. X-ray diffraction analysis of Rogersville Shale samples shows mineralogy that is low in clay content and high in brittle minerals, such as carbonate and quartz. This suggests that the Rogersville will be more susceptible to fracture stimulation than the shallower Nolichucky Shale, which has more ductile clays and less carbonate. Challenges in developing a Rogersville Shale play include interpreting structure and stratigraphy in the deeper fault-segmented parts of the Rome

Trough and predicting the distribution of organic-rich intervals.

### **Source-Rock Potential in the Rough Creek and Mississippi Valley Grabens**

Relatively few wells have been drilled in the Rough Creek and Mississippi Valley Grabens deeper than the Upper Cambrian-Lower Ordovician Knox Group, unlike in the Rome Trough. Of the 10 deep wells in the Rough Creek Graben, only three penetrate the Precambrian (base of rift sequence) and all are in the structurally complex Rough Creek Fault Zone along the northern edge of the structure and not in the deeper areas toward the center of the graben. The Kentucky Geological Survey has the results from 50 analyses of the Cambrian Eau Claire Formation, the Conasauga Group equivalent in the Rough Creek Graben, sourced from eight of the 10 deep wells (Hickman, 2014). Only one sample of that set of 50 had TOC content above 1 percent (cuttings from the Exxon Minerals No. 1 C. Duncan well, Webster County, Ky., at 12,510–12,520 ft depth).

Although these organically lean values are not encouraging for exploration companies, they could be an instance of nonrepresentative sampling because of the locations of existing wells. Current

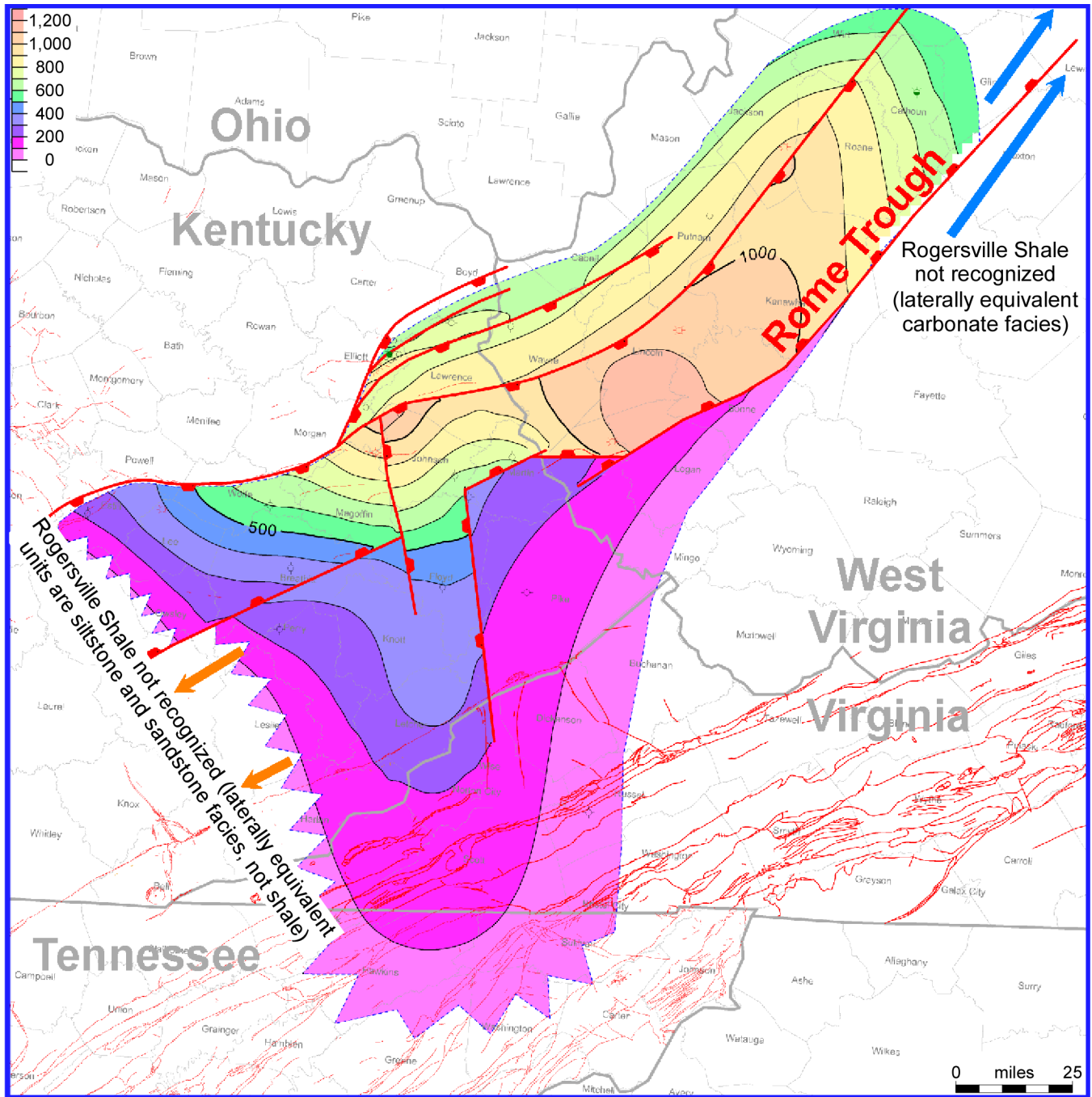


Figure 8. Generalized subsurface thickness of the Rogersville Shale. Contour interval is 100 ft. Basement faults in bold red.

wells are drilled either along the structurally complex margins of the graben, or do not penetrate very far into the Eau Claire Formation (Fig. 7). If the Eau Claire Formation in the Rough Creek Graben is the lateral equivalent of the Conasauga Group, and the adjacent rift basins had similar paleoenvironments and water depths (which they appear to have had), then accumulations of similar algae-based organic

material would be expected in the Eau Claire, but no such accumulations have been encountered during exploration. The organic parts of the Rogersville Shale core in the Exxon No. 1 J.P. Smith well are found starting at a depth of 11,139 ft, which is 2,773 ft, or 71 percent, down into the Conasauga Group rocks. Reflection-seismic analysis suggests that the Eau Claire Formation is up to 10,000 ft thick

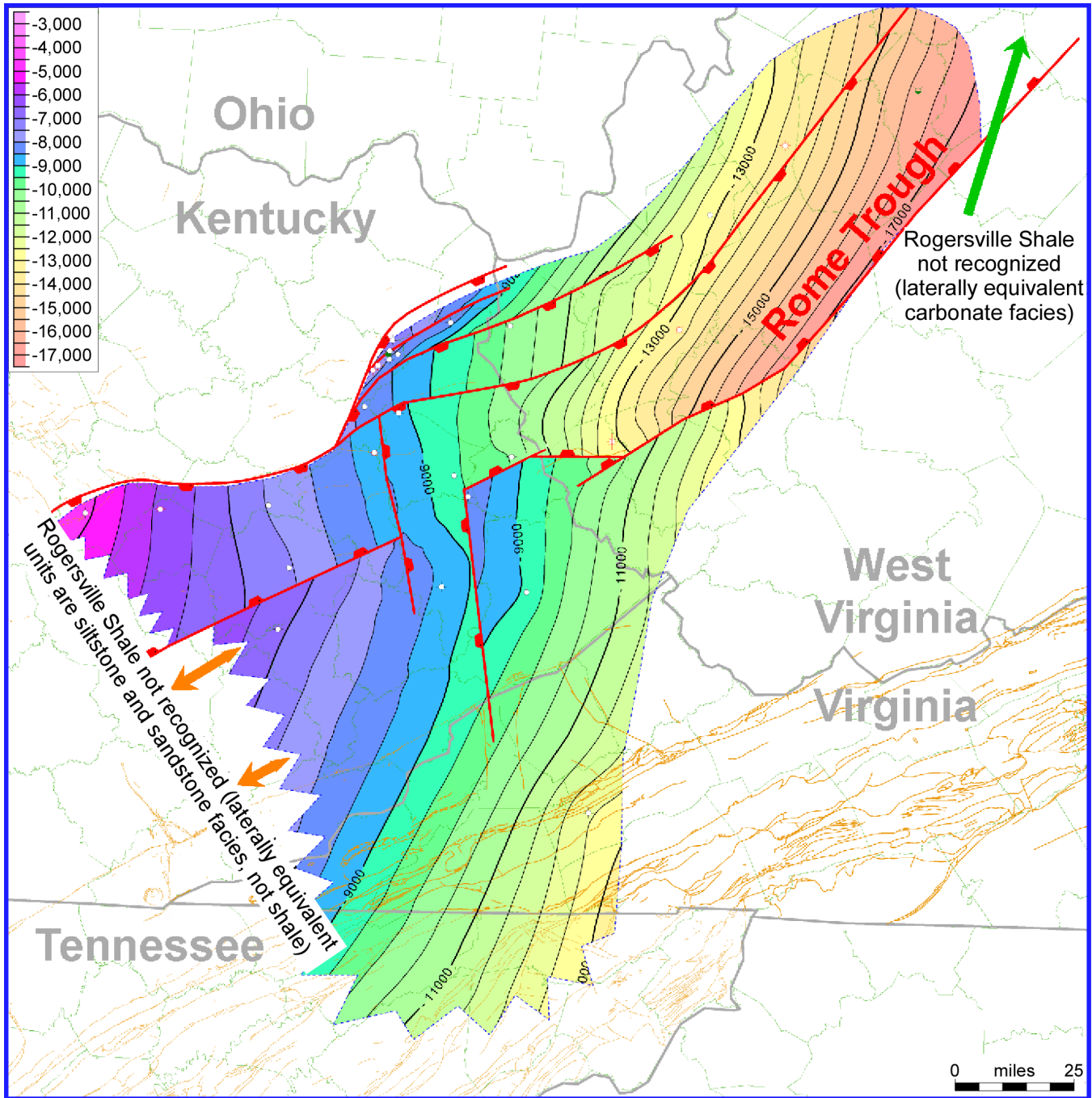


Figure 9. Generalized subsurface structure of the Rogersville Shale. Contour interval is 500 ft. Elevations in feet above MSL. Major basement faults in bold red.

in the center of the Rough Creek Graben (Hickman, 2011). The only well drilled away from the margins of the graben is the Sun Oil Co. No. 1 Stephens, W.W. & Lillie M. well in Caldwell County, Ky. This well did penetrate 566 ft of the Eau Claire, which represents only 14 percent of the overall Eau Claire thickness calculated from reflection-seismic data at

that location (about 4,000 ft), however. A unit similar to the Rogersville Shale may be present in the Rough Creek Graben, but no wells have penetrated it, or none of those footages were tested for organic content while sampling.

Similar to the Rough Creek Graben, in the Mississippi Valley Graben only 10 wells have been



Trough has the potential to produce both gas and liquid hydrocarbons from at least some areas in the rift. Whether it will contain enough volume to become a commercial success is unclear. Given that all three rift segments had similar water depths, paleolatitudes, paleoenvironments, and sediment deposition, it is reasonable to assume that the marine algae that is the source of the Rogersville organic material may have also been present in the Rogersville-equivalent sediments in the Mississippi Valley and Rough Creek Grabens as well. No organic-rich geologic samples from the Cambrian section in those grabens have been identified to date, however.

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