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Major Lower Paleozoic Horizons of the Southern Illinois Basin

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Statement of Benefit to Kentucky

Data on Lower Paleozoic rocks of the southern Illinois Basin were compiled to produce a single, comprehensive set of structural interpretations of eight stratigraphic horizons: the top and base of the New Albany Shale, top and base of the Maquoketa Shale, top of the Knox Supergroup, top of the Eau Claire Formation, top of the Reelfoot Arkose, and top of Precambrian basement rocks. This report will be of value for water-well drillers, oil and gas exploration companies, waste-disposal companies, miners, and others involved in subsurface geological studies.

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Abstract

The geology exposed at the surface in the southern Illinois Basin has been mapped in great detail by countless workers over the past century. With the exception of limited and scattered exposures in incised river valleys, the oldest rocks exposed outside of the Jessamine, Nashville, and Ozark Domes surrounding the Illinois Basin are Mississippian in age. Extensive deposits of Cambrian–Devonian sediments occur in the subsurface above crystalline basement in this region, however. All available data for the region were analyzed to produce a single, comprehensive set of interpretations. The data used in this study include 1:24,000-scale geologic quadrangle maps, oil and gas well data from 1,764 wells, more than 900 mi of proprietary reflection-seismic profiles, and public-domain potential-fields data (gravity and aeromagnetic surveys). The data were used to interpret the structure of eight stratigraphic horizons in the subsurface: 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 basement rocks.

Introduction

This report is the result of incorporating numerous types of data into a single, comprehensive interpretation. The study area extends west from the Cincinnati Arch in central Kentucky to the Ozark Dome in eastern Missouri, and north from the Nashville Dome in western Tennessee to north of Cincinnati in Monroe County, Ohio (UTM zone 16N coordinates 3,986,800–4,350,000 m northing and 240,000–720,000 m easting). All maps in this report are displayed in universal transverse Mercator zone 16 north projection, on a 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. Imperial units were used for Z elevations instead of metric units because all of the well data (mudlogs, geophysical well logs, etc.) were recorded in feet.

These maps incorporate stratigraphic tops data from 1,764 wells across the Illinois Basin and adjacent regions (Fig. 1), including 489 wells with Early Ordovician and older units. Using available geophysical well logs, drillers' logs, and core or cuttings descriptions, stratigraphic tops were picked for the major mapped horizons, as well as several secondary horizons useful for local correlations. In addition to the well data, 106 seismic-reflection profiles totaling more than 900 mi from western Kentucky, southern Indiana, southern Illinois, and northwestern Tennessee were used (Fig. 2). These data were compiled by the Kentucky Geological Survey from numerous sources over the past 20 yr (Plate 1, Fig. 2). All of the data used are proprietary, except for KGS data from Hancock County, which were acquired as part of the Survey's ongoing carbon sequestration research. Synthetic seismograms were produced using bulk-density and sonic logs from several deep wells that are close to one or more 2-D seismic lines that are part of the KGS inventory. After the seismic wavelet character and estimated travel times were matched, these seismograms facilitated the correlation of the major stratigraphic tops onto seismic lines (Fig. 3). These seismic tops were then interpreted as far as possible across the seismic lines.

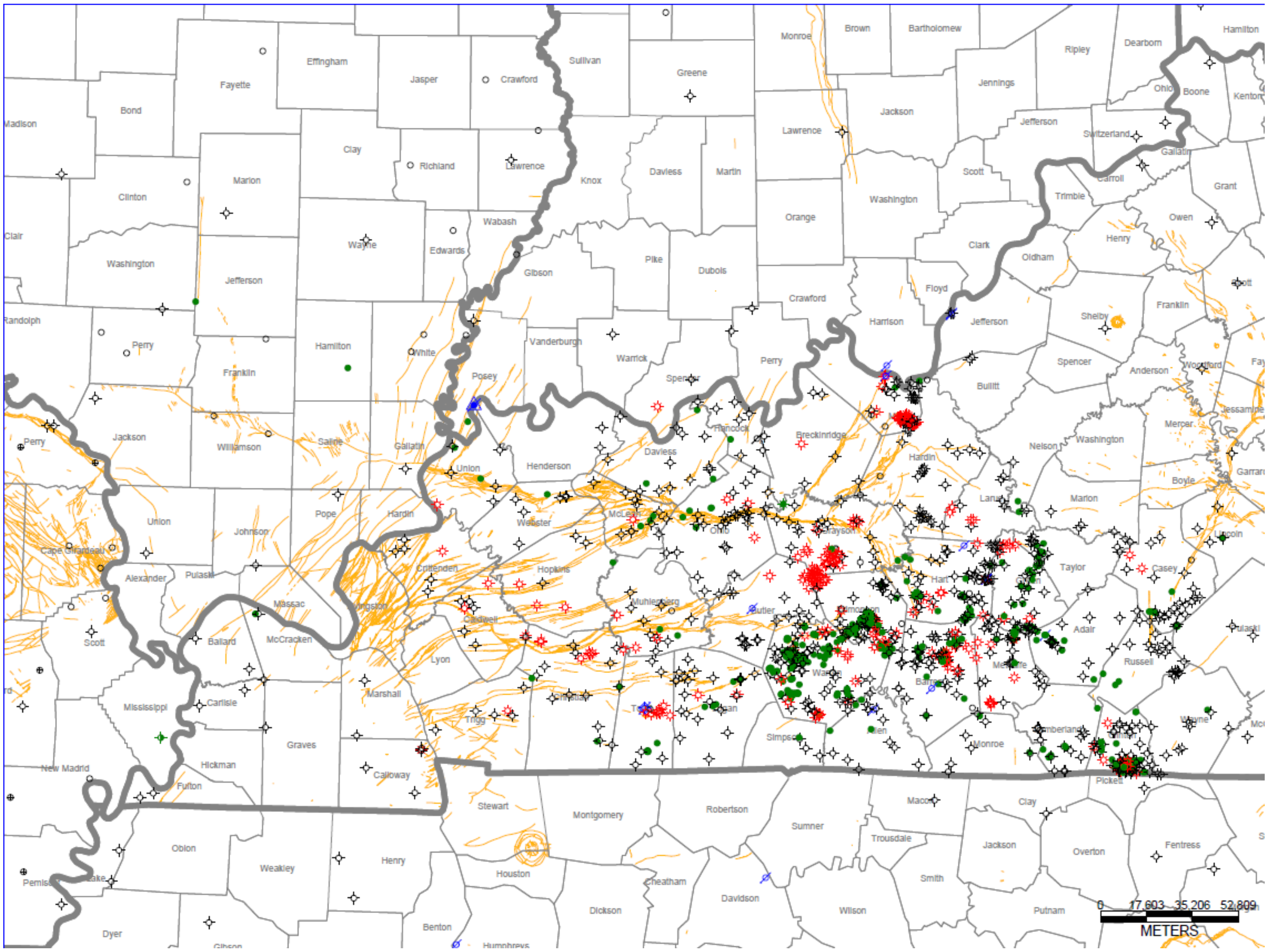

Figure 1. Locations of wells with interpretations of stratigraphic tops. Mapped surface faults are in orange, gas wells are in red, oil wells are in green, injection wells are in blue, and dry (abandoned) wells are in black.

Seismic Data Analysis

Using the Petra[1] family of mapping, petrophysical, and seismic software from IHS/GeoPlus Inc., average surface-to-horizon velocities were computed from the elevations of the mapped tops from wells and the time horizons from the seismic data (Table 1). 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 (or both) 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 location 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 above method worked well outside of the rift grabens, where wells drilled to basement are more common and seismic horizons are shallower than 1 s (two-way travel time). For the deeper horizons in the graben, limited well penetrations meant more uncertainty in velocity calculations (and therefore subsea depth calculations). A dif-

[1]Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the Kentucky Geological Survey.

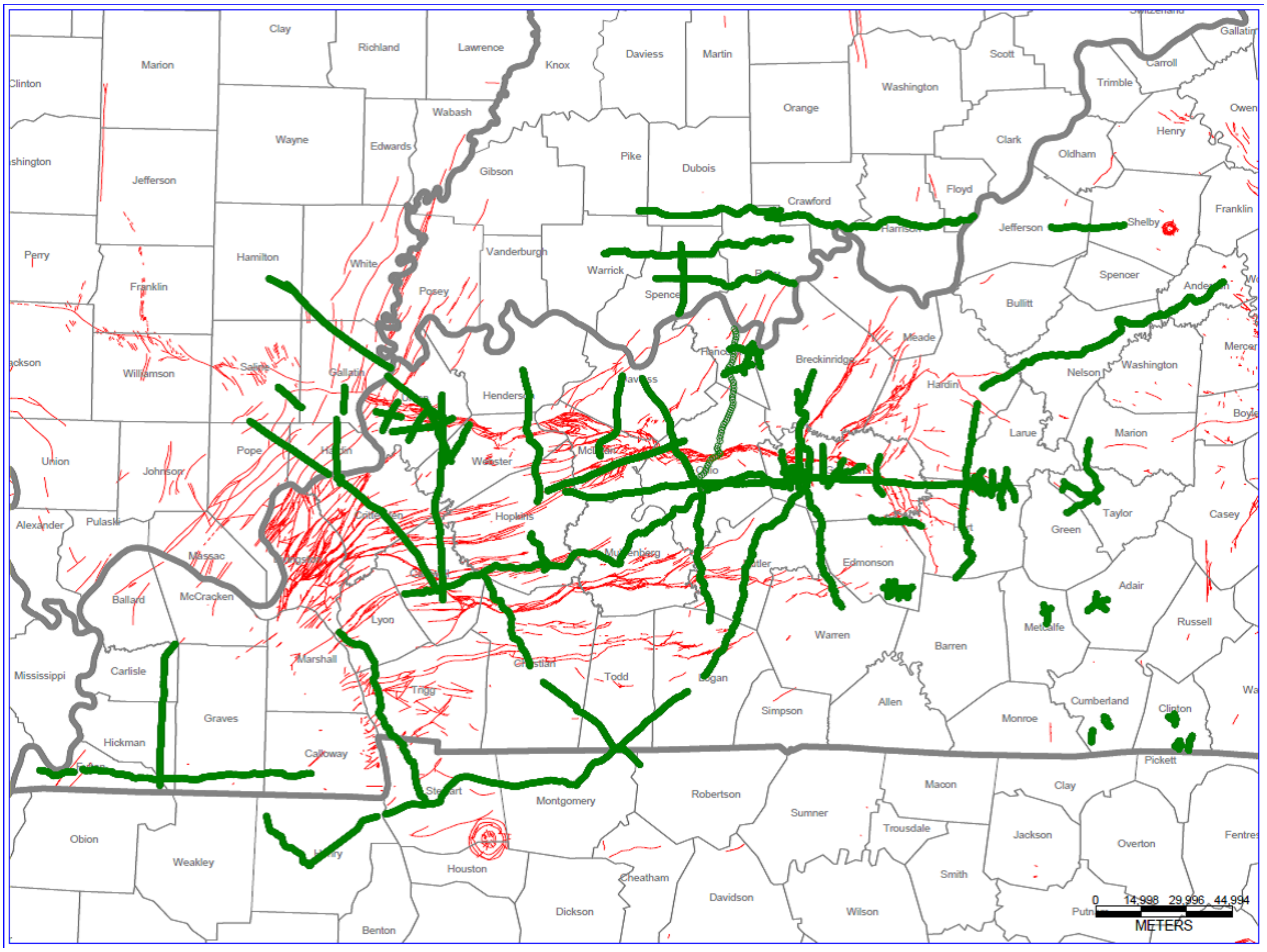

Figure 2. Locations from which reflection-seismic profile data used in this project were acquired (bold green lines).

ferent technique was used to produce maps for 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 thickness calculations below the Eau Claire Formation. Published normal moveout velocities (hyperbolic approximation of the travel-time curve calculated as part of the seismic processing sequence) in a Dix equation layered sequence were used to calculate interval velocities for seismic intervals that had been interpreted as the Eau Claire Formation and the Reelfoot Arkose:

$$V^2_{int(n)} = \frac{V^2_{rms(n)}\, t_{0(n)} - V^2_{rms(n-1)}\, t_{0(n-1)}}{t_{0(n\,1)} - t_{0(n-1)}}$$

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

This technique helped with depth calculations and for interpreting the lithology of deep geologic units.

This method was tested at a few chosen locations near deep wells with ample data and known subsurface lithologies. Interval velocities were then 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 (varying by area, processing company, etc.); seven to eight layers was the most common. Using these velocities, probable lithologies were estimated with the

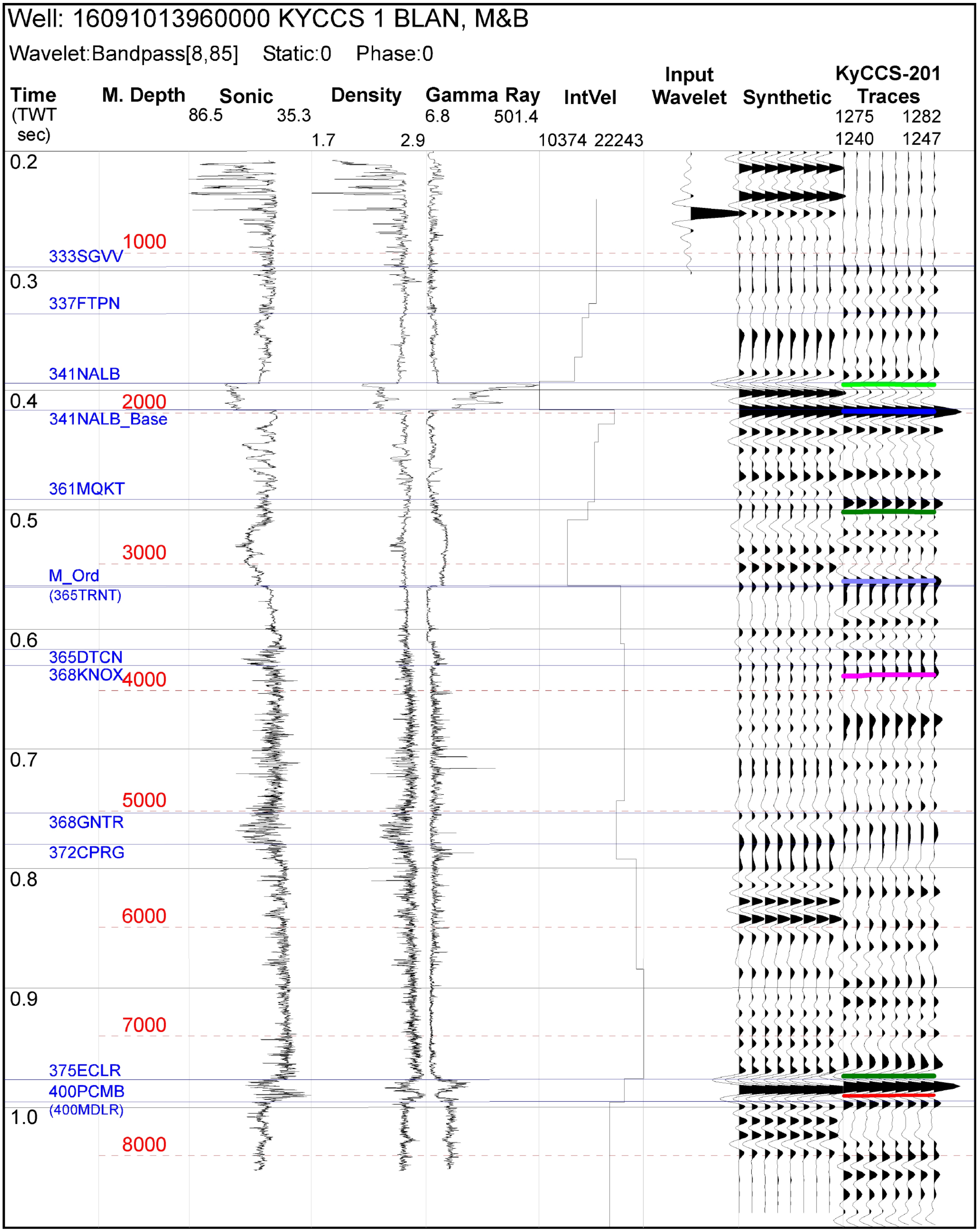

Figure 3. Synthetic seismogram for the KyCCS No. 1 Blan well, with extracted wavelets from the nearby L-201 seismic line. The colored lines on extracted L-201 traces are the interpreted time horizons of the mapped units (excluding the Reelfoot Arkose).

Table 1. Steps in stratigraphic and seismic correlation using Petra software.

1. Interpret stratigraphy from well records
2. Create synthetic seismograms from sonic and bulk-density logs.
3. Tie local stratigraphy to seismic-reflection time horizons.
4. Interpret all regional seismic profiles for tied horizons.
5. Calculate grid surface from seismic time horizons.
6. Use gridded seismic time values at well locations to calculate a datum-to-horizon two-way travel velocity for that location (top depth below seismic datum/TWTT).
7. Calculate grid surface from velocity points at wells.
8. Calculate measured depth grid (relative to seismic datum elevation) from horizon time (step 5) and velocity (step 7) grids.
9. Calculate elevation (relative to mean sea level) of stratigraphic horizon by subtracting the measured depth (step 8) from the seismic datum elevation.

help of some geologic inference (e.g., there are no igneous rocks above the Eau Claire; zones including parts of the Knox Group contain dolomite). 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.

The 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 areas of thicker deposition. Isochron thickness grids of the interpretations were manually produced in a similar manner. The stratigraphic thickness of the Reelfoot was then calculated by multiplying these two gridded data sets, using the following formula:

$$Z = \Delta t \times V_{\text{int}}$$

where Z = stratigraphic thickness (feet), Δt = interval travel time (seconds), and V_{int} = calculated interval velocity (feet/second).

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 Precambrian rocks.

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 has been defined in Missouri (Weaverling, 1987; Houseknecht, 1989) and interpreted from well cuttings as far north and east as southern Illinois. 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 Butler, Edmonson, and Grayson Counties, Ky., in the eastern Rough Creek Graben. The seismic velocities in the unit, as well as the character of the horizons, are 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. These seismic properties were analyzed to interpret a complete map of the depositional (Plate 2, Plate 3).

Potential Fields

Four public-domain potential-fields datasets were used in this study: the USGS Midcontinent magnetic surveys, Tennessee Valley Authority high-resolution aeromagnetic dataset, USGS isostatic residual gravity anomaly dataset, and USGS Bouguer gravity anomaly datasets. These data were used to constrain the strikes and lateral extents of major faults that crossed 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. KGS researchers gridded the flight-line point data into a mathematical surface using Esri's ArcMap software. Because of gaps between flight lines and our intention to produce a continuous surface, a grid sample size of 2.5 km was used.

Hildenbrand and others (1981) compiled aeromagnetic data from various sources, including some earlier TVA data, to produce the "Aeromagnetic Map of East-Central United States." The USGS gravity survey datasets originally came from Phillips and others (1993). Gravity surveys are labor intensive and must be performed on site, in contrast to aeromagnetic data surveys, which are recorded from moving airplanes or helicopters. As a result, either smaller survey areas or wider-spaced data points are chosen for a gravity survey. The USGS gravity data are no exception, and the size of the grids used to produce these map surfaces are 4,000 m on a side. Bouguer anomaly calculations were derived from these data.

Mapping Techniques

After both stratigraphic well tops and seismic horizon time values were converted into subsea elevation in feet, the seismic and well data-point sets could be combined and treated as a single data type. Petra produced 480.0 × 363.2 km gridded areas across the project area (300 × 227 cells with 1,600 m sides) for each mapped stratigraphic horizon using all of the available data. An inverse distance-squared weighting algorithm (the Highly Connected Features function in Petra) was used to produce the grid surfaces. Surface discontinuities were included along the fault traces to allow for vertical offsets of the mapped horizon. The fault lines act as barriers to the inverse distance-squared search function, removing the influence of nearby 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 edge effects created by fault or survey-area irregularities.

Only regional stratigraphic units that are resolvable on seismic reflections were mapped. For the Ordovician–Mississippian strata (Fig. 4), many more units were interpreted from well logs than were possible to trace with current seismic resolution. See Table 2 for a list of well and seismic stratigraphic tops interpreted for this project.

Structural and Stratigraphic Maps

Plates 2–16 are structure-contour maps of eight major stratigraphic horizons and isopach thicknesses between these horizons. These horizons were chosen because of their regional continuity and because they are resolvable on both seismic profiles and geophysical well logs. The Lower Cambrian–Lower Mississippian strata were grouped into seven stratigraphic intervals, referred to as units A–G, in ascending order on top of Precambrian basement. The eight mapped surfaces that define these units are the top (top of unit G) and base (top of unit F) of the New Albany Shale, the top (top of unit E) and base (top of unit D) of the Maquoketa Shale, the top of the Knox Group (top of unit C), the top of the Eau Claire Formation (top of unit B), the top of the Reelfoot Arkose (top of unit A), and the top of Precambrian basement rocks (base of unit A) (Table 3).

Areas where the mapped unit is absent because of either nondeposition or erosional truncation are indicated by a white background. Areas where the mapped units are absent were defined by either the locations of outcrop exposures or by the interpretations of well data for subsurface truncations. Because of the grid-clipping process used to define these areas where the unit is absent on the elevation and isopach thickness grids, the outlines of the outcrop or pinch-out areas generally have jagged edges and are not intended to precisely replicate the actual outcrop patterns. These grid edges should therefore be considered as the extent of the full thickness of that unit, but not the exact location of zero thickness.

The generalized stratigraphy exposed at the current land surface is illustrated on Figure 5, and the names and locations of major regional features discussed in this chapter are illustrated on Figure 6. The age boundaries of the seven stratigraphic units used in this study correspond well with many of the North American cratonic stratigraphic sequences of Sloss (1963, 1988), and so may be useful in regional correlations beyond the geographic scope of this study (Fig. 1). Unit A rocks are interpreted to have been deposited during the first half of the Sauk II sequence (Middle Cambrian),

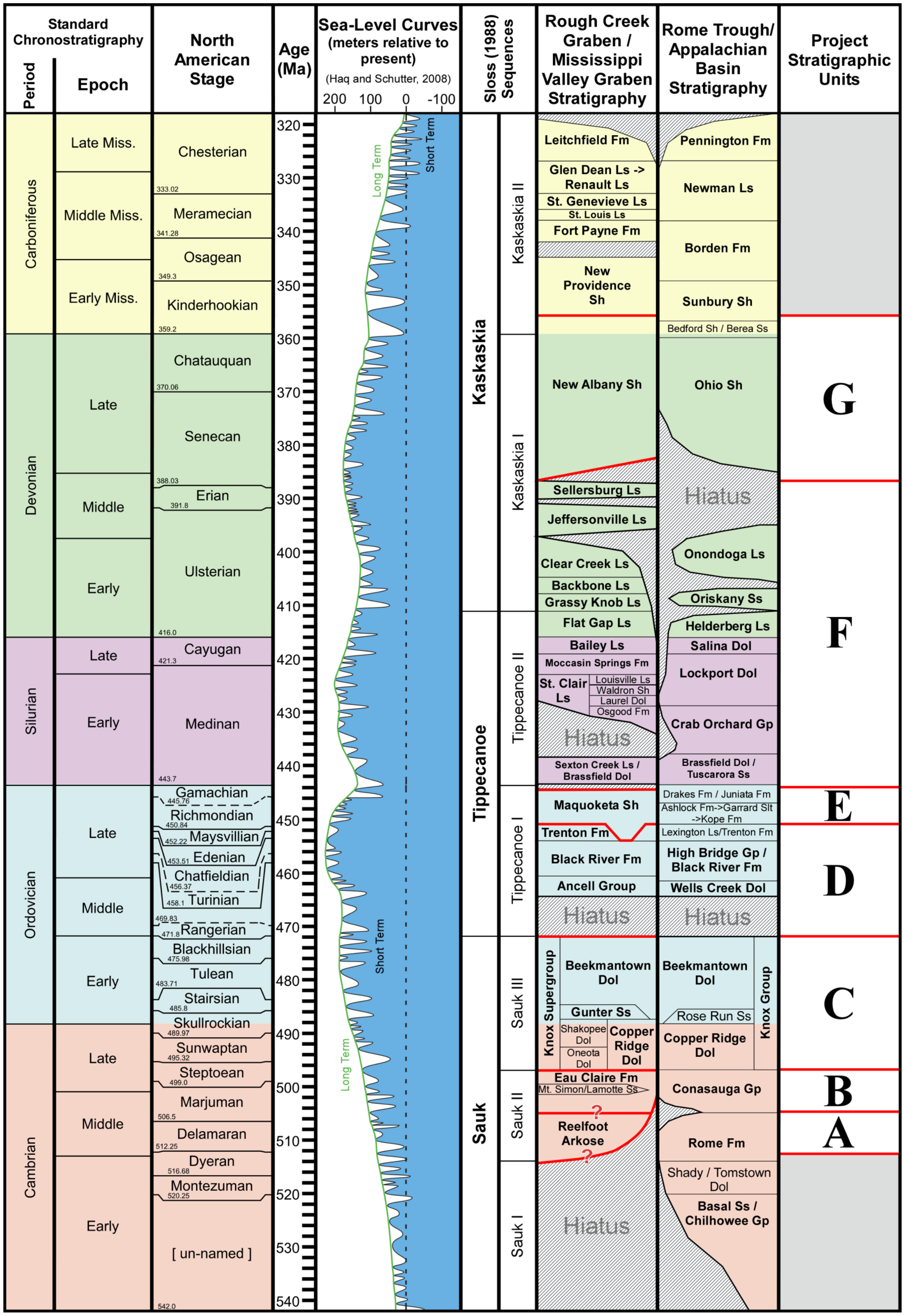

Figure 4. Geologic time scale used in this study. Stratigraphic horizons mapped in this study highlighted in red. Ages of Kentucky stratigraphy from Greb and others (in press). Sea-level curves from Haq and Schutter (2008). North American/Laurentian Stage names and ages from Davydov (1996), Gradstein and others (2005), Webby and others (2004), and Ogg and others (2008). North American sequence names and ages from Sloss (1963, 1988).

Table 2. Stratigraphy used for regional mapping and analysis, including the number of well tops used and data source types for each horizon.

Description	*Well Count*	*Data Source*
Top of Paleozoic strata	36	wells only
Middle Mississippian		
Ste. Genevieve Limestone	64	wells only
Fort Payne Formation	174	wells only
Lower Mississippian		
New Albany Shale	1,381	wells, seismic
Middle Devonian		
Base of New Albany Shale	1,408	wells, seismic
Sellersburg Limestone	495	wells only
Jeffersonville Limestone	482	wells only
Lower Devonian		
Clear Creek/Grassy Knob Formation	514	wells only
Backbone Limestone	28	wells only
Grassy Knob Limestone	68	wells only
Flat Gap Limestone	43	wells only
Upper Silurian		
Bailey Limestone	204	wells only
Moccasin Springs Formation	73	wells only
Lower Silurian		
Moccasin Springs Formation	73	wells only
Louisville Limestone	123	wells only
Waldron Shale	229	wells only
Laurel Dolomite	237	wells only
Osgood Shale	207	wells only
Sexton Creek Limestone	36	wells only
Brassfield Dolomite	238	wells only
Upper Ordovician		
Maquoketa Shale	225	wells, seismic
Middle Ordovician		
Trenton Formation	295	wells, seismic
Black River Group	320	wells only
Joachim Formation, Ancell Group	253	wells only
Dutchtown Formation, Ancell Group	235	wells only
St. Peter Sandstone, Ancell Group	128	wells only
Lower Ordovician		
Beekmantown Dolomite, Knox Group	293	wells, seismic
Gunter Sandstone, Knox Group	50	wells only
Upper Cambrian		
Copper Ridge Dolomite, Knox Group	128	wells only
Eau Claire Formation	82	wells, seismic

Table 2. Stratigraphy used for regional mapping and analysis, including the number of well tops used and data source types for each horizon.

Description	*Well Count*	*Data Source*
Middle Cambrian		
Mount Simon Sandstone/Lamotte Formation	48	wells only
Reelfoot Arkose	9	wells, seismic
Precambrian		
Precambrian basement (undifferentiated)	61	wells, seismic

unit B is equivalent to the second half of the Sauk II sequence (Middle to Late Cambrian), and unit C represents Sauk III deposition (Late Cambrian–Middle Ordovician). The Tippecanoe I sequence (Middle and Late Ordovician) is split between units D (Middle Ordovician–early Late Ordovician) and E (Late Ordovician). Unit F contains all of the Tippecanoe II sequence and the lower half of the Kaskaskia I sequence. The youngest stratigraphic interval mapped (unit G) is the only unit that does not share a boundary age with any of the Sloss (1963, 1988) sequences. Unit G corresponds to the middle of the Kaskaskia sequence, specifically the late Kaskaskia I–early Kaskaskia II sequences.

The well symbols on Plates 2–16 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 the available data.

Table 3. Included and equivalent stratigraphic members of units mapped in this study.

Unit	*Boundaries*	*Included Members*
G	Top to base of the Upper Devonian–Lower Mississippian New Albany Shale	New Albany Shale, equivalent to Ohio Shale, equivalent to Chattanooga Shale
F	Upper Devonian unconformity at the base of the New Albany Shale to the top of the Maquoketa Shale	Entire Silurian–Lower Devonian section
E	Top to base of the Upper Ordovician Maquoketa Shale	Maquoketa Shale, equivalent to Kope Formation
D	Base of the Maquoketa Shale to the Knox unconformity at the top of Lower Ordovician strata	Trenton Formation, Black River Group, Ancell Group, Platteville Formation, Gallatin Formation, equivalent to Lexington Limestone, equivalent to High Bridge Group
C	Upper Cambrian–Lower Ordovician Knox Group (Knox unconformity to the top of the Eau Claire Formation)	Shakopee Dolostone, Oneota Dolostone, Eminence Dolostone, Potosi Dolostone, Elvins Formation, Davis Formation, upper Bonneterre Formation, Gunter Sandstone, Copper Ridge Dolostone, equivalent to Beekmantown Dolostone, equivalent to Rose Run Sandstone
B	Top of the Middle–Upper Cambrian Eau Claire Formation to the top of the Reelfoot Arkose	Eau Claire Formation, lower Bonneterre Formation, St. Francois Formation, Lamotte Formation, Mount Simon Sandstone, equivalent to Conasauga Group
A	Top of the Lower(?) Cambrian Reelfoot Arkose to the top of Precambrian basement	Reelfoot Arkose, equivalent to Rome Formation, equivalent to upper Chilhowee Group?

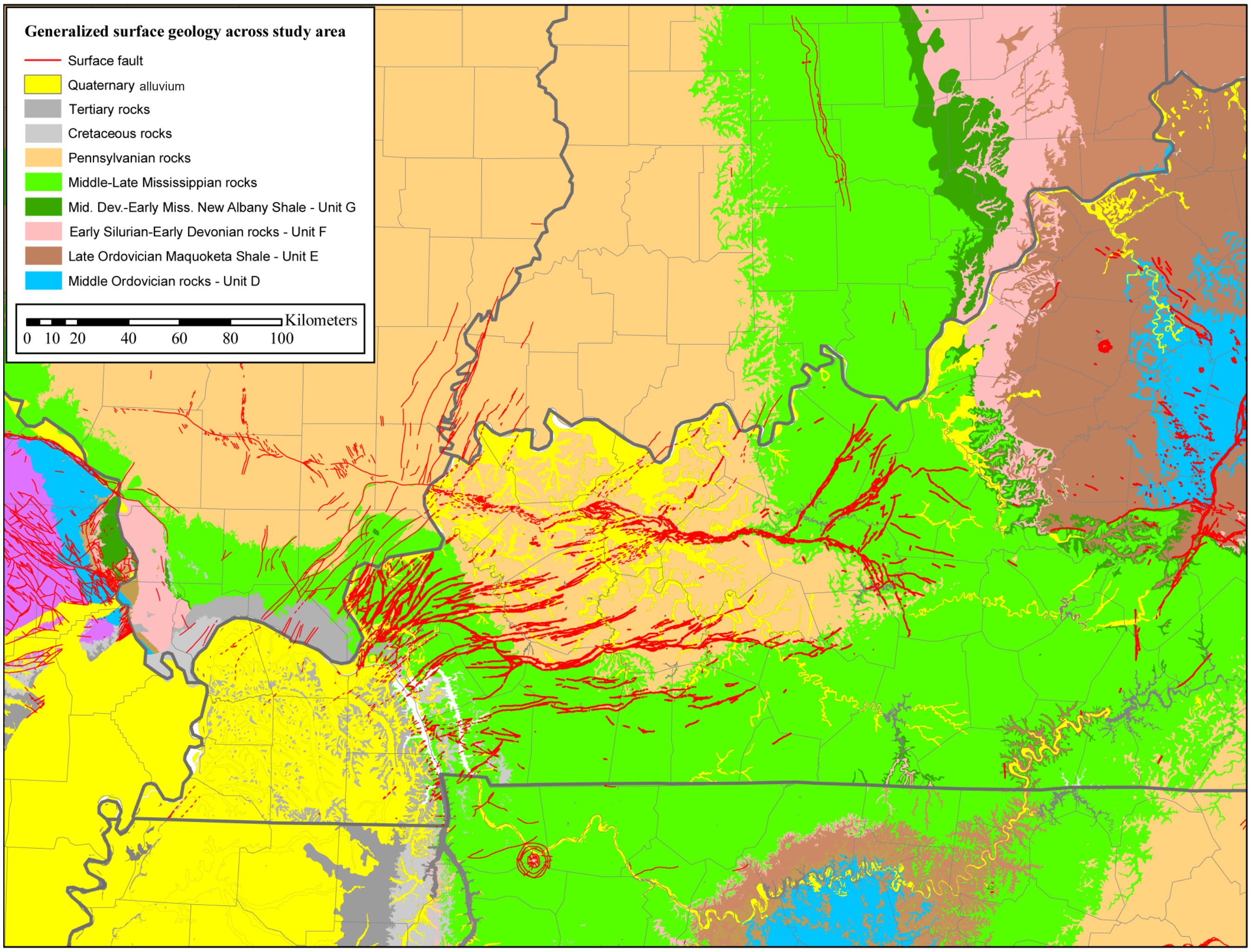

Figure 5. Generalized surface geology across the study area. The areas of surface exposures of units D–G delineate the maximum extent of the subsurface horizon grids. GIS data were compiled from the state geological surveys of Ohio, Kentucky, Indiana, Illinois, Tennessee, and Missouri and the U.S. Geological Survey.

Structure on the Top of Unit G, Top of the New Albany Shale

The youngest stratigraphic unit mapped in this study is the Devonian New Albany Shale (unit G) (Plate 4). Because of its relatively shallow depth, this horizon has the most well penetrations and thus highest data density of all eight mapped stratigraphic units. The New Albany black shale has a 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 features at the top of the New Albany Shale (top of unit G) are the Cincinnati Arch, the Jessamine and Nashville Domes, and the truncation by the pre-Cretaceous unconformity beneath the Mississippi Embayment (Fig. 6). 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, Ky., across the graben to northeastern McLean County, Ky. The western part of the graben (west of McLean County) has a highly asymmetrical, north-dipping half-graben style of structure, whereas the eastern Rough Creek Graben is

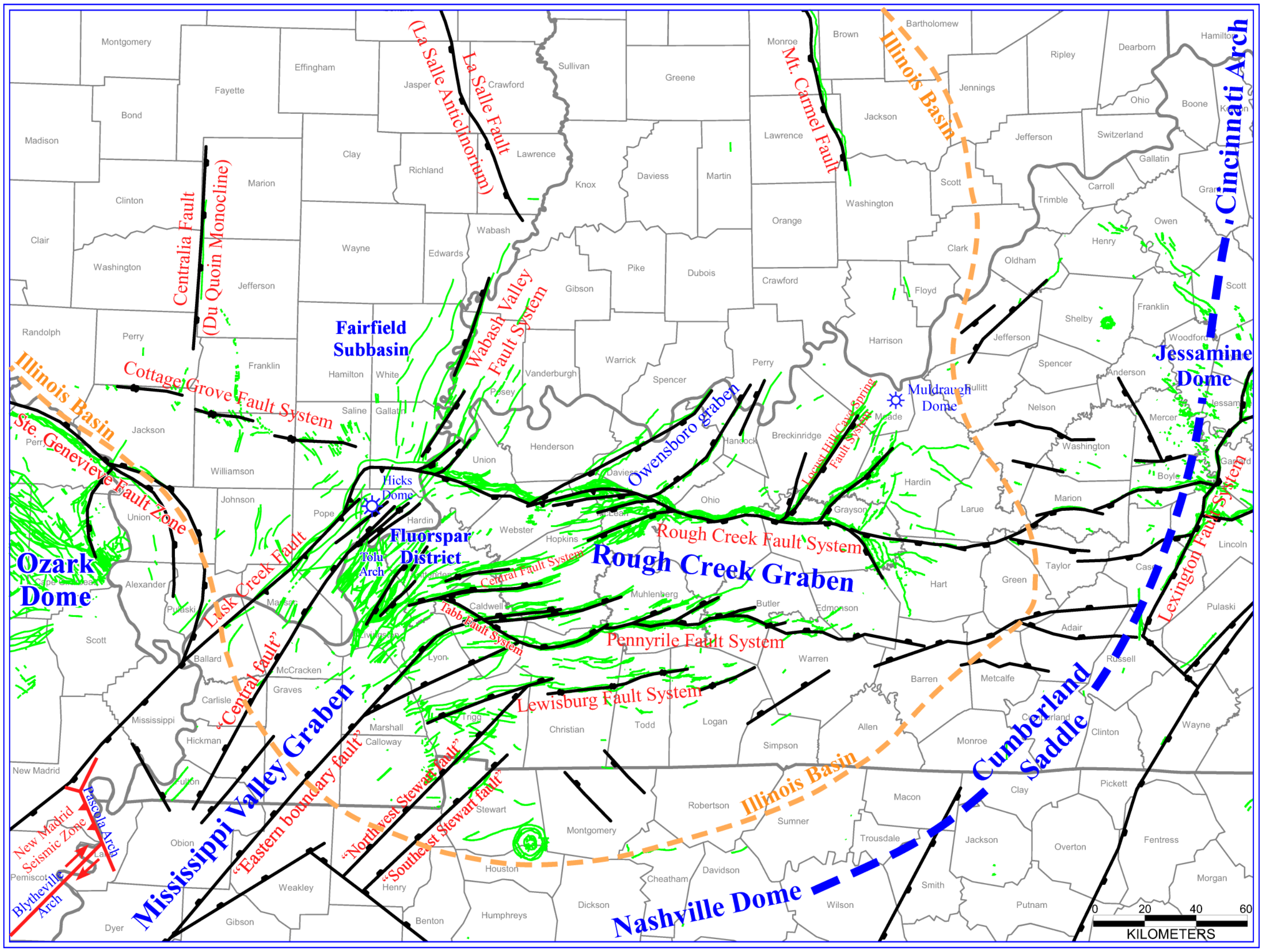

Figure 6. Major structural features around the Rough Creek Graben and Mississippi Valley Graben.

only slightly asymmetrical and dips to the south. The deepest points of the New Albany are around –4,600 ft in the Fairfield Sub-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, Ky., and 500 ft in Grayson County, Ky., along the north side of the graben.

The erosion beneath the Cretaceous cover of the Mississippi Embayment has removed the New Albany from all but the most 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 smooth upper surface, as indicated by wide contour spacing with a 200-ft contour interval on Plate 4.

Uplifted blocks along the Rough Creek Fault Zone in Ohio and Grayson Counties, Ky., as well as a small uplifted fault block in Caldwell County, Ky., 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, Ky., 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. 7). Another post-Devonian structure, observable on Plate 4, is the north–northwest-striking Tolu Arch in Livingston and Crittenden Counties, Ky. (Trace and Amos, 1984). The formation of this arch has been

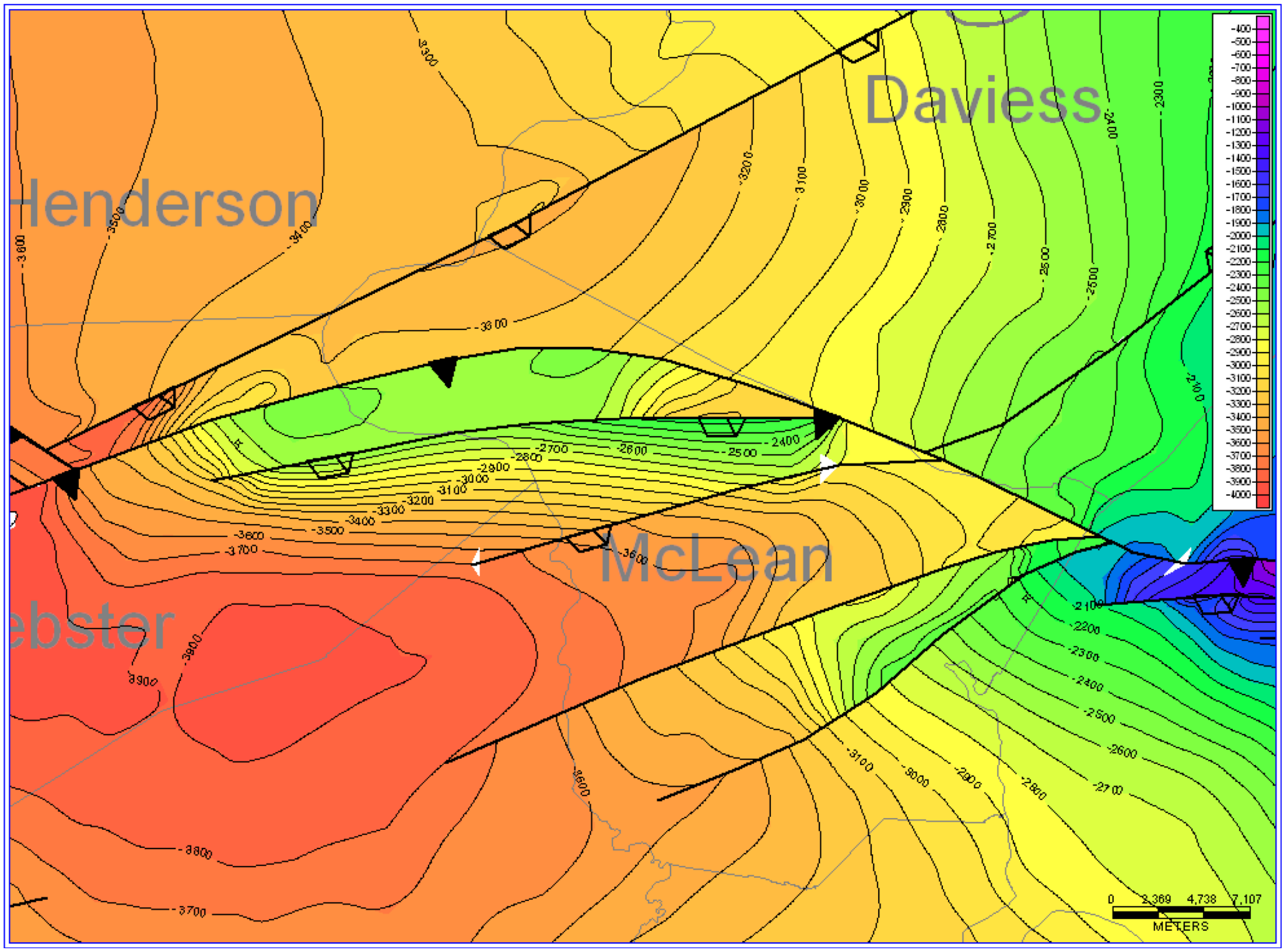

Figure 7. Inversion structures along the Rough Creek Fault Zone at the top of the New Albany Shale (top of unit G), extracted from Plate 4.

associated with the magmatism that produced the numerous Early Permian mafic dikes and sills in the nearby Hicks Dome (Trace and Amos, 1984). The Tolu Arch crosses an area near the intersection of the Mississippi Valley and Rough Creek Grabens and is characterized by numerous chaotic faults exposed at the surface. The amplitude of the arch is 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 Group.

Other notable structures that can be seen at this level are the faults along the DuQuoin Monocline (Centralia Fault) and LaSalle Anticlinorium Belt at the surface. These two roughly north-south faults in south-central Illinois constrain the downwarped Fairfield Sub-basin (Fig. 6).

One other structure shown on Plate 4 is the Muldraugh Dome in northern Meade County, Ky. (McDowell, 1986). This is a relatively small uplift, about 2 mi in diameter with no mapped faults at the surface (Withington and Sable, 1969; McDowell, 1986). Freeman (1951) reported several wells penetrate an undeformed Silurian dolomite directly overlying brecciated dolomite and chert of the Lower Ordovician Knox Group, indicating more than 1,550 ft of missing section. Although the cause of the Muldraugh Dome is uncertain, the circular shape and the uplifted and brecciated nature of the subsurface geology implies a post-Knox and pre-Silurian impact crater origin.

Thickness of Unit G, the New Albany Shale

The New Albany Shale (Plate 5) in this region thins eastward onto the Cincinnati Arch (to less than 50 ft) and around the Jessamine and Nashville Domes (including some pinch-outs in localized areas). The unit thickens toward southeastern Illinois and into the Rough Creek Graben (to as much as 500 ft in Crittenden County, Ky.). This thickening within the graben suggests either syndepositional fault movement/subsidence or possibly fault movement just prior to deposition, which would produce varied topography that the shale later filled. Although unit G is the thinnest unit analyzed in this study, the relative percentage of total thickness change across many of the faults of the Rough Creek Fault Zone is dramatic. In Ohio and Grayson Counties, Ky., wells separated by about 2.8 mi increase in thickness by 20 to 40 percent to the south. This increase is observable in several two-well transects, across at least four fault-system segments along the eastern end of the Rough Creek Fault Zone, suggesting the whole fault trend was active at the same time as part of a larger tectonic framework, and not simply a local event affecting one or two faults.

Later (post-Mississippian) reactivation of the Rough Creek Fault Zone produced tectonic thickening (stratigraphic duplication from high-angle reverse faulting) of the New Albany in several wells that penetrate the deformed fault zone. These wells were not used in the thickening percentage calculations, but the data from these wells produce some areas of chaotic contour patterns on the unit G isopach map (Plate 5) in the intensively faulted Rough Creek Fault Zone in eastern Ohio and western Grayson Counties, Ky.

Structure on the Top of Unit F, Base of the New Albany Shale

The New Albany Shale in the study area unconformably overlies a range of Upper Silurian to Lower Devonian strata. The specific formation at the top of unit F immediately below the New Albany at any point is highly variable across the study area because of numerous shallow-water facies changes and at least two regional unconformities (Plate 6). For simplicity, the top of unit F 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 Sub-basin, and around –4,400 ft in the Rough Creek Graben in Webster County, Ky. Graben-bounding fault offsets along the northern border are slightly less than at the top of the unit (approximately 450 ft of normal offset in Grayson County, Ky., around 400 ft of post-Devonian inverted offset in McLean County, Ky., and around 300 ft in Union County, Ky.). 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 inversion structures along the Rough Creek Fault Zone in Webster, Ohio, and Grayson Counties described for the top of the New Albany Shale are also expressed at the base.

Thickness of Unit F, 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 rocks, and dolostone is the dominant lithology (Plate 7). It includes the entire Silurian section and, in some areas, Lower to Middle Devonian strata as well (Seale, 1981). This package thins to the south and east, resulting in pinch-outs of several units along the Cincinnati Arch. Along the Cumberland Saddle where unit F has been removed at the Lower Devonian unconformity, the New Albany Shale unconformably overlies the Maquoketa Shale, which makes distinguishing the base of the New Albany Shale from the top of the Upper Ordovician Maquoketa Shale in well logs difficult. The unit is thickest in the Fairfield Sub-basin (2,400 ft) and between Hardin County, Ill., and Hopkins County, Ky., along the basinal axis of the Rough Creek Graben (an average of 1,800–2,200 ft thick). In southern Indiana and Illinois, this section is expressed as a relatively uniform, wide body with thicknesses generally more than 1,000 ft.

This package of strata thickens southward across the Rough Creek Fault Zone; the greatest thickening is in the eastern part of the Rough Creek Graben. More subtle thickening is in the fault-bounded Owensboro Graben (Greb, 1989) in Daviess and western Hancock Counties, Ky. (Fig. 6).

Structure on the Top of Unit E, the Maquoketa Shale

The top of the Maquoketa Shale is also the top of the Upper Ordovician strata in this region (Plate 8). The Maquoketa is composed of calcareous shales and siltstones. Unit E crops out at the surface along the edges of the dome of the Cincinnati Arch, and extends down to below –6,200 ft in the Fairfield Sub-basin and to around –6,600 ft in the Rough Creek Graben in Union County, Ky. Unlike the previously described younger stratigraphic units, the deepest points in the study area are in southern Union County, Ky., within the Rough Creek Graben, and not in the Fairfield Sub-basin to the north.

Offsets along the Rough Creek Graben bounding faults range from around 1,000 ft along the Rough Creek Fault Zone in Union County, Ky., to 800 ft in Grayson County, Ky., to 400–800 ft along the Pennyrile Fault System in Muhlenberg County, Ky., to nearly 0 ft of cumulative offset in McLean County, Ky., adjacent to the Owensboro Graben. Currently, interpreted offsets along the borders of the Mississippi Valley Graben are less than 200 ft. The basin axis in the Rough Creek Graben is a linear depression at this level, extending from near the Rough Creek Fault Zone in Union County, Ky., southeastward to Hopkins County, Ky. The difference in 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 is also apparent at the top of the Maquoketa Shale, as are the inversion structures along the Rough Creek Fault Zone.

Thickness of Unit E, the Maquoketa Shale

Across southern Illinois and in west-central Kentucky, the base of the Maquoketa Shale conformably overlies the fossiliferous limestones of the Middle Ordovician Trenton Formation (Plate 9). Between these two areas is a linear zone, the Sebree Trough (Kolata and others, 2001), in which the Trenton is absent and a slightly thickened Maquoketa section apparently unconformably overlies carbonates of the Black River Group (Fig. 8). Whether this is a true unconformity or a lateral facies change in the Trenton Formation is uncertain. For the most part, the gradual thickening of the Maquoketa across the Sebree Trough is not directly evident at the seismic resolution scale and mapped contour interval. A few small areas along this north-south trend in Hopkins and Caldwell Counties, Ky., contain locally elevated thicknesses of unit E (Maquoketa Shale), however, which directly overlie thinned unit D. These areas are also in close proximity to basement fault systems, so a component of local fault movement cannot be ruled out as an additional cause of the thickened Maquoketa section.

The thickness distribution of unit E (Maquoketa Shale) is not uniform; however, the lack of abrupt thickness changes across the graben-bounding faults implies a lack of regional tectonic activity during Maquoketa deposition. Overall, the Maquoketa thickens to the east-northeast. Thicknesses range from less than 300 ft in central Illinois to as much as 600–700 ft along the outcrop belt in central Kentucky. No significant changes in thickness of the Maquoketa Shale were observed in the Mississippi Valley Graben.

Structure on the Top of Unit D, Base of the Maquoketa Shale

Similarly to the base of the New Albany Shale, the base of the Maquoketa Shale directly overlies different formations in different places across the study area (Plate 10). Therefore, the top of unit D is mapped as the base of the Maquoketa rather than the top of the geologic section below it. The base of the Maquoketa Shale defines the Sebree Trough across western Kentucky (Fig. 8). The transition zones along the edges of the Sebree Trough, as indicated by distribution patterns mapped from well logs, appear to be localized gradational facies changes. The lack of any other regional structures that are parallel to the trend implies that the Sebree Trough is depositional in nature and not tectonic.

The top of unit D extends from outcrops around the Jessamine Dome and Nashville Dome

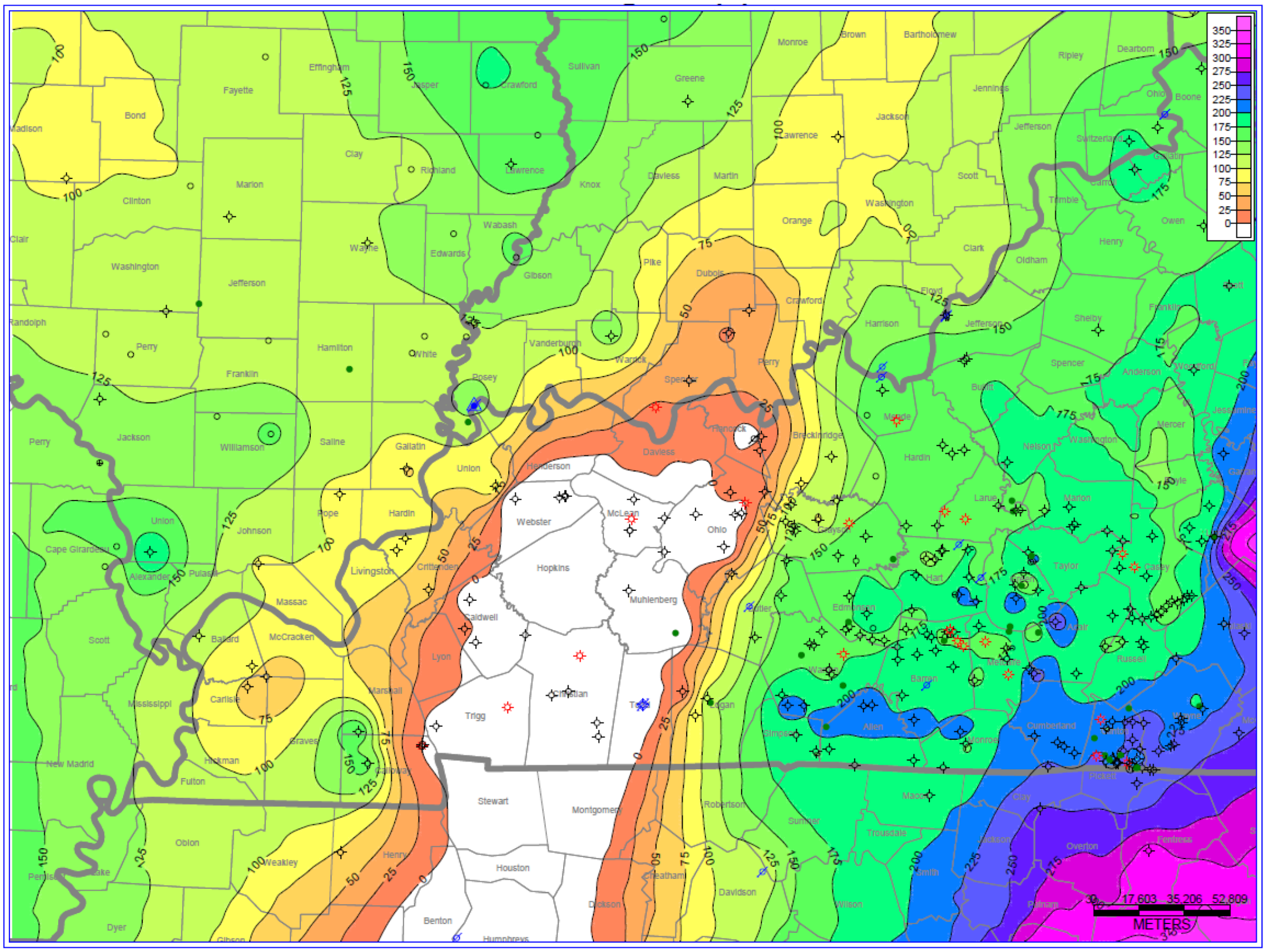

Figure 8. Thickness of the Trenton Formation (from well data only). The Sebree Trough is the region of thin to absent Trenton across the center of the map.

down to –6,800 ft in the Rough Creek Graben in Union County, Ky., and down to –6,400 ft in the Fairfield Sub-basin in White County, Ill. Fault offsets in McLean and Daviess Counties, Ky., are greater at this level than at stratigraphically higher ones, making the Owensboro Graben more prominent at this horizon. The general Illinois Basin and graben structure is very similar to the structure of the top of the Maquoketa Shale: a pronounced Cincinnati Arch and a highly asymmetrical, north-dipping half-graben-shaped basin west of the Owensboro Graben and a more symmetrical synclinal graben shape to the east in the Rough Creek Graben. Fault offsets at the base of the Maquoketa Shale along the Rough Creek Graben border fault zones are around 800 ft each in Union and Grayson Counties, Ky., and less than 100 ft in McLean County, Ky., and 200–400 ft along the Pennyrile Fault System. Interpreted fault offsets along the Mississippi Valley Graben are around 100–200 ft. The structurally inverted blocks are present in the Rough Creek Fault Zone, but much less pronounced than in the younger strata.

Thickness of Unit D, the Interval Between the Base of the Maquoketa Shale and the Top of the Knox Group

Unit D encompasses all of the Middle Ordovician strata in the region, including the Trenton Formation, Black River Group, Ancell Group, and Everton Formation (where present) (Plate 11). The lithology of this unit is predominantly limestone, with only minor amounts of sandstone, shale, and dolomite. The section increases in average thickness toward the southern Illinois Basin and northern Mississippi Valley Graben. It has a maximum thickness of around 1,800 ft along some 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 the Sebree Trough trend in central Christian County, Ky. Locally, the unit thickens adjacent to faults on individual downthrown blocks in the Rough Creek and Mississippi Valley Grabens.

Structure on the Top of Unit C, Top of the Knox Group

The top of unit C, the Cambrian-Ordovician Knox Group, is a regional unconformity surface that marks the top of the Sauk Sequence (Sloss, 1963) (Plate 12). The deepest points are –8,000 ft in the Rough Creek Graben in Webster and Union Counties and –7,700 ft in the Fairfield Sub-basin in White County, Ill. The Knox is shallowest at 200 ft above sea level along the northern Cincinnati Arch and around 400 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 1,100–1,200 ft along the Pennyrile Fault System in Muhlenberg and Christian Counties, Ky., to 400 ft along the Rough Creek Fault Zone in Union County, Ky., to 200 ft in Grayson County, Ky., to approximately 0 ft of cumulative offset in McLean County, Ky., 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 a curvilinear depression at this level, extending from close to the Rough Creek Fault Zone in Union County, Ky., southeast to Hopkins County, Ky., from which point it extends east toward the Cincinnati Arch to at least Taylor County, Ky. The difference in structural styles at this level between the eastern and western halves of the Rough Creek Graben is less pronounced than at shallower levels. This is the deepest horizon in which the inversion structures along the Rough Creek Fault Zone are evident.

At the southwestern edge of the study area, two distinct unconformities truncate the top of the Knox Group. Southwest of the area represented by the bold dashed line on Plate 12, in the Mississippi Embayment, erosion of Paleozoic strata along the sub-Cretaceous unconformity truncated the top of the Knox Group in the central and southern parts of the Mississippi Valley Graben. Northeast of the bold dashed line, the top of the Knox Group is defined by the regional Early to Middle Ordovician unconformity that forms the top of the Sauk Sequence of Sloss (1963) (Fig. 1). Post-Ordovician, pre-Cretaceous uplift of the intersecting Blytheville and Pascola Arches (Fig. 6) produced a small teardrop-shaped area centered in Lake County, Tenn., where the Knox Group (unit C) is unconformably absent and Cretaceous sediments directly overlie the Middle to Upper Cambrian Eau Claire Formation (unit B). The Blytheville and Pascola Arches overlie the basement faults associated with the present-day seismicity in the New Madrid Seismic Zone, and may reflect tectonic thickening from earlier motion along these basement faults (Howe and Thompson, 1984).

Thickness of Unit C, the Knox Group

The rocks of unit C were deposited between the early Late Cambrian and the latest Early Ordovician (Fig. 1, Plate 13). During this time, rising global sea levels (Haq and Schutter, 2008) led to transgression across the study area. In the Rough Creek Graben and Mississippi Valley Graben, fewer faults offset the top of unit C than the base of the unit, implying a decrease in fault activity during the deposition of unit C. The Upper Cambrian–Lower Ordovician Knox Group overlies the Lower to Middle Cambrian synrift strata over the entire region (Schwalb, 1969; Shaver, 1985; Ryder, 1992; Noger and Drahovzal, 2005). This passive-margin succession (Sloss, 1988) is predominantly carbonate, with minor amounts of mature, quartz-rich sandstones. In the project area, the Knox Group is thickest, at more than 11,500 ft in Carlisle County, Ky., along the northwestern, downthrown side of the Mississippi Valley Graben Central Fault (Fig. 6). The thinnest points (including an area where the Knox is absent) are along the Blytheville/Pascola Dome, caused by truncation at the pre-Cretaceous unconformity. Another local area of thinned Knox is present in northern Ohio to Breckinridge Counties, Ky., north of the Rough Creek Fault Zone between the Owensboro Graben and the Locust Hill/Cave Spring Fault System, with a thickness of 3,000 to 3,500 ft. This area also has a thinned interval of Eau Claire Formation (unit B; see below), suggesting that it was a paleohigh during the Late Cambrian, which reduced the accommodation space available for sediment accumulation.

Across the study area, the Knox Group thickens toward and into the Rough Creek Graben and Mississippi Valley Graben. Dramatic thickness changes across fault zones (implied syndepositional fault movement) are present only in the Mississippi Valley Graben, except in the Rough Creek Fault Zone in Ohio and Union Counties, Ky., and the Centralia Fault in Jefferson and Marion Counties, Ill. The majority of Knox Group thickening is not abrupt at graben-bounding fault systems, but gradual (around 100 ft/mi in many places) across areas that extend well beyond the limits of the Rough Creek and Mississippi Valley Grabens. This pattern of thickening suggests an interpretation of regional subsidence (possibly from post-rift cooling of the lower crust) and not tectonic extension along regional fault systems.

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 locations between the top and base of the unit from these differing fault sets lead to irregular, dogtooth-shaped gridding errors or small cell gaps along some fault trends.

Structure on the Top of Unit B, Top of the Eau Claire Formation

This part of the Midcontinent has undergone numerous episodes of deformation and faulting (McDowell, 1986) (Plate 14). These various tectonic events led to different collections of faults that affect different stratigraphic levels. The identities and locations of faults that affect the top of unit B (the top of the Eau Claire Formation) are quite different from those that offset the top of the Knox (see **Mapping Techniques).** Basement-rooted faults are more common in the Eau Claire on the southern shelf area outside of the graben complex and along the eastern end of the Rough Creek Graben than on the northern shelf area north of the Rough Creek Fault Zone. In Grayson and Ohio Counties, Ky., the faults that produced a positive flower structure and an associated structurally inverted block at the top of the Knox Group and shallower horizons along the Rough Creek Fault Zone merge at depth (as interpreted from seismic-reflection data), 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, Ky. (around –14,000 ft), and in Webster and Hopkins Counties, Ky. (–13,500 ft). This contrasts somewhat with the structure of the overlying Knox and younger strata, which exhibit a simple, synclinal shape of the basin. The eastern part of the Rough Creek Graben is fairly symmetrical at this horizon, but the Rough Creek Graben west of McLean County, Ky., has a muted, down-to-the-north half-graben structure. Outside of the graben complex, the Eau Claire in the Fairfield Sub-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 most of the Rough Creek Fault Zone from Union to Grayson Counties, Ky., range from 200 to 500 ft. Along the Pennyrile Fault System, offsets are around 400 ft in Butler County, Ky., and increase to about 1,200 ft in northern Christian County, Ky.

At this horizon in the Mississippi Valley Graben, the deepest area (close to –14,000 ft) is west of the large north–northeast-striking, down-to-the-northwest fault near the center of the Mississippi Valley Graben. This fault is herein referred to as the Central Fault. Fault offsets along the edges of the Mississippi Valley Graben range from less than 500 ft in Graves County, Ky., to more than 2,000 ft across the Lusk Creek Fault Zone along the northwestern border of the Mississippi Valley Graben. In the southwestern corner of the study area, the Blytheville/Pascola Dome (Blytheville and Pascola Arches of McKeown and others, 1990) is a dramatic feature at this stratigraphic level. The uplift associated with this feature led to later truncation of the Eau Claire Formation (unit B) in Lake County, Tenn., at the pre-Cretaceous unconformity.

Thickness of Unit B, the Eau Claire Formation

The Eau Claire Formation extends across the entire study area (Plate 15). Across most of the shelf areas outside 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 Rough Creek Graben in Union, Henderson, and Ohio Counties, Ky. In the Rough Creek Graben, there are two areas of relatively great thickness in Ohio and Grayson Counties, Ky.; the thickest point of around 10,350 ft is near the center of Ohio County, Ky. 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 southeast-striking Rough Creek Fault Zone splay faults in eastern Grayson County, Ky.

In the Mississippi Valley Graben, there is an area of greater thickness in the Blytheville/Pascola Dome in New Madrid and Pemiscot Counties, Mo., and Lake County, Tenn. The dome outlines the region of earthquake activity associated with the New Madrid Seismic Zone. This region of tectonically thickened section (original depositional thickness is unknown) is interpreted to have been produced after deposition by complex faulting in flower or mushwad (Thomas, 2001) structures. 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 at an angular unconformity by the undeformed Cretaceous sediments of the Mississippi Embayment. Farther south along the Mississippi Valley Graben, strata as young as Mississippian (possibly Pennsylvanian) are folded along with the Knox Group (Thomas, 1991).

Structure on the Top of Unit A, the Reelfoot Arkose

Unit A (the Lower 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, Ky. (Plate 2). 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 area may have served as a conduit into the western Rough Creek Graben and northern Mississippi Valley Graben for arkosic detritus from eroding 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, Ky. (–19,500, –19,000, and –21,000 ft, respectively). The prominent, steep-sided sub-basin centered in Ohio County, Ky., 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 in a sub-basin graben on the northwest (downthrown) side of the large north–northeast-striking central fault with a maximum depth of close to –17,800 ft in Carlisle County, Ky. The Reelfoot is shallowest at –7,500 ft in two locations in the project area. One is in southeastern Hart County, Ky., 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, Ky., south to Graves County, Ky. To the south, the top of the Reelfoot also 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.

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.

Thickness of Unit A, the Reelfoot Arkose

In both the Mississippi Valley Graben and Rough Creek Graben, the Reelfoot Arkose has an average thickness of around 3,000–4,000 ft, but is as thick as 17,500 ft in localized areas in Ohio, McLean, and Muhlenberg Counties, Ky. (Plate 3). Data density for the Mississippi Valley Graben area is relatively low, 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. The Reelfoot is interpreted to pinch out by onlap onto the Precambrian surface in the eastern Rough Creek Graben near Hart County, Ky., in Trigg and Christian Counties, Ky., between the Pennyrile and the herein-named Lewisburg Fault Systems, 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 St. Genevieve Fault System at the intersection of the Mississippi Valley and Rough Creek Grabens around Pope County, Ill., and perhaps in other areas (Fig. 6). In the Mississippi Valley Graben, the Reelfoot Arkose thickens toward the northwest border faults, and in contrast, thins toward the Pennyrile faults.

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 are spread between two fault systems: the Pennyrile Fault System to the north and the Lewisburg Fault System to the south (Plate 16). The east end of the graben rises sharply to a plateau around Hart County, Ky. Along the eastern Rough Creek Graben, the spacing between the northern- and southern-bounding fault systems is relatively constant across west-central Kentucky eastward to the Lexington Fault System along the western border of the Rome Trough (Fig. 6). The structurally high shelf areas around the Rough Creek and Mississippi Valley Grabens are fairly smooth when mapped at a 500-ft contour interval. The boundaries of the Mississippi Valley and Rough Creek Grabens appear to be more intensely dissected by faults on the southeastern side than on the northwestern side.

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 within 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 was imaged within the Precambrian basement along regional 2-D seismic lines shot over the eastern part of the Rough Creek Graben (Drahovzal, 1997) and parts of southern Illinois (Pratt and others, 1989, 1992). The most likely scenarios for this seismic response would be from layered clastic deposits such as the Precambrian Middle Run sandstones in an extension of the Midcontinent Rift Basin (Drahovzal and others, 1992), or from layered volcanic deposits in the Eastern Granite-Rhyolite igneous province (Pratt and others, 1989). The KY Operating No. 1 Riordan well in Hart County, Ky., drilled into a lithic arenite sandstone at the bottom of the well, which was later interpreted to be part of the Middle Run Formation (Shrake and others, 1991). In Hancock County, Ky., the KGS No. 1 Marvin Blan well drilled through 542 ft of Middle Run Sandstone before reaching total depth (Bowersox and others, 2016); the Middle Run in this well is interpreted as having been deposited in a low-relief fluvial environment. Further petrographic work is needed to accurately determine provenance of the sandstones of the Middle Run Formation.

Fifty-two miles northwest of the No. 1 Riordan well and 16 mi southeast of the No. 1 Blan well (Fig. 9), the KY Operating No. 1 Braden well in Breckinridge County, Ky., penetrated 458 ft of Precambrian welded rhyolite tuff and basalt nonconformably below the Eau Claire at 6,045 ft, as determined by the Kentucky Geological Survey's analysis of well cuttings. Unfortunately, the resolution of nearby seismic lines at that depth does 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 bimodal basin structure, with the deepest points in southern Union County, Ky. (–31,000 ft), and along the border between McLeanand Muhlenberg Counties, Ky., 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, whereas the western Rough Creek Graben has a north-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

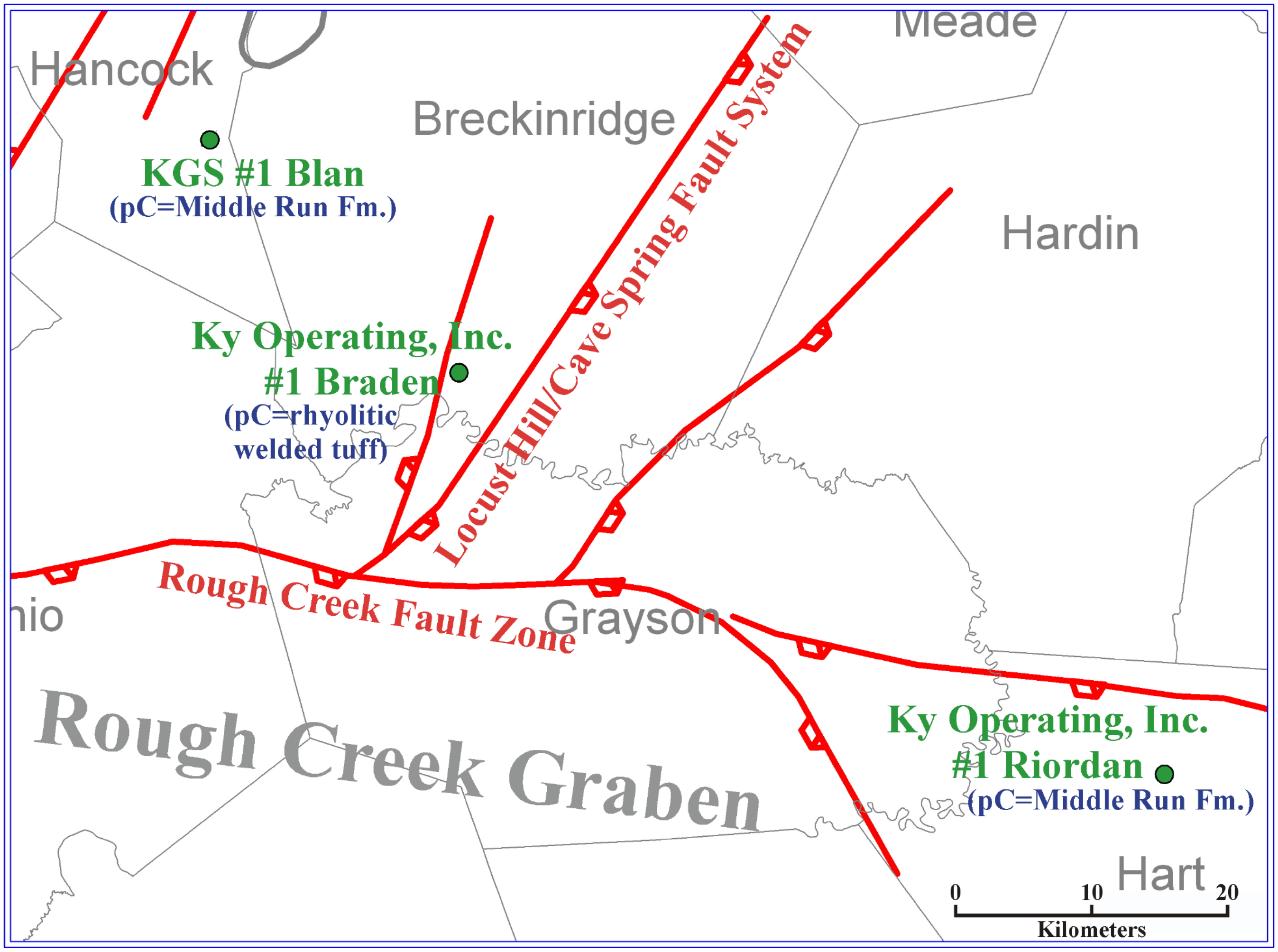

Figure 9. Varied lithologies at the top of Precambrian basement in neighboring wells in western Kentucky.

the western sub-basin and the deepest part of the Mississippi Valley Graben at around –21,000 ft.

Fault offsets at the top of the Precambrian along the Rough Creek Fault Zone range from around 12,000 ft in Union County to 500 to 1,000 ft in McLean County to as much as 16,000 ft of offset in Ohio County, Ky. Along the Pennyrile Fault System, fault offsets decrease eastward from around 4,000 ft in northern Christian County to 1,000 ft down to the north in Edmonson County, Ky.

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