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ABSTRACT OF DISSERTATION

John Bibb Hickman, Jr.

The Graduate School
University of Kentucky

2011

STRUCTURAL EVOLUTION OF AN INTRACRATONIC RIFT SYSTEM;
MISSISSIPPI VALLEY GRABEN, ROUGH CREEK GRABEN, AND ROME
TROUGH OF KENTUCKY, USA

ABSTRACT OF DISSERTATION

A dissertation submitted in partial fulfillment of the requirements for the degree of
Doctor of Philosophy in the Department of Earth and Environmental Sciences at the
University of Kentucky

By
John Bibb Hickman, Jr.

Lexington, Kentucky

Director: Dr. William A. Thomas, Hudnall Professor of Geology

Lexington, Kentucky

2011

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ABSTRACT OF DISSERTATION

STRUCTURAL EVOLUTION OF AN INTRACRATONIC RIFT SYSTEM; MISSISSIPPI VALLEY GRABEN, ROUGH CREEK GRABEN, AND ROME TROUGH OF KENTUCKY, USA

As indicated by drilling and geophysical data, the Mississippi Valley Graben, the Rough Creek Graben, together with the Rome Trough of eastern Kentucky and West Virginia, are fault-bounded graben structures filled with as much as 27,000 feet of Early to Middle Cambrian sediments. Detailed regional mapping of Cambrian and younger strata within and surrounding these structures indicates that they formed contemporaneously. The proximity of these structures suggests they developed within the same regional stress fields and tectonic environments. These three structures are mechanically and kinematically connected, and formed part of a single continent-scale rift system produced during the breakup of Rodinia and the separation of Laurentia from Amazonia.

Data including stratigraphic tops from 1,764 wells, interpretations of 106 seismic profiles, aeromagnetic and gravity survey analysis, and mapped surface geology and structures were used within this project. Seven stratigraphic packages resolvable in both geophysical well logs and reflection seismic profiles were mapped in the subsurface across parts of Kentucky, Ohio, Indiana, Illinois, Missouri, and Tennessee. These stratigraphic units were then analyzed through structure maps, isopachous maps, and across 12 regional well-based cross sections.

Detailed analysis of thickness patterns of seven major stratigraphic packages was used to identify the locations and timing of major fault movements within the study area. The regional patterns of fault movements through time were used to investigate how the structures evolved in response to the tectonic episodes in southeastern Laurentia during the Cambrian through Devonian Periods.

Active rifting of the Precambrian crystalline bedrock began by the Early Cambrian, and resulted in a thick deposit of Reelfoot Arkose and Eau Claire Formation within the Mississippi Valley and Rough Creek Grabens, and the Rome Formation and Conasauga Group within the Rome Trough. Major tectonic extension ended by the Late Cambrian, prior to the deposition of the Knox Supergroup. Counter-clockwise rotation of the

regional sigma-1 stress field between the Middle Ordovician and Early Mississippian (Taconic through Acadian Orogenies) resulted in the reactivation of varying sets of preexisting faults through time. The locations, orientations, and timing of these active faults relate to the deep architecture of the rift system.

KEYWORDS: Cambrian Tectonics, Rough Creek Graben, Mississippi Valley Graben, Rome Trough, intracratonic rift

John Bibb Hickman, Jr.

April 22, 2011

Date

STRUCTURAL EVOLUTION OF AN INTRACRATONIC RIFT SYSTEM;
MISSISSIPPI VALLEY GRABEN, ROUGH CREEK GRABEN, AND ROME
TROUGH OF KENTUCKY, USA

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John Bibb Hickman, Jr.

The Graduate School

University of Kentucky

2011

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1 INTRODUCTION

As indicated by deep drilling and geophysical data, the Mississippi Valley Graben and Rough Creek Graben, together with the Rome Trough of West Virginia and eastern Kentucky, are complex graben structures that are filled with Early to Middle Cambrian sediments (Ervin and McGinnis, 1975; Nelson and Zhang, 1991; Thomas, 1991; Thomas, 1993; Johnson et al., 1994; Marshak and Paulsen, 1996). These extensional features have been interpreted by many authors as continental rift related structures (Ervin and McGinnis, 1975; Nelson and Zhang, 1991; Thomas, 1991; Johnson et al., 1994; Thomas and Baars, 1995). The similar ages of infilling sediments show that the Mississippi Valley Graben, Rough Creek Graben, and Rome Trough formed at the same time. If they formed contemporaneously, then proximity suggests that they probably developed within the same tectonic environment and regional stress field.

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 Pennyriple 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; however, the deepest part (> 12,000 feet) extends eastward at least to Grayson and Edmonson Counties, Kentucky. Smaller faults and fold axes on strike with the Rough Creek and Pennyriple Fault Systems have been mapped at the surface eastward to near the western end of the Rome Trough, at the Lexington Fault System. 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, on the basis of proprietary seismic data, more than 10,000 feet 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 feet along the Rough Creek Fault Zone on the northern edge of the graben and around 2,000 feet of offset on the Pennyriple Fault System along the southern boundary.

The Mississippi Valley Graben (also referred to as the Reelfoot rift) is a northeast-trending graben that borders the Rough Creek Graben on the southwest (Kolata and Nelson, 1997). The Mississippi Valley Graben was initially interpreted from gravity and magnetic surveys by Ervin and McGinnis (1975). In their interpretation, it was formed as part of a failed radial-rift triple junction, with the Mississippi Valley Graben, the Rough Creek Graben, and a northwest-trending “St. Louis Arm” (inferred from gravity and magnetic surveys) as the three rift arms ([Figure 1.1](#)). On the basis of an anomalous high velocity layer at ~30-45 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 this 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 ~ 10 km. In their somewhat 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 southwestward to the Alabama-Oklahoma transform 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 lead to the separation of Laurentia from Amazonia, opening the Iapetus Ocean.

The axis of the Mississippi Valley Graben extends southwestward from the Jackson Purchase region of western Kentucky to east-central Arkansas and northwest Mississippi, extending southward 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 miles (Nelson and Zhang, 1991; Kolata and Nelson, 1997). Only two wells have penetrated the entire stratigraphic section within the study area of this graben (the Dow Chemical #1 Wilson, L. well and the Cockrell Corporation #1 Carter, J. well, both in northeastern Arkansas), but the sediments encountered are similar in lithology and proportion to those found in the Rough Creek Graben to the east, suggesting a similar age of rifting (Early to Middle Cambrian).

The intent of this project is to study the stratigraphy and structural geology of the rock units within and surrounding the Rough Creek and Mississippi Valley Grabens. Fault system analysis will illustrate the mechanical connection between these two features and with the Rome Trough of central and eastern Kentucky into one continent-scale rift system. By analyzing depositional thicknesses and faulting patterns within Cambrian through Mississippian strata in these grabens, the tectonic evolution of the Mississippi Valley Graben / Rough Creek Graben / Rome Trough intracratonic rift system during that time period will be determined.

1.1 Study Area

The study area for this project was expanded beyond the boundaries of the regional grabens to include the surrounding region. This ensures adequate coverage of the transitional areas between the grabens and undeformed shelf areas and provides information about the coeval stratigraphy that was unaffected by rifting. In general terms, the project area extends westward from the Cincinnati Arch in central Kentucky to the Ozark Dome in eastern Missouri, and northward from the Nashville Dome in western Tennessee to north of Cincinnati in Monroe County, Ohio (UTM Zone 16N coordinates 3,986,800 to 4,350,000 meters northing, and 240,000 to 720,000 meters easting).

1.2 Project Data

The total data set used within this project includes 1764 wells with stratigraphic tops (out of 8,073 wells with location and identification information), 356 wells with digitized

geophysical well logs, 179 wells with calibrated raster log images, 106 seismic reflection profiles, USGS Bouguer gravity anomaly data, USGS Aeromagnetic anomaly data, and 1:24,000 digital geologic quadrangle map data from the Kentucky Geological Survey. The analysis of this data resulted in the interpretation of eight regional stratigraphic horizons, which are presented herein on 19 large-scale map plates and 12 regional well-based cross sections. Further analysis of these horizons produced the plate tectonic interpretations discussed in Chapter [6](#).

1.3 Overview of Regional Stratigraphy and Tectonics

The tectonic history that is relevant to this study began in the Middle to Late Neoproterozoic. At that time, the supercontinent of Rodinia began to break up and the Laurentian plate started to rift from the Amazonia plate (Cawood et al., 2001; Li et al., 2008; Allen et al., 2009; Fisher et al., 2010). Southeastern Laurentia developed into a passive margin as the new Iapetus Ocean was formed (Thomas, 1991; Thomas, 2006). Along this margin contemporaneous with continental breakup, numerous graben systems were formed inboard of the continental margin of Laurentia. These 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; Braile et al., 1986; Kolata and Nelson, 1990; Thomas, 1991; Thomas, 1993, 2006).

Ocoee Supergroup synrift rocks that fill the Blue Ridge Rift on the southeastern edge of Laurentia are latest Precambrian in age (Thomas, 1991; Walker and Driese, 1991). Post-rift, passive-margin sediments of the Chilhowee Group overlie the Ocoee in the Blue Ridge Rift and within the newly forming Iapetus Ocean to the southeast. The Chilhowee Group has been biostratigraphically dated as Early Cambrian (Thomas, 1977; Simpson and Sundberg, 1987; Thomas, 1991), indicating that the age of active rifting within the Blue Ridge Rift extended from the late Neoproterozoic to the earliest Cambrian. As active rifting was ending within the Blue Ridge Rift at the beginning of the Cambrian,

synrift volcanic rocks were being emplaced within the Southern Oklahoma Fault System (Ham et al., 1964; Thomas, 1991). These diachronous rifting ages suggest that the active spreading center in southern Laurentia shifted northwestward 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; Thomas, 2006).

As indicated by thickness changes across the respective boundary fault systems, major subsidence and horizontal extension within 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; Thomas, 1993; Shumaker and Wilson, 1996; Harris et al., 2004). To accommodate these sediments, initial rifting of these linked basins began in the late Proterozoic to Early Cambrian and persisted until the early Late Cambrian (Ervin and McGinnis, 1975; Nelson and Zhang, 1991; Thomas, 1991; Thomas, 1993).

Two Precambrian crystalline basement provinces and the Late Precambrian (1020 to 950 Ma) clastic-filled East Continent Rift Basin (Drahovzal et al., 1992; Stark, 1997) lie below the Paleozoic strata within the project area. East of a boundary “front” that roughly follows the Cincinnati Arch through east-central Tennessee, central Kentucky, and west-central Ohio is the Grenville province ([Figure 1.2](#)).

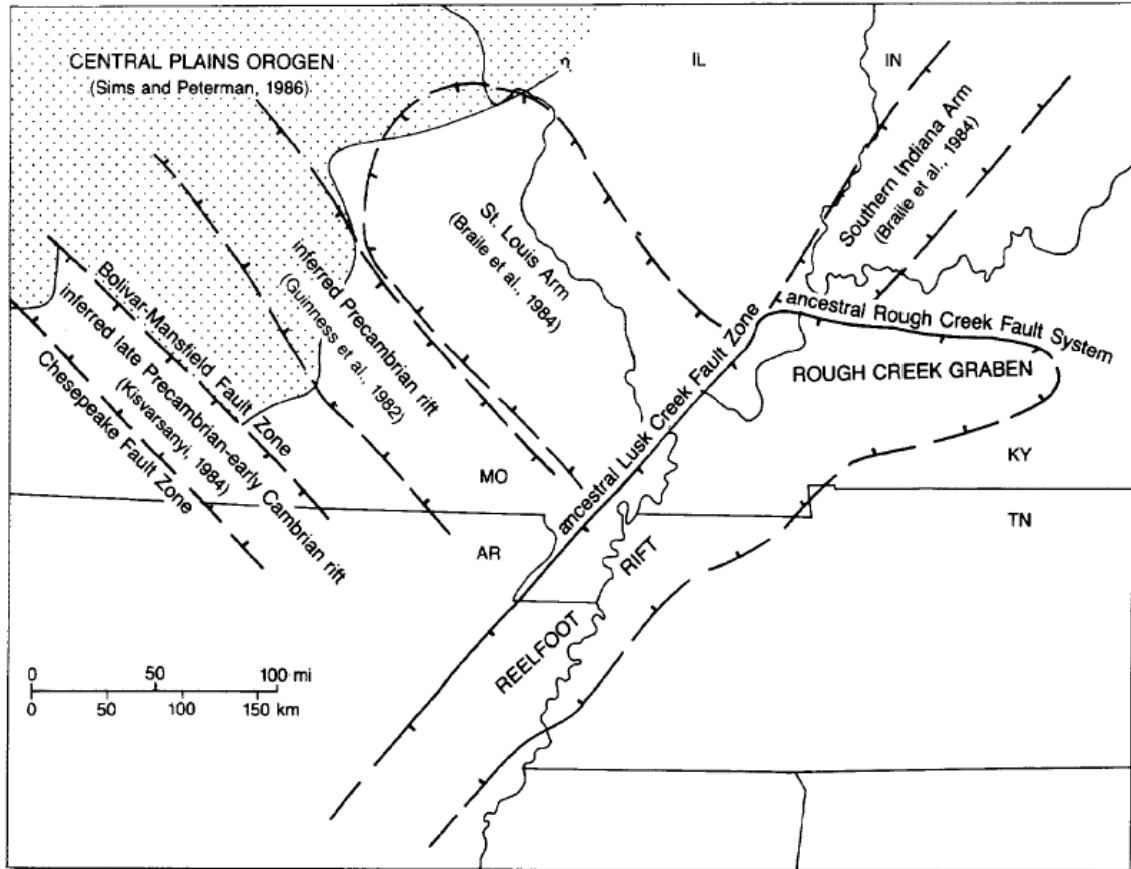


Figure 1.1 – Proposed Precambrian rifts within the southern Illinois Basin, from Nelson (1990).

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

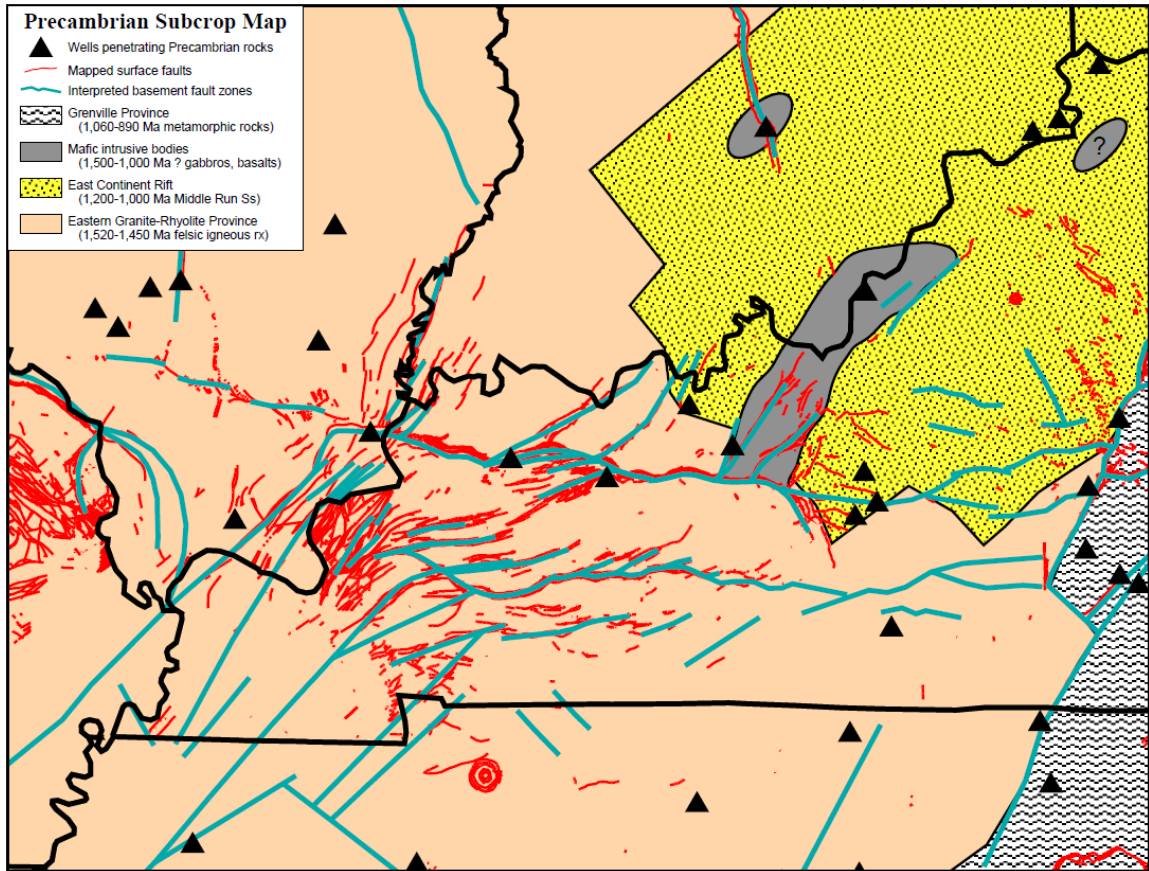


Figure 1.2 - Generalized Precambrian subcrop map for project area. Extents of East Continent Rift Basin modified from Drahovzal et al., 1992, and Stark, 1997.

Following the emplacement of the Grenville Province until at least the Early Cambrian, erosion was extensive, leading to a continent-wide unconformity at the base of the Paleozoic section ([Figure 1.2](#) and [Figure 1.3](#)) (Sloss, 1988). In the Early to Middle Cambrian, average sea level gradually rose ([Figure 1.3](#)), 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 which was eroded from the uplifted igneous and metamorphic basement rocks that surround these grabens (Ammerman and Keller, 1979; Weaverling, 1987; Houseknecht, 1989; Harris et al., 2004).

Although few wells within 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 extends across most of the Rough Creek Graben west of Green County, Kentucky, and throughout the northern part of the Mississippi Valley Graben. This is a clastic fluvial fan-type deposit and represents the first synrift deposition within the Rough Creek Graben (Weaverling, 1987). This unit underlies the Eau Claire Formation within the Rough Creek and Mississippi Valley Grabens, and it has a similar lithologic composition and occupies a similar stratigraphic position as the late Early Cambrian Rome Formation within the Rome Trough to the east (Harris et al., 2004). Unlike in the Rome Trough, there is no evidence of Shady Dolomite or upper Chilhowee Formation equivalent units within the Rough Creek Graben or Mississippi Valley Graben. Different facies of time-equivalent units may be present, but no Early Cambrian fossils or radiometrically dated rocks have been described within these grabens to date.

By the late Middle Cambrian (Shaver, 1985), regional sea level had risen to the point that the entire region was covered by a shallow sea. Middle-Late Cambrian deposition of the Eau Claire Formation in the Rough Creek and Mississippi Valley Grabens (Palmer, 1962; Collins et al., 1992; Collins and Bohm, 1993; Mitchell, 1993), the Conasauga Group in the Rome Trough (Palmer, 1971), and the Elvins and Bonnetterre Formations west of the grabens in eastern Missouri and Arkansas (Houseknecht, 1989) consisted of low-energy siltstones and shales, punctuated by episodic carbonate deposits indicative of a slowly subsiding basin margin.

By the Late Cambrian, tectonic subsidence of the Rough Creek Graben, Mississippi Valley Graben, and Rome Trough had ended (Thomas, 1991; Thomas, 1993; Harris et al., 2004). Sedimentation had filled these grabens with sediment to the point that no topographic relief remained across these structures (Harris et al., 2004). Clastic deposition was replaced by a regional carbonate platform that covered much of eastern Laurentia and lasted for more than 25 million years (Sloss, 1988). The Late Cambrian to Early Ordovician Knox Supergroup overlies the synrift strata over the entire region (Schwalb, 1982; Shaver, 1985; Noger and Drahovzal, 2005). The Knox is a platform to

passive-margin succession, composed predominately of carbonate (mostly dolomite), with minor amounts of mature, quartz-rich sandstones.

A short but apparently intense regression followed, which led to the subaerial exposure and erosion of Lower Ordovician dolomites and limestones, producing a widespread regional Knox Unconformity. This unconformity marks the top of the Sauk Sequence of Sloss (1963). At the beginning of the Middle Ordovician, rising sea levels led to deposition of a transgressive succession consisting of near-shore sandstone followed by argillaceous limestones and dolomites of the Ancell Group (St. Peter Sandstone, Dutchtown Formation, and Joachim Formation), and later by the broad carbonate-bank facies of the Black River and Trenton Formations. By the Late Ordovician, however, the Taconic Orogeny (Sloss, 1988) that was occurring to the east in the incipient Appalachian Mountains had supplied sufficient clastic detritus to the midcontinent that the region was flooded with muddy facies of the Maquoketa Shale (Freeman, 1953; Kolata et al., 2001).

In the Early Silurian, a shallow-water environment existed within the Illinois Basin, lasted through the Middle Devonian, and produced warm-water, shallow-marine deposits of limestone and dolostone, with minor amounts of sandstone and shale. These units include the Brassfield and Laurel Dolomites, the Osgood and Moccasin Springs Formations, and the Sexton Creek, Louisville, Bailey, Flat Gap, Grassy Knob, Backbone, Clear Creek, Jeffersonville, and Sellersburg limestones (Seale, 1981).

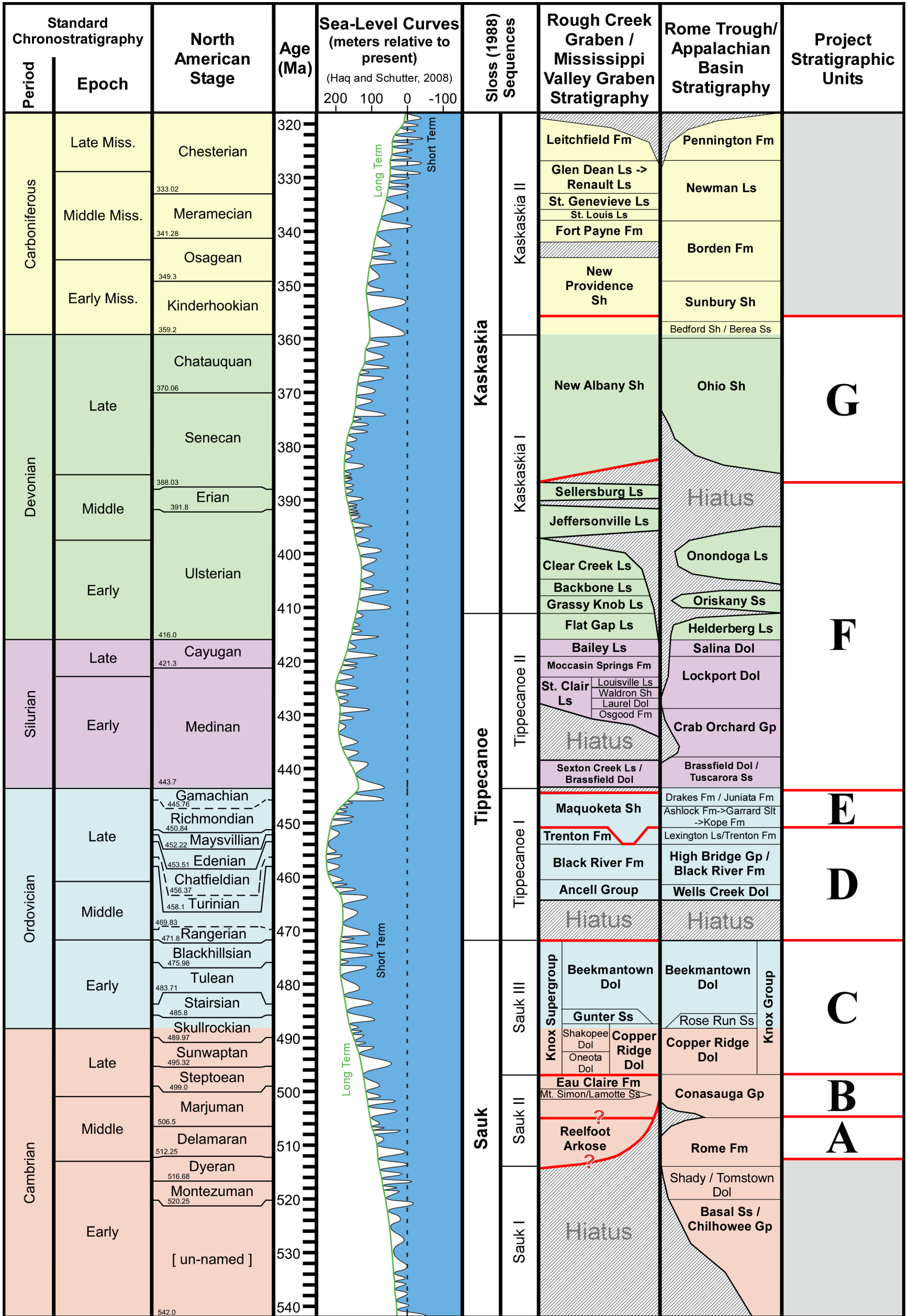


Figure 1.3 - Geologic Time Scale used in this study. Stratigraphic horizons mapped in this study highlighted in red. Ages of Kentucky stratigraphy from Greb et al. (in press), sea level curves from Haq and Schutter (2008), North American/Laurentian Stage names and ages from Davydov (1996), Gradstein et al. (2004), Webby et al. (2004), and Ogg et al. (2008). North American sequence names and ages from Sloss (1963, 1988).

As sea level rose during the Middle Devonian, deeper water environments returned to the region (Sloss, 1988). Extensive organic-rich deposits of prodeltaic black shales (New Albany and New Providence Shales) were formed on the midcontinent during the Middle Devonian to Early Mississippian (Cluff et al., 1981; Hasenmueller, 1993; Morse, 1995). This time was coeval with the subsidence of the Illinois and Appalachian Basins and the subsequent formation of the Cincinnati Arch and uplift of the Nashville Dome. An estimated 500 feet of Devonian through Ordovician strata was removed from the Nashville Dome through erosion during this time (Stearns and Reesman, 1986). The uplift of the arches and domes adjacent to subsiding basin areas lead to extensive depositional thickening of the Devonian black shale in the Illinois and Appalachian basins.

Throughout the Middle to Late Mississippian, dropping sea level lead to the deposition of progressively shallower water sediments across the region (Atherton and Palmer, 1979; Sable and Dever, 1990). Following New Albany/Ohio Shale deposition, prograding deltaic siltstones of the Fort Payne/Borden Formations were deposited. As water depth decreased, the St. Louis and St. Genevieve limestones were deposited in the Middle Mississippian. These carbonate units were then followed by alternate sandstones and limestones of the Chesterian Stage, including the Renault Limestone, Bethel Sandstone, Paint Creek Limestone, Cypress Sandstone, Golconda Formation, Hardinsburg Sandstone, Glen Dean Limestone, Tar Springs Sandstone, and Vienna Limestone.

Additional post-Mississippian tectonic events that affected the geology of this area include the compressive Alleghenian and Ouachita Orogenies (Late Mississippian through Permian) (Sloss, 1988), and the tensile tectonics associated with the extensional basins along the Atlantic coastal plain (Late Triassic), and opening of the Gulf of Mexico to the south (Triassic and Jurassic) and the Atlantic Ocean to the east (Late Jurassic to Early Cretaceous) (Thomas, 2006). Numerous ultramafic intrusions within the fluorspar district of western Kentucky have been dated as Early Permian in age (Zartman et al., 1967; Kolata and Nelson, 1997). Whether this magmatic activity was related to the Ouachita compression or the later extension related to the breakup of Pangea is unknown.

1.4 Oil & Gas Exploration History

All of the data used within this project (with the possible exception of potential fields maps) were originally collected for, or produced from, the exploration projects of commercial oil and gas producers. The petroleum history of western Kentucky began in 1856, when a plant in Breckinridge County began distilling kerosene and paraffin from canal coals (Miller, 1919). Also that year, the first State Geologist of Kentucky, David Dale Owen, described the tar sands of Edmonton County (Owen, 1914). In 1865, natural gas was discovered in Webster County, Kentucky (Orton, 1891); and although the operator chose not to produce it, the first oil well was drilled in western Kentucky, near Calhoun in McLean County (Eyl, 1922). The first commercially produced oil well in western Kentucky was not drilled until 1912 in Hartford, Ohio County, Kentucky (Smith, 1968).

Deep drilling to explore pre-Knox strata in the Rough Creek Graben began in 1974 with the Texas Gas Transmission #1 Herman Shain well. This dry hole was drilled in west-central Grayson County, Kentucky; about 2.6 miles south of the Rough Creek Fault Zone and penetrated 5,120 feet of Eau Claire Formation shales and limestones before reaching total depth.

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

In 1977, the Exxon Minerals Co. #1 Choice Duncan well was drilled in Webster County, Kentucky. The Duncan well was drilled 1.9 miles southwest (local strike of fault set ~N60W) of the Rough Creek Fault Zone. This well reached total depth at 15,200 feet after penetrating 2,690 feet of Eau Claire. No hydrocarbon shows were reported for this

well, and Exxon did not drill any more deep wells within the Rough Creek Graben. This well remains the deepest well drilled in the state of Kentucky.

Four years after the completion of the Duncan well, the Sun Oil Company drilled the #1 Stephens, W.W. & Lillie M. well in 1981. Unlike all of the other deep wells drilled within the graben, this well was drilled away from the intensively deformed and faulted Rough Creek Fault Zone in Caldwell County, Kentucky. 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 (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, Inc. began their deep drilling program in the Rough Creek Graben. Three wells were drilled just south of the Rough Creek Fault Zone during the next three years. The first drilled was the Conoco #1 Turner well in McLean County, Kentucky. The Turner well was drilled about 1.8 miles 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. This basement test well was targeting lower Eau Claire Formation carbonate shoal facies and clastic rocks of the Reelfoot Arkose. Although some oil staining and potential residual bitumen were discovered in core, all potential reservoir zones were tight with no oil or gas shows, and the well was plugged and abandoned.

The second Conoco well was the #1 Issac Shain in west-central Grayson County, Kentucky, drilled in 1993. This well was drilled 1.4 miles south of the Rough Creek Fault Zone and 1.2 miles north of the earlier Texas Gas Transmission #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 feet in the Eau Claire Formation. This well drilled through 4,651 feet 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 feet. Near total depth (TD) of 12,622 feet, the well penetrated what was described on the mud log as an altered (metamorphosed) granite wash and other sands. This geologic description is similar to that of the Reelfoot Arkose; however, reflection seismic data indicate that the top of the Reelfoot at the Shain well location is at about 13,050 feet depth, 428 feet below TD.

The final deep well Conoco drilled was the # 4-1 Einhart Dyhrkopp well in Gallatin County, Illinois. This well was drilled about 1.5 miles south of the surface exposure of the Rough Creek-Shawneetown Fault Zone in the northwestern corner of the Rough Creek Graben. This well also cut at least two faults and reached TD at 14,185 feet on the footwall block (Precambrian igneous basement) after penetrating 740 feet of Eau Claire Formation and 88 feet of Reelfoot Arkose. Similar to the other two Conoco wells, this was also dry and abandoned.

2 DATA AND METHODS

2.1 Well Data

The maps described in the following text are the result of incorporating numerous types of data into a single, comprehensive interpretation. The project includes interpreted stratigraphic tops from 1,764 wells across the Illinois Basin and adjacent regions ([Figure 2.1](#), [Plate 1](#)), including 489 wells with Lower Ordovician and older tops. Using available geophysical well logs, driller's logs, and core or cuttings descriptions, stratigraphic tops were picked for the major mapped horizons, as well as several secondary-level tops useful for local correlations.

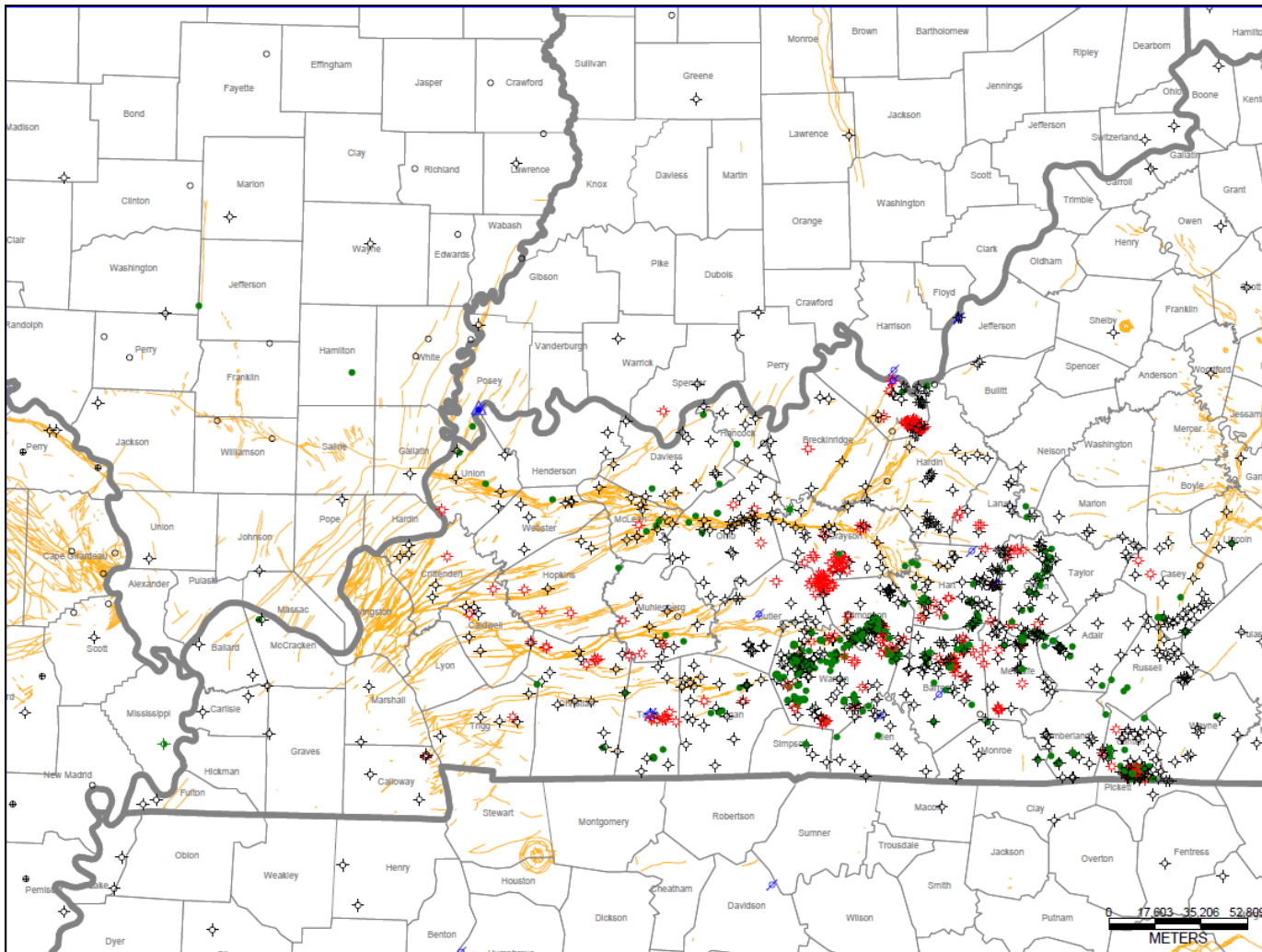


Figure 2.1 - Locations of wells with interpretations of stratigraphic tops. Mapped surface faults marked in orange, gas wells marked in red, oil wells marked in green, injection wells marked in blue, and dry (abandoned) marked with black symbols.

2.2 Seismic Data

The 106 seismic reflection profiles used in this project have been compiled by the Kentucky Geological Survey (KGS) from numerous sources over the past 20+ years. With the exception of the KyCCS data in Hancock County, all of the data used have been donated to KGS in "permanent loan" agreements which allow for internal research but not distribution, reproduction, or sale of the data. The KyCCS data were acquired by KGS as part of its ongoing CO₂ sequestration research, and KGS has full rights to that data set.

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

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

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

DIB (Deep Illinois Basin prospect, Seismic Specialists, Inc.) - KGS has copies of nine of these seismic lines which combine into two north-south, and two northwest-

southeast regional surveys across the Fluorspar District and adjacent areas of southern Illinois. The data quality for these lines is good to very good. The combined line lengths for the northwest-southeast lines are more than 45 miles.

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

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

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

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

Vastar – Six of the seven lines of this data set are in southern Indiana, and the seventh is across the Jefferson/Shelby County area of Kentucky. All are entirely outside of the graben, but are mentioned here because of their good quality and as control

for structural and stratigraphic interpretations away from the major fault systems within the rift system.

In addition to the previously existing seismic data used for this project, a Vertical Seismic Profile (VSP) from Hancock County, Kentucky, was used to help constrain stratigraphic correlations and the time-to-depth conversions for the Hancock, Breckinridge, and Ohio Counties area, north of the Rough Creek Fault zone.

2.2.1 Time horizons

Synthetic seismograms were produced using bulk density and sonic logs from several deep wells that are located close to one or more 2-D seismic lines within the KGS inventory. By matching seismic wavelet character and estimated travel times, these seismograms facilitated the correlation of the major stratigraphic tops onto the seismic lines ([Figure 2.2](#)). These seismic tops were then interpreted as far as possible across 106 seismic lines, totaling more than 900 miles of profiles in western Kentucky, southern Indiana, southern Illinois, and northwestern Tennessee ([Figure 2.3](#)).

2.2.2 Velocity analysis

Using the Petra[®] family of mapping, petrophysical, and seismic software from IHS/GeoPlus Inc., average surface-to-horizon velocities were computed using the elevations of the mapped tops from wells and the time horizons from the seismic data ([Table 2.1](#)). 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 and/or lines were added as necessary to maintain a geologically reasonable output and minimize any "edge effects" created by fault or survey area discontinuities. The two-way-travel times from individual seismic shot points were multiplied by the velocity value from the grid (at the same X/Y 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 (MSL).

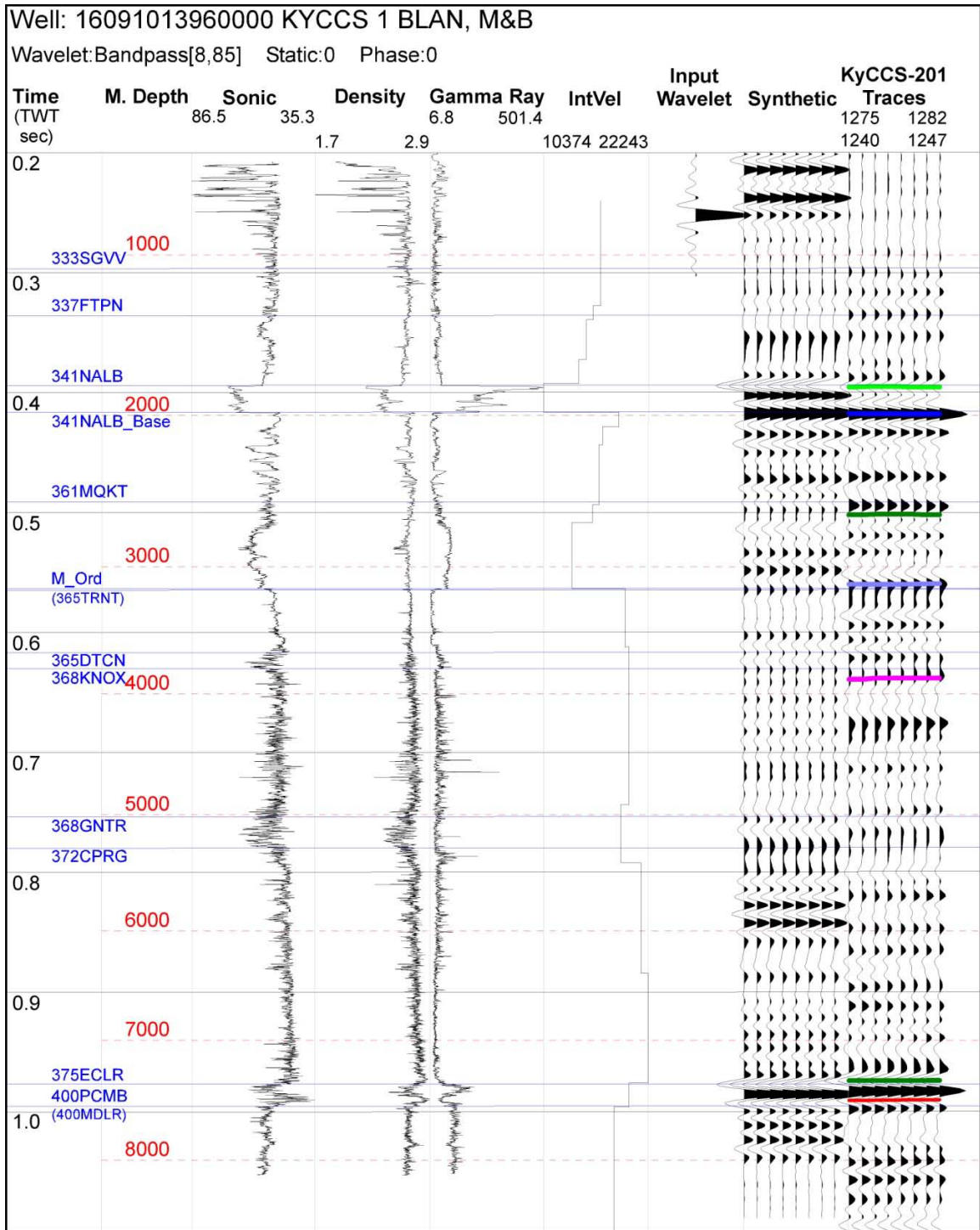


Figure 2.2 - Synthetic seismogram for the KyCCS #1 Blan well, with extracted wavelets from the nearby KyCCS-201 seismic line. The colored lines on extracted L-201 traces are the interpreted time horizons of the mapped units (excluding the Reelfoot Arkose).

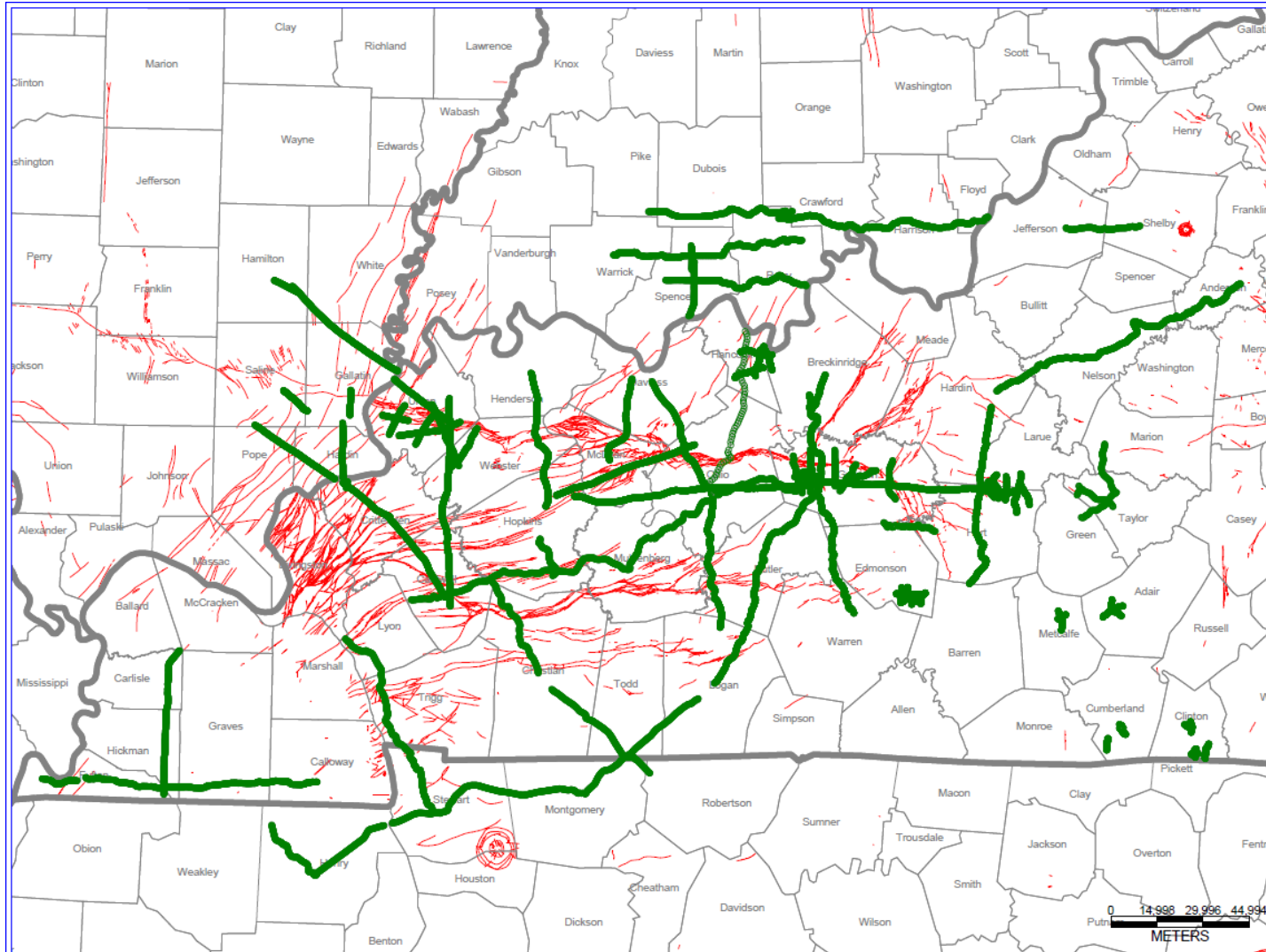


Figure 2.3 - Locations of proprietary seismic profile data used in project (bold green lines).

Table 2.1 - Stratigraphic and seismic correlation within 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 time values at well locations to calculate an average datum-to-horizon two-way-travel velocities for that location ($[\text{top depth below seismic datum}]/\text{TWTT}$)
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 MSL) of stratigraphic horizon by subtracting the measured depth (step 8) from the seismic datum elevation

The method described above worked well outside of the rift grabens where wells drilled to basement are more common and seismic horizons are shallower than one second TWTT. For the deeper horizons within the graben areas, limited well penetrations produce greater uncertainty in velocity calculations (and therefore subsea depth calculations) using the above described method. A different technique was used produce the Reelfoot Arkose and Precambrian basement maps within the Rough Creek and Mississippi Valley Grabens. Interval velocities were calculated directly from reflection seismic data to reduce possible errors in the depth and isopach calculations below the Eau

Claire Formation. Using RMS stacking velocities published on processed seismic profiles in a Dix Equation layered sequence, interval velocities were calculated for seismic intervals that had been interpreted as the Eau Claire Formation and the Reelfoot Arkose. This technique aided in both depth calculations and for the interpretation of the lithology of deep geologic units.

$$\text{Dix Eqn: } V_{\text{int}(n)}^2 = ((V_{\text{rms}(n)}^2 * t_{0(n)}) - (V_{\text{rms}(n-1)}^2 * t_{0(n-1)})) / (t_{0(n)} - t_{0(n-1)})$$

Where:

n = velocity layer number (value of one at surface and increases downward)

$V_{\text{int}(n)}$ = calculated interval velocity of layer “ n ”

$V_{\text{rms}(n)}$ = RMS stacking velocity for layer “ n ”

$t_{0(n)}$ = two way vertical travel time to reflector at top of layer “ n ”

This method was tested at a few chosen locations near deep wells with ample data and known subsurface lithologies. Satisfied with the results, interval velocities were calculated for 1,151 depth ranges (in time) from eleven regional seismic lines.

Depending on location, depth of resolution, etc., the input RMS velocity values for every ~ 200 shot points were used for the calculations. These RMS sets ranged from 4 to 28 layers per location (varies by area, processing company, etc.); seven to eight layers are the most common. Using these velocities, probable lithologies have been estimated with the help of some geologic inference (no igneous rocks above Eau Claire, zones including parts of the Knox Supergroup contain dolomite, etc.). Although this sonic-velocity method of lithologic identification is not necessarily definitive (there are overlaps in the velocity ranges of some rock types), any additional information for these deep horizons will aid in interpretations of depositional history.

The calculated velocity values for the Eau Claire Formation and what was later interpreted to be 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 isopach thickness of the Reelfoot was then calculated by multiplying these two gridded data sets.

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

Where:

Z = stratigraphic thickness (feet)

Δt = interval travel-time (seconds)

V_{int} = calculated interval velocity (feet/second)

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

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

The estimated interval velocity values from Dix equation process also aided in the interpretation of the Reelfoot Arkose within the Rough Creek Graben. The Reelfoot Arkose had been defined in Missouri (Weaverling, 1987; Houseknecht, 1989) and interpreted as far north and east as southern Illinois from well cuttings. A high amplitude

and laterally extensive seismic reflector package below the Eau Claire Formation represented an as yet undefined formation above igneous basement but below the Eau Claire Formation in the eastern Rough Creek Graben counties of Butler, Edmonson, and Grayson, Kentucky. The seismic velocities within 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. This seismic unit was later interpreted westward and a complete map of the depositional area has been interpreted from these data.

2.3 **Faults**

Numerous scales of faults and faulting were used in this study and analyzed in the following discussion. The fault grouping hierarchy listed below will be used in an attempt to clarify the subject. These categories, from largest to smallest are:

Fault system* - entire continuous faulted trend, regional scale

Fault system segment - genetically related trend of faults, group maintains consistent strike across length of segment

Fault set - collection of faults within an area with the same strike, no genetic relation or interconnectedness implied, local scale

Fault zone* - map area of direct deformation from a fault or faults, i.e. gouge or cataclastic zone

Fault plane or trace - single fault surface, expressed in 3-D (plane) or 2-D (trace)

Fault segment - a part of a fault plane or trace with a consistent strike direction (usually only used on curvilinear, complex faults)

* Specific location names (including the use of “Zone” or “System”) supersede this terminology, and will be identified by capitalization.

Similar to other intracratonic rift basins, the features within the Rough Creek Graben that most affect the facies and sedimentation patterns the most are the basement fault systems ([Figure 2.4](#)). The Rough Creek Graben has undergone numerous tectonic events which have produced thousands of faults. Some of these faults probably moved only once, but many more have been reactivated and/or inverted at least once leading to a highly complex structural arrangement of faults. Trying to accurately map individual subsurface offsets from all of these faults is not possible because of both a lack of data for each individual fault block mapped at the surface, and the immense computing power that would be needed to process such a large dataset. Using too few (or no) faults, however, would lead to inaccurate and unrealistic maps. To complete this project, a more generalized fault set was needed to differentiate regionally significant “major” faults from less significant “minor” faults.

Surface fault locations from 1:24,000 Geologic Quadrangle maps and interpreted faults from seismic profiles provided the bulk of the fault location information. The complex array of mapped surface faults was examined for local offset magnitude and direction, as well as proximity to other faults. Local groups of “minor” faults with similar strike and sense of offset were assumed to have acted as a group and were simplified into a single “major” fault. Singular faults with relatively small offsets (< 100 feet) were ignored, but those with larger offsets were treated as faults.

For basement faults that do not reach the surface (and do not cross a seismic line), a combination of magnetic intensity data, Bouguer gravity anomaly data, and the 1:24,000 structure contour data from the project area was used. With these three data sets loaded into a GIS project (ArcMap), extensive linear trends (across two or more 7.5' quadrangles) with a high degree of structural slope were identified throughout the study area ([Figure 2.5](#) and [Figure 2.6](#)).

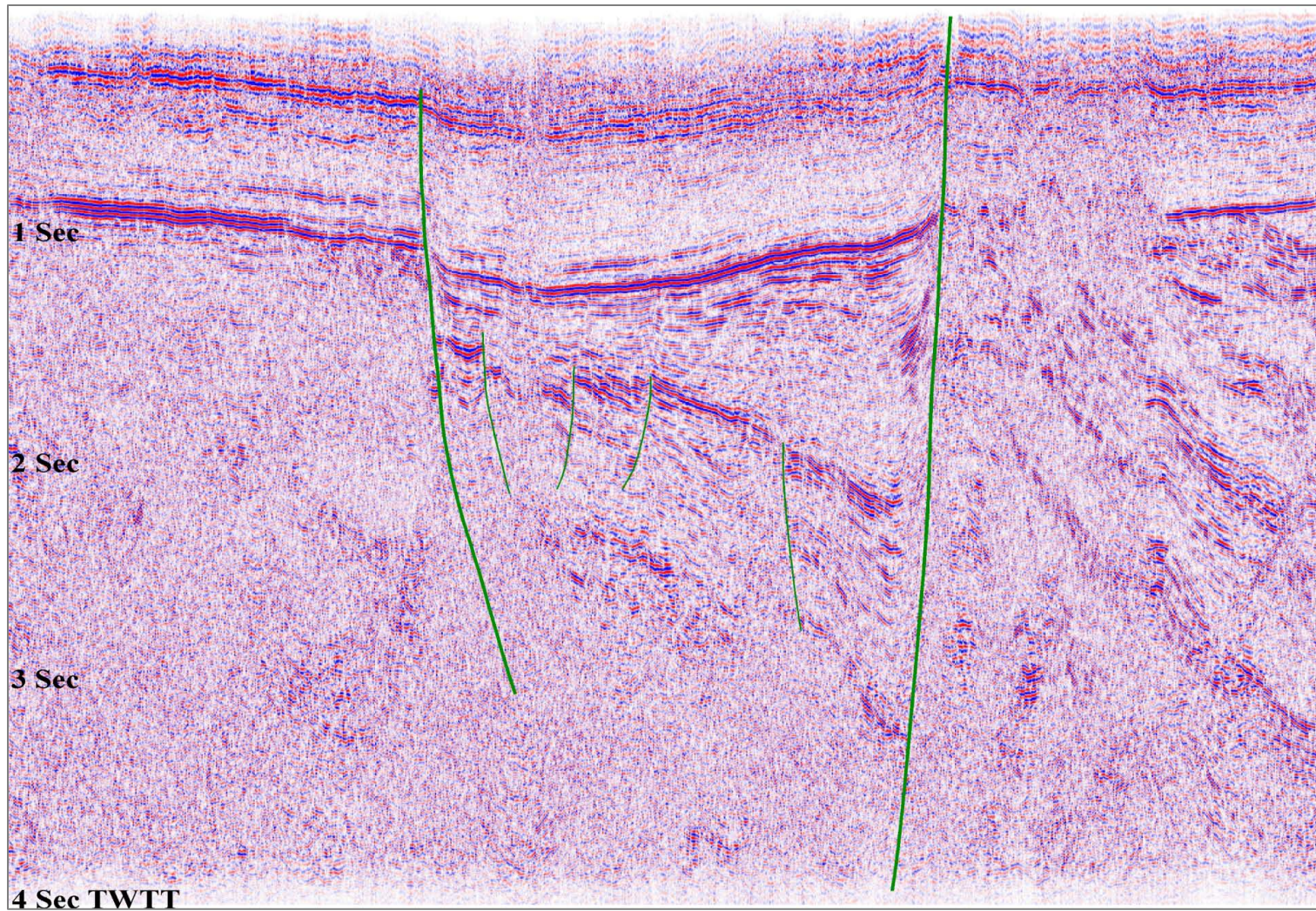


Figure 2.4 - Simplified seismic profile across Rough Creek Graben illustrating major offsets along basement faults. Profile is approximately 100 km long, north is to the right.

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

In the subsurface, a similar technique was used to separate “minor” from “major” faults resolvable on the seismic lines. Where necessary because of a lack of seismic data, potential fields maps (Plates 17-19) were used to help constrain the strike and lateral extent of faults interpreted from 2-D seismic lines. Finally, in the map compilation and gridding process, abrupt and dramatic elevation contrasts along a linear trend were also treated as “major” faults. The traces of these major faults were then used in the gridding process to produce fault discontinuities in the mapped surfaces. Four vertically ordered fault trace collections were used in this project; one for only the New Albany Shale interval, one for the New Albany through Knox section, one for the Eau Claire through Precambrian section, and a final set for the faults within the New Madrid Seismic Zone. Using different faults sets for different stratigraphic intervals compensated for lateral changes in fault position with depth because of fault dip ([Figure 2.7](#)). This also allowed faults that did not necessarily penetrate shallow horizons to be used for deeper layers. See [Plate 1](#) for the generalized fault trends.

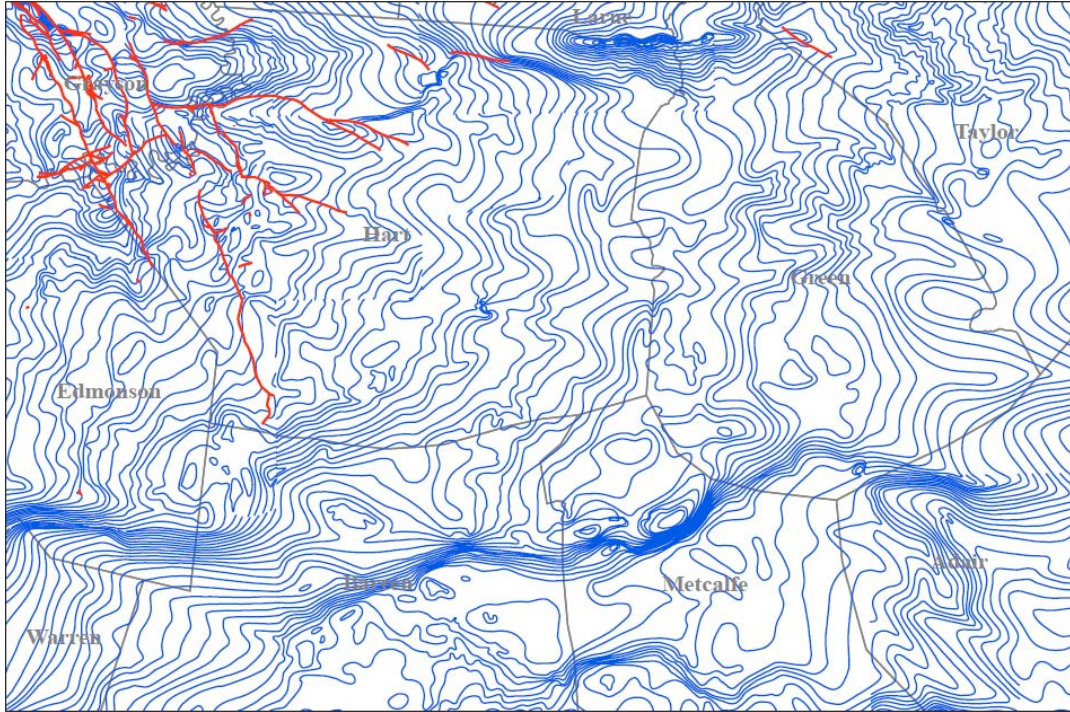


Figure 2.5 - Surface mapped faults (red) and structure contours (blue) in west-central Kentucky. Structure contours displayed map produced from various structural datums.

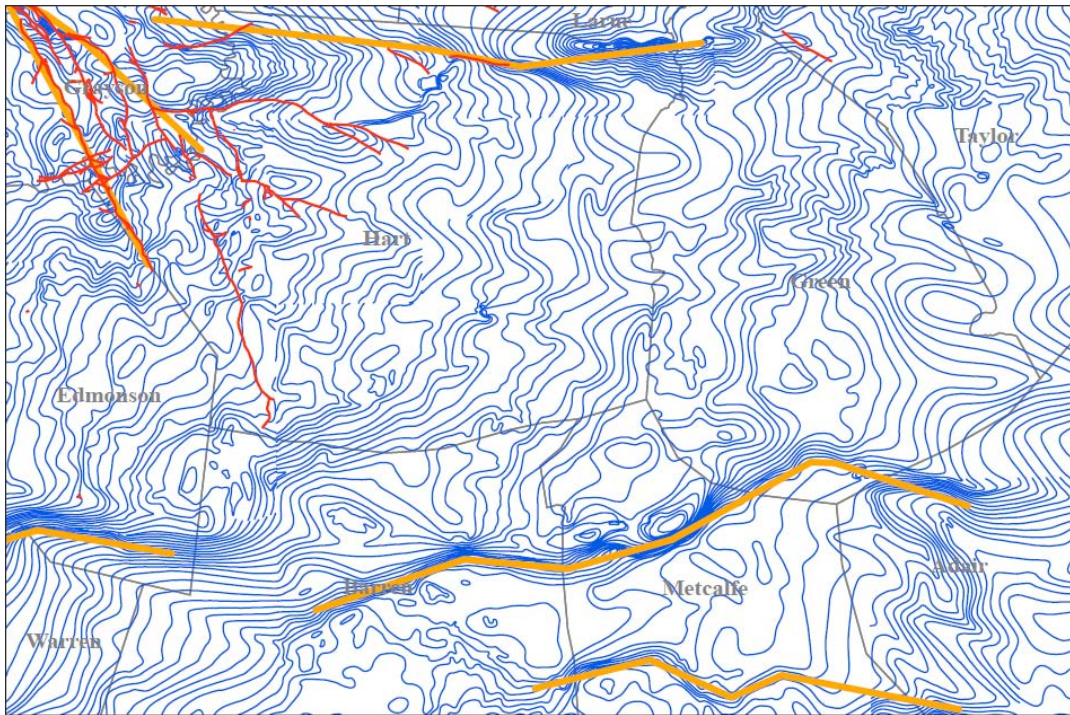


Figure 2.6 - Surface mapped faults and structures from previous figure, with interpreted subsurface fault zones in orange.

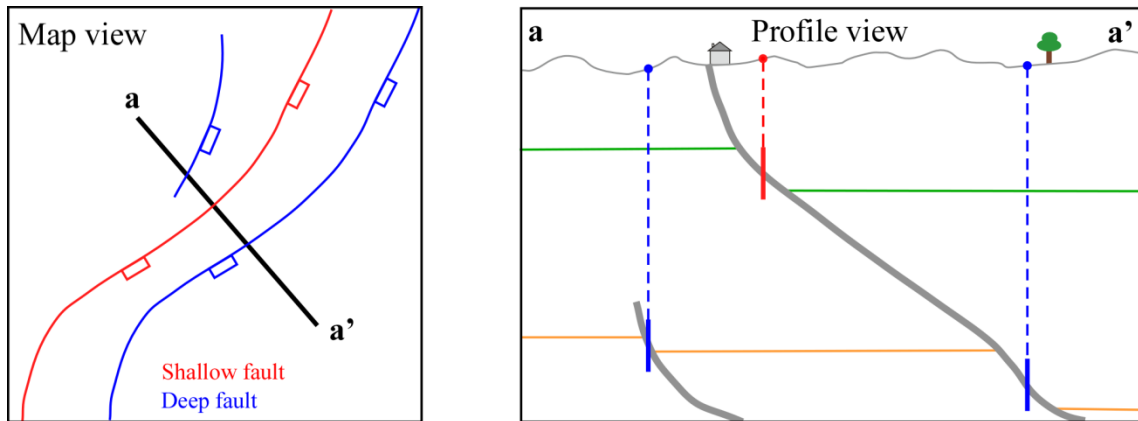


Figure 2.7 - Idealized map and cross section display illustrating use of using different GIS fault traces with depth for the same and different faults.

2.4 Mapping Techniques

After both stratigraphic well tops and seismic horizon time values had been converted into subsea feet elevation units, the seismic and well data point sets could be combined and treated as single data type. Using Petra[®], 480.0 by 363.2 km gridded areas across the project area (300 by 227 cells with 1,600 meter sides) were produced for each mapped stratigraphic horizon using all of the available data. An inverse distance-squared ($1/d^2$) weighting algorithm (the "Highly Connected Features" function in Petra) was used to produce the grid surfaces. Surface discontinuities were included along the fault line sets (see section [2.3 above](#)) to allow for vertical offsets of the mapped horizon. The fault lines act as barriers to the $1/d^2$ search function, removing the influence of 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. These stratigraphic horizon grids are represented in both the map plates (Plates 2-16), and in the grid profiles displayed on the cross sections (see Chapter [4 below](#)).

Only regional stratigraphic units that are resolvable on seismic reflections were mapped. For the Ordovician through Mississippian strata, many more units were interpreted from

well logs than was possible to trace with current seismic resolution. These tops are included with the well data and are displayed on the wells in the geologic cross sections. See [Table 2.2](#) for a list of well and seismic stratigraphic tops interpreted for this project.

All of the maps in this report are displayed in Universal Transverse Mercator (UTM) Zone 16 North projection on a North American 1983 Datum (NAD-83). The "X" and "Y" values for surface locations are in meters and all "Z" elevations are in feet relative to mean sea level (MSL). Imperial units of feet were used for "Z" elevations instead of metric meters because all of the well data (mudlogs, geophysical well logs, etc.) are recorded in feet.

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, Ansell Group	253	Wells only
Dutchtown Formation, Ansell Group	235	Wells only
St. Peter Sandstone, Ansell Group	128	Wells only
Lower Ordovician		
Beekmantown Dolomite, Knox Supergroup	293	Wells & Seismic
Gunter Sandstone, Knox Supergroup	50	Wells only
Upper Cambrian		
Copper Ridge Dolomite, Knox Supergroup	128	Wells only
Eau Claire Formation	82	Wells & Seismic
Middle Cambrian		
Mt. Simon Sandstone/Lamotte Formation	48	Wells only
Reelfoot Arkose	9	Wells & Seismic
Precambrian		
Precambrian basement (undifferentiated)	61	Wells & Seismic

Table 2.2 - Stratigraphy used for regional mapping and analysis, including the number of well tops used and data source types for each horizon.

2.5 Potential Fields data

Four public domain potential fields data sets were used in this study: the USGS Midcontinent magnetic surveys, Tennessee Valley Authority (TVA) High Resolution Aeromagnetic (HRAM) data set, USGS Isostatic Residual gravity, and USGS Bouguer gravity anomaly data sets. These data were used to constrain the strikes and lateral extents of major faults that were interpreted to cross seismic profiles and to define major graben boundary faults where no seismic data are available.

The TVA aeromagnetic data were recorded between 1972 and 1978. These total magnetic field intensity (TMI) data were later reprocessed and corrected for temporal variations in magnetic intensity by Parker Gay of Applied Geophysics, Inc. of Salt Lake City, Utah. The flight line point data were gridded into a mathematical surface using ESRI ArcMap[®] software by KGS researchers. Because of gaps between flight lines and the intention to produce a continuous surface, a grid sample size of 2.5 km (1.55 mi) was used.

The USGS aeromagnetic data were "compiled from various sources" to produce the *Geophysical Investigations Map GP-948 - Aeromagnetic Map of East-Central United States* (Hildenbrand et al., 1981) and include some of the earlier TVA data. This TMI data set covers most of the Rough Creek Graben (west of Green County) and all of the Mississippi Valley Graben within the study area. Close data and no data gaps permitted a much higher resolution grid, an 800 m (0.5 mi) cell sample size, than was possible with the TVA data. With the assistance of Dr. D. Ravat of the Department of Earth and Environmental Sciences at the University of Kentucky, Reduced-to-Pole ([Plate 17](#)) and Second Vertical Derivative ([Plate 18](#)) magnetic values were calculated.

The magnitude of Earth's magnetic field at any one location can be described as the sum of three perpendicular component vectors: X (east), Y (north), and Z (vertical). At the equator, the field is near horizontal ($Y \gg X, Z \approx 0$); whereas at the magnetic poles the magnetic flow vectors are approximately vertical ($X=Y \approx 0$). The Reduced-to-Pole process is a mathematical transformation of the Total Magnetic Field Intensity to calculate the Z component of the field. By using only the vertical component vector, the

anomalies represented in the magnetic survey are displayed so that they are directly above the anomalous structure, aiding in the resolution and definition of large subsurface fault offsets (or igneous intrusions, subsurface voids, etc.). The Second Vertical Derivative magnetic survey maps are a representation of the vertical rate of change of the RTP data. This type of display can produce erratic values for near-surface targets, but can be very useful in defining deep crustal structures and boundaries. By using these two types of data representations together, a more thorough structural interpretation of the region was possible.

The USGS gravity survey data sets originally came from the DDS-0009 data series *National geophysical data grids; gamma-ray, gravity, magnetic, and topographic data for the conterminous United States* (Phillips et al., 1993). Gravity surveys are labor intensive and must be performed "on site" as opposed to aeromagnetic data that are recorded from moving airplanes or helicopters. This tends to lead to either smaller survey areas or wider spaced data points chosen for the survey. The USGS gravity data are no exception, and the sample size grids used to produce these map surfaces are 4,000 m (2.49 mi) on a side. Bouguer anomaly calculations are derived from these data.

A Bouguer Anomaly map ([Plate 19](#)) represents recorded gravity intensity data that have been corrected for elevation ("free-air" correction) and local topography (Bouguer correction); a theoretical reference field value is subtracted to produce the Bouguer anomaly map. Isostatic residual gravity anomaly maps have had long-wavelength anomalies removed from the data (after free-air and Bouguer corrections). Long-wavelength anomalies commonly are associated with isostatic compensation of topographic or tectonic loads. Removing these anomalies can produce higher resolution of near-surface structures while suppressing the effects of the deeper crust and mantle.

3 STRUCTURAL AND STRATIGRAPHIC MAPS

The map plates described in this chapter are structure contour maps of eight major stratigraphic horizons and the isopachous 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. In the following descriptions and discussion, all of the Early Cambrian through Early Mississippian strata are grouped into seven stratigraphic intervals referred to as units A through 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 Supergroup (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).

On Plates 2 through 16, areas where the mapped unit is absent because of either nondeposition or erosional truncation are indicated by the absence of a colored grid scale (i.e., white background). The 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 “null” areas absent of the target units on the elevation and isopach thickness grids, the outlines of the outcrop or pinchout areas generally have jagged edges and are not intended to precisely replicate the actual outcrop patterns. These grid edges, therefore, should 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 3.1](#), and the names and locations of major regional features discussed in this chapter are illustrated on [Figure 3.2](#). Plates 2 through 16 are discussed in the following 15 sections of this chapter, starting with the youngest unit (G) and progressing downward through older units to the top of Precambrian basement. The title of each section includes the number of the appropriate Plate being described.

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 geographical scope of this study (Figure 1.3). Unit A rocks are interpreted to have been deposited during the first half of the Sauk II sequence (Middle Cambrian), unit B is equivalent to the second half of Sauk II (Middle to Late Cambrian), and unit C represents Sauk III deposition (Late Cambrian to Middle Ordovician). The Tippecanoe I sequence (Middle and Late Ordovician) is split between units D (Middle Ordovician to early-Late Ordovician) and E (Late Ordovician). Unit F contains all of the Tippecanoe II sequence and the lower half of 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 sequences. Unit G corresponds to the middle of the Kaskaskia sequence, specifically late Kaskaskia I through early Kaskaskia II.

All of the data used to produce each horizon map are represented on the map plates discussed in this section. The well symbols printed on each map represent only wells that penetrated that horizon for interpretation. In a similar manner, shotpoint locations along seismic lines, where an interpretation of that seismic horizon was possible, are highlighted with small grey squares to distinguish them from locations where the unit is absent or unresolvable from the available data.

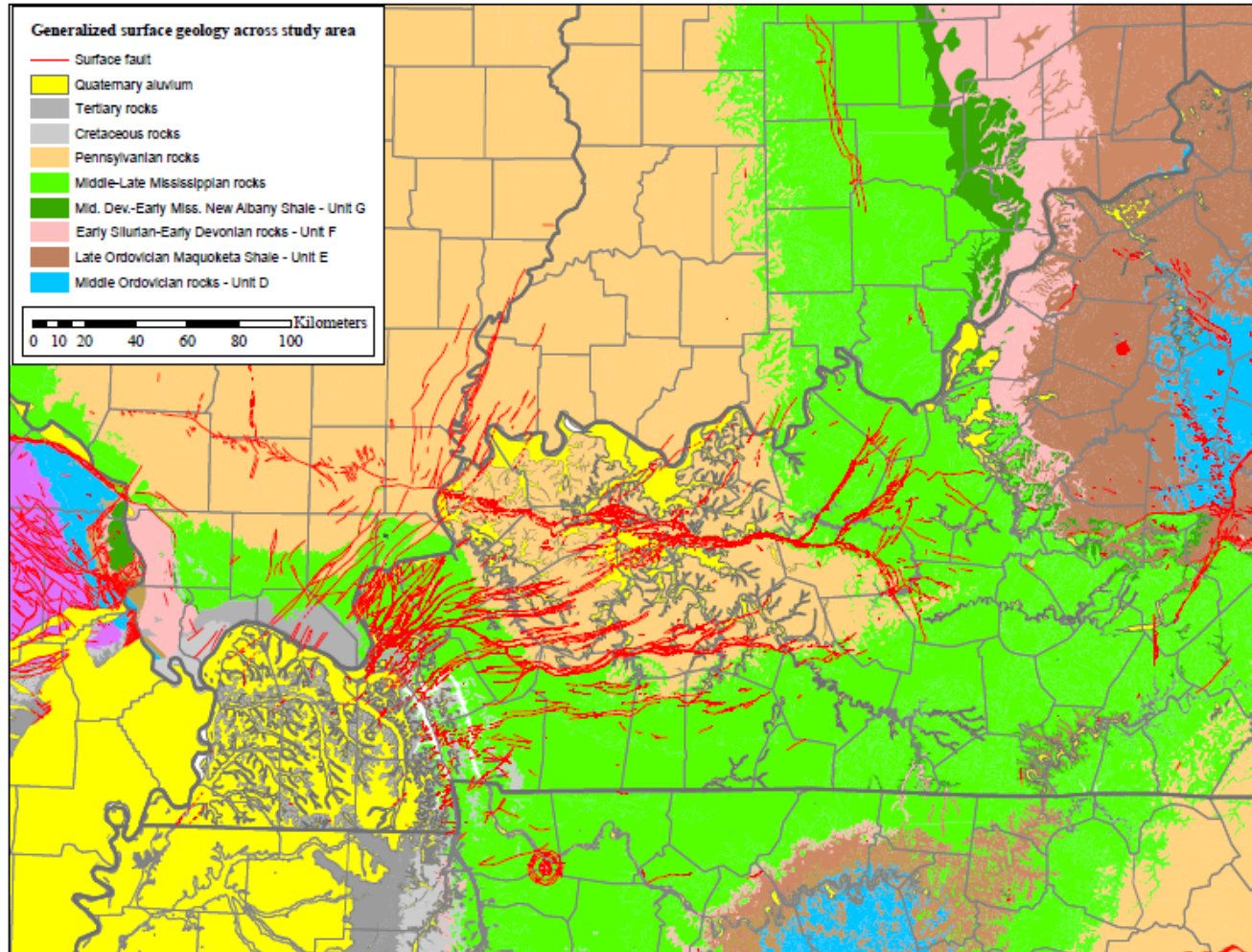


Figure 3.1 - Generalized surface geology across study area. The areas of surface exposures of units D-G delineate maximum extent of those subsurface horizon grids discussed in this chapter. Map GIS data compiled from the state geological surveys of Ohio, Kentucky, Indiana, Illinois, Tennessee, and Missouri and the U.S. Geological Survey.

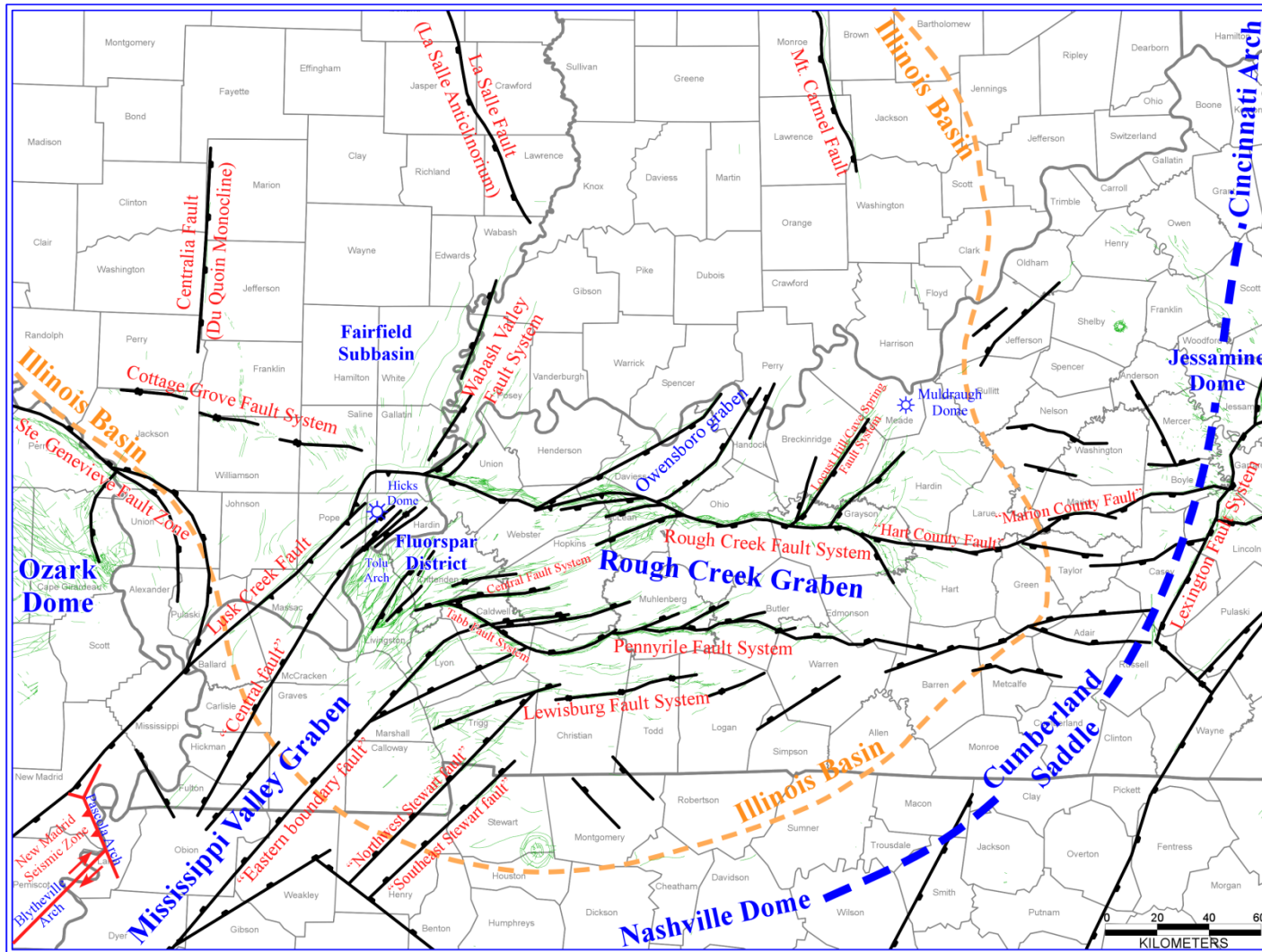


Figure 3.2 - Major structural features around the Rough Creek Graben and Mississippi Valley Graben.

3.1 Structure of the top of unit G ([Plate 2](#)), top of the New Albany Shale

The youngest stratigraphy mapped in this project is the Devonian New Albany Shale (unit G). Because of the 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 also has a strong well log response, especially on the three most common logs used in this region: gamma ray, neutron porosity, and bulk density logs. 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.

Within 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 ([Figure 3.2](#)). The regional shape of the Illinois Basin is roughly triangular at this level.

At the top of the New Albany, as well as for the deeper horizons, a dramatic difference in structural style exists between the eastern and western parts of the Rough Creek Graben. The general boundary between these two halves strikes northeast through northern Caldwell and Hopkins Counties, across the graben to northeastern McLean County, Kentucky. The western part of the graben (west of McLean County) has a highly asymmetric, north-dipping half-graben style of structure, whereas the eastern Rough Creek Graben is only slightly asymmetric and dips to the south. The deepest points of the New Albany are around -4,600 feet in the Fairfield Subbasin in White County, Illinois (outside of the graben complex), and around -4,400 feet in Union County, Kentucky, in the northwestern corner of the Rough Creek Graben. Fault offsets of the New Albany Shale within the major graben-bounding fault zones range from less than 200 feet along the Pennyrite Fault System on the south, to more than 400 feet in Union County and 500 feet in Grayson County, 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 northerly part of the Mississippi Valley Graben. For the remaining northern area, fault offsets appear to be around 100-200 feet 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-foot contour interval.

Uplifted blocks along the Rough Creek Fault Zone in Ohio and Grayson Counties, as well as a small uplifted fault block in Caldwell County have characteristics of traditional positive “flower” structures, a narrow band of faults that merge into a single plane at depth, generally associated with transpression along preexisting faults. In contrast, an uplifted area in McLean County is much wider but not bisected by as many faults and is locally around 600 feet higher than the upthrown side of the Rough Creek Fault Zone ([Figure 3.3](#)). Another post-Devonian structure, observable on this map, is the north-northwest striking Tolu Arch in Livingston and Crittenden Counties, Kentucky (Trace and Amos, 1984). The formation of this arch has been associated with the magmatism that produced the numerous Early Permian mafic dikes and sills within 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 feet at the top of the New Albany Shale. Similar amplitudes for this anticline are interpreted down as far as the top of the Knox Supergroup.

Other notable structures that can be seen at this level are the faults along the Du Quoin Monocline (Centralia Fault) and La Salle anticlinorium belt at the surface. These two roughly north-south faults in south-central Illinois constrain the down-warped Fairfield Subbasin ([Figure 3.2](#)).

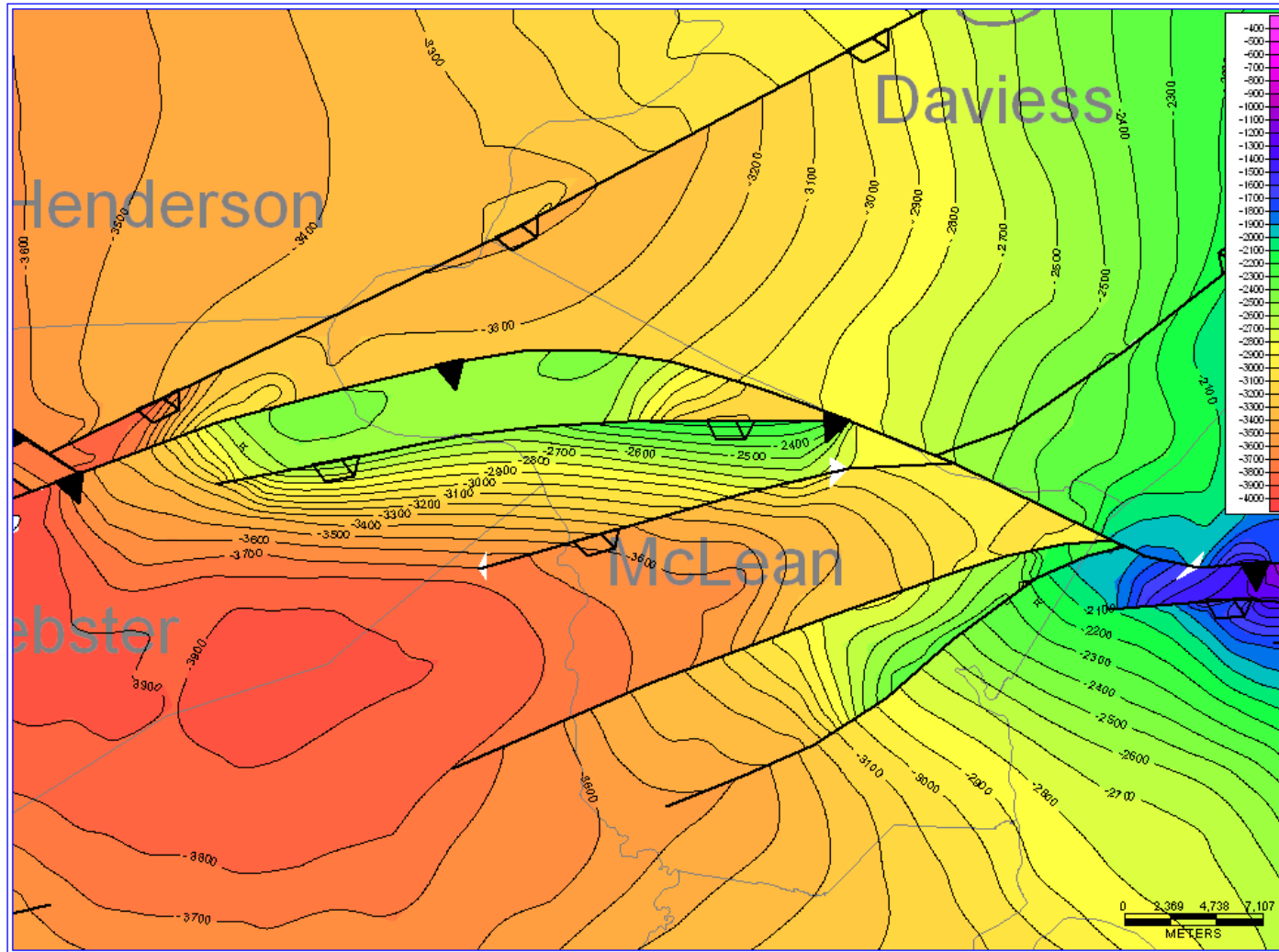


Figure 3.3 - Structural inversion structures along the Rough Creek Fault Zone at the top of the New Albany Shale (top of unit G, extracted from Plate 2).

One other structure shown on this map is the Muldraugh dome in northern Meade County, Kentucky (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 penetrating an undeformed Silurian dolomite directly overlying brecciated dolomite and chert of the Lower Ordovician Knox Supergroup indicating more than 1,550 feet 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.

3.2 Isopach of unit G ([Plate 3](#)), the New Albany Shale

The New Albany Shale in this region thins eastward onto the Cincinnati Arch (< 50 feet) 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 (as much as 500 feet in Crittenden County, Kentucky). This thickening within the graben suggests either syndepositional fault movement/subsidence, or possibly fault movement just prior to deposition, producing varied topography which the shale later filled.

Although unit G is the thinnest unit analyzed in this study, the relative percent of total thickness change across many of the Rough Creek Fault Zone faults is dramatic. In Ohio and Grayson Counties, Kentucky, wells separated by about 2.8 miles (4.5 kilometers) southward across the Rough Creek Fault Zone exhibit around a 20 to 40% increase in thickness southward. 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 within several wells that penetrated the deformed fault zone. These wells were not used in the thickening percent calculations, but the data from these wells produces some areas of chaotic contour patterns on the unit G isopach map within the intensively faulted Rough Creek Fault Zone in eastern Ohio and western Grayson Counties, Kentucky.

3.3 Structure of the top of unit F ([Plate 4](#)), base of the New Albany Shale

The New Albany Shale in the study area unconformably overlies a range of Late Silurian to Early 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. For the simplicity of discussion, the top of unit F will be 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 within the study area are around -4,800 feet within the Fairfield Subbasin, and around -4,400 feet within the Rough Creek Graben in Webster County, Kentucky. Graben-bounding fault offsets along the northern border are slightly less than at the top of the unit (~ 450 feet of normal offset in Grayson County, around 400 feet of post-Devonian inverted offset in McLean County, and around 300 feet in Union County, Kentucky). 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 New Albany Shale (200 and 100—200 feet, 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 and Ohio/Grayson Counties described for the top of the New Albany Shale are also expressed at the base.

3.4 Isopach of unit F ([Plate 5](#)), the interval between the base of New Albany Shale and the top of the Maquoketa Shale

This interval is comprised of shallow-water carbonate and clastic rocks, and dolostone is the dominant lithology. It includes the entire Silurian section and, in some areas, Early 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 Early Devonian unconformity, the New Albany Shale unconformably overlies the Maquoketa Shale, leading to difficulty in

distinguishing the base of the New Albany Shale from the top of the Upper Ordovician Maquoketa Shale in well logs. The unit is thickest in the Fairfield Subbasin (2,400 feet) and between Hardin County, Illinois, and Hopkins County, Kentucky, along the basinal axis of the Rough Creek Graben (averages 1,800 to 2,200 feet thick). In southern Indiana and Illinois, this section is expressed as a relatively uniform, wide body with thicknesses generally more than 1,000 feet.

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 within the fault bounded “Owensboro graben” (Greb, 1989) in Daviess and western Hancock Counties, Kentucky ([Figure 3.2](#)).

3.5 Structure of the top of unit E ([Plate 6](#)), the Maquoketa Shale

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

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

3.6 Isopach of unit E ([Plate 7](#)), 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. Between these two areas is a linear zone, the Sebree Trough (Kolata et al., 2001), where the Trenton is absent and a slightly thickened Maquoketa section apparently unconformably overlies carbonates of the Black River Group ([Figure 3.4](#)). Whether this is a true unconformity or rather a lateral facies change within 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, however, contain locally elevated thicknesses of unit E (Maquoketa Shale) 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 the unit E (Maquoketa Shale) is not uniform; however, the lack of basin-wide systematic 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 feet in central Illinois, to as much as 600-700 feet along the outcrop belt in central Kentucky. No significant thickness changes of the Maquoketa Shale are observed within the Mississippi Valley Graben.

3.7 Structure of the top of unit D ([Plate 8](#)), base of the Maquoketa Shale

Similar 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. Therefore, the top of unit D is mapped as the “base of Maquoketa” rather than the “top” of the geologic section below it. The base of the Maquoketa Shale defines the Sebree Trough feature across western Kentucky ([Figure 3.4](#)). 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 Sebree trend imply that it is depositional in nature and not tectonic in origin.

The top of unit D extends from outcrops around the Jessamine Dome and Nashville Dome down to -6,800 feet in the Rough Creek Graben in Union County, and down to -6,400 feet in the Fairfield Subbasin in White County, Illinois. Fault offsets along the Owensboro graben in McLean and Daviess Counties, Kentucky, are greater at this level than stratigraphically higher ones, making it more prominent. The general Illinois Basin and graben structure is very similar to the structure of the top of the Maquoketa Shale with a pronounced Cincinnati Arch and a highly asymmetric, north-dipping half-graben shaped basin west of the Owensboro graben and a more symmetrical synclinal graben shape to the east within the Rough Creek Graben. Fault offsets at the base of Maquoketa Shale along the Rough Creek Graben border fault zones are around 800 feet each in Union and Grayson Counties, and less than 100 feet in McLean County, Kentucky, and 200-400 feet along the Pennyrite Fault System. Interpreted fault offsets along the Mississippi Valley Graben are around 100-200 feet. The structurally inverted blocks within the Rough Creek Fault Zone are present, but much less pronounced than in the younger strata.

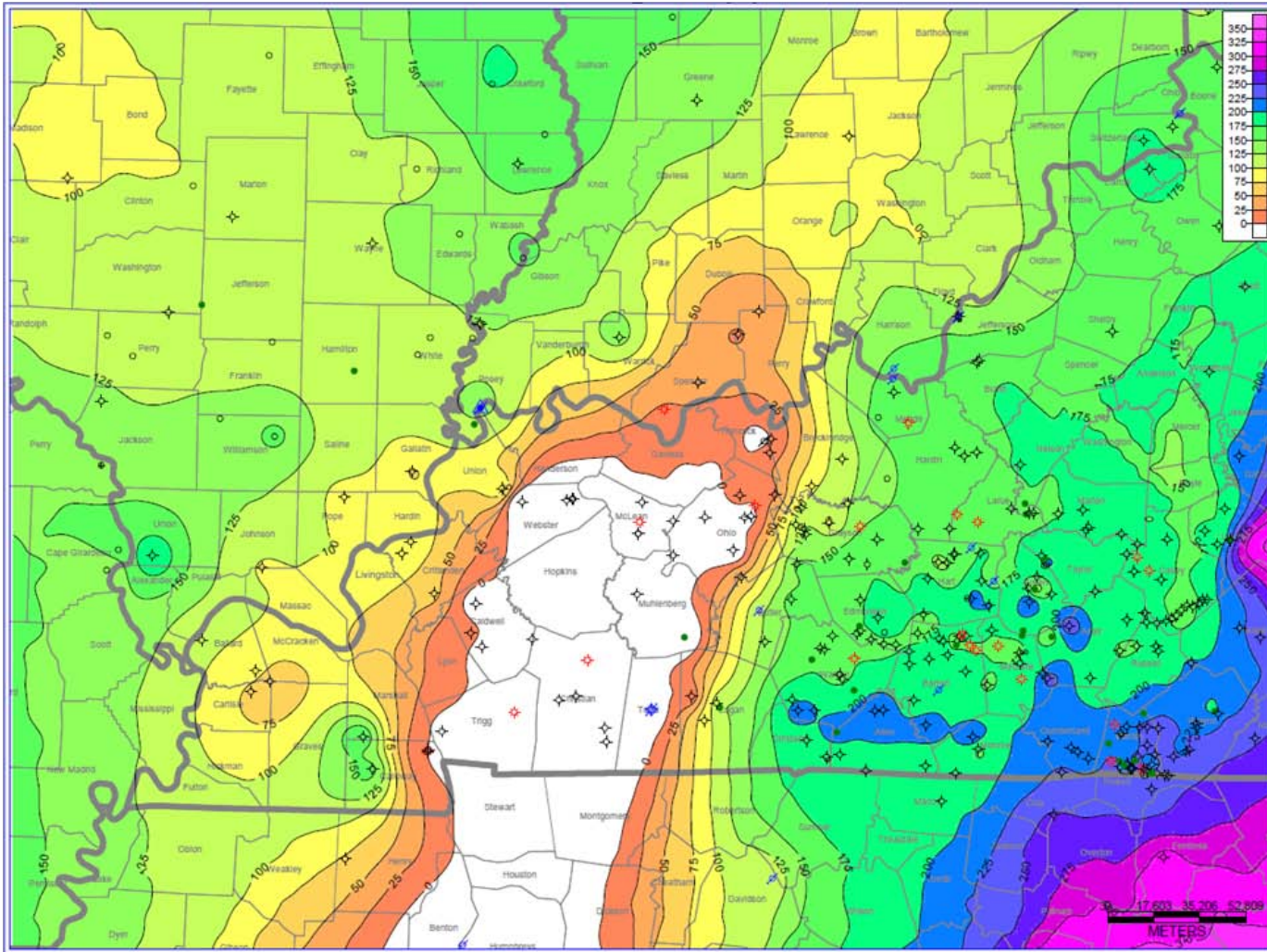


Figure 3.4 - Isopach of Trenton Formation (well data only). The Sebreer Trough is the region of thin to absent Trenton across center of the map.

3.8 Isopach of unit D ([Plate 9](#)), the interval between the base of the Maquoketa Shale and the top of the Knox Supergroup

Unit D encompasses all of the Middle Ordovician strata in the region including the Trenton Formation, Black River Group, Ansell Group, and Everton Formation (where present). The lithology of this unit is predominantly limestone, with only minor amounts of sandstone, shale, and dolomite. This section increases in average thickness toward the southern Illinois Basin and northern Mississippi Valley Graben. It has a maximum thickness of around 1,800 feet along some of the Mississippi Valley Graben bounding faults. Within the study area, the thinnest points are around 400 feet thick in the northeast and in an isolated area within the Sebree Trough trend in central Christian County, Kentucky. Locally, this unit thickens adjacent to faults on individual downthrown blocks within the Rough Creek and Mississippi Valley Grabens.

3.9 Structure of the top of unit C ([Plate 10](#)), top of the Knox Supergroup

The top of unit C, the Cambrian-Ordovician Knox Supergroup, is a regional unconformity surface that marks the top of the Sauk Sequence (Sloss, 1963). The deepest points are -8,000 feet in the Rough Creek Graben in Webster/Union County area, and -7,700 within the Fairfield Subbasin in White County, Illinois. The Knox is shallowest at 200 feet above sea level along the northern Cincinnati Arch and around 400 feet 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 feet along the Pennyriple Fault System in Muhlenberg and Christian Counties, 400 feet along the Rough Creek Fault Zone in Union County, 200 feet in Grayson County, to approximately zero feet of cumulative offset in McLean County adjacent to the Owensboro graben. Interpreted offsets along the borders of the Mississippi Valley Graben are less than 200 feet. The basin axis within the Rough Creek Graben is a curvilinear depression at this level, extending from close to the Rough Creek Fault Zone in Union County, Kentucky, southeastward to Hopkins County, from which point it extends eastward toward the Cincinnati Arch to at least Taylor County, Kentucky. The difference in structural styles 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 Supergroup. Southwest of the bold dashed line on Plate 10 within the Mississippi Embayment, erosion of Paleozoic strata along the sub-Cretaceous unconformity truncated the top of the Knox Supergroup in the central and southern parts of the Mississippi Valley Graben. Northeast of the bold dashed line, the top of the Knox Supergroup is defined by the regional Early-Middle Ordovician unconformity that forms the top of the Sauk Sequence of Sloss (1963) ([Figure 1.3](#)). Post-Ordovician, pre-Cretaceous uplift of the intersecting Blytheville and Pascola Arches ([Figure 3.2](#)) produced a small teardrop-shaped area centered in Lake County, Tennessee, where the Knox Supergroup (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).

3.10 Isopach of unit C ([Plate 11](#)), the Knox Supergroup

The rocks of unit C were deposited between the early-Late Cambrian and the latest-Early Ordovician ([Figure 1.3](#)). During this time, rising global sea levels (Haq and Schutter, 2008) lead to transgression across the study area. Within 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 to Lower Ordovician Knox Supergroup overlies the Early-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 predominately carbonate, with minor amounts of mature, quartz-rich sandstones. Within the project area, the Knox Supergroup is thickest at more than 11,500 feet in Carlisle County, Kentucky, along the northwestern, downthrown side of the Mississippi Valley Graben "Central Fault" ([Figure 3.2](#)). The thinnest points (including an area where the Knox is

absent) are along the Blytheville/Pascola dome because of truncation at the pre-Cretaceous unconformity. Another local area of thinned Knox is present in northern Ohio to Breckenridge Counties, north of the Rough Creek Fault Zone between the Owensboro graben and the Locust Hill/Cave Spring fault system, with a thickness of 3,000-3,500 feet. This area also has a thinned interval of Eau Claire Formation (unit B, see Section [3.12](#)), suggesting that this area was a paleo-high during the Late Cambrian reducing the accommodation space available for sediment accumulation.

Across the study area, the Knox Supergroup thickens toward, and into, the Rough Creek Graben and Mississippi Valley Graben. With the exception of the Rough Creek Fault Zone in Ohio and Union Counties, Kentucky, and the Centralia Fault in Jefferson and Marion Counties, Illinois, dramatic thickness changes across fault zones (implied syndepositional fault movement) are present only in the Mississippi Valley Graben. The majority of Knox Supergroup thickening, however, is not abrupt at graben-bounding fault systems, but gradual (around 100 feet/mile 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 cut locations from these differing fault sets lead to irregular, dogtooth-shaped gridding errors or small cell gaps along some fault trends.

3.11 Structure of the top of unit B ([Plate 12](#)), top of the Eau Claire Formation

This region of the midcontinent has undergone numerous episodes of deformation and faulting (McDowell, 1986). 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 Section [2.3](#)). Basement-rooted faults are more common within 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, the faults that produced a positive flower structure and an associated structurally inverted block at the top of the Knox Supergroup and shallower horizons along the Rough Creek Fault Zone merge at depth (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 (around -14,000 feet) and in the Webster/Hopkins County area of Kentucky (-13,500 feet). This contrasts somewhat with the structure of the overlying Knox and younger strata, for which the deepest structure has a single linear, synclinal shape to 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 has a muted, down-to-north half-graben type structure. Outside of the graben complex, the Eau Claire within the Fairfield Subbasin is at -12,500 feet. The Eau Claire is highest (around -1,500 feet) 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, Kentucky, range from 200 to 500 feet. Along the Pennyrile Fault System, offsets are around 400 feet in Butler County and increase to about 1,200 feet in northern Christian County, Kentucky.

At this horizon within the Mississippi Valley Graben, the deepest area (close to -14,000 feet) is west of the large north-northeast striking, down-to-northwest fault near the center of the Mississippi Valley Graben. This fault is herein referred to as the “Central fault” in the following discussion. Fault offsets along the edges of the Mississippi Valley Graben range from less than 500 feet in Graves County, Kentucky, to more than 2,000 feet 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 et al., 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, Tennessee, at the pre-Cretaceous unconformity.

3.12 Isopach of unit B ([Plate 13](#)), the Eau Claire Formation

The Eau Claire Formation extends across the entire study area. Across the most of the shelf areas outside of the major grabens, the Eau Claire has a relatively smooth undulatory character in profile; thicknesses range from 250 to 2,000 feet. The areas of least thickness lie on the northern shelf immediately adjacent to the graben in Union, Henderson, and Ohio Counties. Within the Rough Creek Graben, two areas of relatively great thickness exist in Ohio and Grayson Counties; the thickest point of around 10,350 feet is near the center of Ohio County, Kentucky. 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, Kentucky.

Within the Mississippi Valley Graben, an area of greater thickness is present within the Blytheville/Pascola dome in New Madrid and Pemiscot Counties, Missouri, and Lake County, Tennessee. This dome structure outlines the region of earthquake activity associated with the New Madrid Seismic Zone. This region of tectonically thickened section (original depositional thickness unknown) is interpreted to have been produced after deposition by complex faulting in "flower" or "mushwad" 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 Supergroup (Thomas, 1991).

3.13 Structure of the top of unit A ([Plate 14](#)), the Reelfoot Arkose

The Early Cambrian Reelfoot Arkose (unit A) (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, Kentucky. The Reelfoot Arkose (unit A) 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 miles 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 within the Rough Creek Graben has a north-dipping, trimodal basin structure; the deepest points are in Union, Webster, and Ohio Counties, Kentucky (-19,500, -19,000, and -21,000 feet, respectively). The prominent, steep-sided subbasin centered in Ohio County apparently was filled before Knox deposition, and thus produced the thickened section of Eau Claire in that area described in Section 3.12 above. Within the Mississippi Valley Graben, the top of the Reelfoot is much deeper within a subbasin graben on the northwest (downthrown) side of the large north-northeast-striking central fault, having a maximum depth of close to -17,800 feet in Carlisle County, Kentucky. The Reelfoot is shallowest at -7,500 feet in two locations within the project area. One is in southeastern Hart County, Kentucky, where the Reelfoot pinches out in the eastern Rough Creek Graben. The other shallow point is in Weakley County, Tennessee, on the downthrown side of the northeast-striking, down-to-northwest normal fault that marks the local southeast boundary of the Mississippi Valley Graben. A wide anticline that formed east of the central fault in the upper surface of the Reelfoot Arkose extends from near the Tolu Arch in Livingston County south to Graves County, Kentucky. To the south, the top of the Reelfoot also rises sharply to the southwest in New Madrid and Pemiscot Counties, Missouri, Lake County, Tennessee, and Fulton County, Kentucky. 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, Illinois. Fault offsets range from 1,000 to 2,000 feet.

3.14 Isopach of unit A ([Plate 15](#)), the Reelfoot Arkose

Within both the Mississippi Valley Graben and Rough Creek Graben, the Reelfoot Arkose has an average thickness of around 3,000 to 4,000 feet, but is as thick as 17,500 feet in localized areas in Ohio, McLean, and Muhlenberg Counties, Kentucky. A relatively low density of available data exists for the Mississippi Valley Graben area; however, and additional data may prove that thickness trends are more complex than portrayed here. The Reelfoot Arkose is bounded on most sides by faults. A few areas where the Reelfoot is interpreted to pinch out by onlap onto the Precambrian surface include the eastern Rough Creek Graben near Hart County, in Trigg and Christian Counties between the Pennyrile and Lewisburg (named herein) Fault Systems, two small areas within 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, Illinois ([Figure 3.2](#)). Within the Mississippi Valley Graben, the Reelfoot Arkose thickens toward the northwest border faults, in contrast to thinning toward the Pennyrile faults.

3.15 Structure of the top of Precambrian basement ([Plate 16](#))

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 (new name) to the south. The east end of the graben rises sharply to a plateau around Hart County, Kentucky. 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 ([Figure 3.2](#)). The structurally high shelf areas around the Rough Creek and Mississippi Valley Grabens are fairly smooth at mapped 500 foot 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 sides.

The lithologic makeup of the Precambrian basement within 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 et al., 1986; Van Schmus et al., 1996). Some sub-horizontal layering is 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 et al., 1989; Pratt et al., 1992). The most likely scenarios for this seismic response would be from layered clastic deposits such as the 1.0-Ga-old Middle Run sandstones within an extension of the Mid-Continent Rift Basin (Drahovzal et al., 1992), or from layered volcanic deposits within the Eastern Granite-Rhyolite igneous province (Pratt et al., 1989). Examples of both possibilities can be found in the region. The KY Operating # 1 Riordan well in Hart County, Kentucky, drilled into a lithic arenite sandstone at the bottom of the well, and this was later interpreted to be part of the Middle Run Formation (Shrake et al., 1991). In Hancock County, Kentucky, the KyCCS #1 Marvin Blan well drilled through 542 feet of Middle Run Sandstone before reaching total depth (Bowersox, 2010). The Middle Run is interpreted in this well as having been deposited in a low-relief fluvial environment. Paleocurrent analysis of crossbed orientations interpreted from a microimaging log suggest a westerly transport direction consistent with the Grenville uplift lying to the east (Bowersox, 2010). Further petrographic work is needed to accurately determine provenance of the sandstones of the Middle Run Formation.

Fifty-two miles northwest of the #1 Riordan well and sixteen miles southeast of the #1 Blan well ([Figure 3.5](#)), on the basis of well cuttings analysis done by the Kentucky Geological Survey, the KY Operating #1 Braden well in Breckenridge County, Kentucky, penetrated 458 feet of un-named Precambrian rhyolitic welded tuff and basalt nonconformably below the Eau Claire at 6,045 feet (Bowersox, 2010). 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.

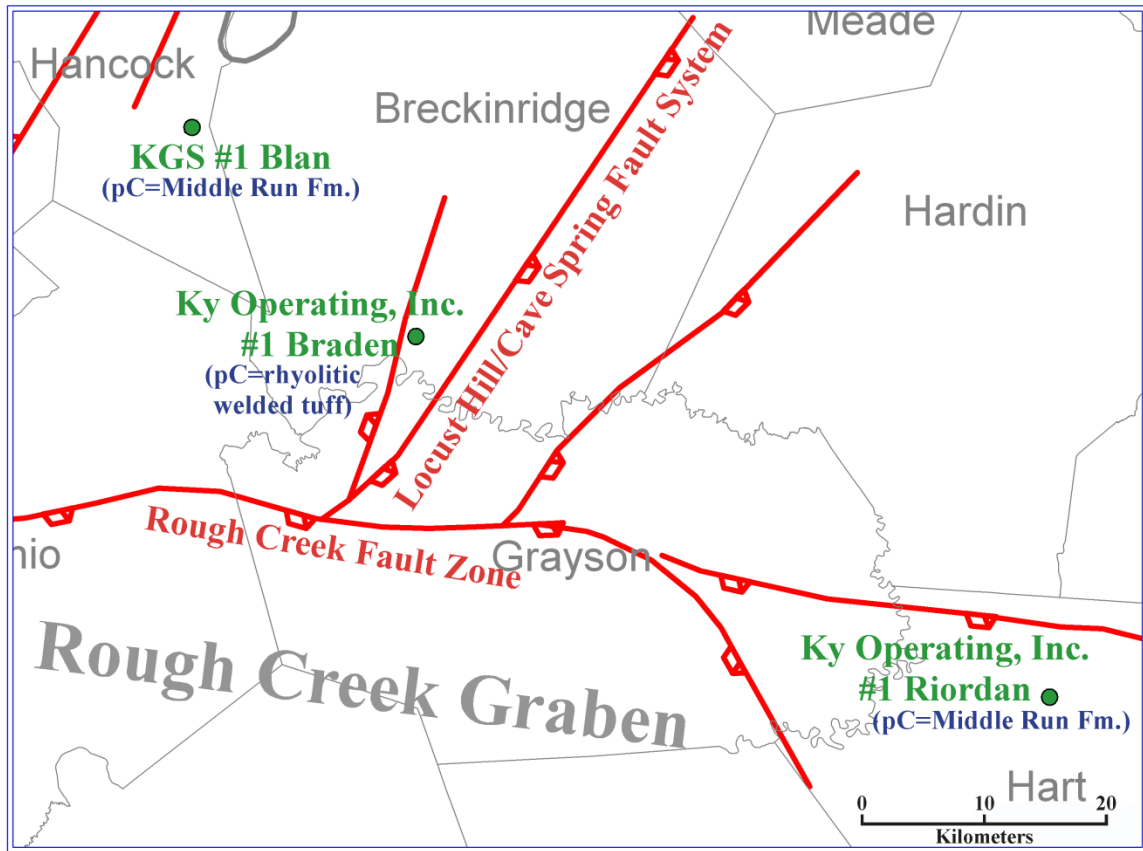


Figure 3.5 - Varied lithologies at the top of Precambrian basement within neighboring wells in western Kentucky.

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

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

4 WELL-BASED CROSS SECTIONS

Twelve regional well-based cross sections were produced for this project ([Figure 4.1](#)). Deeper wells and wells with detailed log suites were preferred over shallower wells or those with limited logs. These lines were constructed to be either parallel to the Rough Creek and Mississippi Valley Graben axes ("strike" lines), or perpendicular to the axes ("dip" lines). Because of the bend in strike of the Rough Creek/Mississippi Valley rift system, the three westernmost dip lines (MVG-A, B, and C) are rotated with respect to the other dip lines (RCG-D1 through D5) so as to cross perpendicular to the axis of the Mississippi Valley Graben. In the following descriptions of cross sections, wells are identified using a three-component identification. These identity designations consist of the line direction and number, followed by a number that corresponds to the sequence of wells along that specific cross section from west or north to east or south. For example, well D3.5 is the fifth well from the north on cross section Dip-3. All of the cross sections are drafted so that this well-sequence number increases to the right on the printed plates. See Table 4.1 for a list of wells used in the cross sections.

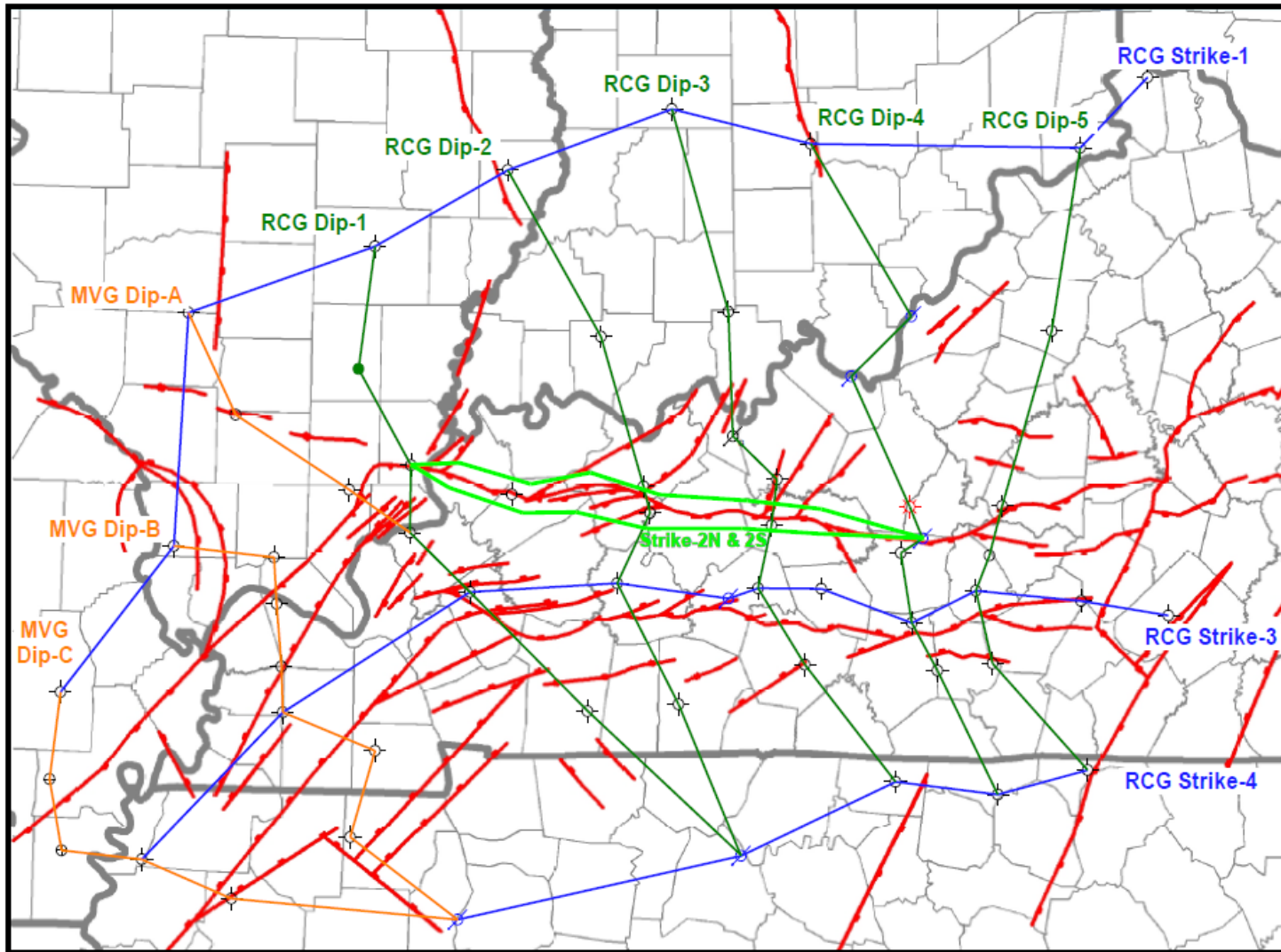


Figure 4.1 - Map of cross sections used in this study.

Table 4.1 - List of wells used in cross sections.

API/UWI	Well Name	County	ST	FM@TD	LAT	LON	GL	TD	Well ID's
120592489400	Conoco, Inc. 4-1 Dyhrkopp, E	Gallatin	IL	400PCMB	37.682120	-88.221870	447	14185	D1.4
120650345000	Texaco Inc 1 Cuppy, E	Hamilton	IL	400PCMB	38.026640	-88.477780	393	13060	D1.2
120872028500	Texas Pacific Oil 1 Farley, B	Johnson	IL	400PCMB	37.341270	-88.863010	594	14284	DB.2
121010742500	Atlantic Richfield 77 Lewis, JB	Lawrence	IL	375MTSM	38.750350	-87.773660	500	9261	D2.1, S1.5
121512030200	Texas Pacific 1 Streich, M.L.	Pope	IL	375RLFT	37.589710	-88.512790	783	14942	DA.3
121810010600	Humble Oil & Ref 1 Pickel, J F	Union	IL	375MTSM	37.373810	-89.336710	424	8492	DB.1, S1.2
121892329000	Brehm Drl 1 Bochantin Comm	Washington	IL	400PCMB	38.216110	-89.293640	458	7338	DA.1, S1.3
121910773100	Union Oil of Cal 1 Cisne	Wayne	IL	400PCMB	38.469160	-88.406750	504	11614	D1.1, S1.4
121992329000	Gallagher 1 Old Ben Coal	Williamson	IL	368KNOX	37.852680	-89.057400	384	7404	DA.2
16001016560000	Ashland Oil & Ref 1 Tarter, R	Adair	KY	375BASL	37.181755	-85.056990	850	6677	S3.10
16009018160000	Ohio Kentucky Oil 1 Bailey, B	Barren	KY	368KNOX	37.113000	-85.855730	700	2287	D4.7, S3.8
16015000010000	Ford, Fm 1 Conner, Cecil	Boone	KY	400MDLR	39.065156	-84.685974	908	4089	S1.9
16027002440000	Ky Operating 1 Braden, E D	Breckinridge	KY	400PCMB	37.635860	-86.486940	623	6511	D3.4
16031001770000	Brown-Cliff Energy 1 Rose	Butler	KY	368KNOX	37.243610	-86.578410	512	4470	D3.6, S3.6
16031004440000	Imco Recycling 1 Intl Metals	Butler	KY	368KNOX	37.206460	-86.717210	446	6450	S3.5
16033000410000	Sun Oil Co 1 Stephens WW&L	Caldwell	KY	375ECLR	37.226410	-87.936670	563	12965	D1.5, S3.3
16035000100000	South Central Pet 1 Cherry PJ	Calloway	KY	372CPRG	36.649070	-88.372910	583	5610	DB.6
16039000030000	Wafakaree Inc 1 Davis Marshal	Carlisle	KY	365TRNT	36.947248	-88.817848	345	2077	DB.4
16047008040000	West Bay Expl 1 Weatherford	Christian	KY	368KNOX	36.798800	-87.379920	604	3375	D1.6
16055000100000	Shell Oil Co 1 Davis Mildred	Crittenden	KY	368KNOX	37.437900	-88.222140	363	8821	D1.4, DA.4
16059056760000	Lafitte Co 13 O'Flynn Rex A	Daviess	KY	347CCEK	37.611514	-87.118909	408	3504	D2.3
16061005790000	Fair Oil Ltd 1 Reynolds	Edmonson	KY	372CPRG	37.240030	-86.279910	664	6514	S3.7
16083000020000	Fulk Perry 1 Hayden Charles B	Graves	KY	368KNOX	36.782610	-88.807270	482	3035	DB.5, S3.2
16085003280000	Texas Gas Transmi 1 Shain, H	Grayson	KY	375ECLR	37.469340	-86.513960	692	13551	D3.5
16091013960000	KYCCS 1 Blan, M&B	Hancock	KY	400PCMB	37.792426	-86.694177	620	8126	D3.3
16099004520000	Ky Operating Inc 1 Riordan TD	Hart	KY	400MDLR	37.366300	-85.903240	684	8019	D4.6
16099004830000	KII Inc 1 Brooks JH	Hart	KY	400MDLR	37.417200	-85.799340	723	8213	D4.5
16111000010000	Dupont 1Wad Ei Dupont	Jefferson	KY	400PCMB	38.219270	-85.840350	452	6011	D4.2
16123000090000	Ky Operating 1 Sherrard V	Larue	KY	400MDLR	37.533140	-85.858680	721	7093	D4.4
16141003280000	Wiser Oil Co 1 Markham W O	Logan	KY	368KNOX	36.824940	-86.953170	625	3613	D2.6
16145000020000	McCracken Expl 2 Gibbs, D	McCracken	KY	360ODVC	37.173949	-88.846685	348	3260	DB.3
16149015810000	Conoco Inc 1 Turner Mark	McClean	KY	400PCMB	37.515960	-87.088150	441	14202	D2.4

16155000230000	Caldwell, Ivo 1 Ball, J A	Marion	KY	372CPRG	37.530567	-85.421629	596	2918	D5.3
16163001540000	Mercury Expl 1 Olin Corp	Meade	KY	368KNOX	38.005210	-86.130790	456	3150	D4.3
16169004830000	G & R Oil Co Inc 1 England B	Metcalfe	KY	375CNSG	36.962330	-85.478920	1072	5500	D5.6
16169015230000	Benz Oil Corp 1 Nunnally, C	Metcalfe	KY	400PCMB	36.940530	-85.737580	757	6114	D4.8
16177027630000	Har-Ken Oil 14 Peabody Coal	Muhlenberg	KY	368BKMN	37.261510	-87.242950	513	6700	D2.5, S3.4
16199003790000	Amerada Hess 1 Daulton	Pulaski	KY	400PCMB	37.122406	-84.647908	1043	6722	S3.11
16211000050000	Beaver Dam Coal 1 Morris, C J	Shelby	KY	372CPRG	38.158360	-85.171953	763	2075	D5.2
16227033080000	Pittman T R 1 Hunt Jack	Warren	KY	372CPRG	36.966840	-86.360310	540	3959	D3.7
41027205440000	Arnco Oil Co 7A Langford	Clay	TN	375ROME	36.488940	-85.463500	640	5918	D4.9, S4.4
41037000080000	Ei Dupont 1 Davidson Plant	Davidson	TN	400PCMB	36.277330	-86.663110	504	5574	D1.7, D2.7, S4.2
41053100010000	Big Chief Drilling 1 Taylor HH	Gibson	TN	400PCMB	36.105850	-89.031710	381	7175	DC.5
41079100010000	Gulf Oil Corp 1A Spinks Clay	Henry	TN	375LMTE	36.336420	-88.484220	482	10748	DB.7
41085000020000	Fee 2 Dupont De Nemours	Humphreys	TN	400PCMB	36.043200	-87.978950	384	7461	DB.8, DC.6, S4.1
41095000100000	Benz Oil Co 1 Merritt Estate	Lake	TN	372CPRG	36.239850	-89.451210	275	6021	DC.4, S3.1
41111100040000	Houghland & Hardy 2 Goad, S	Macon	TN	400PCMB	36.540520	-85.939790	750	5050	D3.8, S4.3
41137001660000	Associated O&G 1 Sells, F&A	Pickett	TN	400PCMB	36.571110	-85.041780	884	5827	D5.7, S4.5
IN-107208	IN Farm Bur/TGT 2614 Brown	Lawrence	IN	400PCMB	38.846420	-86.315320	791	6806	D4.1, S1.7
IN-118307	Citizens Gas 9 Lucille Rollison	Greene	IN	375MTSM	38.973290	-86.983960	552	6785	D3.1, S1.6
IN-155634	Warren Oil 1 Paulin	Perry	IN	368KNOX	38.241870	-86.714873	456	4100	D3.2
IN-156024	Eastern Nat Gas 1 Peabody	Warrick	IN	368KNOX	38.151376	-87.322987	584	7147	D2.2
IN-159292	Ashland Exploration 1 Sullivan	Switzerland	IN	400PCMB	38.816401	-85.017331	779	4151	D5.1, S1.8
KGS-9441	Moore Oil Co 1 Perkins Carl	Green	KY	375CNSG	37.226050	-85.552560	675	5385	D5.5, S3.9
KGS-9668	Jackson Petroleum 1 Turner R	Green	KY	368KNOX	37.352500	-85.485690	605	2150	D5.4
MGS-007222	Strake Petr 1 Russell	Pemiscot	MO	375LMTE	36.264807	-89.825915	271	4740	DC.3
MGS-008742	MH Marr 1 Barnett	Stoddard	MO	375LMTE	36.834944	-89.850698	300	4585	DC.1, S1.1
MGS-008882	USBM 1 Oliver	New Madrid	MO	372BNTR	36.519800	-89.891100	278	3728	DC.2

Precambrian through Lower Mississippian stratigraphic tops were picked using all of the available data for each well (geophysical logs, cuttings descriptions, etc.). For the cross-sectional correlations and displays, seven lithostratigraphic intervals ([Table 4.2](#)) are used to analyze patterns of regional depositional thickness through time. These thickness patterns are then used to interpret the regional structural and tectonic evolution of this intracratonic rift system ([Figure 4.2](#)). The stratigraphic units used in this project consist of the following packages:

Table 4.2 - Included and equivalent stratigraphic members of units mapped within this study.

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

Depth and thickness measurements for each unit in the wells provide the primary control for construction of the cross sections, as well as for construction of structure contour and isopach maps. To aid in structural and stratigraphic interpretation between wells, map grid profiles from each of the structure contour maps of the stratigraphic units are projected onto the cross sections. By not only using tops from wells included along each cross section, but also those from nearby well- and seismic-based stratigraphic horizon interpretations, the data presented in the following cross section descriptions are thoroughly constrained. Major fault system segments (see Section [2.3](#)) along the lines are also drawn with interpreted offsets of the stratigraphic horizons.

The cross sections were produced in Petra[®], edited in ACD Systems Canvas-11[®] software, and printed to Adobe[®] PDF formatted files. These cross sections were produced with a 10X vertical exaggeration to highlight the effects of faults and other structures along the cross section lines.

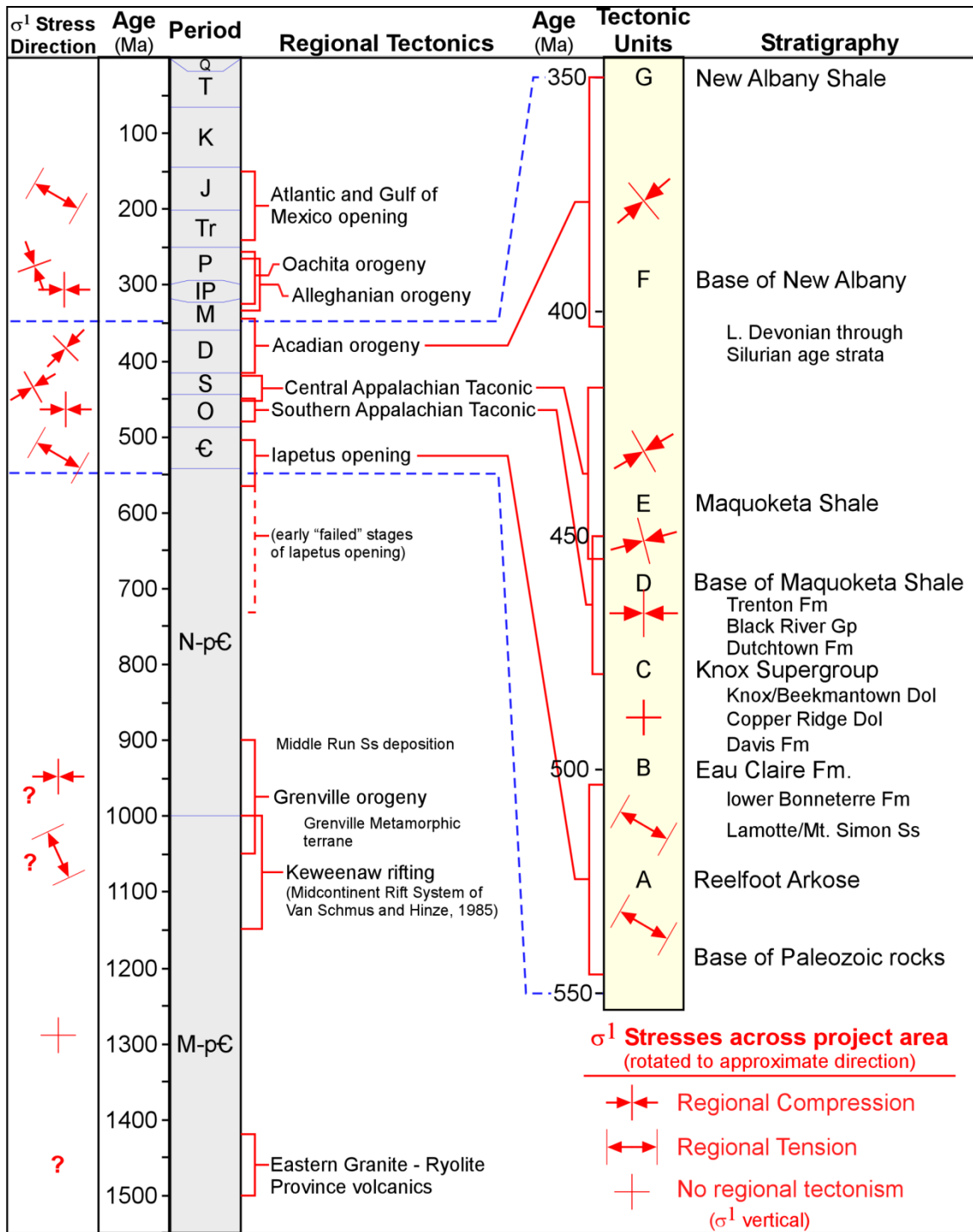


Figure 4.2 - Time scale and generalized relative σ_1 directions of regional tectonic events with respect to the Rough Creek Graben (red arrows) and major stratigraphic horizons used in this project.

4.1 Line RCG Dip-1 ([Plate 20](#))

RCG Dip-1 is composed of seven wells in a roughly north-south 193 mi (310 km) line between Wayne County, Illinois, and Davidson County, Tennessee. This line extends from the north side of the Fairfield Subbasin in Wayne County, Illinois, south-southeastward through the Fluorspar District uplift at the intersection of the Mississippi Valley Graben and the Rough Creek Graben, and up onto the shallow southern shelf in Christian County, Kentucky. The southeastern terminus of the line is on the northwestern limb of the Nashville Dome in Davidson County, Tennessee.

At well D1.1, unit G is 193 feet thick. The unit thickens to 290 feet deeper in the Fairfield Subbasin at well D1.2, in Hamilton County, Illinois. North of well D1.3, unit G is offset about 100 feet down to the south across the Shawneetown Fault System. At well D1.3 in Gallatin County, Illinois, unit G is 358 feet thick. Between wells D1.3 and D1.4, unit G is locally thinned to around 100 feet thick at the top of fault block that is bounded by two left-lateral strike slip faults (possibly a transpressional “flower structure”) in Hardin County, Illinois. At well D1.4 in Crittenden County, Kentucky, along the crest of the Fluorspar District uplift ([Figure 3.2](#)), unit G thickens to 445 feet. On the southeast side of the Fluorspar District uplift, unit G thins to 304 feet at well D1.5 in Caldwell County, KY. Between wells D1.5 and D1.6 in eastern Christian County, Kentucky, RCG Dip-1 crosses the down-to-northeast Tabb Fault System, a buried down-to-north-northwest basement fault (Pennyryle Fault System) in southern Caldwell County, and the left-transensional Lewisburg fault system in central Christian County, Kentucky. Unit G on the footwall against the down-to-north-northwest basement fault of the Pennyryle Fault System is thickened relative to on the hangingwall (northwest) block. This may signify some structural inversion along this fault during the deposition of the New Albany Shale. Unit G thins southeastward to 83 feet thick at well D1.6 and is around 50 feet thick in northern Davidson County, Tennessee, where the unit crops out north of well D1.7. Unit G thickness distributions along RCG Dip-1 appear to have been affected by fault movement; however, the regional thickness is not significantly greater over the deeper parts of the major grabens, suggesting little tectonic subsidence.

Unit F is 1,219 feet thick in well D1.1 and thickens southward between wells D1.2 and D1.3 to more than 1,423 feet in Gallatin County, Illinois. Southward across the Shawneetown Fault System, the top of unit F is downthrown around 100 feet to the south. Between wells D1.3 and D1.4, the trace of this section crosses at least two basement-rooted, sinistral strike-slip faults in central Hardin County, Illinois. At well D1.4 in Crittenden County, Kentucky, near the center of the Fluorspar District uplift, unit F is 1,808 feet thick. To the southeast across the Central Fault System in Caldwell County, unit F is slightly thinner at 1,632 feet thick in well D1.5. To the southeast into southern Caldwell County, unit F thins by about 400 feet across the intersection of the Tabb and Pennyryle Fault Systems. Unit F thins southward from around 900 feet thick south of the Pennyryle Fault System, to 568 feet thick in well D1.6 in southern Christian County, Kentucky, to less than 200 feet thick along the current surface level exposure, northwest of well D1.7 in Davidson County, Tennessee.

Unit E is 192 feet thick in well D1.1 in Wayne County, Illinois. The thickness of unit E is relatively constant southward along line RCG Dip-1 to well D1.4 (at 225 feet thick). To the southeast off of the Fluorspar District uplift, unit E thickens to 365 feet in well D1.5 in Caldwell County, Kentucky. Unit E thickens locally to about 600 feet along the downthrown side of the Pennyryle Fault System in southern Caldwell County.

Southeastward across the Tabb and Pennyryle Fault Systems, the top of unit E is uplifted about 500 feet. South of the graben in northern Christian County, Kentucky, unit E is about 300 feet thick, but thickens steadily to the southeast to close to 600 feet thick in northern Davidson County, Tennessee. Unit E is exposed at the current erosional surface around well D1.7. About 200 feet of the lowermost section of unit E remains in the well.

In well D1.1 in Wayne County, Illinois, unit D is 1,232 feet thick. Unit D thickens to more than 1,400 feet south of well D1.3 in northern Gallatin County, Illinois, but thins slightly to about 1,200 feet on the footwall side of the Shawneetown fault just north of well D1.3. Southward into the Rough Creek Graben, unit D thickens to 1,456 feet in well D1.4 in northern Crittenden County, Kentucky. Unit D thins slightly southward across the Central Faults to 1,197 feet in well D1.5 in Caldwell County, Kentucky. The top of unit D is uplifted by about 300 feet, and unit D thins by about 800 feet southward across

the Pennyrile Fault System. South of the graben in Christian County, Kentucky, unit D is about 550 feet thick. South of the Lewisburg Fault System, unit D thickens southward toward the Nashville Dome. In well D1.6, unit D is 842 feet thick, and increases to 878 feet in well D1.7 at the southern end of line RCG Dip-1.

Unit C is 2,891 feet thick in well D1.1 and steadily thickens southward toward the Rough Creek Graben to about 6,000 feet just north of the Shawneetown Fault in Gallatin County, Illinois. South of the fault, unit C is 6,485 feet thick in well D1.3, but thins southward onto the Fluorspar District uplift to about 5,500 feet thick within and below well D1.4. Near the crest of the Fluorspar District uplift, the top of unit C is at about 4,500 feet below sea level, which is about 3,100 feet higher than the top of unit C in well D1.2 within the Fairfield Subbasin in eastern Hamilton County, Illinois. Southeast and down-dip of well D1.4, unit C thickens to 6,316 feet at an elevation of -5,290 feet in well D1.5 in Caldwell County, Kentucky. Southeastward between well D1.5 and Christian County, Kentucky, the trace of line RCG Dip-1 crosses the down-to-northeast Tabb Fault System at a highly oblique angle, and an unnamed subsurface fault along the Pennyrile Fault System trend. Unit C is about 6,400 feet thick south of the Pennyrile Fault System, and thins southward away from the graben to about 4,800 feet thick below well D1.6. At the southeastern end of the line, unit C is 3,597 feet thick in well D1.7 in Davidson County, Tennessee. Unit C thickens significantly into the Rough Creek Graben; however, this change in thickness occurs gradually over a broad region and is not concentrated along major fault trends. The lack of abrupt changes in isopachous thickness along faults implies regional subsidence (and not syndepositional fault movement) was the dominant thickening mechanism for this area during the deposition of unit C.

At the northern end of RCG Dip-1 in Wayne County, Illinois, unit B is 1,062 feet thick in well D1.1. Unlike the overlying unit C, unit B thins toward the northern edge of the Rough Creek Graben to 740 feet in well D1.3. Unit B thickens dramatically (more than 500%) into the graben across the Shawneetown Fault to about 3,900 feet thick. Unit B thins southward into Crittenden County, Kentucky, and is about 3,000 feet thick below well D1.4. Unit B thickens to the southeast off of the Fluorspar District uplift, to about

4,000 feet below well D1.5 in Caldwell County, Kentucky. Unit B thins to around 3,400 feet across the Tabb and Pennyriple Fault Systems into northwestern Christian County. The Lewisburg Fault System in central Christian County has little vertical effect on shallower horizons; however, unit B thins southward across the fault zone by about 50% to around 1,500 feet thick. Between the Lewisburg Fault System and well D1.6 in southern Christian County, unit B thins to about 400 feet thick on top of a basement high. Unit B thickens to the southeast off of this basement high to 796 feet thick in well D1.7.

Along line RCG Dip-1, unit A is absent in wells D1.1 through D1.3 north of the Rough Creek Graben, and from wells D1.6 and D1.7 south of the Rough Creek Graben, where unit B rests on Precambrian basement. South of the Shawneetown Fault System in Gallatin County, Illinois, unit A is about 4,500 feet thick and increases to about 4,900 feet below well D1.4 in Crittenden County, Kentucky. The thickness of unit A is relatively constant over the Fluorspar District uplift, but thickens in southeastern Crittenden County and northwestern Caldwell County, Kentucky, to about 7,500 feet below well D1.5. Southward across the Tabb Fault System, unit A thins to around 2,500 feet thick in central Caldwell County, Kentucky. In southern Caldwell County, unit A thins southward across the subsurface extension of the Pennyriple Fault System to around 1,200 feet thick. South of the Pennyriple Fault System, unit A thins abruptly to zero thickness near the Caldwell/Christian County border, and is absent from the southern part of RCG Dip-1.

4.2 Line RCG Dip-2 ([Plate 21](#))

RCG Dip-2 is based on seven wells and extends approximately 188 miles (302 km) from Lawrence County, Illinois, to Davidson County, Tennessee ([Figure 4.1](#)). Major structures along this north-northwest to south-southeast line include the Owensboro Graben ([Figure 3.2](#)); the deepest part of the Rough Creek Graben in Ohio and Muhlenberg Counties, Kentucky; the Pennyriple Fault System; and the Nashville Dome.

The northwest terminus of this line is at a well (D2.1) on the eastern limb of the La Salle Anticline. Between wells D2.1 and D2.3 just north of the Rough Creek Fault Zone, the line of the cross section is parallel to regional strike at the top of unit G (New Albany

Shale), which is expressed in a fairly constant thickness and elevation for the top of that unit. The one exception is a small (about 100 feet) down-to-southeast offset across the Curdsville Fault, along the northwestern border of the Owensboro Graben. No thickness changes for unit G are observed across this fault, indicating at least some post-Early Mississippian movement on this fault. Between wells D2.3 and D2.4, the line of this cross section crosses the unnamed southeastern border fault (down-to-northwest) of the Owensboro Graben, as well as the Rough Creek Fault Zone in McLean County, Kentucky. Unit G is offset by all three of these fault system segments, but no thickness variation from syndepositional faulting is evident. South of well D2.4, unit G gradually thins southward across all of the southern part of the cross section, to where the unit crops out on the Nashville Dome. Unit G is offset by about 300 feet (down-to-north) across the Pennyriple Fault System, and by less than 40 feet (down-to-north) across an unnamed fault in the Lewisburg Fault System.

Unit F (Silurian and Lower Devonian strata) thins southward by about 30% (400 feet) between well D2.2 and the Rough Creek Fault Zone, north of well D2.4. Across, and south of, the Rough Creek Fault Zone, unit F thickens by about 600 feet toward the axis of the Rough Creek Graben in northern Muhlenberg County, Kentucky. South of the axial depocenter, unit F gradually thins by about 450 feet near the southern border of the Rough Creek Graben, and decreases another 150 feet in thickness where the line crosses the Pennyriple Fault System. Southeast of the Pennyriple Fault System, unit F progressively thins from around 750 feet thick to where it is completely truncated at the Lower Devonian unconformity on the flank of the Nashville Dome, northwest of well D2.7. Unit F is offset by the Lewisburg fault northwest of D2.6, but no thickness change is obvious across the structure.

Unit E (Maquoketa Shale) gradually thickens, nearly doubling in thickness, southeastward from well D2.1 to the axial depocenter of the Rough Creek Graben in northern Muhlenberg County, Kentucky. This unit also appears to be locally thickened north of well D2.4; the thickening may be a result of later fault imbrication within the reactivated and inverted Rough Creek Fault Zone. This area is near the eastern edge of the Sebree Trough (Kolata et al., 2001), a linear feature produced by reciprocal thickness

changes between units D and E in western Kentucky, where the Trenton Formation is thin to absent ([Figure 3.4](#)). Other than in this small area, the thickness of unit E appears to be unaffected by faulting. Near the McLean/Muhlenberg County line in the Rough Creek Graben is the thickest point of unit E (about 550 feet) along the trace of this cross section. Southward from this point, unit E maintains a relatively constant thickness southward to where it crops out on the Nashville Dome in northern Davidson County, Tennessee.

Unit D (base of Maquoketa Shale to top of Knox Supergroup) maintains a fairly constant thickness north of the Rough Creek Fault Zone along this cross section. South of the Rough Creek faults and well D2.4, the thickness of unit D is reduced across the same area where the overlying unit E has an increased thickness. Unit D thickens south of well D2.5, toward the splays of the Pennyryle Fault System. Unit D thins southward by about 550 feet (~ 40% reduction) across the Pennyryle Fault System along this cross section, suggesting syndepositional fault movement. From this area in southern Muhlenberg County, Kentucky, unit D thickens southward gradually, to where the unit crops out on the Nashville Dome, just south of the southern end of the cross section at well D2.7.

In general terms, unit C (Knox Supergroup) is thinnest at the endpoints of this cross section, and thickest at the center in an area overlying (and overlapping the edges of) the Rough Creek Graben. Unit C thickens southward in a linear but dramatic manner (more than a 70% increase) from well D2.1 in central Lawrence County, Illinois, to the northern edge of the Rough Creek Graben between wells D2.3 and D2.4. Although unit C thickens towards the axis of the Rough Creek and Mississippi Valley Grabens, most of the thickening is regional and not from abrupt thickening across growth faults. The maximum thickness of unit C along this line is about 6,100 feet in the Rough Creek Graben in north-central Muhlenberg County, Kentucky. This unit gradually thins southward from the Rough Creek Graben to about 3,500 feet at D2.7 on the northwest limb of the Nashville Dome in Davidson County, Tennessee. Any changes in thickness across the Pennyryle or Lewisburg Fault Systems are minimal and below seismic resolution (less than 100 feet).

North of well D2.3 near the Rough Creek Fault Zone, unit B (Eau Claire Formation and the Lamotte Formation/Mt. Simon Sandstone) maintains a relatively constant thickness of around 700 feet. In a small area immediately north of the Rough Creek Graben (within the southern end of the Owensboro Graben) unit B thins to less than 500 feet thick. The thickness of this unit doubles southward across the Rough Creek Fault Zone, to around 1,000 feet. Unit B thickens to the south to a maximum thickness of about 9,000 feet in the Rough Creek Graben along the border between McLean and Muhlenberg Counties, Kentucky. This abrupt thickness change is equal to almost a 20-fold increase in stratigraphic thickness over a distance of only 12.5 mi (20 km). From the Muhlenberg County line to well D2.5, unit B thins by 50% to about 4,500 feet thick. South of D2.5, unit B thins southward to around 2,250 feet thick along the Pennyryle Fault System. Although the rate of thinning decreases southward across these faults, no thickening related to syndepositional fault movement is apparent. South of the Pennyryle Fault System, unit B thins to around 750 feet below well D2.6 in Logan County, Kentucky. In a small area just south of well D2.6, unit B thins to less than 500 feet for a few kilometers at an abrupt rise in the top of basement. The thickness of unit B is relatively constant from D2.6 to the end of the cross section at D2.7 on the Nashville Dome in Davidson County, Tennessee. North of the Rough Creek Fault Zone as well as south of the Pennyryle Fault System, unit B directly overlies the Precambrian Granite-Rhyolite Province volcanic rocks. Within the Rough Creek Graben, unit B overlies the Early Cambrian Reelfoot Arkose (unit A).

The deposition of unit A is confined to the Rough Creek Graben between the Rough Creek and Pennyryle Fault Systems. Along the trace of this cross section, unit A pinches out against or just south of the Rough Creek Fault zone, north of well D2.4. From this point south to the deepest part of the Rough Creek Graben near the McLean/Muhlenberg County line, unit A thickens to more than 17,000 feet. Similar to unit B, unit A thins abruptly southward from this area to well D2.5 in western Muhlenberg County. At D2.5, unit A is close to 2,000 feet thick. Unit A thins an additional 1,500 feet between D2.5 and the Pennyryle Fault System, against which unit A terminates southward. Unit A directly overlies weathered volcanic rocks of the Precambrian Granite-Rhyolite Province.

4.3 Line RCG Dip-3 ([Plate 22](#))

RCG Dip-3 is a north-to-south oriented cross section between Greene County, Indiana, and Macon County, Tennessee. It includes eight wells, and is 186 mi (299 km) long. The line crosses the Sebree Trough between D3.2 and D3.4, the Locust Hill Fault System and the Rough Creek Fault Zone between D3.4 and D3.5, the eastern Rough Creek Graben between D3.4 and D3.7, the eastern part of the Pennyryle Fault System between D3.6 and D3.7. The line terminates at D3.8 along the crest of the Cumberland Saddle of the Cincinnati Arch.

The thickness of unit G is 108 feet at the northern end of the cross section at D3.1. Between wells D3.2 and D3.4 the unit is slightly thicker, but it thins locally in the area near D3.4 (87 feet) adjacent to the Locust Hill Fault System. Unit G thickens dramatically southward across the Rough Creek Fault Zone to well D3.5 (171 feet). The Rough Creek Fault Zone is a down-to-south normal fault system, but units G and F are now at higher elevations on the south side of the fault zone because of later (post-Devonian) reactivation of these faults into the present inverted structure. The greater thickness is maintained across the Rough Creek Graben to where the line crosses the Pennyryle Fault System south of well D3.6 in Warren County, Kentucky. South of the Pennyryle Fault System at D3.7, the local thickness of unit G is less than 100 feet. The thickness of unit G is relatively constant from D3.7 southeast to where it crops out along the Nashville Dome, just north of well D3.8, at the end of the section.

The thickness of unit F at well D3.1 in Greene County, Indiana, is 851 feet. Southward from this point, the unit thins to 415 feet at D3.4 in southern Breckinridge County, Kentucky. The thickness dramatically increases (more than 250%) southward across the Rough Creek Fault Zone between wells D3.4 and D3.5 in western Grayson County, Kentucky. Unit F has the maximum thickness of about 1,120 feet along this cross section a few kilometers south of D3.5. Unit F thins from this point south to about 900 feet thick at D3.6. Where the line of the cross section is near and crosses the down-to-northwest fault splays of the Pennyryle Fault System north of D3.7, unit F abruptly thins southward

by 27% to about 600 feet thick. Unit F thins gradually to the southeast, and it pinches out near the Kentucky/Tennessee state border in Allen County, Kentucky.

At well D3.1 in Greene County, Indiana, unit E is 339 feet thick. Unit E increases in thickness to around 546 feet at D3.2, within the Sebree Trough ([Figure 3.4](#)). In a small area north of, and along strike with the Owensboro Graben, unit E has a local maximum thickness of more than 600 feet between wells D3.2 and D3.3. On the southeast side of the Owensboro Graben and Sebree Trough, unit E decreases in thickness to around 400 feet at well D3.4. A slight increase in thickness (~75 feet) is observed across the Rough Creek Fault Zone to well D3.5 in western Grayson County, Kentucky. Similar to the overlying units F and G at this location, the top of unit E on the hangingwall of the Rough Creek Fault Zone has been uplifted above the unit E horizon in the footwall block during fault reactivation and inversion. Within the Rough Creek Graben, unit E thickens southward to almost 600 feet thick at D3.6, and close to 700 feet thick just north of the Pennyriple Fault System in northern Warren County, Kentucky. On the south side of the down-to-north Pennyriple faults, unit E is reduced in thickness to less than 400 feet thick, and maintains this approximate thickness to the end of the line at D3.8 in Macon County, Tennessee. About 13 kilometers southeast of D3.8, this unit crops out along the northern limb of the Nashville Dome.

Unit D has a thickness of 697 feet at the northern terminus of the cross section at D3.1. Unit D is slightly thinner within the Sebree Trough at well D3.2 (633 feet), and thickens southward to 657 feet at well D3.3 in Hancock County, Kentucky, and to 782 feet in well D3.4. South of well D3.4, the line of the cross section crosses both the down-to-east Locust Hill Fault System, and the down-to-south Rough Creek Fault Zone. South of the Rough Creek Fault Zone, unit D is 891 feet thick at D3.5. The unit increases in thickness slightly across the Rough Creek Graben to around 900 feet thick at D3.6, but thins near the Pennyriple Fault System to around 800 feet thick. South of the Pennyriple Fault System, unit D is relatively constant in thickness around 925 feet thick southward to the end of the cross section at well D3.8 in Macon County, Tennessee.

On a basin-wide scale, unit C is thickest within the graben areas and thins outward in all directions. At the north end of RCG-D3, unit C is 2,519 feet thick at well D3.1. Unit C thickens to the south to 2,875 feet at D3.2, and 3,616 feet at D3.3 in Hancock County, Kentucky. The area around well D3.4 has around 3,250 feet of unit C, but a down-to-west fault cut within the Copper Ridge Dolomite of the Knox Supergroup removes part of that section leaving only 2,744 feet within the well bore of D3.4. South across the Rough Creek Fault Zone at D3.5, the thickness of unit C increases significantly to 4,362 feet. The thickest point of unit C along this cross section is 5,100 feet in eastern Butler County, Kentucky, north of well D3.6. Unit C thins southward away from the axis of the graben and toward the Pennyryle Fault System. The top of unit C is offset (down to the north) by about 125 feet and the thickness of unit C also decreases by about 100 feet southward across the Pennyryle Fault System. South of the Pennyryle Fault System, unit C gradually thins to around 3,700 feet at D3.7 in Warren County, Kentucky, and thins to 3,430 feet at well D3.8 in Macon County, Tennessee, at the southern end of RCG Dip Line 3.

Unit B (the Eau Claire Formation and Mt. Simon/Lamotte Sandstone where present) is about 1,650 feet thick at well D3.1 in Greene County, Indiana. Between wells D3.1 and D3.2, unit B has little thickness change (< 100 feet). To the southeast of the Owensboro Graben at well D3.3, unit B abruptly thins to less than 500 feet at D3.3, and thins farther southeast to 89 feet at well D3.4. The thin unit B within the area between the Owensboro Graben to the west and the Locust Hill Fault System to the east suggests that this was an uplifted block during deposition of the Eau Claire Formation. Unit B thickens dramatically southward across the Rough Creek Fault Zone. At well D3.5 in western Grayson County, Kentucky, unit B is around 7,000 feet thick. Unit B is thickest along this cross section just south of D3.5 (around 8,000 feet), and thins southward. At well D3.6, unit B is about 4,100 feet thick and thins southward to around 2,250 feet below well D3.7 in Warren County, Kentucky. No thickness change of unit B is evident across the Pennyryle Fault System segment that RCG-D3 crosses. Southeast of D3.7, unit B thins southward to 158 feet at well D3.8.

Unit A is confined to the deep Rough Creek Graben areas and is absent from wells D3.1, D3.2, D3.3, D3.4, D3.7, and D3.8. Unit A is around 8,500 feet thick at well D3.5, and terminates to the north against the Rough Creek Fault Zone. Unit A thins to the south to around 3,000 feet below well D3.6, and terminates against the Pennyryle Fault System with a thickness around 400 feet. Where present, unit A directly overlies Precambrian basement.

4.4 Line RCG Dip-4 ([Plate 23](#))

Cross section RCG Dip-4 is a north-south oriented dip section composed of nine wells extending 189 mi (304 km) between Lawrence County, Indiana, and Clay County, Tennessee. Line RCG Dip-4 is east of the exposed Rough Creek and Pennyryle Fault Systems, but illustrates the eastward extension of those bands of deformation at depth. The line of this section obliquely crosses the southern end of the Mt. Carmel Fault, just south of well D4.1 in Jackson County, Indiana. Because of this orientation with respect to the fault plane, the vertical offset along RCG Dip-4 is around 40 feet for most of the stratigraphic section.

Unit G is 121 feet thick in well D4.1, and thins to the southeast toward where unit G crops out. In well D4.2 in Jefferson County, Kentucky, although presently covered by Quaternary alluvium, unit G has been truncated to about 38 feet thick by post-Mississippian erosion. To the southwest from well D4.2, the complete thickness of unit G is 96 feet in well D4.3 in Meade County, Kentucky. Southward from well D4.3, unit G thins to 74 feet thick in well D4.4 in Larue County, Kentucky, and to 67 feet thick in well D4.5 in Hart County, Kentucky. South of well D4.5, the line of this section crosses a previously unnamed, down-to-south fault in northern Hart County, Kentucky, herein referred to as the Hart County Fault. This fault is along strike with the Rough Creek Fault Zone to the west, and may act as the local northern boundary fault of the eastward extension of the Rough Creek Graben. Unit G is offset about 75 feet down to the south across the Hart County Fault. Between wells D4.5 and D4.6 in central Hart County, unit G thins slightly to 58 feet. The lack of any significant thickness increase on the downthrown side of the Hart County Fault implies at least some fault movement after

unit G deposition. The thickness of unit G is relatively constant southward from well D4.6 to where the unit crops out in southern Monroe County, Kentucky, and Clay County, Tennessee, on the northern flank of the Cumberland Saddle and north of well D4.9. South of well D4.7 in Barren County, Kentucky, unit G is uplifted about 150 feet to the south across a previously unnamed, down-to-north basement fault, herein referred to as the Barren County Fault. This structure is along strike with the Pennyrile Fault System to the west and may act as the local southern boundary fault of the eastward extension of the Rough Creek Graben.

At the north end of RCG Dip 4, unit F is 437 feet thick in well D4.1 in Lawrence County, Indiana. Unit F is offset about 40 feet up to the southeast across the Mt. Carmel Fault. Unit F thins to the southeast to 275 feet thick in well D4.2 in Jefferson County, Kentucky. To the southwest in well D4.3, unit F is slightly thicker at 277 feet. Southeast of well D4.3, unit F thins to 136 feet thick in well D4.4 in Larue County, Kentucky. The thickness of unit F is relatively constant around 200 feet between wells D4.4 and D4.7 in Barren County, Kentucky. Just south of well D4.5, unit F is downthrown about 75 feet to the south across the Hart County Fault. In central Barren County, Kentucky, unit F is uplifted about 150 feet to the south across the Barren County Fault. Between wells D4.7 and D4.8, unit F pinches out, probably because of truncation by the Middle Devonian regional unconformity. Unit F is absent from well D4.8 in Metcalf County, Kentucky, and well D4.9 on the Cumberland Saddle in Clay County, Tennessee.

Unit E thickens slightly between wells D4.1 (549 feet) and D4.2 (565 feet). Southward from well D4.2, however, unit E progressively thins to 554 feet in well D4.3, 550 feet in well D4.4, and 558 feet thick in well D4.5. Between wells D4.5 and D4.6 in Hart County, Kentucky, unit E abruptly thickens to about 600 feet and is offset about 230 feet down to the south across the Hart County Fault. This 20% increase in the thickness of unit E and the ~300% increase in vertical offset across the Hart County Fault relative to the top of unit F implies significant fault movement during the deposition of units E and F. Southward from well D4.6, unit E thins to 513 feet in well D4.7 and to 494 feet thick in well D4.8. Between wells D4.7 and D4.8, unit E is offset about 180 feet up to the

south across the Barren County Fault. Unit E is truncated and exposed at the current surface level, and about 300 feet is present in well D4.9 on the Cumberland Saddle.

In the region surrounding RCG Dip-4, unit D progressively thickens to the south. In well D4.1, unit D is 599 feet thick and increases southward to 856 feet thick in well D4.5 in northern Hart County, Kentucky. Unit D is offset about 230 feet down to the south across the Hart County Fault. South of the fault, unit D thickens to 851 feet in well D4.6, and 885 feet in well D4.7. Unit D is offset about 180 feet up to the south across the Barren County Fault, but the fault has no apparent effect on the thickness of unit D. In well D4.8 in southwestern Metcalf County, Kentucky, unit D is 900 feet thick, and it continues to thicken southward. At the southern end of RCG Dip-4, unit D is 1,131 feet thick in well D4.9 in Clay County, Tennessee.

In well D4.1, unit C is 2,449 feet thick and increases southward toward the axis of the rift system. In well D4.2 in Jefferson County, Kentucky, unit C is 2,792 feet thick and increases to about 3,200 feet within and below well D4.3, 3,756 feet in well D4.4, and 3,607 feet thick in well D4.5 on the upthrown block of the Hart County Fault. Unit C is offset about 230 feet down-to-south across the Hart County Fault, but with no apparent faulting-related thickness increase on the downthrown side. South of the fault, unit C is 4,020 feet thick in well D4.6, and increases to about 4,200 feet below well D4.7 in Barren County, Kentucky. Unit C is upthrown about 280 feet southward across the Barren County Fault. This is a 55% increase in vertical offset from the top of unit C to the base of unit C and implies significant fault movement during unit C deposition. South of the Barren County Fault, unit C thins to 3,715 feet thick in well D4.8 in Metcalf County, Kentucky, and to 3,290 feet thick in well D4.9, at the southern end of the cross section.

At the north end of the cross section, the thickness of unit B is 1,841 feet in well D4.1. Much like units G through C, the top of unit B is offset about 40 feet up to the east across Mt. Carmel Fault. The vertical offset at base of unit B (top of Precambrian basement), however, is more than 100 feet, implying fault movement along the Mt. Carmel fault contemporaneous with (or prior to) unit B deposition. To the southeast in well D4.2, unit B thins to 1,338 feet, but thickens slightly to the southwest to about 1,550 feet thick

below well D4.3 in Meade County, Kentucky. Southeast of well D4.3, the line of this cross section traverses a region with a thin unit B interval, a possible paleohigh during unit B deposition. In well D4.4, unit B is 910 feet thick and thins to the southeast to 731 feet thick in well D4.5 in northern Hart County, Kentucky. The top of unit B is downthrown about 350 feet to the south across the Hart County Fault. Between wells D4.5 and D4.6, unit B thickens by about 33% to 975 feet in well D4.6, suggesting fault movement during unit B deposition. The southward thickening of unit B reaches a maximum of about 3,000 feet along this line in southern Hart County. Farther south in northern Barren County, unit B is about 2,000 feet thick below well D4.7. Between wells D4.6 and D4.7, the base of unit B is offset about 700 feet down-to-south across an unnamed basement fault in southern Hart County. The top of unit B is offset about 500 feet up to the south across the Barren County Fault, an increase of about 75% compared to the offset at the top of unit C. The base of the unit B interval (locally the top of Precambrian basement) is offset about 1,000 feet up to the south. This dramatic increase in offset with depth suggests that the Barren County Fault was active (down-to-north) during unit B and lower unit C deposition. South of the fault in well D4.8, unit B is noticeably thinner at 582 feet thick, and thins southward to 228 feet thick in well D4.9 on the northwest limb of the Cumberland Saddle. Except for a small area along this line in Hart and northernmost Barren Counties, Kentucky, unit B unconformably overlies Precambrian basement. Between wells D4.6 and D4.7, unit B conformably overlies unit A.

No wells along RCG Dip-4 penetrate unit A; however, interpretation of nearby seismic profiles shows that unit A is present along this section between wells D4.6 and D4.7, in Hart and Barren County, Kentucky. Unit A reaches a maximum thickness of around 2,000 feet on the downthrown side of the unnamed fault between wells D4.6 and D4.7 in southern Hart County. This fault offsets the top of unit A by about 700 feet down to the south. Unit A thins to zero thickness to the north and south of this fault.

4.5 Line RCG Dip-5 ([Plate 24](#))

RCG Dip-5 is an approximately 169-mi-(272-km)-long north-south line, connecting seven wells between Switzerland County, Indiana, and Pickett County, Tennessee. This line tangentially crosses the western side of the Jessamine Dome of the Cincinnati Arch in central Kentucky, and (except for the two southernmost wells) is subparallel to the Cincinnati Arch.

Because of erosion along the uplifted Jessamine Dome and Cincinnati Arch, stratigraphic unit G is absent from wells D5.1, D5.2, and D5.3. A thin (< 100 feet thick) unit G interval is present south of an unnamed, east-west striking down-to-south fault in central Marion County, Kentucky, herein referred to as the Marion County Fault. At well D5.4 in northern Green County, Kentucky, unit G is thickest along this cross section at 61 feet. Unit G gradually thins to the south to 45 feet thick at well D5.5. South of D5.5, unit G thins slightly to around 40 feet thick at well D5.6 in Metcalf County, Kentucky. Between D5.5 and D5.6, the line of this section crosses two unnamed down-to-north faults. These faults are interpreted to offset unit G, but no thickness changes across these faults imply that they were not active during New Albany Shale deposition. The thickness of unit G is constant southward to the southern end of the cross section at D5.7, near the axis of the Cincinnati Arch/Cumberland Saddle.

Similar to unit G, unit F is absent because of erosion at the present land surface from wells D5.1, D5.2, and is truncated in well D5.3. Immediately south of the Marion County Fault, unit F is approximately 100 feet thick. Unit F thickens southward over the eastern extension of the Rough Creek Graben to 167 feet thick at well D5.4. Between well D5.4 and D5.5, unit F thins southward to 92 feet thick. Unit F thins southward across the unnamed down-to-north basement fault in southern Green County, Kentucky, and is unconformably absent adjacent to the fault trace on the upthrown footwall block below the Lower Devonian unconformity. Although not proven by well penetrations, isopachous map grid calculations produced for this project estimate that unit F is present (but thin) within 10 km north of the unnamed down-to-north basement fault in central Metcalf County, Kentucky, but is absent from the footwall along the fault trace. At well

D5.6, unit F is very thin (<10 feet) and thickens slightly to the south in northern Cumberland County, Kentucky; but it thins and pinches out southward in southern Cumberland County along the Cincinnati Arch because of erosion at the Lower Devonian unconformity. Unit F is unconformably absent from well D5.7.

Similar to units F and G, a complete thickness of unit E is not present in wells D5.1 and D5.2. Unit E is exposed at the surface over much of the northern half of the cross section, but thickness of unit E was not calculated over this interval because of the irregular topography. South of the Marion County Fault, unit E is approximately 500 feet thick and thickens southward to 577 feet thick at well D5.4. Southward from D5.4, unit E thins slightly to 511 feet thick at D5.5 in southern Green County, Kentucky. Unit E has a relatively constant thickness southward from D5.5 to near the crest of the Cincinnati Arch, in Clinton County, Kentucky, with no significant thickness changes over the faults. The base of unit E (Maquoketa Shale) along the southern end of this cross section is a somewhat irregular surface, possibly because of inconsistencies in stratigraphic interpretations (well tops) in this locally gradational interval. The thickness of unit E in well D5.7 is 347 feet.

Unit D is the youngest unit along RCG-D5 that is a complete stratigraphic interval over the entire length of the line. At well D5.1 in Switzerland County, Indiana, the thickness of unit D is around 700 feet. Gradual southward thickening is observed between wells D5.1 and D5.3, where unit D is 860 feet thick. Unit D is offset slightly (<100 feet) across the two down-to-south basement faults in Nelson and northern Marion Counties, Kentucky, as well as the two down-to-north basement faults in Green and Metcalf Counties, Kentucky. No thickness changes are recognized across these faults, implying that the offsets are because of post-Middle Ordovician movement. The thickness of unit D varies by less than 10% southward along the line of the cross section between wells D5.3 and D5.7, which crosses the eastern extension of the Rough Creek Graben.

At well D5.1 in Switzerland County, Indiana, unit C is 2,058 feet thick. Unit C gradually thickens southward toward the axis of the Rough Creek Graben. At well D5.2, the thickness of unit C is about 2,650 feet, and increases to around 3,050 feet at D5.3 in

Marion County, Kentucky. Unit C is offset by both of the unnamed down-to-south faults in Nelson and northern Marion Counties, Kentucky. No thickness changes are associated with the traces of the faults, however, indicating that the faults were not active during the deposition of unit C. Southward across the Marion County Fault, unit C abruptly thickens southward into Taylor and Green Counties to a maximum thickness of around 3,800 feet south of well D5.4 in central Green County, Kentucky. In southern Green County, unit C thins to less than 3,500 feet at well D5.5. Lack of significant thickness changes between wells D5.5 and D5.6 suggest that the unnamed down-to-north basement faults in Metcalf and Green County were inactive during unit C deposition. The thickness of unit C decreases near the crest of the Cincinnati Arch to around 3,060 feet at well D5.7.

Unit B thickens toward the boundary faults of the Rough Creek Graben from both the north and the south. At well D5.1 along the west flank of Cincinnati Arch in Switzerland County, Indiana, unit B is 860 feet thick. To the south, unit B more than doubles in thickness to about 2,250 feet between wells D5.1 and D5.2 in Shelby County, Kentucky. Unit B thickens southward to around 3,100 feet thick at well D5.3. This approximate thickness persists through wells D5.4 and D5.5; no growth is observed southward across the Marion County Fault, or the unnamed down-to-south basement fault in Taylor County, Kentucky. South of well D5.5, however, a dramatic thickness change (~30% reduction) is interpreted southward across the unnamed down-to-north basement fault in southern Green County, Kentucky. This fault is the local southern boundary fault for the Rough Creek Graben. Unit B thins to the south between the southern Green County fault and the unnamed down-to-north basement fault in central Metcalf County, Kentucky. Unit B thins southward by about 10% across the Metcalf County fault to about 725 feet at well D5.6. Southeast of D5.6, unit B is locally thickened along this line in Clinton County, Kentucky, but thins to 207 feet thick at well D5.7 in Pickett County Tennessee.

Unit A is absent from the stratigraphic section along RCG Dip Line 5. Along this line, unit B unconformably overlies the top of the Precambrian crystalline basement.

4.6 Line MVG Dip-A ([Plate 25](#))

Dip Line MVG-A is the shortest cross section within this project. It is 83 mi (133 km) long northwest to southeast, crossing from Washington County, Illinois, to Crittenden County, Kentucky, where MVG Dip-A intersects RCG Dip-1. Line MVG Dip-A can therefore be viewed as an alternate, northwestern route for the northern end of RCG Dip-1. Line MVG Dip-A intersects RCG Dip-1 at well DA.4, which is also well D1.4.

Unit G is 30 feet thick at well DA.1, about 7 mi (11 km) west of the Du Quoin Monocline. Between wells DA.1 and DA.2, the line of the section crosses just south of the Du Quoin Monocline and extends to the Cottage Grove Fault System in Williamson County, Illinois, very near well DA.2. Unit G thickens slightly southward between wells DA.1 and DA.2, but thins locally to 44 feet at well DA.2. To the southeast in Pope County, Illinois, unit G is 303 feet thick in well DA.3. Southeast of well DA.3, unit G is offset slightly down to the east by the Shawneetown and Lusk Creek Faults. The thickness of unit G appears to be unaffected by these faults. To the east in western Hardin County, Illinois, unit G is thinned on the upthrown side of an unnamed down-to-southeast fault. This local thinning implies either syndepositional (unit G) uplift of the footwall block, or shale drape over an elevated structure on top of unit F such as a carbonate reef buildup. To the east of this fault, unit G thickens to around 445 feet thick at well DA.4 in Crittenden County, Kentucky, along the crest of the Fluorspar District uplift.

At the northwestern end of MVG Dip-A, unit F is 908 feet thick at well DA.1. Unit F gradually thickens to the southeast to around 1,468 feet thick at well DA.2 in northwestern Williamson County, Illinois, and 1,857 feet thick at well DA.3 in Pope County, Illinois. Unit F thickens to more than 2,200 feet east of the Lusk Creek and Shawneetown Faults on the upthrown side of the unnamed down-to-southeast basement fault in Hardin County, Illinois. The thickening of unit F below a thinned unit G section (see above) suggests a carbonate buildup existed along the fault at the end of unit F deposition. Farther southeast, unit F thins eastward onto the Fluorspar District uplift; and well DA.4 in Crittenden County, Kentucky, unit F is 1,808 feet thick.

The thickness of unit E across MVG Dip-A is relatively constant. Unit E is 191 feet thick at well DA.1, and thins slightly to the southeast through well DA.2 (140 feet), but thickens to 232 feet at well DA.3. The top of unit E is only slightly offset by the Lusk Creek Fault and Shawneetown Fault System; however, the thickness of unit E increases to around 300 feet southeastward across the faults. To the southeast of the westernmost down-to-southeast fault in western Hardin County, Illinois, the local thickness of unit E increases to a maximum around 400 feet thick. Unit E abruptly thins southeastward across the unnamed basement faults in central Hardin County, to 225 feet thick at well DA.4 in Crittenden County, Kentucky.

At well DA.1, unit D is 1,118 feet thick in Washington County, Illinois. Unit D thins slightly southward to 1,091 feet thick at well DA.2 along the Cottage Grove Fault System. Unit D thickens southeast of well DA.2 to 1,643 feet thick at well DA.3, just west of the Lusk Creek Fault and Shawneetown Fault System. The thickness of unit D is unchanged across the Shawneetown Fault System, but the unit thins to around 1,000 feet in the fault block between the Lusk Creek Fault and the unnamed down-to-southeast basement fault in western Hardin County, Illinois, implying possible inversion of the fault block during unit D deposition (Middle Ordovician). This area also coincides with the local uplift associated with the later (Permian) Hicks Dome intrusive igneous structure, but a genetic link between these uplifts appears unlikely. In central Hardin County, unit D thickens to the southeast, to a maximum of 1,456 feet at well DA.4 near axis of the Fluorspar District uplift.

Within the study area, unit C thickens toward, and over, the Rough Creek and Mississippi Valley Grabens from all directions. At well DA.1 west of Du Quoin Monocline and Centralia Fault, unit C is 1,912 feet thick. To the southeast at well DA.2, unit C increases in thickness by more than 80% to around 3,500 feet thick. Unit C thickens to the southeast by another 86% to 6,484 feet thick at well DA.3. The top of unit C is upthrown by around 100 feet to the southeast of the Lusk Creek Fault and Shawneetown Fault System, suggesting post-Early Ordovician structural inversion. Southeast of the Lusk Creek Fault, unit C gradually thins to around 5,700 feet thick at well DA.4 on the Fluorspar District uplift.

Unit B is 379 feet thick at well DA.1 in Washington County, Illinois. To the southeast below well DA.2, unit B is around 500 feet thick. To the southeast, unit B thins slightly to around 300 feet in central Williamson County, Illinois. Unit B thickens to around 1,000 feet along the southern border of Saline County, Illinois, northwest of well DA.3, where unit B is 774 feet thick. The top of unit B is upthrown by around 100 feet to the southeast across the Shawneetown Fault System. Southeast of the Lusk Creek Fault, unit B abruptly thickens to around 2,500 feet thick. Unit B thickens to more than 3,000 feet across the down-to-southeast basement fault in western Hardin County, Illinois. The thickness of unit B is fairly uniform between the Hardin County fault and the southeast end of the section in Crittenden County, Kentucky, where unit B is about 3,000 feet thick at well DA.4.

Unit A is absent from wells DA.1 and DA.2. Unit A pinches out around 8 km to the northwest of well DA.3. At well DA.3 in Pope County, Illinois, unit A is about 1,000 feet thick. Unit A thickens to the southeast to around 1,500 feet near the Shawneetown Fault System (no thickness change across fault). To the east, however, unit A thickens to around 3,000 feet thick southeastward across the Lusk Creek Fault. These thickness patterns suggest that this part of the Lusk Creek Fault was active during unit A deposition, but not active during the deposition of unit B. In contrast, the nearby Shawneetown Fault was active (down-to-southeast) during the deposition of unit B, but not during unit A deposition. Unit A thickens farther to the southeast along MVG Dip-A to around 4,800 feet thick at DA.4 in Crittenden County, Kentucky.

4.7 Line MVG Dip-B ([Plate 26](#))

Cross section Dip Line MVG-B includes eight wells and extends 147 mi (237 km) southeastward from Union County, Illinois, to Humphreys County, Tennessee. Erosion at the sub-Cretaceous unconformity has removed stratigraphic unit G from most of the area crossed by this section. Unit G is present only from the Ste. Genevieve Fault System along the eastern edge of the Ozark Dome, to near the Lusk Creek Fault in Massac County, Illinois. Unit G is 188 feet thick in well DB.2 in southern Johnson County,

Illinois, and maintains this approximate thickness across the small area where it is present along this line.

A complete interval of stratigraphic unit F is missing from well DB.1 because of pre-Cretaceous erosion on the Ozark Dome. East of the down-to-east Ste. Genevieve faults, unit F is around 1,750 feet thick, but thins slightly to 1,684 feet thick at well DB.2. No significant offset is interpreted for unit F across the Lusk Creek Fault, in Massac County, Illinois. The thickness of unit F increases over the Mississippi Valley Graben to 1,875 feet at well DB.3 in McCracken County, Kentucky. Between wells DB.3 and DB.4 in Carlisle County, Kentucky, unit F is truncated at the sub-Cretaceous unconformity; and the complete interval of unit F is absent from wells DB.4, DB.5, DB.6 and DB.7. At well DB.8 in Humphreys County, Tennessee, unit F is 444 feet thick.

Unit E is 183 feet thick at well DB.1 in southern Union County, Illinois. Eastward across the Ste. Genevieve Fault System, the top of unit E is offset about 2,000 feet down to the east, and the unit thickens to around 300 feet thick. At well DB.2, unit E is 212 feet thick. Southward across the Lusk Creek Fault, unit E is offset about 100 feet down to the southeast, but the unit shows no apparent thickening across the fault, implying post-Ordovician movement. The thickness of unit E is about 250 feet at well DB.3, and thickens southward to 295 feet at well DB.4. The sub-Cretaceous unconformity truncates unit E just south of well DB.4, and the interval has been completely removed to the south at well DB.5 in Graves County, Kentucky. The unit E interval emerges from beneath the Cretaceous cover near the Graves/Calloway County border. Unit E is 130 feet thick at well DB.6 southeast of the unnamed eastern boundary fault of the Mississippi Valley Graben. Southward to well DB.7 in western Henry County, Tennessee, unit E has a fairly constant thickness around 125 feet. The unnamed basement fault in central Henry County (herein referred to as the Northwest Stewart fault, after Stewart County, Tennessee, where it was first defined along seismic profiles) offsets the top of unit E by around 300 feet down to the northwest. At well DB.8 in Humphreys County, Tennessee, unit E is 180 feet thick.

At the western end of line MVG Dip-B, unit D is 1,564 feet thick in well DB.1 on the eastern edge of the Ozark Uplift. The top of unit D is offset about 1,800 feet down to the east across the Ste. Genevieve Fault System. The thickness of unit D in well DB.2 is 1,652 feet. Southward from well DB.2, unit D is offset about 100 feet down to the southeast by the Lusk Creek Fault in Massac County, Illinois, on the northwestern border of the Mississippi Valley Graben. Unit D thins to about 1,300 feet below well DB.3, and to about 1,275 below well DB.4 in Carlisle County, Kentucky. To the south at well DB.5, the pre-Cretaceous unconformity has resulted in an incomplete section of unit D. Between well DB.5 and well DB.6, the top of unit D is offset around 50 feet down to the northwest across the unnamed eastern boundary fault of the Mississippi Valley Graben. No thickness change is observed for unit D across this fault. Unit D thickens to 1,574 feet at well DB.6 in Calloway County, Kentucky. Southward from well DB.6, unit D thins to 863 feet at well DB.7. To the southeast, the top of unit D is offset about 100 feet up to the southeast across the down-to-northwest Northwest Stewart fault in western Henry County, Tennessee. East of the Northwest Stewart fault, unit D thickens slightly to 991 feet thick at well DB.8 in Humphreys County, Tennessee.

The Thickness of unit C (Knox Supergroup) increases toward the center of the Mississippi Valley Graben along cross section MVG Dip-B. At well DB.1 on the eastern edge of the Ozark Uplift, unit C is 6,161 feet thick. Eastward across the Ste. Genevieve Fault System, the top of unit C is offset around 2,200 feet down to the east. Unit C thickens slightly to the east to 6,498 feet thick at well DB.2 in Johnson County, Illinois. South of well DB.2, MVG Dip-B crosses the Lusk Creek Fault. The top and base of unit C are offset about 200 feet down-to-southeast across the Lusk Creek Fault, indicating no syndepositional movement during the time of the deposition of unit C. Unit C thickens to the southeast to around 7,250 feet thick at well DB.3 in McCracken County, Kentucky, and to about 11,000 feet thick below well DB.4 in northeastern Carlisle County, Kentucky. The base of unit C at well DB.4 is on the downthrown side of the blind down-to-west "central fault" of the Mississippi Valley Graben. No offset is observed at top of unit C; however, the unit thins by about 1,000 feet eastward across this fault suggesting Early Ordovician or older movement along this fault. Unit C thins southward to about 9,000 feet thick below well DB.5. To the east, unit C is offset about 100 feet up to the

southeast (without any thickness change) across the eastern boundary fault of the Mississippi Valley Graben in eastern Graves County, Kentucky. Unit C thins southeastward to around 7,250 feet at well DB.6, and to 5,508 feet thick at well DB.7 in western Henry County, Tennessee. The top of unit C has little offset or thickness change eastward across the Northwest Stewart fault in Henry County. Another basement fault (herein the Southeast Stewart fault) about 8 mi (10 km) to the east offsets the base (but not the top) of unit C, resulting in local thickening on the downthrown (northwestern) side to around 5,750 feet. Eastward across the Southeast Stewart fault, unit C thins to 5,364 feet thick at well DB.8.

Outside of the rift basin, unit B gradually thickens toward the Mississippi Valley Graben, but abruptly thickens across the graben-bounding faults into the rift graben. At well DB.1 in Union County, Illinois, unit B is about 600 feet thick. The top of unit B is offset about 2,500 feet down to the east across Ste. Genevieve Fault System and thickens eastward to 1,479 feet thick at well DB.2. Southward from well DB.2, the top of unit B is offset about 200 feet down-to-southeast across the Lusk Creek Fault, and thickens to about 3,250 feet thick across the fault below well DB.3. Below well DB.4 in northeastern Carlisle County, Kentucky, unit B is around 3,300 feet thick. About 2,000 feet of up-to-southeast offset at the top of unit B is interpreted eastward across the "central fault" of the Mississippi Valley Graben. Unit B thins southward to around 2,500 feet thick below DB.5. Eastward across the "eastern boundary fault" of the Mississippi Valley Graben, little offset is interpreted at the top of unit B, and the unit thickens only slightly to around 2,600 feet thick at DB.6. Unit B thins southward to about 2,300 feet at well DB.7 in Henry County, Tennessee. The top of unit B is offset about 100 feet and 250 feet up-to-southeast, respectively, across the Northwest Stewart fault and Southeast Stewart fault. To the southeast of the Stewart faults, unit B thins to about 750 feet thick and thins eastward to 117 feet thick at well DB.8 in Humphreys County, Tennessee. Southeast of central Johnson County, Illinois, and northwest of the Northwest Stewart fault, unit B conformably overlies the Reelfoot Arkose of unit A. Outside of this area, unit B directly overlies the eroded Precambrian crystalline rocks of the Granite-Rhyolite Province.

Unit A is absent from wells DB.1 and DB.8. Unit A is around 400 feet thick at well DB.2, and pinches out about 3 mi (5 km) to the west. Southeastward across the Lusk Creek Fault, unit A is offset about 1,100 feet down-to-southeast and thickens to around 3,500 feet thick below well DB.3. Unit A thins southward away from the Lusk Creek Fault to around 1,500 feet thick below well DB.4. Just south of well DB.4, unit A is offset about 1,000 feet up-to-southeast across the "central fault" of the Mississippi Valley Graben. Southeastward across this fault, unit A thins by around 400 feet, but thickens southward from the fault to around 1,500 feet thick below well DB.5. Eastward from well DB.5, unit A thickens to close to 3,800 feet thick west on the downthrown side of the "eastern boundary fault" of the Mississippi Valley Graben. Across this fault, unit A thins by about 900 feet; however, little offset is recorded at the top of the unit. Unit A thins eastward from this fault to about 2,500 feet below well DB.6. Southward from well DB.6, unit A thins to 941 feet at well DB.7. Unit A terminates against the Northwest Stewart fault in western Henry County at a thickness of around 500 feet, and is absent from well DB.8. Wherever present, unit A directly overlies Precambrian crystalline basement.

4.8 Line MVG Dip-C ([Plate 27](#))

Line MVG Dip-C is a six-well, 145-mi-(234 km)-long, west-northwest to east-southeast oriented cross section that extends between Stoddard County, Missouri, and Humphreys County, Tennessee. This cross section is the farthest southwest of the lines within the study, in an area characterized by deep erosional truncation beneath the pre-Cretaceous unconformity. Along the line of this cross section, units D, E, F, and G are present only in well DC.6. Within that well, an erosionally thinned unit G is 162 feet thick, unit F is 444 feet thick, unit E is 180 feet thick, and unit D is 991 feet thick. All of these units pinch out to the northwest beneath the pre-Cretaceous unconformity.

Cretaceous sediments of the Mississippi Embayment unconformably overlie a truncated unit C section in all of the wells in this line except well DC.6. The preserved thickness of unit C is 3,651 feet in well DC.1, 2,234 feet in well DC.2, 1,170 feet in well DC.3, 3,200

feet in well DC.4, and 4,580 feet in well DC.5. Outside of the Mississippi Embayment, well DC.6 penetrated a complete section of unit C of 5,364 feet.

Unit B is 651 feet thick in well DC.1 on the Ozark Uplift in Stoddard County, Missouri, and thickens southward to about 1,400 feet thick beneath well DC.2. Eastward across the southern extension of the Lusk Creek Fault on the northwestern border of the Mississippi Valley Graben, unit B is downthrown about 3,000 feet to the east and thickens to around 5,700 feet thick below well DC.3. In the Mississippi Valley Graben, unit B thickens toward the Blytheville Arch, centered over the active faults of the New Madrid Seismic Zone. Along the axis of the Blytheville Arch, the top of unit B has been truncated at the sub-Cretaceous unconformity with a maximum thickness around 9,000 feet. Unit B thins eastward from the Blytheville Arch to about 8,200 feet thick below well DC.4 near the southeastern end of Pascola Arch. Eastward across two unnamed down-to-northwest basement faults along the southeastern border of the Mississippi Valley Graben in Gibson County, Tennessee, unit B is upthrown about 3,600 feet to the southeast and thins to 211 feet in well DC.5. East of well DC.5, unit B thickens to around 800 feet in eastern Gibson County, Tennessee. In Benton County, Tennessee, unit B is offset around 2,000 feet down to the northeast across an unnamed basement fault. At the eastern end of this cross section, unit B is 296 feet thick in well DC.6. Within the Mississippi Valley Graben, unit B directly overlies the clastic rocks of unit A. Outside of the graben, unit B unconformably overlies rocks of the Precambrian Granite-Rhyolite Province.

Within cross section MVG Dip-C, unit A is completely absent from wells DC.1, DC.2, DC.5 and DC.6. East of the Lusk Creek Fault, unit A is about 5,500 feet thick below well DC.3. Unit A thins to the east across the northeast striking active faults of the New Madrid Seismic Zone, to around 4,600 feet thick beneath well DC.4. Unit A is upthrown almost 6,000 feet to the southeast and thins to around 1,200 feet thick across the eastern boundary fault of the Mississippi Valley Graben in northwestern Gibson County, Tennessee. Unit A terminates against the down-to-northwest basement fault in central Gibson County. Unit A unconformably overlies the Precambrian igneous rocks of the Granite-Rhyolite Province. The majority of hypocentral earthquake foci depths along the New Madrid Seismic Zone crossed by this section are between 16,000 and 29,000 feet

(Pujol et al., 1997). The top of this range corresponds to the local depth of the base of unit A/top of Precambrian basement.

4.9 Line Strike-1 ([Plate 28](#))

Strike-1 is the longest cross section of this study at 404 mi (650 km). This line is composed of 9 wells, extending northward off of the Ozark Dome from Stoddard County, Missouri, northeastward across southern Illinois, eastward across southern Indiana to Boone County, Kentucky, near the crest of the Cincinnati Arch. Strike-1 was constructed so that the line of the cross section is roughly parallel to (but well outside and north of) the Mississippi Valley and Rough Creek Grabens.

Unit G is absent from well S1.1 because of erosion beneath the sub-Cretaceous unconformity, and absent from well S1.2 because of erosion on the present land surface along the Ozark Uplift in southeastern Missouri. On the northern (downthrown) side of the Ste. Genevieve Fault System, unit G terminates southward against the fault at a thickness of about 150 feet. North of the Cottage Grove Fault System, unit G thins northward to 30 feet thick in well S1.3 in Washington County, Illinois. Eastward from well S1.3, the top of unit G is offset about 400 feet down to the east across the Centralia Fault, within the core of the Du Quoin Monocline ([Figure 3.2](#)). The thickness of unit G between wells S1.3 and S1.4 steadily increases eastward to 193 feet. Unit G is deepest (-4,250 feet) along Strike-1 at well S1.4, which lies just north of the depocenter of the Fairfield Subbasin. Eastward from well S1.4 to well S1.7, unit G has a fairly constant thickness around 100 to 150 feet. West of well S1.5, unit G is offset about 750 feet down to the west across the La Salle Fault in Lawrence County, Illinois. East of well S1.7, the trace of this cross section crosses the southern end of the Mt. Carmel Fault where structural offsets are limited with respect to what has been mapped farther north. Unit G is upthrown slightly (<50 feet) eastward across the Mt. Carmel Fault. To the east, unit G crops out west of well S1.8 in Jennings and Jefferson County, Indiana, and is absent from wells S1.8 and S1.9.

Because of erosion of the Ozark Dome, unit F is absent in well S1.1, and only the lowest 50 feet of the unit is present within well S1.2. Unit F terminates southward against the

Ste. Genevieve Fault System at an elevation of the top of unit F around -1,500 feet and a thickness approaching 1,700 feet. Unit F thins northward from the Ste. Genevieve Fault System to 908 feet thick in well S1.3 in Washington County, Illinois. East of well S1.3, the top of unit F is offset about 200 feet down to the east across the Centralia Fault. At well S1.4, unit F is 1,219 feet thick, and the top of unit F is at an elevation of -4,414 feet. Between wells S1.4 and S1.5, unit F thins to 1,114 feet, and is offset about 900 feet up to the east across the fault within the core of the Charleston monocline, just west of well S1.5. Eastward from well S1.5, unit F thins to 851 feet in well S1.6, and to 437 feet thick in well S1.7 in Lawrence County, Indiana. Little offset (<50 feet) is observed across the Mt. Carmel Fault east of well S1.7. Unit F crops out along this line in Jefferson County, Indiana, and is absent from wells S1.8 and S1.9.

At the southwestern end of line Strike-1 on the Ozark Dome, unit E is absent in well S1.1. To the north in well S1.2 in Union County, Illinois, unit E is present and is 183 feet thick. Northward across the Ste. Genevieve Fault System, unit E is offset about 3,650 feet down to the northeast. No thickening of unit E is observed across the Ste. Genevieve Fault System, indicating post-Ordovician fault offset. To the north, unit E is 191 feet thick in well S1.3. Unit E is offset about 500 feet down to the east across the Centralia Fault between wells S1.3 and S1.4 in southern Illinois. At well S1.4 in the Fairfield Subbasin, unit E is 192 feet thick. Unit E is offset about 900 feet down to the west across the La Salle Fault, west of well S1.5. Eastward from well S1.4, unit E thickens to 293 feet thick in well S1.5, 339 feet thick in well S1.6, and 549 feet thick in well S1.7 in Lawrence County, Indiana. Unit E crops out in Jefferson County, Indiana, and only a truncated unit E interval of about 400 feet is present in wells S1.8 and S1.9.

Unit D is absent beneath the sub-Cretaceous unconformity in well S1.1, but is present and 1,564 feet thick to the north in well S1.2 in Union County, Illinois. Northward across the Ste. Genevieve Fault System, unit D is offset more than 3,500 feet down to the north. Unit D thins to the north to 1,118 feet in well S1.3, with no significant offset or thickness change across the Cottage Grove Fault System. Unit D is offset down about 500 feet eastward across the Centralia Fault within the core of the Du Quoin Monocline. Unit D thickens eastward into the Fairfield Subbasin and is 1,232 feet thick in well S1.4 in

Wayne County, Illinois. West of well S1.5, unit D is offset about 800 feet down-to-west across the La Salle Fault. Between wells S1.4 and S1.5, unit D thins eastward by about 30% to 860 feet thick. Unit D thins eastward to 697 feet in well S1.6. East of well S1.6, the thickness of unit D is relatively constant between 600 and 700 feet thick to the end of the line in Boone County, Kentucky.

In well S1.1, 3,651 feet of an erosionally truncated unit C is present below about 300 feet of Cretaceous and younger cover. To the north in Union County, Illinois, a complete 6,161-foot interval of unit C is in well S1.2. Northward across the Ste. Genevieve Fault System, unit C is offset more than 3,000 feet down to the north. Unit C thins dramatically (about 67%) northward from well S1.2 to 1,912 feet thick in well S1.3. Unit C thickens by about 400 feet, and is downthrown about 500 feet, eastward across the Centralia Fault in Washington County, Illinois. At well S1.4 in the Fairfield Subbasin, unit C is 2,891 feet thick. Eastward across the La Salle Fault, unit C is offset about 1,100 feet up to east. Unit C is 2,985 feet thick in well S1.5 and thins eastward to the end of the cross section at well S1.9 in Boone County, Kentucky. Unit C is 2,519 feet thick in well D1.6, 2,449 feet in well S1.7, 2,060 feet in well S1.8, and 1,662 feet in well S1.9 near the axis of the Cincinnati Arch.

Unit B is about 650 feet thick below well S1.1 in Stoddard County, Missouri. Unit B thins to the northeast over the Ozark Uplift in Scott County and eastern Stoddard County, Missouri, but thickens to 642 feet in well S1.2 in Union County, Illinois. Between wells S1.2 and S1.3, unit B is downthrown about 3,000 feet to the north across the Ste. Genevieve Fault System. Unit B also increases in thickness by about 100 feet northward across the fault zone to around 750 feet thick. No abrupt thickness or elevation changes are observed in unit B across the Cottage Grove Fault System in Jackson County, Illinois. North of the Cottage Grove Fault System, unit B thins northward to 379 feet thick in well S1.3. East of well S1.3, unit B is downthrown about 1,100 feet to the east across the Centralia Fault. Unit B thickens eastward to 1,062 feet in well S1.4. East of the La Salle Fault, unit B is about 1,400 feet thick below well S1.5 and the unit thickens eastward to about 1,650 feet below well S1.6, and 1,841 feet in well S1.7 in Lawrence County, Indiana. As with units G through C, unit B is slightly upthrown (<100 feet) eastward

across the Mt. Carmel Fault east of well S1.7. East of the Mt. Carmel Fault, unit B thins eastward to 852 feet in well S1.8, and to 828 feet in well S1.9 near axis of the Cincinnati Arch. Along cross section Strike-1, unit B unconformably overlies Precambrian basement. Unit A is absent from cross section Strike-1.

4.10 Paired Strike Lines-2N and -2S ([Plate 29](#))

The paired strike lines 2N and 2S are 357-mi-(574-km) west-to-east lines, from Gallatin County, Illinois, to Casey County, Kentucky, and are oriented to show the stratigraphic thickening and offset produced by the Rough Creek Fault Zone along the northern border of the Rough Creek Graben. Unlike the other cross sections in this study, these lines are not tied to wells along their entire length, but instead are tied only at their eastern and western endpoints (wells D4.5 and D1.3, respectively). Instead of choosing the paths of cross sections on the basis of available wells, the tracks for lines 2N and 2S were produced using X/Y points that are roughly equidistant (north and south) from the center of the Rough Creek Fault Zone. The traces of strike lines 2N and 2S are sub-parallel, and with the exception of the two merged endpoints, maintain a north-to-south horizontal spacing of about six to nine miles (ten to fifteen kilometers). To better illustrate the stratigraphic thickness changes across the fault zone, these two sections are superimposed on the same plate so that elevation differences can be directly compared. For clarity, the horizons and cross faults north of the fault zone (2N) are dashed, and the tops of units D, E, and F were omitted from both lines. The scale in blue at the top of the plate is the relative distance eastward between the two end wells (in percent) and is intended for location references for description purposes along the paired lines, and not for a quantitative measure of distance.

The west ends of both sections 2N and 2S are tied at well D1.3 along the Rough Creek Fault Zone in Gallatin County, Illinois. Well D1.3 is located along the northern edge of the Rough Creek Graben, and the wellbore crosses the fault plane of the Shawneetown fault of the Rough Creek Fault System. Northeastward from well D1.3, the trace of 2N crosses the Wabash Valley Fault System, at around 4-9% east and enters into Union, Webster, and McLean Counties, Kentucky. Near the Webster/McLean County border,

line 2N crosses the Curdsville Fault eastward into the Owensboro graben around 28% east. Eastward from McLean County, line 2N enters into Daviess County and crosses the unnamed down-to-northwest fault on the eastern edge of the Owensboro graben (47% east). East of Daviess County, line 2N passes through Ohio and Grayson Counties, and across the Cave Spring/Locust Hill fault system and Mount Olive/Pole Bridge fault system at 69-75% east. The east end of lines 2N and 2S merge and terminate just north of the eastern extension of the Rough Creek Fault Zone at well D4.5 in northern Hart County, Kentucky (at 100%).

South of the Rough Creek Fault Zone, line 2S crosses eastern Gallatin County, Illinois and Union, Webster, McLean, Ohio, Grayson and Hart Counties in western Kentucky. In McLean County around 40-45% east, line 2S crosses the Central Fault System. In eastern Grayson County near 85% east, line 2S crosses the down-to-southwest splay faults of the Rough Creek Fault Zone. The northern border fault of the Rough Creek Graben is just southwest of well D4.5 and is crossed at a highly oblique angle to the trace of line 2S around 95% east.

The youngest mapped horizon (uppermost green lines) on this cross section is the top of unit G (Late Devonian-Early Mississippian New Albany Shale). For most of these sections, the elevation of unit G north of the Rough Creek Fault Zone is roughly equal to or slightly higher than the elevation of unit G south of the Rough Creek Fault Zone. The maximum vertical offset of unit G between the two lines is about 450-500 feet down-to-south in Grayson County (near the 75% eastward mark), and also between southeastern Henderson and eastern Webster Counties (around 28% eastward).

The top of unit C (Late Cambrian-Early Ordovician Knox Supergroup) is shown by purple lines. Vertical offsets at this level are close to zero feet at the two endpoints (0-4% and 85-100% eastward) and increase to a maximum of around 1,000 feet down-to-south near 28% and 75% eastward.

At the top of unit B (lower pair of green lines), the maximum offset is about 2,250 feet down-to-south in Ohio County, at around 65% east. Even though offsets are apparent at the tops of unit B and shallower horizons, the general character of the surfaces (regional

slopes, high/low points, etc.) are very similar between lines 2N and 2S. Vertical offsets increase with unit age.

Below the top of unit B, the differences between lines 2N and 2S are dramatic. The thickness of unit B increases on the south side of the Rough Creek Fault Zone by as much as 4,000% (from less than 200 to more than 8,000 feet in western Ohio County).

Furthermore, unit A is completely absent north of the Rough Creek Fault Zone, but is as much as 14,000 feet thick to the south within the Rough Creek Graben. The profiles of the top of unit A (red line on Plate 29) and the top of Precambrian rocks (black line on Plate 29) within the Rough Creek Graben are split longitudinally into two westward dipping half-graben-shaped structures. The boundary between these two half-grabens is the southeast-dipping Central Fault System.

In addition to the large variation in thickness across the Rough Creek Fault Zone, the shapes of the top of Precambrian rocks profiles (black lines) change. In contrast to the similar dips and high and low point locations shared among the profiles of the tops of unit B and shallower horizons, the profiles of the top of unit A and top of Precambrian rocks south of the fault zone in line 2S are both quite dissimilar to the profile of the top of Precambrian rocks north of the Rough Creek Fault Zone (where unit A is absent). This change in profile shapes and the prominent thickening of strata below the top of unit B imply that most of the tectonic extension that produced the Rough Creek Graben began before the deposition of unit A, and ended before the end of unit B deposition.

Also evident along lines 2N and 2S is that deformation from northeast-striking fault systems north of the Rough Creek Fault Zone (Wabash Valley Fault Zone, Owensboro Graben faults, Locust Hill/Cave Spring fault system, and Mount Olive/Pole Bridge fault system) is not through-going into the Rough Creek Graben. Because of the lack of deformation from these structures within the graben, it is probable that they post-date the Early-Middle Cambrian tectonic extension.

4.11 Line Strike-3 ([Plate 30](#))

Cross section Strike-3 includes eleven wells between Lake County, Tennessee, and Pulaski County, Kentucky. The 332-mi-(534-km) trace of this line extends from near the New Madrid Seismic Zone in the Mississippi Valley Graben northeastward to the Rough Creek Graben, eastward to and across the Cincinnati Arch, and enters into the western end of the Rome Trough in Pulaski County, Kentucky.

Unit G is absent from this line southwest of well S3.3 because of erosion at the pre-Cretaceous unconformity within the Mississippi Embayment. The southwestern limit of unit G is buried beneath post-Paleozoic sediment in Marshall County, Kentucky. To the northeast across the down-to-northeast Tabb Fault, unit G is 304 feet thick at an elevation of -1,792 feet in well S3.3 in Caldwell County, Kentucky. Unit G thins eastward into the Rough Creek Graben to 189 feet thick in well S3.4 in Muhlenberg County, 162 feet and 166 feet in wells S3.5 and S3.6, respectively. Eastward from Butler County, unit G steadily thins to around 40 feet in S3.11 at the eastern end of Strike-3 in Pulaski County, Kentucky.

Because of erosion at the pre-Cretaceous unconformity, unit F is absent southwest of well S3.3. The subcrop of unit F below post-Paleozoic Mississippi Embayment sediments is in Graves County, Kentucky. To the northeast, unit F is downthrown about 500 feet to the northeast across the Tabb Fault System and is 1,632 feet thick in well S3.3 in Caldwell County. Unit F has a maximum thickness of more than 1,800 feet along this line in central Hopkins County, but thins eastward to 1,161 feet in well S3.4 in Muhlenberg County. The thickness of unit F decreases steadily eastward because of truncation at the overlying Early Devonian unconformity. Unit F thins from 846 feet thick in well S3.5 in Butler County, updip to 93 feet thick in well S3.9 in Green County. Unit F decreases to zero thickness because of pre-Devonian erosion east of well S3.9, and is absent from wells S3.10 and S3.11.

Unit E is absent from wells S3.1 and S3.2. Unit E is downthrown to the east across the Tabb Fault System and is 365 feet thick in well S3.3. Unit E thickens eastward from 428 feet thick in well S3.4 in Muhlenberg County, to a maximum of 513 feet in well S3.8 in

Barren County. Unit E thins slightly across the crest of the Cincinnati Arch, but thickens east of the Lexington Fault System to 535 feet thick in well S3.11 in Pulaski County, Kentucky.

Unit D is absent from S3.1, but a slightly truncated 1,403 feet of unit D section is present in well S3.2 in southern Graves County. Unit D thins to the east to about 1,200 feet thick west of the Tabb Fault System in Caldwell County. Unit D is offset about 500 feet down-to-northeast across the Tabb Fault System, but the thickness of unit D is constant across the fault zone (unit D is 1,197 feet thick in well S3.3), implying post-depositional movement along the faults. To the east, unit D thins to 917 feet thick in well S3.4. Between wells S3.4 and S3.5, the line of this section crosses a northeastern splay of Pennyrile Fault System (locally the Belton Fault System and other unnamed faults). Unit D is downthrown about 150 feet to the northwest across these faults. The thickness of unit D is relatively constant between 850 and 950 feet eastward through wells S3.5 to S3.10. East of the Lexington Fault System, unit D thickens eastward into the Rome Trough to 1,018 feet thick in well S3.11.

The pre-Cretaceous unconformity truncated unit C to 3,200 feet in well S3.1 on southeast end of Pascola Arch in Lake County, Tennessee. Between wells S3.1 and S3.2, this line obliquely crosses the southern end of the down-to-west "Central fault" of the Mississippi Valley Graben. To the northeast in Graves County, unit C is around 9,000 feet thick below well S3.2. East of well S3.2, unit C thins to 6,316 feet thick in well S3.3, and around 6,100 feet thick below well S3.4. Unit C is offset about 100 feet down-to-northwest and thickens by about 250 feet northwestward across the Belton Fault System near the border between Muhlenberg and Butler Counties, Kentucky. East of the Belton Fault System, unit C thins from about 5,000 feet thick below wells S3.5 and S3.6 in Butler County, to 3,413 feet thick in well S3.9 in Green County. Between wells S3.9 and S3.10, line Strike-3 obliquely crosses an unnamed down-to-north basement fault in Adair County. Unit C is slightly thickened on the northern, downthrown side of the Adair County fault. Unit C is 3,576 feet thick in well S3.10, and thins to 3,260 feet thick in well S3.11 on the eastern end of Strike-3.

At the southwestern end of Strike-3, unit B is about 8,000 feet thick below well S3.1 on southeast end of the Pascola Arch, but thins to about 2,500 feet below well S3.2. About 700 feet of this westward thickening can be attributed to syndepositional down-to-west movement along the Central Fault. The rest of this dramatic local thickening of unit B may be a result of later tectonic compression and structural inversion similar to a positive “flower” structure or a “mushwad” structure of Thomas (2001) along the faults of the New Madrid Seismic Zone just west of well S3.1. Eastward across the Tabb Fault System, unit B thickens by about 700 feet to a total of around 4,200 feet thick below well S3.3, just east of the fault system. To the east of well S3.3 along Strike-3, the thickness of unit B varies locally, but is fairly constant on a regional scale at around 4,200 feet thick through western Muhlenberg County below well S3.4. In eastern Muhlenberg County, unit B thins above a basement high associated with the Belton Fault System. Unit B is offset about 200 feet down-to-northwest across this fault system. Where the line of this section diverges from the strike of the Pennyryle Fault System, unit B thickens to the east to about 3,300 feet thick below well S3.5, and about 4,200 feet below well S3.6 in Butler County. Unit B is around 3,200 feet thick to the east below S3.7 in Edmonson County, and thins to about 2,000 feet thick below well S3.8 where the line approaches the Pennyryle Fault System. To the northeast (away from the trend of the Pennyryle Faults), unit B is around 3,100 feet thick below well S3.9. Unit B thins by about 300 feet eastward (obliquely) across a blind, unnamed down-to-north basement fault in Adair County. Below well S3.10, unit B is about 1,700 feet thick along the Cincinnati Arch west of the Lexington Fault System. Unit B thickens by about 500 feet eastward across the Lexington Fault System. To the east of the Lexington Fault System, the unit B equivalent to the Eau Claire Formation in western Kentucky is the Conasauga Group. The Conasauga Group within well S3.11 is 863 feet thick. Below the Conasauga Group within the Rome Trough are arkosic clastic rocks of the Rome Formation. The similar lithology and stratigraphic position of the Rome Formation suggests that it is equivalent to the Reelfoot Arkose of unit A. If this interpretation is incorrect (and therefore the Rome Formation is equivalent to the lower part of the Eau Claire Formation), then the thickness of unit B in well S3.11 would be 1,548 feet.

At the southwestern end of line Strike-3, unit A is about 4,500 feet thick below well S3.1 in Lake County, Tennessee. Unit A is upthrown about 900 feet northeastward across the southern end of the Central Fault. No thickness change of unit A is apparent across the fault. Unit A thins to the east to about 1,500 feet thick below well S3.2 in western Graves County. Unit A thickens to the northeast to about 4,000 feet thick in western Lyon County, but thins to about 2,600 feet along the upthrown side of the Tabb Fault System. Eastward across the Tabb Fault System, unit A expands by about 170% to around 7,000 feet thick below well S3.3 in Caldwell County. This dramatic thickening indicates significant syndepositional movement of the Tabb Fault System during the deposition of unit A. Unit A thins eastward away from the Tabb Fault System to around 2,500 feet thick below well S3.4, to about 300 feet along the Belton Fault System in eastern Muhlenberg County. East of the Belton Fault System along this line, unit A thickens to around 7,000 feet below the border between Butler and Edmonson Counties between wells S3.6 and S3.7. Below well S3.7 in central Edmonson County, unit A is about 3,000 feet thick and thins eastward to zero thickness in north-central Barren County. Unit A is absent from wells S3.8 through S3.10. East of the Lexington Fault System, the Rome Formation (probable unit A equivalent in the Rome Trough) is 685 feet thick in well S3.11 in Pulaski County, Kentucky.

4.12 **Line Strike-4** ([Plate 31](#))

Strike Line 4 is a 180-mi-(290 km)-long line connecting five wells between Humphreys County, Tennessee, and Pickett County, Tennessee. This west-southwest to east-northeast line crosses northern Tennessee along the northern flank of the Nashville Dome and Cumberland Saddle, far outside the regional graben structures.

At the southwest end of the line at well S4.1, unit G is 162 feet thick. Unit G thins eastward onto the Nashville Dome to less than 50 feet thick where the unit crops out in Cheatham County, Tennessee, west of well S4.2. Unit G is absent from wells S4.2, S4.3, and S4.4. In well S4.5, 33 feet of unit G-equivalent strata (Chattanooga Shale) unconformably overlie unit E strata, in the Cumberland Saddle.

Unit F is 444 feet thick in well S4.1 in Humphreys County, Tennessee. Unit F thins to the east to where it is exposed and eroded along this line in Cheatham and Davidson Counties, Tennessee. Unit F is eroded at the present surface and absent from wells S4.2 through S4.4 along this cross section. Unit F is unconformably absent from well S4.5 below unit G.

Unit E is 200 feet thick in well S4.1, and thickens to the east to where it crops out in Davidson County, Tennessee, west of well S4.2. Unit E is exposed at the present surface at wells S4.2, S4.3, and S4.4 on the northwestern edge of Nashville Dome. A truncated 150-foot-thick interval of unit E is present within well S4.2 in Davidson County, Tennessee. At well S4.3 unit E is truncated to 325 feet thick. To the east in Clay County, a truncated unit E interval is about 300 feet thick in well S4.4. A complete interval with 350 feet of unit E is present at the northeast end of this line in well S4.5.

In well S4.1, unit D is 991 feet thick, and it thins eastward onto the Nashville Dome to 878 feet thick in well S4.2 in Davidson County, Tennessee. Between wells S4.2 and S4.3, the line of this section crosses the northwestern flank of the Nashville Dome just west (down dip) of where unit D crops out at the surface. At well S4.3 in Macon County, Tennessee, unit D is 983 feet thick. Unit D thickens to the east to 1,130 feet thick in well S4.4 along Cincinnati Arch. At the east end of the line at well S4.5, unit D is 1,031 feet thick.

Unit C is 5,364 feet thick in well S4.1 in Humphreys County, Tennessee. Unit C thins abruptly (33% decrease) eastward onto the northwestern side of Nashville Dome to 3,597 feet in well S4.2. Eastward between wells S4.2 and S4.3, however, unit C thins by less than 5% to 3,430 feet thick in well S4.3. Along the Cumberland Saddle, unit C is thinned to 3,291 feet thick in well S4.4, and 3,060 feet thick in well S4.5 in Pickett County, Tennessee.

The thickness of unit B along this line is quite varied. At well S4.1 in Humphreys County, Tennessee, unit B is 296 feet thick. To the east in Davidson County, Tennessee, the thickness of unit B more than doubles to 796 feet in well S4.2. Seventy-one kilometers to the northeast at well S4.3, unit B is only 158 feet thick. Between wells S4.3

and S4.4, the line of this section crosses the northern end of an unnamed, down-to-southeast basement fault in eastern Macon County, Tennessee. The top of unit B is downthrown about 100 feet to the southeast across this fault. In well S4.4, unit B is 228 feet thick along Cincinnati Arch/Cumberland Saddle. At the eastern end of this cross section, unit B is 207 feet thick in well S4.5. Unit B unconformably overlies Precambrian igneous basement rocks, and unit A is absent from all of the wells in this cross section.

5 SUBSIDENCE AND SEDIMENTATION RATES

Some locations within the Rough Creek Graben contain more than 38,000 feet of sediment above the top of the Precambrian basement. Progressive compaction of this thick column of sediments during and after burial must have had a significant effect on the subsidence history of the top surface of the sediment. Furthermore, continental rifting stretches the lithosphere along the rift, causing crustal thinning and passive upwelling of hot asthenosphere (McKenzie, 1978). This intrusion of material from depth creates a local positive thermal anomaly in the crust (McKenzie, 1978; Bond and Kominz, 1984). After rifting ends, the crust cools and contracts which produces thermal subsidence within the area of the rift. The overall burial history of a sediment-filled rift-graben is the result of the combination of sediment loading (tectonic subsidence), post-rift crustal cooling (thermal subsidence), and internal sediment compaction (burial-driven porosity loss).

The compaction of sediments during initial burial is a product of porosity reduction and the resulting expulsion of pore fluids. In order to determine the effect of sediment compaction on subsidence, the relative porosities of each of the stratigraphic units must be calculated through time. Empirical analysis of geologic data shows that porosity varies exponentially with depth of burial (Sleep, 1971; Sclater and Christie, 1980; Schmoker and Halley, 1982; Heidlauf et al., 1986; Hegarty et al., 1988). This relationship can be expressed as:

$$\Phi = \Phi_i e^{-Cz}$$

where,

Φ = porosity (at depth z)

Φ_i = initial porosity (at surface)

C = lithologic compaction coefficient

Z = depth (km)

After the relation between porosity and burial depth for a specific lithology has been determined, the uncompacted thickness of a lithologic unit can be calculated.

$$T_z = [(1-\Phi_i)*T_i]*(1+\Phi_z)$$

where,

Φ_z = porosity (at depth z)

Φ_i = initial, uncompacted porosity (at surface)

T_i = initial unit thickness

T_z = unit thickness at depth z

Integrating the previous two equations together allows a direct calculation of compaction-corrected unit thicknesses at any selected burial depth (Sclater and Christie, 1980):

$$T_{z'} = z'_2 - z'_1 = (z_2 - z_1) - [\Phi_i/C(e^{-Cz_1} - e^{-Cz_2})] + [\Phi_i/C(e^{-Cz'_1} - e^{-Cz'_2})]$$

where,

$T_{z'}$ = unit thickness, with top at depth z'_1

Φ_i = initial porosity of unit at surface (constant)

C = lithologic compaction coefficient of unit (constant)

z_1 = present depth to top of unit

z_2 = present depth to base of unit

z'_1 = past depth to top of unit (or base of overlying unit)

z'_2 = past depth to base of unit

Using the above equation from Sclater and Christie (1980), unit thicknesses were calculated for the seven stratigraphic units of this study (A through G). By calculating the thicknesses of progressively deeper units through the stratigraphic column, the calculated base of the previous unit can be used as the depth to the top of the next unit, simplifying the calculations.

The specific values of initial porosity (Φ_i) as well as the compaction coefficient (C) vary depending on the lithologic content of the sedimentary unit. Because of the lack of sufficient well cores or high-quality geophysical well logs (calibrated logging tools, no excessive washouts in the well bore, etc.) within the study area, values for Φ_i and C for different lithologies were compiled from the existing literature. The values used and the respective sources are presented in [Table 5.1](#). Because the stratigraphic units studied in this project (A through G) are not composed of a single, homogeneous lithology type, composite values were calculated using appropriate percentages of the different lithologies included in each specific unit. The respective lithologic percentages used for each unit (as well as time intervals of deposition) are presented in [Table 5.2](#).

Table 5.1 – Values and sources of initial sediment porosities (Φ_i) and compaction coefficients (C) used for burial calculations. The ‘mixed clastic’ lithology type is appropriate for interbedded sandstone and shale units, as well as for siltstone units. Compaction coefficients determined empirically from subsurface well data. For limestone, Sclater and Christie (1980) and Schmoker and Halley (1982) used chalk, and Hegarty et al. (1988) used calcarenite data.

<u>Lithology</u>	Sclater & Christie, 1980	Hegarty et al., 1988	Schmoker & Halley, 1982	Heidlauf et al., 1986
	Pore volume fraction	Pore volume fraction	Pore volume fraction	Pore volume fraction
Shale $\Phi_i =$	0.63	0.52	n/a	n/a
Sandstone $\Phi_i =$	0.49	0.34	n/a	n/a
Mixed clastic $\Phi_i =$	0.56	0.50	n/a	0.56
Limestone $\Phi_i =$	0.70	0.42	0.51	n/a
Dolostone $\Phi_i =$	n/a	n/a	0.30	n/a
Mixed carbonates $\Phi_i =$	n/a	n/a	0.42	n/a
	<u>km⁻¹</u>	<u>km⁻¹</u>	<u>km⁻¹</u>	<u>km⁻¹</u>
Shale $C =$	0.510	0.700	n/a	n/a
Sandstone $C =$	0.270	0.400	n/a	n/a
Mixed clastic $C =$	0.390	0.333	n/a	0.450
Limestone $C =$	0.710	0.556	0.518	n/a
Dolostone $C =$	n/a	n/a	0.217	n/a
Mixed carbonates $C =$	n/a	n/a	0.400	n/a

Table 5.2 - Parameters used to calculate decompaction of stratigraphic units used in this study. Initial porosities and compaction coefficients were calculated using the lithologic percentages shown with values within Table 5.1. Lithologic components expressed as volume fractions. Time intervals between units (if present) represent depositional hiatuses and/or erosional unconformities.

Unit	Begin Ma	End Ma	Shale Vol.	Sandstone Vol.	Limestone Vol.	Dolomite Vol.	Siltstone Vol.	Avg. C	Avg. Φ_i
G	387	356	0.95	0.00	0.00	0.00	0.05	0.593	0.573
F	436	390	0.05	0.25	0.15	0.40	0.15	0.344	0.416
E	451	444	0.50	0.00	0.15	0.00	0.35	0.518	0.555
D	463	451	0.00	0.00	0.85	0.15	0.00	0.538	0.509
C	497	471	0.00	0.15	0.05	0.80	0.00	0.253	0.335
B	505	497	0.60	0.00	0.20	0.10	0.10	0.540	0.538
A	514	505	0.00	0.85	0.00	0.00	0.15	0.339	0.432

5.1 Burial History

Using the backstripping technique described by Sclater and Christie (1980) with the lithologic attributes in Tables 5.1 and 5.2, stratigraphic units are removed sequentially downward and the remaining layers are progressively decompacted at each successively shallower level. Removing the effects of sediment loading and compaction from burial allows the calculation of tectonically forced subsidence. Sediment compaction in this model is assumed to be from porosity loss and not from the introduction of pore-filling cements from outside of the layer being analyzed. The loading effect from water depth was not included in the calculations; however, because no deep water deposits are present within the analyzed section, the influence of the load of the water column is minimal.

Burial, sedimentation, and subsidence rates were calculated at four locations within the study area ([Figure 5.1](#)). Stratigraphic depths and thicknesses were used from two wells outside graben system: the Texaco #1 Cuppy well from within the Fairfield Subbasin in Hamilton County, Illinois, and the KGS #1 Blan well north of the Rough Creek Graben in Hancock County, Kentucky. The compaction-corrected burial histories for these two wells are displayed in [Figure 5.2](#).

Burial and subsidence calculations were also performed for two locations within the deepest parts of the Rough Creek Graben: the Cambrian-aged depocenters in Ohio and Union Counties, Kentucky ([Figure 5.1](#)). Because no wells have been drilled to basement within the centers of these depocenters, the stratigraphic depths and thicknesses used in the subsidence calculations were taken from the mapped surfaces described in Chapter 3. The burial history calculations for the graben depocenter locations are presented in [Figure 5.3](#). Although higher precision depth measurements from well data would be preferred to these interpolated horizons, the calculated subsidence locations within the Rough Creek Graben depocenters are near deep wells and are located in areas with a high density of seismic profile data. The distribution of these alternate data sources minimizes the chances of large errors in depth values used in the compaction and subsidence calculations.

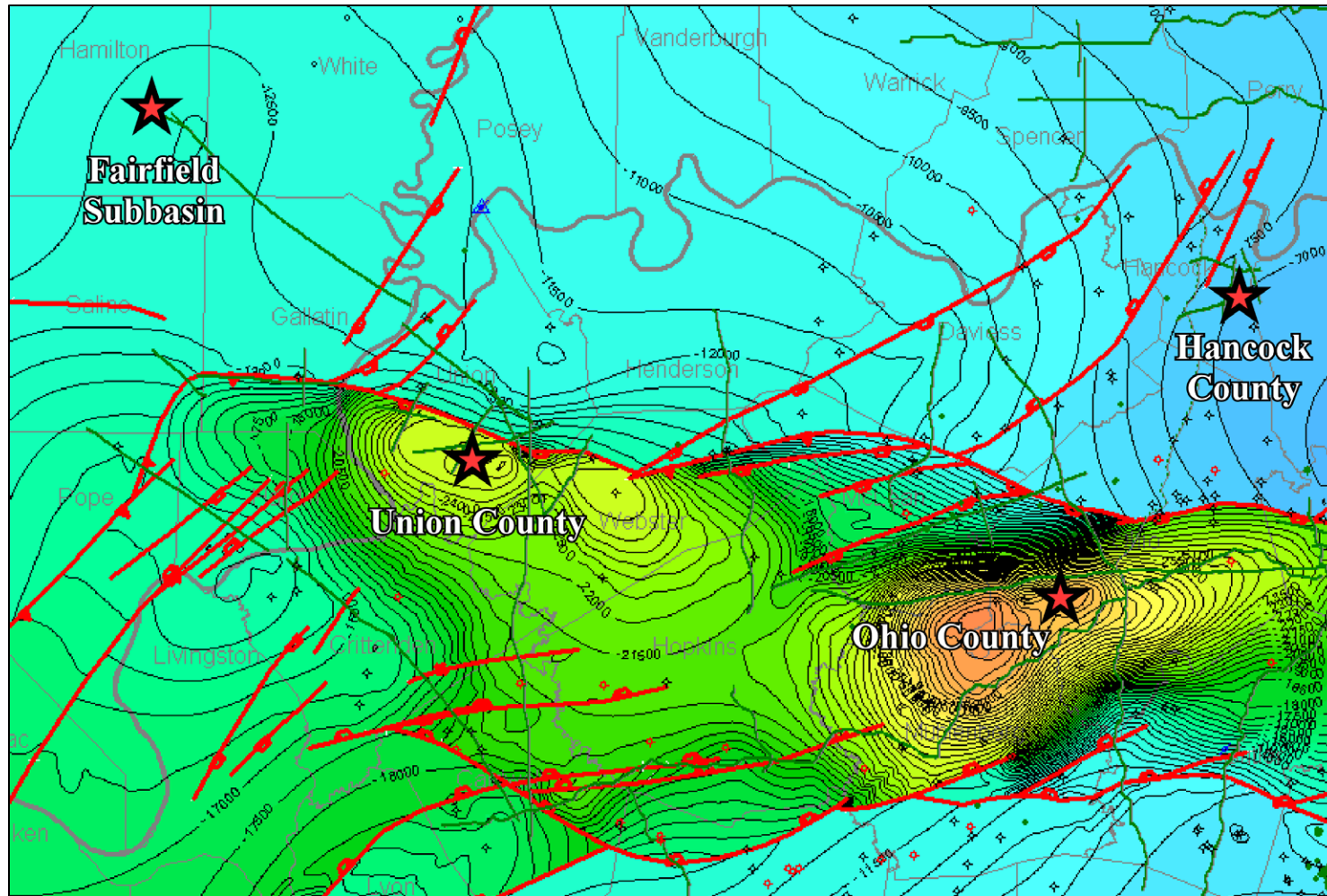


Figure 5.1 – Map of site locations used for burial history and subsidence calculations. Colored contour basemap extracted from Plate 16 (top of Precambrian basement). Red lines represent active fault system segments; dark green lines indicate seismic profile locations. Well data points are displayed with the original completion code symbols.

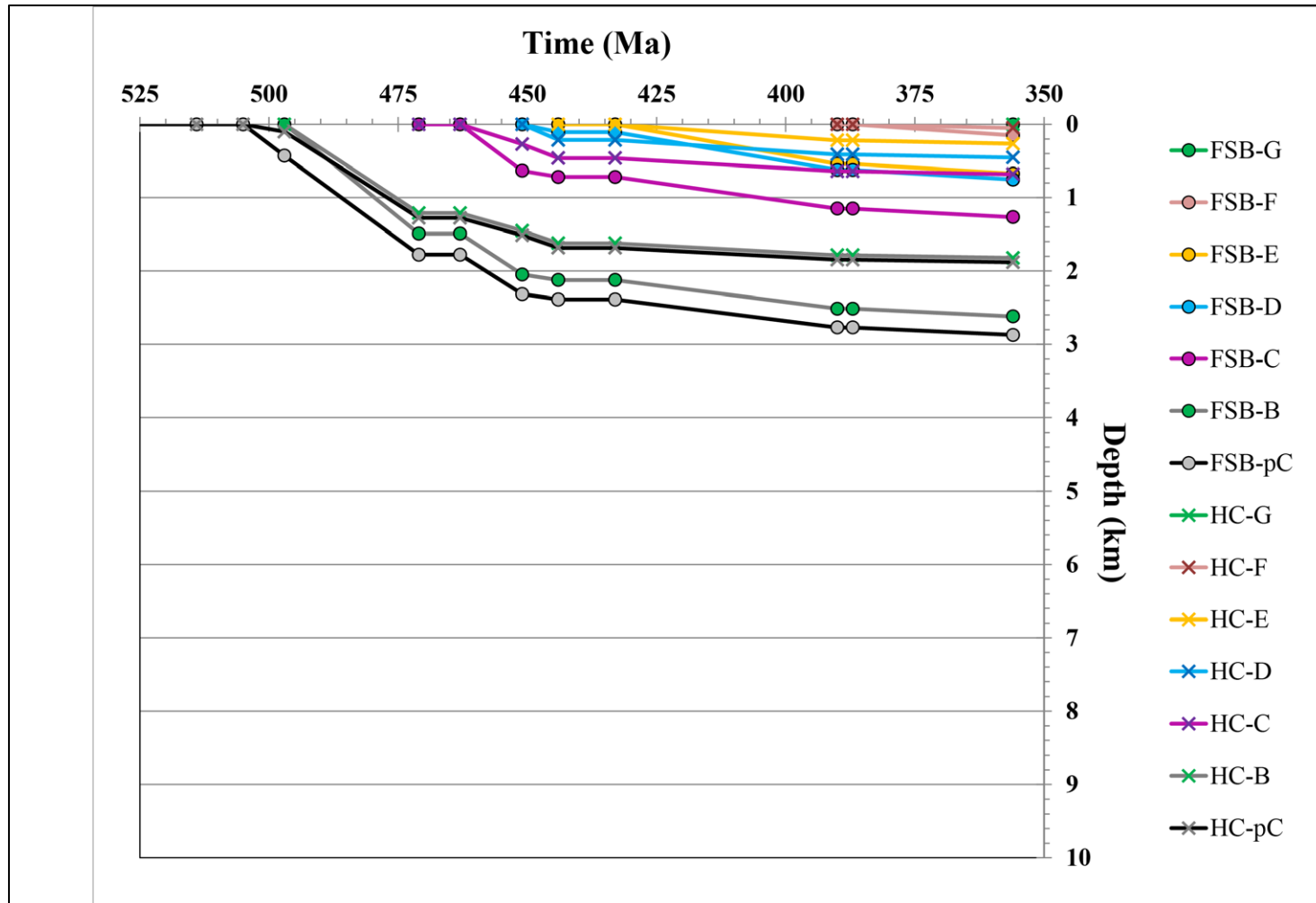


Figure 5.2 - Burial history calculations for the tops of Precambrian basement (pC) and stratigraphic units B-G for locations in the Fairfield Subbasin (FSB) and Hancock County, Kentucky (HC), north of the Rough Creek Graben. Note: Unit A is unconformably absent from these locations.

In Figures 5.2 through 5.6, the major unconformities between units C and D, E and F, and F and G are depicted by times of zero deposition (a horizontal line) and, therefore, represent the minimum subsidence possible. Subaerial erosion during these times probably removed some of the older geologic section, the inclusion of which would add to the sediment column and, therefore, steepen the calculated subsidence curve for the unit beneath the unconformity. Because of the difficulty in calculating exactly how much was removed during these erosional episodes, those estimates were not used in the subsidence calculations.

The burial history curves for the tops of each of the seven stratigraphic units A through G in Figures 5.2 and 5.3 are color coded so that comparisons can be made between the two pairs of sites. Differences in burial history rates at any age between the two locations on each figure are expressed by a convergence or divergence of similarly colored lines. For the two locations studied outside the graben ([Figure 5.1](#)), the Hamilton County, Illinois (Fairfield Subbasin), site had a slightly higher rate of burial for all of the studied units, except for during the deposition of unit E (Late Ordovician Maquoketa Shale). It is possible, however, that this is the result of erosional truncation of unit E strata in Hamilton County, Illinois, during the subsequent subaerial exposure that produced the Early Silurian unconformity between units E and F.

Unlike the relatively smooth, low-angle burial curves for the locations north of the Rough Creek Graben, the burial history calculations for the Ohio and Union County, Kentucky, areas in the graben exhibit steep initial burial gradients associated with the active opening and spreading of the rift graben. During the deposition of unit A, the Ohio County depocenter subsided at a much greater rate than the Union County depocenter. During and after unit B deposition, however, the Union County depocenter subsided at a faster rate. Even though the locations within the Rough Creek Graben subsided at a much greater rate than shelf areas initially, the rates of burial of units F and G are very similar to those in the “shelf” areas of Hamilton County, Illinois, and Hancock County, Kentucky.

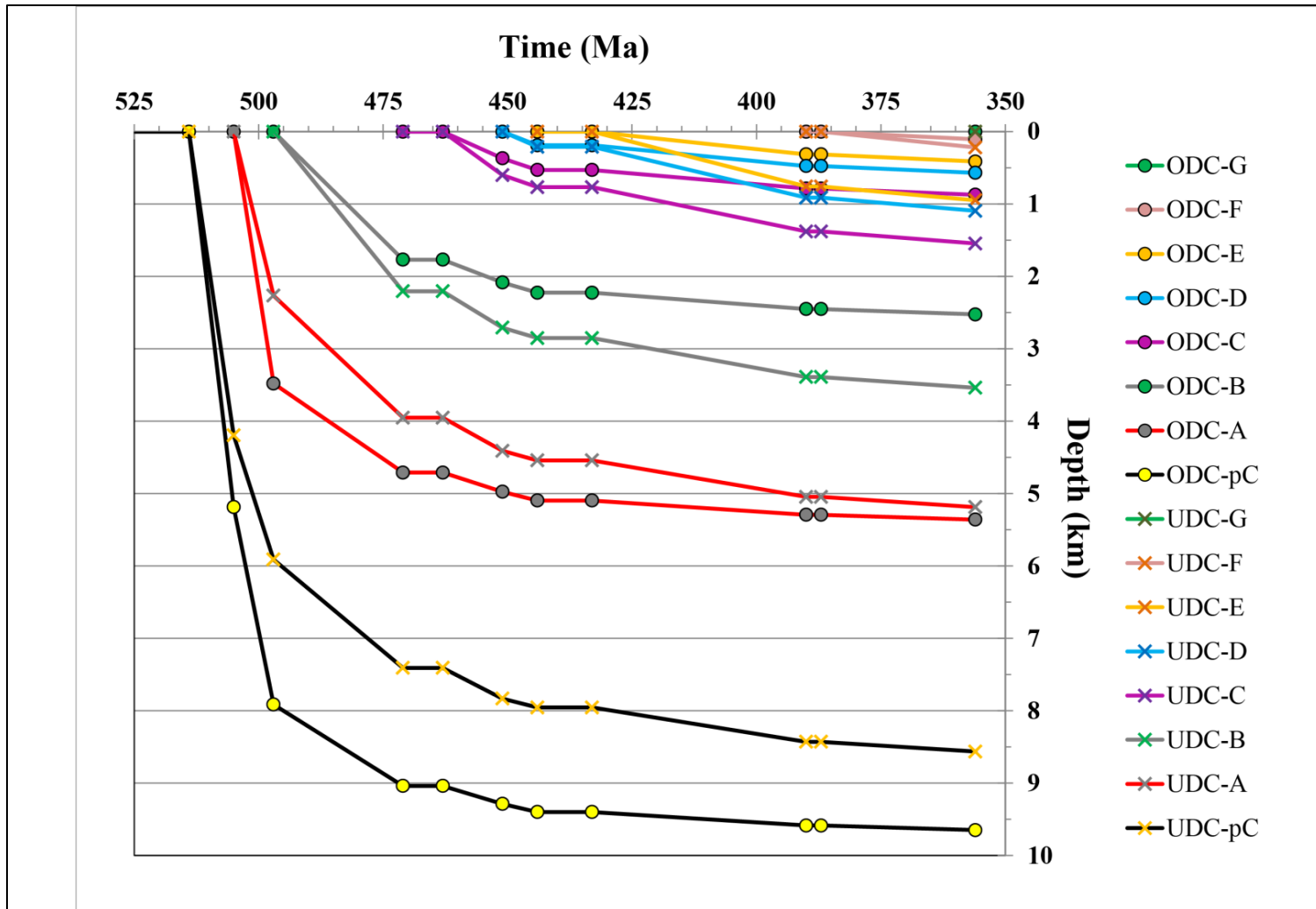


Figure 5.3 – Burial history calculations for the top of Precambrian basement (pC) and stratigraphic units A-G for the Ohio County, Kentucky, depocenter (ODC) and the Union County, Kentucky, depocenter (UDC) within the Rough Creek Graben.

5.2 Calculated Subsidence

Subsidence is the lowering of the earth's surface because of volume reduction in the subsurface and/or a change in local isostasy because of a change in crustal loading. Types of subsurface volume reductions which can produce subsidence include the mechanical compaction of sediments, thermal contraction of rock or magma bodies during heat loss, thinning of the crust by stretching during tectonic extension, and the removal of mass by chemical dissolution and migration of these solutes out of the system (Figure 5.4). Subsidence produced from crustal loading (tectonic subsidence) can be from the addition of mass in the form of sediment load (weight of deposited sediments) or tectonic thrust-loading within an orogenic foreland basin. Using well and map data, the sediment load and degree of sediment compaction at a given location can be calculated through time. By subtracting these subsidence values from the overall burial history of the top of basement at a location, the combined effect of thermal subsidence and crustal thinning can be determined. Crustal thinning is fault-controlled and ends at the cessation of active rifting. The end of active rifting also stops the introduction of additional heat into the crust from the isostatically uplifted mantle material beneath the thinned and extended crust. Therefore, the calculated combined subsidence values in this study can be viewed as results from crustal thinning during active rifting and from thermal cooling (thermal subsidence) after the active rifting stage of the graben system had ended.

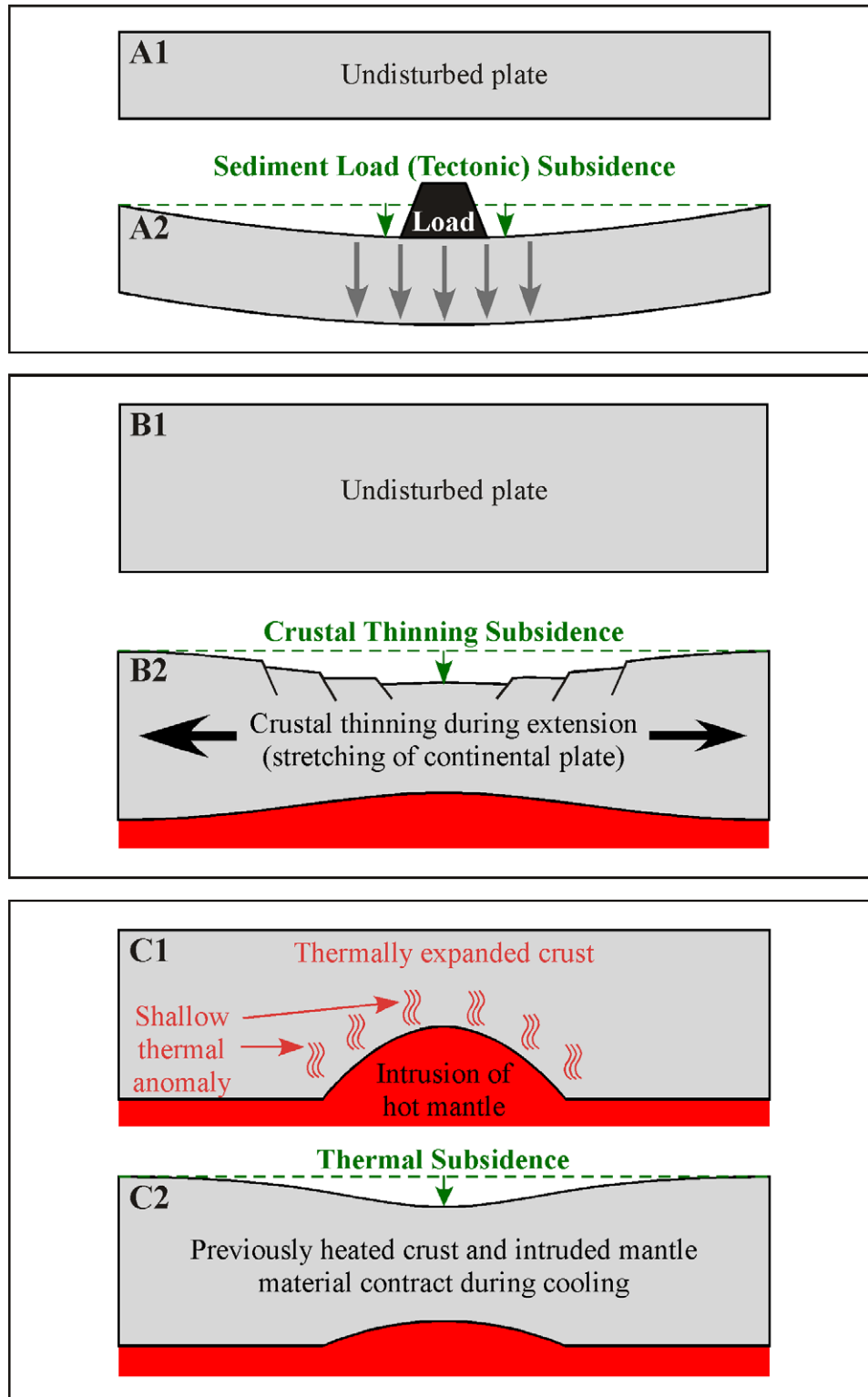


Figure 5.4 – Generalized models of geologic subsidence: A- Tectonic subsidence from sediment load, B- Subsidence from crustal thinning during extension (stretching) of continental plate, C- Thermal subsidence following rift-related heating from upwelling mantle material.

No evidence of substantial rock dissolution and solute migration within the area around the Rough Creek Graben has been reported affecting Cambrian through Mississippian rocks. Furthermore, no thrust-faulted terrains were present within or bordering the Rough Creek Graben area during that time. Little detailed information is available on the depositional environment of the Reelfoot Arkose within the Rough Creek Graben; however, data on the Eau Claire Formation (unit B) and later strata suggests shallow marine water with depths less than 1 km. This indicates that the high rate of sedimentation within the Rough Creek Graben during at least the Middle-Late Cambrian “kept pace” with the extension of the rift graben and, thereby, limiting the effective amount of crustal thinning to around 3 to 4 percent (assuming a mantle density of 3.34 g/cm³ and an initial crustal thickness of 30-35 km) (Sclater and Christie, 1980). The minor component of overall subsidence produced from this crustal thinning within the Rough Creek Graben was fault-controlled and would only be effective during active rifting (Early-Middle Cambrian). The calculations described in this section assume that overall subsidence in the Rough Creek Graben area is the result of a combination of tectonic subsidence (sediment loading), subsurface sediment compaction (compaction subsidence), and the contraction of the crust (thermal subsidence and crustal thinning).

Tectonic subsidence is the isostatic response of the crust to loading, including the added weight of sediment deposited on the surface. By using the porosity to depth relationships defined in Section 5.1 for all seven stratigraphic units, the weight of the stratigraphic column (tectonic load) can be calculated through time. The compaction-corrected saturated sediment bulk density for unit x at depth z can be determined by:

$$\rho_{zx} = [\Phi_{zx}\rho_w + (1-\Phi_{zx})\rho_{sgx}]$$

where,

ρ_{zx} = compaction-corrected saturated sediment bulk density for unit x at depth z

ρ_{sgx} = sediment grain density (g/cm³) of unit x (see [Table 5.3](#))

ρ_w = pore fluid density (1.03 g/cm³ used for all calculations)

Φ_{zx} = porosity (volume fraction) of unit x , corrected for compaction at depth z

Table 5.3 - Average sediment grain densities for common lithologies. Project stratigraphic unit sediment grain densities determined using the average of the lithologic densities listed here with the lithologic percentages for each unit listed in Table 5.2.

<u>Lithology</u>	<u>Sclater & Christie, 1980</u> g/cm ³	<u>Hegarty et al., 1988</u> g/cm ³	<u>Schmoker & Halley, 1982</u> g/cm ³	<u>Heidlauf et al., 1986</u> g/cm ³
Shale $\rho_{sg} =$	2.72	2.70	n/a	n/a
Sandstone $\rho_{sg} =$	2.65	2.66	n/a	n/a
Mixed clastic $\rho_{sg} =$	2.68	2.68	n/a	2.70
Limestone $\rho_{sg} =$	2.71	2.80	2.71	n/a
Dolostone $\rho_{sg} =$	n/a	n/a	2.87	n/a
Mixed carbonate $\rho_{sg} =$	n/a	n/a	2.78	n/a

The bulk density of entire saturated sedimentary column can be determined by:

$$\rho_{sed} = \sum_x [(\rho_{zx} T_{zx}) / S]$$

where,

ρ_{sed} = bulk density of saturated sedimentary column (g/cm³)

ρ_{zx} = compaction-corrected saturated sediment bulk density for unit x at depth z

T_{zx} = unit thickness (km) of unit x , corrected for compaction at depth z

S = thickness (km) of sedimentary column corrected for compaction

After the average density of the sedimentary column is determined, the magnitude of tectonic subsidence at the top of crystalline basement from sediment loading can be calculated with the equation (Sclater and Christie, 1980; Bond and Kominz, 1984; Heidlauf et al., 1986):

$$Y=S[(\rho_m-\rho_{sed})/(\rho_m-\rho_w)]$$

where,

Y = tectonic subsidence (km)

S = thickness of sedimentary column corrected for compaction (km)

ρ_m = density of mantle (3.33 g/cm³ used for all calculations)

ρ_{sed} = bulk density of saturated sedimentary column (g/cm³)

ρ_w = marine water density (1.03 g/cm³)

After the burial history curves (corrected for compaction) for the seven stratigraphic units were calculated, the magnitude of tectonic subsidence from sedimentary loading through time was calculated for all four study locations ([Figure 5.1](#)). The tectonic loading and compaction-derived subsidence estimates for the age of the top of each respective unit were then subtracted from burial history depths to the top of Precambrian basement (which represents total subsidence) in order to isolate the thermal subsidence values. The calculated values for the components of subsidence for the Hamilton County, Illinois (Fairfield Subbasin), and Hancock County, Kentucky, locations are presented in [Figure 5.4](#), and the values for the Rough Creek Graben depocenters in Union and Ohio Counties, Kentucky, are presented in [Figure 5.5](#).

For most of the time between 515 and 356 Ma, the slopes of the compaction, thermal, and tectonic subsidence curves for the Hamilton County, Illinois, and Hancock County, Kentucky, locations are very similar ([Figure 5.4](#)). The primary difference between the

subsidence curves is that the Hamilton County, Illinois, location began to tectonically subside about 7 to 10 million years earlier than the Hancock County, Kentucky, location. Whether this offset in the tectonic subsidence curves is because of accelerated Early-Middle Cambrian subsidence within the Fairfield Subbasin, or a result of earlier marine flooding from a rising sea level (and initiation of sedimentation) because of lower pre-rift topographic elevations is unknown. The differences in the sediment compaction components of subsidence are a result of a thicker sedimentary section at the Hamilton County, Illinois, site which leads to a proportionally greater compaction offset.

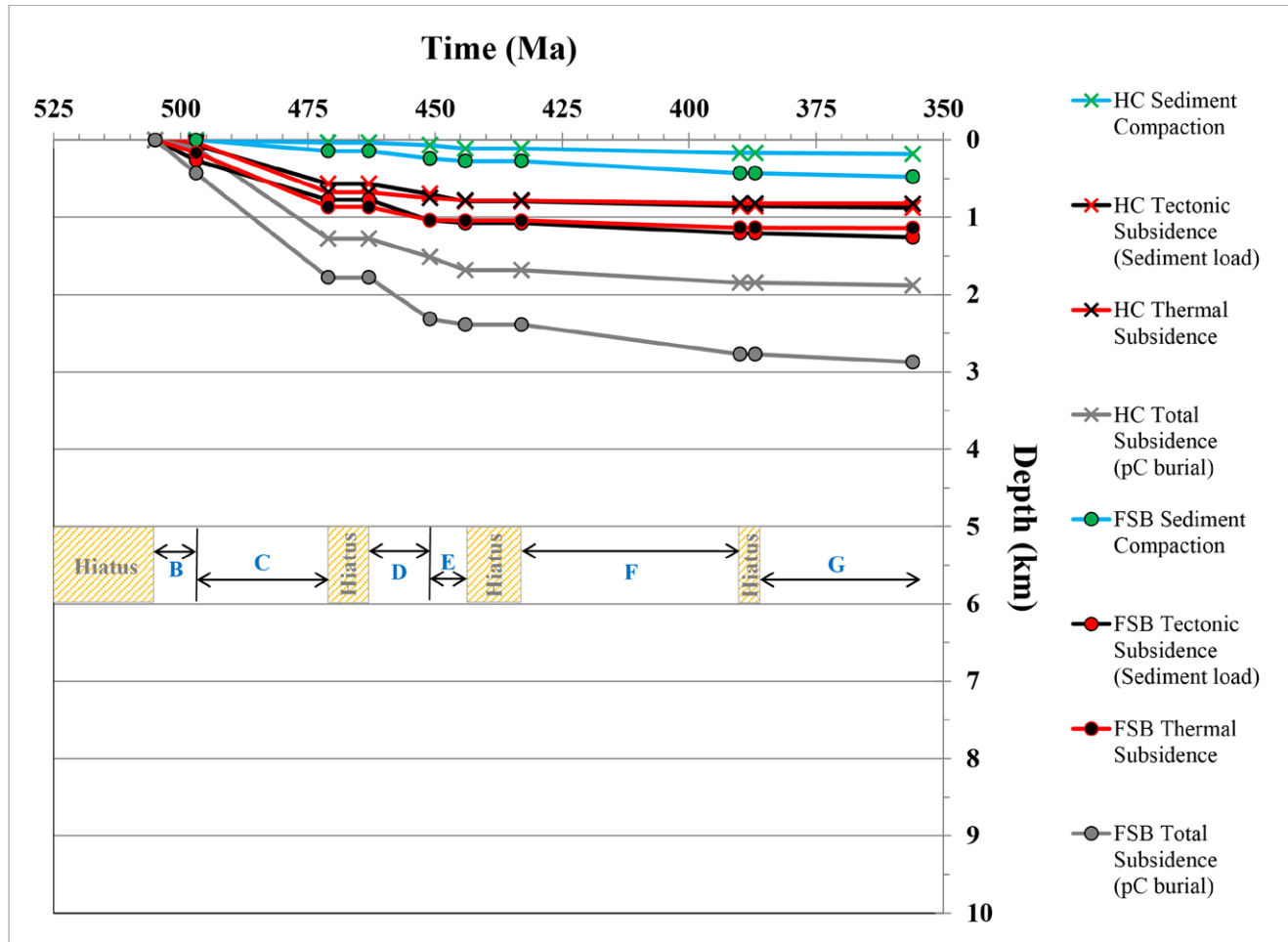


Figure 5.5 - Calculated tectonic (sediment load), thermal, and sediment compaction subsidence curves for the Fairfield Subbasin (FSB) and eastern Hancock County, Kentucky (HC). Depths to the top of Precambrian basement (pre-rift surface) constitute total subsidence. The ages of deposition for the six stratigraphic units B through G (unit A is absent outside of the rift graben) are labeled for reference. These areas are outside of the rift graben, so no subsidence from crustal thinning is represented.

The calculated tectonic (sediment load), thermal, and compaction-driven subsidence curves for Ohio County and Union County, Kentucky, within the Rough Creek Graben are presented in [Figure 5.5](#). The calculated curves for sediment load and compaction subsidence are subparallel and of similar magnitudes (less than 0.5 km of difference) between these two sites. This difference is similar to those between all three subsidence components at the Hamilton and Hancock County sites. A much greater difference exists between the thermal subsidence curves within the Ohio and Union County Cambrian depocenters after around 500 Ma (about halfway through the depositional history of unit B). The Ohio County site experienced about 1 km greater cumulative thermal subsidence for the remaining time of study between 500 and 356 Ma ([Figure 5.6](#)).

The subsidence curves calculated for the two locations within the Rough Creek Graben indicate that subsidence from active faulting and the associated crustal stretching from rifting ended during the deposition of unit B. A subjective analysis of the slopes of the subsidence curves for the Union County and Ohio County, Kentucky, Cambrian depocenters suggests a date around 502 Ma for the end of significant tectonic subsidence within the Rough Creek Graben ([Figure 5.5](#)). Because unit A is limited to the graben areas, the formation of the grabens must have begun before the initial deposition of unit A. Therefore, tectonic fault movement and subsidence within the Rough Creek Graben (and through stratigraphic correlation the adjacent Mississippi Valley Graben) began by at least 514 Ma (latest Early Cambrian) and lasted until around 502 Ma (latest Middle Cambrian) ([Figure 1.3](#)). The cooling of the middle and lower crust within rift zones extends beyond the time of active rifting. The relatively constant thermal subsidence values calculated for units D through G suggest the post-rift thermal subsidence within the Rough Creek Graben ended around 485 to 480 Ma.

Similar to the Rough Creek Graben, the Birmingham Graben in central Alabama also formed during the breakup of Rodinia (Thomas, 1991; Thomas and Astini, 1999). The calculated tectonic subsidence history within the Rough Creek Graben, however, differs somewhat from what Thomas and Astini (1999) calculated for the Birmingham Graben. Tectonic subsidence within the Birmingham Graben was estimated to be about 1.75 km, beginning around 545 Ma (exact start date uncertain) and lasting until 503 Ma (Thomas,

1991). In contrast, the total synrift tectonic subsidence within the Rough Creek Graben is estimated to be 2.75 to 3 km (157—171% the offset of the Birmingham Graben) occurring over 12 Ma (55% of the duration of the Birmingham Graben subsidence interval). Differences in geologic time scales used for subsidence calculations may account for some of the difference in subsidence duration between the grabens, but would not affect the magnitude of calculated subsidence-derived offset. Note that the estimated ends of tectonic subsidence for both grabens are roughly equivalent (503 versus 502 Ma).

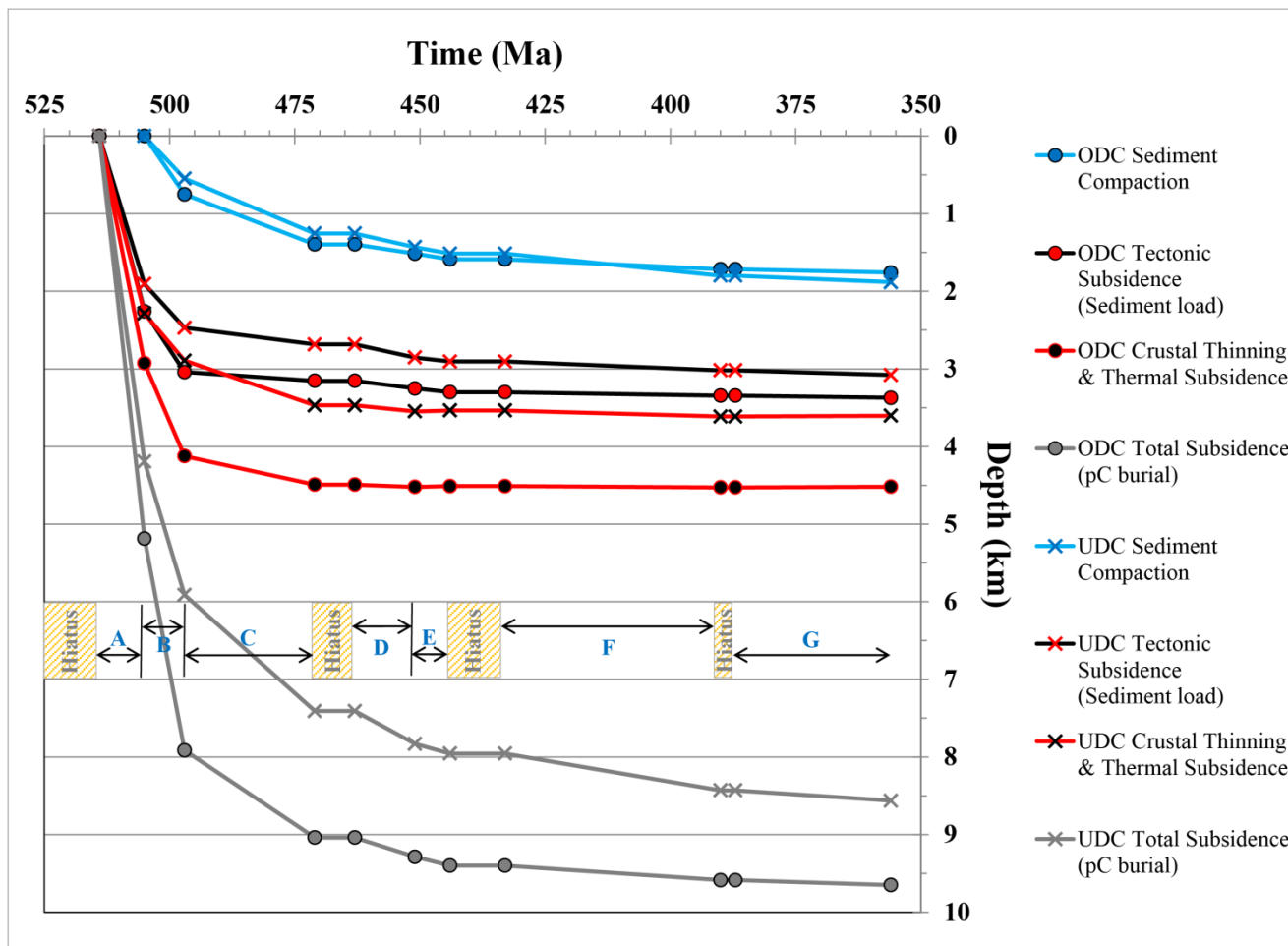


Figure 5.6 - Calculated tectonic (sediment load), sediment compaction, and combined crustal thinning (rift stage) and thermal (post-rift stage) subsidence curves for the Ohio County (ODC) and Union County (UDC) depocenters within the Rough Creek Graben. Depths to the top of Precambrian basement (pre-rift surface) constitute total subsidence amount. The times of deposition for the seven stratigraphic units A-G labeled for reference.

5.3 Sedimentation Rates

The original, uncompacted thicknesses of each of the seven stratigraphic units were calculated as part of the burial history analysis. This permits a comparison of the rates of sediment accumulation for each of the stratigraphic units at the four study locations ([Figure 5.1](#)). These rates were calculated by dividing the overall uncompacted thicknesses of each unit by the entire time period of deposition of that unit ([Figure 1.3](#)). These values, therefore, represent an average depositional rate for each unit; the actual rate of deposition at any given moment during these periods may have varied. The rates of deposition calculated for the four study sites are presented in [Figure 5.6](#).

During the Middle-Late Cambrian, a thick sediment accumulation was deposited within Rough Creek Graben (units A and B); however, during that time, no unit A and very little unit B was deposited in Hamilton and Hancock Counties outside of the graben. The average rate of deposition of unit B was 53.6 m/Ma in Hamilton County, Illinois, and 12.6 m/Ma in Hancock County, Kentucky. The average rates of sedimentation of unit A at the Rough Creek Graben locations were 466 m/Ma in Union County, Kentucky, and 576.2 m/Ma in Ohio County, Kentucky. The average rates of deposition of unit B were lower at 283.2 m/Ma in Union County and 434.9 m/Ma in Ohio County. The reduced sedimentation outside of the graben during the deposition of units A and B was probably from a combination of sediment bypass into deeper water areas (grabens), and from delayed flooding of higher elevations during sea level rise (thus delaying the start of deposition).

The average rate of sedimentation in Hamilton County, Illinois, remained nearly constant at 57.3 m/Ma during the deposition of unit C. In Hancock County, Kentucky, sedimentation increased between the time of deposition of unit B and that of unit C by 369% to 46.5 m/Ma. Within the Union County and Ohio County, Kentucky, sites, however, sedimentation decreased 70% to 84.8 m/Ma, and 84% to 68.0 m/Ma, respectively over this same time. For units C through G, all four locations experienced decreasing rates of sedimentation during each successive depositional interval ([Figure 5.6](#)). For each stratigraphic unit after B, the differences between sedimentation rates for

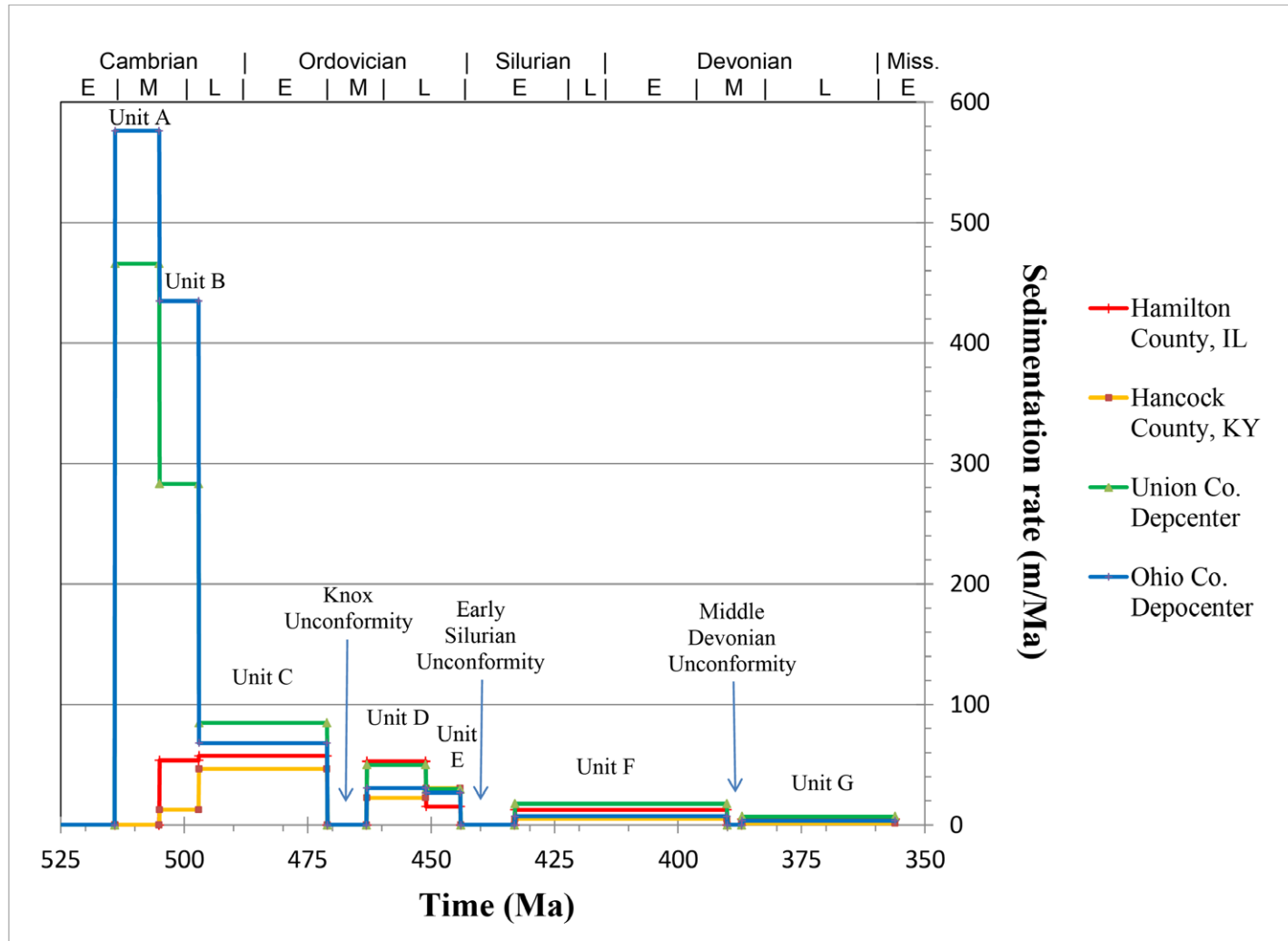


Figure 5.7 - Rates of sediment accumulation (meters/Ma) within two deep depocenters in the Rough Creek Graben, and the Fairfield Subbasin and in Hancock County, Kentucky, area outside the graben.

each location also diminish with time. With the exception of unit E deposition, the Hamilton County, Illinois, location had greater sedimentation rates than to the east in Hancock County, Kentucky. Similarly for units C through G, the Union County location had greater sedimentation rates than to the east in Ohio County, Kentucky. This may be a result of enhanced thermal subsidence near the intersection of the Rough Creek Graben and the Mississippi Valley Graben during the deposition of unit C. For units D, F, and G, the increased sedimentation westward could be a product of the initial formation of what would become the Illinois Basin.

6 DISCUSSION

6.1 Confidence levels and degrees of uncertainty within the project data set

This research incorporated numerous types of data. This diverse dataset was compiled from various sources, and includes data of varying ages, resolutions, and designed intents. The inherent resolution (or degree of uncertainty) of each data type is discussed below.

Well data are the most precise for of data within this project. As part of the well permitting process, the surface locations of oil and gas wells are determined prior to drilling by licensed surveyors. Because all of the wells used in this project are vertical (non-directional), the surface X and Y locations can be assumed to be accurate for the subsurface portions of the well bores. Modern geophysical logs have a vertical resolution (Z) around 0.5 feet. While this does not guarantee accurate interpretations of these logs, a high confidence level can be placed upon the X, Y, Z locations of the stratigraphic horizons. Furthermore, the project stratigraphic units A through G were chosen, in part, because of their well-defined log character. The limiting factor of well data is that they consist of isolated point data, and not two-dimensional profiles (like seismic data) or as a three-dimensional surface (like map data). While well data have high resolution at the well bore itself, the spacing between wells at appropriate stratigraphic depths can often be quite large (tens of kilometers).

The locations of stratigraphic contacts, fault locations, and other structural features at the present surface were acquired from 7.5' USGS Geologic Quadrangle maps. Overall, the accuracy of these data are quite good. While the ultimate quality of these maps depends of the interpretations of the original mapper, the maps were peer reviewed prior to publication, as well as edge-matched to adjacent quadrangles. These 1:24,000 data were primarily used to determine the horizontal locations of fault system segments and associated drape folds for regional mapping at 1:500,000 or larger scales, further reducing the magnitude of possible inaccuracies.

Potential fields data (gravity and magnetic anomaly maps) are the lowest resolution data type used in this project. The primary reason for this is that the source of these fields is not concentrated at the surface, but rather encompasses the entire upper crust. This results in relatively low horizontal resolution. Because of this, the potential fields data was only used as additional control for the placement of basement faults between seismic profiles (but not for calculating depth to basement).

The principal data type used for subsurface analysis in this project, especially within the deeper parts of the rift basins, was seismic reflection profile data. The data quality and resolution of these profiles varied substantially, which are discussed in more detail in Section [2.2](#). In general, the resolution of reflection seismic data depends on the source used (initial amplitude and frequency range), recording parameters (geophone type and spacing, sonic properties of the surface medium, ambient noise), and the processing techniques used to transform the raw geophone records into a seismic profile.

In order to interpret the elevations of stratigraphic units from seismic profiles, the depths of the correlated reflection horizons must be converted from units of time (seconds) to units of distance (feet). This is accomplished by multiplying the depth in seconds by the sonic velocity of the rocks. If wells with sonic logs are available nearby, subsurface interval velocities can be determined and synthetic seismograms can be produced to tie well tops to seismic horizons ([Figure 2.2](#)). As distances increase from points of known sonic velocity along a seismic profile, lateral changes in facies, lithology, porosity, or pore-fluid content can alter the interval velocities of the rocks and increase the level of uncertainty in subsurface elevation calculations. This was problematic for the deeper parts of the rift grabens (below unit B) because of a lack of well data at those depths. In these areas, sonic velocities were calculated from the RMS stacking velocities used to process selected seismic profiles. Using these velocities, coupled with reasonable seismic facies interpretations, an interpreted interval velocity map for unit A was used to calculate the isopach thickness of unit A ([Plate 15](#)). This isopach was then added to the depths of the base of unit B to produce an elevation map of the base of the base of unit A (top of Precambrian basement within the graben complex).

6.2 Proposed connection between the Rough Creek Graben and the Rome Trough in central Kentucky

The structure of the Rome Trough beneath the Appalachian Basin in eastern Kentucky and West Virginia has been documented through well, seismic, and potential fields data analysis (McGuire and Howell, 1963; McGuire, 1968; Silberman, 1972; Ammerman, 1976; Ammerman and Keller, 1979; Webb, 1980; Drahovzal and Noger, 1995; Gao et al., 2000; Harris et al., 2004). Similarly, the Rough Creek and Mississippi Valley Grabens beneath the Illinois Basin and northern Mississippian Embayment have also been demonstrated (Schwalb, 1982; Bertagne and Leising, 1990; Goetz et al., 1992; Nelson and Lumm, 1992; Drahovzal, 1997; Kolata and Nelson, 1997). Because these graben structures are in close proximity and are filled with sediments of similar ages and lithologies, a probable connection between these features has been proposed by previous researchers (Thomas, 1985; Thomas, 1991; Thomas, 1993; Gao et al., 2000; Thomas, 2006), but the exact locations of the connecting structures or fault systems have not been established. Using a combination of surface and subsurface geologic and geophysical data, the specific connecting structures between these two rift graben systems are proposed here.

The western limit of the Rome Trough of eastern Kentucky and West Virginia ([Figure 6.1](#)) is generally considered to be the down-to-southeast normal faults of the Lexington Fault System south of the Kentucky River Fault System (Harris et al., 2004). These faults are exposed in Jessamine, Garrard, Lincoln, and Casey Counties, Kentucky ([Figure 6.2](#)). The southern limit of the Rome Trough is poorly defined west of the Rockcastle River Uplift, and appears to include a southern extension (sub-graben) stretching from Wayne and McCreary Counties into northern Tennessee similar to the Floyd County “Channel” in extreme southeastern Kentucky (Drahovzal and Noger, 1995; Harris et al., 2004).

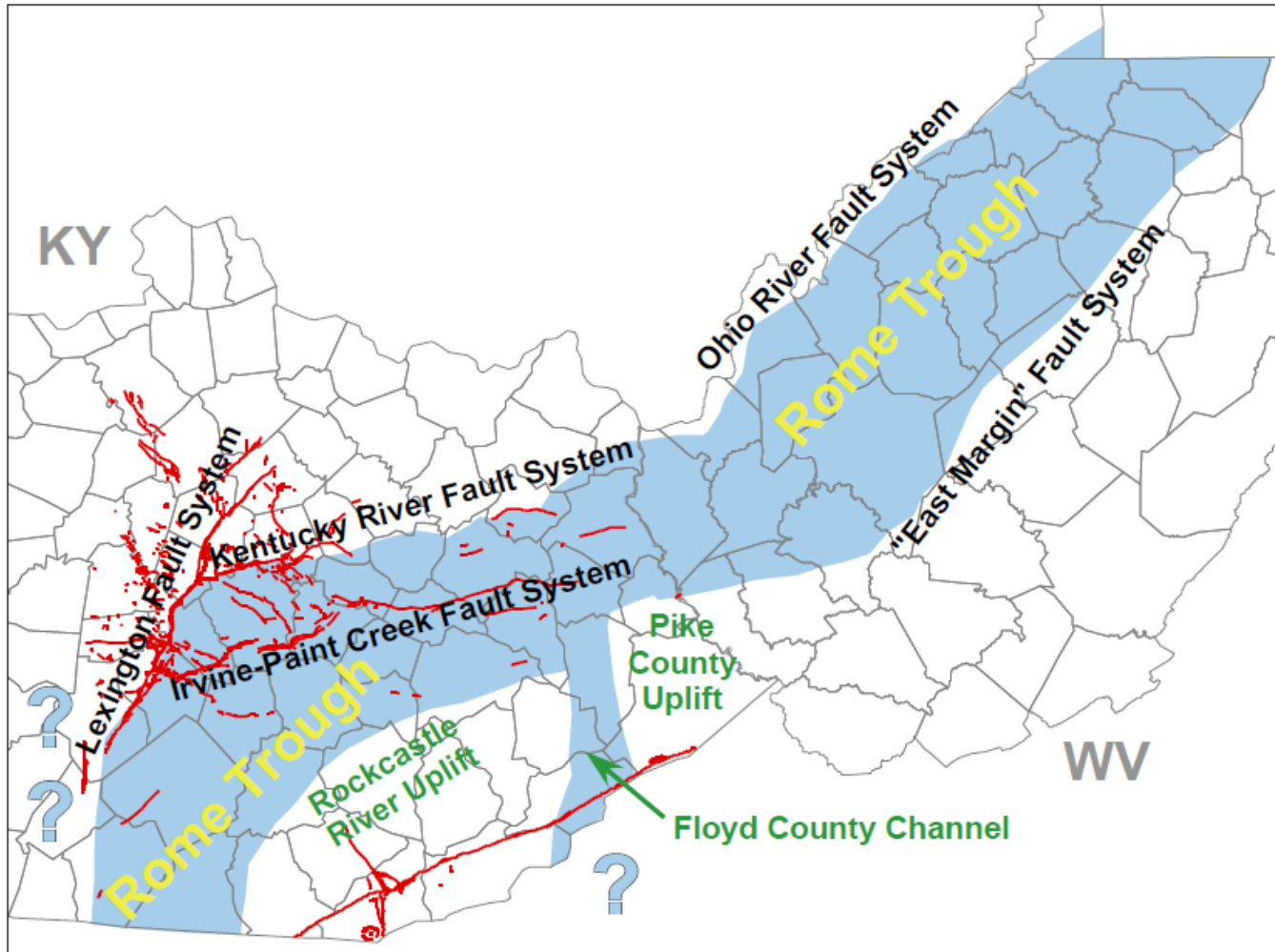


Figure 6.1 - Major structural features in and around the Rome Trough (graben area highlighted in blue) of eastern Kentucky and western West Virginia (Harris et al., 2004). Mapped surface faults shown in red. (The Pine Mountain thrust fault and faults within the Middlesboro impact structure in southeasternmost Kentucky are not basement-rooted and postdate the rift system.)

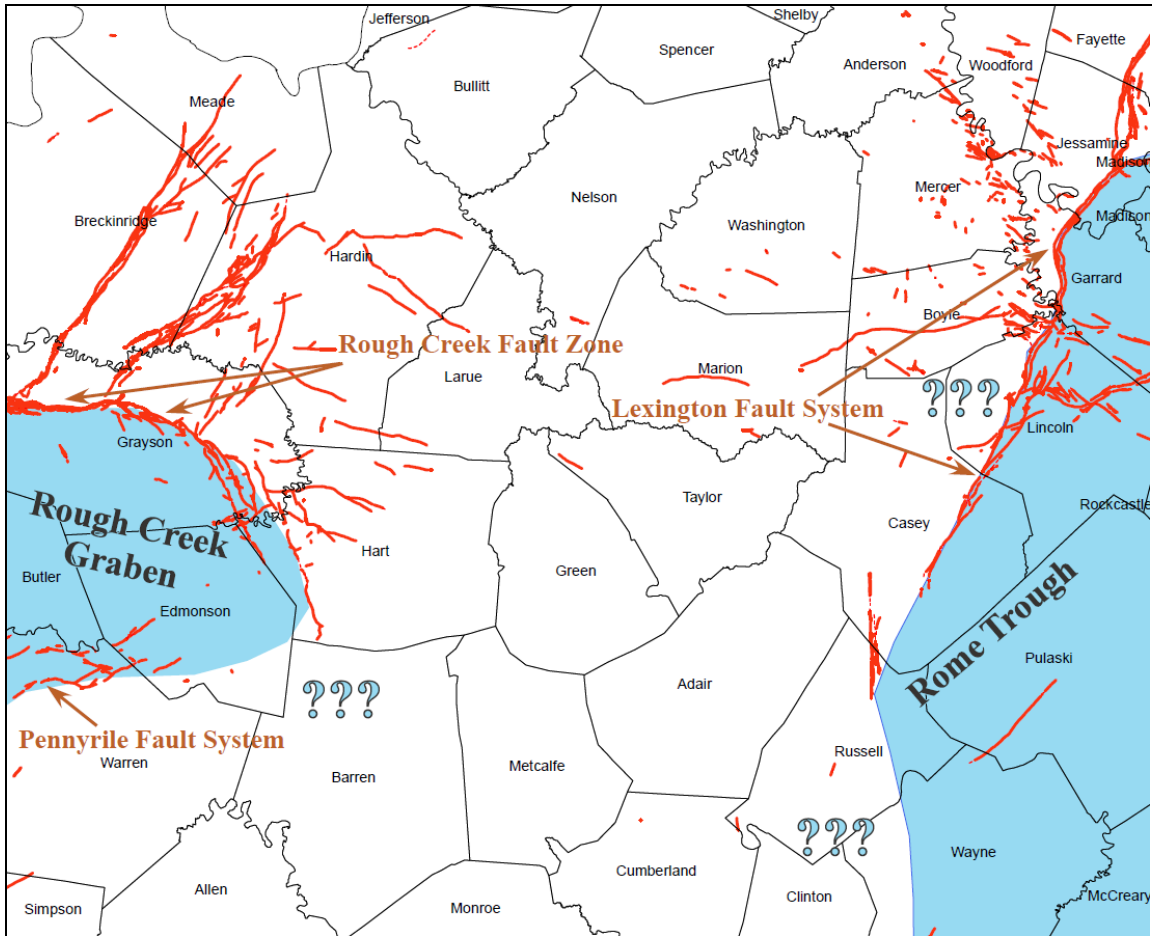


Figure 6.2 - Region in west-central Kentucky between the Rough Creek Graben and the Rome Trough. Note the gap between the well-defined regional fault systems.

Traditionally, the eastern limit of the Rough Creek Graben has been considered to be the down-to-southwest normal faults exposed in southeastern Grayson County and western Hart County, Kentucky; between the Rough Creek Fault Zone on the north and the Pennyriple Fault System on the south (Figure 6.2). The surface expression of the Pennyriple Fault System terminates eastward near the border between Butler and Edmonson Counties (Figure 6.2). At the currently exposed level, these fault traces are within lower Pennsylvanian and upper Mississippian strata (Noger, 1988). South of the Pennyriple Fault System, the outcrop belt of Middle-Late Mississippian rocks has a northeasterly strike (salmon- and dark blue-colored patterns respectively, in Logan, Simpson, and Warren Counties in Figure 6.3). Along strike with the exposed Pennyriple

Fault System to the west, however, the strike of the outcrop belt curves to the east in southernmost Edmonson County and northwestern Barren County, Kentucky. A less dramatic shift in strike to the northwest is also present in northern Hart County along the approximate strike of the Rough Creek Fault Zone (Figure 6.3). Closer analysis of the near-surface structural contours digitized from the 1:24,000 USGS 7.5-minute Geologic Quadrangle maps, however, suggests that the brittle deformation that created the Pennyryle Fault System continues eastward at least to central Adair County, Kentucky (Figure 6.4 and Figure 6.5). Down-to-north monoclinical structures are interpreted to be drape folds that formed over deeper fault offsets (Figure 6.6).

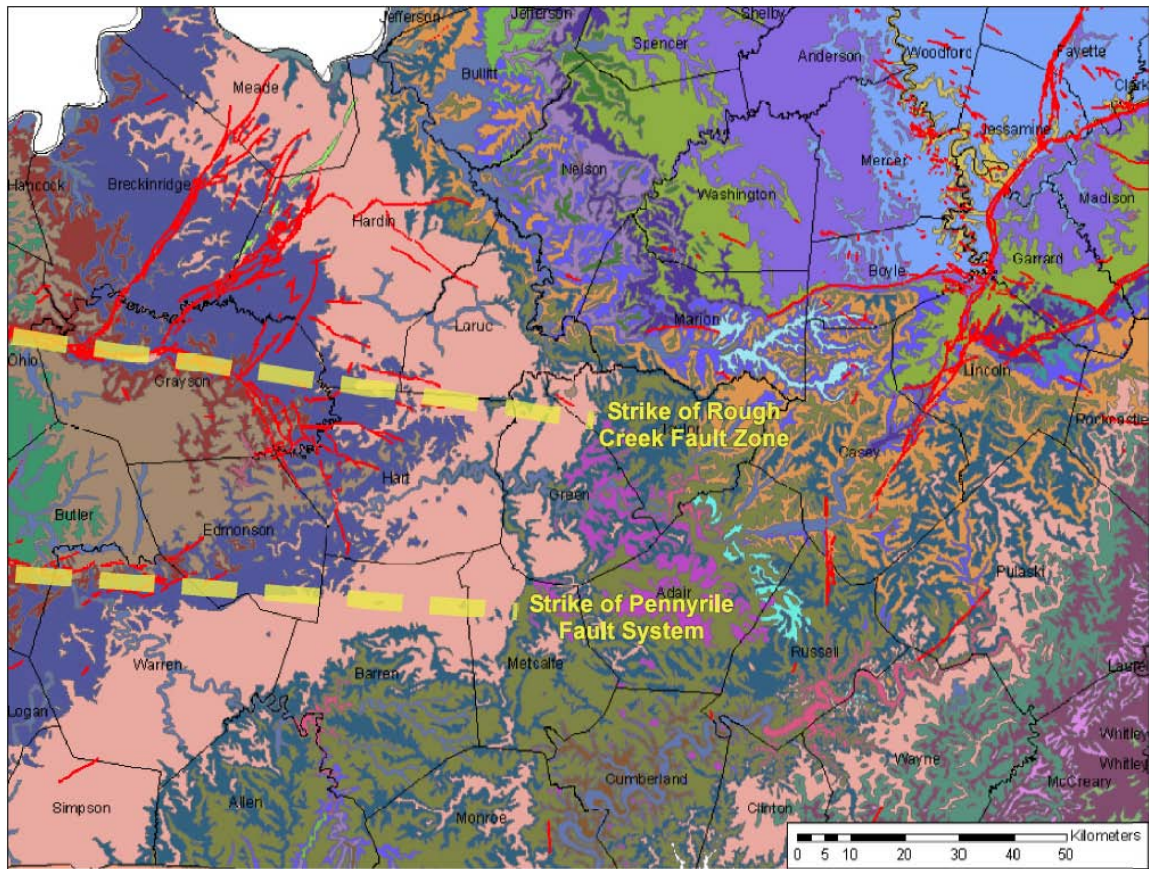


Figure 6.3 - Geologic outcrop patterns within the "gap" between the Rough Creek Graben and Rome Trough are dominated by the Illinois Basin and localized incision-type drainages, and not by comingling regional fault system segments similar to the Rough Creek and Kentucky River Fault Systems. Mapped geology from Noger (1988).

On the north side of the graben, the surface exposure of the Rough Creek Fault Zone terminates to the east in southeastern Grayson and western Hart Counties, Kentucky. The strike for most of that fault system is roughly east-west; however, at the eastern end, the exposed fault traces curve to the southeast (Figure 6.4). Although not as well defined as those to the south near the Pennyriple Fault System, several east-west lineation patterns in the near-surface structure contours east of Grayson County imply that the down-to-south deformation expressed in the Rough Creek Fault Zone extends farther eastward than the exposed fault traces (Figure 6.4).

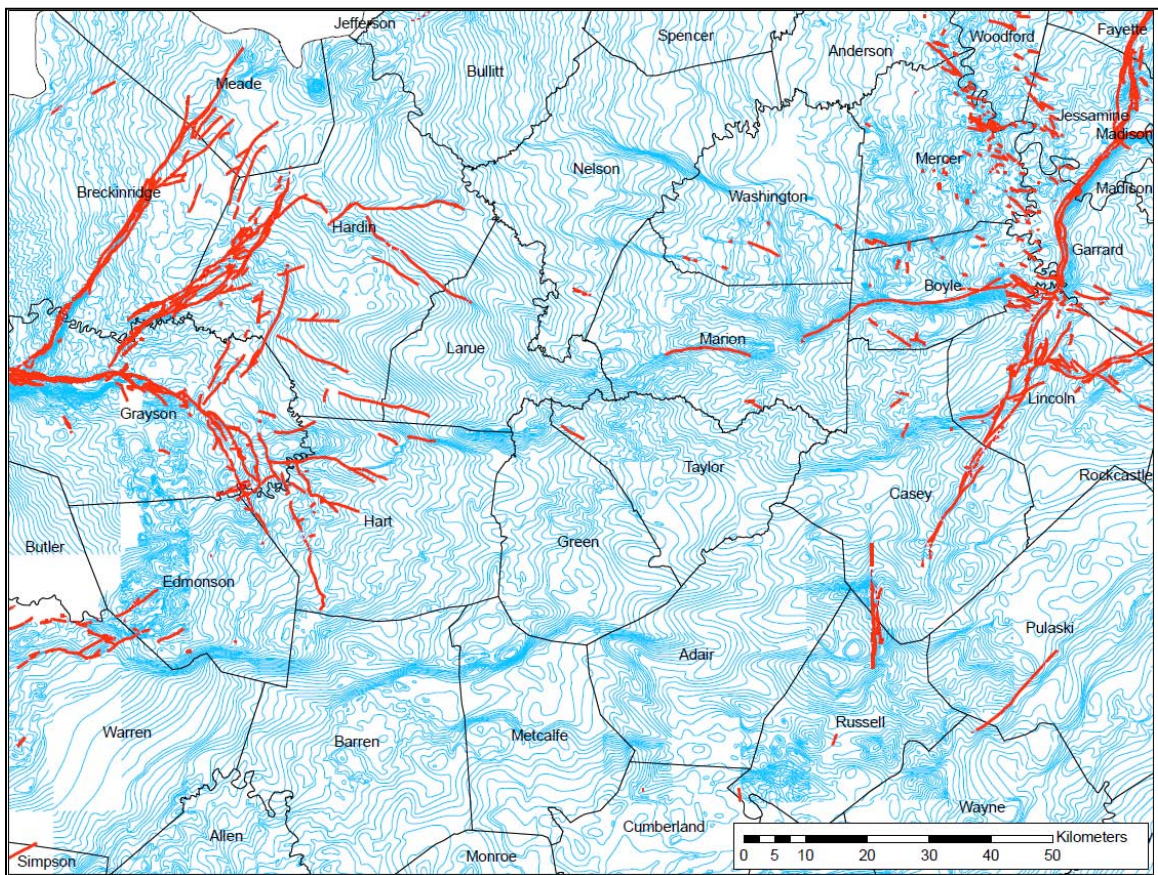


Figure 6.4 - Structural contours (light blue) and surface fault traces (red) digitized from 1:24,000 USGS 7.5' Geologic Quadrangle maps. Contour elevations based upon numerous structural datums and contour intervals across the mapped area.

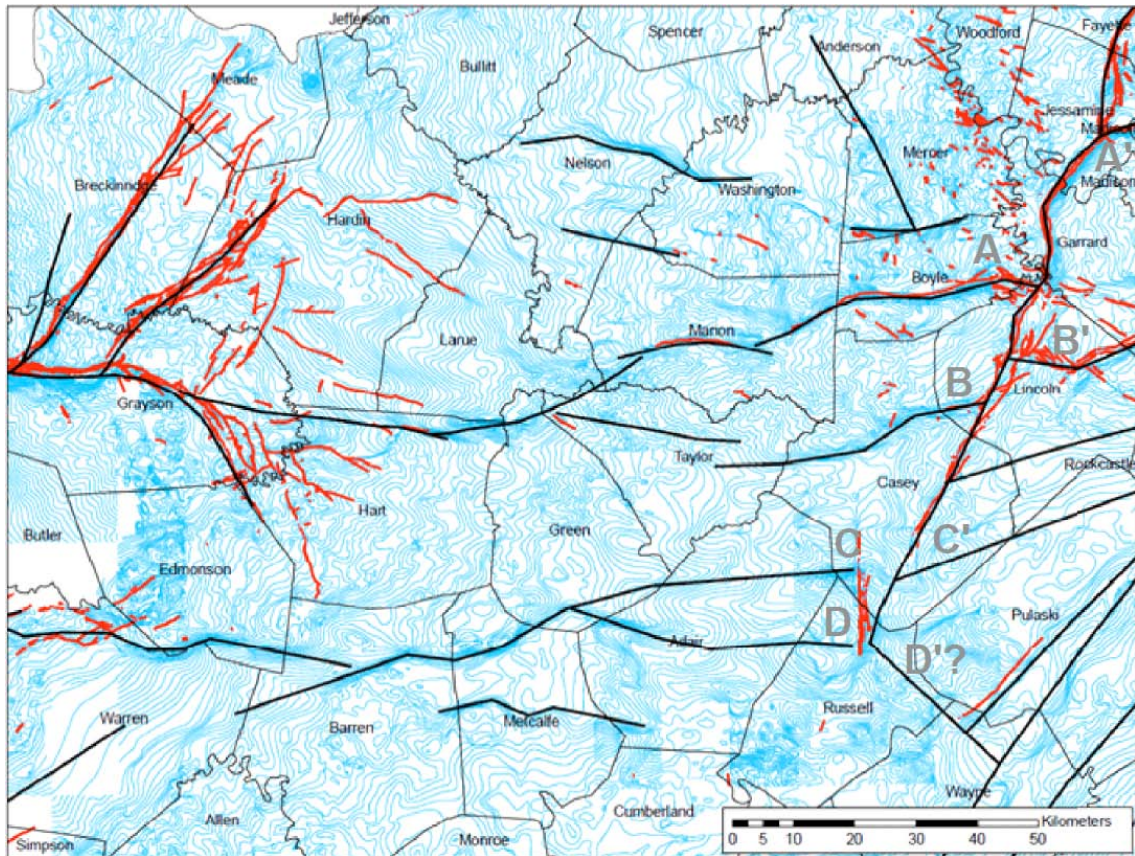


Figure 6.5 - Basement fault system segments (heavy black lines) interpreted from surface structural trend patterns from [Figure 6.4](#).

At the surface, mapped structural contours at a 1:24,000 scale are available across most of the study area, but because of the high cost of deep drilling and seismic profile acquisition, geologic data densities tend to decrease with depth. Without deeper control, interpreting basement structures from surface expressions can be misleading and problematic. By using the elevation of the base of the Middle Devonian-Lower Mississippian New Albany Shale ([Figure 6.7](#)) and the top of the Middle Ordovician Trenton Formation ([Figure 6.8](#)) from well data, it is clear that the offsets from buried faults or drape-folds are present to at least those depths. At the few locations where available proprietary seismic profiles cross these structures within the “gap” between the Rough Creek Graben and the Rome Trough, deep seismic reflectors (interpreted as top of basement) are offset; rollover or monoclinical structures are visible in shallow reflectors

above the basement offsets. These structures are interpreted to be basement-rooted normal faults buried beneath drape folds from later fault reactivation ([Figure 6.6](#)).

The apparent drape-fold axes that help define the proposed eastern extensions of the Rough Creek Fault Zone and Pennyryle Fault System each appear to split into two separate fault system segments in northwestern Taylor County, and southern Green County, respectively. The reason for the eastward bifurcations of the fault systems along the same longitude is unclear, but may be from changes in crustal strength and/or composition at depth. The area where these two fault systems split is near the edge of a strong positive magnetic anomaly ([Plate 17](#)) which suggests possible magmatic intrusion. Because no volcanic material has been reported from surface mapping or drilling records, the intrusion (if present) is probably within basement below the Paleozoic section.

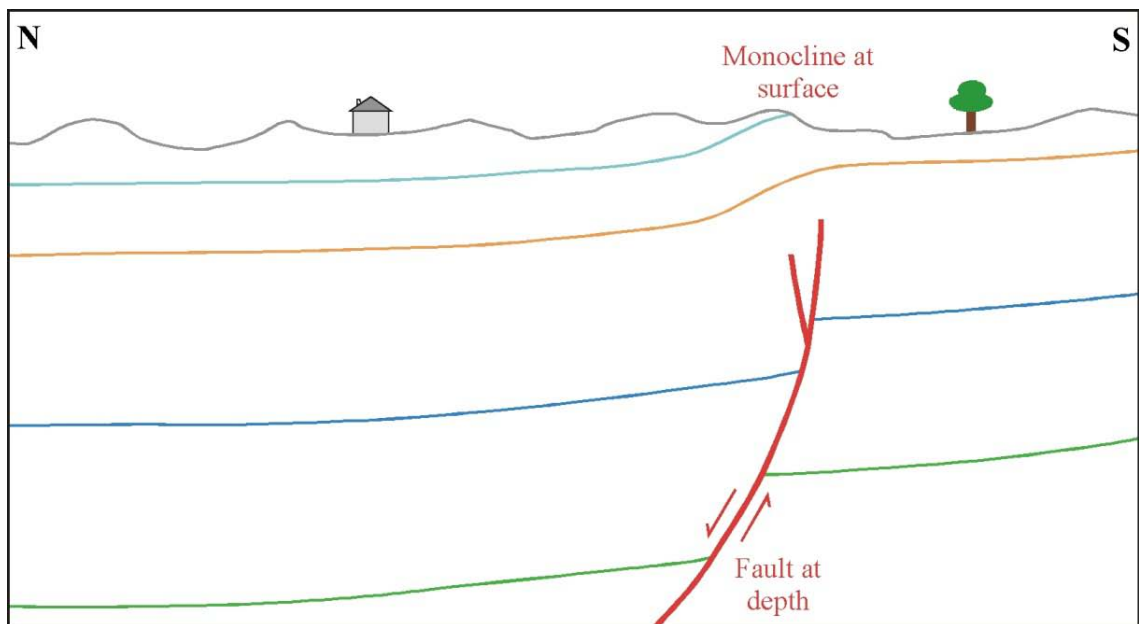


Figure 6.6 - Schematic cross section across monoclinial surface structures, illustrating drape folding over deeper fault offsets.

For the eastern extension of the Rough Creek Fault Zone, the northern segment strikes east-northeast and connects with surface faults exposed in central Marion and Boyle Counties, Kentucky. This interpreted fault system segment (labeled A on [Figure 6.5](#)) is along a similar strike (although offset about 30 kilometers to the south) to the Kentucky River Fault System ([Figure 6.1](#), labeled A' on [Figure 6.5](#)) that defines the northern boundary of the Rome Trough in central and eastern Kentucky (Cable and Beardsley, 1984; Harris et al., 2004). The southern fault system segment that is interpreted from surface data extends through central Taylor, northern Casey, and western Lincoln Counties, Kentucky (marked B on [Figure 6.5](#)). The axis of the monocline evident in the surface structure contours intersects the Lexington Fault System in central Lincoln County. This is very close to where the Irvine-Paint Creek Fault System (labeled B' on [Figure 6.5](#)) intersects the Lexington Fault System from the east, suggesting a possible through going, down-to-south regional fault system ([Figure 6.5](#)).

The proposed eastern fault system segments of the Pennyrite Fault System east of the split in Green County both have smaller vertical offsets than their counterparts for the Rough Creek Fault Zone. The northern segment (labeled C on [Figure 6.5](#)) crosses southern Green County and northern Adair County, and extends into southwestern Casey County, Kentucky. About 5 miles (8 kilometers) east from the eastern end of that segment across the Lexington Fault System, Patchen et al. (2006) interpreted an unnamed basement fault in southeastern Casey County with a similar strike (labeled C' on [Figure 6.5](#)), which may be an eastward continuation of that down-to-north deformation. Although more speculative because of the ~60 degree change in strike, the down-to-north offset from the southern extension of the Pennyrite Fault System in Adair and northern Russell Counties (labeled D on [Figure 6.5](#)) may be accommodated by an unnamed fault in eastern Russell County that intersects the Lexington Fault System (labeled D' on [Figure 6.5](#)).

The fault system segments east of the Pennyrite and Rough Creek Fault Systems described here are interpreted to have formed during the same tectonic episodes that produced the exposed, rift graben-bounding fault systems to the east in the Rome Trough and to the west in the Rough Creek Graben. Therefore, the downthrown area between

these interpreted fault system segments is an eastern extension of the Rough Creek Graben and acted as a mechanical and depositional connection between the Rough Creek Graben and the Rome Trough ([Figure 6.9](#)).

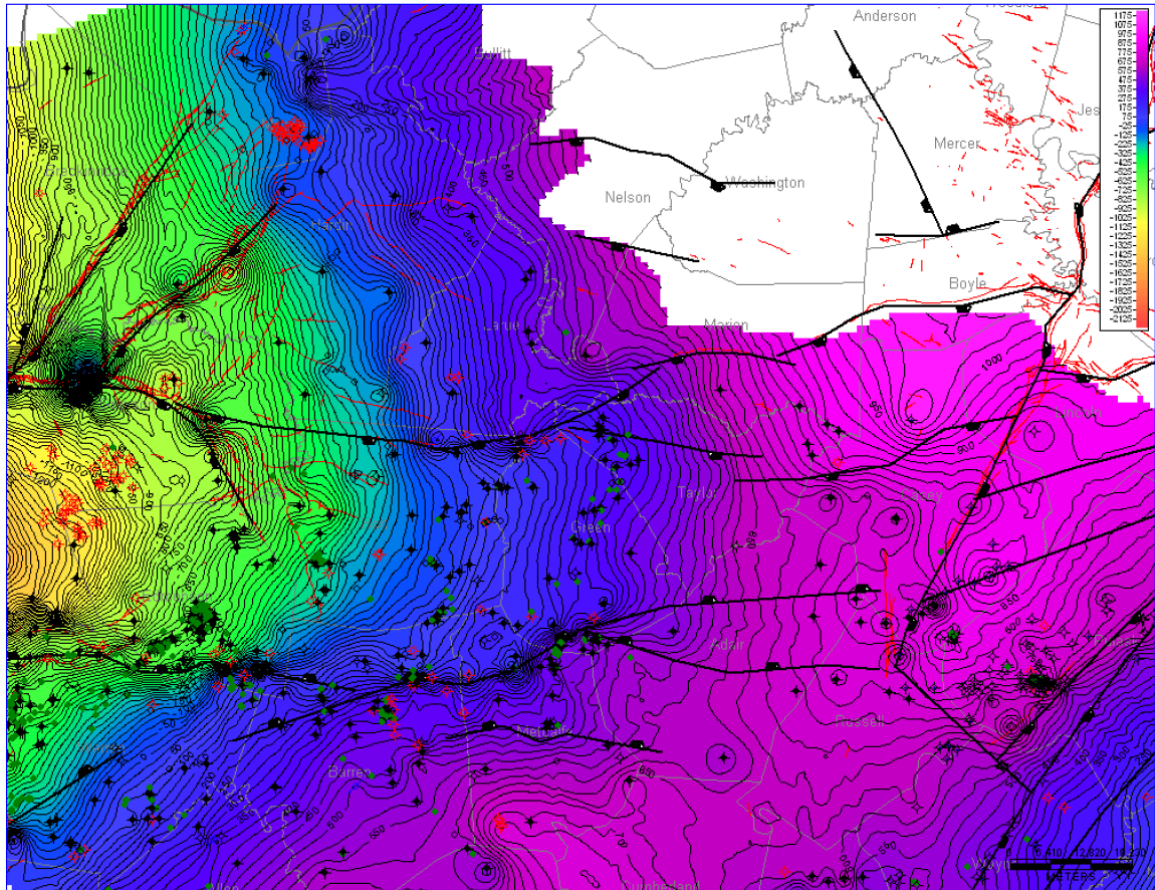


Figure 6.7 - Structure of the base of the Devonian New Albany Shale across “gap” region. Surface produced with only well data, using a simple inverse distance squared gridding algorithm to ensure an unbiased test of linear offset trends. Interpreted fault locations are for display only (no vertical offsets present in grid) and were not used to constrain the grid surface. The grid has been cropped to remove the area where the New Albany Shale is absent because of later erosion.

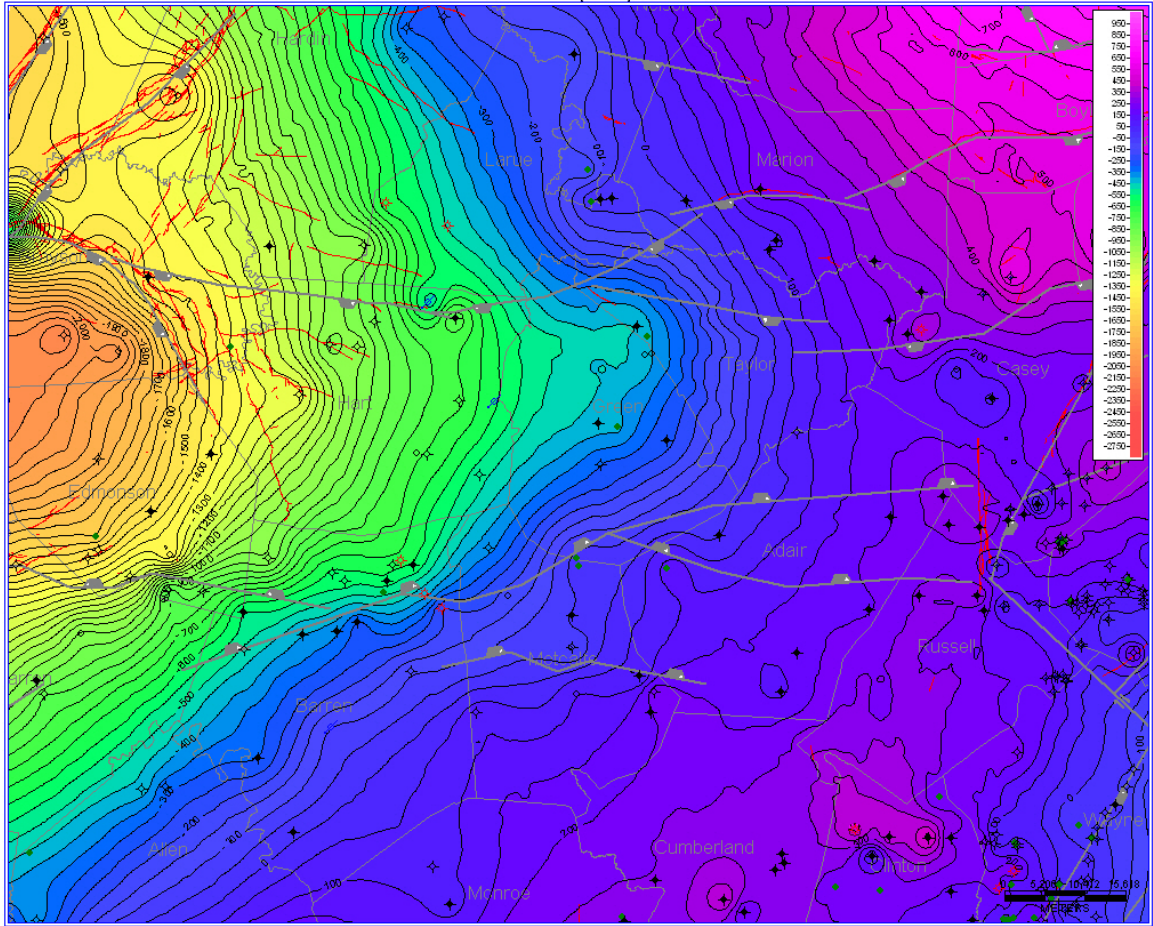


Figure 6.8 - Structure of the top of the Middle Ordovician Trenton Formation, with interpreted basement fault system segments in grey. Surface produced with only well data, using a simple inverse distance squared gridding algorithm to ensure an unbiased test of linear offset trends. Interpreted fault locations are for display only (no vertical offsets present in grid) and were not used to constrain the grid surface.

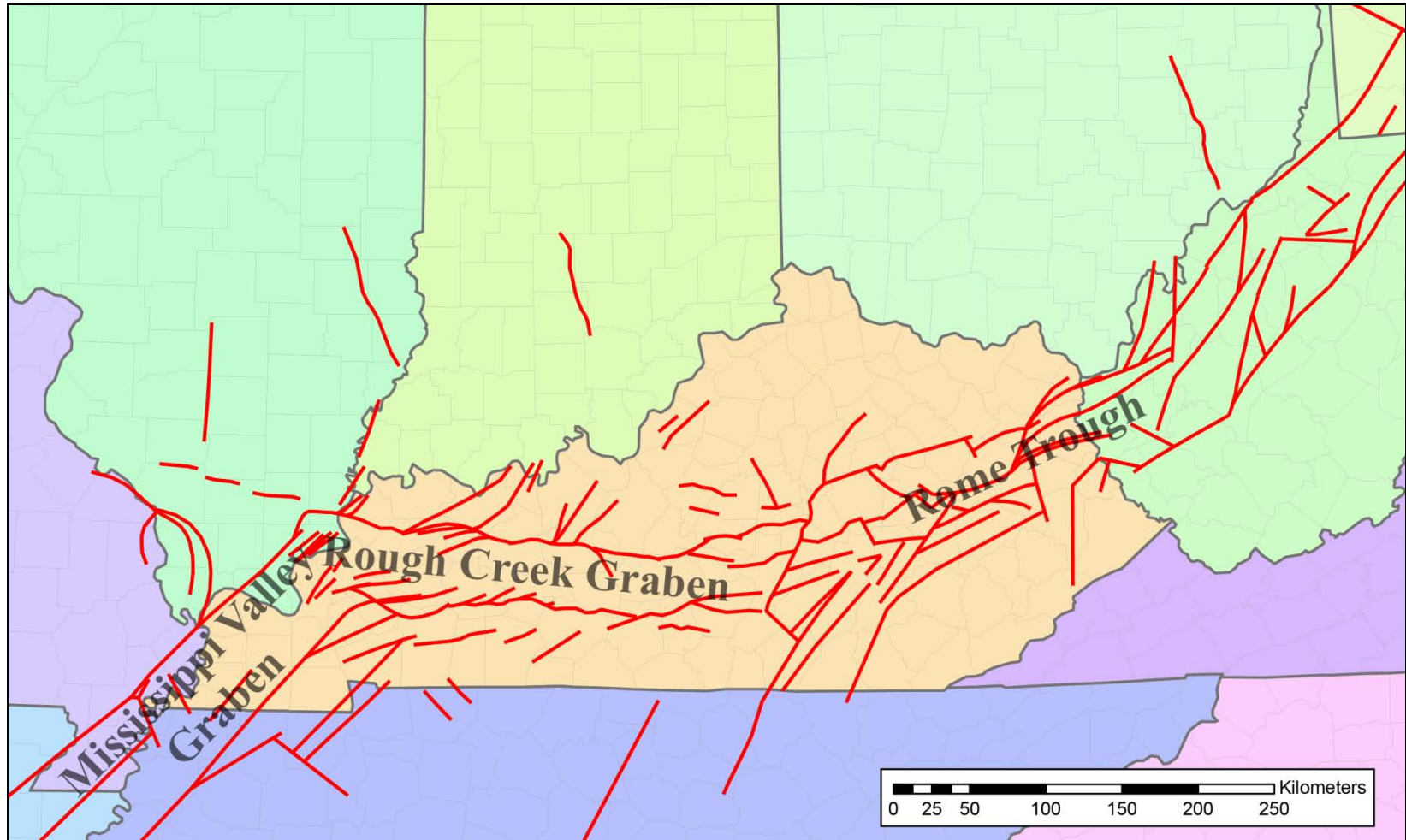


Figure 6.9 - Large offset basement faults (in red) interpreted within and surrounding the Mississippi Valley Graben/Rough Creek Graben/Rome Trough intracratonic rift system. Rome Trough fault locations from Harris et al. (2004) and Patchen et al. (2006).

6.3 Map and Cross Section Analysis

The thicknesses and structural elevations of seven Paleozoic stratigraphic packages (units A through G) have been described in both regional plan views (Chapter 3) and cross sectional profiles (Chapter 4). The vertical components of fault movement alter the available accommodation space above the hanging wall block, relative to the footwall block. If this movement is immediately prior to (or during) the deposition of sedimentary strata, the relative increase of accommodation space on the downthrown side leads to a proportional increase in depositional thickness of the contemporary unit. Care must be taken; however, to isolate plate tectonic versus diagenetic origins of surface fault movements. Near-surface syndepositional fault movements can be produced by regional tectonic movements (active regional fault systems, graben formation, etc.), differential subsidence produced from differential compaction of deeper sediments, or from a combination of these two forces (Figure 6.10). The following discussion utilizes these interpreted fault movements to study the structural evolution of the Mississippi Valley Graben and Rough Creek Graben rift systems.

For the Eau Claire Formation and older units within the Rough Creek/Mississippi Valley Graben system, very little is known about local facies patterns or depositional rates. The kinematic analysis for the Cambrian section is based on the assumptions that sediment thickness is proportional to local subsidence rates, and that subsidence rates are proportional to local fault movements. No regional unconformities have been defined above the base of the Paleozoic section within the Cambrian strata of the Mississippi Valley and Rough Creek Grabens. Therefore, this stratigraphic interval is assumed to be a complete record of the deposition of that time without any major hiatuses.

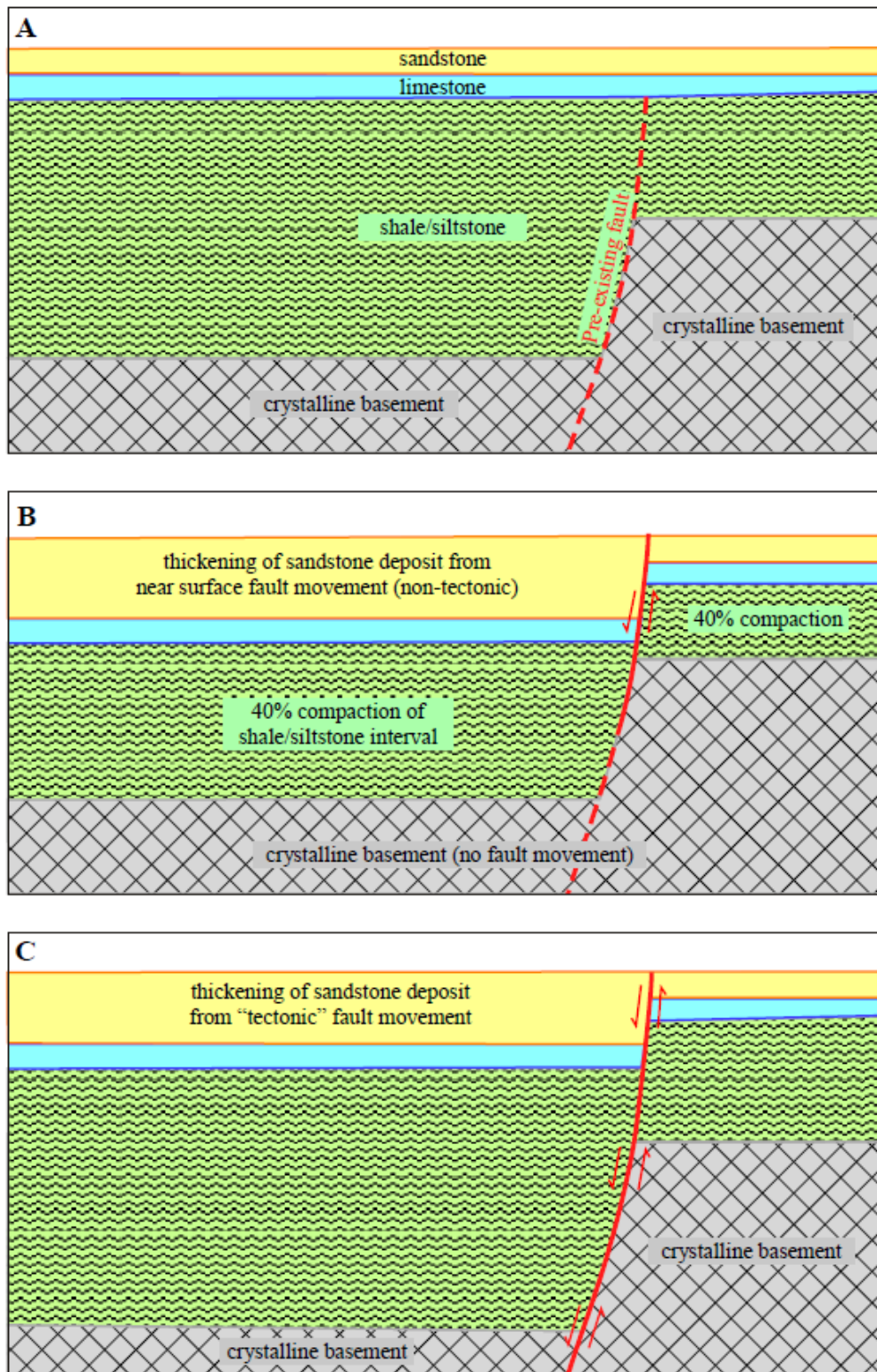


Figure 6.10 - Generalized examples of fault-related changes in sediment thickness: A) no fault movement (original condition), B) near-surface fault movement from differential compaction of deeper strata, C) fault movement from basement offset (tectonic extension).

Initiation of continental rifting that produced the Rough Creek Graben and adjacent Mississippi Valley Graben has been interpreted to be earliest Cambrian in age (Ervin and McGinnis, 1975; Cawood et al., 2001), and to post-date the active rifting stage of the Blue Ridge rift along eastern Laurentia (Thomas, 1991; Thomas, 2006). The oldest fossils identified within the Mississippi Valley Graben and Rough Creek Graben are Marjuman (uppermost Middle Cambrian to lowest Upper Cambrian); however, these were sampled from within the Eau Claire Formation and not from the underlying Reelfoot Arkose (Grohskopf, 1955; Palmer, 1962; Collins et al., 1992; Collins and Bohm, 1993; Mitchell, 1993).

The Reelfoot Arkose (stratigraphic unit A) is composed of poorly sorted, immature sandstones and siltstones. It is the oldest unit deposited within the Mississippi Valley Graben and Rough Creek Graben and appears to be stratigraphically equivalent to the arkosic clastic sediments of the lower Rome Formation of the Rome Trough (Harris et al., 2004). The probable source of the clastic sediment of the Reelfoot Arkose is from local erosion of the crystalline basement rocks of the Granite-Rhyolite Province and the Precambrian Middle Run Sandstone along the Cincinnati Arch (Weaverling, 1987; Houseknecht, 1989); however, geochronological detrital zircon analysis would be needed to exclude the more distal Superior Province as a possible detrital source. The lack of metamorphic mineral assemblages within the Reelfoot Arkose suggests that the Grenville Province was not a major contributor of detrital sediment.

Thickness distribution indicates that the boundary fault systems of the Mississippi Valley Graben and Rough Creek Graben underwent normal dip-slip movement during the deposition of the Reelfoot Arkose, but the large “central fault” ([Figure 3.2](#)) within the Mississippi Valley Graben did not. Within the Mississippi Valley Graben, the Reelfoot Arkose thickens toward the northwest border faults. Whether this thickening is a result of numerous proximal deposits in alluvial fans coming off the Ozark Dome to the west, or from lateral transport and depositional filling of the increased accommodation space produced by continuous offset along the border faults within the graben is unknown. Tectonic subsidence was greatest within an east-striking, linear depocenter in central Ohio County, and in a slightly smaller depocenter in Union County, Kentucky. These

localities are not equidistant from the graben-bounding fault systems, but instead are just south of the Rough Creek Fault Zone, implying that the current asymmetric, north-dipping base of the graben basin formed early.

The borders of rift grabens commonly are depicted as rotated half-grabens. In this study, the base of the Rough Creek Graben has been interpreted as an asymmetrical syncline with limbs dipping away from both border fault systems (Plates 14 and 16). Because most of the stratigraphic tops used for the production of the maps described in Chapter 3 were interpreted from seismic profile data, the most probable reason for the synclinal shape is the presence of numerous faults with individual offsets smaller than the seismic resolution threshold ([Figure 6.11](#)). This scenario is reasonable given the unlikelihood that the entire 40 to 60 km wide graben consists of a single rift block (Rosendahl, 1987). If the width (or length) of the Rough Creek Graben includes numerous rift blocks, some probably have sub-seismic offsets. The cumulative down-to-basin offsets from these rift blocks could produce enough sag as to be obvious from regional seismic mapping, even without having individual offsets that are discernable on the seismic profiles.

In addition to the effect of multiple sub-seismic faults, another possible contributor to the synclinal (as opposed to rotated half-graben) shape of the Rough Creek Graben is plastic deformation of deeper rocks from depth-dependent thermal weakening ([Figure 6.11](#)). It is evident from the calculations presented in Chapter 5 that significant post-rift thermal deformation of the crust occurred within the Rough Creek Graben during the Middle-Late Cambrian. At the end of the time of thermal subsidence, more than 8 km of strata had been deposited within the depocenter in Ohio County, Kentucky. The weight of this mass of sediment produced tectonic subsidence ([Figure 5.5](#)). This subsidence pushed the older sediments deeper into the crust, and closer to the elevated heat flow of the asthenosphere. Increased heat flow could theoretically reduce the elastic strength of the upper crust, and allow the rift basin to stretch vertically ([Figure 6.11](#)).

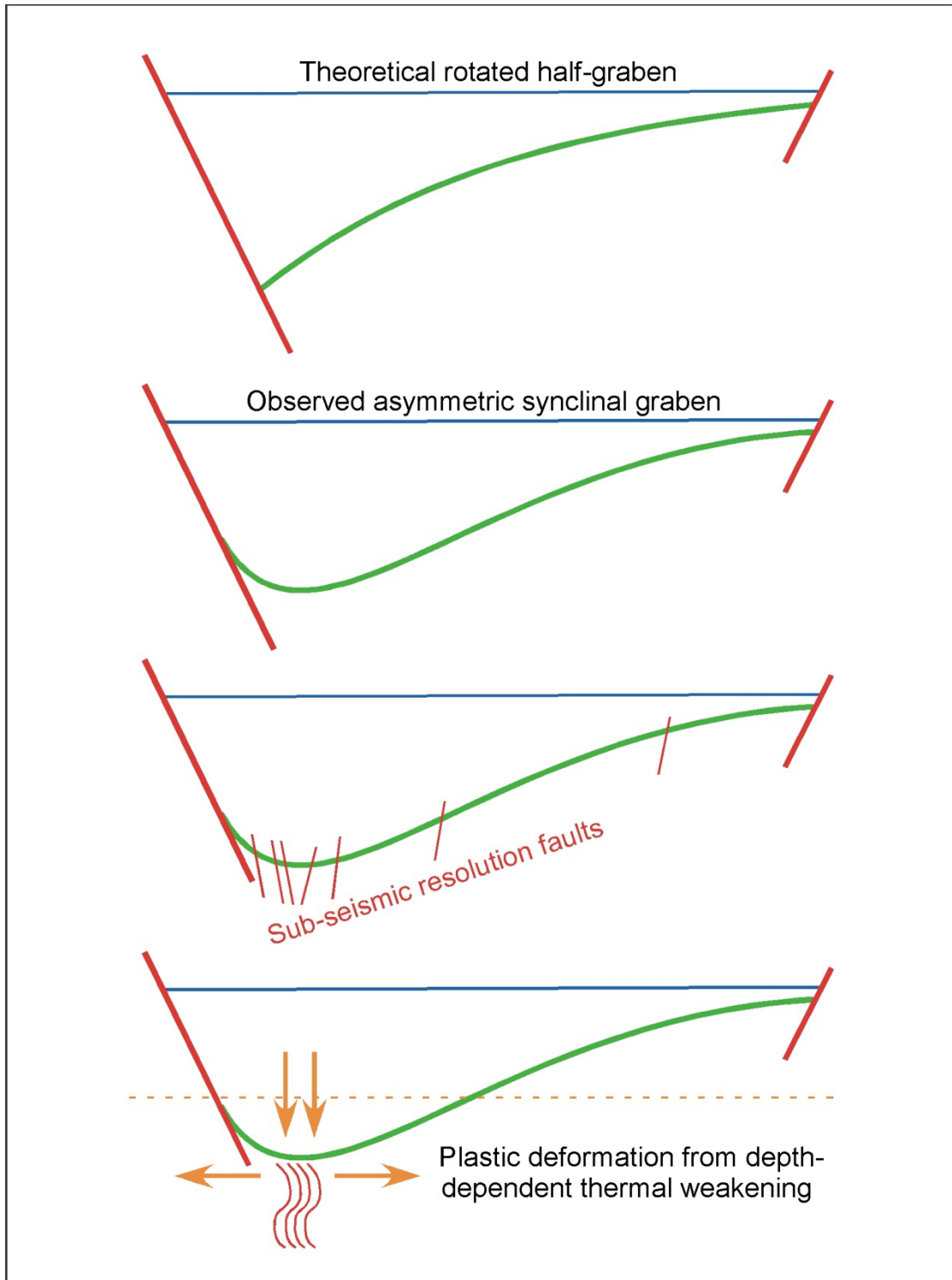


Figure 6.11 - Possible scenarios for producing an asymmetric synclinal profile to the Rough Creek Graben.

In most areas, the seismic velocity of the rocks immediately overlying the Reelfoot Arkose was determined to be within the range of carbonate strata, probably limestone (around 21,000 to 25,000 feet/second). The high-amplitude seismic reflection at the top of the Reelfoot is also consistent with a transition from a fast, clean carbonate to a seismically slower, coarse clastic deposit. This high-carbonate unit (exact lithology is unknown) is probably an extension of the St. Francois Formation proposed in southeast Missouri and northeastern Arkansas by Weaverling (1987), and may be stratigraphically equivalent to the upper limestone unit of the Rome Formation in the Appalachian Basin. The approximate age, bedding patterns resolvable on seismic profiles, and stratal position above an arkosic clastic unit all appear to be similar to the characteristics of the upper limestone unit of the upper Lower Cambrian Rome Formation within the adjacent Rome Trough in eastern Kentucky, West Virginia, and Pennsylvania.

In the Rome Trough, the upper Rome limestone unit is overlain by the Middle Cambrian Pumpkin Valley Shale of the Conasauga Group. Within the Rough Creek Graben, there is no regional seismic reflection horizon between the top of the Eau Claire and the top of the Reelfoot Arkose similar to the Pumpkin Valley Shale-Rome Formation transition ([Figure 6.12](#)). This is interpreted as an indication of a gradational transition (at a seismic scale) between the high carbonate units of the lower Eau Claire Formation directly above the Reelfoot Arkose and the siltstones and shales of the upper Eau Claire Formation. The lower Eau Claire carbonate unit may also be equivalent to the lower limestone units (Maryville and Rutledge Limestones) of the Middle-Late Cambrian Conasauga Group of the Appalachian Basin. Without further data, the exact age and interbasinal stratigraphic correlations of the Eau Claire Formation cannot be determined.

Rough Creek Graben (Illinois Basin)

Rome Trough (Appalachian Basin)

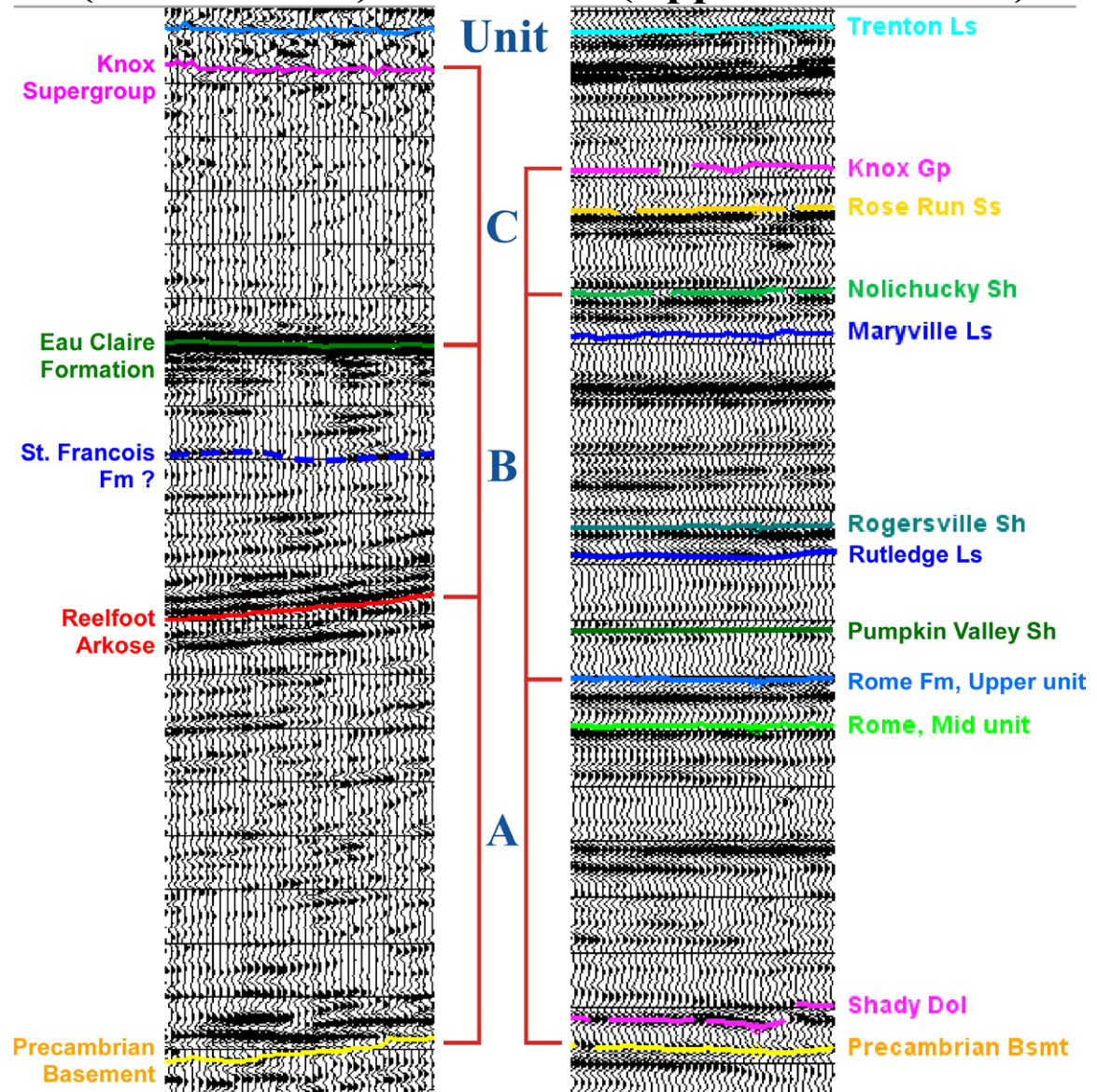


Figure 6.12 - A comparison of seismic reflection responses of units A - C in the Rough Creek Graben, and the equivalent intervals within the Rome Trough of eastern Kentucky.

Within the Rough Creek and Mississippi Valley Grabens, dramatic thickness increases in units A (Reelfoot Arkose) and B (Eau Claire Formation) across the graben-bounding faults indicate that the greatest amount of syndepositional fault movement occurred during the deposition of those units. Southward across the Rough Creek Fault Zone in Ohio and Grayson Counties, Kentucky, unit B thickens by as much as 6,500 feet and unit A thickens from zero to as much as 10,000 feet (the Reelfoot Arkose is absent outside of the rift system). This variation in depositional thickness indicates the minimum magnitude of syndepositional fault movement during this time. Assuming later compaction and dewatering of shale and siltstone units within units A and B, the component of syndepositional fault movement may have been much greater.

During deposition of the unit B (Eau Claire Formation), the smaller depocenter that had formed in southern Union County, Kentucky, during deposition of unit A (Reelfoot Arkose) diminished in size and relative magnitude. The linear depocenter in Ohio, Grayson, and McLean Counties, however, increased in both length and depth during this time. A possible implication of this is that the center of deformation (zone of highest extension) migrated eastward along the northern Rough Creek Graben during the Middle to Late Cambrian from Union County near the Kentucky/Illinois border to Ohio County, Kentucky.

Although both units thicken into the Rough Creek Graben, neither the structure at the top of unit B nor the isopach thickness of the overlying unit C (Knox Supergroup) displays the same distinct, short-wavelength thickening trends over the earlier Union and Ohio County depocenters. The syndepositional growth of the linear depocenter in Grayson and Ohio Counties had, therefore, ended prior to the deposition of the unit C (Knox Supergroup). Similarly, the relatively smooth isopach of unit C southward into the Rough Creek Graben indicates that large (tectonic) movements along the Rough Creek Fault Zone had also ended by the end of the unit B deposition (Late Cambrian).

Thinning of the Eau Claire over the Tolu Arch and Fluorspar region of western Kentucky indicates that this region, where the Mississippi Valley Graben and Rough Creek Graben intersect, has been uplifted relative to the surrounding area since at least the late Middle

Cambrian. This area in Livingston and Crittenden Counties, Kentucky, is near the centerline of the Mississippi Valley Graben, but is separated from the graben bounding faults by the Mississippi Valley Graben Central Fault to the west and by three unnamed basement fault system segments to the east.

The Blytheville and Pascola arches (herein the Blytheville/Pascola dome) in the Mississippi Valley Graben outline the region of earthquake activity associated with the New Madrid Seismic Zone and imply an interconnected origin. Using published seismic lines (Howe and Thompson, 1984; Sexton, 1988) and well data analyzed in this project, this dome is interpreted to be intersecting fault-cored anticlines formed above the New Madrid Seismic Zone faults. The up-warped base of the Knox Supergroup over these features is evident on seismic profiles (Howe and Thompson, 1984; Sexton, 1988). The Dow Chemical #1 Garrigan well in Mississippi County, Arkansas, drilled into the center of this feature and penetrated more than 7,600 feet of shale and siltstone (Collins et al., 1992) interpreted as Eau Claire Formation. The tectonically thickened shale and mudstone section of the Eau Claire Formation was deformed into an arched structure below the rigid Knox Supergroup (southwest corner of [Plate 13](#)). The specific age of formation for these structures is unknown, but must be after the Early Ordovician and before the Cretaceous as indicated by an uplifted Knox section that is truncated and overlain by the Cretaceous sediments of the Mississippi Embayment.

During deposition of the Knox Supergroup, the area of active faulting and extension shifted from the eastern Rough Creek Graben southwestward to the Mississippi Valley Graben. The Lusk Creek fault zone (northwestern boundary of the Mississippi Valley Graben), and the central fault ([Figure 3.2](#)) were active during Knox deposition as indicated by the large thickness differences of the Knox Supergroup across these faults. Although the top of the Knox Supergroup (unit C) is a regional unconformity (Sloss, 1963), the isopach thickness of the overlying unit D rocks suggests that this is a difference in depositional thicknesses and not a product of later erosion of the uplifted footwall blocks. Subsidence of the Rough Creek Graben continued to decrease during Knox time, as indicated by fewer faults displacing the top of Knox than the base. The isopachous thickness of the Knox Supergroup (unit C) increases into the western part of

the Rough Creek Graben and the northern part of the Mississippi Valley Graben ([Figure 3.2](#)) from all directions. This gradual thickening toward the grabens includes a large area beyond the graben-bounding faults. The relative timing of the end of graben subsidence from fault offsets and the observed thickening of unit C across the graben-bounding faults are in agreement with the time and magnitude of the thermal subsidence calculated in Chapter [5](#).

Unit D thickens to the south toward the Nashville Dome, and to the west into the Fairfield Subbasin and northernmost Mississippi Valley Graben area ([Figure 3.2](#)). Thickness distribution of the Trenton and Black River Formations (unit D) indicate that the subsidence of the Illinois Basin was active as early as the Middle Ordovician. Directly overlying this unit, a roughly north-south corridor of thickened Maquoketa Shale (unit E) interval crosses western Kentucky over a thinned corridor of the Trenton Formation called the Sebree Trough ([Figure 3.4](#)). The transition along the edges of the Sebree Trough can be observed in well logs, and appears to be a gradational depositional change unrelated to fault movement. This interpretation is further supported by the lack of any other regional structures that are parallel to the Sebree Trough. Other than an isolated area in southern Hopkins and Caldwell Counties, Kentucky, there is little apparent effect of fault movement on the thickness of the Maquoketa Shale within the Mississippi Valley and Rough Creek Grabens. Why only the southern Hopkins County area faults moved (and not the rest of the graben fault systems) during this time is unknown.

In the time between deposition of the Late Ordovician Maquoketa Shale and that of the Middle Devonian-Early Mississippian New Albany Shale, tectonic subsidence was reactivated within the Rough Creek Graben. During this time, most of the subsidence within the Rough Creek Graben appears to have occurred closer to the graben axis rather than along the northern border faults (the Union County and McLean/Ohio/Grayson County depocenters of units A and B). Along the southern border of the Rough Creek Graben, most subsidence (interpreted from isopach thicknesses) shifted northward from the Pennyrile Fault System to the Tabb Fault System ([Figure 3.2](#)) in Caldwell and Hopkins Counties, Kentucky. Unit F thins over the Fluorspar District of southwestern

Crittenden and Livingston Counties, Kentucky. This implies the possible reactivated uplift and/or reduced subsidence of that region similar to what is observed during the Knox Supergroup interval. The combined uplift of the Fluorspar District interpreted for these two stratigraphic units, however, does not equal the present day structural offset. Because of this fact, it is possible that this is an inverted fault block produced by later (post-Mississippian) compression.

In Ohio and Grayson Counties, Kentucky, the Middle Devonian-Early Mississippian New Albany Shale (unit G) increases in thickness 20 to 40% (30 to 75 feet) southward across the Rough Creek Fault Zone. This increase is observable between 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.

Regional post-Devonian deformation is indicated by uplifted Devonian strata within inversion structures along the Rough Creek Fault Zone, and in the fault offsets observed in the outcrop patterns surrounding the Jessamine Dome in central Kentucky (McDowell et al., 1981; Noger, 1988). Reactivation of the Rough Creek Fault Zone also produced tectonic thickening (stratigraphic duplication from high-angle reverse faulting) of the New Albany within several wells that penetrated the deformed fault zone.

6.4 Kinematic Evolution of the Mississippi Valley and Rough Creek Grabens: Early Cambrian to Early Mississippian

In the previous chapters, the current structural expressions and thicknesses of seven stratigraphic packages within and surrounding the Mississippi Valley Graben and Rough Creek Graben are described. By analyzing changes in thickness of these stratigraphic intervals across major fault systems, inferences can be made regarding syndepositional fault movement during their respective deposition. Using the detailed subsurface mapping of units A through G, a map-view summary of interpreted fault movements from the Early-Middle Cambrian (Reelfoot Arkose) to the Early Mississippian (New Albany Shale) is presented in [Figure 6.12](#) through [Figure 6.18](#). In all of these figures, basement fault systems (thin grey lines) are highlighted in red where significant thickening across the faults (arrows toward thickened side) are observed for each stratigraphic unit (implying syndepositional fault movement). Bold, solid red lines signify large fault offsets and thinner, dashed red lines highlight faults with smaller offsets and/or with less conclusive stratigraphic thickening across the fault. The major thickness differentials across faults (bold lines) are large enough to be interpreted as having evidence of tectonic-related syndepositional fault movement. The smaller thickness differentials across faults (thin dashed lines) may be from smaller (tectonic) fault offsets, or produced from differential subsidence produced by compaction of deeper sediments. Areas outlined by thin blue dashed lines show where the units are absent because of non-deposition or later erosional truncation (and therefore no fault movement interpretations are possible).

The interpreted contemporary tectonic strain direction(s) that produced these fault movements are displayed in small insets in the upper right of each figure. Because the stress vector for thermal subsidence is vertical, the overall fault offsets during post-rift thermal subsidence (see [Chapter 5](#)) were probably amplified, but would not affect the directions of maximum and minimum horizontal strain (σ^1 and σ^3 , respectively) from regional tectonic stresses. Refer to [Figure 3.2](#) for the names of faults and structures described in this chapter.

The earliest synrift sediments to cover the exposed Precambrian rocks and fill the Rough Creek and Mississippi Valley Grabens are the clastic deposits of unit A. Calculations performed for locations within the Rough Creek Graben (Section [5.2](#)) indicate a high rate of initial graben subsidence coincident with the deposition of unit A. With the exception of a small area in southern Illinois around Johnson, Pope, and Saline Counties, unit A is absent outside of the Mississippi Valley and Rough Creek Grabens ([Figure 6.12](#)).

Dramatic thickness changes are present across the Lusk Creek fault, the eastern boundary fault of the Mississippi Valley Graben, the Rough Creek Fault Zone, and across the northeast-striking splays of the Pennyrile Fault System in Butler County, Kentucky ([Figure 6.12](#)). Where unit A is absent outside of the graben areas, the activity of faults in those areas cannot be determined, and the faults of the eastern extensions of the Rough Creek Fault Zone and Pennyrile Fault System may also have been active during this time.

Vertical displacements along normal faults are greatest along faults that are perpendicular to the extension direction, and decrease to zero along faults that are parallel to the extension direction. Given the set of faults that were active during the deposition of unit A, the interpreted extension (σ^3) direction is northwest-to-southeast ([Figure 6.12](#), inset). During the time that unit A was being deposited (earliest Middle Cambrian), the Laurentian tectonic plate was separating from the Amazonian plate, and the active spreading center that ultimately produced the Iapetus Ocean was shifting from the Blue Ridge rift to the Ouachita rift (Thomas, 1985; Thomas, 1991). The strain vector interpreted from syndepositional fault movement corresponds well with this tectonic environment.

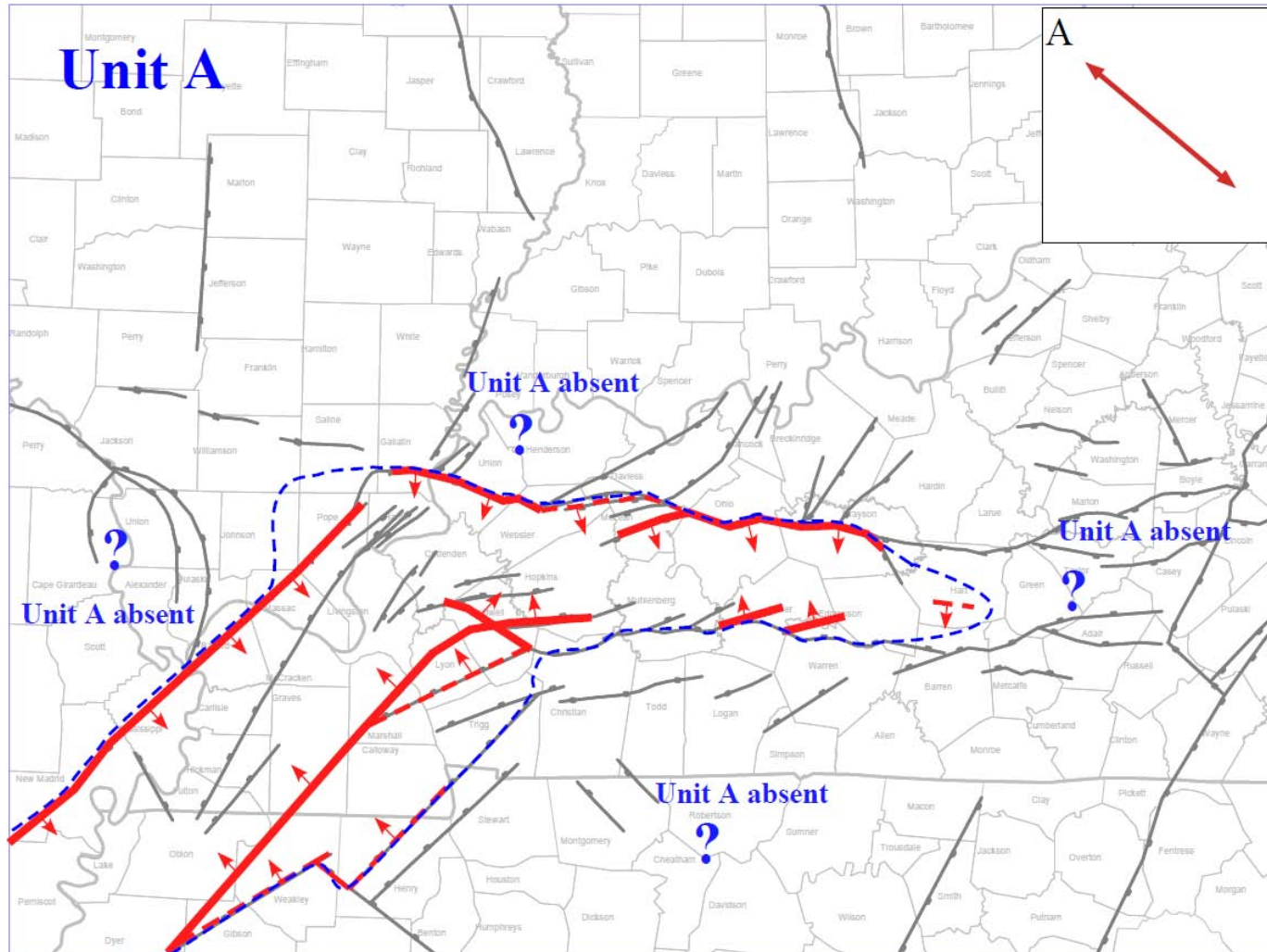


Figure 6.13 - Syndepositional fault movement and thickening directions of unit A (Early-Middle Cambrian). Interpreted regional extension direction shown in inset (red arrows).

Evidence of fault movement during the deposition of unit B is more widespread than for unit A, and includes most of the basement faults within the study area. Faults active during this time include almost all of the Rough Creek Fault Zone (including the eastern extension in Hart, Green, and Marion Counties), the Lusk Creek Fault, the Central Fault of the Mississippi Valley Graben, the Northwest Stewart fault, the Centralia and La Salle Faults surrounding the Fairfield Subbasin, and most of the Pennyrile Fault System ([Figure 6.13](#)). Smaller displacements are interpreted along the northeast-striking faults north of Rough Creek Fault Zone (including around the Owensboro Graben), the southern part Eastern Boundary fault, and the southern part of the Grenville Front fault along the Cincinnati Arch.

The varying orientations of faults active during the deposition of unit B add complexity to the interpretation of a tectonic situation which would produce the resulting sedimentation patterns. Some fault systems suggest northwest-to-southeast extension (Lusk Creek, Lexington, Centralia, etc.) and others north-northwest-to-south-southeast extension (Rough Creek, eastern extension of Pennyrile, etc.). These patterns may indicate two directions of simultaneous extension which, when combined, create a general northwest-to-southeast extension ([Figure 6.13](#), inset B₁), producing left-lateral transtension along the rift axis in the Rough Creek Graben. It is also possible that the extension direction evolved during deposition of unit B, rotating the tensional strain direction vector clockwise through time, away from the more northwestward direction indicated for unit A ([Figure 6.14](#), inset B₂). An estimated 17 to 21 km of extension during the Cambrian across the Southern Oklahoma Fault System (McConnell and Gilbert, 1986) at the northwestern end of the Alabama-Oklahoma Transform fault (Thomas, 1991) suggests that this north-to-south component of extension was widespread, and not a local event affecting only the faults of the Rough Creek Graben.

Although slightly limited by a lack of internal data points (below unit scale) for age dating, the subsidence curves calculated for the two locations within the Rough Creek Graben (Chapter 5) indicate that the initial, high rate of subsidence associated with the opening of the rift graben ended during the deposition of unit B ([Figure 5.6](#)). A subjective analysis of the slopes of the subsidence curves for the Union County and Ohio

County, Kentucky, depocenters suggests a date around 502 Ma for the end of significant tectonic subsidence within the Rough Creek Graben ([Figure 5.5](#)). Because unit A is limited to the graben areas, the formation of the grabens must have begun before the initial deposition of unit A. Therefore, tectonic fault movement and subsidence within the Rough Creek Graben (and through stratigraphic correlation the adjacent Mississippi Valley Graben) began by at least 514 Ma (latest Early Cambrian) and lasted until around 502 Ma (latest Middle Cambrian) ([Figure 1.3](#)).

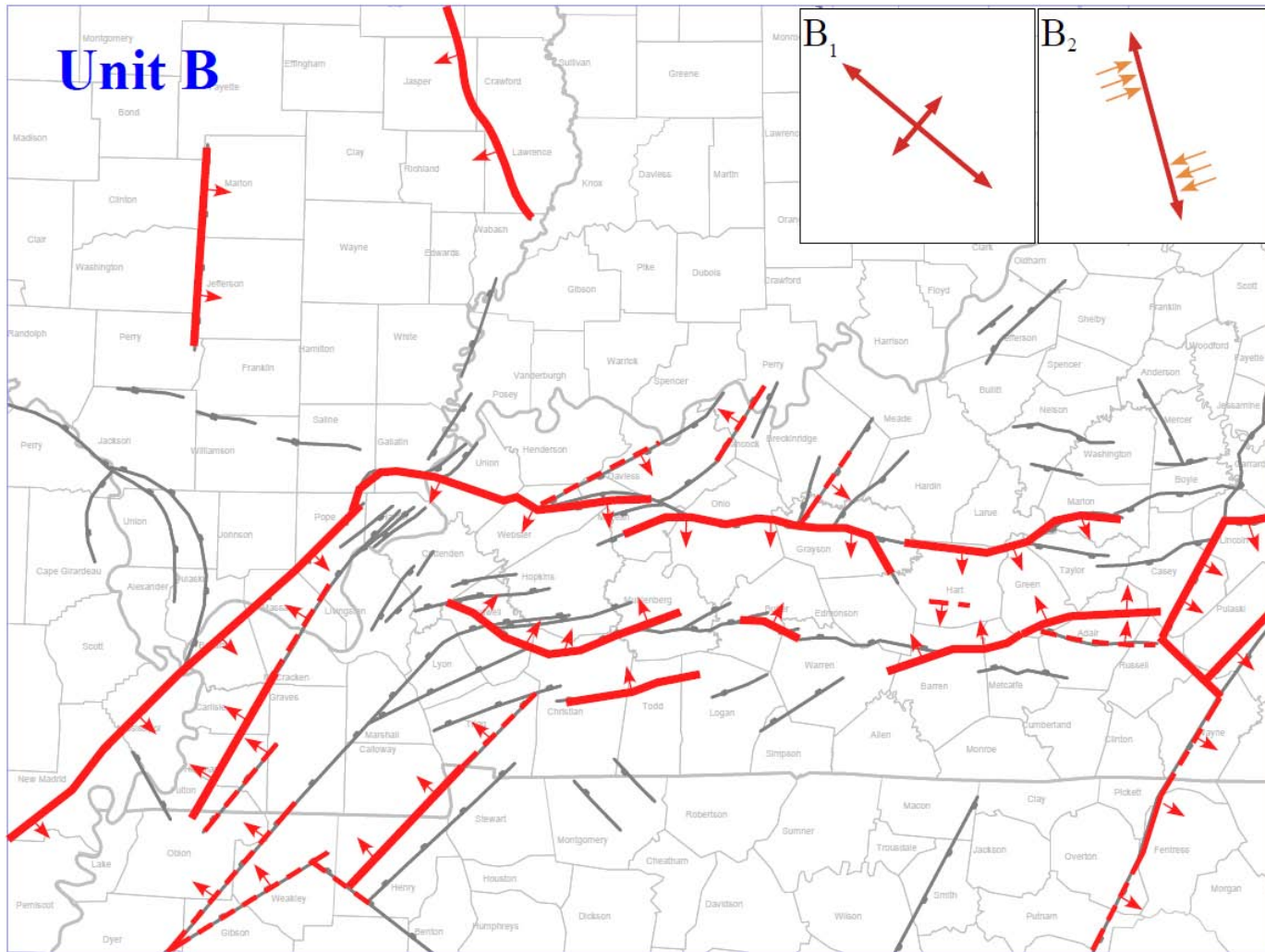


Figure 6.14 - Syn depositional fault movement and thickening directions of unit B (Middle-Late Cambrian). Interpreted regional extension directions shown in inset (red arrows).

The deposition of unit C occurred during the Late Cambrian to Early Ordovician ([Figure 1.3](#)), when Laurentia had completely rifted away from the rest of Rodinia. Both the eastern (Blue Ridge) and southern (Ouachita) continental margins of Laurentia are characterized by passive-margin sedimentation during this time (Sloss, 1988; Thomas, 1991). Despite the lack of regional tectonism, the southern Lusk Creek Fault, Mississippi Valley Graben Central fault, eastern Rough Creek Fault Zone, eastern Pennyryle Fault System, the “Southeast Stewart” fault, the basement faults in Montgomery County, TN, Centralia fault, and eastern boundary fault of the Owensboro Graben all appear to have been active ([Figure 6.16](#)). Fault movement from differential compaction of the thickened Eau Claire and Reelfoot Arkose (units B and A, respectively) probably contributed to this movement, but the fact that the fault movement appears to have been greater in areas away from the thickest isopachs in Union and western Ohio Counties, Kentucky, suggests the dominant fault-driving mechanism was different.

It should be noted that unit C was deposited over a time period that was 400 to 500 percent longer than the time periods of the deposition of either unit A or unit B ([Figure 1.3](#)). With this long interval, even fault systems with very low rates of fault movement could accumulate large offsets over the entire ~25 Ma depositional interval of unit C. According to the subsidence calculations in Chapter 5, fault-controlled subsidence from active rifting ended prior to the end of the deposition of unit B. Therefore, the subsidence that produced the fault offsets and associated thickness changes in unit C is from a combination of residual sediment compaction (from increased burial) and post-rift thermal subsidence, not from active extensional tectonics. The dissipation of residual heat from rifting (and the related passive upwelling of the asthenosphere) condensed and contracted the overall volume of crustal material, producing thermal subsidence ([Figure 5.4](#)). This post-rift thermal subsidence is calculated to have lasted until around 485 Ma, about halfway through the deposition of unit C ([Figure 5.6](#)). Unlike tectonic subsidence, the regional thermal anomaly produced during continental rifting (followed by stratigraphic thickening) propagates outward from the rift center and is not constrained along the border faults of the rift graben ([Figure 6.15](#)). The fact that unit C thickens around (and not just into) the Rough Creek Graben and Mississippi Valley Graben supports the result of the subsidence calculations of Chapter 5. Thermal subsidence

warped both the grabens and the areas surrounding the grabens downward, which lead to the thickened section of unit C in those areas ([Plate 11](#)).

For unit C, the dominant extension direction interpreted for syndepositional fault movement ([Figure 6.14](#), inset) is north-northwest-to-south-southeast. If the clockwise rotation of the direction of maximum extension hypothesized above for units A and B occurred as described, the regional extension direction for unit C is very similar to the extension direction present during the end of unit B deposition.

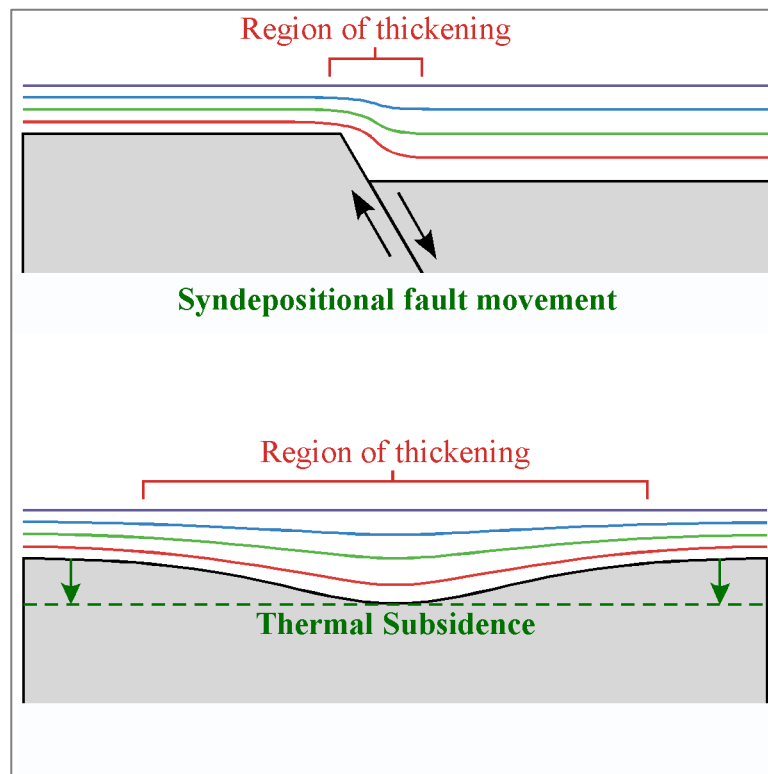


Figure 6.15 - Differences between stratal thickening patterns produced by syndepositional fault movement (narrow 5-10 km zone adjacent to fault system) and by thermal subsidence (wide 30-40 km zone adjacent to rift system).

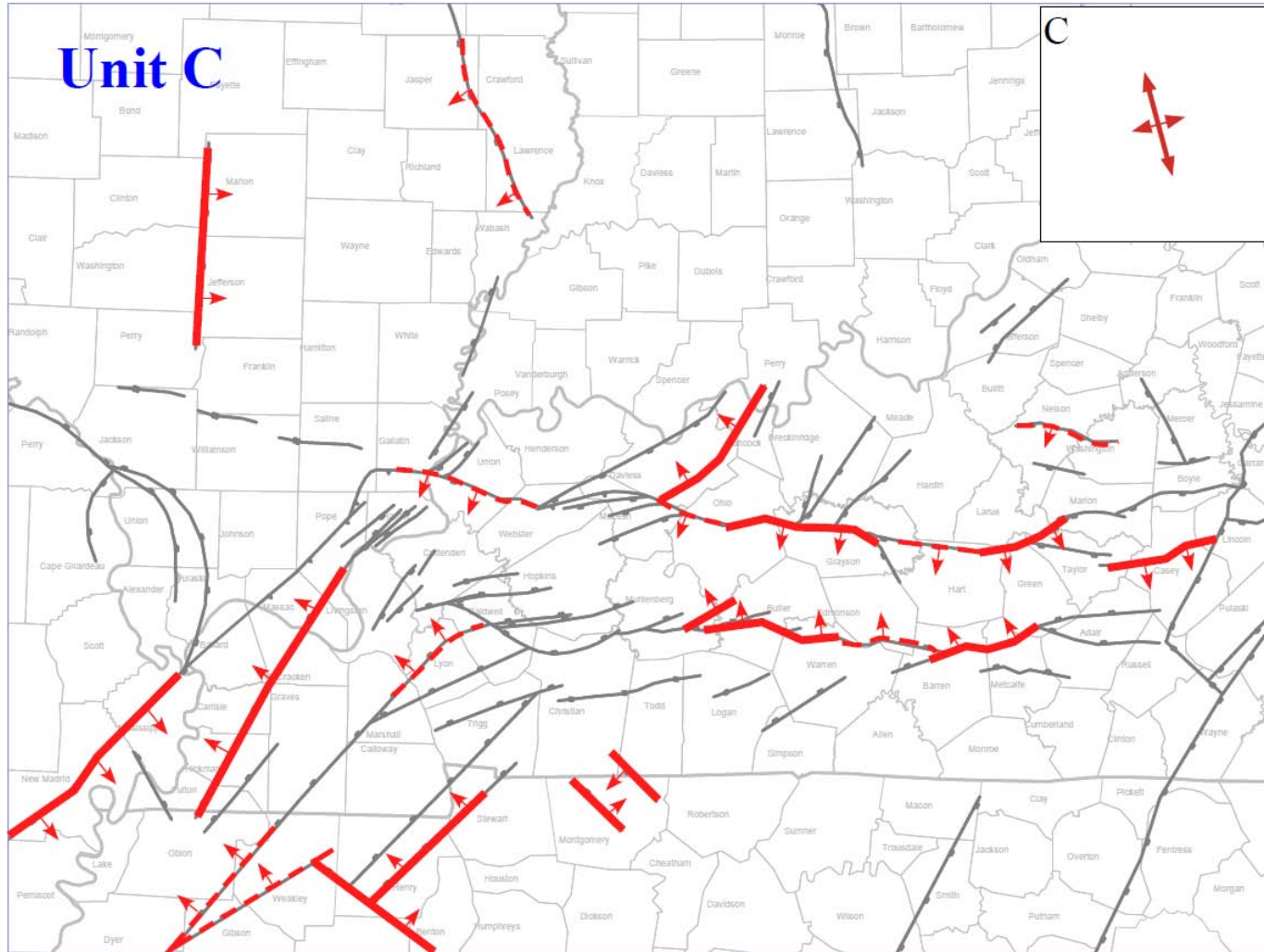


Figure 6.16 - Syn depositional fault movement and thickening directions of unit C (Late Cambrian-Early Ordovician). Interpreted regional extension direction shown in inset (red arrows).

On the basis of stratigraphic thickness patterns, the faults that were active during unit D deposition were the Pennyryle Fault System (including the unnamed southern basement fault in Lyon County, Kentucky), the southern end of La Salle Fault, the northwestern border fault of the Owensboro Graben, the Cave Spring/Locust Hill Fault System, and a fault system segment of the eastern extension of the Pennyryle Fault System in Barren and Metcalf Counties, Kentucky (Figure 6.15). This indicates a north-northwest-to-south-southeast extensional regime, but the limited number of active faults suggests a reduced magnitude of extensional stress (Figure 6.17, inset).

Unit D deposition in the study area occurred during the arc-continent collisions of the Taconic Orogeny (Sloss, 1988; Thomas, 2006), which began along the Virginia Promontory in the Middle Ordovician and followed along the New York Promontory (Thomas, 1977, 2006). This collisional event would last in the southern Appalachians throughout the end of unit D, and all of unit E deposition. Although the orogenic belt was fairly distant to the east (more than 500 km), it is possible that some of the compressive stress (σ^1 , blue arrows in inset of Figure 6.15) extended into the continent as far as the study area, as evidenced by the presence of some active fault zones. In the presence of this east-west compressive stress, the least compressive regional stress direction (σ^3) becomes roughly north-south, promoting extension in that direction.

Only two fault system segments that were active during unit D deposition were also active during the deposition of unit C. Whether this swapping of active faults is because of a significant change in the regional stress field, or just a natural migration of the zone of fault movement along fault systems through time is unknown. Overall, the thickening across these faults is less dramatic than that in older units and probably indicates only small-scale tectonic adjustments along the Mississippi Valley Graben/Rough Creek Graben intracratonic rift system.

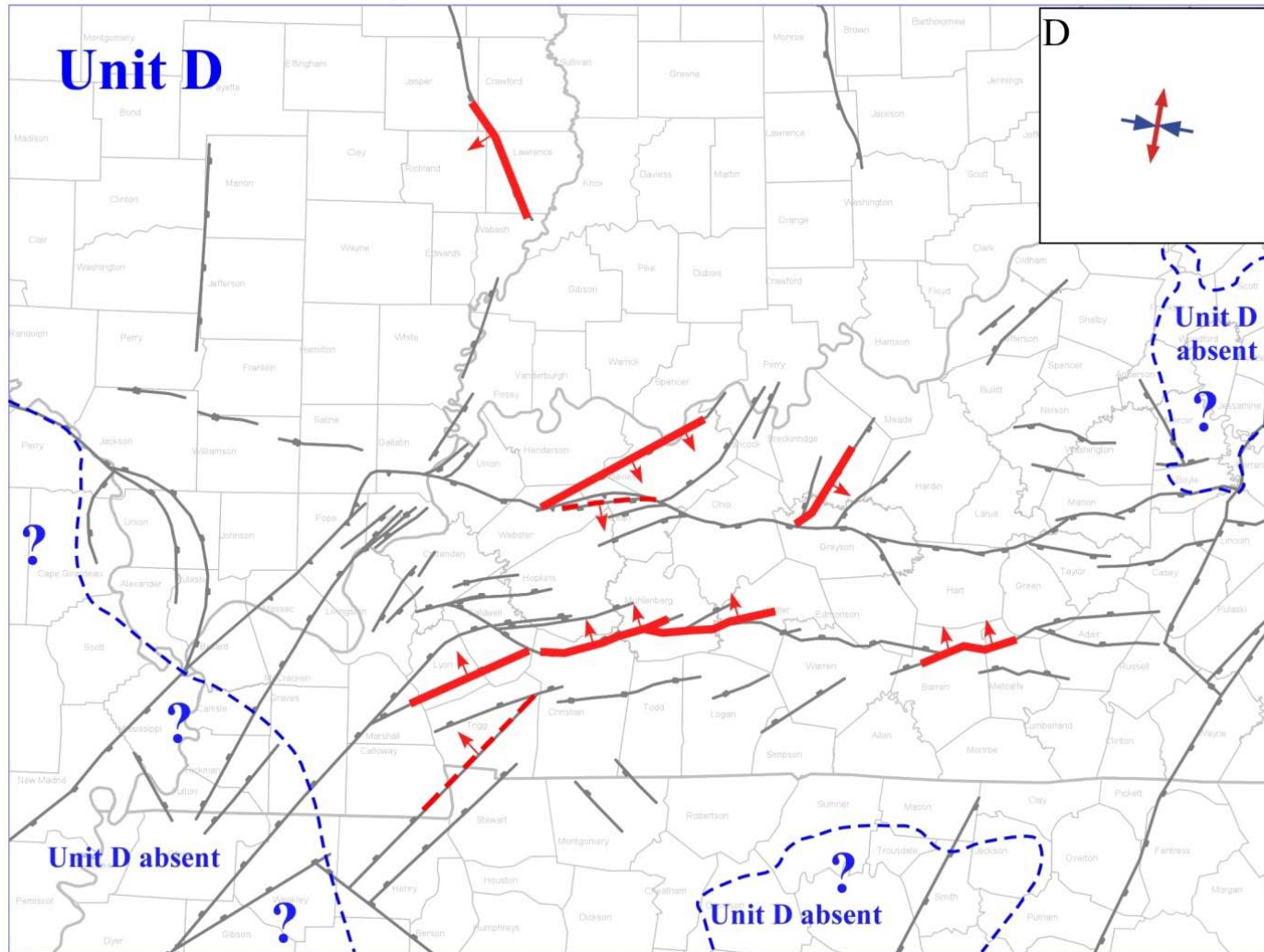


Figure 6.17 - Syndepositional fault movement and thickening directions of unit D (Middle Ordovician). Interpreted regional compression (blue arrows) and extension (red arrows) directions shown in inset.

During the deposition of unit E, the Taconic Orogeny was still happening in the southern and central Appalachians to the east (Sloss, 1988; Thomas, 2006), but relatively few faults were active in the Rough Creek and Mississippi Valley Grabens. Only a few fault system segments in southern Hopkins and Lyon Counties appear to have been active; smaller offsets are interpreted along the central Pennyryle Fault System ([Figure 6.16](#)). This suggests limited local tectonic stress contemporaneous with unit E deposition ([Figure 6.16](#), inset).

The areal extent of unit F is limited within the study area because of erosional truncation by the Middle Devonian regional unconformity that forms the top of unit E. The lack of existing unit F strata prohibits the use of cross-fault thickness changes as an indication of fault movement across most of the Mississippi Valley Graben faults, or for faults along the axis of the Cincinnati Arch or Cumberland Saddle ([Figure 6.17](#)). In areas where unit F rocks are present, the faults that were active during this period were the faults along the central and eastern Rough Creek Fault Zone (including the eastern extension in Hart County), the northeast-striking splays of the Pennyryle Fault System in Butler County, Kentucky, the northern end of the Eastern Boundary Fault of the Mississippi Valley Graben and continuing through the unnamed fault system south of Central Fault System ([Figure 6.17](#)).

The main deformation stage of the Taconic Orogeny ended about halfway through the deposition of unit F strata; however, there appears to have been significant regional stress to produce a pattern of north-northwest-to-south-southeast extension ([Figure 6.19](#), inset). The large regions that are absent of unit F may mask components of other tectonic movement, however.

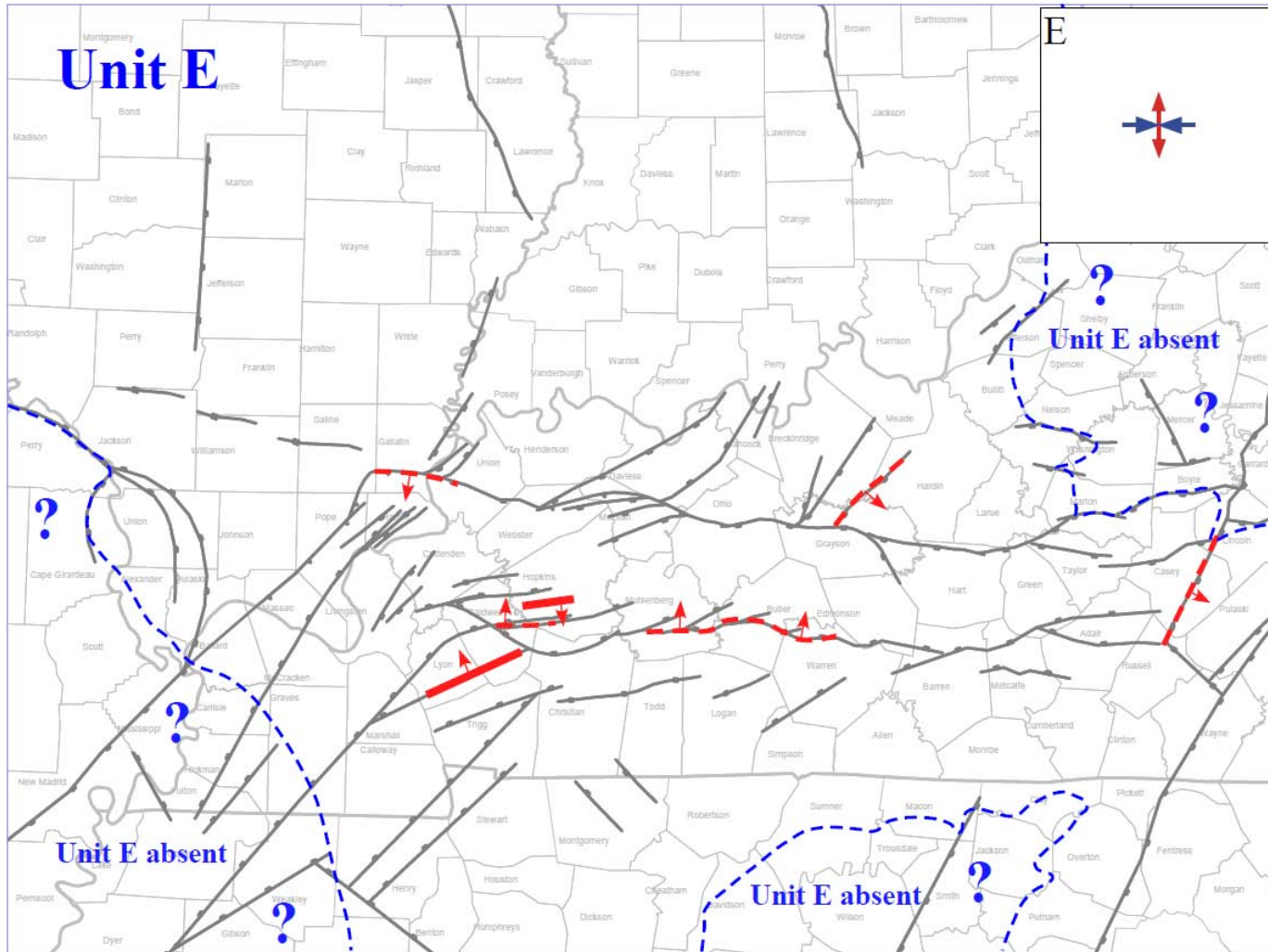


Figure 6.18 - Syndepositional fault movement and thickening directions of unit E (Late Ordovician). Interpreted regional compression (blue arrows) and extension (red arrows) directions shown in inset.

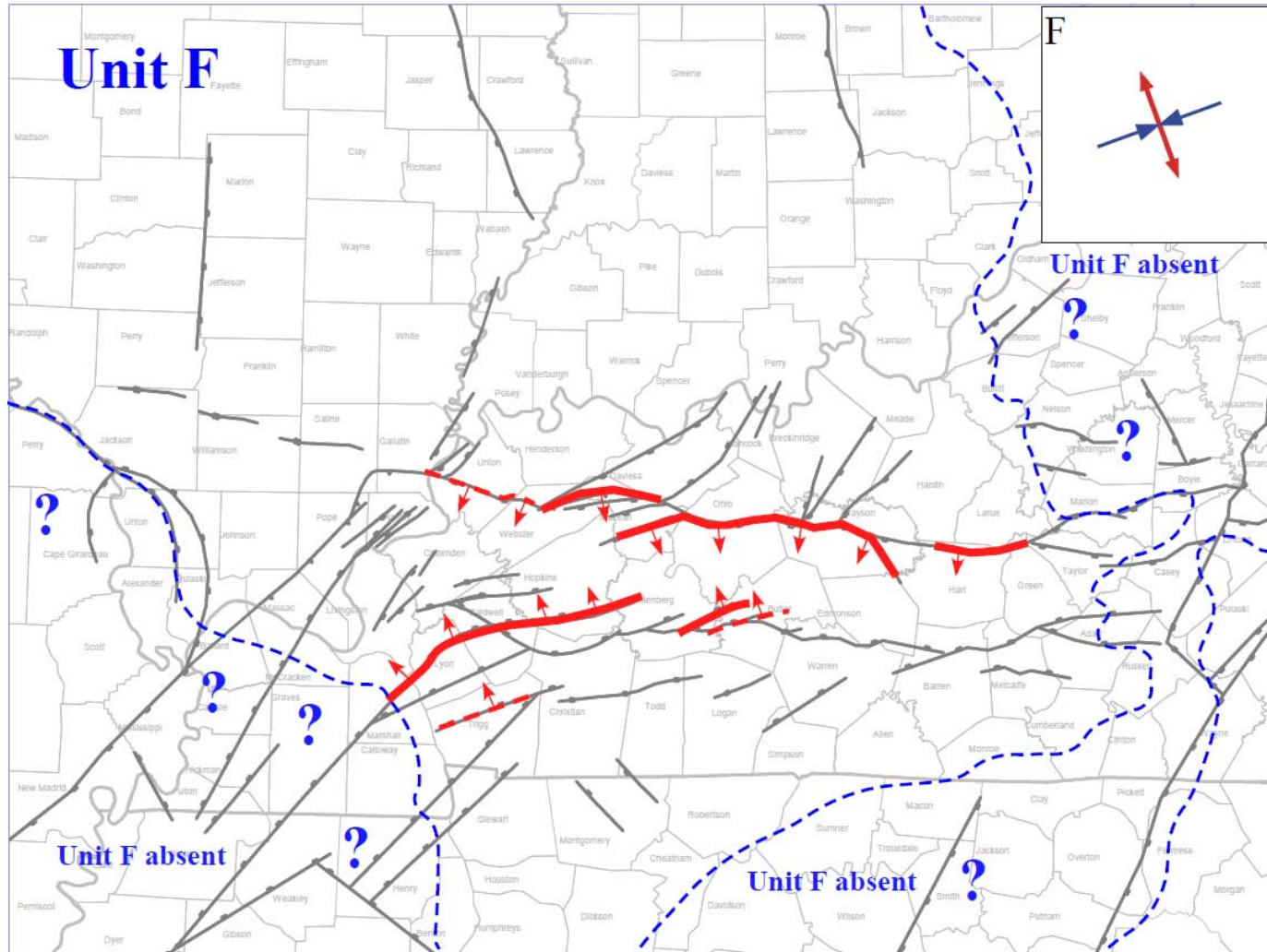


Figure 6.19 - Syndepositional fault movement and thickening directions of unit F (Early Silurian-Early Devonian). Interpreted regional compression (blue arrows) and extension (red arrows) directions shown in inset.

Similar to unit F before it, unit G is absent from over most of the Mississippi Valley Graben faults (removed by pre-Cretaceous erosion), and from the Jessamine and Nashville Domes (at the current exposure surface, [Figure 3.1](#)). From areas where unit G is still present, it is apparent that the northern end of the Eastern Boundary Fault of the Mississippi Valley Graben, the central Rough Creek Fault Zone, and the Pennyrile Fault System segments in Christian and Muhlenberg Counties, Kentucky, were all active during unit G deposition. Smaller syndepositional offsets are interpreted along the eastern end of the Cottage Grove Fault System, the unnamed fault system east of the Tabb Fault System in Hopkins and Caldwell Counties (along strike with the northern end of the Eastern Boundary Fault), as well as the Northwest and Southeast Stewart County faults ([Figure 3.2](#)).

The faults that were active during the deposition of unit G have east-to-west or east-northeast-to-west-southwest strike orientations. This would suggest a north-to-south extensional regime ([Figure 6.20](#), inset G₁). The active faults surrounding the Rough Creek Graben are not the opposing faults across the graben, however. The eastern Rough Creek Fault Zone was active north of the graben, and the western Pennyrile Fault System and northernmost Eastern Boundary Fault were active south of the graben. This may signify northeast-southwest shear strain southwestward across the axis of the Rough Creek Graben ([Figure 6.20](#), inset G₂), producing a local transtensional stress regime within the graben.

Contemporaneous with unit G deposition (Middle Devonian to Early Mississippian), the Acadian Orogeny was occurring in the central and northern Appalachians (Sloss, 1988; Thomas, 2006). The southward progression of the Acadian synorogenic clastic wedge has been interpreted to be a result of oblique (dextral) convergence and southward migration of the collision zone (Ettensohn, 1985, 1987; Ferrill and Thomas, 1988). This collision zone to the east of the Rough Creek and Mississippi Valley Grabens may have produced northeast-to-southwest compression within the study area ([Figure 6.20](#), inset G₂). Furthermore, if the oblique, dextral convergence of the Acadian Orogeny propagated stresses into the cratonic interior and along the preexisting trace of the Cambrian Mississippi Valley Graben/Rough Creek Graben/Rome Trough intracratonic

rift system, the east-west striking Rough Creek Graben may have acted as a releasing bend to these stresses ([Figure 6.21](#)), leading to apparent north-south extension. The large synorogenic clastic wedge produced during the Acadian Orogeny implies that a tectonic collision occurred along the New York Promontory (Thomas, 2006). Most of the New York Promontory is south of the axis of the northernmost part of the Rome Trough. With this geometry, dextral compression would apply more force south of the intracontinental fault system than north of it ([Figure 6.21](#)). The cratonward propagation of these stresses could have produced localized zones of tension, which could result in the observed fault movement along the eastern Rough Creek Fault Zone, as well as southwestward across the graben along the western Pennyrile Fault System ([Figure 6.20](#)).

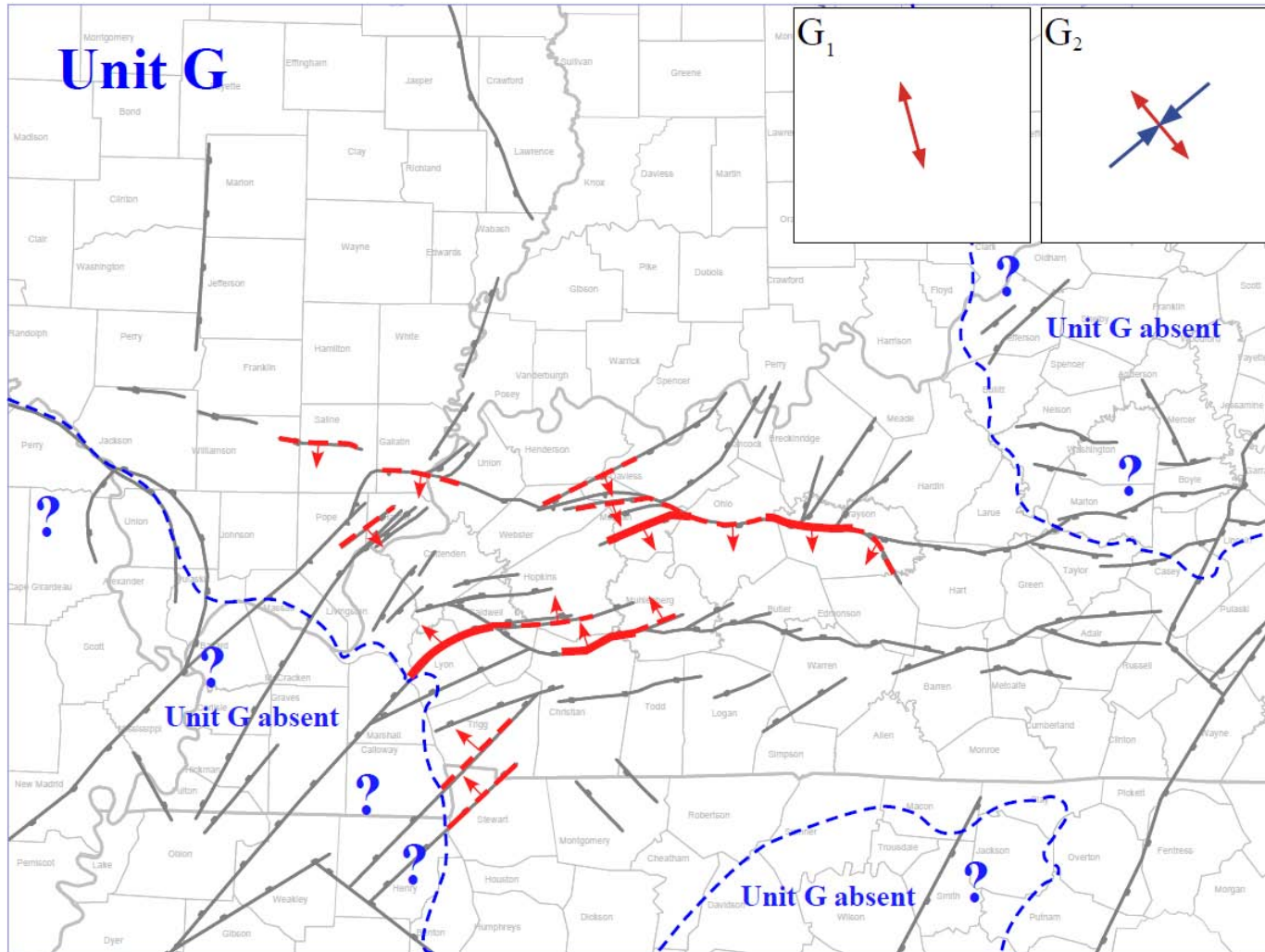


Figure 6.20 - Syndepositional fault movement and thickening directions of unit G (Middle Devonian-Early Mississippian). Interpreted regional compression (blue arrows) and extension (red arrows) directions shown in inset.

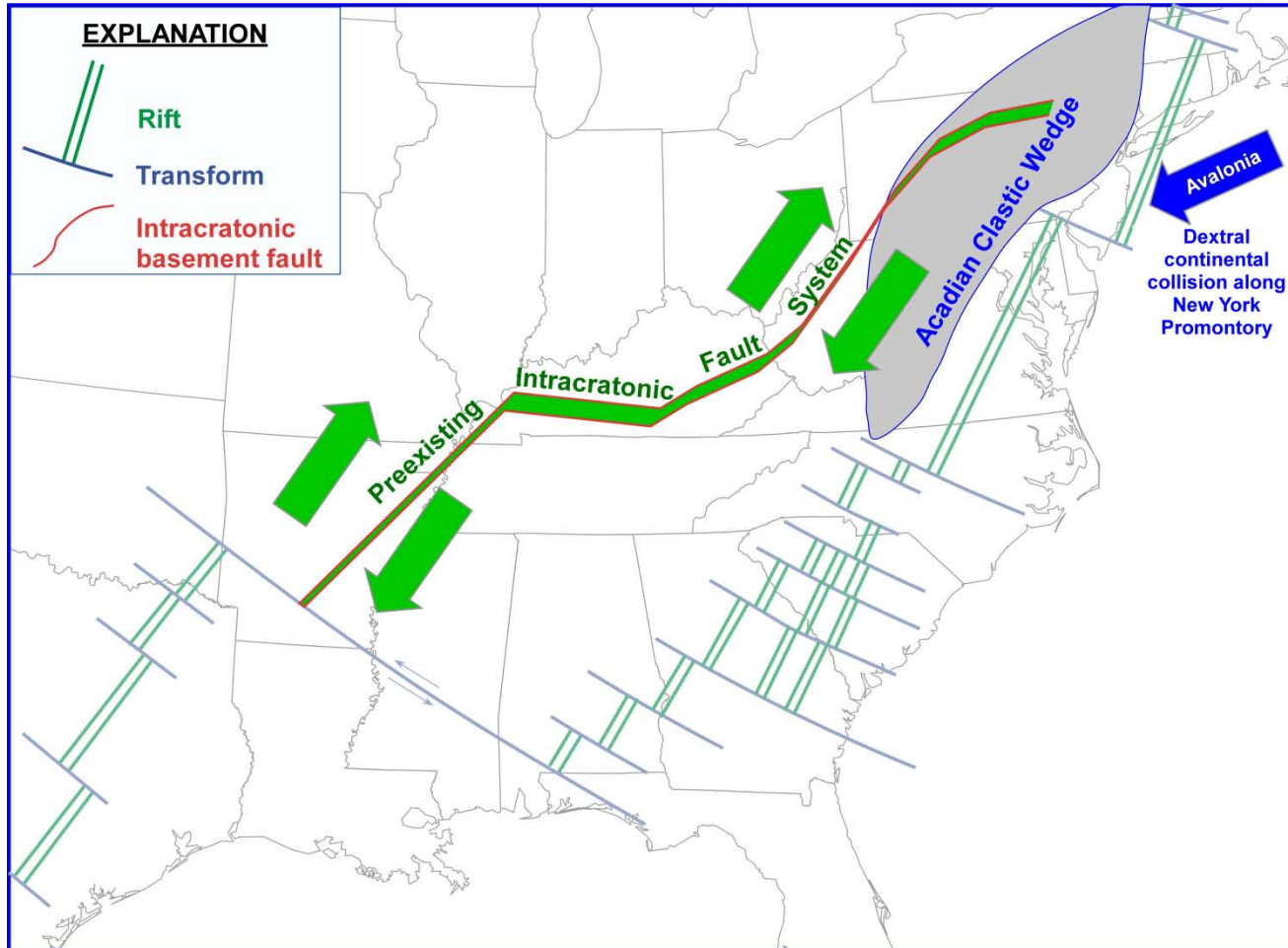


Figure 6.21 – Possible implications of dextral continental collision during the Acadian Orogeny (Ettensohn, 1985, 1987; Ferrill and Thomas, 1988) on the Mississippi Valley Graben-Rough Creek Graben-Rome Trough intracontinental fault system. Width of green polygon represents local ratio of extension-to-transfer along fault system. The locations of the Laurentian margin and clastic wedge from Thomas (1991, 2006).

6.5 Summary of the Evolution of the Intracratonic Rift System

At the end of the Precambrian, the supercontinent of Rodinia began to break up (Aleinikoff et al., 1995; Cawood et al., 2001; Thomas, 2006). Along the southeastern (current day) margin of Laurentia, volcanism within the Blue Ridge Rift between Laurentia and Amazonia evolved into the Mid-Iapetan Ridge as oceanic crust and Iapetus Ocean was initiated in the latest Precambrian. Early in the Early Cambrian, the southeastern rifted edge of Laurentia had developed into a passive margin (Sloss, 1988).

Around this time period, normal faulting and southeastward extension began in the Rome Trough (Webb, 1980; Harris et al., 2004). The northeastern part of the Rome Trough was flooded by at least the middle-Early Cambrian, as evidenced by the presence of deposits of the Early Cambrian Shady Dolomite (Webb, 1980). By the late-Early Cambrian, the Rome Trough, Rough Creek Graben, and the Mississippi Valley Graben had begun forming and were being filled with the Rome Formation and Reelfoot Arkose, coarse clastic detritus from the exposed crystalline basement. Sediment thickness patterns of the Reelfoot Arkose (unit A) suggest that the Mississippi Valley Graben flooded northward into the Rough Creek Graben. The absence of Reelfoot Arkose and a thin Eau Claire Formation along the Cincinnati Arch/Grenville Front area implies that these fault blocks acted as a topographic high until the early-Late Cambrian.

The location of the Rome/Rough Creek/Mississippi Valley rift system ([Figure 6.9](#)) appears to have been determined by a combination of two traditional rift grabens and an oblique transfer zone. The regional southeastward extension of continental rifting was more than likely the dominant force producing the Mississippi Valley Graben and northern part of the Rome Trough because these grabens are parallel to the active rift segments of the Blue Ridge Rift to the southeast ([Figure 6.22](#)). Between these two graben systems, the Rough Creek Graben and western Rome Trough in Kentucky and southernmost West Virginia acted as an oblique transfer zone (Thomas, 1993), separating the areas to the south and east of this intracratonic rift system from the tectonic blocks to the north and west of the rift. The steep nature of the graben-bounding Rough Creek Fault Zone (implying more strike-slip component to motion), the very thick synrift

deposits (much thicker than those of the Mississippi Valley Graben, northern Rome Trough, or Birmingham Graben (Thomas and Astini, 1999)), the presence of cross-graben splays of the Central Fault System (and others), and the fact that the Rough Creek Graben has an asymmetrical half-graben shape (Figure 6.23) perpendicular to the axis direction (Plates 20-23) as well as parallel to the graben axis (Plate 29) are all characteristics consistent with transtensional extension.

Most of the post-rift thermal subsidence calculated for the Rough Creek Graben occurred during the deposition of the Knox Supergroup (Section 5.2). An analysis of the thickness of the Knox-equivalent passive-margin interval along the entire trace of the Cambrian rift system reveals that the relative thickening proximal to the fault system is greatest at the northwestern end of the Alabama-Oklahoma Transform margin along the Southern Oklahoma Fault System at about 7,400 feet, around 6,000 feet thick in the Rough Creek Graben, about 4,500 feet thick in the southern Mississippi Valley Graben, and around 3,000 feet thick in the northeastern part of the Rome Trough (Johnson et al., 1988; Thomas and Astini, 1999). The differences in these thicknesses are roughly proportional to the degree of obliquity of the local graben system to the Cambrian rifting direction vector. The sections that had tectonic movements closer to pure transfer zones experienced more post-rift thermal subsidence than those sections with movement closer to pure extension (Southern Oklahoma Fault System > Rough Creek Graben > southern Mississippi Valley Graben > northern Rome Trough). Why transfer zones would be more prone to thermal subsidence is unclear, but may be related to the steep, through going (surface to mantle) nature of continental-scale strike-slip fault systems.

The relative dimensions of the Rough Creek Graben, Mississippi Valley Graben, and Rome Trough are similar to Rosendahl's (1987) "Rift Branches" of the East African Rift System, which also includes elements of oblique extension. Unlike the known volcanic shields that helped deviate the trace of the East African Rift system, the reasons for locations of the "bends" between the Mississippi Valley Graben, Rough Creek Graben, and Rome Trough are unknown, but may be from older, inherited structures deeper in the crust. Possible features associated with the rift bend locations are the South-Central Magnetic Lineament of Heigold and Kolata (1993) near the intersection of the

Mississippi Valley Graben and Rough Creek Graben, the Grenville suture zone along the Cincinnati Arch between the Rough Creek Graben and the Rome Trough ([Figure 3.2](#)), and the bend between the northeastern and western parts of the Rome Trough along-strike from the rift-transform which separates the Tennessee Embayment and the Virginia Promontory ([Figure 6.22](#)). If these rift transforms represent vertical planes of weakness and/or shear through the entire lithosphere (Thomas, 2009), then the sub-crustal extension of this transform into the craton may have influenced the growth and strike of the Rome Trough.

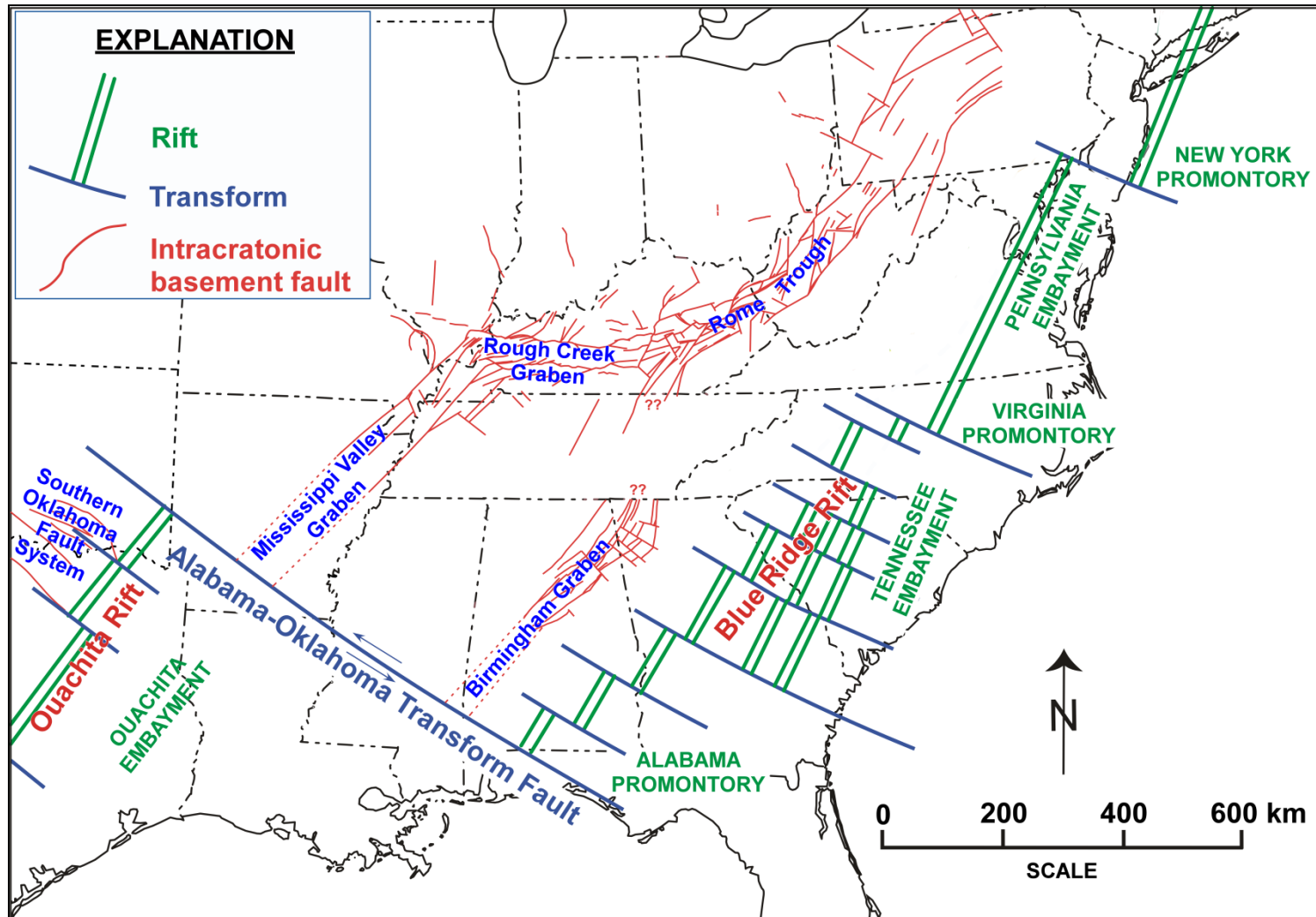


Figure 6.22 - Reconstructed southeast margin of Laurentia with basement faults of the Rome Trough/Rough Creek Graben/Mississippi Valley Graben in red. Rome Trough faults from Patchen et al. (2006). Cambrian rifted margin from Thomas (1991).

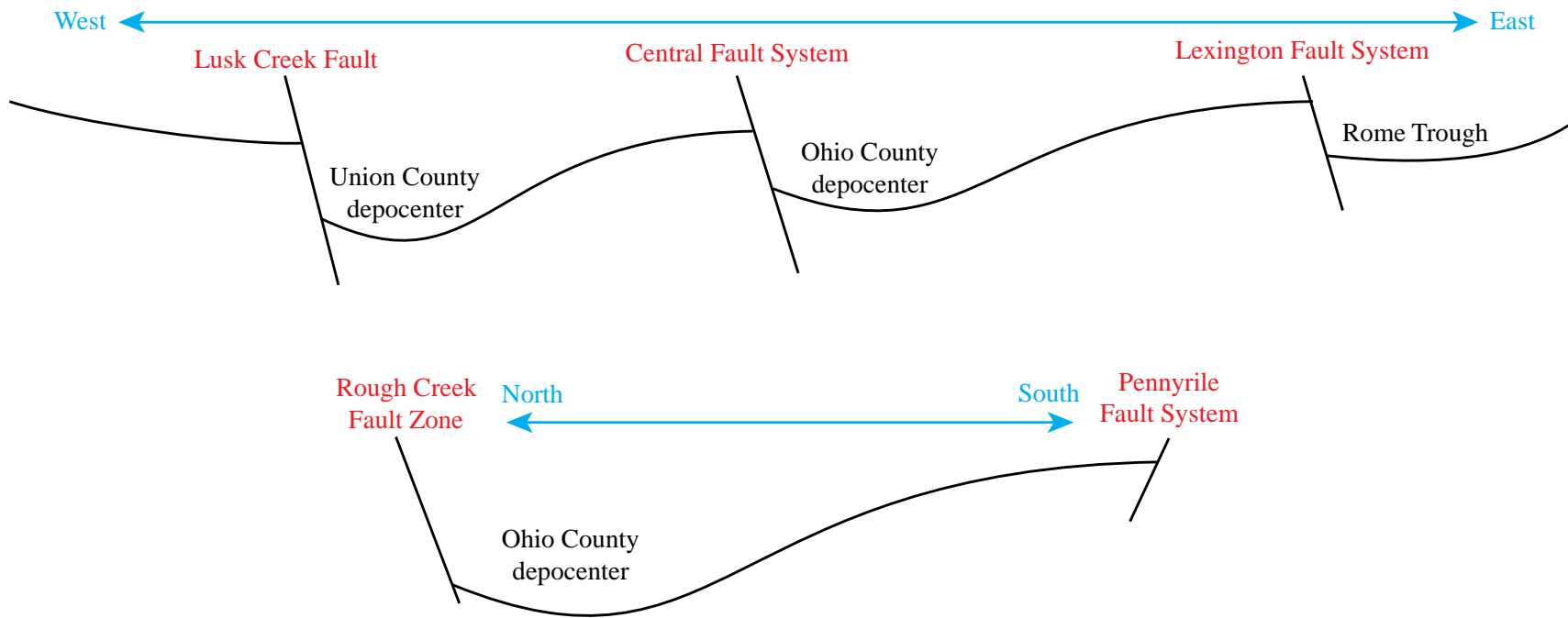


Figure 6.23 - Simplified profiles (not drawn to scale) of the Rough Creek Graben illustrating asymmetric shape in both strike (east-west) and dip (north-south) directions.

Just prior to the deposition of units A and B in the Mississippi Valley Graben and Rough Creek Graben, the zone of active Iapetan rifting along southern Laurentia began to shift from the Blue Ridge Rift to the Ouachita Rift in the Early Cambrian and produced the Alabama-Oklahoma Transform Fault ([Figure 6.22](#)) between the Laurentian craton and the Precordillera microplate (Thomas, 1985; Thomas, 1991). As the Precordillera microplate migrated to the southeast along the Alabama-Oklahoma Transform Fault during the Cambrian, the spreading center of the Ouachita Rift migrated southeastward across the southern edge of Laurentia (Thomas, 1991). Plutonic and volcanic rocks along the Southern Oklahoma Fault System ([Figure 6.22](#)) have been dated (Rb/Sr) at 539-530 Ma which suggest the Ouachita Rift and Alabama-Oklahoma Transform Fault were active in eastern Oklahoma during the Early Cambrian (Ham et al., 1964; Thomas, 1991; Thomas and Astini, 1999). As new oceanic crust was produced at the spreading center, the Ouachita mid-ocean ridge migrated southeastward from the Southern Oklahoma Fault System. Undeformed sediments of the Knox Supergroup overlie the continental crustal margin in southern Alabama along the Alabama-Oklahoma Transform Fault and indicate that the spreading center of the Ouachita mid-ocean ridge was east of the Birmingham Graben by earliest-Late Cambrian (Thomas and Astini, 1999). Assuming a constant velocity, the spreading center of the Ouachita Rift crossed the 295 km to beyond the eastern boundary fault of the Mississippi Valley Graben around 512 ± 14 Ma. The parts of the Alabama-Oklahoma Transform Fault northwest of the spreading center became an inactive, continent-ocean passive margin ([Figure 6.24](#)). Therefore, after the active spreading center of the Ouachita Rift passed the far (southeastern) edge of the Mississippi Valley Graben, the two sides of that graben were “welded” in place by the new oceanic crust to the southwest, thereby limiting further southeastward tectonic extension of the Mississippi Valley Graben along that margin.

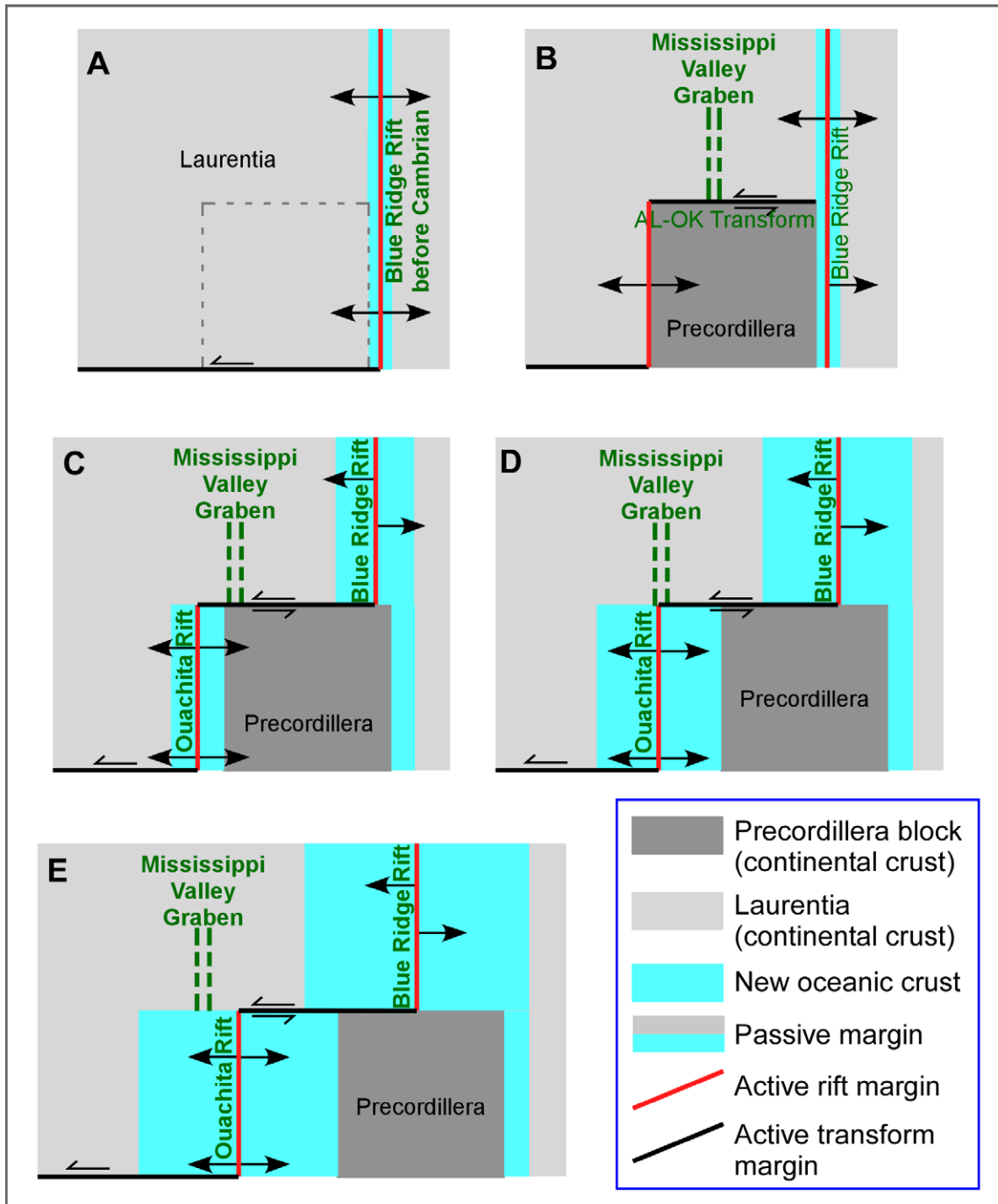


Figure 6.24 - Block diagrams illustrating evolution (A to E) of Alabama-Oklahoma Transform from active to passive margin as the Precordillera plate separated from Laurentia during the Cambrian. Points along Alabama-Oklahoma Transform northwest of the active spreading center are inactive and under the same stress regime as the rest of southern Laurentia.

As regional sea level rose throughout the Cambrian (Sloss, 1988; Haq and Schutter, 2008), deposition shifted from coarse clastic sediment to the alternating carbonate and clastic mudstones of the Conasauga Group and the Eau Claire Formation. In the Middle Cambrian during the deposition of the Eau Claire Formation, the average strike of the faults which were active (indicated by abrupt stratigraphic thickness changes) changed, suggesting that the regional stress field had also changed. If the separation of the Precordillera block from Laurentia (Thomas, 1991) was oblique (transtensional), this north-to-south extension (in addition to the sinistral transfer along the Alabama-Oklahoma Transform) may have contributed to the rotation of stresses during the deposition of the Eau Claire Formation. The calculated time of the Ouachita mid-ocean ridge spreading center passing the southeastern edge of the Mississippi Valley Graben (512 ± 14 Ma) partly coincides with the time of the clockwise rotation of the regional stress field interpreted from fault activity during the deposition of unit B. McConnell and Gilbert (1986) calculated 17 to 21 km of northeast-southwest extension during the Early Cambrian across the Southern Oklahoma Fault System, indicating a possible component of transtension along the Alabama-Oklahoma Transform Fault. If this crustal transtension (northwest-southeast primary extension, northeast-southwest secondary extension direction) persisted until the Middle Cambrian, it may have contributed to the component of north-to-south extension that produced the rotation of stresses interpreted during the deposition of unit B.

One additional possible cause of the observed rotation of maximum extension during the deposition of unit B was the tectonic trajectory of Laurentia with respect to the Baltica and Amazonia plates, from which it was rifting during the Cambrian. Using paleomagnetic apparent polar wander data Torsvik et al. (1996) calculated as much as 180 degrees of counterclockwise rotation of Laurentia during and after the breakup of Laurentia. If the Precordillera microplate did not rotate with Laurentia as the rifting progressed (or rotated at a slower rate), this would produce a component of north-south tension across the study area.

Using stratigraphic thicknesses, fault offsets, and basin modeling (subsidence) calculations, it is apparent that the Mississippi Valley Graben, Rough Creek Graben, and

Rome Trough were tectonically active and extending the continental crust of southeastern Laurentia during the Early and Middle Cambrian. With all three of these graben structures active at the same time and mechanically connected (see Section 6.2), it is probable that they all formed as a result of the same tectonic forces. A regional analysis of the locations of Cambrian-aged faults and rift segments (Figure 6.22) suggests a close relationship between the graben structures of this study and what would become the southern edge of the post-Rodinia continent of Laurentia (Blue Ridge Rift, Alabama-Oklahoma Transform Fault, and Ouachita Rift). The strikes of the Mississippi Valley Graben and the northeastern Rome Trough are parallel to the “successful” Blue Ridge and Ouachita rifts, signifying similar spreading directions (Figure 6.22). During Cambrian rifting, the Rough Creek Graben and the southwestern part of the Rome Trough acted as an oblique transfer zone resulting in transtensional faulting in those areas. As the obliquity increases with respect to the regional extension direction, the complexity of the transtensional fault patterns increases. Evidence for this transtensional motion is apparent in the Rough Creek Graben from the steep nature of the graben-bounding faults (implying more strike-slip component to motion), the cross-graben splays of the Central Fault Zone, and extremely thick accumulation of synrift deposits. The varying fault complexity along the axial trend of the Mississippi Valley Graben / Rough Creek Graben / Rome Trough system can be observed in Figure 6.22. Variations in the proportion of pure strike-slip to pure extensional motions through time produced the rotations in the σ_1 and σ_3 stress fields discussed in Section 6.4. By the Late Cambrian, rifting in the region had ceased and craton-wide passive-margin carbonate sedimentation followed during the deposition of the Knox Supergroup.

The pre-existing faults within the Rough Creek and Mississippi Valley Grabens from the breakup of Laurentia continued to be active (at least episodically) through at least the Early Mississippian. Different fault sets moved at different times in response to the changing regional stress field, as well as from the differential compaction of buried synrift strata. Regional fault movement decreased throughout the deposition of the post-rift strata of units C, D, and E, but the extension direction remained fairly constant north-to-south. Beginning with unit F in the Silurian, the regional σ_1 and σ_3 directions of stress started to rotate counterclockwise around the study area. During the deposition of unit G,

tectonic influence from the Acadian oblique continental collision to the northeast produced northeast-southwest compression and slight dextral shear along the Rome Trough/Rough Creek Graben/Mississippi Valley Graben intracratonic rift system.

7 CONCLUSIONS

Detailed subsurface stratigraphic mapping and analysis of numerous and diverse geophysical data sets were used to examine the geology and possible mechanical and kinematic connections between three deep graben systems in Kentucky; the southwestward striking Mississippi Valley Graben under the Jackson Purchase, the westward striking Rough Creek Graben in western Kentucky, and the east-northeastward oriented Rome Trough under central and eastern Kentucky ([Figure 6.9](#)). These data sets include stratigraphic “tops” interpreted from the geophysical logs and well cuttings descriptions from 1,764 wells, interpretations of 106 seismic profiles, aeromagnetic and gravity survey analysis, and mapped surface geology and structures. Eight regional subsurface horizons encompassing seven stratigraphic intervals resolvable in both geophysical well logs and reflection seismic profiles were defined and interpreted across parts of Kentucky, Ohio, Indiana, Illinois, Missouri, and Tennessee. These stratigraphic interpretations were then combined and incorporated into eight regional structure maps, seven isopachous maps, and across twelve cross sectional displays. This permitted a direct comparison between the stratigraphy of the northern Mississippi Valley and Rough Creek Grabens in the Illinois Basin to the Cambrian stratigraphy within the Rome Trough of the Appalachian Basin, as well as the locations and relative offsets of the framework of faults that connect these three features. By examining geologic growth across fault systems for different stratigraphic units, the relative activity of those fault systems through time can be determined. Finally, analyzing which collections of fault system segments were active at different times allows a determination of paleo-stresses and the tectonic evolution of the intracratonic rift system between the end of the Precambrian and the Early Mississippian.

The development of the Rough Creek Graben and Mississippi Valley Graben through time reflects the history of regional tectonic forces applied to the faults formed in the Late Proterozoic to Early Cambrian during the breakup of Rodinia. This prolonged history includes the time of continental rifting and at least the next 155 million years until at least the Early Mississippian. Subsidence calculations from Cambrian depocenters within the Rough Creek Graben indicate that active tectonic subsidence ended around

502 Ma (latest-Middle Cambrian) and post-rift thermal subsidence continued until around 485 Ma (latest-Late Cambrian).

These three regional graben structures vary greatly in depth, boundary fault geometries, and in the strike of axes. All of these dissimilarities can be explained by relative obliquity to the southeastward tectonic extension vector during the Cambrian. The Mississippi Valley Graben and the northeastern part of the Rome Trough are close to perpendicular to the Early Cambrian vector of separation between Laurentia and Amazonia (evident from the strike of the Alabama-Oklahoma Transform fault and the general strike of the southern Blue Ridge Rift). The Rough Creek Graben and the western part of the Rome Trough acted as an oblique transfer zone resulting in transtensional faulting. More than 17,000 feet of synrift Middle Cambrian Reelfoot Arkose and 10,000 feet of Middle-Late Cambrian Eau Claire Formation are present within the Rough Creek Graben.

Although the major graben-bounding fault systems originated from the initial southeastward tectonic extension and breakup of Laurentia, an analysis of active fault system segments suggests an additional, north-south extensional component during the latest-Middle Cambrian to the earliest-Late Cambrian. This fault activity was a product of the rotation of the regional tectonic stress field caused by the migration of active spreading from the Blue Ridge Rift to the Ouachita Rift and the subsequent separation of the Precordillera microplate from Laurentia.

Thermal subsidence modeling using measured and interpreted stratigraphic thicknesses indicates accelerated subsidence during the deposition of the Knox Supergroup (Late Cambrian to Early Ordovician) within and adjacent to the Rough Creek Graben. An analysis of Knox and equivalent passive-margin units suggests a correlation between tectonic transfer zones (such as the Rough Creek Graben) and elevated amplitudes of thermal subsidence with respect to purely extensional graben or rift segments.

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