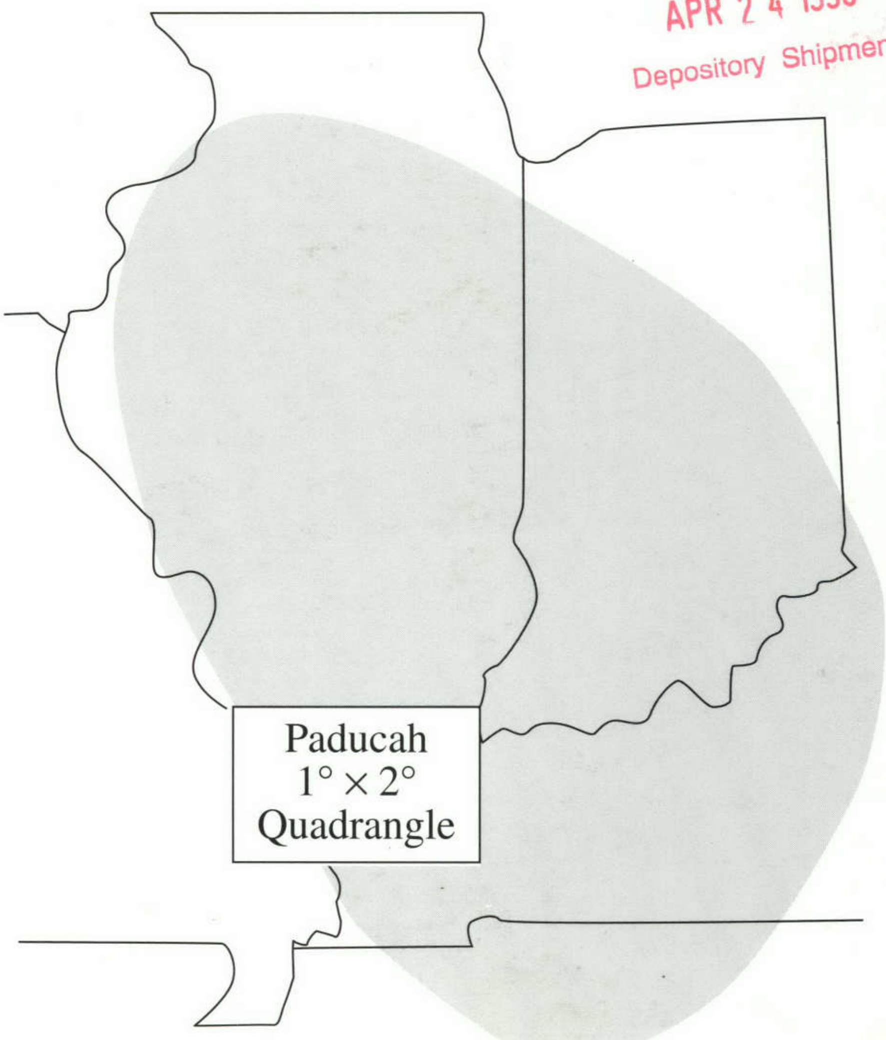
Bedrock Geology of the Paducah 1°×2° CUSMAP Quadrangle, Illinois, Indiana, Kentucky, and Missouri

U.S. GEOLOGICAL SURVEY BULLETIN 2150–B



Cover. Index map showing the approximate location of the Illinois Basin (shaded area) and the location of the Paducah 1°×2° CUSMAP quadrangle

Bedrock Geology of the Paducah 1°×2° CUSMAP Quadrangle, Illinois, Indiana, Kentucky, and Missouri

By W. John Nelson

THE PADUCAH CUSMAP QUADRANGLE: RESOURCE AND TOPICAL INVESTIGATIONS
Martin B. Goldhaber, *Project Coordinator*

U.S. GEOLOGICAL SURVEY BULLETIN 2150–B

A joint study conducted in collaboration with the Illinois State Geological Survey, the Indiana Geological Survey, the Kentucky Geological Survey, and the Missouri Division of Geology and Land Survey

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Bedrock Geology of the Paducah 1°×2° Quadrangle, Illinois, Indiana, Kentucky, and Missouri

By W. John Nelson[1]

ABSTRACT

The Paducah 1°×2° quadrangle (hereafter referred to as the Paducah quadrangle) encompasses the eastern flank of the Ozark dome, the southern end of the Illinois Basin, and the northern end of the Mississippi Embayment. Resting on Proterozoic basement, sedimentary rocks of Cambrian through Permian age in the Illinois Basin and Ozark dome are overlapped by weakly lithified Cretaceous, Paleocene, Eocene, and Pliocene strata in the embayment. This is one of the most intensely faulted areas of the North American Midcontinent. A Proterozoic crustal terrane boundary (coincident with part of the Ste. Genevieve fault zone) and a failed intracratonic rift (Reelfoot rift and Rough Creek graben) have been reactivated repeatedly under various stress fields from Proterozoic through late Tertiary times.

INTRODUCTION

The Paducah quadrangle encompasses some of the most diverse and complex geology in the North American Midcontinent. Overlying a Cambrian rift system, the Paducah quadrangle has undergone recurrent tectonic deformation throughout Phanerozoic time. Immediately to the south is the New Madrid seismic zone, scene of the Midcontinent's most intense earthquake activity.

Ultramafic intrusive and explosive features, including the enigmatic Hicks dome, are within the quadrangle. The report area contains the largest fluorspar and tripoli deposits in the United States and important resources of coal, petroleum, and limestone.

This report interprets the geologic history of the Paducah quadrangle. It focuses on depositional and tectonic evolution, particularly on tectonic events that influenced sedimentation. Events are discussed in historical fashion, applying the sequences of Sloss and others (1949) and Sloss (1963). Another report (Nelson, 1995) emphasizes map compilation, stratigraphic nomenclature, and correlation of units. That report also contains descriptions of map units and structural features.

This work is a synthesis of previous mapping and research combined with my own observations and interpretation. The bedrock geologic map (plate 1) was compiled from published and unpublished geologic maps by dozens of authors. Although some source maps date as far back as 1920, most of the area has been geologically mapped within the last 25 years. My personal contribution includes mapping (as sole author or coauthor) more than a dozen quadrangles in southern Illinois. Also, I have conducted topical studies of most of the major fault systems in the region along with stratigraphic studies, mainly of Mississippian and Pennsylvanian rocks.

Synthetic mapping such as this yields a wealth of new insights on depositional and tectonic history of the region. In especially rapid flux are ideas on late Paleozoic sedimentation and on post-Cretaceous tectonism. Programs such as CUSMAP (Conterminous United States Mineral Assessment Program) force State survey geologists to break the constraints of State boundaries and politics. Many ideas written herein will be obsolete by the time this is published. The saying that "every geologic map is a progress report," was never more true than with this project.

REGIONAL GEOLOGIC SETTING AND STRUCTURAL OVERVIEW

The Paducah quadrangle lies in a tectonically unstable part of the interior craton of North America. Portions of three major structural provinces are within the quadrangle (fig. 1). On the west, the Ozark dome was a persistent positive area throughout Paleozoic time and stands as a plateau today. Ordovician through Devonian strata, largely carbonates, dip gently eastward and are transected by many northwest- and northeast-trending fault zones. The southern part of the

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Illinois Basin, a "typical" interior cratonic basin (Leighton and others, 1991), is in the central and eastern part of the report area. Surface bedrock in the basin is mostly Mississippian and Pennsylvanian carbonate and siliciclastic rock. The northern end of the Mississippi Embayment, an extension of the Gulf Coastal Plain, extends into the Paducah quadrangle. Weakly lithified Cretaceous and Tertiary siliciclastic strata are found in the embayment.

Among structural features within the report area, several long-lived fault systems (fig. 1) controlled much of the region's geologic history. The Ste. Genevieve fault zone on the northwest separates the Ozark dome from the Illinois Basin and exhibits as much as 4,000 ft (1,200 m) of vertical separation. The Ste. Genevieve may have originated along the margin of a Proterozoic orogen (Heigold and Kolata, 1993). The fault zone was active during the Middle and Late Ordovician (reverse faulting), Middle and Late Devonian (normal faulting), Late Mississippian and Early Pennsylvanian (reverse faulting), and post-Pennsylvanian (reverse and probably sinistral strike-slip faulting).

A dogleg-shaped Cambrian failed rift underlies the southeastern part of the quadrangle. The rift comprises two segments, the northeast-trending Reelfoot rift and the east-trending Rough Creek graben (fig. 1). The Lusk Creek fault zone and Rough Creek–Shawneetown fault system mark the northwestern and northern margins of the rift, and the Tabb and Pennyrile fault systems mark part of the southeastern and southern margins. The rift area subsided rapidly throughout Paleozoic time, serving as a "depocenter" for the Illinois Basin (Klein and Hsui, 1987; Kolata and Nelson, 1991a, 1991b). Boundary faults were reactivated periodically. Post-Pennsylvanian displacements along the Rough Creek–Shawneetown split the Illinois Basin into two unequal parts: the broad but shallow Fairfield Basin to the north and the narrow but deep Eagle Valley–Moorman syncline to the south. Repeated movements shattered the junction area; alkalic igneous activity produced Hicks dome, and fluorspar and related minerals were emplaced. Beginning in Cretaceous time, the Reelfoot rift area again subsided, forming the Mississippi Embayment. Northeast-trending faults were rejuvenated with dextral shear in and near the New Madrid seismic zone.

GEOLOGIC HISTORY

PRECAMBRIAN

Most, if not all of the major structural features of the Paducah quadrangle were established during the Precambrian Era. Precambrian events here are dimly known because not a single Precambrian outcrop or borehole penetration exists in the Paducah quadrangle. Nevertheless, significant portions of the Precambrian history of the area can be reconstructed. That history is based on geophysical data, especially published and industry seismic reflection profiles and gravity and magnetic maps, and also on inferences drawn from neighboring areas where Precambrian rocks crop out or have been drilled.

Most boreholes that have reached Precambrian rocks north of the Paducah quadrangle encountered granite and rhyolite similar to that exposed in the St. Francois Mountains of southeastern Missouri (Sargent, 1991a). The St. Francois Mountains are part of the eastern granite-rhyolite province, which ranges in age from approximately 1,480 to 1,380 Ma (Kisvarsanyi, 1981; Bickford and others, 1986). In the past, many geologists presumed that the entire Illinois Basin area lay in the eastern granite-rhyolite province. That view has been challenged by new interpretations based mainly on geophysical studies.

Sims and Peterman (1986) delineated the Central Plains orogen, an Early Proterozoic fold belt that extends eastward from northeastern Colorado across Kansas and Nebraska into Missouri (fig. 2). The orogen is composed of metamorphic (mainly amphibolite facies) and granitic rocks that range in age from 1,800 to 1,630 Ma. Sims and Peterman did not extend the orogen east of Missouri, but it may continue into Illinois and may underlie part of the eastern granite-rhyolite terrane. Xenoliths of biotite schist and biotite gneiss reportedly occur in a diatreme near Farmington, Mo., about 50 mi (80 km) west of the Paducah quadrangle (Tarr and Keller, 1933). The xenoliths must have come from older rocks (Central Plains orogen?) underlying the granite and rhyolite, which are near the surface at Farmington.

Published reflection seismic data (Sexton and others, 1986; Pratt and others, 1989; Heigold, 1991; Pratt and others, 1992) and proprietary seismic profiles show strong, coherent Precambrian layering beneath a large area of Illinois, Indiana, and western Ohio. Pratt and others (1992) informally named these layers the Centralia sequence. The Centralia sequence underlies the northern part of the Paducah quadrangle and thickens northward. It extends to 11 mi (18 km) below the surface in east-central Illinois (Heigold, 1991, p. 257–259), and is 4 to 8 mi (6 to 12 km) thick along the COCORP seismic profile across southern Indiana and Illinois (Pratt and others, 1992). Downlap and truncation of layering suggest that the Centralia sequence may consist at least partly of sedimentary rocks. Apparent grabens and half-grabens imply deposition in an extensional tectonic regime. Because the Centralia sequence is either overlain by, intruded by, or intercalated with rocks of the eastern granite-rhyolite province, the Centralia sequence can be no younger than 1,480–1,380 Ma (Pratt and others, 1992).

The southern limit of the Centralia sequence coincides with a region of higher Bouguer gravity and magnetic intensity values. Heigold and Kolata (1993) inferred a Proterozoic crustal boundary separating layered Proterozoic rocks on the north from denser, more magnetic, "altered lower crust" on the south. The inferred boundary trends east-southeast from

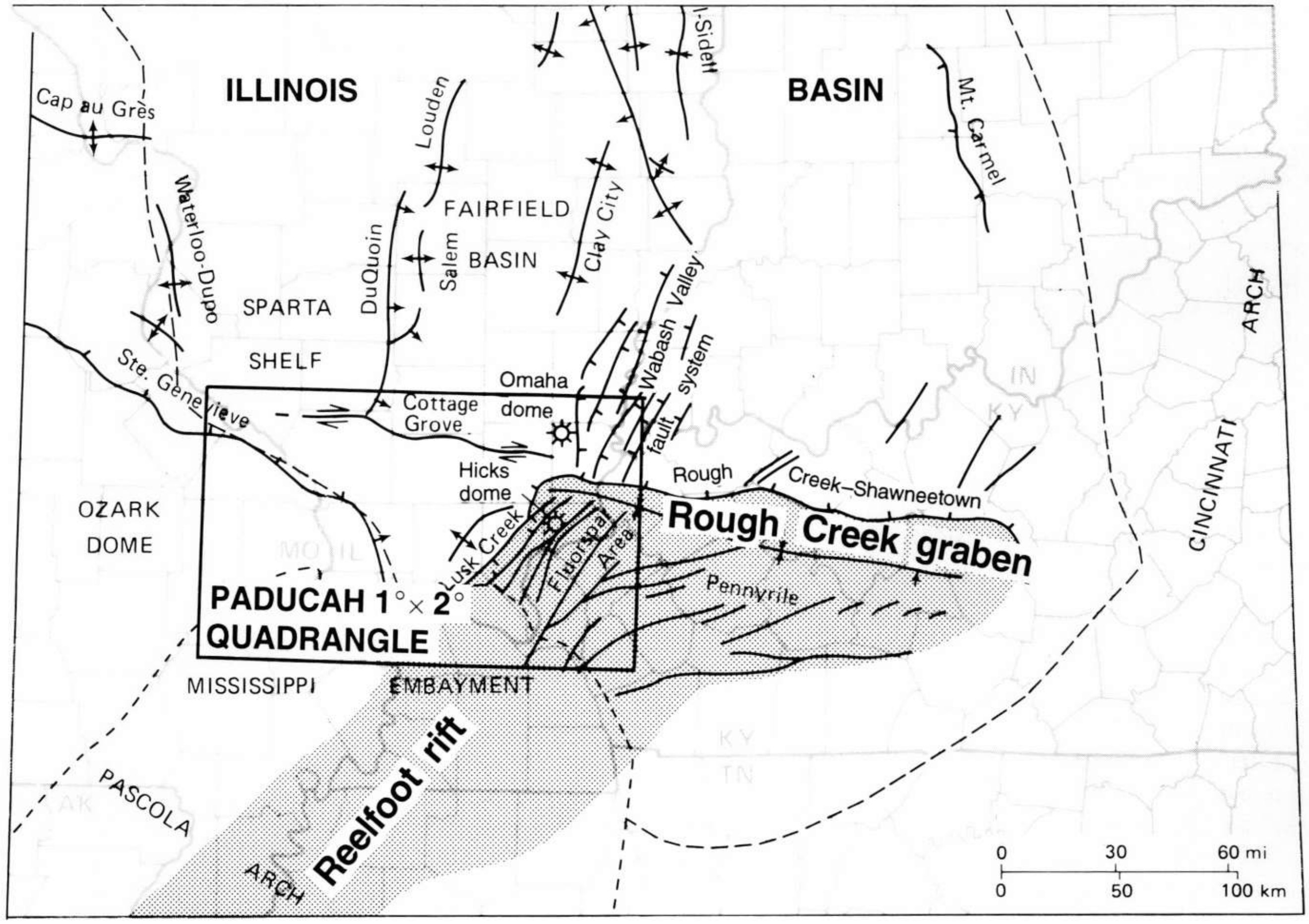


Figure 1. Structural setting of the Paducah quadrangle.

eastern Missouri across southern Illinois, through the Paducah quadrangle into western Kentucky (fig. 2). Part of the boundary coincides with the Ste. Genevieve fault zone. It also corresponds, in part, to the 38th Parallel lineament of Heyl (1972). The crustal boundary could be an eastward extension of the northern, convergent margin of the Central Plains orogen (Heigold and Kolata, 1993).

A northwesterly structural grain is prevalent throughout Missouri and in parts of adjacent States (fig. 3). Strong northwest-trending magnetic (Zietz and others, 1984) and gravity (Hildenbrand and others, 1982) anomalies in Missouri parallel fault zones at the surface (McCracken, 1971; Kisvarsanyi, 1984). The northwest-trending grain was attributed by Sims and Peterman (1986) to the Central Plains orogen. Northwest-trending faults and geophysical anomalies extend across the St. Francois Mountains, consistent with the idea that the eastern granite-rhyolite terrane is a veneer overlying the Central Plains orogen. Faults of the Central Plains orogeny may have been reactivated, displacing granite-rhyolite and Paleozoic sedimentary cover.

A new Proterozoic province recently was discovered east of the Paducah quadrangle. The East Continent rift basin contains a thick succession of red to gray lithic sandstone and intercalated basalt in eastern Indiana, western Ohio, and central Kentucky (fig. 2). Borehole samples of rocks from the rift basin are radiometrically dated as 1,380 to 1,000 Ma. Younger (990 to 880 Ma) metamorphic rocks of the Grenville province apparently were thrust westward over the East Continent rift basin along the Grenville front (Drahovzal and others, 1992). The westward extent of the East Continent rift basin is not defined. It does not equal the Centralia sequence, which, as mentioned above, cannot be younger than the eastern granite-rhyolite province (ca. 1,380 Ma).

In summary, the following Precambrian events took place in the Paducah region:

1. The Central Plains orogeny took place at about 1,800 to 1,630 Ma. Metamorphic and granitic rocks on the southwest were driven against a layered terrane (Centralia sequence) to the northeast. Alternatively, the Centralia sequence could represent foreland deposits coeval with the Central Plains orogeny.
2. The eastern granite-rhyolite terrane (1,480 to 1,380 Ma) was intruded into and extruded upon older rocks.

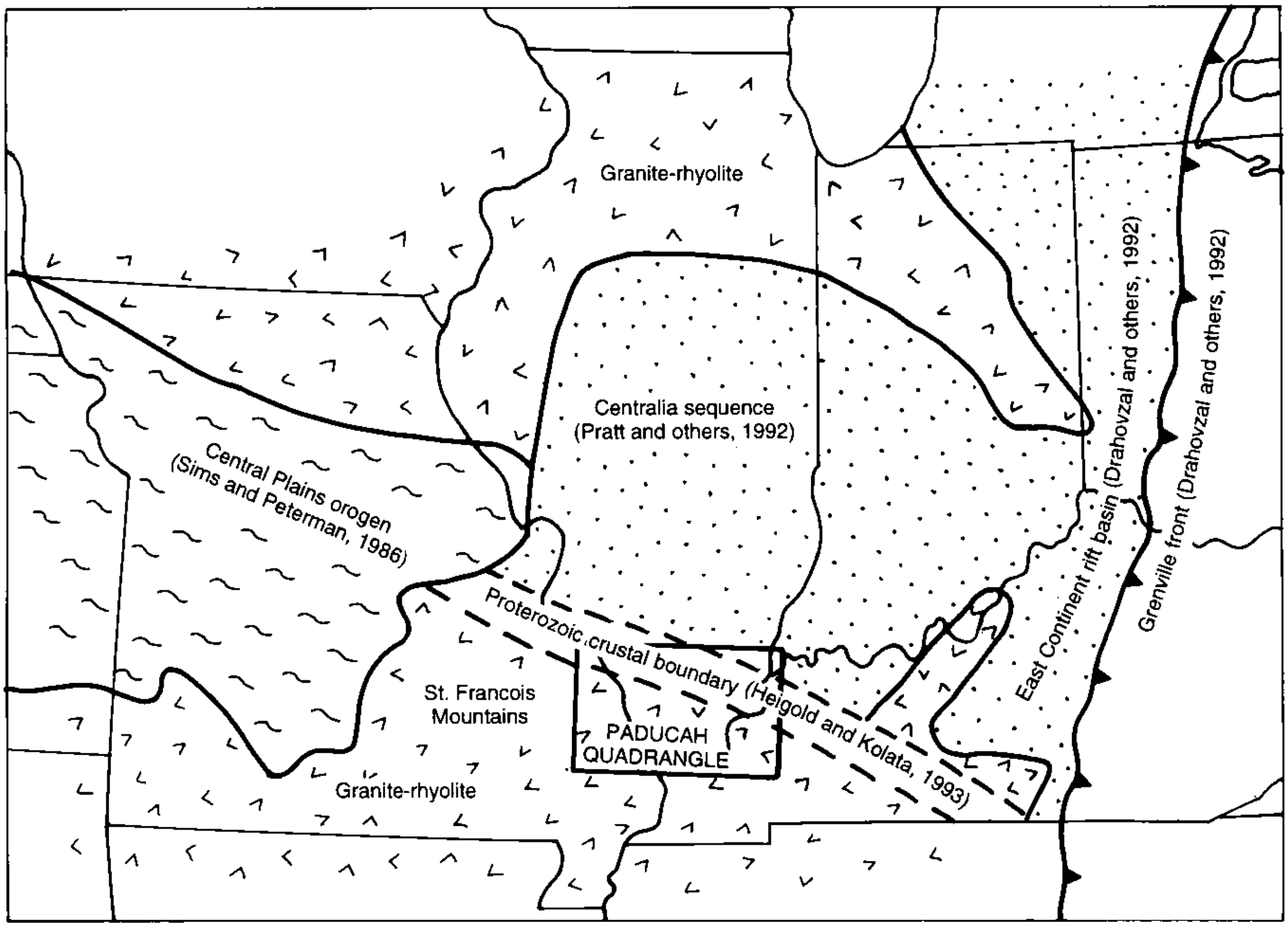


Figure 2. Precambrian geology of the Paducah quadrangle and surrounding area.

3. The East Continent rift basin developed east of the Paducah quadrangle at about 1,380 to 1,000 Ma.
4. The Grenville orogeny occurred at about 990 to 880 Ma; metamorphic rocks were thrust westward over the East Continent rift basin.

SAUK SEQUENCE

The informally named Sauk sequence (Sloss and others, 1949; Sloss, 1963) in the study area comprises rocks of Cambrian and Lower Ordovician (Canadian) age (fig. 4). In this report, strata filling the Reelfoot rift and Rough Creek graben are included in the Sauk sequence, although the rift-filling rocks likely belong to a separate sequence.

RIFT-FILL STRATA

The northeast-trending Reelfoot rift and the east-trending Rough Creek graben (fig. 1) form a dogleg-shaped trough known from well penetrations, gravity and magnetic surveys (Ervin and McGinnis, 1975; Soderberg and Keller, 1981; Hildenbrand and others, 1982; Hildenbrand, 1985), and published and proprietary reflection seismic data (Howe and Thompson, 1984; Bertagne and Leising, 1991). Seismic profiles indicate complex grabens outlined by high-angle, listric normal faults that penetrate seismically transparent crystalline "basement" rocks. The grabens are filled with thousands of feet of layered rocks.

The northwest margin of the Reelfoot rift is the Lusk Creek fault zone and its southwestward extension beneath the Mississippi Embayment (fig. 1). The northern margin of the Rough Creek graben is the Rough Creek–Shawneetown fault system. The curving southeastern margin of the graben follows the Tabb fault system and part of the Pennyrile fault system. Displacement on the northern boundary fault is as great as 8,000 ft (2.4 km) near the east edge of the Paducah quadrangle (Bertagne and Leising, 1991). Displacement decreases westward and is probably less than 3,000 ft (1 km) along the Lusk Creek fault zone. Cambrian displacement along the Pennyrile and Tabb fault systems in the Paducah quadrangle is roughly 5,000 ft (1 1/2 km). The Reelfoot–Rough Creek rift appears to comprise several paired half-grabens connected by "accommodation zones." The modern East African rift has similar configuration (Kolata and Nelson, 1992).

Layered rocks below the Eau Claire Formation (Upper Cambrian) attain a maximum thickness of more than 9,000 ft (2.7 km) in the Rough Creek graben at the east edge of the Paducah quadrangle (Sargent, 1991b). The composition of these rocks is little known because only a handful of wells (none in the Paducah quadrangle) have penetrated them. East of the quadrangle, a well in the Rough Creek graben in Grayson County, Kentucky, encountered a thick marine shale succession beneath the Eau Claire. The shale contains thin arkosic streaks and a few thin beds of oolitic limestone. A trilobite recovered from the shale indicated Middle Cambrian age (Schwalb, 1982). The well did not reach crystalline basement.

LAMOTTE OR MOUNT SIMON SANDSTONE

Outside of the Reelfoot rift and Rough Creek graben, the basal unit of the Sauk sequence is a transgressive sandstone called the Lamotte Sandstone in Missouri and the Mount Simon Sandstone in Illinois and Kentucky. Deep boreholes in the Paducah quadrangle partially penetrate this unit, showing it to be fine- to coarse-grained, cross-bedded sandstone, commonly arkosic near the base and becoming more quartzose upward (Sargent, 1991a). The Lamotte or Mount Simon thickens from less than 500 ft (150 m) at the northwest corner of the Paducah quadrangle to about 3,000 ft (900 m) in southernmost Illinois (Sargent, 1991b). The sandstone overlaps an irregular, hilly topography on granite-rhyolite "basement," and is thin or absent overlying buried hills on the Precambrian surface. Within the rift, the Mount Simon has not been differentiated from older layered rocks.

BONNETERRE OR EAU CLAIRE FORMATION

The Bonneterre Formation is a unit of limestone and dolomite overlying the Lamotte Sandstone on the Ozark dome in Missouri, whereas the Eau Claire Formation is a unit of thin-bedded, shaly, fossiliferous sandstone overlying the Mount Simon in the subsurface in Kentucky and Illinois. These two units are facies equivalents (Buschbach, 1975). In the southeastern part of the Paducah quadrangle, the interval is predominantly limestone, some of which is silty to sandy and contains interbeds of calcareous shale and siltstone. Northwestward, the interval becomes dolomitic, grading to more than 80 percent dolomite at the northwest corner (Sargent, 1991c). The siliciclastic content of the Bonneterre or Eau Claire is greatest near the base and diminishes upward (Treworgy and others, 1992; Sargent and others, 1992; Whitaker, Treworgy, and Noger, 1992; Whitaker, Treworgy, Sargent, and Noger, 1992).

The Bonneterre or Eau Claire thickens from less than 500 ft (150 m) at the northwest corner of the quadrangle to more than 1,800 ft (550 m) in northern Crittenden County, Kentucky (Sargent, 1991d). The thick area corresponds with the rapidly subsiding Rough Creek graben. By the time this unit was deposited, active faulting had ceased in the graben. The graben area continued to subside rapidly, however, as a consequence of contraction of cooling igneous masses in the lower crust and isostatic sinking of dense igneous rocks (Klein and Hsui, 1987; Kolata and Nelson, 1991b).

KNOX GROUP AND EQUIVALENT ROCKS

Overlying the Bonneterre Dolomite or Eau Claire Formation is a thick succession of dolomite, more or less cherty and sandy, ranging from Croixian (Late Cambrian) through Canadian (Early Ordovician) age. Some authors also include the Everton Formation (Whiterockian; Middle Ordovician) in the Knox Group. On the outcrop in Missouri, these rocks are divided into formations and no group name is used. The term Knox Group is used in the subsurface of Illinois, Indiana, and Kentucky. Subdividing the Knox in the subsurface is rather difficult; formation names used in the subsurface differ from those used on the outcrop (fig. 4). The Knox is equivalent lithologically and temporally to the Arbuckle Group in Oklahoma and partially equivalent to the Ellenburger Group in Texas. Like their equivalents in neighboring regions, Knox sediments were deposited in predominantly shallow subtidal and peritidal environments on a vast shelf, distant from sources of terrigenous clastics (Droste and Shaver, 1983).

The Knox Group thickens from less than 2,000 ft (600 m) at the northwest corner of the Paducah quadrangle to more than 8,000 ft (2,400 m) at the southeast corner (Sargent, 1991e). The rate of thickening is greatest in Perry County, Missouri, near the Bodenschatz-Lick fault zone, and in northern Jackson and Perry Counties, Illinois, near the Du Quoin monocline. In the southeast part of the quadrangle, the area of thickest Knox sediments coincides with the Reelfoot rift and Rough Creek graben, denoting rapid subsidence of these structures during Knox sedimentation.

The Davis Formation (Missouri) or Davis Member of the Franconia Formation (Illinois) is one of the few units in the Knox readily identifiable on wireline logs. It is a discontinuous unit of shale and shaly carbonate less than 100 ft (30 m) thick, contrasting with relatively pure carbonate rocks above and below (Treworgy and others, 1992; Sargent and others, 1992; Whitaker, Treworgy, and Noger, 1992; Whitaker, Treworgy, Sargent, and Noger, 1992). Because strong velocity contrasts take place at both boundaries of the Davis, the Davis produces strong seismic reflections and is a key unit in interpreting seismic profiles (Heigold and Oltz, 1990).

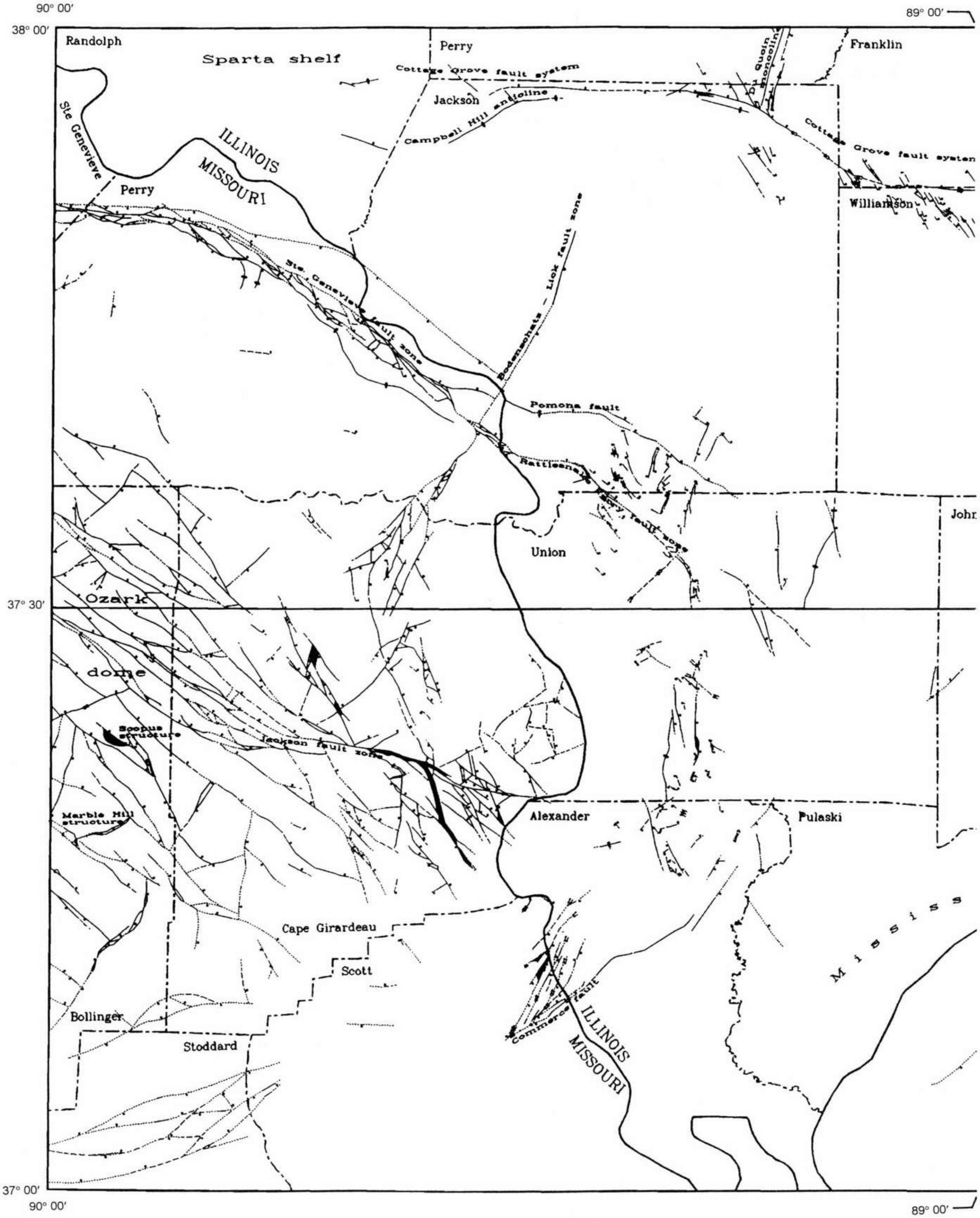
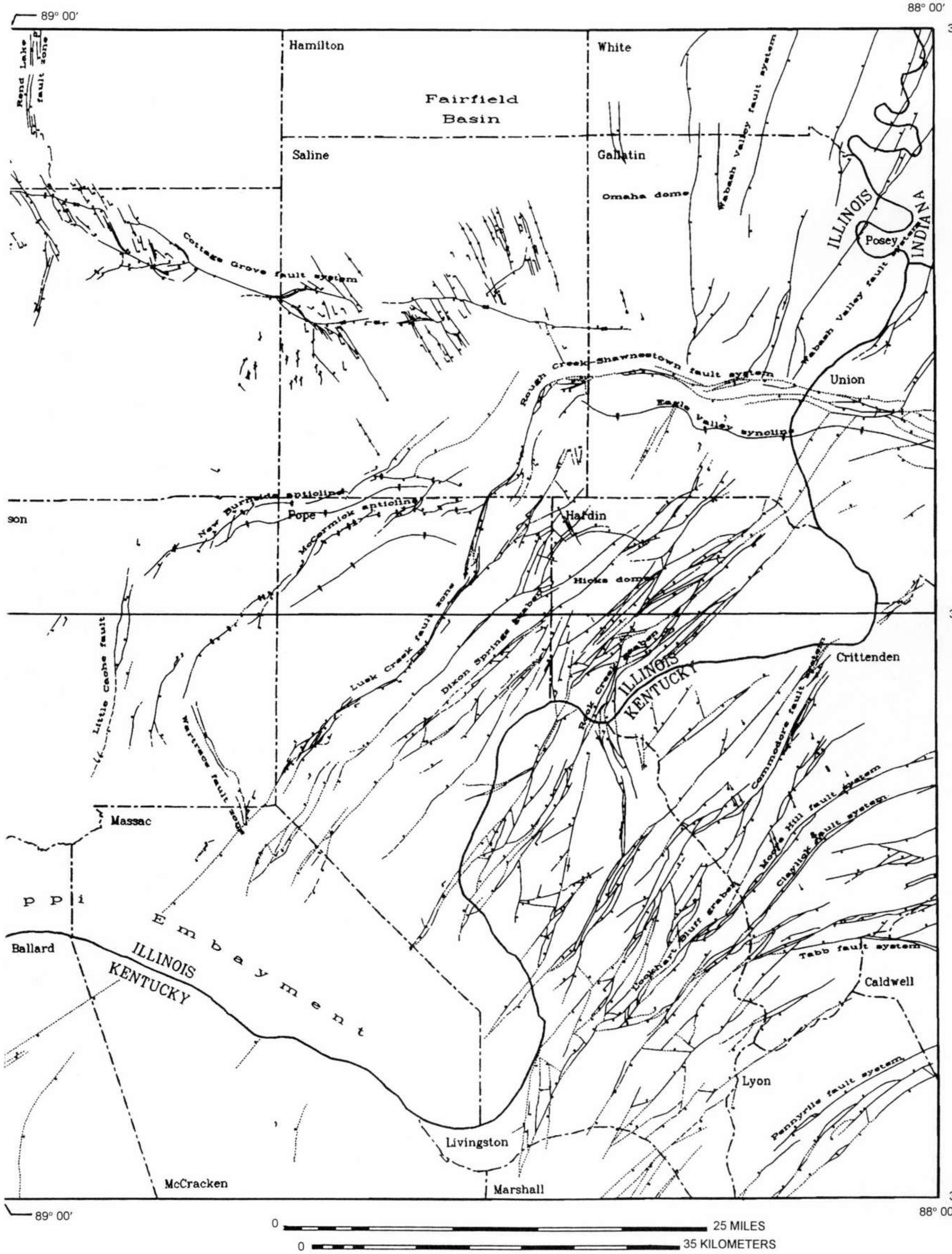
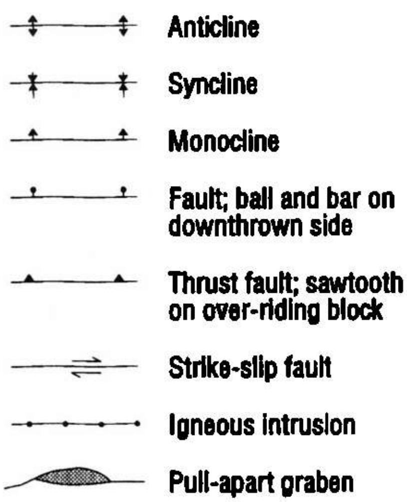


Figure 3 (above, facing, and following pages). Structural features in the Paducah quadrangle.


89° 00′
88° 00′
38° 00′
37° 30′
37° 00′
Rend Lake fault zone
Hamilton
White
Fairfield Basin
Saline
Gallatin
Omaha dome
Wabash Valley fault system
ILLINOIS
INDIANA
Posey
Cottage Grove fault system
Rough Creek–Shawneetown fault system
Union
Eagle Valley syncline
New Burnside anticline
McCormick anticline
Pope
Hardin
Hicks dome
son
Little Cache fault
Lusk Creek fault zone
Dixon Springs graben
Rock Creek graben
ILLINOIS
KENTUCKY
Crittenden
Commodore fault system
Wartrace fault zone
Massac
Moore Hill fault system
Claylick fault system
p p i
E m b a y m e n t
Lockhart Bluff graben
Ballard
ILLINOIS
KENTUCKY
Tabb fault system
Caldwell
Lyon
Pennyrile fault system
Livingston
McCracken
Marshall
0
25 MILES
0
35 KILOMETERS

EXPLANATION FOR FIGURE 3



Overlying the Davis is a thick interval of dolomite, some of which is shaly or sandy and contains abundant chert and drusy quartz. At outcrops in Missouri west of the Paducah quadrangle, this interval includes, from oldest to youngest, the Derby and Doe Run Formations (undivided), the Potosi Dolomite, and the Eminence Formation. Within the Paducah quadrangle, these units generally cannot be differentiated using wireline logs, but, in some cases, they can be identified by study of insoluble residues (Treworgy and others, 1992).

The Cambrian-Ordovician contact is apparently conformable and generally cannot be identified on wireline logs. The oldest Ordovician unit is the Gasconade Dolomite (Missouri) or Oneota Dolomite (Illinois and Kentucky). A basal sandstone, the Gunter Sandstone Member, occurs sporadically in the subsurface of the southern Illinois Basin (Treworgy and others, 1992). The upper part of the Gasconade or Oneota is composed of dolomite.

The Roubidoux Formation, which overlies the Gasconade, is the oldest bedrock formation that crops out in the Paducah quadrangle. On the outcrop, the Roubidoux is composed of intercalated sandy dolomite and dolomitic quartz sandstone. The sand content decreases eastward into the subsurface, rendering the Roubidoux difficult to identify in well records. Sand in the Roubidoux was probably recycled from Cambrian formations around the Ozark dome.

The Jefferson City (oldest), Cotter, Powell, and Smithville Dolomites overlie the Roubidoux Formation near the western edge of the Paducah quadrangle in Missouri. These formations all consist of more or less silty, sandy, and cherty dolomite, and they were not mapped consistently in adjacent 7 1/2-minute quadrangles within the report area. In the subsurface, the Jefferson City, Cotter, Powell, and Smithville are indistinguishable, except possibly through study of insoluble residues. The Shakopee Dolomite in the subsurface of the Paducah quadrangle is equivalent to the Roubidoux through Smithville Formations of the outcrop belt (Treworgy and others, 1992; Sargent and others, 1992; Whitaker, Treworgy, and Noger, 1992; Whitaker, Treworgy, Sargent, and Noger, 1992). The lower contact of the Shakopee on these sections was placed at the change from relatively sand-free, cherty dolomite below to sandy and shaly, less cherty dolomite above. On gamma-ray logs, the Shakopee has a more "ragged" character than the underlying Oneota, reflecting greater shale-sand content of the Shakopee.

A previously unrecognized interval of argillaceous dolomite overlies the Shakopee in several wells in southernmost Illinois and adjacent Kentucky. This unnamed dolomite attains a maximum thickness of 706 ft (215 m) in the Texas Pacific No. 1 Streich well in northeastern Pope County, Illinois. Whether the unnamed dolomite belongs in the Sauk sequence or the Tippecanoe sequence is uncertain. Thickness variations in the western part of the Rough Creek graben suggest that faults were active concurrent with deposition of this unit (Treworgy and others, 1992).

The Sauk-Tippecanoe sequence boundary is at the base of the Everton Formation. This contact is unconformable throughout the Everton outcrop belt in the Paducah quadrangle (Thompson, 1991). Continuous sedimentation may have occurred, however, in the deepest part of the Illinois Basin, particularly in the Reelfoot rift and Rough Creek graben (Collinson and others, 1988; Kolata and Noger, 1991).

TIPPECANOE SEQUENCE

The informally named Tippecanoe sequence of Sloss (1963) in the Paducah quadrangle comprises strata ranging in age from Middle Ordovician (Whiterockian) through Early Devonian (fig. 5). The Tippecanoe is mostly carbonate rock, but it contains quartz sandstone near the base, a clastic wedge in the Upper Ordovician, and bedded chert in the upper part. Significant hiatuses occur in the lower Cincinnatian (Upper Ordovician), at the top of the Cincinnatian, and at the top of the Alexandrian Provincial Series.

EVERTON FORMATION

The Everton Formation at the base of the Tippecanoe sequence is a unit of interbedded quartz arenite, dolomitic sandstone, and sandy dolomite. It crops out along a belt from

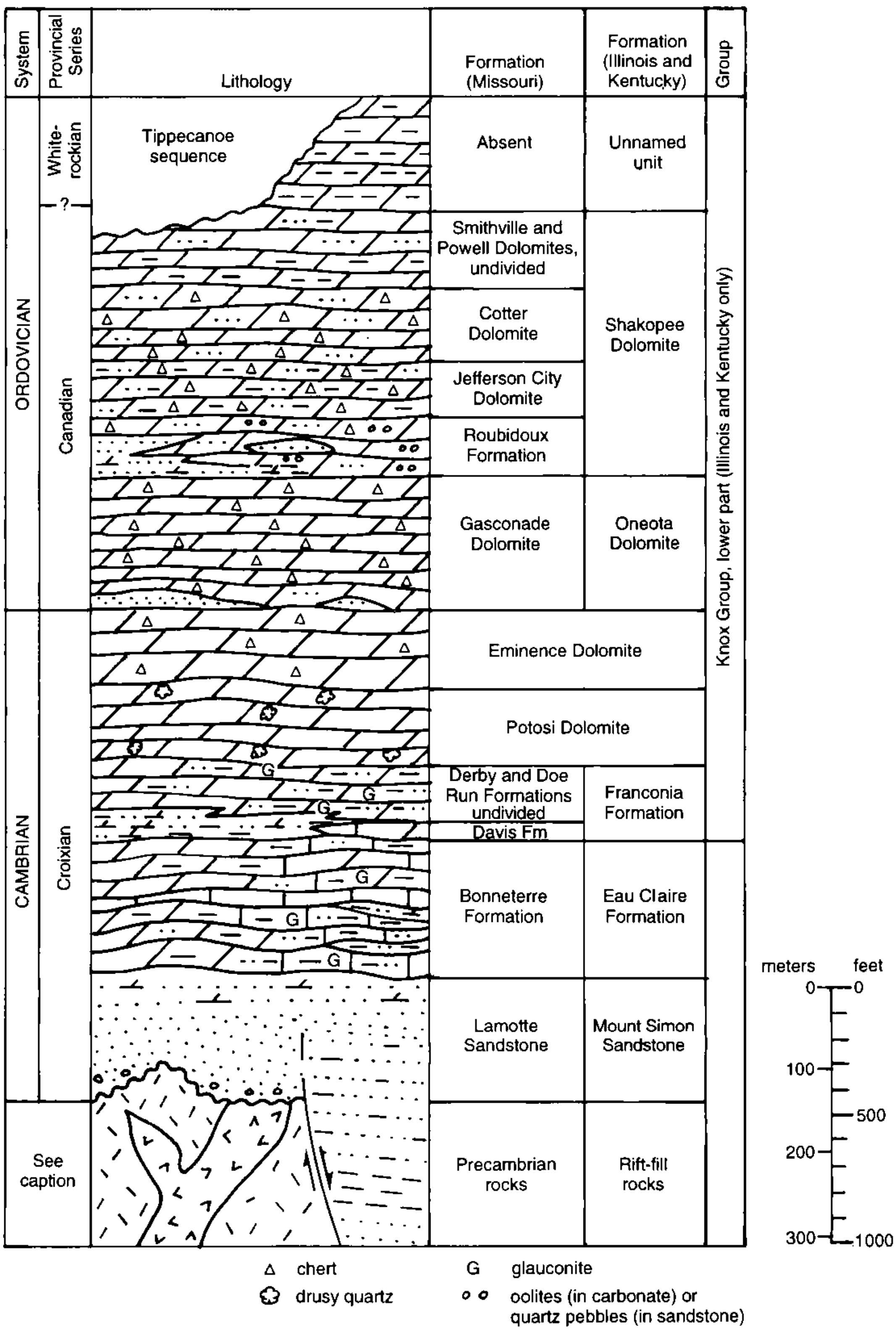


Figure 4. Generalized stratigraphic column of the Sauk sequence. Rift-fill rocks as thick as 9,000 ft (2,700 m) occur in the Reelfoot rift and Rough Creek graben. These rocks, of largely unknown lithology, are believed to be of Cambrian age. Outside of the rift, Upper Cambrian strata rest on Proterozoic rocks.

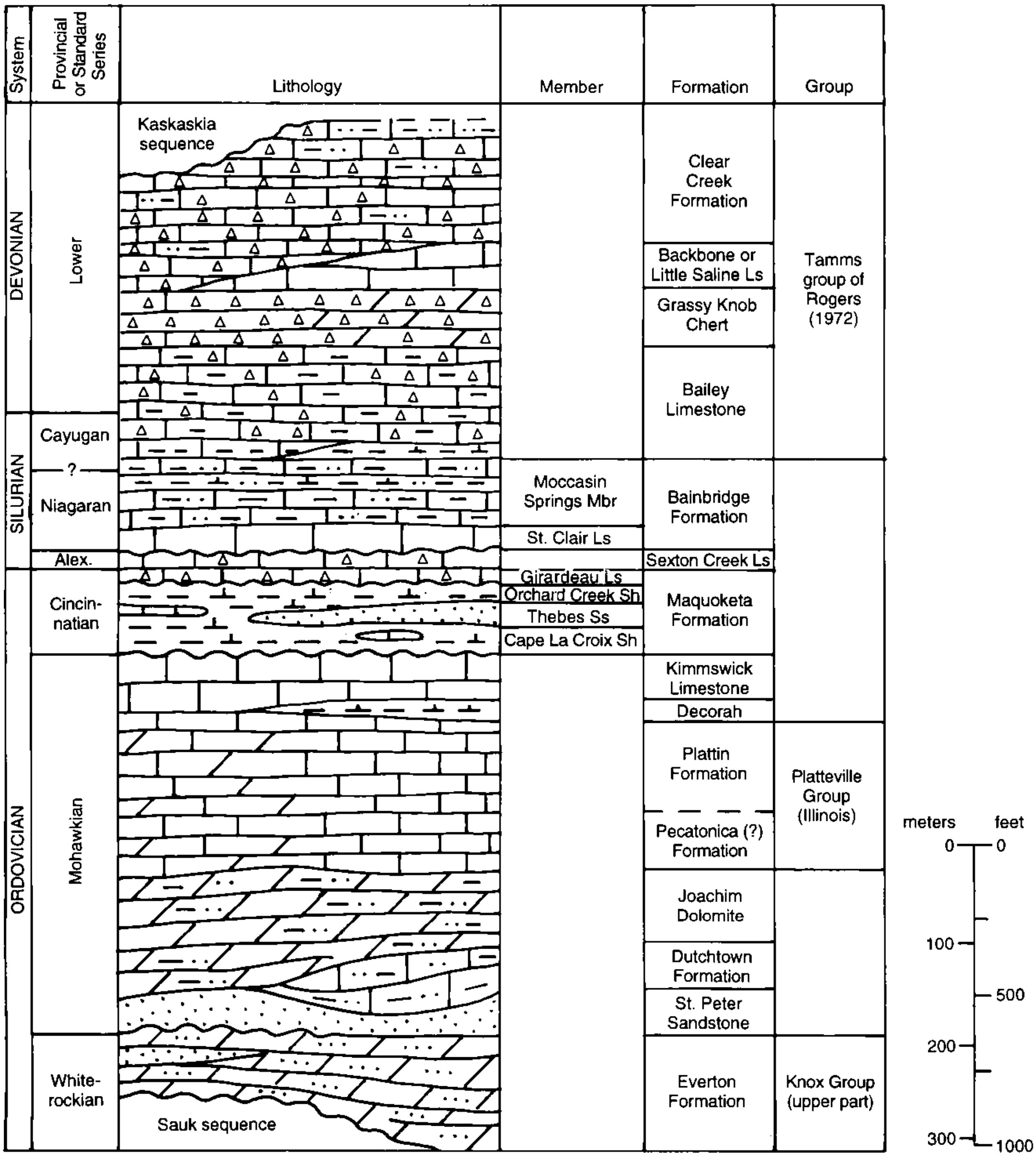


Figure 5. Generalized stratigraphic column of the Tippecanoe sequence. Alex., Alexandrian.

northwest Perry County to northwest Scott County, Missouri. The Everton is the uppermost formation of the Knox Group and is assigned to the Whiterockian Provincial Series (Shaver, 1985).

In outcrop, the Everton ranges from about 70 ft (21 m) thick in Perry County, Missouri, to 380 ft (116 m) southward in Cape Girardeau County. It is 320 to 480 ft thick in wells in southern Illinois and western Kentucky (Sargent, 1990a). Deposition of the Everton was not noticeably influenced by the Reelfoot rift and Rough Creek graben. Local thickness variations are abrupt, reflecting deposition on an irregular surface and facies variations. The contact to the overlying St. Peter Sandstone is reported to be disconformable in most geologic quadrangles in Missouri, except in the Thebes–Scott City quadrangles, where Johnson (1985) described the contact as conformable. In the subsurface of the deep Illinois Basin, this contact is difficult to locate and may be conformable (Kolata and Noger, 1991).

ST. PETER SANDSTONE

The St. Peter Sandstone is composed of nearly 100 percent well rounded, frosted quartz sand grains. The St. Peter varies from 0 to 210 ft (64 m) thick in outcrops; available well records show the sandstone to be 100 to 120 ft (30 to 37 m) thick in the northern part of the quadrangle and also near Cairo, Ill. Elsewhere in the Paducah quadrangle the St. Peter is generally 50 to 100 ft (15 to 30 m) thick (Sargent, 1990b). Tectonic influence on St. Peter deposition in the study area cannot be demonstrated.

The St. Peter is a transgressive, nearshore to shallow subtidal deposit. Its sand was derived from Cambrian and Proterozoic sandstones to the north. Age of the St. Peter is early Mohawkian (Thompson, 1991) or, using different terminology, Chazyan to early Blackriveran (Shaver, 1985).

MOHAWKIAN CARBONATES

Overlying the St. Peter Sandstone is a succession of Middle Ordovician carbonate formations: the Dutchtown Formation (oldest), Joachim Dolomite, Pecatonica(?) Formation, Plattin Formation, Decorah Formation, and Kimmswick Limestone. An isopach map by Sargent (1990c) shows that these rocks thicken from less than 700 ft (210 m) at the northwest corner of the Paducah quadrangle to 1,450 ft (440 m) in northern Pope County, Illinois. Mohawkian carbonates are thickest along a belt that runs northeast from southern Pulaski County to Pope County, following the northwest margin of the Reelfoot rift.

The Dutchtown Formation is dark-colored, micritic, silty to sandy limestone interbedded with lesser amounts of dolomite. The rock contains bitumen-filled vugs and emits a petroliferous odor when hammered. The Dutchtown thins northward from 180 ft (55 m) in southern Cape Girardeau County to less than 20 ft (6 m) in Perry County, Missouri. The Dutchtown is interpreted as supratidal to peritidal deposits (Kolata and Noger, 1991).

The Joachim Dolomite is lighter colored than the Dutchtown and consists primarily of micritic to finely crystalline dolomite, with thin interbeds of sandstone and shale. Gypsum and anhydrite beds (in subsurface), along with mud cracks, ripple marks, and sparse fauna, suggest that the Joachim was deposited in sabkha environments (Okhravi and Carozzi, 1983). The Joachim thins northwestward from 280 to 135 ft (85 to 40 m) along the outcrop in Missouri. The Dutchtown and Joachim are difficult to differentiate in the subsurface; limestone and dolomite intertongue in variable fashion, generally becoming shalier toward the base (Treworgy and others, 1992). The combined Dutchtown and Joachim are more than 600 ft (183 m) thick in extreme southeastern Illinois within the Reelfoot rift (Willman and others, 1975, p. 63).

The Pecatonica(?) and Plattin Formations are lithologically similar units that are separable only in optimal exposures, such as roadcuts and quarry walls. Thompson (1991, p. 109) stated that, for this reason, use of the name Pecatonica in Missouri has a "tentative and questionable future." Kolata and Noger (1991) reported that the Pecatonica and Plattin can be differentiated in subsurface by use of electric and gamma-ray logs. The difference must reflect subtle lithologic changes that are not readily apparent in outcrops. Some geologists who mapped 7½-minute geologic quadrangles in Missouri distinguished the Pecatonica, but they did not do so in a consistent fashion (Nelson 1995).

Thompson (1991) refers to the Plattin as a group, but I consider it a formation because no formational units within the Plattin have been mapped within the Paducah quadrangle (Nelson, 1995; Nelson and others, 1995). The Plattin and Pecatonica(?) were combined with the Decorah Formation into a single unit on the map that accompanies this report (plate 1).

The Pecatonica(?) and Plattin are composed of laminated and burrowed, brownish-gray micritic dolomite and limestone (lime mudstone). Mud cracks, algal mats, intraformational breccias, and sparse fauna point to deposition in tidal flats and shallow lagoons (Kolata and Noger, 1991). The Platteville Group (Pecatonica(?) and Plattin) thickens southeastward from 350 ft (107 m) from the northwest corner to more than 600 ft (183 m) in the southeast part of the Paducah quadrangle (Willman and others, 1975, p. 66).

The Decorah Formation (Rocklandian age) thins from about 35 ft (10 m) in the northwestern part of the study area to a feather-edge in the central part. The Decorah is composed of thin-bedded, argillaceous, highly fossiliferous limestone intercalated with greenish-gray calcareous shale. It is the distal edge of a clastic wedge derived from the Transcontinental arch far to the northwest (Kolata and Noger, 1991). The upper contact is disconformable.

The Kimmswick Limestone is a distinctive unit of white to light-gray and pink, medium- to coarse-grained, cross-bedded crinoidal grainstone that is quarried as a source of high-calcium limestone. The Kimmswick outcrop belt curves southward through eastern Perry County, Missouri, into Alexander County, Illinois, along the Mississippi River. Thickness of the Kimmswick is typically 110 to 165 ft (35 to 50 m); no regional thickness trends are apparent in the study area. Apparently, the rift had little influence on Kimmswick sedimentation. The Kimmswick was deposited on a shallow, open-marine shelf, well agitated by waves and currents. The upper contact is a pronounced unconformity, which accounts for much of the local thickness variation.

A thin, lenticular unit of darker, finer grained, more argillaceous limestone, the Cape Limestone, locally overlies the Kimmswick.

MAQUOKETA FORMATION

Cincinnatian siliciclastic strata of the Paducah quadrangle are assigned to the Maquoketa Formation. Although previously ranked as a group by some geologists (Thompson 1991; Nelson 1995), the Maquoketa is classified as a formation here because the smaller units that comprise it are not mappable at scales of 1:24,000 or smaller (Nelson and others, 1995).

In most of the quadrangle, the Maquoketa is composed of dark-gray to greenish-gray, partly silty and calcareous shale with thin limestone interbeds. Isopach mapping by Sargent and Roemelle (1990) and Whitaker (1988) shows the Maquoketa regionally thickening eastward from about 150 ft (45 m) to more than 300 ft (90 m). Eastward thickening reflects provenance of most Maquoketa sediment from the Taconic orogenic belt in the Northeastern United States. The Maquoketa locally thickens in extreme western Kentucky (Whitaker, 1988), suggesting accelerated subsidence of the Reelfoot rift.

In the southwestern part of the Paducah quadrangle, the Maquoketa is divisible into four members (Thompson, 1991; Nelson, Devera, and Masters, 1995). The Cape La Croix Shale Member at the base is dark-gray, marine clay shale that contains thin interbeds of micritic limestone. The Cape La Croix becomes silty near the top and grades into the overlying Thebes Sandstone Member. The Thebes is more than 100 ft (30 m) thick in places and is composed of calcareous siltstone and very fine grained, argillaceous sandstone, much of it intensively burrowed. Red and green variegated claystone occurs at the top of the Thebes in some places. Above the Thebes is the Orchard Creek Shale Member, which, like the Cape La Croix, consists of dark-gray marine shale containing micritic limestone interbeds. The Orchard Creek grades into the overlying Girardeau Limestone Member. Eastward and northward into the subsurface the Thebes and Girardeau grade to shale (Maquoketa Shale undivided).

Evidently, part of the Ozark dome was subaerially exposed during Cincinnatian time, providing a local source of sediment for the Thebes Sandstone Member. The Girardeau Limestone Member probably accumulated in relatively shallow water on the flank of the dome. Two shoaling-upward sequences are evident in the Maquoketa. The first comprises the Cape La Croix and Thebes; the second the Orchard Creek and Girardeau.

Both the Kimmswick Limestone and the Maquoketa Formation thin abruptly on the southwest side of the Ste. Genevieve fault zone in Perry County, Missouri, and adjacent Jackson County, Illinois (fig. 6). The Kimmswick is 50 to 100 ft (15 to 30 m) thick southwest of the fault zone in the Altenburg (Amos, 1985a) and Neelys Landing (Whitfield and Middendorf, 1989) quadrangles and in a well southwest of the fault in southwestern Jackson County, Illinois. These thicknesses compare to 135 to 165 ft (40 to 50 m) in wells drilled a short distance northeast of the fault zone. Moreover, the Kimmswick is locally dolomitized southwest of the fault zone (Amos, 1985a, 1985b, 1986a; D.R. Kolata, oral commun., 1992). The Maquoketa thickens from 60 to 100 ft (18 to 30 m) southwest of the fault zone to 130 to 165 ft (40 to 50 m) northeast of the fault (Amos, 1985a, 1986b). Thickness changes appear to affect all the members of the Maquoketa proportionately. Evidently, the southwest side of the Ste. Genevieve fault zone was progressively uplifted during deposition of the Kimmswick and Maquoketa.

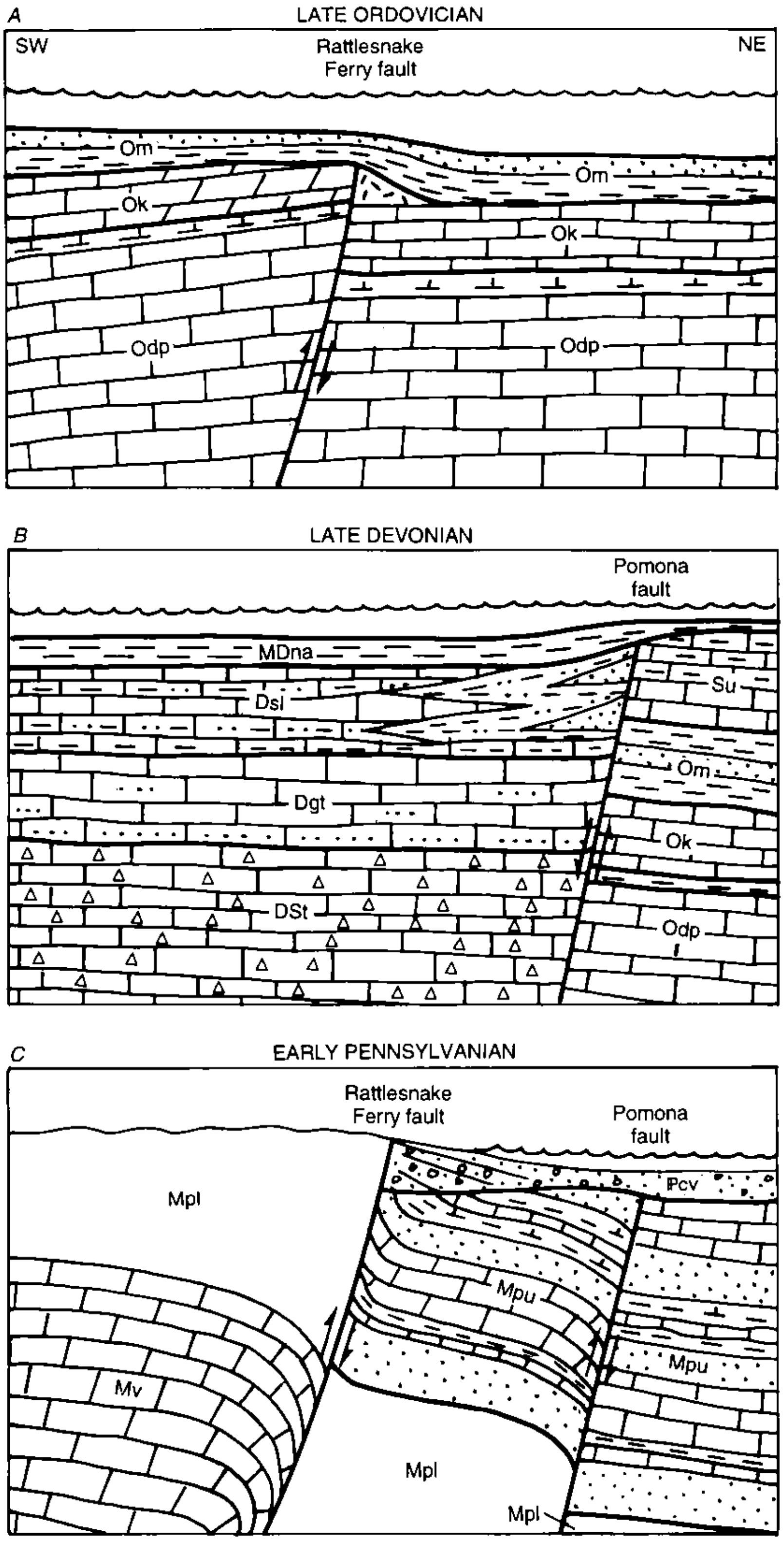
The upper surface of the Maquoketa is a disconformity. The thin, discontinuous Leemon Formation (formerly mapped as the Edgewood Formation) locally overlies the Maquoketa near Cape Girardeau. The Leemon is oolitic and skeletal limestone of latest Ordovician age (Thompson and Satterfield, 1975).

SILURIAN STRATA

Disconformably overlying the Maquoketa Formation (or the Leemon Formation, where present) is the Alexandrian (Lower Silurian) Sexton Creek Limestone. This is a unit of cherty, dense, micritic, wavy-bedded limestone that thickens from 15 to 65 ft (5 to 20 m) in outcrop belt near the Mississippi River to more than 125 ft (38 m) in the subsurface in Franklin County, Illinois (Willman and others, 1975, p. 96). The upper contact of the Sexton Creek is disconformable.

Overlying the Sexton Creek is the Bainbridge Formation, divided into the older St. Clair Limestone Member and the younger Moccasin Springs Member (Thompson, 1993; Nelson, Devera, and Masters, 1995). The St. Clair is gray lime mudstone to wackestone that is mottled in red and green and contains red echinoderm fragments, ostracods, and foraminifera. It thickens from 5 to 30 ft (2 to 9 m) on the outcrop to about 60 ft (18 m) in the subsurface in the southeast part of the quadrangle (Ross, 1964). The Moccasin Springs is composed of argillaceous to silty lime mudstone intercalated with calcareous shale and siltstone, all of which are

Figure 6 (facing page). Structural development of the Ste. Genevieve fault zone, depicted by cross sections near where the fault zone crosses the Mississippi River. *A*, Rattlesnake Ferry fault undergoes reverse displacement, with southwest block upthrown, in Cincinnatian time. Kimmswick Limestone on upthrown block is thinned and dolomitized; Maquoketa Formation is thinned. *B*, Pomona fault undergoes normal displacement in late Middle to Late Devonian time. Devonian rocks are eroded from the upthrown northern block while syntectonic sandstone and conglomerate are deposited along the base of the fault scarp in the St. Laurent Formation. By end of Devonian Period (as depicted here), fault activity was waning and thin New Albany Shale was deposited northeast of the fault. The Rattlesnake Ferry fault, southwest of the Pomona fault, was inactive during the Devonian. *C*, Both Rattlesnake Ferry and Pomona faults undergo reverse displacement during Morrowan (Early Pennsylvanian) time. The result is an angular unconformity between Mississippian and Pennsylvanian rocks and syntectonic conglomerates in Morrowan sediments near the fault zone.



Om—Maquoketa Formation
Ok—Kimmswick Limestone
Odp—Decorah, Plattin, and Pecatonica (?) Formations undivided

MDna—New Albany Shale
DSl—St. Laurent Formation
Dgt—Grand Tower Limestone
DSt—Tamms group of Rogers (1972)
Su—Silurian rocks, undivided
Other symbols as above

Pcv—Caseyville Formation
Mpu—Pope Group, above Glen Dean Limestone
Mpl—Pope Group, Glen Dean Limestone and below
Mv—Valmeyeran Series

variegated in shades of red, green, and gray. The Moccasin Springs is 60 to 140 ft (18 to 43 m) thick in outcrop, and thickens to 250 to 300 ft (80 to 100 m) in parts of Pulaski and Massac Counties, Illinois, and the adjacent part of Kentucky. This area lies within the Reelfoot rift.

Depositional environments of Silurian rocks in the Paducah quadrangle have not been studied much. The Sexton Creek, St. Clair, and Moccasin Springs all were deposited in relatively quiet, but not necessarily deep, marine water. Red and green colors in the Moccasin Springs may reflect colors of source sediments from southwest of the area (Becker and Droste, 1978). Equivalent lighter colored carbonate sands were deposited in shallow reef-forming environments north of the Paducah quadrangle. Authors disagree on whether the reefs grew along a distinct shelf-slope margin (Becker and Droste, 1978; Droste and Shaver, 1980, 1987; Mikulic, 1991), or along a gradual south-sloping ramp (Whitaker, 1988).

The upper contact of the Bainbridge is reported to be disconformable near the Ste. Genevieve fault zone in Perry and Ste. Genevieve Counties, Missouri (Amos, 1985a, 1985b, 1986a). Elsewhere, this contact appears to be conformable (Pryor and Ross, 1962; Ross 1963; Becker and Droste, 1978; Droste and Shaver, 1987).

TAMMS GROUP OF ROGERS (1972)

The name Tamms group was used in a thesis by Rogers (1972) for the interval of cherty carbonate rocks and bedded chert that overlies the Bainbridge Formation and extends to the top of the Tippecanoe sequence. The group includes four formations: Bailey Limestone (oldest), Grassy Knob Chert, Backbone Limestone (Illinois) or Little Saline Limestone (Missouri), and Clear Creek Formation.

The Tamms group of Rogers (1972) crops out in western Alexander and Union Counties, Illinois, eastern Cape Girardeau and Perry Counties, Missouri, and in fault blocks within the Ste. Genevieve fault zone. Deep surficial weathering, extensive silicification, lack of marker beds, scarcity of easily extracted fossils, and poor exposures hamper study of these rocks. Formations have been mapped inconsistently by various geologists.

The Bailey Limestone is composed of light olive gray, argillaceous to silty, cherty lime mudstone, with thin interbeds of greenish-gray shale in the lower part. Upper and lower contacts are gradational. The Bailey is approximately 250 to 400 ft (75 to 120 m) thick. Sparse fossil evidence indicates that the lower part of the Bailey is of Late Silurian (Cayugan) age (Becker and Droste, 1978), whereas the upper part is Early Devonian (Collinson and others, 1967).

The Grassy Knob Chert is largely thick-bedded, tripolitic to novaculitic, burrowed chert in outcrop; it contains beds of siliceous limestone and dolomite in the subsurface. The Grassy Knob generally thickens southward in the outcrop belt from about 165 to 300 ft (50 to 90 m).

The Backbone Limestone (Illinois) or Little Saline Limestone (Missouri) is a unit of white to light-gray, high-calcium, coarse skeletal grainstone. The limestone is as thick as 200 ft (60 m) on the north and pinches out southward. Lenses of limestone of similar lithology occur at various positions within the Tamms group of Rogers (1972) in the subsurface.

The Clear Creek Formation is light gray, siliceous, cherty, mostly thin-bedded and micritic limestone that contains common brachiopods and trilobites. It thickens southeastward from an erosional feather-edge in the northwestern Paducah quadrangle to at least 650 ft (200 m) in the Reelfoot rift area (Droste and Shaver, 1987, p. 12). In much of the outcrop belt in Illinois, the Clear Creek is altered to microcrystalline silica (tripoli), the purest beds of which are mined commercially.

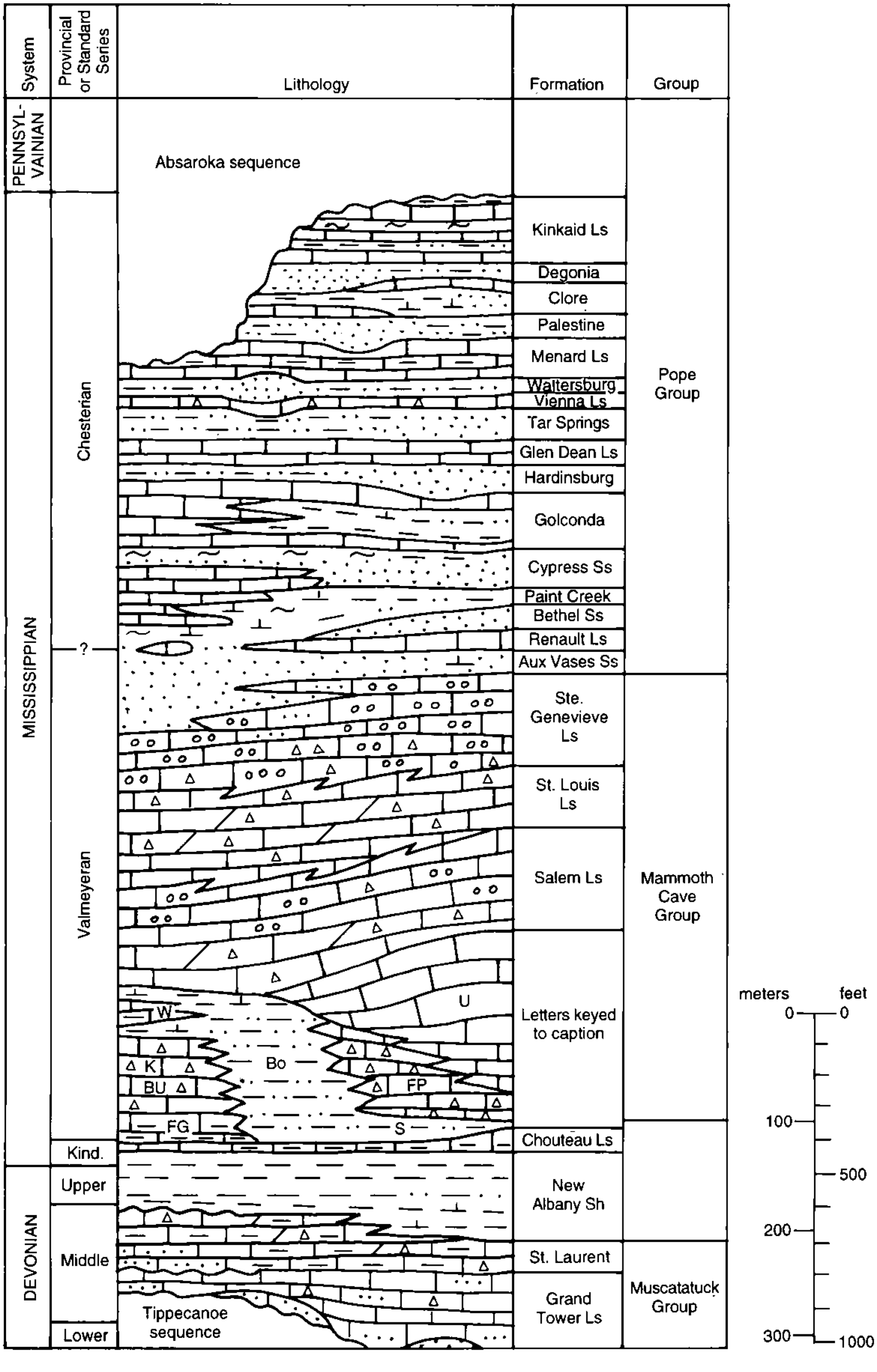
The Bailey and Grassy Knob probably were deposited in a sea that gradually deepened. The Backbone or Little Saline Limestone is a high-energy deposit that accumulated in shoal areas bordering the proto-Illinois Basin. The Clear Creek Formation represents deposition in relatively shallow, but quiet, marine waters. Primary silica in the Tamms group of Rogers (1972) is partly biogenic, produced by organisms such as sponges, and partly detrital (Nelson, Devera, and Masters, 1995).

The unconformity at the top of the Tippecanoe sequence is well-marked only in the northwest part of the Paducah quadrangle. The Grand Tower Limestone (Kaskaskia sequence) directly overlies the Little Saline Limestone in part of Ste. Genevieve County, Missouri (Weller and St. Clair, 1928). Silurian rocks may directly underlie the Kaskaskia sequence at the northwest corner of the Paducah quadrangle (Willman and others, 1967). But in the deepest part of the Illinois Basin, near the common corner of Indiana, Illinois, and Kentucky, sedimentation was continuous from Early Devonian into Middle Devonian time (Devera and Fraunfelter, 1988).

KASKASKIA SEQUENCE

The informally named Kaskaskia sequence of Sloss and others (1949) and Sloss (1963) comprises strata that range from Middle Devonian through Late Mississippian (Chesterian) age (fig. 7). The sequence is mostly limestone, except for the Devonian and Mississippian New Albany Shale and Chesterian mixed carbonates and siliciclastics.

Figure 7 (facing page). Generalized stratigraphic column of Kaskaskia sequence. Kind., Kinderhookian. Letter symbols: FG, Fern Glen Formation; Bu, Burlington Limestone; K, Keokuk Limestone; W, Warsaw Formation; Bo, Borden Siltstone; S, Springville Shale; FP, Fort Payne Formation; U, Ullin Limestone. Due to space limitations, not all named formations can be shown. See figure 8 for more detail of Valmeyeran units and figure 9 for more detail of Pope Group.


System
Provincial or Standard Series
Lithology
Formation
Group
PENNSYLVANIAN
Absaroka sequence
MISSISSIPPIAN
Chesterian
Kinkaid Ls
Degonia
Clore
Palestine
Menard Ls
Waltersburg
Vienna Ls
Tar Springs
Glen Dean Ls
Hardinsburg
Golconda
Cypress Ss
Paint Creek
Bethel Ss
Renault Ls
Aux Vases Ss
Pope Group
?
Valmeyeran
Ste. Genevieve Ls
St. Louis Ls
Salem Ls
Letters keyed to caption
Mammoth Cave Group
W
U
K
Bo
BU
FP
FG
S
Kind.
Chouteau Ls
DEVONIAN
Upper
New Albany Sh
Middle
St. Laurent
Grand Tower Ls
Muscatatuck Group
Lower
Tippecanoe sequence
meters
feet
0
0
100
500
200
300
1000

MUSCATATUCK GROUP

The Muscatatuck Group in the Paducah quadrangle comprises the Grand Tower or Jeffersonville Limestone and the St. Laurent or Sellersburg Formation (Shaver, 1985; Nelson, 1995). The group crops out in a narrow strip in Union and Alexander Counties, Illinois, and in fault slices along the Ste. Genevieve fault zone in Missouri.

The Grand Tower (Missouri and Illinois) or Jeffersonville (Kentucky and Indiana) Limestone is commonly regarded as early Middle Devonian (Eifelian). However, at least locally, the lower part contains late Early Devonian (Emsian) fossils (Boucot and Johnson, 1968; Devera and Fraunfelter, 1988).

The Dutch Creek Sandstone Member at the base of both formations is a lenticular unit composed of well-rounded, frosted quartz sand (Meents and Swann, 1965). The Dutch Creek is best developed on the flank of the Ozark dome. Its sand probably was derived from the St. Peter Sandstone and older Paleozoic sandstones exposed on the dome. Fossils, taphonomy, and sedimentology indicate that the Dutch Creek was distributed by tidal currents. The remainder of the Grand Tower and Jeffersonville is largely skeletal grainstone with floating sand grains, probably windblown. Patch reefs occur in the middle Grand Tower and Jeffersonville. The upper part of the limestone is more micritic and contains tempestites. Overall, the Grand Tower reflects sedimentation in seawater of normal salinity and oxygen content in depths ranging from shallow subtidal to below fair-weather wave base (Devera and Fraunfelter, 1988).

The Grand Tower or Jeffersonville is thickest (more than 240 ft; 73 m) in an east-trending belt immediately south of the Rough Creek–Shawneetown fault system. Evidently normal, down-to-the-south displacements took place along the Rough Creek during Eifelian sedimentation (Freeman, 1951). The Grand Tower thins to less than 20 ft (6 m) on the flank of the Ozark dome in Alexander County, southernmost Illinois (Nelson and others, 1995). In that area, only the Dutch Creek Sandstone Member is present; it onlaps older strata.

The upper part of the Muscatatuck Group comprises the St. Laurent Formation (Missouri and Illinois) and the Sellersburg Limestone (Kentucky). The Lingle and Alto Formations, previously used in Illinois, have been abandoned in favor of the St. Laurent Formation because the Lingle and Alto were inadequately defined and are not mappable (Nelson, Devera, and Masters, 1995). The St. Laurent and Sellersburg are similar in lithology: argillaceous limestone and dolomite, which is darker and more micritic than that of the Grand Tower or Jeffersonville, interbedded in some areas with shale, siltstone, sandstone, and conglomerate. The St. Laurent is more than 200 ft (60 m) thick along the Ste. Genevieve fault zone and ranges up to about 110 ft (35 m) thick south of the Rough Creek–Shawneetown fault system (North, 1969). These areas of thickened strata reflect contemporaneous movements along faults. Elsewhere in the Paducah quadrangle, the St. Laurent or Sellersburg is generally less than 100 ft (30 m) thick. Carbonate rocks thin westward and intertongue with shale and siltstone in Union and Alexander Counties, southwestern Illinois (Nelson, Devera, and Masters, 1995). Farther east in the subsurface, the upper part of the St. Laurent intertongues with the overlying New Albany Shale (North, 1969; Cluff and others, 1981).

The Ste. Genevieve fault zone was active from Givetian time to nearly the end of the Devonian Period. The active faults lay along the northern border of the zone and extended from west of the study area through Missouri into western Jackson County, Illinois. The northern (Sparta shelf) block was raised as much as 1,000 ft (300 m) and deeply eroded prior to Mississippian sedimentation. North of the fault zone, Mississippian rocks unconformably overlie units as old as Late Ordovician; south of the fault, the complete Devonian and Silurian section is preserved (fig. 6). Syntectonic deposits of quartz sandstone and conglomerate containing clasts of older formations occur in the St. Laurent Formation south of the active Devonian fault in Missouri (Weller and St. Clair, 1928; Croneis, 1944; Nelson and Lumm, 1985).

Meents and Swann (1965) proposed that a deep fault-bounded trench called the Wittenberg trough lay along the Ste. Genevieve fault zone during Middle Devonian time. Other studies, however, do not support existence of such a trough. The Grand Tower Limestone and St. Laurent Formation contain patch reefs and other sedimentary features characteristic of shallow subtidal deposition in the area of the "Wittenberg trough" (Devera and Fraunfelter, 1988). The narrow strip of Devonian outcrops along the fault zone is the product of a reversal of displacement. During Middle and Late Devonian time, shallow marine sediments were deposited south of the active fault, while the crustal block north of the fault was upthrown and eroded. Then, in Late Mississippian and Pennsylvanian time, faults near the southern margin of the Ste. Genevieve fault zone underwent reverse displacement, with the southern (Ozark dome) block uplifted (fig. 6). The younger faults were located a few miles south of and parallel to the older faults. Silurian and Devonian rocks were eroded south of the fault zone and were preserved only in the narrow strip between the older (northern) and younger (southern) strands of the Ste. Genevieve fault zone (Weller and St. Clair, 1928; Nelson and Lumm, 1985; Devera and Fraunfelter, 1988).

NEW ALBANY SHALE

Overlying the Muscatatuck Group is the New Albany Shale. The New Albany previously was classified as a group in Illinois, but Nelson (1995) reduced it to a formation because its subdivisions do not meet the test of mappability. The New Albany is part of the body of Upper Devonian black shale, which, under many names (Chattanooga Shale, Woodford Shale, Ohio Shale, Bakken Formation, etc.), covers much of the North American craton. The New Albany is mostly of Frasnian and Famennian age, but it includes Givetian (Middle Devonian) beds at the base and Kinderhookian (Lower Mississippian) beds at the top.

The New Albany reaches a maximum thickness of more than 460 ft (140 m) in Hardin County, Illinois, and the adjacent part of Kentucky (Cluff and others, 1981). Continuing a familiar pattern, the New Albany is thickest near the western end of the Rough Creek graben. Thickness changes of the New Albany east of the report area (Schwalb and Potter, 1978) demonstrate that both the northern (Rough Creek) and southern (Pennyrile) boundary faults of the graben underwent normal displacements concurrent with New Albany sedimentation. In and near the subsiding graben, the New Albany is conformable and intertongues with underlying carbonates (North, 1969). The New Albany rests disconformably on carbonate rocks of the Muscatatuck Group in outcrops along the flank the Ozark dome in southern Illinois (Nelson and others, 1995). On the Sparta shelf, north of the Ste. Genevieve fault zone, the New Albany is thin and lenticular, and it disconformably lies on rocks as old as Ordovician. Uplift of the southern margin of the shelf thus was winding down by the end of Devonian time.

The New Albany is a unit of dark-gray to black, fissile, phosphatic, organic-rich shale, interbedded in part with less fissile and organic-rich, mottled, greenish to olive-gray shales. Fossils include fish remains, small brachiopods, conodonts, the "spore" *Tasmanites*, and a variety of trace fossils. Deposition in quiet water under dysaerobic to anaerobic conditions is implied (Cluff and others, 1981).

CHOUTEAU OR ROCKFORD LIMESTONE

The thin but widely persistent Chouteau (Missouri and Illinois) or Rockford (Kentucky) Limestone overlies the New Albany Shale in much of the report area. Too thin to map separately, the Chouteau or Rockford was combined with either the New Albany or the overlying Springville Shale and Fort Payne Formation by various map authors. The discrepancy is insignificant at the scale of plate 1.

The Chouteau or Rockford is composed of argillaceous to silty lime mudstone that contains scattered fossil fragments, including echinoderms, goniatites, conodonts, and foraminifera. Maximum thickness is about 8 ft (2.4 m). Conodont faunas indicate Kinderhookian (Early Mississippian) age (Collinson and Scott, 1958). Phosphatic nodules in the Chouteau, a faunal gap, and a weathering profile at the top of the New Albany imply a disconformity at the base of the Chouteau in outcrops of southwestern Illinois (David Macke, written commun., 1992). The Chouteau or Rockford was deposited in quiet water on a sea floor having little relief (Sable and Dever, 1990).

VALMEYERAN CARBONATE BANK

Valmeyeran (Middle Mississippian) strata of the report area represent three facies assemblages: (1) a lower Valmeyeran carbonate bank in the northwestern part of the quadrangle, (2) deltaic siliciclastics partly equivalent to and partly overlapping the carbonate bank, and (3) upper Valmeyeran shelf carbonates that overlie the deltaic clastics (fig. 8).

Carbonate-bank strata (map symbol Mkb) crop out in small fault slices along the Ste. Genevieve fault zone in Missouri and occur in the subsurface on the western Sparta shelf in Illinois. Constituent units are the Fern Glen Formation (oldest), Burlington Limestone, and Keokuk Limestone. The Fern Glen is composed of fossiliferous, cherty limestone that contains interbeds of red and green shale, especially near the base. The Burlington and Keokuk Limestones are both light-colored, largely crinoidal limestones that contain abundant chert layers and nodules. Aggregate thicknesses of these three units range from about 250 to 400 ft (75 to 120 m).

VALMEYERAN DELTAIC CLASTICS

While the carbonate bank developed on the Sparta shelf, a delta (Borden delta) prograded into the Illinois Basin from the east. Deltaic clastics are assigned to three formations in the study area: the Springville or New Providence Shale, the Borden Siltstone, and the Warsaw Formation.

The Springville (Illinois) or New Providence Shale (Kentucky) consists of prodeltaic clay shale, silty shale, and siltstone that form an upward-coarsening interval 5 to 60 ft (1.5 to 18 m) thick. The Springville crops out in Union and Alexander Counties, Illinois, where it lies conformably on the Chouteau Limestone or unconformably on older units (Nelson and others, 1995). The Springville also crops out at Hicks dome in southeastern Illinois; the New Providence crops out in fault slices in western Kentucky. This unit underlies the entire eastern half of the report area in the subsurface.

Delta-front deposits of the Borden Siltstone occurs in the subsurface in northern Jackson and adjacent counties, Illinois. Well records indicate a succession of calcareous, glauconitic silty mudstone, siltstone, and fine-grained sandstone as thick as 290 ft (88 m) (Lineback, 1966, 1981). The Borden is a lateral equivalent of the Springville and lies east of the carbonate-bank rocks (Lineback, 1966).

The Warsaw Formation is equivalent to the upper part of the Borden and overlaps the carbonate bank near the northwest corner of the Paducah quadrangle. The Warsaw is a unit of intercalated gray calcareous shale and oolitic and skeletal limestones.

Swann and others (1965) and Lineback (1966, 1969, 1981) envisioned the carbonate bank as having a steep margin that stood 200 to 300 ft (60 to 90 m) above the floor of a

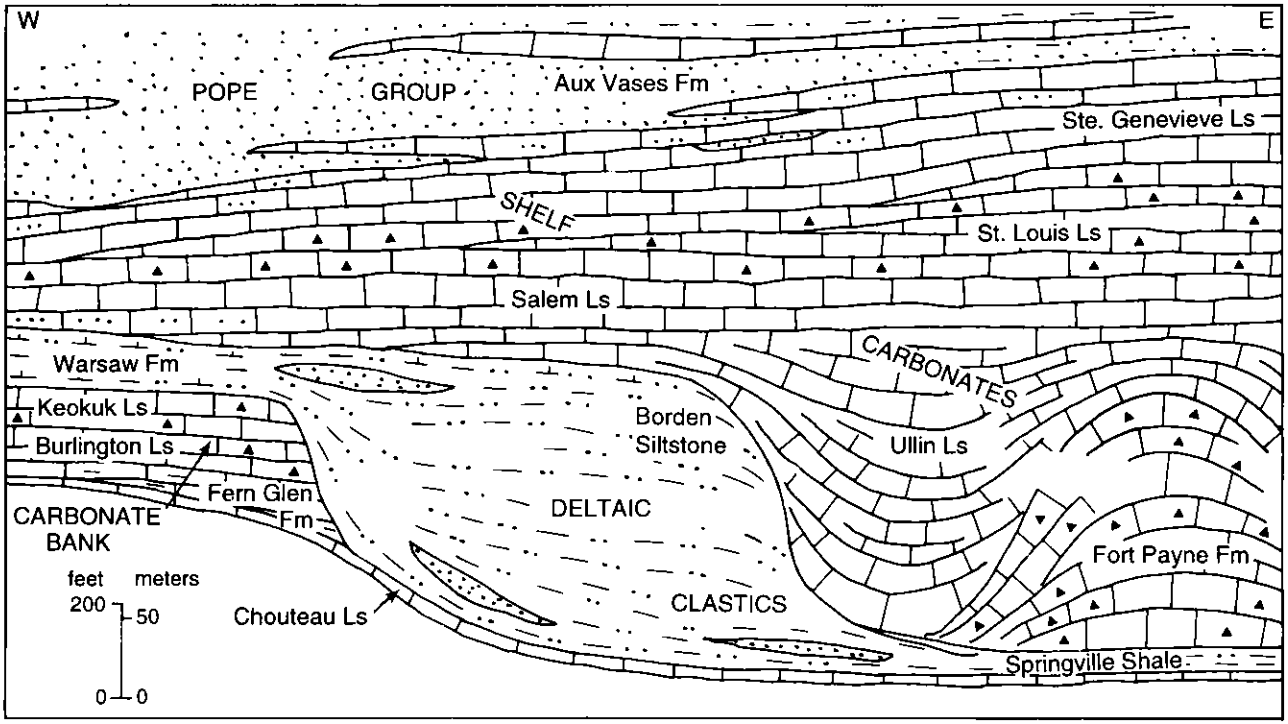


Figure 8. Cross section depicting Valmeyeran facies relationships in study area. No horizontal scale, but left side of diagram corresponds to northwest corner of Paducah quadrangle and right side to south-central part of quadrangle.

deep basin to the east. The Sparta shelf, which had been uplifted during the Devonian, provided a stable foundation. The Borden delta prograded into the deep basin from the Acadian orogenic belt in the Eastern United States (Sable and Dever, 1990). The western side of the delta butted against the flank of the carbonate bank, then overtopped the bank, choking off carbonate production. Well data reveal that the bank-to-delta margin is less than 2 mi (3 km) wide and that little intertonguing of limestone and siltstone occurs along the margin (Swann and others, 1965; Lineback, 1981).

VALMEYERAN SHELF CARBONATES

Valmeyeran deltaic clastics are overlain by a thick succession of limestone called the Mammoth Cave Group (Nelson, 1995). The Mammoth Cave Group comprises the Fort Payne Formation (oldest), Ullin Limestone, "Warsaw" Limestone (Kentucky), Salem Limestone, St. Louis Limestone, and Ste. Genevieve Limestone. Definitions of these formations vary among different workers, and mismatched contacts are common, particularly at State lines. Problems of nomenclature and correlation are discussed at greater length in Nelson (1995).

The Fort Payne Formation thickens from a feather-edge in southwestern Illinois to more than 600 ft (180 m) in parts of Livingston, Lyon, and Marshall Counties, Kentucky. The Fort Payne consists of dark, siliceous dolomitic limestone (60 to 90 percent) and nodular and bedded chert (10 to 40 percent). The limestone varies from lime mudstone to fine-grained crinoid-bryozoan packstone. The Fort Payne disconformably overlies the Springville Shale in Union and Alexander Counties, Illinois (Nelson and others, 1995). Northward, the Fort Payne pinches out against the flank of the Borden delta. Lineback (1966, 1969, 1981) interpreted the contact of the Fort Payne with the Borden delta in Illinois as sharp and conformable, with no intertonguing of lithologies. Lineback further interpreted the Fort Payne as sediments that partly filled a deep-water "starved basin" south of the prograding Borden delta. In Kentucky, this contact is interpreted as either sharp and disconformable(?) or as gradational and intertonguing (Sable and Dever, 1990). A recent cross section in the Paducah quadrangle (Whitaker, Treworgy, and Noger, 1992) depicts intertonguing of the Fort Payne and Borden Siltstone on the flank of the delta.

The Ullin Limestone of southern Illinois and the roughly equivalent "Warsaw" Limestone in western Kentucky are composed of light-gray, cross-bedded crinoid-bryozoan grainstone and packstone. (The name Warsaw Limestone has long been used in Kentucky for a unit that is roughly the same age as the type Warsaw Formation in western Illinois. The name Warsaw Limestone is inappropriate because this limestone differs greatly in lithology from the Warsaw Formation. See Nelson (1995) for further discussion.) Thickness of the Ullin ranges from about 125 ft (38 m) in the northwestern part of the quadrangle to about 700 ft (210 m) in the subsurface of Hamilton County, Illinois (Lineback, 1966). Although Lineback (1966, p. 29) described the

Ullin–Fort Payne contact as sharp, this contact is gradational and intertonguing (Cluff and Lineback, 1981, p. 38; Lasemi and others, 1994; Nelson and others, 1995). Lineback (1966, 1969, 1981) and Cluff and Lineback (1981) interpreted the Ullin as a deep-water deposit that largely filled a "starved basin" that developed seaward from the Borden delta. Cluff and Lineback (1981, p. 38) further proposed that the Ullin was deposited in water 300 ft (90 m) or deeper. These interpretations are questioned on the basis of new research. Lasemi and others (1994) identified Waulsortian mounds in the lower part of the Ullin and "Warsaw." These mounds coalesced laterally and vertically, forming several large carbonate banks surrounded by deeper water where the Fort Payne was deposited. The sea gradually shallowed; cross-bedded grainstone of the upper part of the Ullin and "Warsaw" was deposited in well-agitated water above storm wave base (Sable and Dever, 1990; Lasemi and others, 1994).

The Salem Limestone comprises carbonate rocks of widely varying textures overlying the Ullin Limestone and equivalent units. Salem lithologies include light-colored oolitic and skeletal grainstones, intercalated with darker packstones, wackestones, and lime mudstones. Nearly black, petroliferous lime mudstone has been mapped in the Salem in the Illinois portion of the fluorspar district. The Salem is generally characterized by presence of oolites and endothyrid foraminifera (sparse or absent in enclosing units) and scarcity of dolomite and chert. Both upper and lower contacts of the Salem are gradational and intertonguing (Lineback, 1972; Cluff and Lineback, 1981). Placement of these contacts differs markedly among different geologists, particularly across the Illinois-Kentucky State line (Nelson, 1995).

Thickness trends of the Salem are difficult to assess because of varying definitions of the unit. It is thinnest, 105 to 175 ft (36 to 55 m) thick, in the northwestern corner of the quadrangle and reportedly reaches 500 ft (152 m) in White County, Illinois (Cluff and Lineback, 1981), and in parts of Hardin and adjacent counties, southeastern Illinois (Baxter and others, 1963, 1967; Baxter and Desborough, 1965). In adjacent parts of Kentucky, however, much of the interval assigned to the Salem in Illinois was mapped as "Warsaw" and St. Louis Limestones.

The Salem evidently reflects shallow marine sedimentation. Cluff and Lineback (1981) recognized three to four shoaling-upward cycles in the Salem in the subsurface of southern Illinois. Each cycle contains sediments deposited in shallow subtidal shelf, oolite shoal, lagoon, and intertidal environments. I have observed cycles similar to those described by Cluff and Lineback at outcrops in Union County, Illinois.

The St. Louis Limestone, overlying the Salem, consists mainly of fine-grained cherty limestone and dolomite. The most typical St. Louis lithology is bluish-gray "sublithographic" limestone that contains dark gray to black vitreous chert nodules. Other rock types include fine-grained skeletal wackestone and packstone, microsucrosic dolomite, and (in subsurface) anhydrite (Cluff and Lineback, 1981). The St. Louis contains more chert than adjacent units, and oolitic limestone is uncommon. Both the upper and lower contacts are gradational and intertonguing in most of the report area and have been mapped at different positions by different geologists.

The colonial corals *Acrocyathus proliferus* and *A. floriformis* are widespread and common in the St. Louis (Grabowski, 1986). In southwestern Illinois the acme zone of *A. proliferus* is at or close to the Salem–St. Louis contact, whereas *A. floriformis* occurs in the upper part of the St. Louis (Nelson, Devera, and Masters, 1995).

The St. Louis thickens from about 75 ft (23 m) in northern Perry and Ste. Genevieve Counties, Missouri, to as much as 500 ft (150 m) in outcrops of southeastern Illinois and western Kentucky. An isopach map by Willman and others (1975, p. 141) shows more than 500 ft (150 m) of St. Louis in the subsurface of Saline and Gallatin Counties, Illinois. Intertonguing contacts and differing concepts of the formation prevent precise delineation of St. Louis thickness trends.

Cluff and Lineback (1981, p. 65) attributed fine-grained carbonates of the St. Louis to shallow, subtidal, highly restricted environments similar to modern Florida Bay. Abundant subaerial exposure indicators and evaporites around the margins of the Illinois Basin imply intertidal to supratidal environments. Sable and Dever (1990) supported those interpretations but suggested that upper part of the Salem and the lower part of the St. Louis might have been deposited in deep water below wave base.

The Ste. Genevieve Limestone is the youngest formation in the Mammoth Cave Group. White to light-gray, commonly cross-bedded, oolitic and skeletal grainstone is the most typical lithology. Also present are packstones and wackestones and intervals of dark, cherty lime mudstones and dolomites similar to the St. Louis. The upper part of the Ste. Genevieve is commonly sandy and contains lenses and interbeds of sandstone and greenish-gray shale.

In most of the Paducah quadrangle, the lower contact of the Ste. Genevieve is gradational and intertonguing; its placement is somewhat arbitrary. However, this contact is an angular unconformity in parts of Ste. Genevieve and Perry Counties, Missouri, near the northwest corner of the quadrangle. Here, the bedding of the St. Louis is truncated, and Ste. Genevieve sediments fill fissures at the top of the St. Louis. Locally, the Ste. Genevieve has a basal conglomerate of pebbles derived from the St. Louis along with clasts of chert and limestone holding Middle Devonian corals and brachiopods (Weller and St. Clair, 1928). These features suggest tectonic activity along the Ste. Genevieve fault zone prior to or during deposition of the Ste. Genevieve Limestone.

Thickness of the Ste. Genevieve varies from as little as 20 ft near Lithium, Missouri, where it is unconformable on the St. Louis (Weller and St. Clair, 1928), to about 300 ft (90

m) in the southeastern part of the study area. The Ste. Genevieve intertongues on a large scale with siliciclastic rocks of the overlying Aux Vases Formation. Regionally, lower sandstone tongues of the Aux Vases pinch out toward the southeast, so that the top of the Ste. Genevieve rises southeastward across time lines in a series of steps (Swann, 1963; Nelson and Cole, 1992).

The Ste. Genevieve represents high-energy oolite shoals surrounded by lower energy open-marine and lagoonal areas where lime mud was deposited. Probably the Ste. Genevieve was deposited in slightly deeper water than the St. Louis (Cluff and Lineback, 1981).

POPE GROUP

The upper part of the Kaskaskia sequence is a succession of mixed carbonate and siliciclastic rocks assigned to the Pope Group. Exposures of these strata along the Mississippi River in southwestern Illinois and southeastern Missouri constitute the type section of the Chesterian Provincial Series (Upper Mississippian); however, placement of the lower boundary of the series is still unresolved (Maples and Waters, 1987). The contact between the Mammoth Cave and Pope Groups is time transgressive and involves large-scale intertonguing of carbonate and siliciclastic units (Swann and Willman, 1961; Swann, 1963; Nelson and Cole, 1992).

On the geologic map (plate 1), the Pope Group is divided into upper and lower units (map units Mpu and Mpl, respectively) at the top of the Glen Dean Limestone, a regionally continuous unit. The Pope outcrop belt extends from the northwestern corner through the south-central part of the quadrangle into the Rough Creek graben area, where it is greatly dissected by faulting.

The Pope Group is divided into many formations, the definitions of which commonly change at State boundaries. Descriptions of individual formations are given in Nelson (1995). A cross section (fig. 9) shows the relationships in the lower part of the Pope Group in southern Illinois.

Thickness of the Pope Group ranges from about 500 ft (150 m) near the northwest corner of the quadrangle to more than 1,400 ft (430 m) in parts of southeastern Illinois and western Kentucky. The thickness pattern reflects maximum subsidence near the junction of the Reelfoot rift and Rough Creek graben. Recent studies (Nelson, unpub. data) suggest that faults in the Dixon Springs graben and Wabash Valley area underwent small displacements during deposition of the Pope Group. The Ozark dome was a positive area, as evidenced by thinning of units and changes from offshore to shoal facies on its flanks.

The Pope Group contains roughly equal proportions of limestone and siliciclastic rocks. Many limestones are regionally extensive but intergrade laterally with siliciclastics (fig. 9). Limestones in the lower part of the Pope Group (Glen Dean Limestone and older) lithologically resemble the Ste. Genevieve Limestone. Light-colored crinoidal and oolitic grainstones and packstones predominate; wackestones, lime mudstones, and micro-grained dolomites are subordinate. Limestones in the upper part of the Pope Group are generally darker, more argillaceous lime mudstones and skeletal wackestones. Siliciclastic rocks include dark-gray, olive-gray, and greenish-gray clay shales and silty shales; burrowed and laminated siltstones; and light-gray, very fine to fine-grained quartzarenitic sandstones. Variegated claystones, rooted intervals, and lenticular, shaly coals commonly occur in the upper part of siliciclastic intervals.

Limestones of the Pope Group contain abundant, diverse, marine fossils and sedimentary features indicative of shallow-marine deposition. They represent such environments as shallow subtidal shelf or ramp, ooid shoals, and lagoons (Vincent, 1975; Treworgy, 1988). Most previous geologists interpreted Pope siliciclastic rocks as largely fluvial and deltaic deposits laid down during regressive cycles (Potter, 1962, 1963; Swann, 1963, 1964). Recent studies (Cole, 1990; Nelson and Cole, 1992) indicate that siliciclastics, like carbonates, represent primarily shallow subtidal and intertidal environments and that multiple provenance areas were involved.

Following deposition of the Pope Group, the entire region was subjected to erosion. A system of paleovalleys was cut into Pope strata and filled with sediments of the Absaroka sequence (Sevier, 1951; Bristol and Howard, 1971).

ABSAROKA SEQUENCE

The informally named Absaroka sequence of Sloss and others (1949) and Sloss (1963) comprises rocks ranging from Pennsylvanian through Early Jurassic age. In the Paducah quadrangle, the sequence is represented by Morrowan (Early Pennsylvanian) through Wolfcampian (Early Permian) rocks (fig. 10). The great bulk of the sequence is Pennsylvanian; Permian rocks are present only in small downfaulted slices in Kentucky.

Classification of Pennsylvanian rocks has differed historically between Illinois, Indiana, and Kentucky. For this project, I standardized formational nomenclature, following recent interstate agreements of Jacobson and others (in press). Thus, Absaroka sequence rocks in the Paducah quadrangle are divided into four map units: Caseyville Formation (oldest), Tradewater Formation, Carbondale Formation, and McLeansboro Group.

CASEYVILLE FORMATION

The Caseyville Formation (Morrowan age) occurs in numerous grabens in the Illinois-Kentucky fluorspar district and also around the rim of the Eagle Valley–Moorman

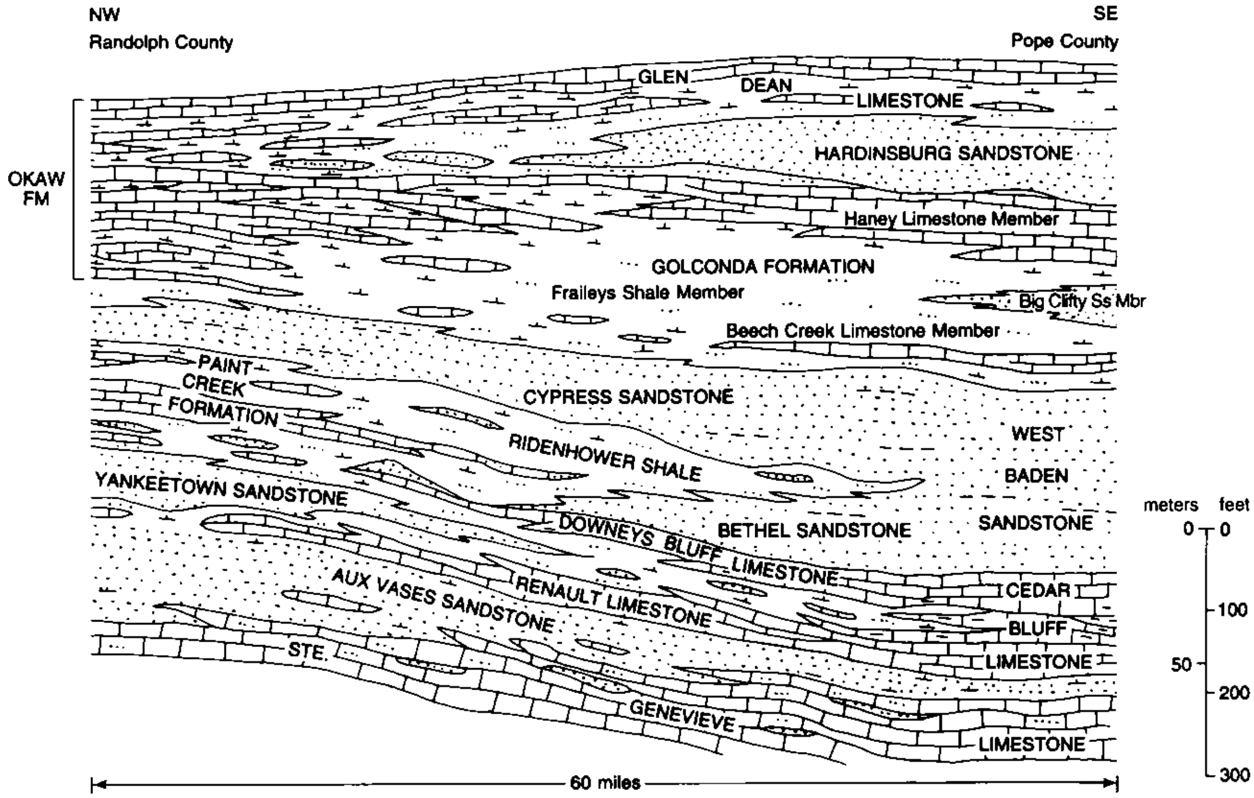


Figure 9. Cross section depicting facies relationships in the lower part of the Pope Group in the Paducah quadrangle. The Aux Vases Sandstone was derived from the northwest; it intergrades with limestone toward the southeast. Younger sandstones, derived from the northeast or east, thin westward.

syncline and in a belt that curves northwestward from Pope to southern Jackson Counties, Illinois. In northern Jackson and Randolph Counties, the Caseyville and overlying Tradewater Formations were mapped as a single unit. The Caseyville is characterized by bluff-forming massive and cross-bedded quartzarenites that contain common well-rounded quartz pebbles. These sandstones are coarser than any of the Pope Group and are petrographically more mature than younger Pennsylvanian sandstones. Caseyville sandstones are interbedded with light- to dark-gray shale and siltstone, thin lenticular coal, and rare impure limestone. Sandstones are lenticular; rapid lateral facies changes are the rule.

Thickness of the Caseyville in the mapped area varies from about 100 to 500 ft (30 to 150 m). It is thickest in the southeast part of the quadrangle and thinnest in the northwest part. The regional thickness trend reflects continued rapid subsidence of the Reelfoot rift and Rough Creek graben.

Several structures were active during deposition of the Caseyville (fig. 11). These include segments of the Rough Creek fault system in western Kentucky (Greb, 1989) and the Lusk Creek fault zone in southern Illinois (Weibel and others, 1993). The Ste. Genevieve fault zone was active during Caseyville deposition; the southwestern block was uplifted (fig. 6). Evidence for displacement along the Ste. Genevieve includes chert clasts derived from the upthrown block in basal Caseyville conglomerates (Poor, 1925), abrupt diversion of Caseyville paleo-drainage (Desborough, 1961a), and intra-Caseyville angular unconformities (Desborough, 1961b). The Pomona fault, which may be regarded as a segment of the Ste. Genevieve fault zone, also was active during deposition of the Caseyville, as shown by the fact that the Pope Group is faulted but the Caseyville merely warped into a gentle monocline.

Another active structure was the Du Quoin monocline (fig. 11), which lies mostly north of the study area. The east side of the monocline was downwarped throughout, as well as after, Pennsylvanian time, but the largest displacements took place early in the Pennsylvanian (Siever, 1951; Nelson, 1991). The Bodenschatz-Lick fault zone in Jackson County, Illinois, also may have been active during the Morrowan. Borehole data indicate that Mississippian and older rocks are faulted, whereas Caseyville rocks that outcrop along the Bodenschatz-Lick are merely folded (Nelson and Lumm, 1985). Farther east, the McCormick and New Burnside anticlines both appear to have been positive during Morrowan time, as shown by thinning of the Caseyville on the crests of the folds. Potter (1957) described a large paleoslump in the Caseyville on the south flank of the McCormick and attributed it to contemporaneous uplift and seismic activity.

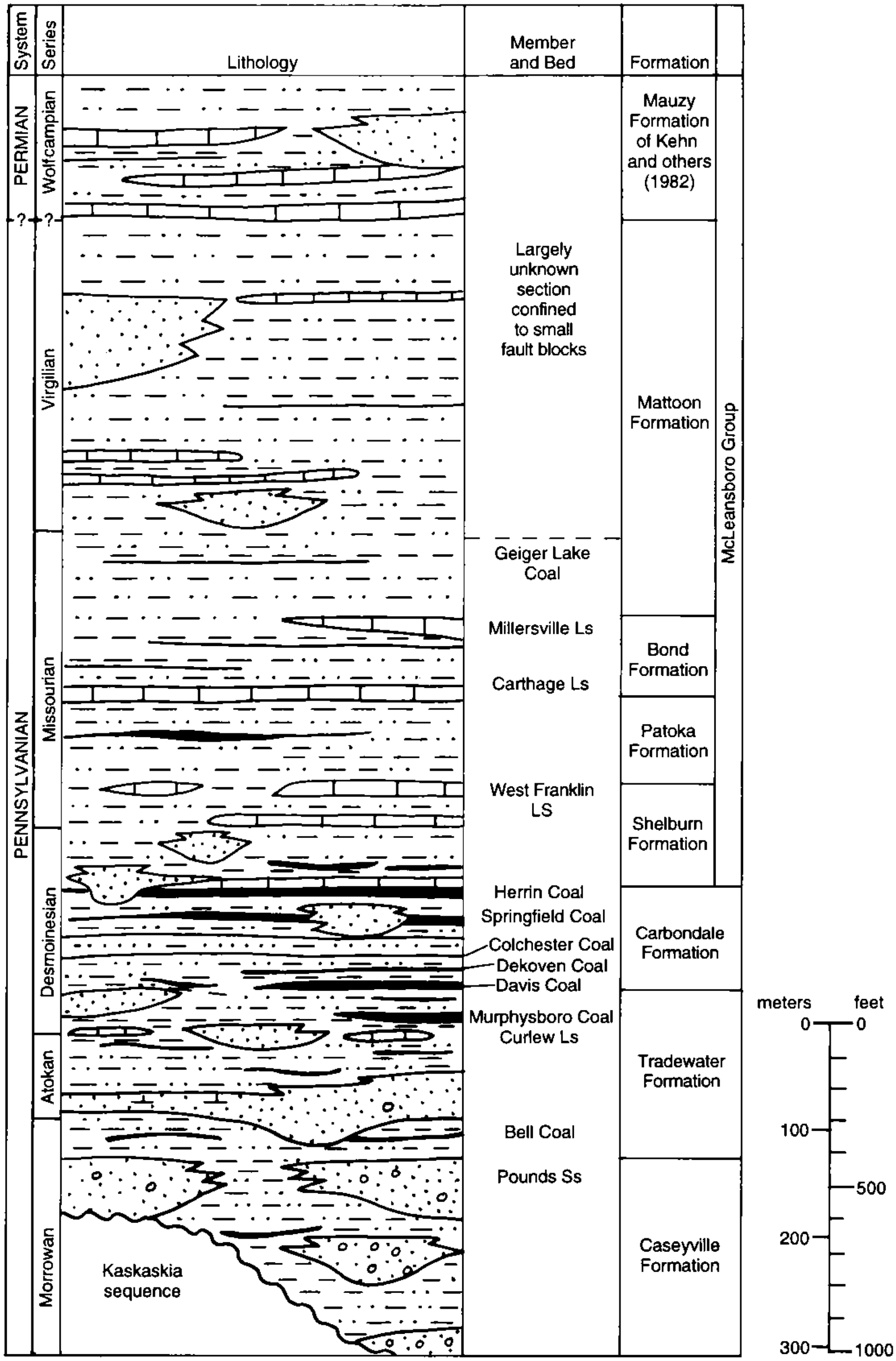


Figure 10. Generalized stratigraphic column of Absaroka sequence. The upper one-third of the sequence is based on the electric log of a single drill hole in a graben south of the Rough Creek fault system in the Grove Center quadrangle, Kentucky. Coals are ranked as beds (informal) in Kentucky and as members (formal) in Illinois.

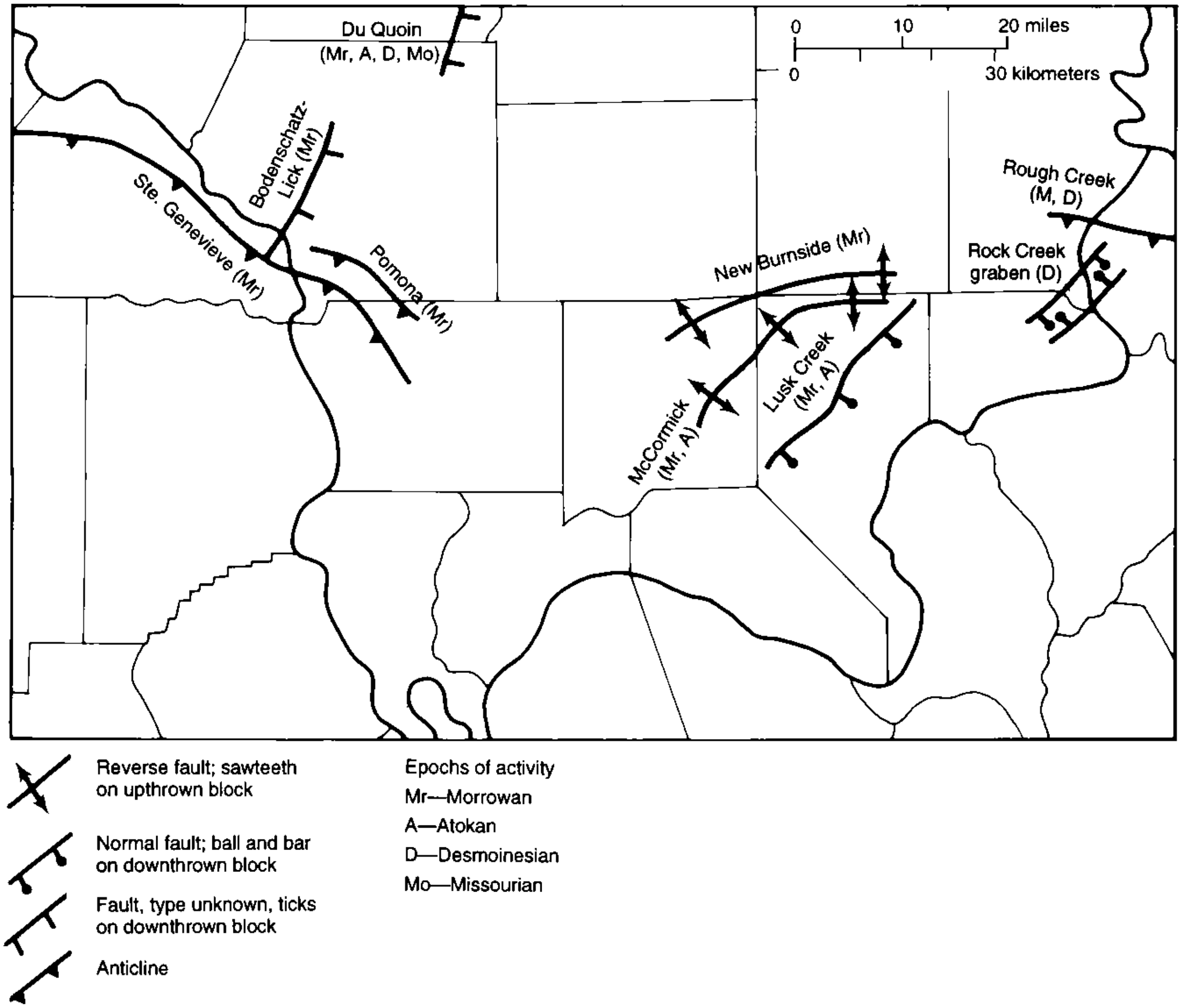


Figure 11. Map of Paducah quadrangle showing structures that were active during the Pennsylvanian Period, with epochs of activity indicated by letter symbols.

In synopsis (fig. 11), the east-west-trending Rough Creek and northwest-southeast-trending Pomona and Ste. Genevieve fault zones underwent reverse displacement during the Morrowan (the hanging wall, on the south or southwest, was elevated). These displacements are consistent with compression from the south or southwest. Normal displacements (hanging wall down) on the Lusk Creek fault zone also are consistent with compression from the south or southwest. The direction of dip of the Bodenschatz-Lick fault zone is unknown, as is the dip direction of the basement fault that presumably underlies the Du Quoin monocline. If these are normal faults, they would fit the pattern. The McCormick and New Burnside anticlines seemingly do not fit the pattern. If viewed as compressional structures, a compressive stress axis oriented northwest-southeast would be required. An alternate model views these anticlines as the surficial expression of normal faulting at depth (fig. 12). In this model, the Lusk Creek fault zone originated as a normal fault during Cambrian rifting, whereas the McCormick and New Burnside originated as parallel, incipient fracture zones (fig. 12*A*). During Morrowan time, Lusk Creek, McCormick and New Burnside faults were reactivated, tilting Mississippian strata as Caseyville sediments were being deposited (fig. 12*B*). This model fits available data, although the existence of faults, as shown in fig. 12*B*, cannot be verified.

The Caseyville thickens in sub-Absaroka paleovalleys. The lower members of the Caseyville are generally confined to paleovalleys, whereas the upper members overlap intervening divides (Sedimentation Seminar, 1978; Greb and others, 1992; and unpublished subsurface studies in Illinois by the author and Russell J. Jacobson of the Illinois State Geological Survey). The upper contact is gradational and locally intertonguing; it is mapped at the highest occurrence of quartzarenite and quartz-pebble conglomerate.

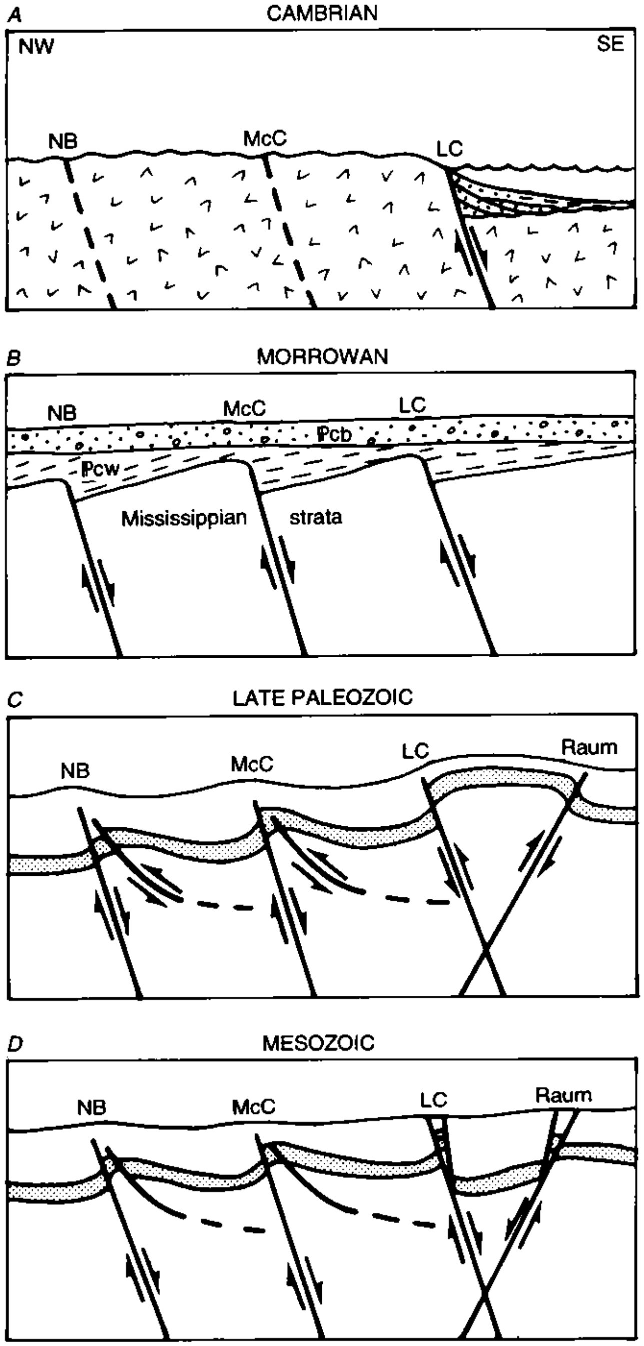


Figure 12. Diagram (not to scale) illustrating four episodes of tectonic activity involving the New Burnside anticline (NB), McCormick anticline (McC), Lusk Creek fault zone (LC), and Raum fault zone, all in southern Illinois. In diagram *B*, Pcb, Battery Rock Sandstone Member of Caseyville Formation; Pcw, Wayside Member of Caseyville Formation.

Regionally, the Caseyville is part of a system of Lower Pennsylvanian quartzarenites and conglomerates extending from southwestern New York State to southern Illinois. Grain-size trends, petrology, and paleocurrent orientations indicate a northeastern source, most likely highlands in New England and southeastern Canada uplifted during early phases of the Alleghany orogeny (Potter and Sevier, 1956; Nelson, 1989).

Previous workers (Potter, 1963; Ethridge and others, 1973; Koeninger and Mansfield, 1979) attributed the Caseyville to fluvial and deltaic environments similar to the modern Mississippi delta. More recent studies of body fossils (Devera and others, 1987), trace fossils (Devera, 1989), and sedimentary features (Kvale and Uhlir, 1988) demonstrate that portions of the Caseyville were deposited in shallow marine, tidal-flat, and estuarine settings. Eustasy may have influenced Caseyville sedimentation. Valleys eroded during regressions were backfilled by coarse, pebbly sand as sea level rose. Fine-grained Caseyville strata may be largely deposits of regional highstand (maximum sea level).

TRADEWATER FORMATION

In its type area of western Kentucky, the Tradewater Formation is the interval of strata from the top of the Caseyville Formation to the base of the Davis coal bed (Greb and others, 1992). The Tradewater is mapped in southern Illinois using the same definition (Jacobson and others, in press). In the Paducah quadrangle, the Tradewater was mapped using the base of the Davis coal bed[2] as the upper boundary east of long. 89° W. and the base of the slightly younger Colchester Coal Member west of long. 89°W. This shift of boundary was made because the Davis has not been mapped west of long. 89° W.

The Tradewater Formation consists predominantly of sandstone, siltstone, and shale. Sandstones are sublitharenites and litharenites that rarely contain quartz pebbles. They contain mica, feldspar, lithic fragments, and interstitial clay. Siltstones and shales are similar to those of the Caseyville. Coals are generally lenticular but locally attain minable thickness. Argillaceous and arenaceous limestones and black, fissile shales are also present, becoming more numerous and widely traceable in the upper part of the formation.

The Tradewater regionally thickens southeastward from about 300 ft (90 m) in Jackson County, Illinois, to more than 650 ft (200 m) in parts of western Kentucky. The Reelfoot rift–Rough Creek graben area continued to subside rapidly. Faults including the Rough Creek fault system, the Lusk Creek fault zone (Weibel and others, 1993), and other faults in the Fluorspar Area fault complex were active during Tradewater sedimentation. In western Kentucky, segments of the Pennyrile fault system may have been active during Tradewater deposition (Lumm and others, 1991). The Tradewater thickens markedly on the east side of the Du Quoin monocline (fig. 11), reflecting continued growth of this structure (Siever, 1951).

[2] In Kentucky, coal seams are ranked as beds and considered informal (Davis coal bed). In Illinois, most coal seams are ranked as members and considered formal units: (Davis Coal Member).

Scarcity of marine body fossils, common occurrence of coal and plant fossils, and presence of cross-bedded channel-form sandstones led previous geologists to conclude that the Tradewater was deposited in largely nonmarine, fluvial, and deltaic environments (Potter, 1963; Ethridge and others, 1973). Widespread marine indicators, including trace fossils and tidally laminated sediments, have been described in recent studies of the Tradewater (Devera, 1989; Devera and others, 1992; Nelson and others, 1991; Kvale and Archer, 1989). Probably the Tradewater, like the Caseyville, represents alternating fluvial, deltaic, estuarine, and shallow subtidal sedimentation controlled by eustasy, tectonic activity, and autocyclic processes. The change from quartz arenites of the Caseyville to lithic arenites of the Tradewater may reflect "unroofing" of the crystalline basement in the eastern source areas (Potter and Sevier, 1956; Nelson, 1989).

CARBONDALE FORMATION

The Carbondale Formation contains most of the minable coal deposits of the Illinois Basin. As mapped on plate 1, the Carbondale comprises strata from the base of the Davis coal (east of long. 89° W.) or Colchester coal (west of long. 89° W.) to the top of the Herrin coal (throughout the quadrangle).

The Carbondale Formation is characterized by great lateral persistence of certain members—the coals, limestones, and black fissile shales. The sandstones, siltstones, and gray shales that volumetrically make up 90 to 95 percent of the Carbondale are lithologically similar to those of the Tradewater. Carbondale strata exhibit pronounced cyclicity in vertical succession. The concept of the cyclothem originally developed from studies of the Carbondale Formation (Langenheim and Nelson, 1992).

The Carbondale thickens eastward across the report area, from about 175 ft (55 m) on the west to 400 ft (120 m) on the east. Tectonic movements were less pronounced than earlier in Pennsylvanian time. The Du Quoin monocline continued to rise (fig. 11), and small-scale movements along the Rough Creek fault system may have triggered paleoslumping during Carbondale deposition (Nelson and Lumm, 1987; Kolata and Nelson, 1991a).

In the typical Carbondale cyclothem, the coal (in situ peat) is overlain by black fissile shale (highly restricted marine, anoxic waters) and limestone with shelly fauna (open-marine shelf). In some cases, a gray shale wedge (estuarine, deltaic, or lacustrine) intervenes between coal and black shale. The marine limestone is overlain by upward-coarsening siliciclastics, locally incised by channel-filling sandstones and reflecting progradation of deltas or shoreline. The cycle ends with rooted underclay, representing the paleosol on which the peat (coal) of the next cycle accumulated.

Unquestionably, the Carbondale contains both marine and terrestrial sediments. Because less siliciclastic sediment was coming into the region, deposition of limestone was more frequent. Greater tectonic stability is implied by the great regional extent of many thin units. Arguments over the factors that controlled cyclicity, including tectonic, eustatic, autogenic, and others, are summarized in Langenheim and Nelson (1992).

McLEANSBORO GROUP

Pennsylvanian strata overlying the Carbondale Formation in the report area are assigned to the McLeansboro Group. The name McLeansboro replaces Sturgis Formation, previously used for these rocks in western Kentucky, because McLeansboro has priority (Nelson, 1995). The McLeansboro underlies a broad area covering the north-central and northeastern parts of the Paducah quadrangle along with the core of the Eagle Valley–Moorman syncline south of the Rough Creek fault system. The McLeansboro outcrop belt is mostly mantled by Quaternary deposits; the succession is based largely on borehole data.

The McLeansboro Group contains four formations: Shelburn, Patoka, Bond, and Mattoon Formations (Jacobson and others, in press). All are lithologically similar; boundaries are defined at the tops or bases of widespread limestone members. No maps showing these limestones in the Paducah quadrangle are available. Therefore, formations of the McLeansboro Group are not differentiated on plate 1.

The McLeansboro Group lithologically resembles the Carbondale Formation, containing numerous cyclic deposits of sandstone, siltstone, shale, coal, and limestone. Coals of the McLeansboro generally are thinner, and limestones of the McLeansboro are thicker and more numerous than those of the Carbondale. Coals, black fissile shales, and limestones are widely traceable.

The top of the McLeansboro Group is an erosional surface overlain by Quaternary sediments throughout the Paducah quadrangle. The thickest preserved section is about 2,600 ft (790 m) thick, in a borehole just east of the Ohio River in the Grove Center quadrangle, Union County, Kentucky (Palmer, 1976). The borehole lies in a deep northeast-trending graben on the south side of the Rough Creek fault system. Wolfcampian (Early Permian) fusulinids were described from a core about 2,150 ft (655 m) above the Herrin coal bed in another graben a few miles east of the Grove Center quadrangle (Kehn and others, 1982). Therefore, Permian strata probably are present in the graben in the Grove Center quadrangle also. These are the youngest known Paleozoic rocks in the Illinois Basin.

Depositional and tectonic patterns established earlier in Pennsylvanian time seem to have persisted into McLeansboro deposition. Thickness and facies patterns suggest, however, that the primary source of siliciclastic material shifted from the northeast to the south in late Missourian and Virgilian time (Nelson, Trask, and others, 1991; Weibel, 1992). The shift in source area may reflect the uplift of mountains south of the Illinois Basin as a consequence of the Ouachita orogeny.

POST-PENNSYLVANIAN TECTONISM

Widespread faulting took place in the Paducah quadrangle after deposition of the Absaroka sequence and before deposition of the Zuni sequence (Cretaceous). Two major tectonic episodes have been inferred. The first involved reverse and strike-slip faulting, folding, and igneous activity consistent with compressional stress. This activity is believed to be late Paleozoic (Late Pennsylvanian and Permian) and probably was associated with the compressional Alleghany and Ouachita orogenies. The second episode involved normal faulting indicative of extensional stress and most likely was connected with widespread rifting during Triassic and Jurassic time.

COMPRESSIONAL EVENTS

Compressional deformation took place in many parts of the Paducah quadrangle. Deformation in the western part of the quadrangle took place both during and after Pennsylvanian deposition, whereas that in the eastern part was largely, if not entirely, post-Pennsylvanian.

In the western part of the report area, the Ste. Genevieve fault zone underwent reverse displacement with attendant monoclinal folding (fig. 6). Movement may have begun during late Chesterian time and definitely was under way in Morrowan time while the Caseyville Formation was being deposited (Poor, 1925; Desborough, 1961a, 1961b; Nelson and Lumm, 1985). Displacement continued after Morrowan sedimentation, producing as much as 4,000 ft (1,200 m) of stratigraphic separation across the fault zone. The timing of later movements cannot be deduced because post-Morrowan strata have been eroded from the area.

The Du Quoin monocline, as previously mentioned, rose intermittently during Pennsylvanian deposition, being particularly active during Atokan and early Desmoinesian time. The monocline underwent additional post-Pennsylvanian uplift, folding the youngest (Missourian) strata in the area.

Numerous northwest-trending fault zones have been mapped in Missouri southwest of the Ste. Genevieve fault zone. These faults displace Devonian and older rocks and appear to be offset by northeast-trending faults that also displace Cretaceous rocks. Little is known of the style of deformation on northwest-striking faults in the Paducah quadrangle. Using evidence from west of the Paducah quadrangle, Clendenin and others (1989) inferred late Paleozoic(?) "upthrust" high-angle reverse and sinistral strike-slip displacement along northwest-trending faults.

The events outlined above generally are consistent with a stress field having maximum compression oriented NE.-SW. to NNE.-SSW. Such a stress field is reasonably associated with the late Paleozoic Ouachita orogeny, southwest of the area.

In the eastern half of the Paducah quadrangle, high-angle dip-slip reverse displacements took place along the Rough Creek–Shawneetown fault system and Lusk Creek fault zone (fig. 12). The greatest vertical separation is about 3,500 ft (1,070 m) along the east-trending portion of the Rough Creek–Shawneetown just east of the big bend in the fault system in southeastern Saline County, Illinois (Nelson and Lumm, 1987). The big bend represents juncture of Reelfoot rift and Rough Creek graben boundary faults. West of the big bend, the McCormick and New Burnside anticlines are seismically shown to be thrust-folds detached within the Paleozoic section (Nelson, 1987, and unpub. data). Farther north, the Cottage Grove fault system is a right-lateral system that exhibits less than a mile (1.6 km) of strike-slip and as much as 200 ft (60 m) of dip-slip displacement. The Cottage Grove displaces Missourian and older rocks, whereas peridotite dikes dated as Early Permian have intruded along some of the faults (Nelson and Krausse, 1981; Nelson and Lumm, 1987). All deformation mentioned in this paragraph is consistent with NW.-SE. compressional stress applied in Late Pennsylvanian and Permian time (Kolata and Nelson, 1991a).

The "crypto-explosive" structure Hicks dome, centered in Hardin County, Illinois, was a center for igneous activity. Ultramafic dikes radiate from the dome along a NNW.-trending axis, forming a bow-tie pattern (fig. 3). The dikes are radiometrically dated as Early Permian (Zartman and others, 1967). Some of the dikes follow small strike-slip faults that are offset by northeast-trending mineralized faults in the fluorspar district (Hook, 1974; Trace, 1974). On Hicks dome itself are shatter breccias, vent breccias, and carbonatites, along with unusual minerals (Bradbury and Baxter, 1992). Explosive release of gases heated by or derived from alkalic magma at depth is postulated (Bradbury and Baxter, 1992). The orientation of dikes implies the principal compressive stress axis was NNW.-ESE.

EXTENSIONAL EVENTS

Early Mesozoic(?) NW.-SE. extension of the eastern part of the report area is implied by northeast-trending, high-angle normal faults. The greatest concentration of such faults is in the Fluorspar Area fault complex. These faults, which are mineralized with fluorite and metallic sulfides, parallel major Cambrian normal faults of the Reelfoot rift. Some of them displace Early Permian ultramafic dikes. At the edge of the Mississippi Embayment, the Fluorspar Area faults displace Cretaceous strata, but vertical separations are much greater on Paleozoic than Cretaceous rocks (Rhoades and Mistler, 1941; Amos, 1967). Those observations indicate that most of the normal faulting was post-Permian, pre-Cretaceous.

North of the Fluorspar Area fault complex, north- and northeast-trending normal faults of the Wabash Valley fault system displace Missourian (Upper Pennsylvanian) and older rocks and apparently do not deform Quaternary sediments (Ault and others, 1980; Bristol and Treworgy, 1979). Whether these faults exploited preexisting fractures is undetermined. A northeast extension of the Reelfoot rift into southern Indiana was postulated (Braile and others, 1982; Sexton and others, 1986), but published and proprietary seismic data fail to confirm existence of such a structure (Pratt and others, 1989; Nelson, 1991).

Large-scale normal displacements took place along the Lusk Creek fault zone and Rough Creek–Shawneetown fault zone. The normal displacements post-dated late Paleozoic(?) reverse displacements, returning the blocks south and southeast of the faults to, or below, the pre-Pennsylvanian position (fig. 12). Slices of the hanging walls of the faults were sheared off and left high within the fault zone. For example, at Horseshoe, on the Gallatin-Saline County line along the Shawneetown fault zone, a hanging-wall slice of New Albany Shale (Upper Devonian) and Fort Payne Formation (Mississippian) is juxtaposed with Pennsylvanian rocks on both sides of the fault zone. As the hanging wall was lowered during normal movements it was drag-folded, creating the northern limb of the Eagle Valley–Moorman syncline (Smith and Palmer, 1981; Nelson and Lumm, 1987; Nelson, 1991).

ZUNI SEQUENCE

The informally named Zuni sequence of Sloss and others (1949) and Sloss (1963) is represented in the Paducah quadrangle by Upper Cretaceous and Paleocene strata in the Mississippi Embayment (fig. 13). These weakly lithified sediments crop out in an arcuate belt from southeastern Missouri across southernmost Illinois to western Kentucky, at the northern edge of the embayment. Outliers occur farther north on isolated hilltops and in grabens.

The oldest unit in the Zuni sequence is the Tuscaloosa Formation (Upper Cretaceous), which is composed mainly of chert gravel. The pebbles are mostly white to light gray, stained yellow to brown, subrounded to subangular, and 1 to 3 inches (2.5 to 7.5 cm) in diameter. Occasional cobbles are as large as 10 inches (25 cm). The gravel has a matrix of light-gray clay, silt, and quartz sand and contains lenses of the same materials. Cement is absent, except locally along faults where ferruginous cements are present. Reddish-brown fine- to medium-grained sand and sandstone in the Eddyville quadrangle, Kentucky, was mapped as Tuscaloosa (Rogers, 1963). The Tuscaloosa is lenticular, and ranges from a few feet to 75 ft (23 m) thick in most of the report area, reaching a maximum thickness of about 180 ft (55 m) in the Calvert City quadrangle, Kentucky (Amos and Finch, 1968).

The McNairy Formation (Upper Cretaceous) conformably overlies the Tuscaloosa or rests on Paleozoic bedrock where the Tuscaloosa is absent. The McNairy consists of sand and weakly indurated sandstone intercalated with lesser amounts of clay, silt, gravel, and lignite. Sand is white to yellow, red, and brown, fine to medium grained, and is composed of quartz with conspicuous amounts of mica and some glauconite. Scattered chert granules are present. A local facies of the McNairy is white, well-sorted, cross-bedded quartzarenite (informally known as Commerce quartzite), found south and east of Cape Girardeau, Mo. (Johnson, 1985; Nelson and others, 1995). Clay and silt in the McNairy are light to dark gray, micaceous and lignitic. Gravel is found mostly near the base of the McNairy and can be difficult to distinguish from Tuscaloosa gravel. Lignite beds are discontinuous and less than 1 ft (30 cm) thick. The McNairy attains a maximum thickness of 450 ft (137 m) in southern Illinois.

The McNairy was interpreted as fluvial and deltaic sediments derived from metamorphic source terranes in the Appalachians (Potter and Pryor, 1961). However, the Commerce quartzite (informal), a supermature quartzarenite that contains bidirectional cross-bedding, probably is a nearshore marine deposit.

The youngest Cretaceous unit in the report area is the Owl Creek Formation, a discontinuous unit of micaceous, glauconitic clay and silt. Sand occurs as scattered grains and as laminae and lenses. Gastropods, pelecypods, cephalopods, and U-shaped burrows are common, indicating marine sedimentation. The Owl Creek, identified at scattered localities in Illinois and Missouri, is less than 20 ft (6 m) thick.

Unconformably overlying Cretaceous strata is the Midway Group (Paleocene). Two formations are recognized: the Clayton Formation and the Porters Creek Clay. The Clayton Formation, which was not separated from the McNairy by quadrangle mappers in Kentucky, is a thin but widespread unit of green, greenish-brown, and orange-brown glauconitic clay. It is micaceous and contains lenses of sand, particularly near the base. The clay is commonly bioturbated, and it contains bivalves, gastropods, and foraminifera. The Clayton is about 5 to 20 ft (1.5 to 6 m) thick in the report area. The overlying Porters Creek Clay is largely massive and blocky greenish-gray, olive-gray to black calcium montmorillonite clay, mined for use as absorbants. Silt, sand, mica, glauconite, and lignite flakes are common near the base. Fossils include gastropods, bivalves, radiolarians, palynymorphs, and fish remains. The Porters Creek is 45 to 220 ft (14 to 67 m) thick, reaching its maximum in parts of Ballard and McCracken Counties, Kentucky.

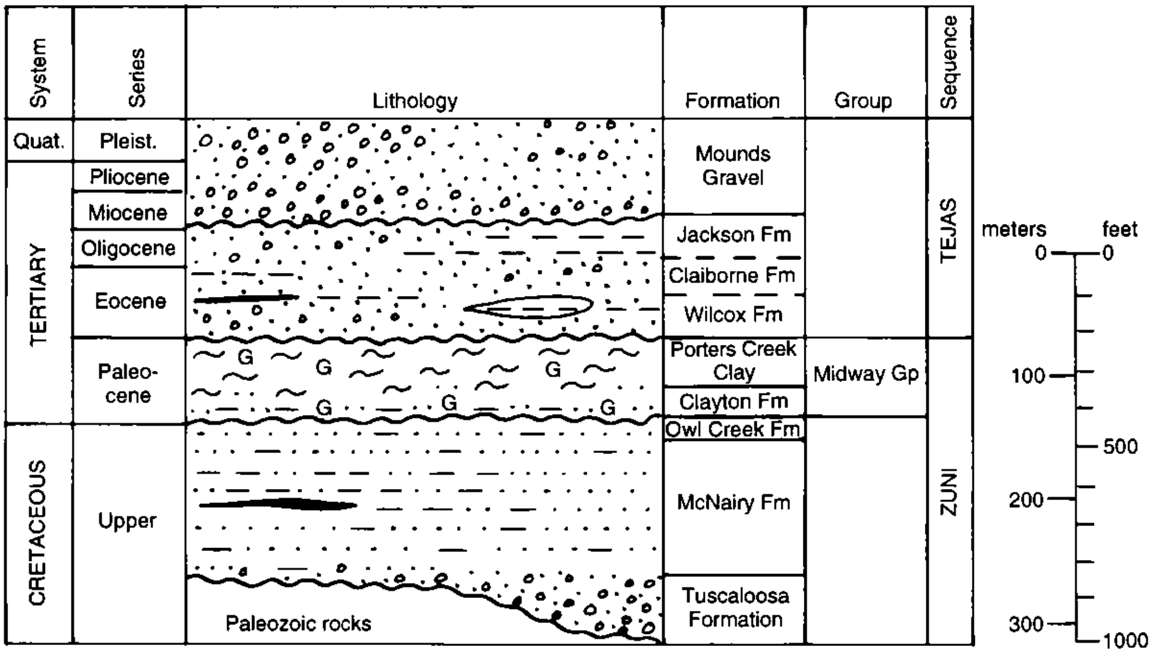


Figure 13. Generalized stratigraphic column of the Zuni and Tejas sequences. Quat., Quaternary; Pleist., Pleistocene.

TEJAS SEQUENCE

The informally named Tejas sequence (Sloss and others, 1949; Sloss, 1963) in the report area comprises Eocene and younger sedimentary deposits (fig. 13). The Eocene Wilcox, Claiborne, and Jackson Formations occur in the Mississippi Embayment along the south-central edge of the Paducah quadrangle. Small outliers of Eocene sediments lie north of the embayment in Union and Alexander Counties, Illinois. Post-Eocene deposits of the Tejas sequence were considered "surficial deposits" in CUSMAP and are not shown on the bedrock geologic map. They are mentioned briefly below because some of them are tectonically deformed in the report area.

The Wilcox Formation is composed of white to yellowish-brown unlithified to weakly lithified sand, with lenses of clay and lignite. The sand is fine to very coarse and commonly contains laminae and lenses of rounded light- to dark-gray chert granules and small pebbles. Sand-size grains of kaolinitic clay, called "sawdust sand," are characteristic of the Wilcox in some areas. Clay of the Wilcox is gray to reddish-brown and partly silty. Within the Mississippi Embayment, the Wilcox ranges up to 125 ft (38 m) thick in Missouri and 250 ft (75 m) in Kentucky and Illinois.

Deposits similar to the Wilcox are found as hilltop outliers and in small grabens in Alexander and Union Counties, Illinois (Nelson, Devera, and Masters, 1995). These sediments are composed of sand and gray to black rounded chert gravels, similar to but coarser than Wilcox gravels found farther south. Near Mountain Glen, Cobden quadrangle, Union County, kaolinitic clay formerly was mined from fault-bounded depressions in Paleozoic bedrock (St. Clair, 1917; Devera and Nelson, 1995). Intercalated with the clay was sand, Wilcox-type gravel and lenses of lignite. Palynymorphs from the lignite were identified as Eocene age (D.J. Nichols, written commun., 1993).

The Claiborne (older) and Jackson Formations occur in Ballard and McCracken Counties, Kentucky. These units are not differentiated on available source maps and were combined with the Wilcox Formation on the geologic map that accompanies this report (plate 1). Moreover, some strata that have been called Wilcox in southern Illinois and Missouri match the descriptions of the Jackson and Claiborne Formations given by Olive (1980). The Claiborne is of middle Eocene age; the Jackson is late Eocene and Oligocene (Olive, 1980). The Claiborne and Jackson are composed mostly of sand, with interbeds of clay and silt. Sand is white, yellow, red, and brown; fine to very coarse; and cross-bedded. Clay pebbles and rip-up clasts are common. Clay and silt are light gray to brown, sandy, and kaolinitic. The undivided Claiborne and Jackson Formations reach a maximum thickness of about 180 ft (55 m) in the Paducah quadrangle.

The Mounds Gravel (called Lafayette Gravel or continental deposits by many geologists) occurs as ridge-top deposits throughout the Mississippi Embayment and lies directly on Paleozoic bedrock north of the embayment. The Mounds is composed predominantly of rounded chert pebbles that bear a glossy bronze or yellow-brown patina. Palynymorphs from western Kentucky indicate Miocene(?) to early Pleistocene(?) age (Olive, 1980). Willman and Frye

(1970) assigned a Pliocene to early Pleistocene age to the Mounds based on regional relationships.

POST-CRETACEOUS TECTONISM

The Paducah quadrangle lies immediately north of the most active earthquake region of the North American Midcontinent—the New Madrid seismic zone. The New Madrid zone is an ancient zone of weakness, the Reelfoot rift, that has been reactivated repeatedly since Cambrian time (Braile and others, 1982; Kolata and Nelson, 1991). Documenting post-Cretaceous tectonism is difficult because Cretaceous and younger sediments are largely unlithified and occur in areas of low relief. Recent mapping provides convincing evidence of widespread tectonic faulting of Cretaceous and younger units in the southern part of the Paducah quadrangle. The style and trend of these faults are mostly consistent with the contemporary stress regime and with the inferred style and trend of active faults in the New Madrid area (fig. 14).

Northeast-trending faults of the Fluorspar Area fault complex displace the Tuscaloosa and McNairy Formations (Upper Cretaceous) at the edge of the Mississippi Embayment east of Paducah, Ky. (Rhoades and Mistler, 1941; Amos, 1967, 1974; Amos and Finch, 1968; Amos and Wolfe, 1966). Post-Cretaceous vertical separations are small: 100 ft (30 m) or less, compared to separations as great as 2,400 ft (730 m) on the same faults in Mississippian bedrock. The possibility of a strike-slip component to post-Cretaceous faulting has not been investigated.

Post-Cretaceous faulting is well known in the Thebes Gap area, Missouri-Illinois (south of Cape Girardeau). Early work in the area was summarized by McCracken (1971; p. 20, under heading "Commerce anticlinorium"), who concluded, "***deformation may still be in progress." Johnson (1985) mapped several northeast-trending faults displacing the Wilcox Formation (Eocene) in the Missouri part of the Thebes quadrangle. New mapping by Harrison and Schultz (1992) at Thebes Gap shows a series of northeast-trending fault zones that exhibit fracture patterns consistent with dextral strike-slip. Small pull-apart grabens (divergent wrenching) contain chaotically oriented blocks of Paleozoic, Cretaceous, and early Tertiary formations. Units as young as the Mounds Gravel (Miocene to early Pleistocene?) are folded and offset by faults that bear horizontal striations. Equivocal evidence further suggests that Pleistocene loess may be faulted (Harrison and Schultz, 1992).

Thebes Gap is at the northeast end of the Benton Hills, a range of hills known as Crowleys Ridge farther to the southwest. Crowleys Ridge and the Benton Hills are composed of Cretaceous and Tertiary sedimentary formations that rise above Holocene alluvium of the Mississippi flood plain. Geophysical studies in northeast Arkansas indicate that Crowleys Ridge is a tectonic uplift bounded by northeast-trending, post-Eocene strike-slip faults (Van Arsdale and others, 1992).

On the eastern flank of the Ozark dome are small grabens that have anomalously large displacements. Examples of such grabens are the Marble Hill, Scopus, Randol Creek, and Radio Tower structures (McCracken, 1971) and other, unnamed grabens mapped near the Jackson fault zone and near the city of Cape Girardeau (Amos 1987a, 1987b; Satterfield, 1973). These structures are surrounded by Lower and Middle Ordovician carbonate rocks (mostly dolomite) and contain chaotic blocks of Ordovician, Silurian, and Devonian formations downdropped as much as 2,400 ft (730 m) relative to the wallrocks. Such displacements contrast with throws of less than 300 ft (90 m) on most other mapped faults in the area. The McNairy Formation (Cretaceous) is downdropped in three of these structures, located in the Scopus (Amos, 1987b), Marble Hill (Amos, 1987a), and Dongola (Amos, 1981) quadrangles (fig. 14). A detailed map of the Marble Hill structure is presented here (fig. 15). The structure occurs at the intersection of a lengthy fault zone that strikes northwest and a shorter fault zone that strikes ENE. The country rock is largely Ordovician Cotter Dolomite. Blocks of various formations as young as the Silurian and Devonian Bailey Limestone are in grabens along the northwest-trending fault zone. The narrower, ENE.-trending graben contains slices of Ordovician Powell and Smithville Dolomites, displaced only a few hundred feet at most, along with slices containing McNairy Formation. The picture shown in figure 15 is incomplete because much of the structure (particularly west of the town of Marble Hill) is concealed by Quaternary alluvium.

McCracken (1971) suggested that features such as the Marble Hill structure were produced by a combination of tectonic activity and solution collapse. I contend that solution played, at most, a minor role in creation of these features. The Cotter Dolomite is less subject to karstification than many other units in the study area, such as the Ordovician Kimmswick and Mississippian Salem and St. Louis Limestones, wherein no such structures are found. These grabens are closely similar to pull-apart structures created by divergent wrench faulting in the Thebes Gap area (Harrison and Schultz, 1992). Given a region broken by two or more sets of intersecting fractures, any tangential stress would produce extensional grabens along one or more sets of fractures.

Tectonic faults that displace Cretaceous and Eocene sediments occur in Alexander and Union Counties, Illinois. The longest of these faults trend mostly north-south; shorter faults strike east-west and northeast-southwest. All faults dip more or less vertically. Some display small "flower structures," pull-apart grabens, and horizontal striations, which imply an important element of strike-slip (Nelson and Devera, 1994; Nelson, Devera, and Masters, 1995; Devera and Nelson, 1995). The largest post-Cretaceous fault in the area is labeled "Iron Mountain fault" in figure 14. The Iron

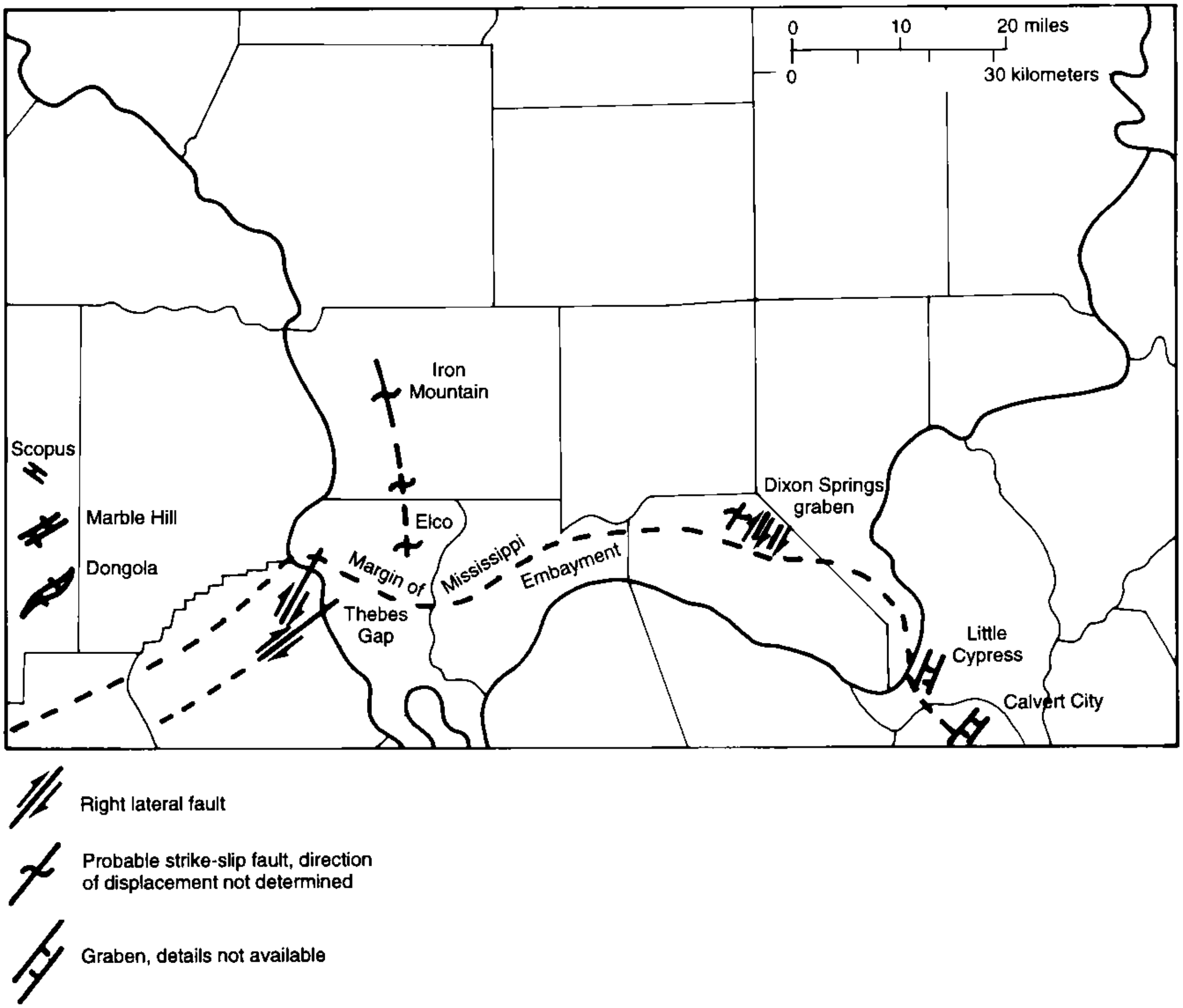


Figure 14. Map of Paducah quadrangle showing faults that displace Cretaceous and younger strata within the Paducah quadrangle.

Mountain fault appears to be a southward branch or extension of the Ste. Genevieve fault zone. Devonian and Mississippian rocks on the west side are in fault contact with probable Eocene sediments on the east; the vertical component of displacement is at least 100 ft (30 m). Farther south, near Elco, a light-colored chert gravel lithologically similar to the Cretaceous Tuscaloosa Formation is juxtaposed with Lower Mississippian rocks along faults that strike E.-W., NNW.-SSE., and NE.-SW.

New mapping reveals faults that displace units as young as the Miocene to early Pleistocene(?) Mounds Gravel in Pope and Massac Counties, Illinois. These displacements occur where faults forming the Dixon Springs graben pass into the Mississippi Embayment (fig. 14). The faults strike northeast and outline narrow grabens that may be pull-apart structures created by transtensional wrenching. Previously, Ross (1963, p. 20) and Kolata and others (1981, p. 19) discussed the Round Knob site (sec. 28, T. 14 S., R. 5 E., Massac County), where the McNairy Formation and Mounds Gravel are downdropped and tilted. This site is directly in line with a fault zone in Mississippian bedrock to the northeast. A cored test hole drilled by the Illinois State Geological Survey in 1994 shows that the Mounds is downfaulted 200 ft (60 m) relative to nearby outcrops and boreholes.

The present-day stress regime of the Paducah area is one of horizontal compression with the principal stress axis oriented E.-W. to N. 65° E. Consistent stress readings are given by earthquake focal-plane solutions, borehole breakout and hydrofracturing data, and direct strain measurements in underground mines. Also, small north-trending thrust faults in coal mines of southeastern Illinois and western Kentucky fit the contemporary stress field. This stress is sufficient to create north-trending thrusts in relatively incompetent rocks, such as coals and shales (Nelson and Bauer, 1987). This stress orientation also is consistent with the orientation and

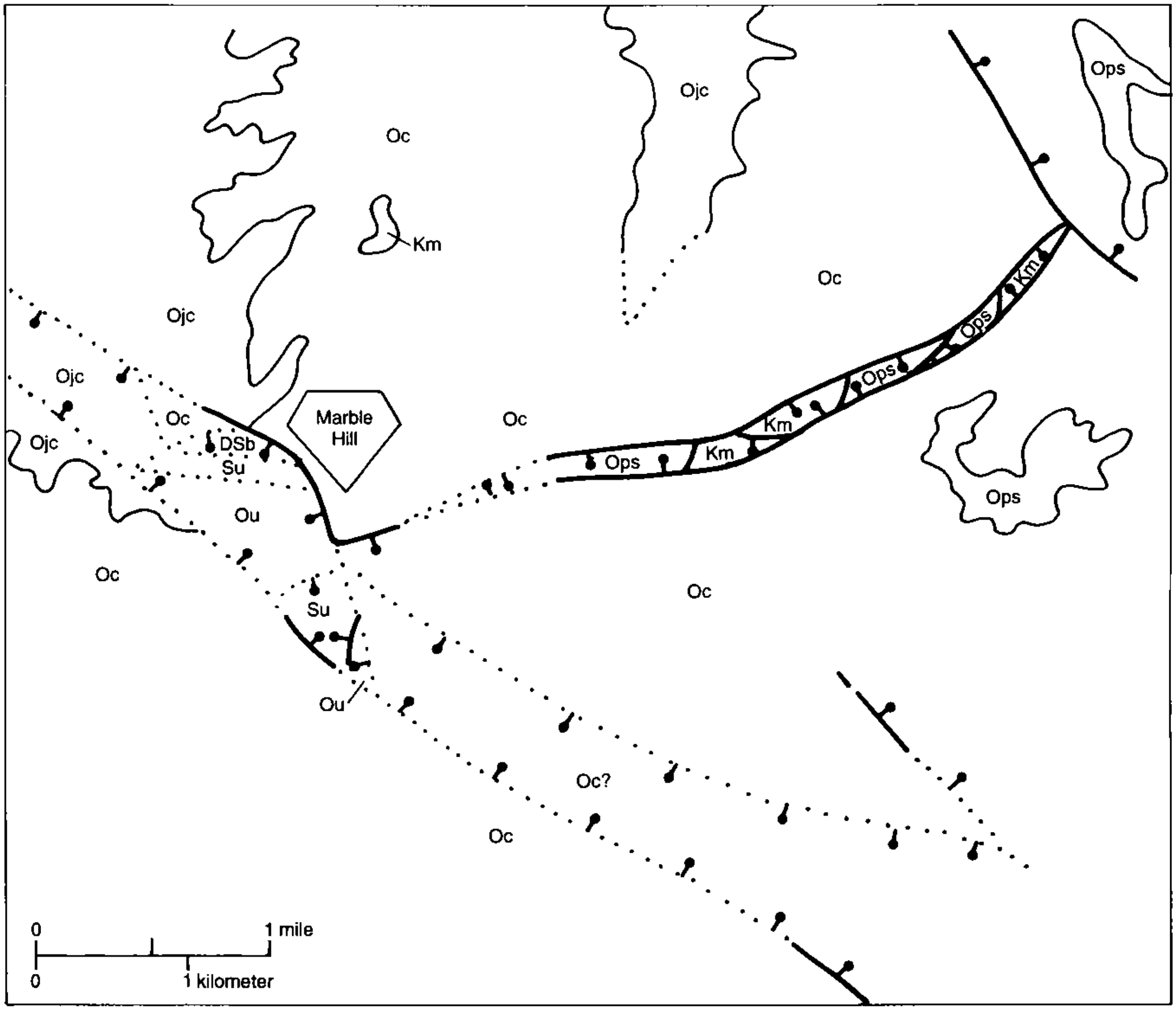


Figure 15. Map showing the Marble Hill structure in Bollinger County, Missouri, from Amos (1987a). See figure 3 for location (near west edge of Paducah 1°×2° quadrangle). Unit symbols: Ojc, Jefferson City Dolomite; Oc, Cotter Dolomite; Ops, Powell and Smithville Dolomites undivided; Ou, Ordovician rocks undivided; Su, Silurian rocks undivided; DSb, Bailey Limestone; Km, McNairy Formation. Displacements are as great as 2,400 ft (730 m) in the graben south of Marble Hill; this compares to displacements of 300 ft (90 m) or less on other faults in the area. The graben east of Marble Hill has relatively small displacements, but Cretaceous strata are involved. These structures are interpreted as pull-apart grabens induced by wrench faulting.

sense of slip on most post-Cretaceous faults in the Paducah quadrangle (Nelson and Harrison, 1993).

In summary, Cretaceous and Tertiary sedimentary rocks as young as the Mounds Gravel are displaced by tectonic faults in the southern part of the Paducah quadrangle. Faulting has been documented in Illinois, Kentucky, and Missouri. Most faults strike northeast and exhibit transtensional, dextral shear. Small vertical separations on most of these faults partially explain why they were not readily recognized. The sense of slip is consistent with that of seismically active elements of the New Madrid seismic zone and also fits the measured contemporary stress field. The northeast-trending faults originated in Cambrian rifting and have been recurrently active for some 550 million years. We have no reason to believe that they are inactive today.

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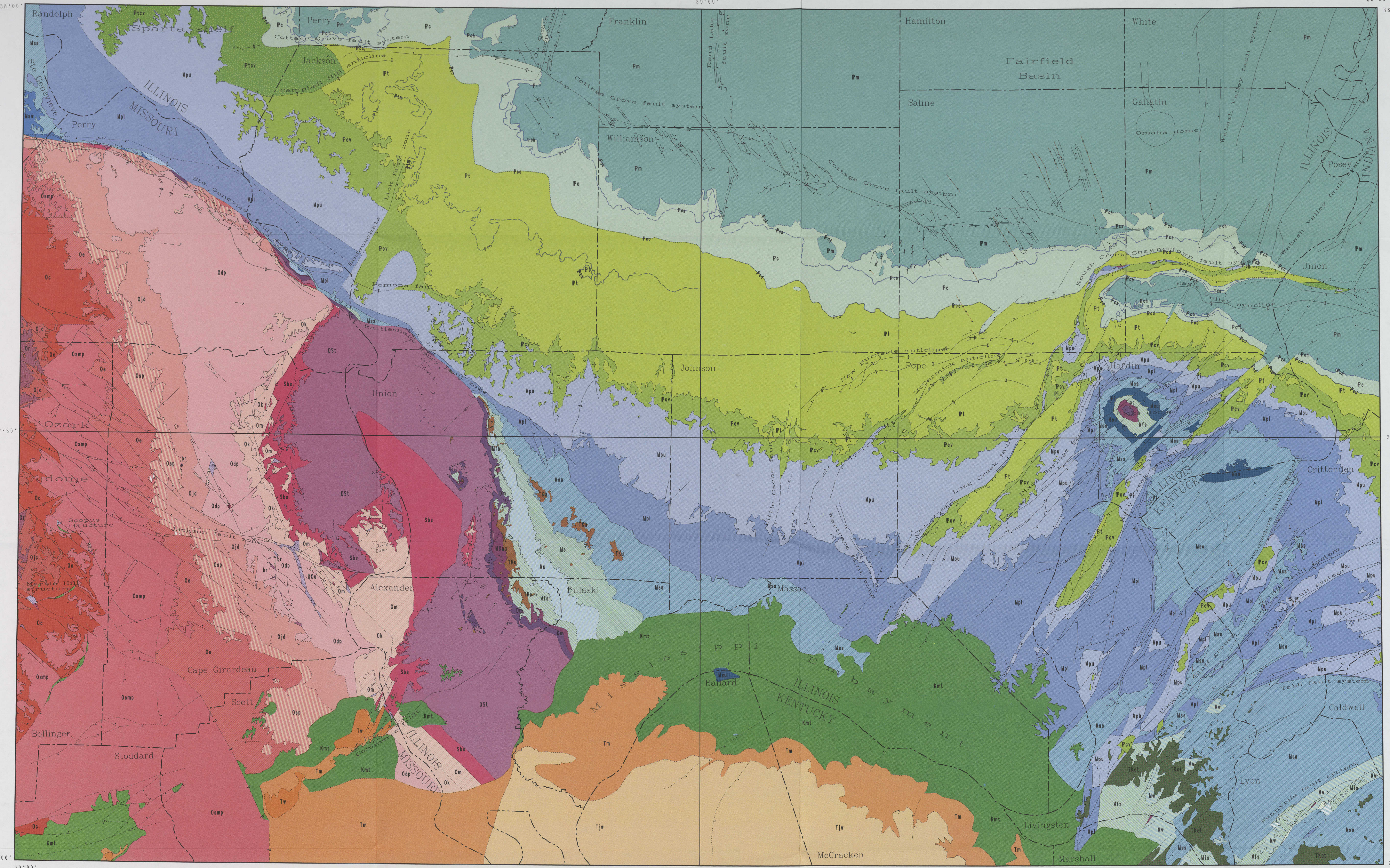
PLATE 1



Digital geologic data prepared with ARC/INFO 7.0.4 running on a Sun workstation (Solaris 2.4)

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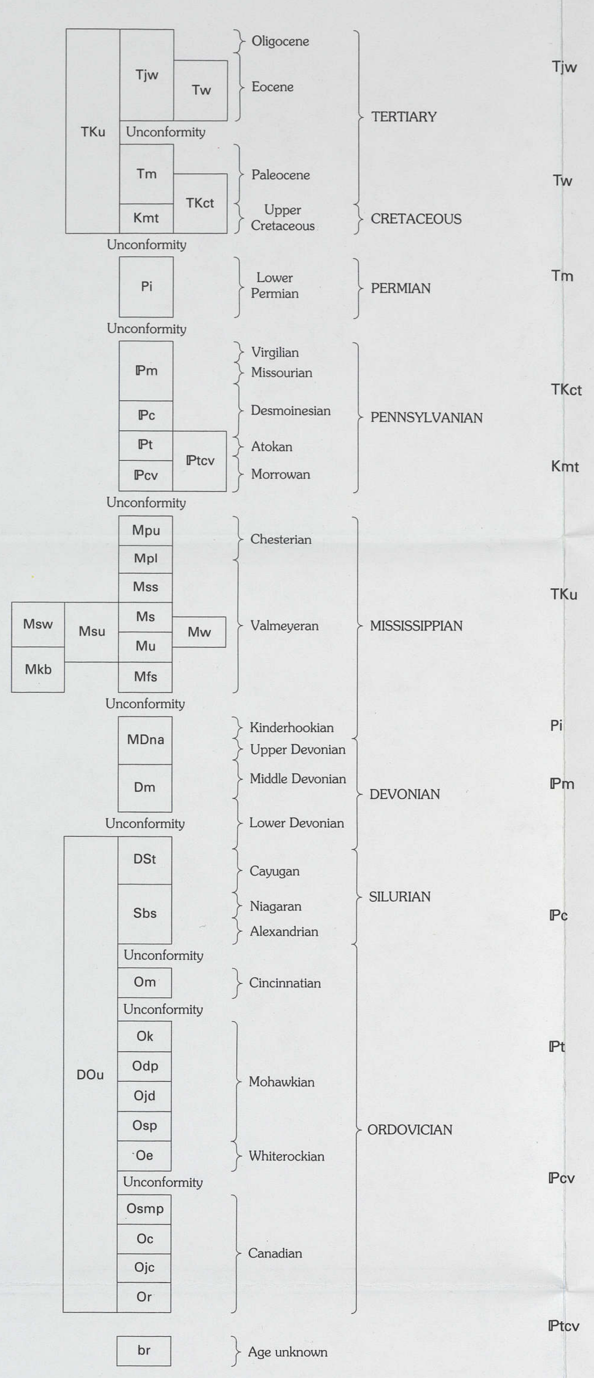
CORRELATION OF MAP UNITS



DESCRIPTION OF MAP UNITS

Tjw **Jackson, Claiborne, and Wilcox Formations, undivided (Oligocene and Eocene)**—Fine- to coarse-grained multihued sand, with lenses and interbeds of kaolinitic clay and silt. Small, well-rounded pebbles of quartz and gray to black chert are common. Maximum thickness 430 ft

Tw **Wilcox Formation (Eocene)**—White to yellowish-brown, fine to coarse sand, with lenses of clay and lignite. Small, well-rounded, gray to black chert pebbles are common. May include Jackson and Claiborne equivalents in some areas. Maximum thickness 250 ft

Tm **Midway Group (Paleocene)**—Comprises the Porters Creek Clay (younger) and the Clayton Formation. The Porters Creek is 45 to 220 ft thick and is mostly blocky montmorillonitic clay that is greenish gray, olive gray, and black. The Clayton is a thin (5 to 20 ft thick) unit of sandy, glauconitic clay

TKct **Clayton Formation of the Midway Group (Paleocene) and McNairy and Tuscaloosa Formations, undivided (Upper Cretaceous)**—Undifferentiated at east edge of Mississippi Embayment in Kentucky

Kmt **McNairy and Tuscaloosa Formations, undivided (Upper Cretaceous)**—The McNairy is composed of white to red, yellow, orange, fine-grained, micaceous sand and medium- to dark-gray, laminated, micaceous clay and silt. Maximum thickness about 450 ft. The Tuscaloosa is a discontinuous unit composed largely of light-colored chert gravel as much as 180 ft thick

TKu **Tertiary and Cretaceous strata, undivided**—Gravel, sand, silt, clay, lignite, conglomerate, and sandstone. Includes lithologies typical of Tuscaloosa and McNairy Formations (Cretaceous), lignitic clay with Eocene pollen, and possibly younger Tertiary gravel. Occurs in outliers and downfaulted blocks in southwestern Illinois. Maximum thickness at least 100 ft

Pi **Permian igneous intrusion (Lower Permian)**—Ultramafic rocks and breccias in dikes and diatremes near Hicks dome

Pm **McLeansboro Group (Pennsylvanian; upper Desmoinesian through Virgilian)**—Cyclically repetitive sandstone, siltstone, shale, limestone, and thin coal. Many units of limestone, black fissile shale, coal, and underclay are regionally traceable. The thickest known section, in a graben in Union County, Kentucky, is 2,600 ft thick and may include Permian strata at the top

Pc **Carbondale Formation (Pennsylvanian; Desmoinesian)**—Cyclically repetitive sandstone, siltstone, shale, limestone, and coal with regionally traceable units of limestone, black fissile shale, coal, and underclay. The Carbondale contains most of the commercially minable coal beds in the Illinois Basin. Thickness 175 to 400 ft

Pt **Tradewater Formation (Pennsylvanian; upper Morrowan through lower Desmoinesian)**—Sandstone, siltstone, shale, lenticular coal, and limestone. The Tradewater has less obvious cyclicity than younger Pennsylvanian rocks, and marker beds are more difficult to trace. Sandstones are generally sublitharenites. Thickens to the southeast; 300 to 700 ft thick

Pcv **Caseyville Formation (Pennsylvanian; Morowan)**—Sandstone, siltstone, shale, thin coal, rare limestone. Cross-bedded to massive quartz arenite containing well-rounded quartz pebbles is characteristic of the Caseyville. Lateral facies changes are rapid, and cyclicity is generally not evident. Thickness 190 to 500 ft; rapid thickness changes on deeply incised sub-Pennsylvanian unconformity

Ptcv **Tradewater and Caseyville Formations (Pennsylvanian)**—Undifferentiated near northwest corner of map area

Mpu **Pope Group, upper part (Mississippian; Chesterian)**—Sandstone/shale formations alternate with limestone/shale formations. The upper part of the Pope Group comprises units from the Kinkaid Limestone downward through the Tar Springs Sandstone and is 200 to 700 ft thick

Mpl **Pope Group, lower part (Mississippian; Chesterian and upper Valmeyeran)**—Sandstone/shale and limestone/shale formations alternate. Units from the Glen Dean Limestone downward through the Aux Vases Sandstone are included. Thickens eastward from about 400 to 700 ft thick

Mss **Ste. Genevieve and St. Louis Limestones, undivided, of the Mammoth Cave Group (Mississippian; Valmeyeran)**—The Ste. Genevieve Limestone, 45 to 300 ft thick, is largely light-gray, cross-bedded, oolitic and skeletal grainstone. The St. Louis Limestone, 75 to 500 ft thick (as mapped), is typically medium- to dark-gray, cherty lime mudstone to fine-grained packstone. Boundaries of units intertongue and were mapped inconsistently by different geologists. In Kentucky, the Salem Limestone was mapped together with the St. Louis and Ste. Genevieve

Ms **Salem Limestone of the Mammoth Cave Group (Mississippian; Valmeyeran)**—Fossil-fragmental limestone, ranging from light-gray grainstone and packstone to dark-gray, argillaceous and cherty wackestone and lime mudstone. Rounded and oolitically coated fossil grains are common. The Salem, like most Valmeyeran limestone formations, was mapped inconsistently by different authors. Thickness (as mapped) ranges from 110 to 500 ft

Mu **Ullin Limestone of the Mammoth Cave Group (Mississippian; Valmeyeran)**—The upper part is light-gray, coarse, cross-bedded, crinoid-bryozoan packstone and grainstone; the lower part is darker, finer grained, and slightly cherty. Contacts are gradational and intertonguing. The Ullin was mapped in Illinois only. Thickness ranges from 125 to 700 ft; commonly thins as underlying Fort Payne thickens

Mw **"Warsaw" Limestone of the Mammoth Cave Group (Mississippian; Valmeyeran)**—The "Warsaw" Limestone in Kentucky is lithologically similar and temporally equivalent to the Ullin Limestone and lower part of the Salem Limestone in Illinois

Msu **Salem and Ullin Limestones, undivided, of the Mammoth Cave Group (Mississippian; Valmeyeran)**—Mapped near Hicks dome in Hardin County, Illinois

Msw **Salem Limestone of the Mammoth Cave Group and Warsaw Formation, undivided (Mississippian; Valmeyeran)**—Mapped in Missouri only. The Warsaw Formation is composed of interbedded shaly, fossiliferous limestone and gray, calcareous, fossiliferous shale. Thickness ranges from 130 to 210 ft

Mfs **Fort Payne Formation and Springville Shale (Mississippian; Valmeyeran)**—The Fort Payne consists of limestone and dolomite that are dark colored, fine grained, glauconitic, and very cherty and siliceous. It thickens eastward from a feather-edge to 600 ft thick. The Springville consists of 5 to 60 ft of greenish-gray silty shale and siltstone that generally coarsen upward

Mkb **Keokuk, Burlington Limestones and Fern Glen Formation (Mississippian; Valmeyeran)**—The Keokuk and Burlington Limestones are mostly white to light brownish gray, coarse crinoidal limestones that contain abundant chert layers and nodules. Together, they are 200 to 400 ft thick. The Fern Glen is yellowish brown, fossiliferous, cherty limestone with interbeds of green to brown shale; it is 50 to 160 ft thick

MDna **New Albany Shale (Mississippian (Kinderhookian) and Upper Devonian)**—Dark olive to greenish-gray and black shale that is fissile, silty, pyritic, and rich in disseminated organic matter. Absent in places in western third of quadrangle; maximum thickness is 460 ft in Hardin County, Illinois

Dm **Muscatatuck Group (Middle and upper Lower Devonian)**—Comprises the St. Laurent Formation and the Grand Tower Limestone. The St. Laurent, 100 to 200 ft thick, is largely dark, fine-grained, cherty limestone that is interbedded with calcareous shale and siltstone. The Grand Tower is lighter gray, coarser, skeletal limestone that is sandy and includes a basal quartz arenite, the Dutch Creek Sandstone Member. The Grand Tower is as much as 230 ft thick and thickens to the east

DSt **Tamms group of Rogers (1972) (Lower Devonian and Silurian; Cayugan)**—Constituent units are the Clear Creek Formation (youngest), Backbone or Little Saline Limestone, Grassy Knob Chert, and Bailey Limestone. Light-colored, fine-grained, highly siliceous and cherty limestone and dolomite predominate. The Backbone or Little Saline is coarse crinoidal grainstone. Largely absent northeast of Ste. Genevieve fault zone due to Late Devonian erosion; the group thickens southward to 1,200 ft

DOu **Devonian, Silurian, and Ordovician rocks, undifferentiated**—Tilted and jumbled blocks, as much as several thousand feet in maximum dimension, of various Canadian through Lower Devonian formations; found in pull-apart grabens in Missouri

Sbs **Bainbridge Formation and Sexton Creek Limestone, undivided (Silurian; Cayugan to Alexandrian)**—The Moccasin Springs Member of the Bainbridge (Cayugan and Niagaran) is composed of interbedded reddish to greenish-gray marly limestone and calcareous shale, 60 to 200 ft thick. The St. Clair Limestone Member of the Bainbridge (Niagaran) is reddish-gray lime mudstone that contains scattered red crinoid grains and is 12 to 60 ft thick. The Sexton Creek Limestone (Alexandrian) is thinly bedded, light-gray lime mudstone and skeletal wackestone that contains numerous layers of caramel-colored chert. It is 15 to 125 ft thick

Om **Maquoketa Formation (Ordovician; Cincinnatian)**—Comprises four members, in descending order: Girardeau Limestone Member, lime mudstone with dark shale interbeds; Orchard Creek Shale Member, dark-gray calcareous shale with thin limestone interbeds; Thebes Sandstone Member, siltstone to very fine grained sandstone that is laminated and burrowed; Cape La Croix Shale Member, dark-gray, very soft shale. Total thickness of Maquoketa is 100 to 300 ft

Ok **Kimmswick Limestone (Ordovician; Mohawkian)**—Coarse-grained, white to light-pink and gray crinoidal grainstone that is quarried for high-calcium limestone. Thickness 50 to 165 ft

Odp **Decorah Formation, Plattin Limestone, and Pecatonica(?) Formation, undivided (Ordovician; Mohawkian)**—The Decorah is a thin unit (10 to 30 ft thick) of interbedded fossiliferous limestone and greenish-gray calcareous shale. The Plattin and Pecatonica(?) both are dominantly dark-gray micritic limestone that is commonly laminated and burrowed ("fucoidal"). Thickness is 350 to 600 ft, increasing to the south. Distinguishing the Pecatonica(?) from the Plattin is problematic

Ojd **Joachim Dolomite and Dutchtown Formation (Ordovician; Mohawkian)**—The Joachim is 130 to 275 ft thick and is composed of gray to brownish-gray, microcrystalline to finely crystalline dolomite that contains thin interbeds of shale and sandstone. The Dutchtown is dark-gray micritic limestone and dolomite that contains bitumen-filled vugs and emits a petroliferous odor when struck. It thickens southward from 20 to 185 ft

Osp **St. Peter Sandstone (Ordovician; Mohawkian)**—The sandstone is composed of nearly 100 percent white to clear quartz grains that are frosted and well-rounded. Thickness varies in irregular fashion from 50 to 210 ft

Knox Group (Ordovician; Canadian and Whiterockian)

Oe **Everton Formation (Whiterockian)**—Contains varying proportions of quartz arenite (similar to St. Peter Sandstone), dolomitic sandstone, and sandy dolomite. Thickness 70 to 400 ft, increasing to the southeast

Osmp **Smithville and Powell Dolomites (Canadian)**—Largely light brownish gray, microcrystalline to finely crystalline dolomite that is cherty and contains greenish shale interbeds. Thickness ranges from 170 to 600 ft. The two formations were not defined or mapped consistently by various authors

Oc **Cotter Dolomite (Canadian)**—Light brownish gray, microcrystalline to medium-crystalline dolomite that is silty and sandy, thickly bedded, and contains thick chert bands and nodules. Thickens eastward from 90 to 380 ft

Ojc **Jefferson City Dolomite (Canadian)**—Microcrystalline to finely crystalline dolomite that is shaly, thin bedded to medium bedded, and cherty. Thickness is 165 to 280 ft

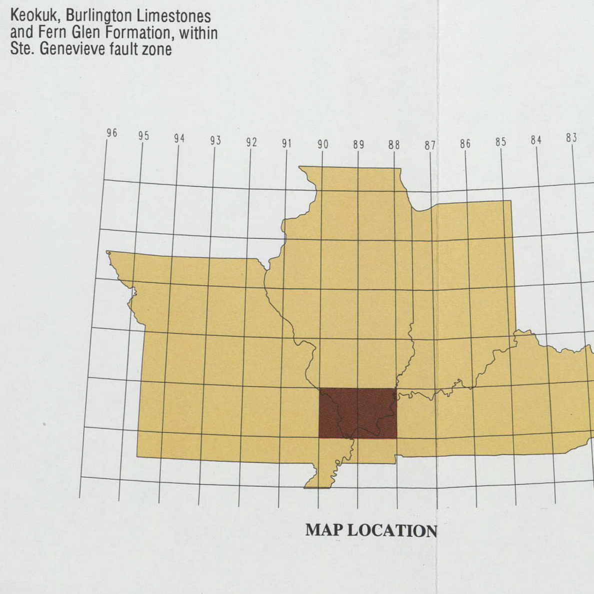
Or **Roubidoux Formation (Canadian)**—Light to medium brownish gray, sandy dolomite, most of which is thickly bedded. Interbeds of dolomitic sandstone composed of rounded, frosted quartz grains. Maximum exposed thickness 160 ft; total thickness 155 to 320 ft

br **Breccia (age unknown)**—Confined to small pipes and pull-apart grabens in northern Cape Girardeau County, Missouri. Consists of sedimentary rock fragments, including chert derived from the Bailey Limestone (Upper Silurian and Lower Devonian), in a groundmass of dark-red, plastic clay. Origin may be a combination of tectonic extension and solution collapse

LIST OF MAP UNITS

Line symbols are dashed where inferred, dotted where concealed, and queried where unknown.

- Tjw — Jackson, Claiborne and Wilcox Formations
- Tw — Wilcox Formation (in Scott and Stoddard Counties, Missouri)
- Tm — Midway Group
- TKct — Clayton and McNairy Formations and Tuscaloosa Gravel
- Kmt — McNairy Formation and Tuscaloosa Gravel (in Illinois)
- TKu — Tertiary and Cretaceous strata undivided (in Alexander and Union Counties, Illinois)
- Pi — Permian igneous intrusion
- Permian igneous dike
- Permian intrusion along a fault
- Pm — McLeansboro Group
- Pc — Carbondale Formation
- Pt — Tradewater Formation
- Pcv — Caseyville Formation
- Ptcv — Tradewater and Caseyville Formations
- Pch — Herrin Coal Member or coal bed
- Pcs — Springfield Coal Member or coal bed
- Pcc — Colchester Coal Member
- Pcd — Davis Coal Member or coal bed
- Pcm — Murphysboro Coal Member (in Tradewater Formation)
- Mpu — Pope Group, above Glen Dean Limestone
- Mpl — Pope Group, below Glen Dean Limestone
- Mss — Ste. Genevieve and St. Louis Limestones (includes Salem Limestone in Kentucky)
- Ms — Salem Limestone
- Mu — Ullin Limestone
- Mw — 'Warsaw' Limestone (in Kentucky)
- Msu — Salem and Ullin Limestones (in Illinois)
- Msw — Salem and Warsaw Formations (in Missouri)
- Mfs — Fort Payne Formation and Springville Shale
- Mkb — Keokuk, Burlington Limestones and Fern Glen Formation, within Ste. Genevieve fault zone
- MDna — New Albany Shale
- Dm — Muscatatuck Group
- DSt — Tamms group of Rogers (1972) (Clear Creek, Backbone, Grassy Knob, and Bailey Formations)
- DOu — Devonian, Silurian, and Ordovician strata, undivided
- Sbs — Bainbridge Formation and Sexton Creek Limestone
- Om — Maquoketa Formation
- Ok — Kimmswick Limestone
- Odp — Decorah, Plattin and 'Pecatonica' Formations
- Ojd — Joachim and Dutchtown Formations
- Osp — St. Peter Sandstone
- Knox Group:
  - Oe — Everton Formation
  - Osmp — Smithville and Powell Formations
  - Oc — Cotter Dolomite
  - Ojc — Jefferson City Dolomite
  - Or — Roubidoux Formation
- br — Breccia of sedimentary rock fragments (in grabens in Cape Girardeau County, Missouri)
- Contact
- Anticline
- Syncline
- Monocline
- Fault, normal or type unknown
- Reverse fault
- Small thrust fault
- Strike-slip fault
- Oblique strike-slip fault
- Oblique reverse fault
- Contact unknown
- State boundaries
- County boundaries



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BEDROCK GEOLOGIC MAP OF THE PADUCAH 1°×2° QUADRANGLE, ILLINOIS, INDIANA, KENTUCKY, AND MISSOURI

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