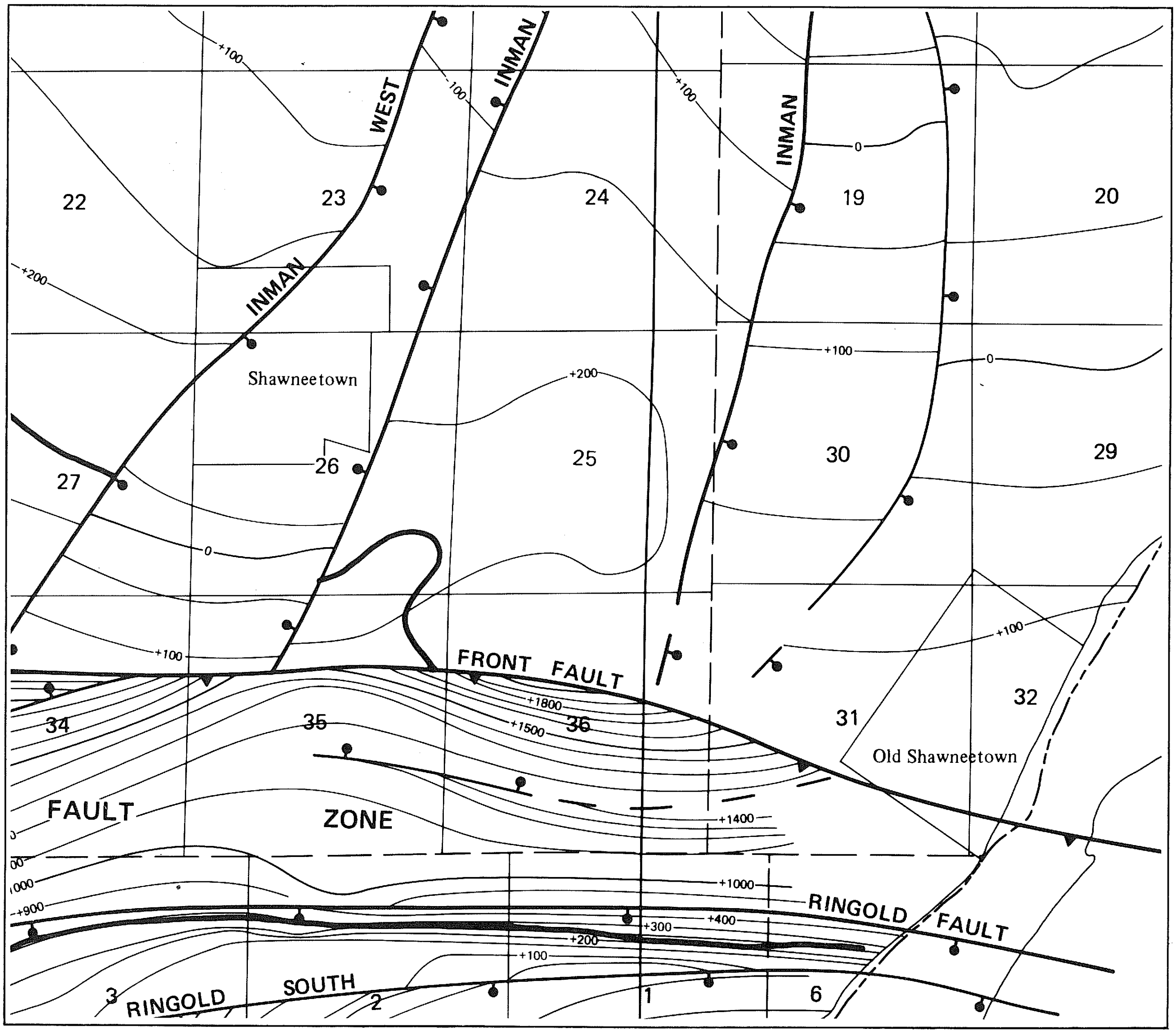
STRUCTURAL GEOLOGY OF SOUTHEASTERN ILLINOIS AND VICINITY

W. John Nelson and Donald K. Lumm



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1987

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FIGURES

TABLE

PLATES

The Illinois State Geological Survey recently published three multicolored 7½-minute geologic quadrangle maps:

IGQ-1: Shawneetown Quadrangle

IGQ-2: Equality Quadrangle

IGQ-3: Rudement Quadrangle.

These maps, prepared by W. John Nelson and Donald K. Lumm, can be used to supplement plates 1 and 2, which accompany this circular; they provide a detailed picture of the Shawneetown Fault Zone, which extends westward from just south of Old Shawneetown through all three quadrangles.

The U.S. Geological Survey partially funded preparation and printing of the maps through its Cooperative Geologic Mapping Program (COGEOMAP). Lumm received financial support from the COGEOMAP program also during preparation of the maps.

Each of the three maps contains a geologic column, a geologic cross section, and descriptive material on the structural and economic geology of the quadrangle.

ABSTRACT

The structural history of southeastern Illinois and adjacent parts of southwestern Indiana and western Kentucky is long and complex. Numerous fault systems developed under different stress regimes acting from late Precambrian through at least late Cretaceous time. The current stress field, E-W to ENE-WSW horizontal compression, differs from any known ancient stress field. Lateral tension in late Precambrian and early Cambrian time produced a deep, fault-bounded trough, the Reelfoot Rift, along the present Mississippi Embayment. An east-trending branch of this trough across southern Illinois and western Kentucky is called the Rough Creek Graben. Reactivation of these ancient rift zones produced the modern bedrock fault systems. The Cottage Grove and Rough Creek-Shawneetown Fault Systems follow the northern wall of the Rough Creek Graben, and the Pennyrile Fault System follows the southern wall. The Wabash Valley and Fluorspar Area Fault Systems follow ancient lines of weakness in the Reelfoot Rift.

The Rough Creek-Shawneetown Fault System is a braided zone of steeply dipping faults. The master fault is a high-angle reverse fault inclined to the south. Net vertical displacement across the zone is slight, but many slices of older rocks are upthrown within the fault zone. Strata north of the zone dip gently, but beds to the south dip steeply into the Eagle Valley and Moorman Synclines. We propose that the fault system formed through essentially vertical uplift of the southern block, and subsequent return of the block to approximately its original position. Major movements were post-Pennsylvanian and probably pre- late Cretaceous.

The Cottage Grove Fault System extends westward from, but does not directly connect with, the Rough Creek-Shawneetown Fault System. The Cottage Grove is a right-lateral fault system. Included peridotite intrusions show the age of faulting to be latest Pennsylvanian to early Permian.

The Wabash Valley Fault System comprises north- to northeast- trending high-angle normal faults that developed under horizontal extension. The time of faulting is not established, but contemporaneity to the Cottage Grove Fault System is suggested.

The Fluorspar Area Fault Complex includes ultramafic dikes and diatremes, radiometrically dated as early Permian, radiating from the circular uplift of Hicks Dome, a crypto-volcanic feature. Cross-cutting these are numerous high-angle faults, mostly normal but having some reverse and strike-slip displacements. Multiple and recurrent episodes of tectonism and mineralization, from late Pennsylvanian through late Cretaceous time, are indicated.

The Pennyrile Fault System of en echelon normal faults apparently marks the hinge line of the southern block of the Rough Creek-Shawneetown Fault System. The action of the block was comparable to that of an obliquely hung trap door.

No Quaternary faulting can be documented; however, the modern horizontal-compressive stress field is strongly indicated by focal mechanisms of earthquakes, hydrofracturing experiments, in situ stress tests, and patterns of joints and ground failures observed in underground mines. Small north-trending thrust faults, also observed in mines, may be relatively recent features. Some faults in the study area are correctly oriented to reactivate under the modern stress regime, but further evaluation of seismicity versus bedrock faulting is beyond the scope of this report.

ACKNOWLEDGMENTS

This Circular is a condensed and revised version of ISGS Contract/Grant Report 1984-2 (Nelson and Lumm, 1984). The research for that report was carried out under a grant from the U.S. Nuclear Regulatory Commission (NRC-04-81-016, grant no. 1-5-24465). The goal of the study was to determine the nature, extent, age, and origin of faults in southeastern Illinois and adjacent parts of Kentucky and Indiana, and to work out the tectonic history of the region as an aid in assessing the potential for earthquakes along these faults. We worked as part of the NRC's New Madrid Study Group, which was composed of geologists, geophysicists, and seismologists from numerous research institutions in east-central United States. The overall goal of the New Madrid Study Group was to better understand and, if possible, predict seismicity, particularly as it affects nuclear facilities, within a 200-mile radius of New Madrid, Missouri.

INTRODUCTION

Purpose and scope of report

During the winter of 1811-12, the central Mississippi Valley was shaken by one of the greatest series of earthquakes ever felt in North America. Centered near the pioneer village of New Madrid, Missouri, the quakes were felt through most of the eastern United States. They rang church bells in Richmond, Virginia, and threw down chimneys in Cincinnati and St. Louis. Devastation was almost total in the epicentral region. According to contemporary accounts the ground rose and fell like waves at sea, tearing open fissures, snapping trees, and triggering landslides; waterfalls formed in the Mississippi River, boats were sunk, and islands disappeared. Whole sections of the flood plain were uplifted as other areas subsided, forming swamps and lakes such as Reelfoot Lake, where upland forests had formerly grown. The loss of life, fortunately, was slight (most fatalities apparently were caused by drownings on the river) because the area was thinly populated, and the houses (mostly log cabins) withstood the shocks long enough for the inhabitants to get outside (Fuller, 1912). Were such earthquakes to reoccur today, the casualties and destruction of property could be appalling.

Geologists and geophysicists have since established that the New Madrid area is a zone of ongoing seismic activity. Within a recent 4-year period, Stauder (1982) recorded 731 tremors, of which several were strong enough to cause localized damage. These tremors were attributed to a buried fault zone known as the Reelfoot Rift (fig. 1). The rift apparently

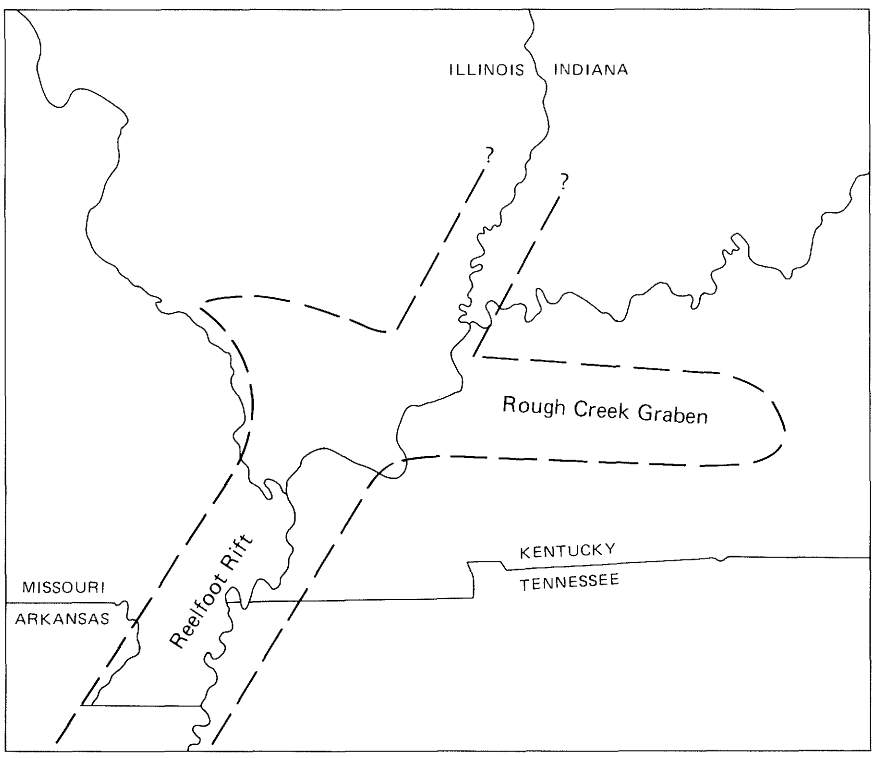


FIGURE 1. Precambrian rift zones in northern Mississippi Embayment.

is an ancient zone of weakness that has been active throughout much of geologic time. The nature and extent of the Reelfoot Rift thus is a matter of pressing concern to inhabitants of the central Mississippi Valley.

Occasional earthquakes occur in Illinois, particularly in the southern portion. While none to date has been truly destructive, several have damaged property and alarmed the population. People are naturally concerned about these quakes and their pattern of reoccurrence. Is southern Illinois in danger of cataclysmic shocks comparable to the New Madrid events?

The bedrock of southern Illinois is riddled with faults. A regional map (fig. 2) reveals two major trends of fractures: east-west and northeast-southwest. The Cottage Grove Fault System and Shawneetown Fault Zone cross Illinois from west to east; the Rough Creek Fault System continues eastward into Kentucky. North of the Shawneetown Fault Zone, the Wabash Valley Fault System extends north-northeastward along the Illinois-Indiana boundary, while to the south the multitudinous fractures of the Fluorspar Area Fault Complex project—in seemingly ominous fashion—directly toward the Reelfoot Rift and New Madrid. Little wonder, then, that some geologists have assumed the worst. For example, Heyl (1972) labeled the combined Fluorspar Area Fault Complex-Wabash Valley Fault System as the "New Madrid Fault Zone"—implying that all of this zone is susceptible to catastrophic earthquakes. The Shawneetown Fault Zone also is said to be active (Heyl and Brock, 1961; Heyl et al., 1965).

To aid in assessing the seismic risk of southern Illinois, we conducted this study investigating the nature, extent, age, origin, and history of faulting. Specific goals were to deter-

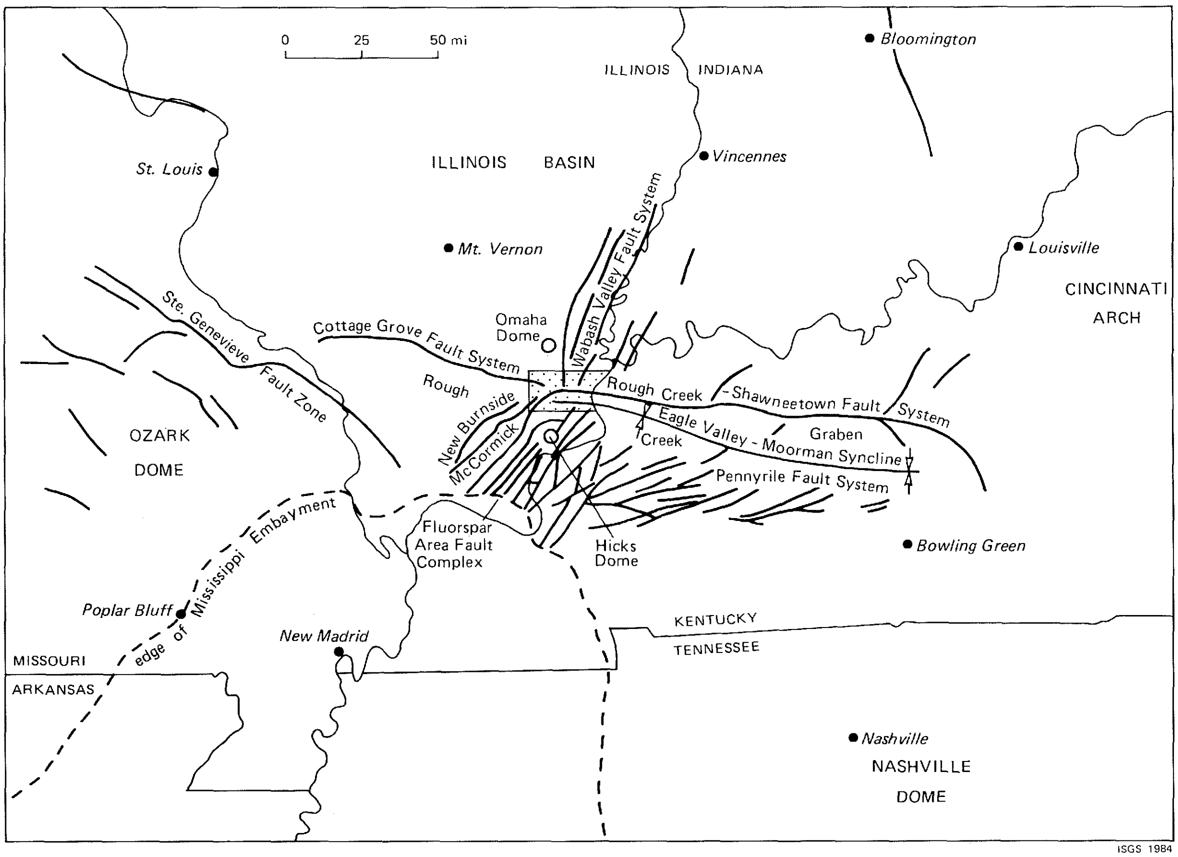


FIGURE 2. Regional tectonic setting of study area. Stippled area, showing region where detailed mapping was done, includes the Rudement, Equality, and Shawneetown Quadrangles.

mine whether the Fluorspar Area Fault Complex connects with the Wabash Valley Fault System, and whether the Shawneetown Fault Zone joins the Cottage Grove Fault System.

We focused our attention on southeastern Saline and south-central Gallatin Counties, where all of these fracture zones converge. Because no detailed studies of structural geology had been made in this area for more than 50 years despite the concern about earthquakes, our first step was to map the region in as much detail as newly available data would allow.

Geographic setting

Our area of immediate interest comprises the Rudement, Equality, and Shawneetown USGS quadrangles (IGQ-1, 2, 3) in southeastern Saline and southern Gallatin Counties, Illinois (fig. 2). The three quadrangles form a rectangle approximately 8½ miles north to south by 20 miles east to west. The easternmost quadrangle, Shawneetown, includes the Ohio River and a small area in Kentucky already mapped by Palmer (1976). The study area includes nearly all of the Shawneetown Fault Zone and portions of the Fluorspar Area Fault Complex and Wabash Valley and Cottage Grove Fault Systems that approach or intersect the Shawneetown Fault Zone.

The Shawneetown Fault Zone marks the boundary between the Central Lowland and Interior Low Plateaus physiographic provinces in southeastern Illinois. The Central Lowlands lie north of the fault zone and consist of level to gently rolling plains of Quaternary glaciolacustrine and alluvial sediments, above which low, isolated bedrock hills rise like islands. Elevations of the plains range from about 340 to 375 feet above sea level; bedrock islands locally reach 550 feet or higher. The Interior Low Plateaus south of the Shawneetown Fault Zone are rugged, maturely dissected hills mostly composed of resistant, massive to thick-bedded lower Pennsylvanian sandstone. Maximum elevation in the study area is 923 feet. Eagle Valley, the elongate lowland south of and parallel to the fault zone, follows the structural axis of the Eagle Valley Syncline. Sandstones crop out as cuestas and hogbacks with dip-slopes facing inward, toward Eagle Valley.

The region has a warm, temperate climate, which promotes rapid weathering of bedrock. Exposures are limited to steep slopes and ravines, and to artificial excavations such as roadcuts and surface mines. Lowlands are extensively farmed in row crops, but uplands are mostly wooded. Much of the plateau region of southeastern Illinois has been incorporated into the Shawnee National Forest.

Geologic setting

The area under investigation is located near the southern part of the Illinois Basin (fig. 2). The Rough Creek-Shawneetown Fault Zone divides the larger Illinois Basin into the Fairfield Basin (north) and the Eagle Valley-Moorman Syncline (south). Within the Illinois Basin, sedimentary rocks of Cambrian through Pennsylvanian age are overlapped by unconsolidated Quaternary sediments. Bordering the Illinois Basin on the west is the Ozark Uplift, where Precambrian crystalline rocks locally occur at the surface. The Cincinnati Arch, with Ordovician rocks exposed along its crest, separates the Illinois Basin from the Appalachian Basin to the east. Paleozoic rocks are buried beneath partly lithified Cretaceous and Tertiary deposits in the Mississippi Embayment, a northward projection of the Coastal Plain Province.

Previous research

The first geologist to explore the study area was Cox (1875). Writing on the geology of Gallatin County, he remarked on the "axis of disturbance or upheaval that crosses it, in an east and west direction." This is, of course, the Shawneetown Fault Zone. Cox described many exposures of tilted or fractured strata along the fault; some of these outcrops are no longer accessible for study. Cox's concepts of stratigraphy and structural geology have been revised considerably through the years, but they laid the groundwork for all subsequent investigations.

By far the most comprehensive examination of the area was that of Butts (1925). His report includes a geologic map (scale 1:62,500) covering all of the Rudement, Equality, and Shawneetown Quadrangles, plus the rest of the Saline and Gallatin Counties south of these quadrangles. Stratigraphy, structural geology, and economic geology are covered in his text. Butts' discussion of faults is rather cursory, but he had only limited surface exposures and very few subsurface data from which to work. Butts did not speculate on the origin or tectonic significance of the faults; he limited his remarks to field observations.

The geology of the Illinois fluorspar district was discussed, and mapped (at 1:24,000) in three ISGS Circulars (Baxter, Potter, and Doyle, 1963; Baxter and Desborough, 1965; and Baxter, Desborough, and Shaw, 1967). The area covered extends from the southern edge of our mapping area to the Ohio River (Illinois-Kentucky state line). The Fluorspar Area Fault Complex and southern terminus of the Shawneetown Fault Zone and their relationship to mineralization were treated in detail. In addition, Trace (1974), Hook (1974), and Trace and Amos (1984) provided excellent structural overviews of the Illinois-Kentucky Fluorspar District, and Klasner (1982) mapped the area where the Shawneetown Fault Zone joins the Fluorspar Area Fault Complex.

The entire state of Kentucky has been mapped geologically on 7.5-minute quadrangles. Many of the geologic quadrangles include cross sections illustrating the structure of fault zones. The Grove Center Quadrangle, immediately east of Shawneetown, was mapped by Palmer (1976).

Geologic quadrangle maps are not available for the region north and west of the study area, mostly because the cover of Quaternary deposits hides all but a few scattered exposures of bedrock in those quadrangles. Quaternary deposits of Illinois were mapped by Lineback et al. (1979).

The Cottage Grove Fault System was mapped (scale about 1:100,000) and described in detail by Nelson and Krausse (1981). The faults are known from numerous exposures in underground coal mines and also from test drilling. The Wabash Valley Fault System in Indiana was discussed by Ault et al. (1980) and mapped at a scale of approximately 1:31,680 on six separate maps by Tanner, Stellavato, and Mackey (1981). Bristol and Treworgy (1979) mapped Wabash Valley Faults in Illinois and discussed the fault system as a whole.

In addition to these published sources, unpublished manuscripts and field notes on file at the ISGS contain much useful information on our area of interest.

METHOD OF STUDY

Field mapping

The entire Rudement, Equality, and Shawneetown quadrangles were mapped geologically (plate 1; IGQ-1, 2, 3) for this report. We visited almost every exposure of bedrock-natural and artificial—during our surficial mapping. We examined the highwalls of all abandoned strip mines and made repeated visits to active mines, since virtually none of these mines existed during the early 1920s when Butts mapped. Mines provide excellent views of structural attitude of the rocks; in a number of cases, faults are visible in the highwalls.

We used U.S. Geological Survey 7.5-minute quadrangle topographic maps as base maps in areas having little or no structural complexity; for complexly faulted sections, we enlarged these maps two to three times. In some places we used a portable altimeter to determine altitude, especially in strip mines where topography has been altered.

Ground work was supplemented by stereoscopic study of aerial photographs taken by the U.S. Department of Agriculture during the 1950s. These summertime photos are not ideal for geologic interpretation, but in spite of the dense vegetation, a number of linear features, interpreted as faults, could be detected on the photographs. Many linear features revealed on aerial photographs are not apparent on the ground or on topographic maps.

Mapping focused on faults and related tectonic structural features, and on identification of bedrock-stratigraphic units. Surficial deposits were mapped in places where they dominate the landscape and/or completely mask the bedrock. For identification of surficial sediments we relied mainly on published work of others, primarily Heinrich (1982) and Lineback et al. (1979).

Subsurface mapping

The structure-contour map of the Rudement, Equality, and Shawneetown Quadrangles (plate 2; IGQ-1, 2, 3) is based on logs of several thousand wells, almost none of which were available to Butts (1925). Most of the wells are coal-test borings; also included are roughly 150 tests for oil and gas, and a few water wells and foundation borings. In compiling plate 2, we also used maps (provided by coal companies) that were based upon thousands of drill holes, spaced as closely as 100 feet apart. Such maps cover a large portion of the Eagle Valley Syncline and structurally complex areas near Cottage Grove and Equality. Extremely accurate placement of faults and igneous intrusions is possible with these maps.

The unequal distribution of datum points on plate 2 reflects the mineral economics. Because coal is found in rocks of middle Pennsylvanian age, coal companies have not explored the hills rimming Eagle Valley, where these rocks have been eroded. Petroleum test holes are concentrated north of the Shawneetown Fault Zone; few operators have explored the region south of the fault zone because it is widely regarded as unproductive. This belief persists in spite of the fact that many significant finds have been achieved within and south of the Rough Creek Fault System in Kentucky.

The Springfield—formerly Harrisburg (No. 5)—Coal Member was selected as a contouring horizon because it is the most common target for coal exploration and is reported on more logs than any other stratum. In some regions, drilling penetrated only to the younger Herrin (No. 6) Coal Member; beyond the outcrop of the Springfield Coal, the deeper Davis and Dekoven Coal Members were tested. In such cases the elevation of the Springfield Coal was extrapolated. Fortunately, these coal seams are nearly continuous throughout the study area, and the thicknesses of the intervals between the seams are remarkably consistent. Contoured elevations projected from data on Herrin, Davis, and Dekoven Coals probably are accurate within 25 feet throughout the study area. Beyond the outcrop of the Davis Coal the elevation of the Springfield Coal had to be extrapolated from the elevation and structural attitude at lower Pennsylvanian or upper Mississippian marker beds mapped in the field. Mapping is naturally less accurate in such areas; accordingly, the contour interval on plate 2 increases from 50 feet inside the Davis outcrop to 100 feet outside the Davis cropline, giving an optical impression of lesser dip in these areas.

Geophysical surveys

We used published gravity and magnetic surveys by McGinnis and Bradbury (1964), McGinnis et al. (1976), and Strunk (1984) that encompass the study area. We also viewed several proprietary seismic sections across the Rough Creek-Shawneetown Fault System in Illinois and western Kentucky. These sections reveal several faults and show the deep structure of the Eagle Valley-Moorman Syncline, but do not allow definitive interpretation of the deep subsurface structure of the Rough Creek-Shawneetown Fault System, because of interference among reflectors within the fault zone.

Investigations outside immediate study area We visited a number of localities outside the Rudement, Equality, and Shawneetown Quadrangles to obtain additional information on faults. All currently active fluorspar mines and one abandoned prospect pit in Hardin and Pope Counties, Illinois, were visited. These mines include four underground operations and two open pits. Two mines and the abandoned prospect pit are in vein deposits, where mineralization follows northeast-trending fault zones in the Fluorspar Area Fault Complex. The mine workings provide nearly continuous exposures of the fault zones for up to several thousand feet along strike and show a wealth of structural detail. The other three mines are exploiting bedded-replacement deposits and contain only small faults and fractures, but such structures rarely are visible in natural exposures.

Nelson and Krausse (1981), delineating the Cottage Grove Fault System, did extensive, detailed mapping of faults in underground coal mines of Saline and Williamson Counties. In the current study we examined new exposures of faults at several of these mines, and also checked surface mines, roadcuts, and railroad cuts. Samples of igneous rocks from drill cores and outcrops of dikes in the Cottage Grove Fault System were submitted to Geochron Laboratories of Cambridge, Massachusetts for potassium-argon age determination. We also examined faults in several underground coal mines in Union and Webster Counties, Kentucky, including faults in portions of the Rough Creek and Wabash Valley Fault Systems, and small faults in the Moorman Syncline. Coal companies provided maps and drill-hole information that yielded additional information on geologic structure.

STRATIGRAPHY

The bedrock of the study area comprises at least 15,000 feet of Paleozoic sedimentary rock overlying Precambrian basement presumably composed of crystalline rock. All the Paleozoic systems except the Permian are represented. The succession begins with transgressive Cambrian sandstone, which is succeeded by Croixan (upper Cambrian) through Valmeyeran (middle Mississippian) limestone and dolomite, some with abundant chert and smaller amounts of sandstone and shale. These strata were almost all deposited in marine waters of shallow-to-moderate depth, on a stable cratonic platform subject to periodic, gentle, regional uplift and subsidence. The Chesterian (late Mississippian) marked the beginning of cyclical sedimentation in which alternating layers of limestone, shale, and sandstone were deposited in marine and coastal environments. After a brief hiatus caused by the retreat of the sea from the area, deposition began again in the Pennsylvanian Period: first, thick basal fluvial sandstone and shales, then further cyclical deposits of deltaic shale and sandstone alternating with shallow marine limestone and minable beds of coal. Permian rocks have been identified in a small downfaulted block in Kentucky, and presumably once covered a much larger area. Ultrabasic igneous rock was injected as narrow dikes and sills during early Permian time.

The Mesozoic and Cenozoic Erathems are not represented in the study area save for scattered remnants of latest Tertiary gravels in the Shawneetown Hills. The Quaternary glaciers did not quite reach our area, but lacustrine sediments up to 150 feet thick accumulated in the lowlands, and windblown silt and sand mantled large areas of the uplands. The most recent sediments in the study area consist of alluvium of the Ohio River and its tributaries.

Precambrian rocks

No direct information is available on the Precambrian basement because no wells have yet reached it in our study area; and the nearest outcrops lie 120 miles to the west in the Ozark region. Nevertheless, several lines of evidence allow us to make some reasonable inferences on the nature of the ancient substrate. Precambrian rocks in the St. Francois Mountains of Missouri consist mainly of granite and rhyolite cut by small intrusions of diabase. All 32 deep borings that have reached Precambrian rocks in Illinois have encountered granitic or rhyolitic rock. A new deep well in southeastern Hamilton County (well 12, fig. 3), the closest well to our area to reach basement, encountered pink granite at a depth of 12,967 feet. Thus, it appears likely that acidic intrusive and extrusive rocks underlie the Paleozoic strata in our study area.

The depth to basement in the immediate study area is at least 15,000 feet and probably considerably more. The Texas Pacific Oil test (well 5, fig. 3, and table 1), immediately southwest of our study area in Pope County, went to 14,942 feet without reaching basement, while the Exxon well in Webster County, Kentucky (well 8, fig. 3, and table 1) was short of Precambrian at 15,200 feet. These are the deepest holes in Illinois and western Kentucky, respectively. Seismic profiles in Union and Webster Counties, Kentucky, indicate that basement is as deep as 25,000 feet at the axis of the Moorman Syncline (Norman Hester, personal communication, 1983). This Precambrian deep is further confirmed by gravity and magnetic surveys (Lidiak and Zietz, 1976; Soderberg and Keller, 1981; Schwalb, 1982; and Hildenbrand et al., 1982). Soderberg and Keller (1981) refer to the Precambrian trough as the Rough Creek Graben and believe it to be bounded on the north and south by fault scarps, precursors of the Rough Creek-Shawneetown and Pennyrile Fault Systems, The Rough Creek Graben is an eastward extension of the Reelfoot Rift, a similar fault-bounded trough underlying the Mississippi Embayment (fig. 1).

Cambrian System

Throughout most of the east central United States, the basal Paleozoic deposit is a quartzose to arkosic transgressive sandstone of Croixan (late Cambrian) age, called the Lamotte

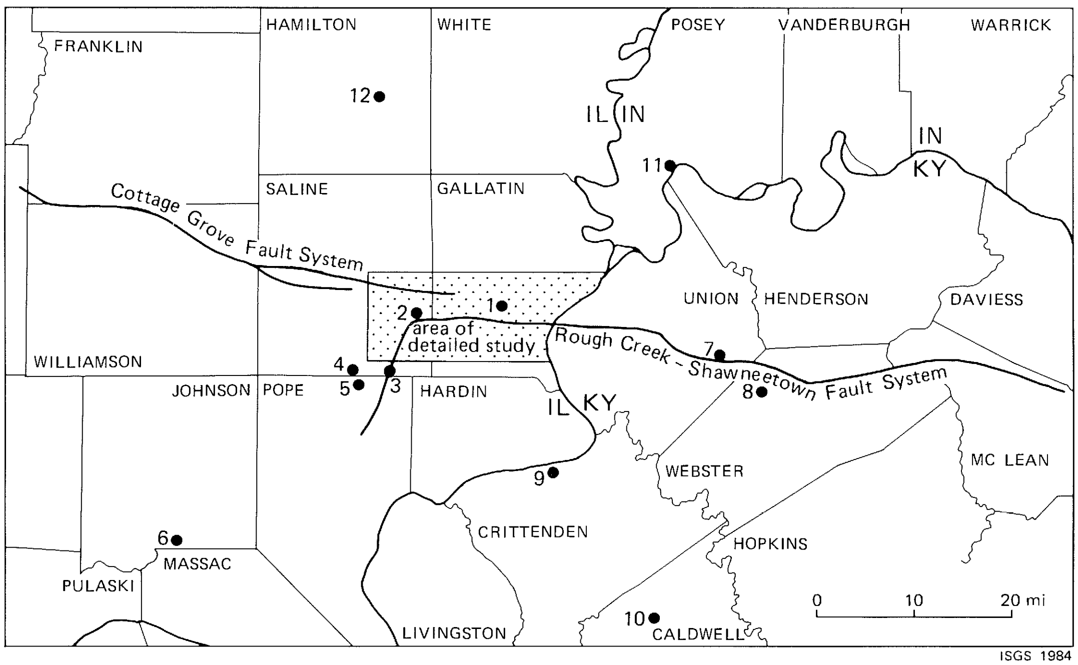


FIGURE 3. Locations of deep wells in study area.

1. Texaco, J. M. Walters No. 1, SW¼ NE¼ SW¼ Sec. 29, T9S, R9E, Gallatin Co., IL. Tops by H. Schwalb.
2. John Dunnill, Margaret Karsch No. 1, 1150 ft from N.L., 675 ft from E.L., Sec. 35, T9S, R7E, Saline Co., IL. Tops by H. Schwalb.
3. Texota, King No. 1, NE¼ SE¼ Sec. 32, T10S, R7E, Saline Co., IL. Tops by driller and Y. Lasemi.
4. Texas Pacific, John Wells No. 1, 460 ft from N.L., 660 ft from W.L., Sec. 34, T10S, R6E, Saline Co., IL. Tops by Y. Lasemi.
5. Texas Pacific, Mary Streich Comm. No. 1, 1815 ft from S.L., 2310 ft from E.L., Sec. 2, T11S, R6E, Pope Co., IL. Tops by E. Atherton.
6. Texas Pacific, Farley et al. No. 1, 680 ft from N.L., 730 ft from W.L., SE¼ Sec. 34, T13S, R3E, Johnson Co., IL. Tops by H. Schwalb.
7. Ashland Oil, Camp Breckinridge No. F-1-F, Sec. 15-N-21, Union Co., KY. Tops by H. Schwalb.
8. Exxon Corp., Choice Duncan No. 1, 1200 ft from N.L., 2460 ft from E.L., Sec. 5-M-22, Webster Co., KY. Tops by H. Schwalb.
9. Shell Oil, Davis No. 1, Sec. 17-L-16, Crittendon Co., KY. Tops by M. McCracken and H. Schwalb.
10. Sun Oil Co., Stephens No. 1, Sec. 9-I-19, Caldwell Co., KY. Tops by H. Schwalb.
11. General Electric No. 2 Disposal Well, Sec. 9, T7S, R13W, Posey Co., In. Tops by H. Schwalb.
12. Texaco, Cuppy No. 1, SE¼ SW¼ Sec. 6, T6S, R7E, Hamilton Co., IL. Tops by E. Atherton and T. Buschbach.

TABLE 1. Sub-Mississippian formations penetrated by deep wells in and near the study area (see fig. 4 for identification).

	Well numbers											
Formations	1	2	3	4	5	6	7	8	9	10	11	12
Devonian System	1,960	768+	745+	2,065	1,802	1,525	1,750	1,766	1,906	1,809	1,375	1,351
New Albany Group	385	278	369	350	320	206	366	304	400	302	305	257
Lingle Limestone	64	70					92	86	46	44	0?	38
Grand Tower Limestone	355	68	349				242	290		266	345	101
Clear Creek Chert	390	352+	27+	1,715+	1,482	1,319	288	285		488	360	
Backbone Limestone	50	*					24?	30	1,460	52	725	30
Grassy Knob Chert	530						292?	400		200		565
Bailey Limestone	186						446	371		457		?
Silurian System	290			248+	358	337	220	154	350	165	475	328
Moccasin Springs Fm.	124							59		53		171
St. Clair Limestone	90							55		76		63
Sexton Creek Limestone	76							40		36		94
Ordovician System	1,580				?	5,543	2,302	3,300	5,145	4,228	1,539	?
Maquoketa Shale Group	238				232	237	342	373	225	418	315	200
Galena Group	114				760	92	108	37	95	15	116	127
Platteville Group	576					584	562	500	610	535	546	562
Joachim/Dutchtown Fms.	480				690	593	420	220	555	950	344	266
St. Peter Sandstone	50				190	65	50	160?	71	?	115	152
Everton Dolomite	122+				?	312	570?	136	3,589	2,310	103	62
Knox Megagroup (in part)					6,350**	3,660	250+	1,874				?
Cambrian System					?	4,724+		5,530+	416+	4,500		4,324+
Eminence Formation						870		860	360	660		
Potosi Dolomite						1,030		790	56+	900		
Franconia Formation						440		1,190?		1,340		
Eau Claire Formation					920	1,160		†2,690+		‡1,700+		823
Mt. Simon Sandstone					150+	660						None
Pre-Mt. Simon						546+						Precambrian granite
Total depth	7,688	2,683	3,172	6,200	14,942	14,284	8,594	15,200	8,821	12,960	7,980	13,051

*Well cut fault and went into Pennsylvanian at 2,380 ft. Probably additional faults in hole (note abnormally thin Grand Tower Limestone).
**"Knox" in this well includes undifferentiated Cambrian and Ordovician between St. Peter Sandstone and Eau Claire Formation.
†Igneous rock 14,440–14,450 ft.
‡Igneous rock 12,110–12,130 ft.

Sandstone in the Ozarks and the Mt. Simon Sandstone elsewhere (fig. 4). It rests on an irregular, knobby Precambrian surface and is absent over some of the buried hills, as in the Hamilton County well (well 12, fig. 3, and table 1).

The Rough Creek Graben and Reelfoot Rift contain a thick succession of sediments older than the Mt. Simon Sandstone. The deep oil test drilled by Texas Pacific in southern Johnson County, Illinois (well 6, fig. 3, and table 1), first cut about 660 feet of Mt. Simon, then passed through 564 feet of coarse-grained, reddish arkose containing layers of red and green shale, and bottomed in this material without reaching basement. Another well near the eastern end of the Rough Creek-Shawneetown Fault System in Grayson County, Kentucky, encountered a thick succession of marine shales, containing trilobites indicating middle Cambrian age, beneath the Eau Claire (Howard Schwalb, personal communication, 1983). Mt. Simon Sandstone was not recognized in the latter well. The seismic sections in western Kentucky indicate as much as 8,000 feet of Cambrian deposits (Norman Hester, personal communication, 1983). Deep drilling in southeastern Missouri, eastern Arkansas, and western Tennessee reveals similar extremely thick pre-Mt. Simon deposits in the Reelfoot Rift (Ervin and McGinnis, 1975; Houseknecht and Weaverling, 1983).

The Croixan (upper Cambrian) and Canadian (lower Ordovician) rocks above the Mt. Simon Sandstone, including the Everton Dolomite (fig. 4), are classified as the Knox Dolomite Megagroup. Outside the boundaries of the Rough Creek Graben and the Reelfoot Rift, the Knox generally consists mainly of dolomite and dolomitic sandstone with chert and small amounts of shale and siltstone. The Knox thickens abruptly and changes to shale, probably of deep-water marine origin, in the Rough Creek and Reelfoot troughs (Schwalb, 1982; Houseknecht and Weaverling, 1983). The thickening and facies change is most pronounced in the basal Knox (Eau Claire Formation) and becomes less marked upward.

Thus, the Reelfoot and Rough Creek troughs evidently opened in early Cambrian or possibly late Precambrian time, and were invaded by the sea, into which the surrounding uplands shed vast amounts of clastic detritus. The troughs filled rapidly with sediment, but still were deep during the late Cambrian, when the ocean spread onto the craton and deposited Lamotte/Mt. Simon sand. Not until Ordovician time were these trenches generally leveled enough to receive shallow-water carbonates. Although no direct evidence has been obtained as to the nature of the boundaries of the Reelfoot Rift and Rough Creek Graben, these boundaries are generally presumed to be faults. They definitely were lines of weakness in the crust, and are precursors of faults that experienced recurrent movements in Paleozoic and subsequent time.

Ordovician System

Sedimentation continued from Cambrian into Ordovician time with no apparent hiatus or marked change in the character of the rocks; therefore, the systemic boundary is difficult to identify from well records. The Ordovician portion of the Knox Megagroup, including the overlying Everton dolomite, consists of shallow-water carbonates within and outside the Rough Creek Graben. Overlying the Everton is the widespread and readily recognized St. Peter Sandstone, which is composed of very well-sorted quartz sand deposited in shallow water during a marine transgression. The St. Peter ranges from 50 to 200 feet thick (table 1; fig. 4), and typically is overlain by 1000 feet or more of limestone and dolomite of the Platteville and Galena Groups, which in turn are overlain by the Cincinnatian (upper Ordovician) Maquoketa Shale Group, which ranges from 200 to a little more than 400 feet thick.

Silurian System

Strata assigned to the Silurian System range from about 150 to 475 feet thick, as identified from well logs and cuttings (table 1). Three formations commonly are recognized. At the base is the cherty Sexton Creek Limestone, of Alexandrian age. This is overlain by the relatively pure limestone of the St. Clair Formation, which is lower Niagaran. Upper Niagaran and probably Cayugan strata are assigned to the Moccasin Springs Formation, which typically consists of reddish gray, very silty or argillaceous limestone, and calcareous siltstone. Apparently sedimentation continued without hiatus from Silurian into Devonian time.

ERA	SYSTEM	SERIES	GROUP	FORMATION	GRAPHIC COLUMN	THK.(ft)
CENOZOIC	QUATERNARY	PLEISTOCENE		loess, alluvial and lacustrine deposits,		0 - 150
	TERT. - QUAT.	PLIO. - PLEISTO.		Mounds Gravel		0 - 20
PALEOZOIC	PENNSYLVANIAN	MISSOURIAN	McLeansboro	Bond		0 - 125
				Modesto		375 - 475
		DESMOINESIAN	Kewanee	Carbondale		350 - 400
				Spoon		350 - 400
		ATOKAN	McCormick	Abbott		300 - 400
		MORROWAN		Caseyville		250 - 450
	MISSISSIPPIAN	CHESTERIAN		Many (see fig. 6)		900 - 1200
		VALMEYERAN		Ste. Genevieve-others		150 - 200
				St. Louis Ls.		400 ±
				Salem Ls.		400 ±
				Ullin Ls.		300 ±
				Ft. Payne		200 ±
	DEVONIAN	UPPER	New Albany	undifferentiated		200 - 400
		MIDDLE		Lingle Ls.		0 - 100
				Grand Tower Ls.		100 - 350
		LOWER		Clear Creek Chert		250 - 450
				Backbone Ls.		30 - 50
				Grassy Knob Chert		200 - 550
				Bailey Ls.		200 - 450
	SILURIAN	NIAGARAN ALEXANDRIAN		three formations		150 - 350
	ORDOVICIAN	CINCINNATIAN	Maquoketa	undifferentiated		200 - 425
		CHAMPLAINIAN	Galena	undifferentiated		15 - 130
			Platteville	undifferentiated		500 - 600
			Ancell	Joachim Dutchtown		250 - 950
				St. Peter		50 - 200
			Knox Megagroup	Everton Dolomite		50 - 600?
		CANADIAN		undifferentiated		1800 - 3600
	CAMBRIAN	CROIXAN		Eminence Dolomite		350 - 900
				Potosi Dolomite		800 - 1000
				Franconia Ss.		900 - 1350
				Eau Claire Dolomite		800 - 2700
			Potsdam Sandstone Megagroup	Mt. Simon Ss.		0 - 700?
		MIDDLE AND LOWER?		pre - Mt. Simon (Mermet Ss., Rome, Conasauga?)		564 +
PRECAMBRIAN						ISGS 1984

FIGURE 4. Generalized stratigraphic column for study region.

Devonian System

The Devonian System is classified into numerous formations having an aggregate thickness of 1500 to 2000 feet in the vicinity of the study area (table 1). Lower and Middle Devonian strata are composed mainly of very cherty limestone; some units are formed mostly of bedded chert. Clastic sediments are sparse in this part of the section, although the Dutch Creek Sandstone Member of the Grand Tower Limestone has been identified in some wells. Clear Creek Chert comes to the surface in the vicinity of Hicks Dome, about 10 miles south of the study area, and is the oldest rock to crop out in the region. Lower and Middle Devonian carbonates sometimes are assigned, along with carbonates of the Silurian System, to the Hunton Limestone Megagroup.

The Upper Devonian Series, in contrast, consists of dark gray, greenish gray, and black shales assigned to the New Albany Shale Group. This interval, evidently laid down in fairly deep water, represents the finest detritus washed out of the Catskill deltaic complex during the Acadian Orogeny in New England. New Albany shales are easily recognized in well cuttings, on radioactive logs, and in outcrop. The oldest bedrock actually exposed within our immediate study area is believed to be New Albany Shale; it is found in an abandoned roadstone quarry at Horseshoe (NE 1/4 NE 1/4 NE 1/4, Sec. 36, T 9 S, R 7 E) Rudement Quadrangle, Saline County. The shale dips vertically in a narrow fault slice on the north well of the cut near the northwest corner of the quarry. The highly fractured shale is hard, brittle, and silty and contains small irregular phosphatic nodules. Such lithology is typical of portions of the New Albany Shale, but similar dark shale (generally very thin) occurs within the Valmeyeran Fort Payne Formation.

Mississippian System

Fort Payne Formation This Formation, of Valmeyeran age, is exposed only at the Horseshoe Quarry (IGQ-3), where it is a dark gray, high silicified, silty limestone (fig. 5).

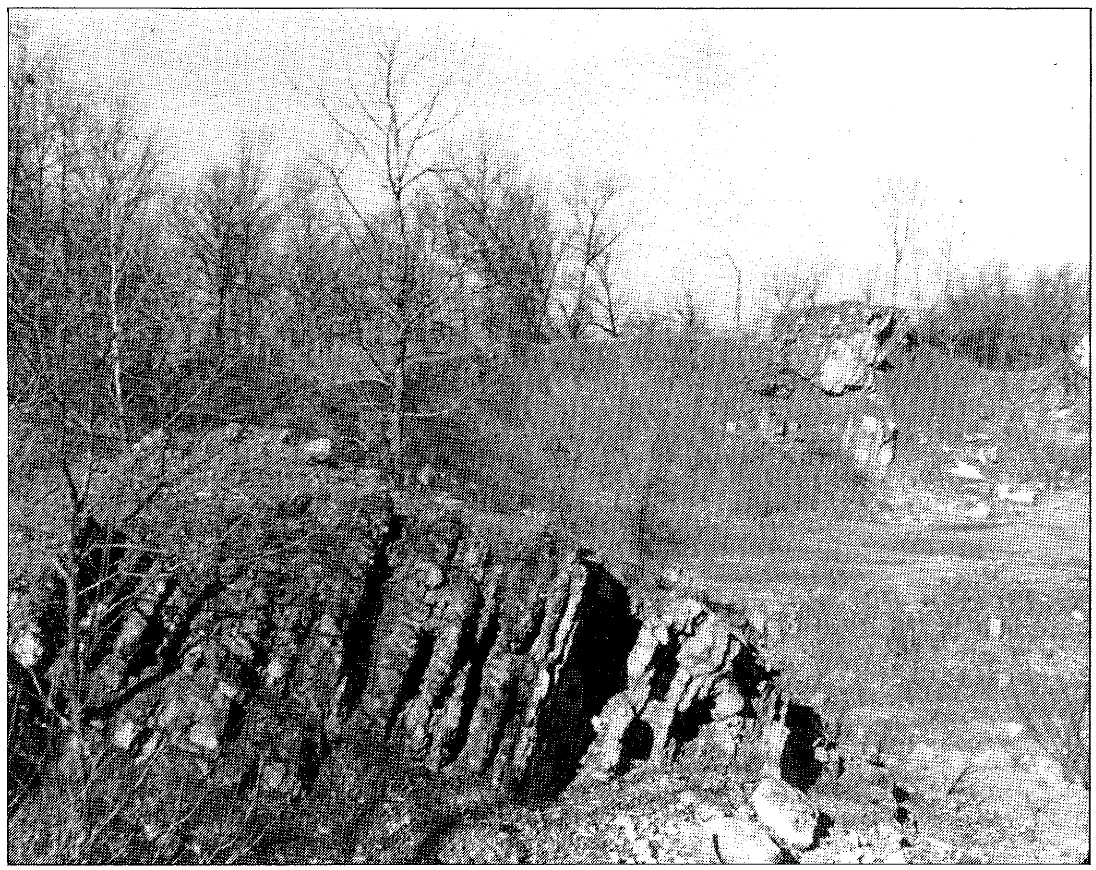


FIGURE 5. Siliceous limestone of Ft. Payne Formation dips steeply southward in narrow fault slice in Shawneetown Fault Zone (at Horseshoe Quarry, Rudement Quadrangle).

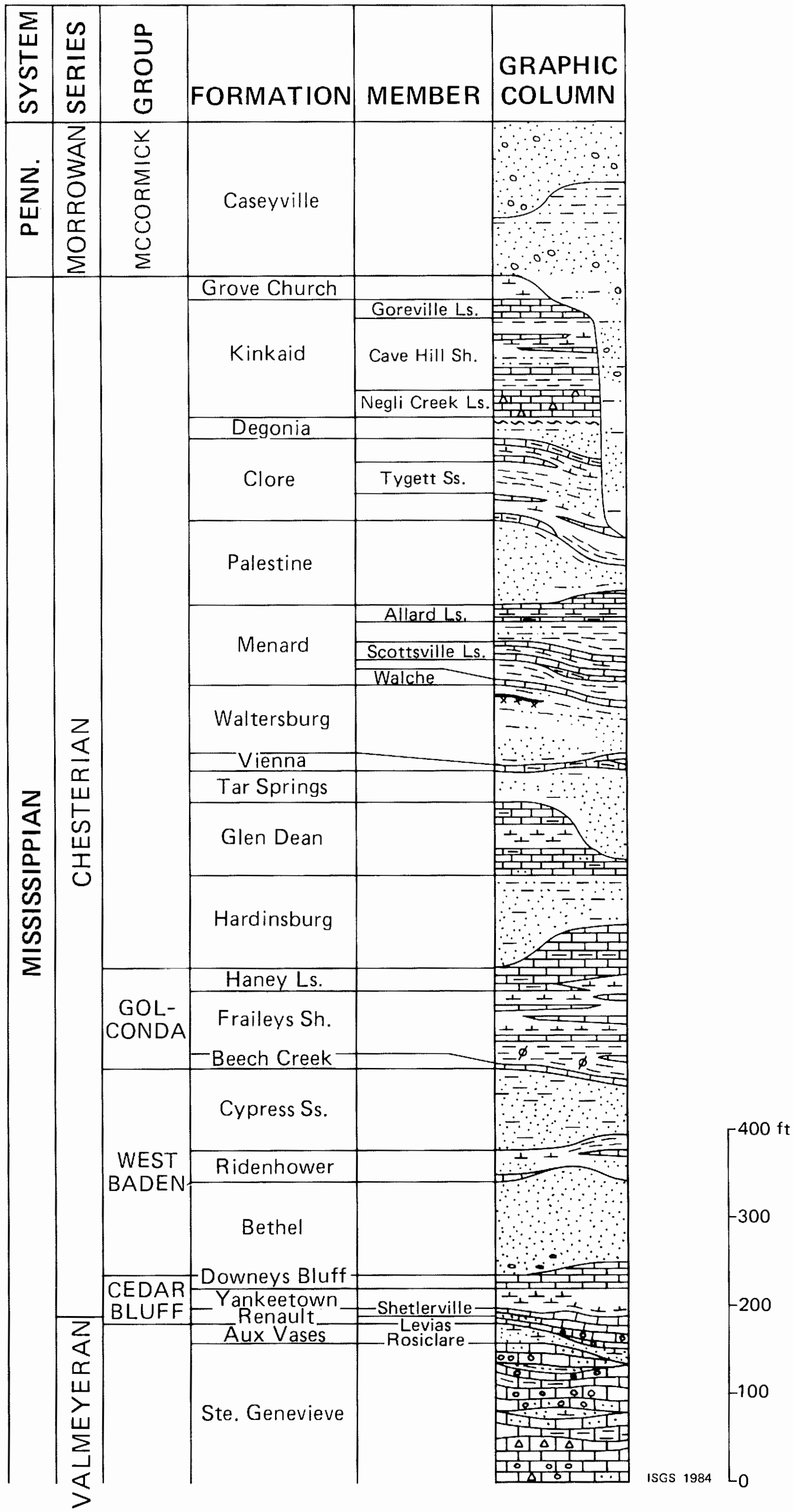


FIGURE 6. Generalized stratigraphic column of Chesterian Series (Chesterian-Valmeyeran boundary after Swann, 1963). Many geologists still include the Renault Limestone and Aux Vases Sandstone in Chesterian.

It lies in fairly regular beds, ranging from less than an inch to about a foot thick, occasionally separated by partings of black siliceous shale. Most of the original carbonate has been replaced by dull to vitreous silica. Such silicification, typical through much of the Ft. Payne, makes the formation relatively resistant to erosion. The 150 feet or more of Ft. Payne at Horseshoe Quarry probably is less than the total thickness of the formation. The rock is faulted and thoroughly fractured; it dips at 40° to 90° from horizontal. It occupies a narrow fault slice in the heart of the Shawneetown Fault Zone.

Ullin, Salem, and St. Louis Limestones Overlying the Fort Payne Formation, in ascending order, are the Ullin, Salem, and St. Louis Limestones, which constitute the middle portion of the Valmeyeran series. Deposited on a carbonate shelf in shallow to moderately deep marine water, these formations contain little or no terrigenous material and variable amounts of secondary chert. We found no outcrops of the Ullin, Salem, or St. Louis in our study area, but they probably lie directly beneath the alluvium near Horseshoe, and possibly along the north side of the Wildcat Hills. The units are difficult to distinguish on geophysical logs; careful study is required to separate them in well cuttings. The contacts apparently are conformable and gradational in the study area. The Ullin is roughly 300 feet thick; the Salem and St. Louis average about 400 feet thick each.

Ste. Genevieve Limestone Typically a light to medium gray, coarse, biosparite or oolitic limestone, the Ste. Genevieve records shoaling conditions toward the end of Valmeyeran time. Beds of sandstone and sandy limestone in the upper part of the formation reflect the beginning of cyclical deposition that prevailed subsequently during the Chesterian Epoch. Also present are partings of greenish shale and nodules of chert. The Ste. Genevieve typically is thick-bedded to massive in outcrop.

The upper portion of the Ste. Genevieve Limestone is exposed in an abandoned quarry at the north edge of the Wildcat Hills in the SE 1/4 NW 1/4 SE 1/4, Section 27, T 9 S, R 8 E, Equality Quadrangle. This steeply tilted limestone lies within a fault slice of the Shawneetown Fault Zone. Float and obscure outcrops identified as Ste. Genevieve also occur near the road junction adjacent to Sulphur Springs Church, in the SW 1/4, Section 34, T 9 S, R 7 E, Rudement Quadrangle, also within a steeply dipping fault slice. Ste. Genevieve Limestone is the deepest formation ordinarily penetrated by oil drilling in the area. Its thickness ranges from about 120 to 180 feet.

Chesterian Series The Chesterian Series, roughly 1,000 feet thick in southeastern Illinois, comprises numerous formations of marine shale and limestone alternating with shallow-marine, coastal, fluvial, and deltaic sandstone and shale (fig. 6). This alternation reflects large-scale fluctuation of shoreline and fluvial depocenters, conditions that prevailed during the Pennsylvanian period as well. Traditionally, the base of the Chesterian Series was placed at the base of the Aux Vases Sandstone, but on the basis of fossil evidence, Swann (1963) reclassified the Aux Vases and the Levias Member of the Renault Formation as Valmeyeran. Nevertheless, some stratigraphers, among them Jennings and Fraunfelter (1983), still prefer to include the Levias and Aux Vases with the Chesterian. Mainly for the sake of convenience, we have mapped and will discuss the Aux Vases and Levias with the Chesterian Series.

The Aux Vases (Rosiclare) Sandstone is 10 to 40 feet thick within the study area. It is important economically, both as a focus of fluorspar mineralization and as a reservoir for petroleum. Typically, the Aux Vases is a white to light greenish gray, very fine-grained, quartzitic, calcareous sandstone, often interbedded with greenish gray shale near the top. It is well exposed on the highwall of the abandoned quarry in the SW 1/4 SE 1/4, Section 27, T 9 S, R 8 E, Equality Quadrangle (IGQ-2).

The Renault Limestone ranges from 17 feet thick in the Rudement Quadrangle to as much as 50 feet in the Shawneetown Quadrangle. The Levias and Shetlerville Members are not readily differentiated in the subsurface. The Renault consists dominantly of light gray, crystalline limestone, commonly oolitic, with distinctive pink crinoid grains. Varying proportions of shale are present in some locations. The overlying Yankeetown Shale is 18 to 35 feet thick; the shale contains thin interbeds of limestone. Above this is the Downeys Bluff Limestone, a reliable marker stratum in most wells. It is massive, light gray, crystalline, fossiliferous limestone, 25 to 40 feet thick.

The West Baden Group contains the Bethel Sandstone (oldest), the Ridenhower Shale, and the Cypress Sandstone. In several wells the entire group consists of sandstone, and the Ridenhower Shale cannot be recognized. Cypress and Bethel Sandstones both are light gray, very fine-grained quartzitic sandstones, commonly with thin parallel or ripply interlaminations of siltstones or silty shale. Either or both may exceed 100 feet thick; the entire West Baden Group is 215 to 265 feet thick. The Ridenhower, where present, is mainly shale, with local lenses of limestone. It can be difficult to distinguish from shaly facies of the Cypress and Bethel.

A good exposure of the West Baden Group and the Downeys Bluff Limestone is found on the north side of the stream in the SE 1/4 NW 1/4 NW 1/4, Section 3, T 10 S, R 7 E, Rudement Quadrangle. The strata in this exposure strike north-south and dip almost vertically adjacent to the Shawneetown Fault. Cypress or Bethel Sandstone also can be seen in the small roadcut in the SE 1/4 NE 1/4 NW 1/4, Section 35, T 9 S, R 7 E (IGQ-3).

The Golconda Group is extremely obscure in outcrop but readily recognized in the subsurface. The basal Beech Creek ("Barlow") Limestone is widely used as a structural datum in subsurface mapping. This limestone is seldom over 10 feet thick but is present in practically every hole drilled to its position. Above the Beech Creek is up to 50 feet of dark gray, thinly laminated marine shale, grading upward to interbedded gray calcareous shale and thin-bedded highly fossiliferous limestone, all in the Fraileys Shale. The Haney Limestone at the top of the Golconda Group is thick-bedded to massive. The group ranges from 100 to 170 feet thick, generally thinning toward the northeast.

The Hardinsburg Sandstone consists of 50 to 105 feet of shale, siltstone, and sandstone in highly variable proportions. The overlying Glen Dean Limestone typically has upper and lower limestone members 15 to 20 feet each, separated by shale. Locally, the upper limestone bench is missing because of erosion at the base of the Tar Springs Sandstone. The Tar Springs is 30 to 110 feet thick and forms prominent hogbacks north and west of Cave Hill, especially in Three Springs Hollow near the center of Section 35, T 9 S, R 7 E, Rudement Quadrangle. This formation is largely buff to light gray sandstone but may contain shaly zones near the top. Planar bedding, ripple marks, and tabular crossbedding are commonly seen in surface exposures and in cores.

The Vienna Limestone rarely exceeds 15 feet and generally is less than 10 feet thick. Two benches of limestone, separated by shale, are present locally. The Vienna forms narrow strike valleys between hogbacks of Waltersburg and Tar Springs Sandstone. The limestone, which appears mainly as float, is dark brownish gray, very fossiliferous and siliceous, weathering to a rotten texture.

The relative content of shale and sandstone varies considerably in the Waltersburg Sandstone, as in the Hardinsburg. The thickest sands generally are near the base. Thin coal horizons were observed near the top of the Waltersburg in the west-flowing tributary of Three Springs Hollow just southeast of the center of Section 35, T 9 S, R 7 E, Rudement Quadrangle. The Waltersburg varies from about 45 to 100 feet thick.

Distinctive on electric logs and in outcrop is the Menard Limestone. The three members are not always easy to pick, but individual beds of limestone are persistent in the subsurface. Limestones range from a few inches to 10 feet (occasionally they are 20 feet thick) and are typically darker and finer grained than older Chesterian limestones. Some beds are highly siliceous, and others weather to a distinctive ochre color and are finely silty. Fossils are abundant. Interbedded with limestones in the Menard are medium to dark gray, platy, siliceous or calcareous shales and thinly laminated siltstone. The Menard is a thick formation, ranging from 85 to 125 feet thick. The best exposure is beside the trail to Cave Hill in the NE 1/4 SW 1/4 SE 1/4, Section 34, T 9 S, R 7 E, Rudement Quadrangle (IGQ-3).

The Palestine Sandstone forms a low but persistent ledge around the northwest side of Cave Hill and also on the north slope of the Wildcat Hills in the SW 1/4 SW 1/4, Section 28, T 9 S, R 8 E, Equality Quadrangle. In both places it is brown to yellowish gray and very fine-grained and argillaceous, with thin planar- or ripple-bedded laminae of shale. Not more than 20 feet are exposed in outcrop, but electric logs reveal as much as 90 feet of interbedded sandstone and shale between the Menard and Clore Formations. The Palestine Formation is thicker in the Shawneetown and Equality Quadrangles than in the Rudement Quadrangle.

The Clore Formation includes limestone that is similar lithologically to the Menard, but individual limestone beds are thinner, generally less than 5 feet, and a greater proportion of the formation is shale. The Tygett Sandstone Member near the middle of the Clore can be recognized in some wells in the eastern part of the study area but was not identified in outcrop. The total thickness of the Clore is 75 to 120 feet.

The Degonia Formation normally is 25 to 35 feet thick, but sandstone is present only locally and is very thin. Degonia Sandstone is similar lithologically to Palestine Sandstone in outcrop. Dark red or variegated shale and claystone at the top of the Degonia is an excellent marker, easy to recognize in well cuttings. The remainder of the Degonia is gray silty shale or siltstone. A complete exposure of the Degonia was found at the east end of the abandoned limestone quarry in the NE 1/4 NW 1/4 SW 1/4, Section 3, T 10 S, R 7 E, Rudement Quadrangle.

The Kinkaid Limestone is the youngest mappable Chesterian Formation. The Kinkaid is divided into three members, the Negli Creek Limestone (lowest), the Cave Hill Shale, and the Goreville Limestone. The type section of the Cave Hill Shale Member is at the above-mentioned quarry, where the Negli Creek Limestone Member was quarried and is well exposed. The Negli Creek Limestone is massive, but commonly riddled by solution cavities and underground drainage; the cave on Cave Hill is in this unit. Goreville Limestone also is massive, but widely removed by pre-Pennsylvanian erosion. The Cave Hill Member includes olive-gray to dark gray shale and claystone, with interbeds of limestone similar to those of the Clore. The total Kinkaid Formation reaches 160 feet thick where not affected by pre-Pennsylvanian erosion.

The youngest Chesterian Formation in the Illinois Basin is the Grove Church Shale. Although this shale was not observed in outcrop, it is believed to be indicated on the electric logs of several oil-test holes in the Rudement and Equality Quadrangles. The greatest thickness interpreted was approximately 30 feet. Like other Chesterian shales, the Grove Church is distinguished from Pennsylvanian shales by its slightly lower electrical resistivity.

A major unconformity marks the base of the Pennsylvanian System throughout the Illinois Basin (Bristol and Howard, 1971). Within the study area the hiatus is less profound than in most places: basal Pennsylvanian strata rest on uppermost Chesterian rocks. A few subsurface records indicate that the Grove Church Shale, the youngest identified Chesterian formation, may be present beneath the unconformity. In most wells and surface exposures, basal Pennsylvanian rocks overlie the Goreville Limestone or Cave Hill Shale Members of the Kinkaid Limestone. The major exception is in the Inman Channel (Howard, personal communication, 1983) in the Shawneetown Quadrangle, where pre-Pennsylvanian erosion locally removed strata down to about 30 feet above the base of the Clore Formation. The maximum relief on the unconformity thus amounts to about 250 feet.

At all exposures examined, the Mississippian and Pennyslvanian strata are parallel. Thus, there is no evidence, such as Ekblaw (1915) found in the Alto Pass area of southwestern Illinois, for post-Chesterian pre-Pennsylvanian tectonic movement.

Pennsylvanian System

Caseyville Formation The basal Pennsylvanian of southeastern Illinois is assigned to the Caseyville Formation (fig. 7). All the highest hills of the study area are formed by the Caseyville, which is composed mostly of thick, massive sandstone that is very resistant to erosion.

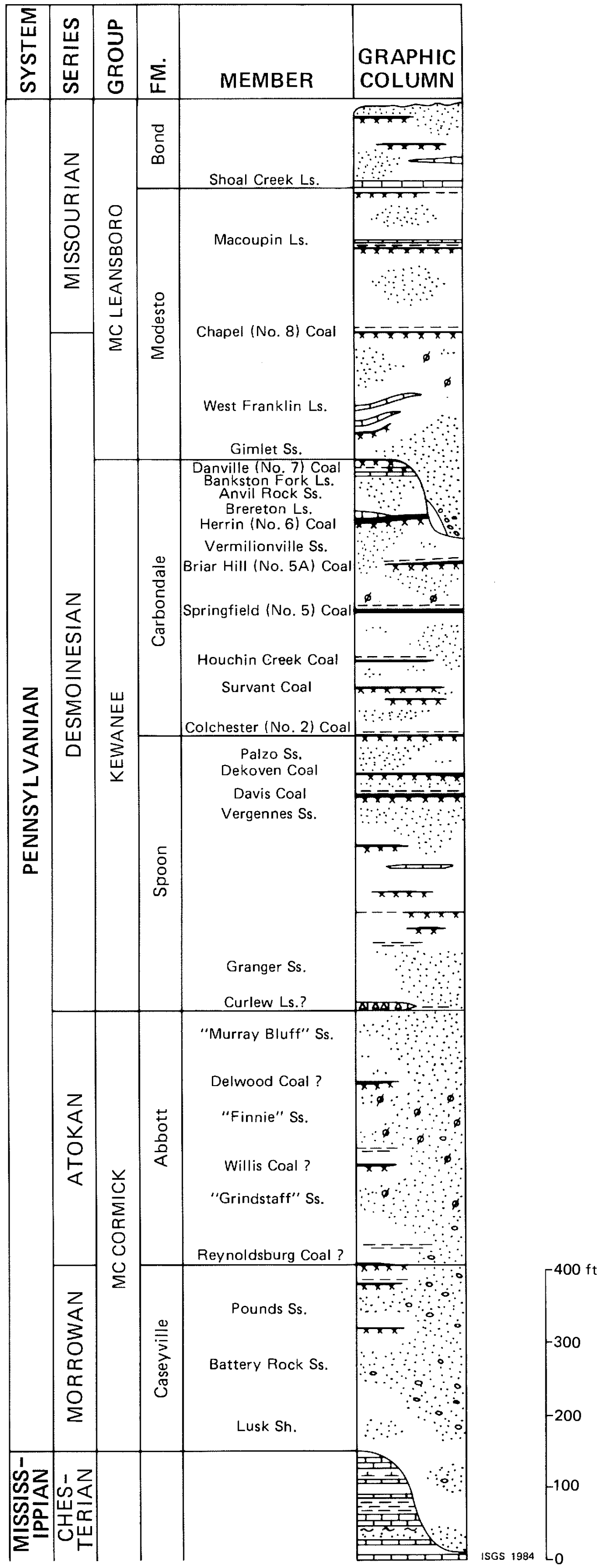


FIGURE 7. Generalized stratigraphic column of Pennsylvanian System.

A nearly continuous escarpment of Caseyville sandstone marks the upturned rim of the Eagle Valley Syncline south and east of the Shawneetown Fault Zone, through Gold Hill, the Wildcat Hills, Cave Hill, and from there southwestward to the limit of the mapping area. A similar south-facing escarpment marks the southern limb of the Eagle Valley Syncline a short distance south of the quadrangles surveyed.

The Caseyville Formation includes siltstone, shale, and thin, discontinuous seams of coal, but sandstone normally constitutes more than half of the thickness of the formation. No limestone or rocks containing marine fossils were observed in the study area, although such rocks have been reported elsewhere in Illinois. Petrography, fabric, and sedimentary structures indicate a dominantly fluvial and deltaic origin for the Caseyville (Palmer and Dutcher, 1979). The cyclicity that is characteristic of Chesterian and younger Pennsylvanian strata is not much in evidence in the Caseyville.

The cliff-forming, channel-phase Caseyville sandstones are often 100 feet or more thick. Commonly they are so massive that structural attitudes are difficult to determine. Large-scale crossbedding is prominent in many exposures. A diagnostic feature of the Caseyville is the presence of well-rounded pebbles of white quartz (occasionally quartzite, chert, and hematite) up to 1/2 inch in diameter, either scattered throughout the sandstone or concentrated as lag conglomerates up to several feet thick. Such pebbles do not occur elsewhere in the stratigraphic section, although scattered quartz granules are found in some places in the next younger Abbott Formation. Otherwise, Caseyville sandstones range from very fine to coarse grained and are clean, mature, quartz arenites or orthoquartzites, cemented by silica or iron. Mica, clay, feldspar, and dark grains, common in younger Pennsylvanian sandstones, are rare in the Caseyville. Fine-grained Caseyville sandstone can be confused with Chesterian but not with younger Pennsylvanian sandstone.

Siltstone and shale of the Caseyville range from medium to dark gray or brown to black and commonly contain more mica and carbonaceous debris than do Chesterian rocks, but they cannot be distinguished reliably from fine-grained rocks of younger Pennsylvanian formations.

We have identified and mapped three members of the Caseyville Formation in the study area. The basal Lusk Shale Member, a few tens of feet to about 200 feet thick, is largely sandstone in many exposures. Lusk sandstone is generally very fine to fine-grained orthoquartzite in irregular strata ranging from a few inches to 3 or 4 feet thick. Locally it is a ledge former. Overlying the Lusk is the massive, channel-phase Battery Rock Sandstone Member, which forms continuous cliffs from south of Bald Knob to the northern face of Cave Hill. The overlying Pounds Sandstone Member has a similar character but is less prominently exposed than the Battery Rock in most areas. A poorly exposed shaly interval normally separates the Pounds from the Battery Rock, but near the summit of Cave Hill the two massive units appear to have merged. Near the eastern end of Gold Hill the members cannot be identified, and the exposed Caseyville consists largely of shale, with beds of argillaceous sandstone and thin coals.

The top of the Caseyville Formation is defined as the top of the Pounds Member, which in most places is easy to recognize in the field, but difficult to place in most well records.

Abbott Formation Like the Caseyville Formation, the Abbott Formation (fig. 7) is composed primarily of resistant sandstone, which forms ridges and cuestas. It crops out in a broad belt on the southern dip-slope of Gold, Wildcat, and Cave Hills, and on the north-dipping slope at the southern edge of the study area. The Abbott also is found west of the Shawneetown Fault Zone in the southwestern part of the Rudement Quadrangle (plate 1).

Abbott sandstones are less massive and less mature than those of the Caseyville. The Abbott contains more mica, feldspar, and clay than the Caseyville, and these components become progressively more abundant upward in the formation. Scattered quartz granules and pebbles occur locally in the lower part of the Abbott. Iron oxide or siderite cement and Liesegang banding are prominent, particularly in the middle part of the formation.

The remainder of the Abbott consists of siltstone, shale, and thin local coals similar to those of the Caseyville Formation.

In mapping the areal geology of the fluorspar district, Baxter et al. (1963, 1965, and 1967) distinguished three sandstone members (the Grindstaff, Finnie, and Murray Bluff) in the Abbott. Although we could recognize features of these units in many exposures, we found that we could not reliably map these members in our area. Rapid lateral facies changes are common; in some exposures the Abbott is almost entirely sandstone, but elsewhere large portions of the formation grade to shale. Furthermore, recent work by Peppers and Popp (1979) indicates that the Grindstaff and Finnie Sandstones at their type sections actually are the same sandstone. This is not surprising, considering that Abbott sandstones apparently were deposited by meandering, shifting streams.

The upper boundary of the Abbott Formation is defined as the top of the Murray Bluff Sandstone; however, because of the previously mentioned facies variations and the fact that the members cannot be positively identified in the field, this contact cannot be placed precisely in most areas, and is shown with a broken line on most of plate 1. Similarly, well records can provide only approximate placement of the Spoon-Abbott contact.

Spoon Formation The Spoon Formation contains more shale and less sandstone than the Caseyville and Abbott and therefore is less prominent topographically than the latter two formations. Spoon sandstones locally form prominent hogbacks in the inner range of hills surrounding the Eagle Valley Syncline, but large areas of outcrop belt are concealed by Quaternary alluvial and lacustrine deposits.

Sandstone in the Spoon can be distinguished from that of the Abbott on the basis of abundant coarse mica, feldspar, carbonaceous debris, and clay matrix in the former. Secondary iron oxide and carbonate is less prominent in the Spoon than in the Abbott. In these respects the Spoon sandstone does not differ significantly from younger Pennsylvanian sandstone. The thickest sandstones are generally in the lower portion of the Spoon, but rapid lateral changes in thickness and facies are the rule.

During Spoon time the sedimentary regime gradually changed from one dominated by fluvial processes to the "cyclothemic" alternation of marine and nonmarine strata characteristic of the middle Pennsylvanian. The Spoon is the oldest Pennsylvanian formation to contain limestone in the study area. The "Curlew Limestone" of Butts (1925) appears as abundant float of white to yellowish orange chert containing molds of large productid brachiopods, crinoids, gastropods, and other marine fossils; it was found on several hilltops near Somerset and also in Horseshoe Hollow southwest of Glen O. Jones Lake in the Rudement Quadrangle. Whether this is actually the Curlew Limestone Member, as now defined, is uncertain, but it lies near the base of the Spoon Formation and provides the most reliable field indicator of the Spoon-Abbott contact. Other thin limestones in the Spoon were identified in well logs, but none can be correlated with named members.

Coal seams are more numerous, more continuous, and thicker in the Spoon than in older Pennsylvanian rocks. Coals of the middle shaly portion of the Spoon are thin and discontinuous and cannot be correlated, but the Davis and Dekoven Coal Members (fig. 7) are practically continuous in our study area and throughout much of the Illinois Basin. These coals are widely exposed in abandoned surface mines in the Eagle Valley Syncline and central Rudement Quadrangle, and are identified in hundreds of coal-test borings.

Carbondale Formation The Carbondale Formation is characterized by minable coal seams and marine black fissile shales and limestones that exhibit great lateral continuity; however, the bulk of the formation is composed of deltaic and marginal-marine shale, siltstone, and sandstone. Natural exposures are rare, but portions of the Carbondale are extensively exposed in surface mines and are known from thousands of coal-test records, many of which include core descriptions. The Carbondale Formation is found along most of the central portion of the Eagle Valley Syncline and also in the region north of the Shawneetown Fault Zone, where it is largely concealed by Quaternary deposits.

The Colchester (No. 2) Coal Member marks the base of the Carbondale Formation in Illinois. The coal is only a few inches thick but is continuous throughout the study area and readily identified on geophysical logs. The Springfield (No. 5), Briar Hill (No. 5A), and Herrin (No. 6) Coal Members have been mined widely and also are easy to identify. The Springfield Coal, 4 to nearly 6 feet thick, was selected as structural datum for plate 2; it is mined at the surface and underground. The Briar Hill Coal is 1 to 3 feet thick and has been strip-mined in conjunction with the Springfield seam. The Herrin Coal, which has been mined underground and at the surface, normally is 3 to 4½ feet thick, but locally is thin or absent as a result of erosion in paleochannels. Too thin for commercial mining, but widely recognizable in drill records, are the Shawneetown and Houchin Creek Coal Members. The top of the Carbondale Formation is defined as the top of the Danville (No. 7) Coal Member, which is less than 2 feet thick where present and widely eroded at the base of the overlying Modesto Formation.

Modesto Formation Although its coal seams are too thin for commercial mining, the Modesto Formation is lithologically similar to the Carbondale. The Modesto occurs along the axis of the Eagle Valley Syncline and in grabens in the northern part of the study area, where it is largely covered by Quaternary sediments. A massive channel phase of the Gimlet Sandstone Member is topographically prominent in Eagle Valley, where it caps numerous hills. The base of the Gimlet is eroded into the Carbondale Formation, below the level of the Herrin Coal in places. Most of the areas that Butts (1925) mapped as Anvil Rock Sandstone (Carbondale Formation) actually are Gimlet. Cliffy exposures up to 50 feet high, commonly with large-scale crossbedding, are found around Maher Hill in the Equality Quadrangle.

Bond Formation The youngest bedrock in the study area belongs to the Bond Formation, of Missourian age. It has been identified only in the subsurface at the far eastern end of the Eagle Valley Syncline and in some of the grabens north of Shawneetown. The Shoal Creek Limestone Member, which marks the base of the Bond, is easy to pick in well records. Overlying the Shoal Creek is up to 125 feet of shale and sandstone having thin layers of coal and limestone.

Permian System

No rocks of Permian age have been identified in Illinois, but their original presence in the study area can be inferred. Kehn, Beard, and Williamson (1982) reported Permian rocks, identified on the basis of fusulinids, in a drill core near Cap Mauzy Lake, Union County, Kentucky. These rocks, assigned to the Mauzy Formation, are preserved in a narrow graben within the Rough Creek Fault System. Approximately 390 feet of Mauzy are present in the type-section core, but structural projections indicate that up to 1300 feet of Permian may occur in the deepest part of the graben. The contact of the Mauzy Formation with underlying Pennsylvanian rocks apparently is conformable.

The existence of post-Pennsylvanian rocks up to several thousand feet thick (now eroded) was previously inferred from coalification studies in the southern part of the Illinois Basin (Damberger, 1971 and 1974).

Tertiary System

The only Tertiary materials recognized to date in the study area are scattered outliers of the Mounds Gravel in the Shawneetown Hills, north of the Shawneetown Fault Zone (Butts, 1925). The Mounds is composed of well-rounded pebbles of chert and vein quartz, weathered to a brown or yellow color. It occurs near the tops of hills near an elevation of 500 feet, overlies bedrock, and is covered by Pleistocene loess. Its maximum thickness is probably less than 20 feet. This gravel represents erosional remnants of extensive deposits in the Mississippi Embayment. The Mounds Gravel is believed to be partly Pliocene and partly Quaternary in age.

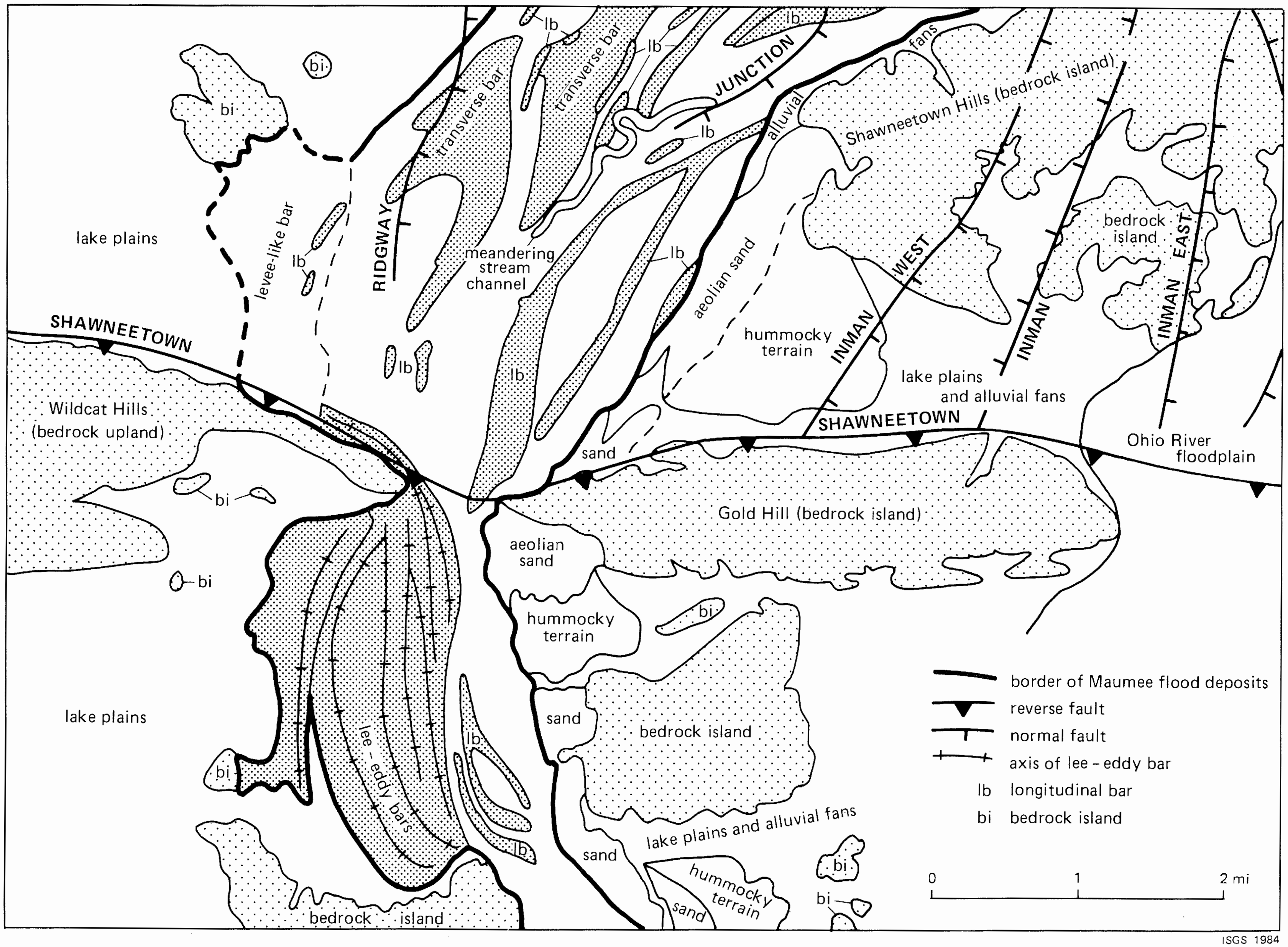


FIGURE 8. Maumee Flood deposits and faults in Shawneetown Quadrangle, Gallatin County, Illinois (after Heinrich, 1982).

Quaternary System

Sediments of Pleistocene age cover Paleozoic bedrock in most of the study area, including all the lowlands and large portions of the uplands. Our mapping of them is based largely on published works, especially Heinrich (1982). We have mapped Quaternary materials in (plate 1; IGQ-1, 2, 3) only where they create the dominant landform (as on alluvial flats, in sand dunes) or completely mask the bedrock. Most areas mapped as bedrock are, mantled by Quaternary sediments over 90 percent or more of their area. Some classes of sediments, such as talus, have not been mapped at all. Boundaries of most mapped Quaternary units are gradational and, to a large degree, arbitrary.

The classification that follows is, for the most part, generic. Our examinations rarely were thorough enough to enable us to distinguish the formally named stratigraphic units of the Pleistocene Series. Reference to these formal names will be made occasionally, as appropriate. Readers desiring more information on Quaternary deposits should consult Willman and Frye (1970) and Lineback et al. (1979).

Glacial deposits No sediments believed to have been deposited directly by or from glacial ice are known within our study area. The southernmost limit of glaciation (Illinoian Stage) is placed a few miles north of our maps (Lineback et al., 1979). The mass of the Shawneetown Hills probably blocked the flow of the ice to some degree.

Lake deposits During Pleistocene time, lowlands north of the Shawneetown Fault Zone and in Eagle Valley were flooded repeatedly by slackwater lakes that have been called Lake Saline (Frye et al., 1972; Heinrich, 1982). The former bed of Lake Saline is filled with clay and silt and smaller amounts of sand and gravel to depths approaching 150 feet. The surface of these lake deposits, virtually level, stands about 355 to 370 feet above sea level. Heinrich recognized at least five distinct sedimentary units, three of them Illinoian and two Wisconsinan, within the deposits of Lake Saline. We made no attempt to distinguish these units in mapping. Because the lake deposits in most places are capped with a veneer of Holocene alluvium and cultivated soils, information on lacustrine sediments comes only from scattered well records and from a few artificial cuts, mostly where the Saline River has been channelized.

Maumee Flood sediments and other fluvial deposits About 13,000 years ago the natural dam restraining one of southern Illinois' slackwater lakes failed, and lacustrine waters were released in great torrents, profoundly reshaping the landscape. This event has been called the Maumee Flood (Heinrich, 1982). The floodwaters entered our area about two miles north of Shawneetown, skirting the Shawneetown Hills in a channel 2 to 2½ miles broad (fig. 8). Turning southward at Junction, the torrent forced its way through the half-mile gap between the Wildcat Hills and Gold Hill, and from there followed the present course of the Saline River down to the Ohio. As the flood waters receded they left behind a channel more than 100 feet deep in places, filled with sand and gravel. Many subtle depositional features, including transverse and longitudinal bars, still can be recognized (Heinrich, 1982).

The Maumee floodwaters followed, in part, an older channel of the Ohio River. This old course flowed southwestward, around the northwest side of the Shawneetown Hills, and turned abruptly eastward at Junction to cut between the Shawneetown Hills and Gold Hill. Apparently this channel dates to pre-Illinoian time (Heinrich, 1982). Up to 150 feet of sand and gravel, containing fossil logs, has been encountered in wells between Gold Hill and Shawneetown. The sands are an important source of groundwater in the area.

Loess and windblown sand Most of the uplands in the study area are mantled with loess—firm, compact silt that was deposited by the wind. Loess is thin and rather sporadic in the Rudement and most of the Equality Quadrangles. Undisturbed loess 2 to 3 feet, occasionally 5 feet or thicker, is found on relatively flat areas along divides on Cave Hill, the Wildcat Hills, and hills in Eagle Valley. On the slopes most of the loess has been eroded and either bare rock, or slope wash and alluvium can be seen. The rounded hills north of the Shawneetown Fault Zone bear thicker loess, up to 20 feet. This thicker silt possibly was derived from the bed of Lake Saline, which repeatedly was drained and exposed to the wind.

Thick loess, probably 15 to 20 feet of it, mantles the narrow eastern spur of the Wildcat Hills east of Illinois Route 1. Here the source of silt clearly was the adjacent Maumee Flood plain. East of the Maumee Flood channel the windblown deposits reach their greatest thickness. Prominent sand dunes line the eastern side of the flood course from the southwest end of the Shawneetown Hills across Gold Hill nearly to the southern edge of the Shawneetown Quadrangle. Longitudinal ridges of sand are very prominent around McGhee and Kanady Cemeteries, north of Gold Hill. Very thick dunes cover the west end of Gold Hill itself. Quarry pits (that do not reach bedrock) near the NW corner of Section 5, T 10 S, R 9 E, reveal sand deposits 30 feet thick. Nearby, the topographic map shows two small natural depressions, evidently blow-outs between dunes.

The sand grades rapidly eastward into silt. The Shawneetown Hills are almost entirely mantled with loess. Many roadcuts reveal 10 to 15 feet of silt, but do not reach bedrock. Similar or greater thicknesses cover the western end of Gold Hill and the hills to the south (where not disrupted by strip mining). Loess thins eastward on Gold Hill; ravines contain sufficient bedrock exposures to map structure. Westward, and in the southern foothills, hogbacks and fault-slice ridges retain their characteristic form, but the bedrock is buried.

Loesses in the study area include the Loveland Silt of Illinoian age and the Roxanna Silt and Peoria Loess of Wisconsinan age. The first two silts, more thoroughly weathered, are reddish brown; the third is grayish brown or yellowish brown. Most of the loess we observed appears to be Peoria Loess. Older, reddish silts underlying Peoria Loess can be seen in a few roadcuts and strip mines, but we made no effort to distinguish the various loesses in mapping.

Alluvium Materials mapped as alluvium range from coarse, unsorted rock debris in ravines to fine silt and clay on the modern Ohio River flood plain. Most of these deposits probably are of Holocene age, but some may date from earlier in the Pleistocene.

Distinguishing between alluvium and lacustrine sediments is difficult in the field: any mapped boundary would be quite arbitrary. As noted previously, most lake sediments are covered by at least a veneer of Holocene alluvium. Furthermore, the materials left by Lake Saline were brought there by streams, so lacustrine and alluvial sediments must intergrade and interfinger. We have avoided the problem by not distinguishing alluvium from lake deposits on the maps.

Talus and colluvium Talus and colluvium are found on all slopes in the study area except those covered with thick loess or aeolian sand. These materials were not mapped, even though they hide large areas of bedrock and locally make significant landforms. Some talus/colluvium at the foot of escarpments on Cave, Wildcat, and Gold Hills may be 100 feet or thicker. Talus forms cones or coalescing fans, deeply dissected by modern ravines. Beneath cliffs of Caseyville sandstone, huge blocks up to the size of a house commonly have detached themselves and slid many hundreds of feet from their original positions. These can be mistaken for outcrops, and mapped as such, if the surrounding area is not thoroughly scouted.

Surface mines All areas in which the land has been disturbed by surface mining or quarrying are designated on plate 1a. Mines are shown regardless of the degree of reclamation (if any). The boundaries of mines were taken from company maps, when available; otherwise, they were mapped on the basis of aerial photographs and field inspection.

Plate 1a also shows the entrances of active and abandoned coal mines observed in the field. This mapping is not comprehensive, because time has erased traces of many old mines. The most complete information on active and abandoned mines is found in the Mined-Out Area Maps published by the ISGS.

STRUCTURAL GEOLOGY

Rough Creek-Shawneetown Fault System

The Rough Creek-Shawneetown Fault System (fig. 9) is a continuous and integral structure; however, disjointed terminology arose because early geologists, working in different regions, thought they were dealing with separate fault zones.

Faults were first observed along the Ohio River near Shawneetown, Illinois by Owen (1856), who named the "Shawneetown Fault." This eventually was modified to "Shawneetown Fault Zone," reflecting the compound nature of the break. Meanwhile, other geologists mapped structural dislocations, variously interpreted as an anticline or a fault zone, along the Rough Creek in Ohio and Grayson Counties, Kentucky. Norwood (1876) apparently was the first to apply the name "Rough Creek Anticline" to the structure. By the time the link between the Shawneetown and Rough Creek elements was established, the separate names were well fixed by long usage. Numerous variants of these names have arisen through the years. Some geologists refer to the entire system as "Rough Creek Fault Zone, System, or Lineament," but most preserve the dual nomenclature in one form or another.

In this report we will apply the name "Rough Creek-Shawneetown Fault System" (RC-SFS) to the system as a whole, "Shawneetown Fault Zone" (SFZ) to the portion in Illinois, and "Rough Creek Fault System" (RCFS) to the part in Kentucky.

Shawneetown Fault Zone The Shawneetown Fault Zone (SFZ) is a narrow but complex fracture system. Our mapping shows it to be composed of three principal elements:

- The front fault, a high-angle, reverse fault that is the master fault of the zone. The front fault is so named because it generally lies at the northern or northwestern front of the Shawneetown Fault Zone.
- Secondary high-angle faults that join the front fault at one or both ends, and commonly form a braided pattern in map view. With the front fault, secondary faults outline a series of narrow, steeply tilted upthrown and downthrown slices.
- Smaller faults and sharp monoclinal flexures detached from, but parallel with and south of, the front fault.

Because the Eagle Valley Syncline is closely associated with the structure of the SFZ, it will be discussed in this section.

The front fault The front fault is in all respects the master break of the SFZ. It is continuous the length of the zone in Illinois and can be traced at least 35 miles into Kentucky. The front fault has the largest displacement and broadest breccia zone of any fault in the system; it also produces prominent topographic expression. The steep west and north faces of Cave Hill, and the north faces of the Wildcat Hills and Gold Hill, are the recedent fault-line scarp of the front fault.

The front fault is a high-angle reverse fault with the southern block upthrown; this is demonstrated by the log of the John C. Dunhill No. 1 Margaret Karsch well (well 2 table 1, fig. 3), which was spudded approximately 750 feet south of the surface trace of the fault. The well penetrated the fault at a depth of about 2,380 feet, passing from Clear Creek Chert (Lower Devonian) to Caseyville or Abbott Formation (lower Pennsylvanian) (fig. 16). The calculated dip of the fault is approximately 72° southward, and the stratigraphic displacement is roughly 3,500 feet. Several other wells, spudded short distances north of the fault and drilled to considerable depth, did not encounter the fault, demonstrating that it is either vertical or dips southward. In Kentucky the logs of more than a dozen wells drilled through the front fault show repeated section, indicating a reverse fault with the southern side upthrown (Smith and Palmer, 1981).

Outcrop data confirm subsurface evidence of the attitude of the fault. The surface trace of the fault is nearly straight across rugged terrain, indicating a steep dip. In several places strata adjacent to the front fault are vertical or overturned. New Albany Shale at

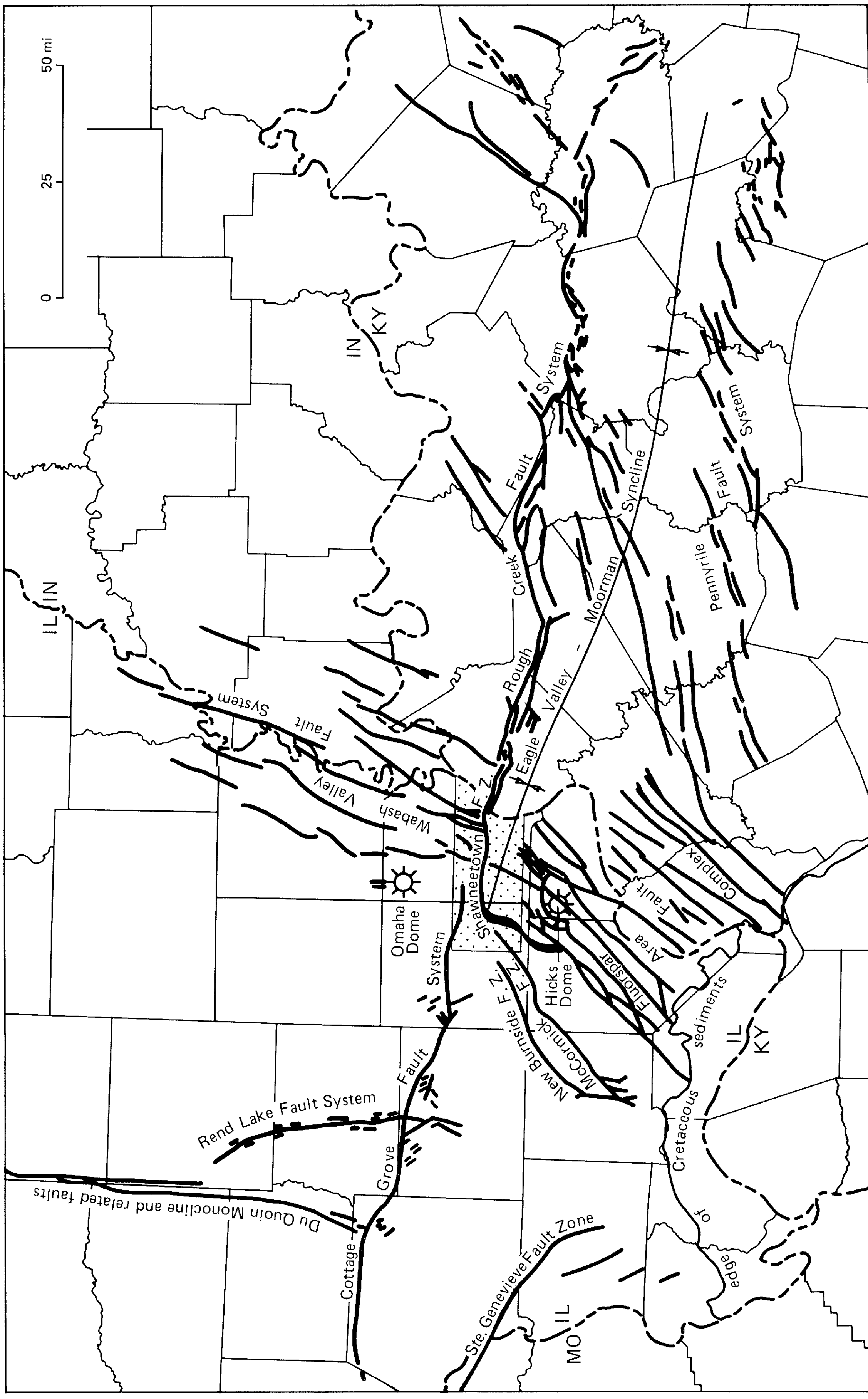


FIGURE 9. Structural features of southern Illinois, southwestern Indiana, and western Kentucky. Stippled area indicates study region.

Horseshoe Quarry dips vertically; vertical Chesterian beds can be seen alongside the ravine in the SE 1/4 NW 1/4 NW 1/4, Section 3, T 10 S, R 7 E, Rudement Quadrangle. In an abandoned sandstone quarry just west of Illinois Route 1 and south of the Saline River, NE 1/4 NW 1/4 NW 1/4, Section 35, T 9 S, R 8 E, Caseyville Sandstone dips 65° to 70° south, and the attitude of crossbedding and small unconformities indicates that the beds are overturned. Vertical and overturned rocks are characteristic of reverse faults, not of normal faults.

The maximum recorded vertical separation on the front fault is about 3,500 feet in the Karsch well. At Horseshoe the displacement is approximately 3,100 feet. Southwestward the offset decreases rapidly to about 700 feet at the southern edge of the Rudement Quadrangle. Between Horseshoe and the Ohio River the vertical separation varies from about 1,000 to 2,600 feet.

Rocks along the front fault are intensely shattered or brecciated. Jagged spinelike ridges of brecciated sandstone, recrystallized so that it resembles metamorphic quartzite in hand specimen, locally mark the fault trace. These breccia zones are commonly several tens of feet to more than 100 feet wide. Small amounts of fluorite and sulphide mineralization were noted in small mines or prospect pits along the front fault in Section 21, T 10 S, R 7 E, and also in the NW 1/4 NW 1/4 NE 1/4, Section 16, T 10 S, R 7 E, Rudement Quadrangle. According to local residents, silver ore was mined at the latter location around the year 1870.

Secondary faults Most secondary faults in the Shawneetown Fault System lie south or southeast of the front fault, and intersect the latter at one or both ends. Most of the secondary faults are roughly parallel with the front fault, but a number of short perpendicular cross-faults have been mapped. The general map pattern of fractures is anastamosing or branching, somewhat like a map of a braided stream.

Together with the front fault, the secondary faults outline a series of steeply tilted, sharply upthrown and downthrown blocks and slices. Most remarkable are the slivers of older rocks sandwiched between much younger rocks. The most notable example is at Horseshoe, where New Albany and Ft. Payne strata occupy a narrow slice surrounded by Chesterian and Pennsylvanian rocks. Numerous blocks of Mississippian rocks surrounded by Pennsylvanian have been mapped on the north side of the Wildcat Hills, northwest of Cave Hill, and in the W 1/2, Section 21, T 10 S, R 7 E. Downthrown slices are neither as common nor as greatly displaced as upthrown slices. Most downthrown blocks contain Caseyville or Abbott Formation rocks juxtaposed with Chesterian rocks. No rocks younger than the Abbott Formation have been recognized within the fault slices.

Almost without exception the rocks in these slices dip away from the front fault and toward the Eagle Valley Syncline. Only in the most complexly faulted areas are slices tilted obliquely to the front fault. The angles of inclination range from about 10° to vertical or locally overturned, but the dip seldom changes much within a given fault block; these slices generally appear to have remained rigid, being tilted or rotated rather than internally folded. Exceptions are found only in plastic lithologies, such as shales, where small drag folds record dip-slip displacement.

Secondary faults are vertical or steeply inclined, as shown by topographic expression and by actual exposures of fault surfaces. All faults visible in the field were seen to be steeply dipping normal faults. Slickensides indicate dip-slip movement, except in highly deformed areas, where several sets of striations might be seen on a single surface. Brecciated and recrystallized sandstone marks the larger faults, but is not as extensive as along the front fault.

Vertical separation along mapped secondary faults ranges from less than 100 to slightly more than 1,000 feet. Minor faults observed in outcrop have displacements of several inches to a few feet.

Rocks in tilted fault blocks typically display prominent systematic jointing normal to bedding. The major fracture set generally is parallel to the front fault and the secondary set perpendicular, but some outcrops show rhomboidal or conjugate jointing, with the long axes of the rhombs parallel to the dip of the strata. The former case suggests tensional stress, the latter compressional stress perpendicular to the front fault.

Detached faults and flexures Small faults and monoclinal flexures, which do not connect with the front fault at either end, strike parallel with the front fault and lie 1/2 to 1 1/2 miles south or southeast of it. All these structures strike parallel to sedimentary bedding and are downthrown away from the front fault.

Detached faults include the Ringold and Ringold South Faults in the Shawneetown Quadrangle, the Jones Fault in the Rudement Quadrangle, and the two faults in Sections 21 and 28, T 10 S, R 7 E, Rudement Quadrangle. The Ringold and Ringold South Faults were named in Nelson and Lumm (1984) for Ringold Church, in Section 4, T 10 S, R 9 E, and the Jones Fault was named in the same report for nearby Glen O. Jones Lake. Only the north-trending fault in Section 21 is directly exposed in the field. It is a steep normal fault with slickensides parallel to dip. This fault dies out northward into a narrow monocline. The trace of the Jones Fault was not found in the field, but coal-test holes passing through it show missing section, indicative of normal faulting. High-angle fractures and abrupt changes of elevation of coals in strip mines, and steeply dipping sandstone, also indicate the Jones Fault. The Ringold and Ringold South Faults are inferred entirely from subsurface data, and may be sharp folds rather than faults. The indicated offsets increase eastward, and these faults appear to link with faults mapped by Palmer (1976) in Kentucky.

Plate 2 shows both large and small monoclinal flexures. The best-marked large one lies northwest of the Jones Fault, mainly in Section 2, T 10 S, R 7 E. The dip of exposed Pennsylvanian strata increases from about 12° in the NW 1/4 of the section, abruptly increasing to 20° and then decreasing just northwest of the Jones Fault. Typical small flexures are mapped in Sections 31 and 33, T 9 S, R 8 E, Equality Quadrangle. They strike east-west, range from a few feet to almost 2,100 feet wide, and show dips as steep as 40°. Steeply dipping to vertical fractures invariably run parallel with flexural axes. Some flexures can be followed for more than 1,000 feet along strike, but most are seen only in single outcrops.

The relationship of flexures to detached faults indicates that the monoclines probably represent faults initiated at depth that died out upward before reaching the surface as strata accommodated to stress by ductile rather than brittle failure. Since detached faults apparently dip away from the front fault, they probably do not intersect it at depth.

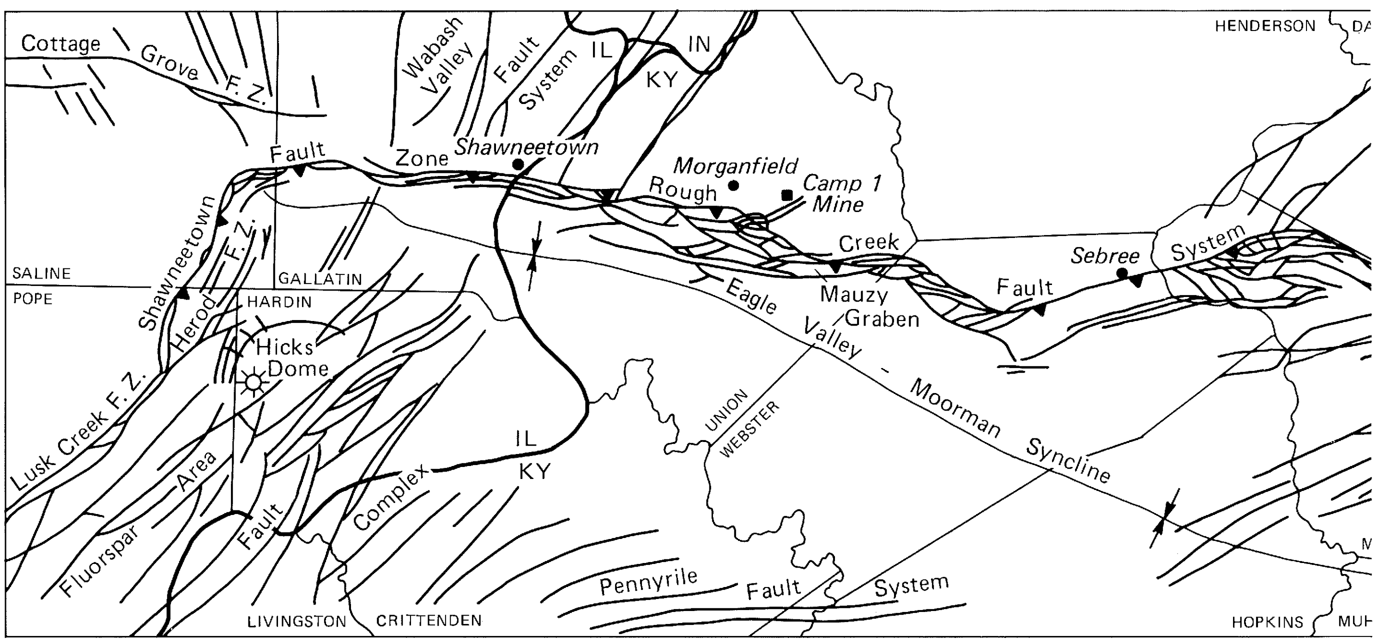


FIGURE 10. Rough Creek-Shawneetown Fault System and associated structures (adapted from Schwalb and Potter, 1978 and Treworgy, 1981).

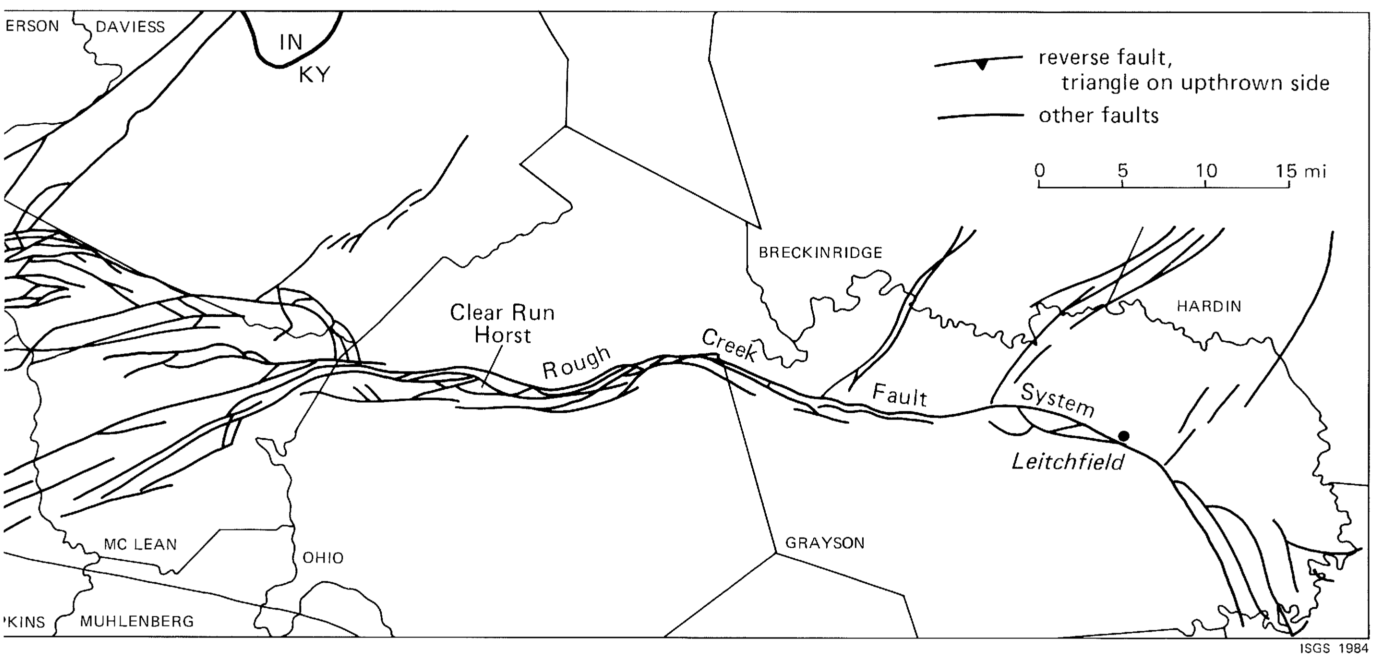
Only three secondary faults have been mapped north of the front fault. All are known solely from drill-hole information. The largest such fault is the Negro Spring Fault which was named in Nelson and Lumm (1984) for Negro Spring Salt Well, Section 26, T 9 S, R 8 E, in the Equality Quadrangle. The second fault is in Section 34, T 9 S, R 7 E, Rudement Quadrangle, and the third in Sections 33 and 34, T 9 S, R 9 E, Shawneetown Quadrangle. All three are downthrown toward the front fault. The electric log of one borehole along the Negro Spring Fault showed two intervals of Chesterian strata missing, indicating normal faulting. The other two small secondary faults are known only from one or two boreholes, so their length and extent are questionable.

Remarkably little deformation is shown north and west of the front fault, in contrast to the intense fracturing and tilting of strata south of the fault. Aside from the three small faults mentioned above, the most notable structure northwest of the front fault is the half-anticline in Sections 20 and 21, T 10 S, R 7 E, Rudement Quadrangle. Lower Pennsylvanian sandstones on the flanks of this structure dip as steeply as 55°. Elsewhere, the strata dip gently northward toward the center of the Illinois Basin. No dips greater than about 5° were observed except adjacent to the Cottage Grove and Wabash Valley Fault Systems. Subsurface data indicate gentle anticlinal noses north of the front fault near Horseshoe and in Section 32, T 10 S, R 9 E, Shawneetown Quadrangle. Enough boreholes are available to demonstrate that the rock layers remain essentially horizontal in most places to within a few hundred feet of the front fault.

Thus, the Shawneetown Fault Zone is a highly asymmetrical structure. The southern upthrown block is severely faulted and sharply tilted, but the downthrown block in most places is scarcely deformed.

Eagle Valley Syncline The Eagle Valley Syncline (fig. 10) lies immediately south of, and runs parallel to, the Shawneetown Fault Zone in Illinois. The syncline is narrow at its western end, and widens abruptly in the Shawneetown Quadrangle. The Eagle Valley Syncline merges eastward with the broad Moorman Syncline, which parallels the entire length of the Rough Creek Fault System in Kentucky (fig. 9).

The Eagle Valley Syncline is an asymmetrical trough. Rocks on the southern limb dip gently and quite uniformly northward. The average inclination of rocks on the southern flank increases from about 6° at the western end of the syncline to 8° to 9° near the eastern



end. The Lee, Grindstaff, and Herod Fault Zones, members of the Fluorspar Area Fault Complex, cross the southern limb (plate 2). The western closure and northern limb of the Eagle Valley Syncline display much steeper and more variable dips than does the southern flank. Most inclinations on the northern and western flanks fall within the range of 20° to 30°, but much steeper tilts are measured along monoclinal flexures and faults, as mentioned previously.

The axis of the Eagle Valley Syncline is sinuous and does not run exactly parallel with the limbs. A series of smaller satellite synclines, anticlines, and saddles occupies the axial region (plate 2). Dips on the limbs of these are quite marked in places. Between the Pisgah Syncline and Kuykendall Anticline (Section 7, T 10 S, R 9 E) the elevation of the Springfield Coal rises 500 feet within a lateral distance of 4,000 feet—an average dip of 7½°. Nelson and Lumm (1984) named Pisgah Syncline for Pisgah Church, Section 12, T 10 S, R 8 E, and Kuykendall Anticline for Kuykendall Valley, Sections 4 and 5, T 10 S, R 9 E. Butts (1925), who had far fewer subsurface datum points than we do, attributed this change in elevation to faulting. Coal-test borings on centers of 300 feet or less reveal that Butts' "Saline River Fault" does not exist. East of this point, the axis of the syncline, as traced on the Springfield Coal, drops nearly 1,000 feet within 4 miles. The youngest preserved Pennsylvanian rocks in the Illinois Basin are found along the centerline of the Moorman Syncline in adjacent Union County, Kentucky.

Overall structure (geologic cross sections) We have prepared four geologic cross sections to illustrate the overall structure of the Shawneetown Fault Zone (plate 1). Cross sections A-A', B-B', and C-C' are north-south transects of the SFZ and Eagle Valley Syncline. Section D-D' is an east-west profile from Rudement to the Ohio River. The lines of the four sections are plotted on plate 2.

Cross sections A-A', B-B', and C-C' all show much the same structural configuration. The asymmetrical Eagle Valley Syncline, with a gentle southern limb and steeper northern limb, shows itself clearly. The front fault of the SFZ is plotted as a high-angle reverse fault, dipping southward. Other faults are shown with appropriate dips, or drawn as vertical if the direction of inclination is unknown.

The most striking feature evident in these profiles is that the great vertical displacements of the SFZ are confined to the narrow, highly deformed zone just south of the front fault. Individual fault slices or blocks are upthrown as much as several thousand feet, but the net vertical displacement across the fault zone as a whole is slight. Any given stratum generally is lower at the axis of the Eagle Valley Syncline than immediately north of the front fault. Thus, it is incorrect to say that the south side of the SFZ is upthrown. Only rocks within the fault zone and along the upturned rim of the Eagle Valley Syncline are uplifted relative to the same rocks to the north and south.

The most extreme example is at Horseshoe (cross section A-A'), where a slice of Fort Payne Formation and New Albany Shale is upthrown more than 3,000 feet within the fault zone. Other fault slices contain Valmeyeran, Chesterian, and lower Pennsylvanian strata. The arrangement of secondary faults, as shown in the section, is hypothetical; we assume that they merge with the front fault at depth. South of the fault slices, lower Pennsylvanian sandstones dip steeply into the Eagle Valley Syncline.

In cross section B-B' the structure of the SFZ is simpler. A small wedge of Mississippian rock is caught between the front fault and Level Hill Fault. The wedge is juxtaposed with Caseyville Formation on the south and Spoon Formation on the north. Rocks south of the Level Hill Fault decline to the south. Nelson and Lumm (1984) named the Level Hill Fault for Level Hill cemetery, in Section 36, T 9 S, R 8 E.

The situation is similar in cross section C-C'. Chesterian strata and Caseyville Formation are found in tilted fault blocks between middle and upper Pennsylvanian rocks outside the fault zone.

All three profiles demonstrate the highly asymmetrical structure of the SFZ. Note the contrast between the steeply dipping, highly faulted rocks south of the front fault, and the very gently dipping rocks to the north.

Cross section D-D′ runs west to east near the southern edge of the mapping area. The SFZ in this section shows relatively little displacement but peculiar structure. It can be described as a sharp anticline with dips steepening toward the faulted crest. A small sliver of Chesterian rock is upthrown in the fault zone between Pennsylvanian rocks on either side. A detached fault east of the front fault may increase in throw downward. Farther east, the section more or less parallels the axis of the Eagle Valley Syncline, and shows the small horsts and grabens of the northernmost part of the Fluorspar Area Fault Complex.

These cross sections demonstrate that the Shawneetown Fault Zone cannot be the product of a single episode of vertical uplift. Either a large component of horizontal (strike-slip) motion, or more than one phase of dip-slip motion, would have been necessary to produce the SFZ.

Rough Creek Fault System The Rough Creek Fault System is the eastward continuation of the Shawneetown Fault Zone into Kentucky. Numerous published geologic maps and reports indicate that the structure is essentially the same in Kentucky as in Illinois.

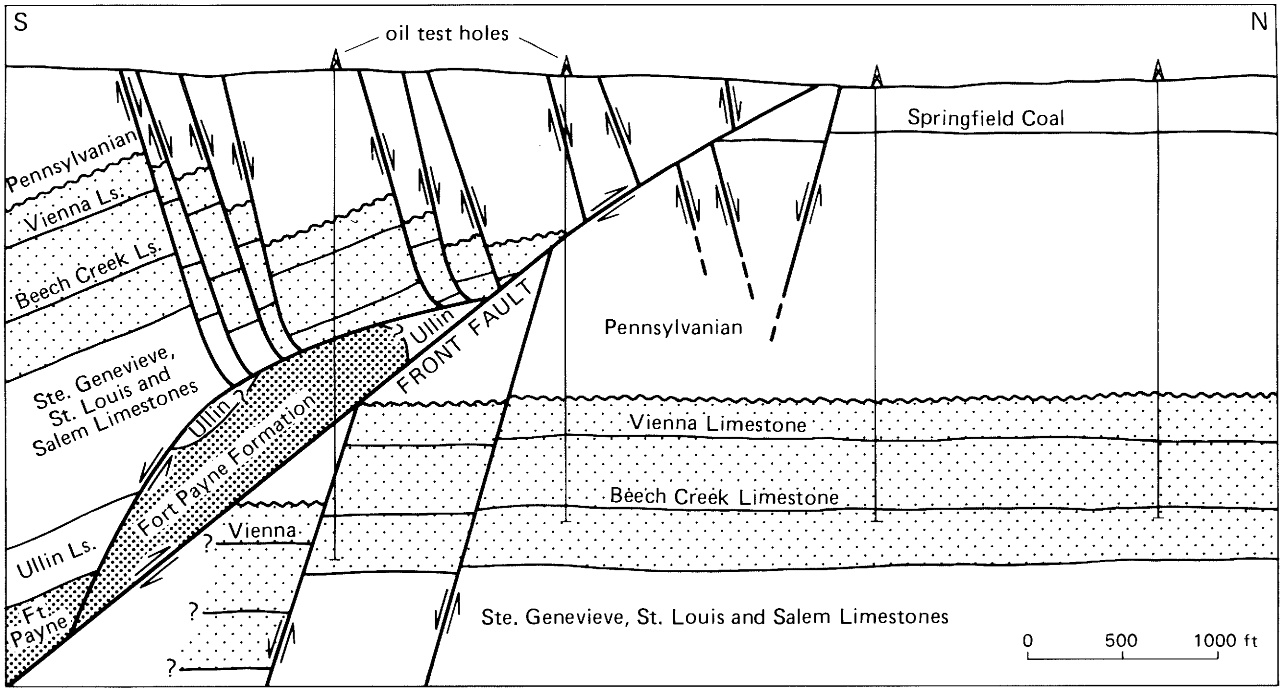
The Rough Creek Fault System has been traced about 100 miles from the Ohio River to eastern Grayson County (fig. 10). The system is gently sinuous in map view and is composed of numerous interconnected fractures forming a braided or anastamosing pattern. The fault zone widens from about one mile at the state line to five miles in McLean County, about midway between the two ends of the system. Farther eastward the fault zone narrows, and it curves southeastward, splinters, and dies out southeast of Leitchfield, Grayson County.

The largest fault in the Rough Creek Fault System is a high-angle reverse fault with its south side upthrown. This fault has been traced at least as far east as the Calhoun Quadrangle, McLean County (fig. 11, Section F) and probably connects with the front fault of the SFZ in Illinois. The reverse fault is known mainly from the presence of repeated section in the logs of numerous oil-test holes that cut the fault. Vertical separation along the front fault in Kentucky ranges from 660 to more than 1,500 feet, and in most places the fault dips 65° or more to the south. Near Morganfield, eastern Union County, however, geometric construction from numerous test holes that penetrate the fault indicates a dip as low as 25° (Smith and Palmer, 1981).

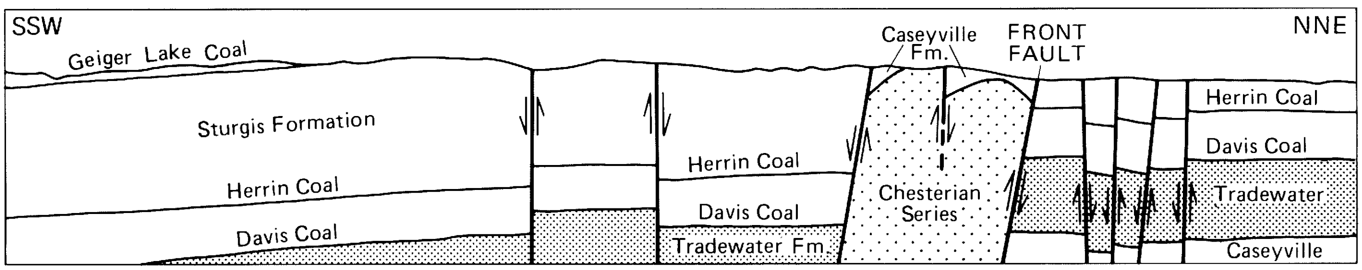
Six cross sections of the Rough Creek Fault System, taken from geologic quadrangle maps and other published sources, are presented in figure 11. The western four cross sections (E, A, B, and F) demonstrate reverse faulting. As in Illinois, narrow fault blocks or slices of Mississippian and lower Pennsylvanian rocks are upthrown on the front fault and steeply tilted southward into the Moorman Syncline. The fault slices are separated by steeply inclined normal or vertical faults, some of which intersect the front fault at depth. Strata north of the front fault are horizontal or dip gently, and are broken by steep normal faults of small displacement.

The most interesting cross section is Smith and Palmer's (1981) profile from Morganfield (fig. 11, cross section A). Here five wells encountered a lens of Fort Payne Formation, up to 450 feet thick, along the front fault. The lens is completely surrounded by younger rocks and is more than 1,000 feet above the normal position of Ft. Payne on either side of the fault. This structure immediately calls to mind the situation at Horseshoe (plate 1, cross section A-A′). Clearly, no single episode of overthrusting can account for the anomalous slices of Ft. Payne. Smith and Palmer (1981) concluded that the overriding block must have originally moved farther north than its present position; the slice of Ft. Payne was left behind in the fault zone when the overthrust block later moved back down dip to the south.

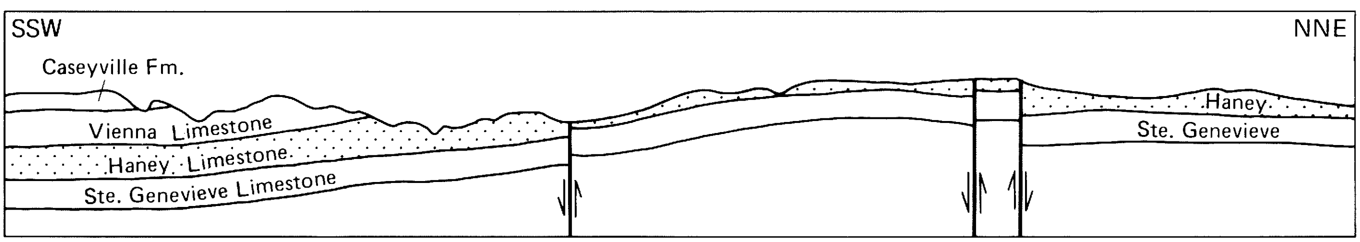
We observed a smaller but equally striking example of reversed dip-slip movement on a fault in underground workings of Peabody Coal Company's Camp 1 mine northeast of Morganfield. The fault is the northwestern member of a pair of faults that branch northeastward off the front fault and produce a graben. The northwestern fault conveniently aligned the Springfield and Herrin Coals so that the coal company could mine directly from the former seam to the latter. In drill holes and most exposures in the mine, the fault ap-



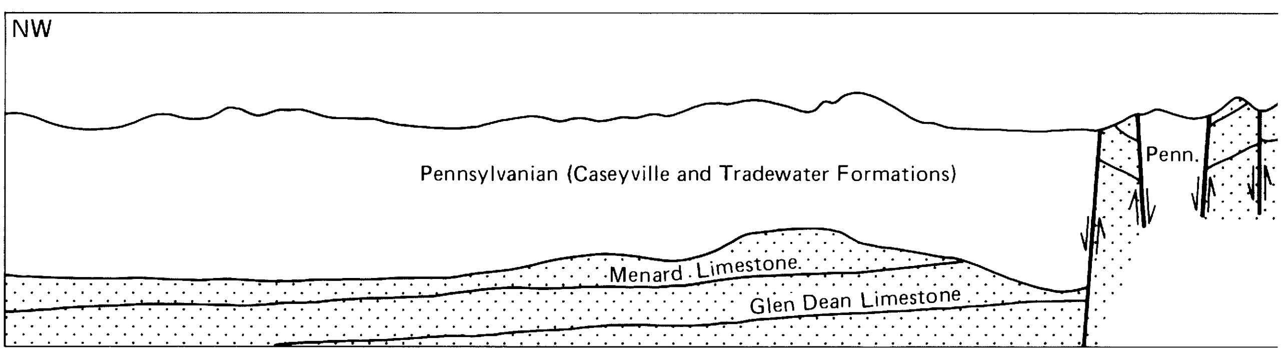
A. Near Morganfield, Union County (Smith and Palmer, 1981): no vertical exaggeration.



B. Dixon Quadrangle, Webster County (Hansen, 1976): vertical exaggeration 2x.

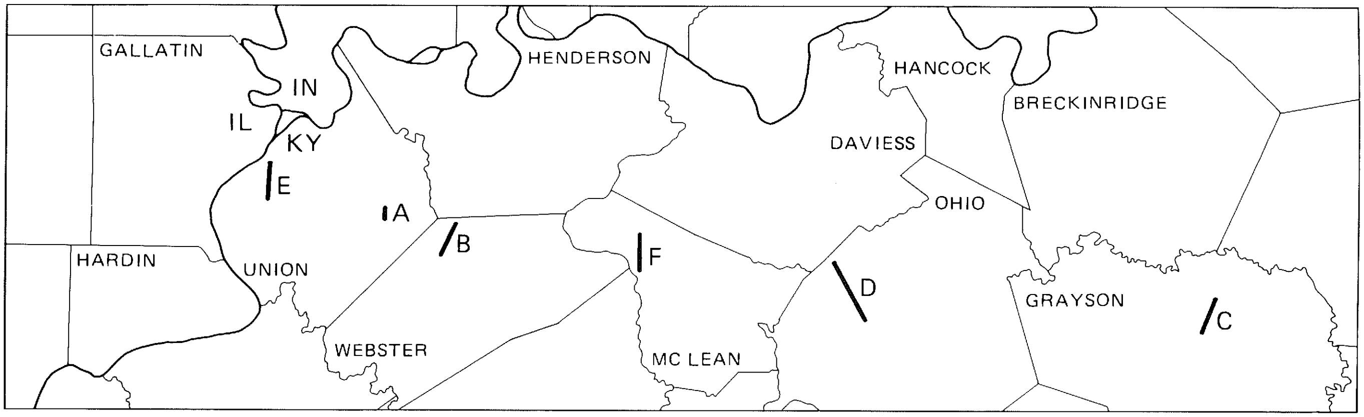


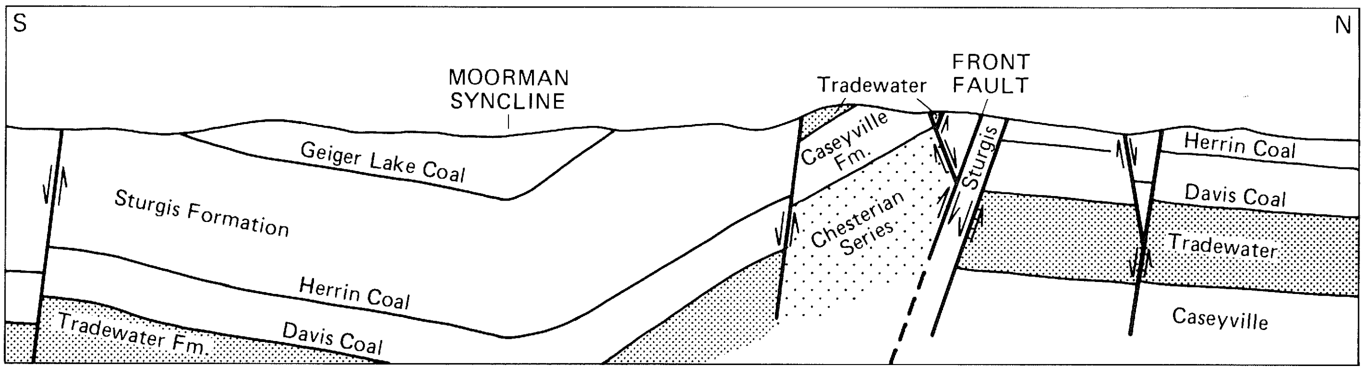
C. Leitchfield Quadrangle, Grayson County (Gildersleeve, 1978): vertical exaggeration 4x.



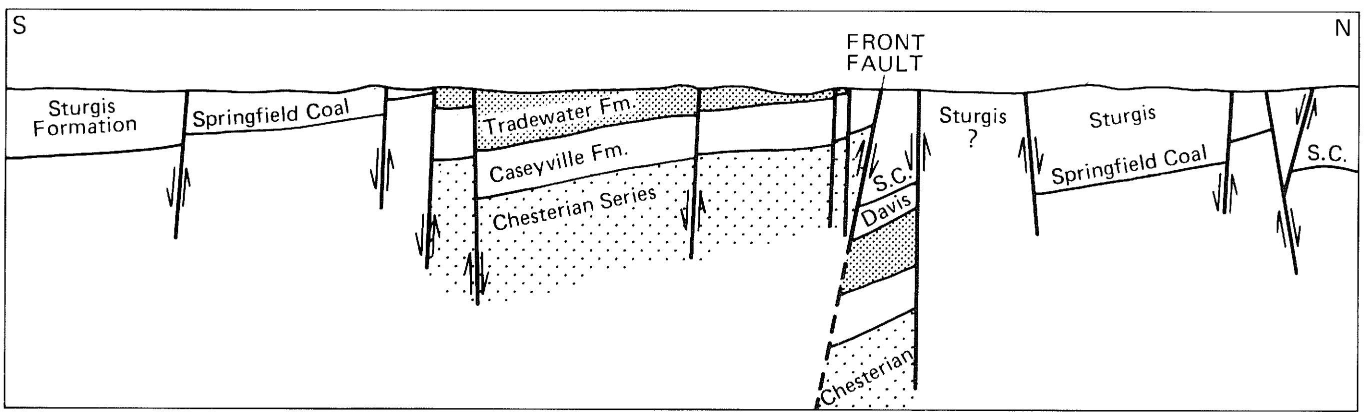
D. Pleasant Ridge Quadrangle, Ohio County (Goudarzi and Smith, 1968): vertical exaggeration 4x.

FIGURE 11. Cross sections of Rough Creek Fault System in western Kentucky.

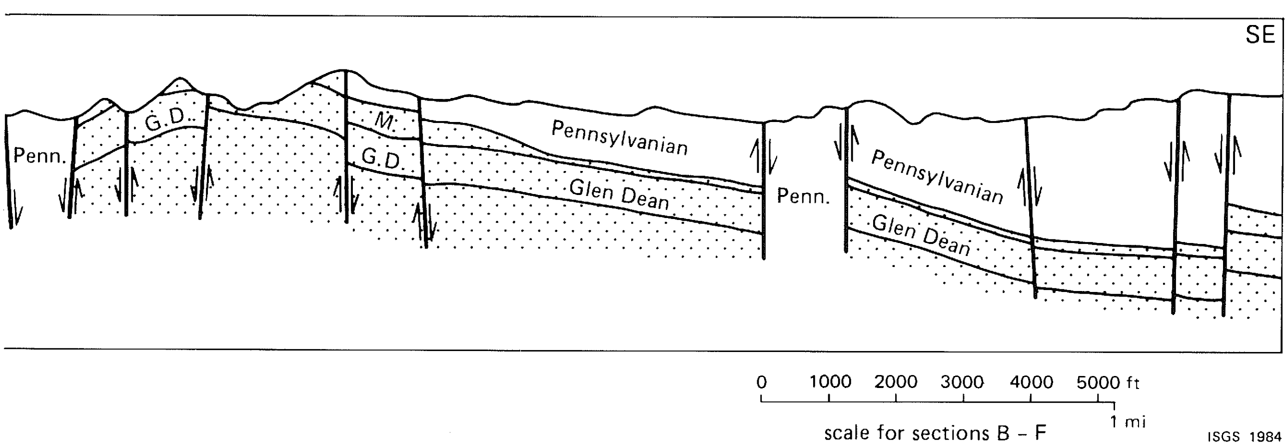




E. Grove Center Quadrangle, Union County (Palmer, 1976): vertical exaggeration 2x.



F. Calhoun Quadrangle, Mc Lean County (Johnson and Smith, 1975): vertical exaggeration 2x.



pears to be a simple high-angle normal fault with a narrow zone of breccia or fault slices. Slickensides and drag folds indicate dip-slip movement. On one exposure, however, the fault splits into two parallel branches; the central block is downthrown with respect to both sides (fig. 12). The history of this fault must have included an episode of reverse faulting, opposite to the dominant normal faulting.

Notable downthrown slices occur in the Rough Creek Fault System. One in eastern Union County contains the only Permian strata identified to date in the Illinois Basin. They are known from a single drill core, which recovered approximately 390 feet of rock containing Permian fossils (fig. 10, Mauzy Graben). Structural projections suggest that Permian rocks may reach 1,300 feet thick elsewhere in the same graben. The graben lies near the south edge of the Rough Creek Fault System. The discovery of this graben indicates that faulting took place after early Permian time, preserving a small remnant of sediments that elsewhere have been eroded (Kehn, Beard, and Williamson, 1982).

The front fault of the Rough Creek Fault System has not been mapped as a reverse fault east of McLean County, but there is no evidence that it dies out there. In the absence of proof that a fault is reverse, most geologists take the conservative course and map the fault as normal, or vertical. Apparently no boreholes have penetrated the fault east of the Calhoun Quadrangle (fig. 11, cross section F). Surface exposures of faults are scarce, and it is difficult at best to determine the attitude of a large, nearly vertical fault from scattered outcrops.

The eastern part of the Rough Creek Fault System (Ohio and Grayson Counties) is mapped as a faulted anticline or a belt of tilted upthrown and downthrown (mostly upthrown) blocks. Cross section D (fig. 11) is typical for Ohio County. The strata rise northward out of the Moorman Syncline, and are broken by numerous high-angle faults. Chesterian rocks reach the surface at the crest of the fractured arch. The largest faults are generally near the north edge of the system; north of these, the strata lie nearly flat. Eastward the width and complexity of the zone and the number and magnitude of faults decrease. A section in the Leitchfield Quadrangle, Grayson County, shows an arch broken by only three faults (cross section C, fig. 11).

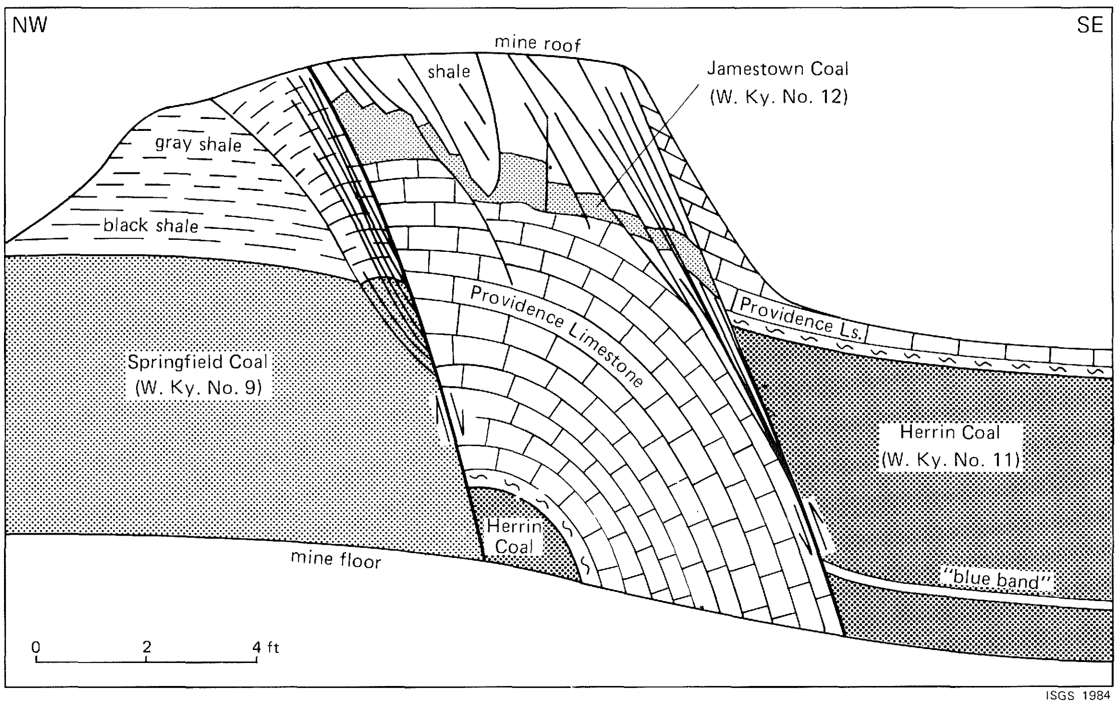


FIGURE 12. View of fault in underground workings of Camp 1 Mine. Although overall displacement is normal, central slice of fault zone has dropped below its level on either side of zone, indicating reverse movement on right-hand fault. Note small reverse flexure in Springfield Coal and overlying shales, left of center.

An excellent exposure of part of the Rough Creek Fault System can be viewed in a roadcut along the Green River Parkway in the Pleasant Ridge Quadrangle, Ohio County. Detailed drawings and a description of this cut were presented in Krausse, Nelson, and Schwalb (1979). In the roadcut a narrow slice of Chesterian limestone and shale (Menard Formation) is faulted upward between lower Pennsylvanian rocks. The Menard is folded into a tight asymmetrical anticline and appears as though it were punched upward through the covering Pennsylvanian strata. Attitudes of faults range from vertical to horizontal, but most of the large ones are steep reverse or vertical faults. Many examples of recurrent movement—one fault offsetting another—were found. The attitudes of drag folds and rare slickensides indicate dominantly dip-slip movements within the roadcut.

Another interesting roadcut is on U.S. 231 at Hoover Hill, about 2 miles west of the cut on the Green River Parkway. One large fault and many small ones are visible in the Hoover Hill roadcut. The large fault strikes east-west, is vertical, and has breccia and faint vertical slickensides. We could not determine which side is downthrown; drag along the fault gave contradictory indications, suggesting reversals of movement. Most other faults in the roadcut are steeply inclined and normal. However, a number of vertical surfaces, perpendicular to the main fault on both sides of the highway, bear horizontal slickensides. The amount of offset on these fractures could not be measured, but evidently is small.

These little fractures provide the only direct evidence we have seen for strike-slip movement within the Rough Creek-Shawneetown Fault System. In this case the lateral movement not only is minor, but is perpendicular to the main direction of faulting, which shows evidence of dip-slip only. The strike-slip fractures apparently segment a fault block and accommodated small north-south adjustments during vertical movement on the main faults.

Origin of the Rough Creek-Shawneetown Fault System Three major theories have been advanced to explain the origin of the Rough Creek-Shawneetown Fault System: horizontal compression, strike-slip faulting, or recurrent vertical movement.

Horizontal compression Weller (1940) apparently was the first to advocate horizontal compression as the cause of the Rough Creek-Shawneetown Fault System (RC-SFS). He proposed that a push from the south or southeast first formed an anticline, and then broke it, to produce the fault system. He pointed to the New Burnside and McCormick "anticlines" (fig. 9), northwest of, and roughly parallel to, the southwest-trending portion of the Shawneetown Fault Zone as further products of the same stresses. Weller suggested that the thrusting forces from the Appalachian orogeny were transmitted far inland to the preexisting zone of weakness along the Rough Creek-Shawneetown Fault System.

Smith and Palmer (1974 and 1981) likewise argue that post-Pennsylvanian faults of the RC-SFS were produced by compression from the south, but they do not speculate on the origin of the compressive forces. As previously mentioned, Smith and Palmer theorized that a late relaxation of compression allowed the overthrust block to slide back down to the south; slices of Ft. Payne and older rocks were sheared off the hanging wall and caught along the fault zone during this action. Smith and Palmer allow for the possibility that pre-Pennsylvanian movements in the RC-SFS may have been strike-slip or vertical.

Surface exposures and available subsurface data lend little support to the horizontal compression theory. The front fault is a high-angle reverse fault, except near Morganfield, and most other faults in the system are normal or vertical. No parallel folds, thrust faults, or other structures indicative of horizontal compression have been mapped in the vicinity of the RC-SFS. The McCormick and New Burnside structures, which Weller (1940) described as anticlines, actually are zones of high-angle faulting (Jacobson and Trask, 1983).

This lack of surface evidence for horizontal compression does not rule out the possibility that the front fault may flatten with depth and merge with a low-angle thrust fault or decollement. The little information available on deep structure of the RC-SFS however, indicates that faults remain steep at depth. Drilling and seismic sections indicate that surface faults extend downward at least to the Eau Claire and probably into the Mt. Simon. The seismic sections are not entirely conclusive—reflectors tend to break up in the fault zone—but they generally show that the RC-SFS is steeply inclined. The seismic section in Illinois (running southward from Equality across the Shawneetown Fault Zone and Eagle Valley Syncline), shows a steep fault zone from surface down to Cambrian. One of the sections in Kentucky having a prominent reflector of probable basement at 25,000 feet showed no trace of structural discontinuities along or south of the axis of the Moorman syncline.

Where could a decollement have originated? The RC-SFS is at least 120 miles from the nearest compressional structures in the Appalachian-Ouachita foldbelt. A decollement connecting the foldbelt with the RC-SFS would have to cover nearly the entire state of Tennessee plus southern Kentucky and northern Alabama and Mississippi. The numerous drill holes in those states—many of them reaching basement—have revealed no sign of such a vast feature. The idea that horizontal compression originated more locally, within the Rough Creek Graben itself, has been suggested, but falls into the realm of pure speculation.

In conclusion, barring new evidence from deep drilling or seismic surveys, we find that a horizontal compressive origin for the RC-SFS is extremely unlikely.

Strike-slip faulting Many geologists have noted a basic silimarity between the Rough Creek-Shawneetown Fault System and large strike-slip faults. Clark and Royds (1948) were the first to suggest wrench-faulting as the origin of the RC-SFS. Heyl and Brock (1961), Heyl et al. (1965), Heyl (1972), McGinnis et al. (1976), and Viele (1983), among others, also advocated a strike-slip origin for the system. Heyl regards the RC-SFS as a major link in his 38th Parallel Lineament, and claims that geophysical evidence suggests 50 km of right-lateral slip in the basement.

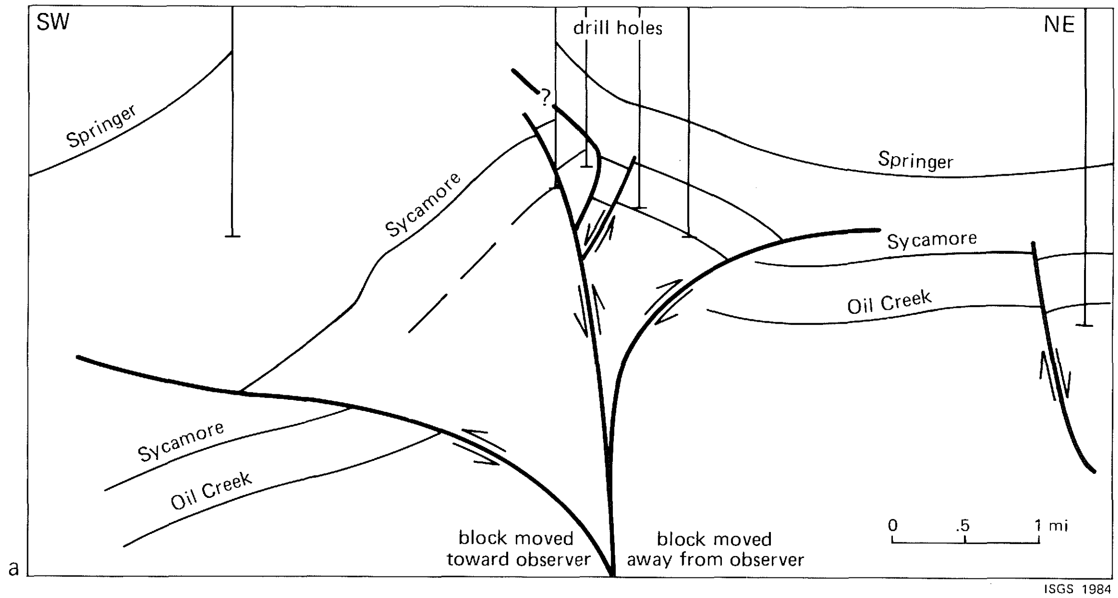
The absence of consistent vertical offset across the RC-SFS does suggest wrench faulting. So does the braided pattern of high-angle fractures, with numerous narrow upthrown and downthrown slices. When a wrench fault moves, wedges of rocks may be literally squeezed, like a watermelon seed, toward the surface. This is especially apparent when the wrench fault has a component of convergence, or horizontal compression. A characteristic upthrust structural style, recognized in many large strike-slip faults and often producing petroleum traps, has been termed a "flower structure" (Harding and Lowell, 1979). In a flower structure, reverse faults diverge upward away from the vertical "stem" fault at depth, and flatten toward the surface (fig. 13). Flower structures are well-developed along California's San Andreas Fault and along large wrench faults in the Ardmore Basin of Oklahoma (Harding and Lowell, 1979). They also occur in the right-lateral Cottage Grove Fault System of Illinois (Nelson and Krausse, 1981; fig. 38, p. 43). Our interpretive cross sections of the Shawneetown Fault Zone resemble these and other "flower structures" associated with known strike-slip faults and described in the literature.

Be that as it may, other evidence rules against the idea that the RC-SFS is a wrench fault. First, we have the field observations. With very few exceptions, slickensides and mullion on fault surfaces indicate vertical or nearly vertical dip-slip, and the orientation of drag folds shows the same movement. The only indications of horizontal or oblique-slip are found in complexly faulted zones, and only on minor fractures in such zones. Such indications, which probably can be found in any large fault zone, represent rotation or differential uplift of slices rather than a dominant strike-slip action. The large faults, as far as can be determined, are consistently dip-slip fractures: the front fault is a south-dipping reverse fault, and most other faults normal.

Anticlinal and monoclinal flexures along the RC-SFS strike essentially parallel with the major faults and with the zone as a whole. They do not show the oblique, en echelon relationship to the master fault that is diagnostic of strike-slip. En echelon folds result from the compressional component of the horizontal shearing stress, and their orientation indicates the direction of wrenching. The Cottage Grove Fault System has a well-developed belt of en echelon folds. So do many other known wrench faults around the world (Moody and Hill, 1956; Wilcox, Harding, and Seely, 1973; and Thomas, 1974). These fold belts are eagerly sought by petroleum explorationists because of their obvious trapping potential.

Another feature of strike-slip lacking in the RC-SFS is the complementary system of en echelon or pinnate normal faults created by the tensional component of wrenching stress. At first glance, the Wabash Valley and Fluorspar Complex faults, and other northeast-trending fractures along the RC-SFS, suggest that the RC-SFS is a left-lateral shear zone. However, the detailed structure of those faults and their relationship to the RC-SFS preclude such an interpretation—as will be discussed later in this report.

As we have noted, cross sections of the RC-SFS are reminiscent of flower structures. However, some characteristics of true flower structures are lacking. In a wrench-fault flower the upthrust faults curve off both sides of the master strike-slip fault in the base-



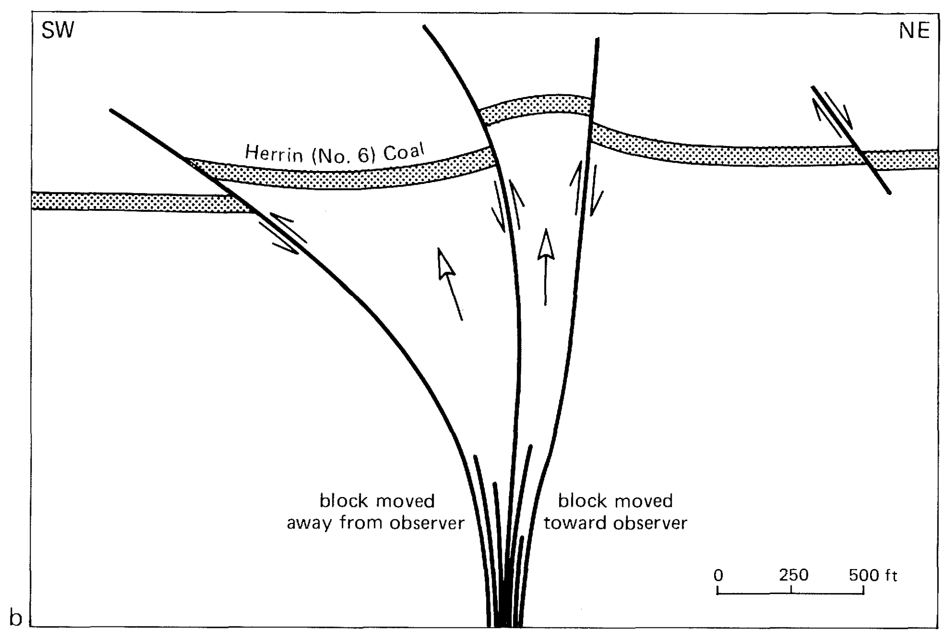


FIGURE 13. "Flower structures" produced by upthrust faulting in wrench-fault zones. Top: Ardmore Basin of Oklahoma, based on seismic profile and drill hole data from Harding and Lowell (1979); bottom: Cottage Grove Fault System, Williamson County, Illinois, based on mine surveys and drill holes from Nelson and Krausse (1981).

ment. The RC-SFS, in contrast, has an upthrust (the front fault) only on the north side; no northward-dipping reverse faults have been recognized. Also, the rollover anticlines associated with most true flower faults are not present in the RC-SFS. Instead, the fault blocks are either tilted southward toward the Moorman Syncline, or segmented into an asymmetrical, block-faulted arch.

Strike-slip faults typically are linear along strike. If the fault bends, part of the lateral slip must be transformed to either divergent (extensional) or convergent (compressional) deformation, depending upon the configuration of the bend and the direction of strike-slip. The Shawneetown Fault Zone makes an abrupt 70° bend in southeastern Saline County, but the structural style remains the same around the curve. Neither the extension indicative of left-lateral movement on the main fault nor the compression indicative of right-lateral slip is apparent.

The most conclusive evidence against a major element of wrench-faulting in the RC-SFS is found in paleochannels that cross the fault zone without being offset laterally. The best examples are found in Davis, Plebuch, and Whitman (1974), who report on a large area in west-central Kentucky, including a 40-mile segment of the Rough Creek Fault System. Faults and geologic structure compiled from geologic quadrangle maps and other sources are shown in plate 4, Davis et al. (1974). Plate 2 of Davis et al. is a map of pre-Pennsylvanian geology, as mapped from borehole data. This map shows a system of steep-sided anastomosing paleochannels cut into Chesterian strata beneath the basal Pennsylvanian deposits. The dominant direction of these ancient valleys is southwesterly, as it is throughout most of the Illinois Basin (Bristol and Howard, 1971). One of the largest paleochannels, the Madisonville Valley, crosses the Rough Creek Fault System at the common corner of Daviess, McLean, and Ohio Counties. Well data here is adequate to limit the maximum possible horizontal offset of the channel to less than 1,000 feet, which is less than the local maximum vertical separation in the fault zone. In Webster County, just west of the town of Sebree, two smaller paleovalleys cross the fault zone without noticeable horizontal offset. Here again, well control limits the possible error in detection to less than 1,000 feet. At

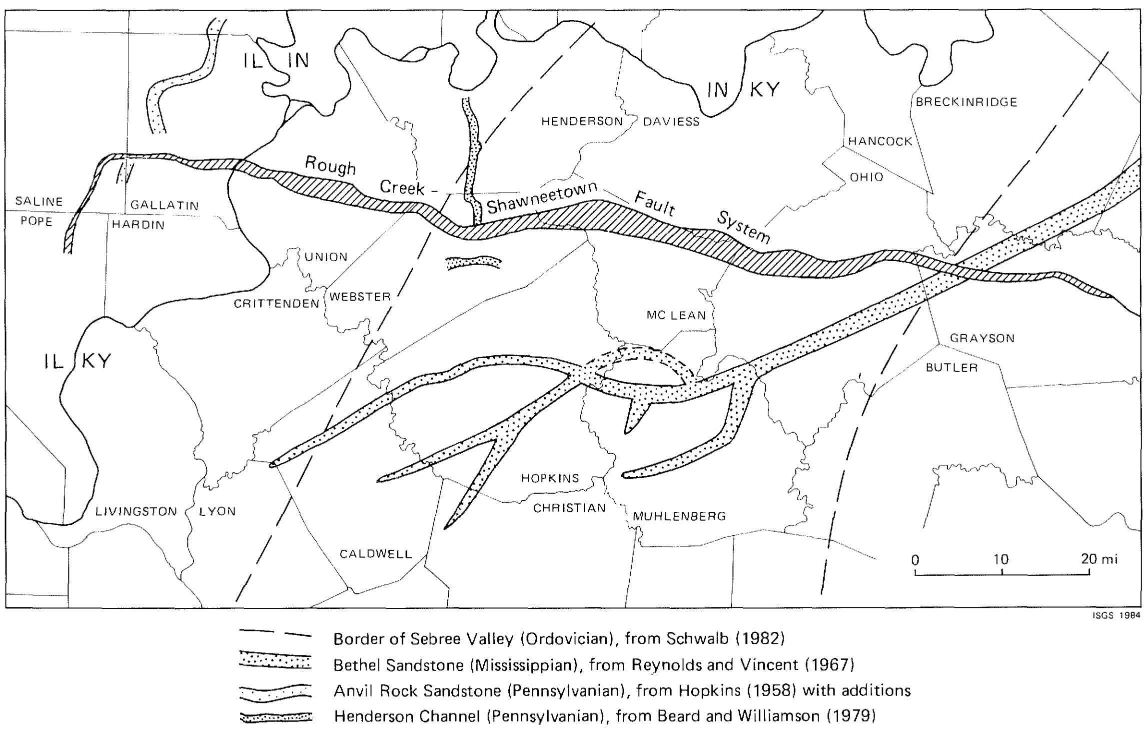


FIGURE 14. Paleochannels crossing the Rough Creek-Shawneetown Fault System.

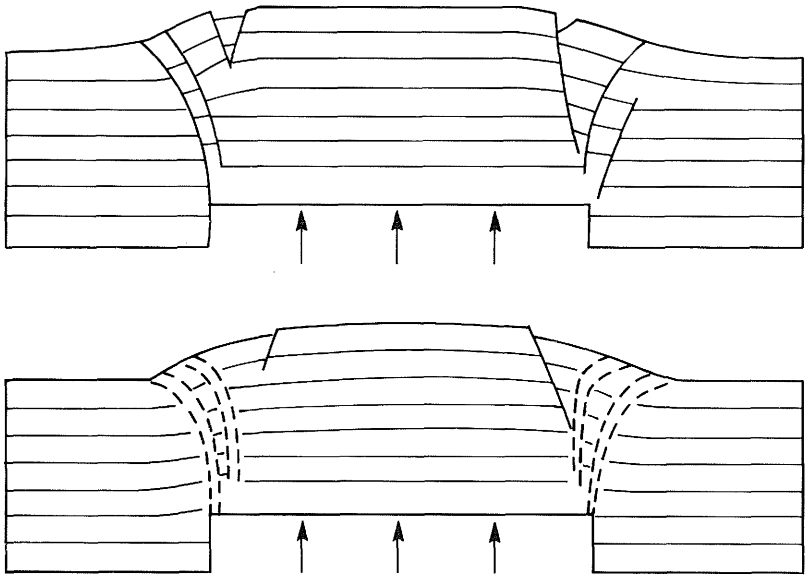


FIGURE 15. Sketches from Sanford (1959) illustrating results of experiments simulating simple vertical uplift of rigid basement block. Layers of sand and clay represent sedimentary strata. Faults, vertical at depth where they begin, curve outward and become thrust faults near the surface. Central part of uplifted block is under horizontal tension, which produces normal faults.

Sebree the main fault is a high-angle reverse fault with approximately 1,500 feet of vertical separation; it lies at the north edge of the fault system.

Other paleochannels are mapped as crossing the RC-SFS without lateral offset, but on these the degree of control is either not indicated or not as precise as that of Davis et al. (1974). The 30-mile-wide Sebree Valley (fig. 14), filled with Maquoketa Shale (Ordovician), crosses the fault zone without interruption; datum points at the critical junction are less than a mile apart (Schwalb, 1982). Other channels include one filled with the Chesterian Bethel Sandstone (Reynolds and Vincent, 1967, fig. 1); sub-Pennsylvanian channels mapped by Potter and Desborough (1965), and Bristol and Howard (1971); and Pennsylvanian paleovalleys of Hopkins (1958) and Beard and Williamson (1969) (fig. 14). None of these authors suggests strike-slip, although some attribute local deflections of paleostream courses to possible contemporaneous tectonic activity, as will be mentioned later in this report.

To summarize, the data show that any strike-slip movements that may have occurred were subordinate to dip-slip movements in the RC-SFS. The later phases of faulting were almost purely vertical and may have erased signs of earlier but minor horizontal slippage. Although post-Pennsylvanian faulting was mostly vertical, we cannot preclude the possibility of major strike-slip motion along an ancestral Rough Creek Fault in Cambrian time or earlier.

Recurrent vertical movements The foregoing discussion leads us to the third hypothesis: that the Rough Creek-Shawneetown Fault System was produced by vertical movements. Clearly, a single state of uplift cannot account for the complex structure of the RC-SFS, especially the narrow slices of rock upthrown thousands of feet within the fault zone. Therefore, at least two stages of movement must have taken place. That is, one side of the fault zone must have been first uplifted, and then dropped back approximately to its original position.

The front fault is the master break, and its configuration indicates that the southern block was first uplifted. The front fault is a reverse fault, consistently inclined to the south. Faults formed by direct vertical uplift invariably bend outward from the uplifted block (fig. 15). This has been demonstrated repeatedly in laboratory experiments in which layered materials are deformed by raising rigid basement blocks (Sanford, 1959; Couples, 1978; Logan et al., 1978). The faults generated in these experiments are vertical at depth and curve away from the uplifted block upward, becoming reverse faults. In some cases (fig. 15) the fractures break the surface as low-angle overthrusts. The central portion of the upraised block is placed in horizontal tension; high-angle normal faults develop, forming steps or grabens that may intersect the master reverse fault at depth.

These experiments illustrate a mechanism whereby low-angle reverse faults, such as the one at Morganfield, could have been produced without horizontal compression. Vertical uplift also accounts for the secondary normal faults south of the front fault.

Vertically uplifted blocks bounded by outward-bending reverse faults apparently are common in nature. Kerr and Christie (1965) report this style of deformation in the Boothia uplift of arctic Canada (fig. 16), and Gibbons (1974) describes most faults of the eastern Ozarks area, Missouri, as upthrusts. Probably the best examples of vertical uplifts bounded by reverse faults are found in the Central Rocky Mountains and on the Colorado Plateau (Stearns, 1978; Matthews, 1978). In all of these, however, as in the laboratory experiments cited above, the uplifted mass remained high and did not settle back, as we postulate for the RC-SFS.

Upheaval of the southern block, therefore, was apparently the first step in the development of the RC-SFS (fig. 17). The amount of uplift must have been equal to or greater than the maximum vertical separation of strata as observed today. This means that in the vicinity of Horseshoe, the southern block must have risen at least 3,500 feet. The uplift was 2,000 feet or more at Morganfield, 1,500 feet at Sebree, and less farther east along the fault system. The portion of the SFZ that runs southwestward from Cave Hill shared in the upward movement, which appears to have diminished rapidly toward the southwest. This sharp bend of the fault zone may reflect the areal configuration of the uplifted basement block. (The regional extent and nature of this block will be discussed in a later section, after other fault systems of the area have been described.)

After the initial uplift of the southern block, the southern block dropped back downward, reactivating the front fault and other fractures (fig. 17). As the great mass of rock settled, it became wedged against the front fault. The rocks immediately adjacent to the front fault were held in place by friction and confining pressure as the main mass dropped. This differential movement produced the great drag fold that is the north line of the Eagle Valley-Moorman Syncline. As the southern block continued to sink, slices of it were sheared off and left stranded high in the fault zone. These blocks, caught in a rotational couple, rotated southward, until in extreme cases (as at Horseshoe Quarry) the bedding became vertical or even overturned. Meanwhile, additional vertical breaks propagated upward from the front fault. Some of these, such as the Jones, Ringold, and Ringold South Faults, broke the surficial strata, but others did not break through to the surface; overlying sedimentary layers draped over these faults as monoclinal flexures.

Therefore, the narrow upthrown slices that characterize the RC-SFS are remnants of the original upthrown southern block that were trapped above the fault and prevented from returning to their original position.

Grabens are rare in comparison to horsts in the RC-SFS, because grabens formed only under special conditions. Some grabens, such as the small one immediately north of the

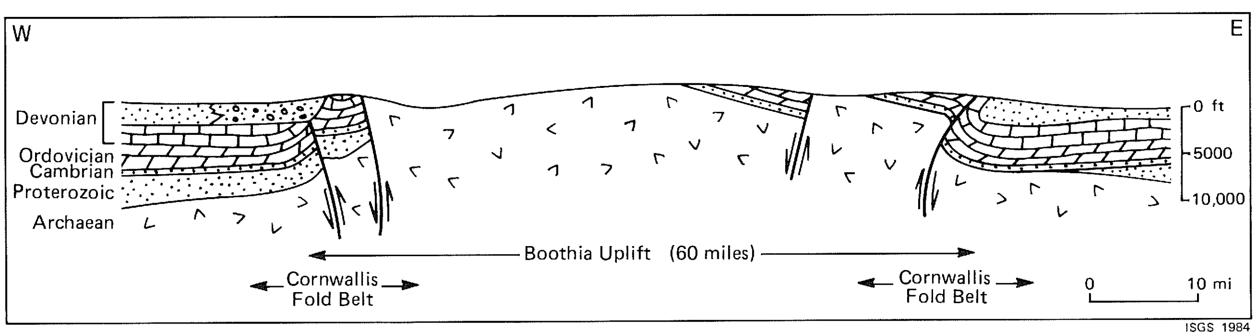


FIGURE 16. Cross section of Boothia Uplift, arctic Canada (Kerr and Christie, 1955). Direct vertical uplift of basement during Paleozoic is indicated. Note similarity between this sketch and those of Sanford (fig. 15).

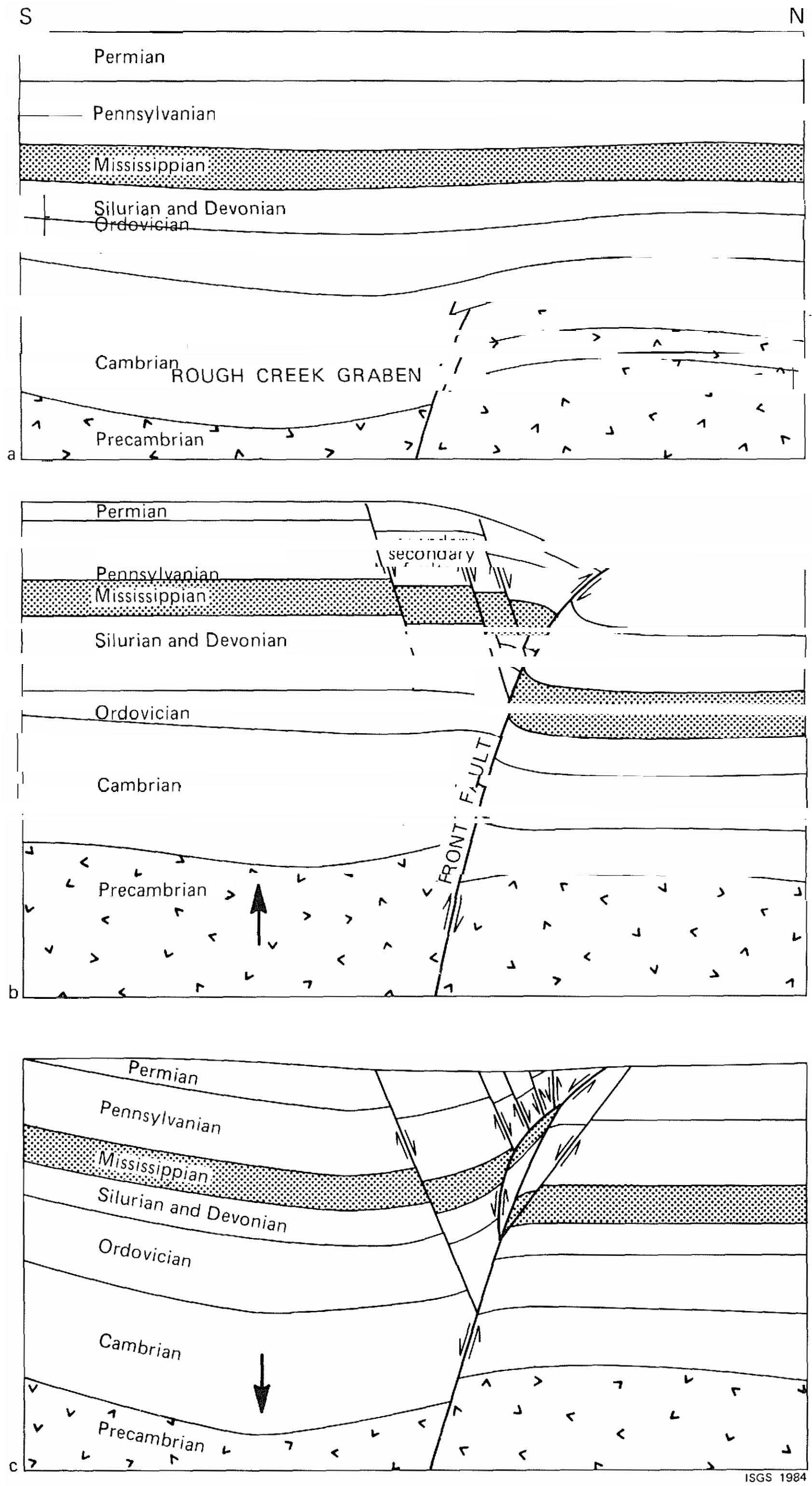


FIGURE 17. Proposed events during development of the Rough Creek-Shawneetown Fault System. (a) Prior to faulting, in Permian time, basement is broken by northern fault of Rough Creek Graben, which had developed in Cambrian time. (b) Southern block is uplifted, reactivating Cambrian fault as an upthrust. Secondary faults develop under horizontal tension near top of upthrown block; the raised block presumably is subjected to erosion. (c) Southern block drops back to approximately its original elevation; overhanging portion of southern block is wedged in position and held up by friction so that it cannot drop. Flexure and tilting of sedimentary strata produce steep northern limb of Eagle Valley-Moorman Syncline, while narrow slices of rock are sheared off within fault zone and trapped there. Secondary faults undergo renewed movement, and many additional faults are created.

front fault in the Shawneetown Quadrangle, may have resulted from extensional shearing of the footwall, perhaps combined with downward friction exerted by the subsiding hanging wall. Such a mechanism may account for the configuration in the Margaret Karsch well, where lower Devonian rock was found in fault contact above lower Pennsylvanian strata. The Pennsylvanian rock at the bottom of the hole may be a slice of the footwall that dropped or was pulled down as the hanging wall sank (fig. 18). A different mechanism is required to account for the graben with Permian rock in Union County, Kentucky. This graben is situated near the southern edge of the RC-SFS, about two miles south of the front fault (fig. 10). This area would have been under north-south extensional stress during the first stage of faulting, as the southern block rose (fig. 15). The graben probably developed during uplift, and was preserved when the southern block sank back down.

The irregularly shaped subordinate anticlines and synclines in the axial region of the Eagle Valley Syncline may reflect differential subsidence of the southern block in the late stages of movement. Perhaps the block is segmented at depth by faults of varying attitudes over which the surficial strata are draped in forced folds. Additional subsurface information will be needed to confirm this hypothesis.

Although we believe that the structural evolution of the RC-SFS can be defined on the basis of surface exposures and shallow subsurface data, we wish to emphasize that very little is known about the deep structure of the fault zone. Very few wells have penetrated the zone, and the few seismic lines we have been privileged to view reveal little about the attitude and continuity of faults at depth. More seismic information and/or drilling is required to reveal the nature and hydrocarbon potential of the Rough Creek-Shawneetown Fault System below the Devonian and Mississippian rocks.

Time of faulting The present-day Rough Creek-Shawneetown Fault System obviously developed after early Permian time, but an ancestral RC-SFS was active during Cambrian and Devonian, and possibly Mississippian and Pennsylvanian time. Major movements probably are pre-Cretaceous; no evidence for Pleistocene tectonism has been uncovered.

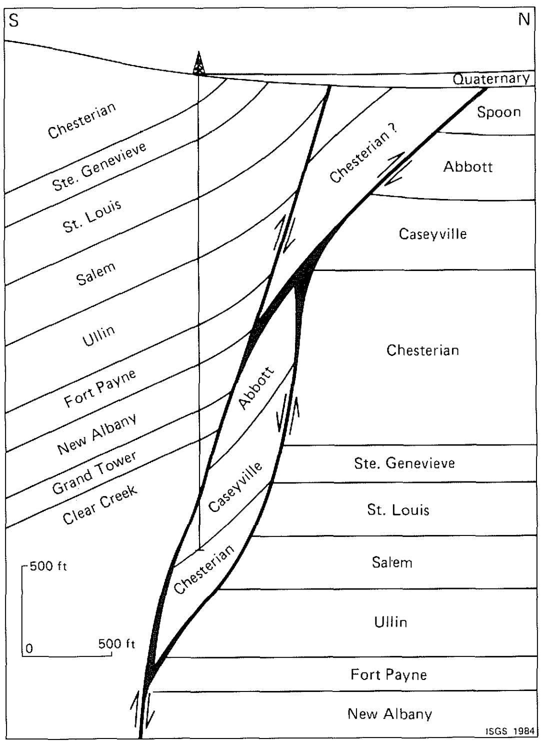


FIGURE 18. Interpretation of structure in Margaret Karsch well, about one mile west of Horseshoe. At a depth of 2,380 feet, drill cut the front fault of Shawneetown Fault Zone and passed from lower Devonian to lower Pennsylvanian strata. The Pennsylvanian rocks occupy a fault slice that presumably was sheared off the northern (footwall) block and dragged downward when the southern (hanging wall) mass moved down.

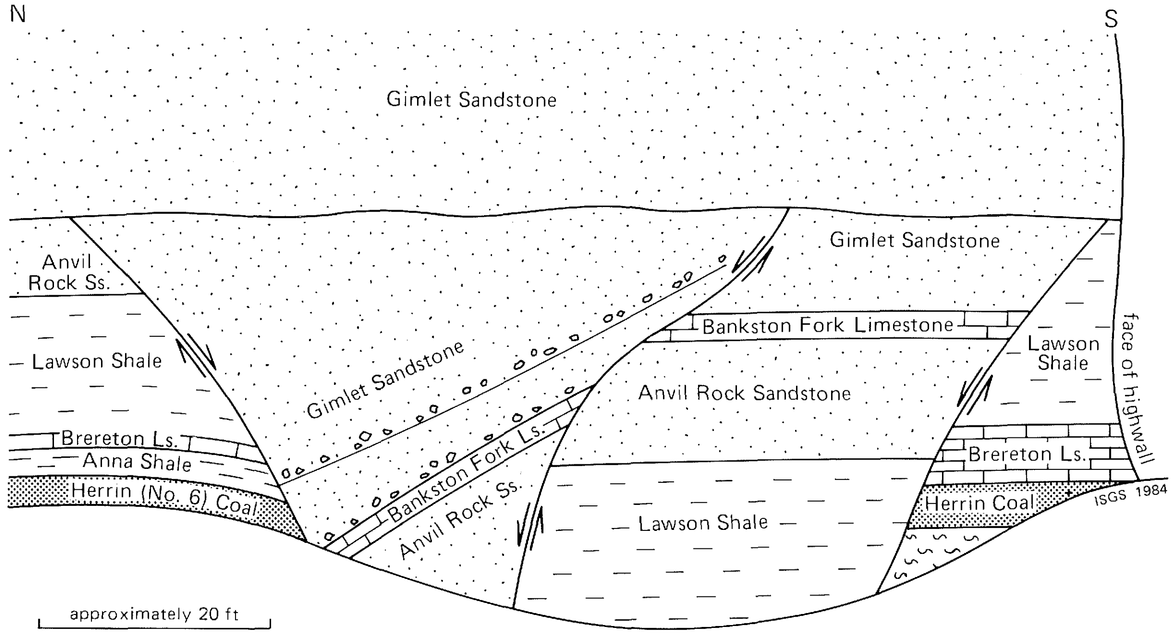


FIGURE 19. Paleoslump in highwall of Peabody Coal Company's Eagle Surface Mine.

Pre-Pennsylvanian movements The ancestral Rough Creek-Shawneetown Graben Fault System came into existence in latest Precambrian or early Cambrian time, as the northern edge of the Rough Creek Graben. The graben, several thousand feet deep, filled rapidly with detrital sediments shed from adjacent uplands. Faults may have been reactivated from time to time during the Cambrian, but by Champlainian (middle Ordovician) time the graben was filled with sediments (Schwalb, 1982).

The Rough Creek Graben was quiescent during Ordovician time. As mentioned earlier, the Sebree Valley, a submarine channel filled with Cincinnatian (upper Ordovician) shale, crosses the fault zone without apparent interruption (Schwalb, 1982). Local abrupt thickening of Silurian rocks in the graben suggest renewed movement in Silurian time (Schwalb, personal communication, 1983).

Schwalb suggests that the eastern portion of the graben apparently was reactivated during the Devonian Period. The Lower and Middle Devonian section within the graben is considerably thicker than that outside the trough. Outside the graben, Middle and Lower Devonian rocks were uplifted and partially eroded; Upper Devonian New Albany Shale unconformably overlies rocks as old as Silurian. Not only the RC-SFS proper, but also a northeast-trending fault north of the RC-SFS in Breckinridge County, Kentucky, show evidence of Devonian activity (Howard Schwalb, personal communication, 1983).

Mississippian movements on the RC-SFS have been suspected, but evidence is scanty. Wood (1955) attributed local thickening of Chesterian sandstones in the Morganfield area to contemporaneous tectonism. Davis et al. (1974) suggested that local deflections of pre-Pennsylvanian valleys along the central portion of the RC-SFS may be the result of localized contemporaneous uplift in that area.

Pennsylvanian movements Localized uplift along the RC-SFS may have played a role in the origin of narrow, deeply incised paleochannels and large paleoslump structures that occur in Carbondale and Modesto strata of Eagle Valley and western Kentucky.

Spectacular paleoslumps formerly were exposed close to the axis of the Eagle Valley Syncline in now-reclaimed pits of Peabody Coal Company's Eagle Surface Mine, in and near Section 14, T 10 S, R 8 E, Equality Quadrangle, Gallatin County. Narrow elongate grabens, generally trending east-west, are the most common type of slump (fig. 19). They are up to 2,000 feet long and 50 to several hundred feet wide, and their faults have as much as 40 feet of throw. The time of faulting can be fixed precisely; the tops of grabens (and other paleo-

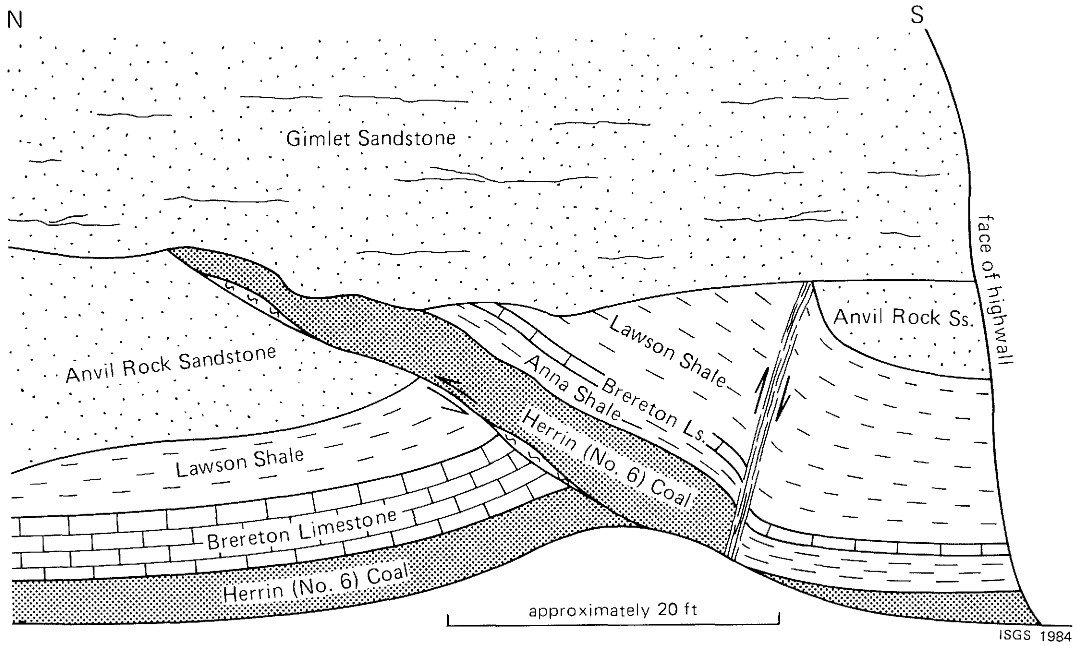


FIGURE 20. Thrust fault exposed on highwall of abandoned Peabody Eagle Surface Mine. Fault is truncated at base of Gimlet Sandstone, so it must have developed before that unit was deposited. The thrust is probably the toe of a paleoslump, but direct tectonic faulting cannot be ruled out.

slumps) are erosionally truncated and overlain by the Gimlet Sandstone. In some cases (as in fig. 19), conglomeratic Gimlet Sandstone also is included in downfaulted, tilted blocks. Therefore, the faulting took place slightly before and/or during deposition of the Gimlet Sandstone.

Other slumps show more complicated structure, including thrust faults. In one exposure the Herrin Coal is repeated three times on the highwall as a result of multiple thrusting. Figure 20 illustrates a slump that combines low- and high-angle reverse faulting. The Gimlet Sandstone unconformably overlies the faulted and tilted Carbondale rocks.

Structures such as these are commonly attributed to failure of undercut riverbanks. Drilling and exposures in the mine reveal that the Gimlet Sandstone locally fills channels cut into or through the Herrin Coal; however, none of these channels can be related to paleoslumps. Furthermore, most rocks show brittle structural deformation rather than the plastic or ductile deformation normally associated with landsliding and slumping of unconsolidated sediments. Coal near faults is intensely slickensided and shattered; shale is so thoroughly fractured in some places that its bedding is obscured. These materials must have been already fairly brittle at the time of failure: they were not soft, unstable sediments. Tectonic activity—either actual slippage along surface fractures or strong seismic shocks—is thus a likely triggering mechanism for the deformation at Eagle Surface Mine.

Coal-test drilling near Peabody Coal Company's Camp 11 Mine immediately north of the RC-SFS in Union County, Kentucky has revealed a deep, narrow, west-northwest-trending paleochannel. Within the channel the Herrin Coal is eroded and replaced by shale or sandstone probably equivalent to the Gimlet Sandstone. The cutout is at least 3,500 feet long, only 150 feet wide, and more than 50 feet deep in places. Closely spaced test holes show that the walls are steep; in several places, slump blocks, probably undercut banks of the stream, lie within the channels.

The slumping seems readily explainable, but the form of the channel arouses suspicion of tectonic control. The Gimlet Sandstone of southern Illinois is a flood-plain or deltaic deposit; mapped channels are sinuous or meandering and branching, and rarely more than 30 feet thick (Orlopp, 1964). Broad, sluggish, and shallow distributaries, rather than narrow and deeply incised cutouts, would be expected. Perhaps abrupt tectonic uplift of a portion of the delta induced rapid downcutting, as streams sought base level.

Within the Camp 11 Mine a series of linear structures, known to the miners as "horsebacks," have been mapped. Horsebacks are narrow protrusions of the overlying Providence (Brereton) Limestone into the Herrin (W. Ky. No. 11) Coal. They are straight, or nearly so, and all of them trend N 45° W. Their width varies from a few feet to about 25 feet, and they can be traced for several hundred to more than a thousand feet along strike. In cross section (fig. 21) a horseback may resemble a graben; bounded by curving, medium to low-angle, normal faults that die out both upward and downward; however, some horsebacks displace the coal without faulting—the coal layers are ruptured or pushed downward.

The horseback clearly formed while the peat and enclosing sediments were still soft, not yet lithified. Limy material intricately injected into coal can be seen along margins of some horsebacks. The layers of coal are bent, sometimes contorted; they may be offset by shear planes but never are shattered or brecciated. Claystone bands in the coal seam and in the floor deformed in a totally plastic manner.

Normal faults associated with horsebacks indicate an origin by horizontal extension of the peat before it was coalified. Under tensional stress the peat ruptured, allowing overlying sediments to slip downward. Since all the horsebacks run in the same direction, the stresses that produced them must have been directed, rather than random. We suggest the stresses were tectonic ones involved with movement along the Rough Creek Fault System in middle Pennsylvanian time.

Permian and later movements Although the RC-SFS was active recurrently for much of the Paleozoic era, most, if not all, of the faults mapped at the surface are post-early Permian in age. Upper Pennsylvanian and lower Permian rocks are cut by the faults and, with a few possible exceptions (noted in the preceding section), they were fully lithified when they were deformed. Permian strata probably covered much of the region when tectonism commenced. These rocks have been removed by later erosion, except in the graben in Union County, Kentucky.

Rocks of Mesozoic age are totally unknown and only a few scattered outliers of Tertiary deposits have been found near the RC-SFS. Remnants of Mounds Gravel in the Shawneetown Hills are widely removed from their closest counterparts south of the fault zone. The only other Tertiary sediments near the zone are gravels (fragments of terraces) in the Curdsville (Fairer and Norris, 1972) and Calhoun (Johnson and Smith, 1975) Quadrangles, McLean County, Kentucky. These gravels occur at approximately similar elevations on opposite sides of the fault zone; but no conclusions regarding possible Tertiary tectonism can be drawn from such meager findings.

Definitive Pleistocene outcrops overlying bedrock faults are rare. The best we have found is in the roadcut near the summit of Gold Hill, where Peoria and older loesses show

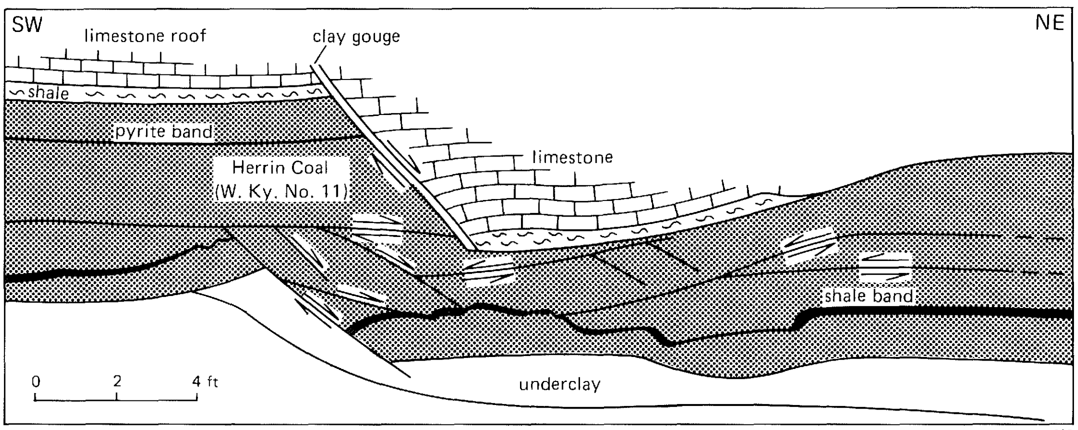


FIGURE 21. Sketch of "horseback" in Camp 11 Mine. Limestone overlying coal has slipped downward along a slickensided fault surface (some horsebacks have faults on both sides). Lower part of coal seam is cut by numerous low-angle to horizontal faults, and blocks of coal are rotated; shale band is thinned and contorted; these features all attest to lateral extension in NE-SW direction.

no deformation above a fault cutting Pennsylvanian rocks. Several small exposures in stream beds reveal no offset of the bedrock surface along faults overlain by Quaternary alluvium. These findings are scarcely definitive, but do serve as negative evidence.

We found no traces of fault scarps, offset terraces, or other possible tectonic disturbances in any Quaternary deposits in or near the RC-SFS. To our knowledge, neither have any other geologists.

Heinrich (1982) examined in detail the deposits of glacial Lake Saline, and noted no structural disruptions that could be interpreted as resulting from seismic activity. He also mapped a series of subtle ridges, apparently longitudinal bars, in the Maumee flood deposits above the Shawneetown Fault Zone (fig. 8). No sign of offset can be detected in these features.

In contrast, Quaternary alluvium in the Reelfoot Rift area displays obvious deformation resulting from seismic events. Such features as sand blows, fault scarps, fissures, and sunken and uplifted areas were evident to the earlier observers and can be seen today (Fuller, 1912; Nuttli, 1973). Many disturbances date from the 1811–12 earthquakes, but others are older. Faults displacing Tertiary sediments also have been documented (Stearns, 1980; Hamilton and Zoback, 1982). The fact that no such items have been identified or even suspected along the RC-SFS leads to a strong presumption that they do not exist.

To summarize, field evidence indicates that near-surface faults in bedrock of the RC-SFS developed after the early Permian Period and before the Pleistocene Epoch. Regional considerations, to be discussed later in this report, indicate that major movements were pre-Cretaceous.

Cottage Grove Fault System

The Cottage Grove Fault System (CGFS) extends westward across southern Illinois from west-central Gallatin County at least as far as northwestern Jackson County, roughly 70 miles (fig. 9). The Cottage Grove is a right-lateral strike-slip fault system that contains three structural elements (Nelson and Krausse, 1981):

- The "master fault," a single west-trending fault or zone of subparallel high-angle faults forming a braided pattern.
- Subsidiary faults, mostly northwest-trending high-angle normal and oblique-slip faults, and associated ultramafic intrusions.
- Subsidiary anticlines, adjacent to the master fault, subparallel with it, or obliquely oriented in right-handed en echelon sets.

Although lateral offset has not been demonstrated directly, the structural pattern presents a textbook case of wrench faulting. Maximum possible horizontal slip is less than a mile, probably considerably less, as shown by mapping of Pennsylvanian paleochannels that cross the fault zone. The largest measured vertical separation is approximately 200 feet (Nelson and Krausse, 1981).

The Cottage Grove Fault System displaces Pennsylvanian strata as young as the Modesto Formation. Associated ultramafic dikes were dated by Geochron Laboratories, Cambridge, Massachusetts as early Permian (235–270 million years old) by the potassium-argon method. The dikes follow northwest-trending extensional faults, which evidently acted as pathways for the magma. In a few cases the dikes themselves have been offset by later faulting of small magnitude. These facts indicate that the Cottage Grove Fault System developed in latest Pennsylvanian and/or early Permian time, with subsequent minor adjustments.

Surface traces of the Cottage Grove and Rough Creek-Shawneetown Fault Zone do not connect. Borehole data and surveys from abandoned coal mines imply that the eastern terminus of the Cottage Grove Fault System is near the village of Equality (Section 17, T 9 S, R 8 E), about 2 1/2 miles north of the Shawneetown Fault Zone. However, the two fault systems probably share a common ancestor. Regional subsurface data and gravity and magnetic surveys suggest that the Cottage Grove and Rough Creek-Shawneetown Fault

Systems follow the northern side of the late Precambrian-early Cambrian Rough Creek Graben (Schwalb, 1982). This buried trend evidently is a fault zone with the south side downthrown several thousand feet. The detailed gravity and magnetic surveys of Strunk (1984) confirm this deep-seated connection.

In conclusion, the ancestral Cottage Grove and Rough Creek-Shawneetown Faults probably are continuous at depth, but near-surface, post-Pennsylvanian faults do not connect, and they formed under different stress regimes.

Wabash Valley Fault System

The Wabash Valley Fault System (WVFS) extends northward from the Rough Creek-Shawneetown Fault System along the Wabash River valley in southeastern Illinois, southwestern Indiana, and Union and Henderson Counties, Kentucky (fig. 9).

Extent and nature of faulting The WVFS system is about 55 miles long and up to 30 miles wide; it is composed of north-northeast striking high-angle normal faults with vertical offsets as great as 480 feet. The faults are known from subsurface information and exposures in underground coal mines; surface expression is lacking because of the cover of glacial and alluvial sediments. Because many areas along the faults have been densely drilled for oil, gas, and coal, detailed data is available on structure (Bristol and Treworgy, 1979).

A few Wabash Valley faults reach, but do not cross, the Rough Creek-Shawneetown Fault System. In the Shawneetown Quadrangle (plates 1a and 2), the Inman and Inman West Faults definitely intersect the Shawneetown front fault. Drilling in Sections 26 and 35, T 9 S, R 9 E, reveals nearly 200 feet of vertical offset on the Inman Fault 1/4-mile north of the front fault. This displacement increases to 300 feet northward in Section 13. The Inman West Fault has a similar amount of throw; together with the Inman Fault it forms a graben. The Inman Graben does not cross the front fault. No faults with the proper orientation and throw can be seen in the lower Pennsylvanian sandstones that are almost continuously exposed on the north face of Gold Hill immediately south of the Inman Graben. The Inman East Fault may also connect with the front fault, but its displacement is 50 feet or less at the junction point. About 8 miles eastward, in Union County, Kentucky, the Hovey Lake Fault reaches the northern edge of the RC-SFS. The Hovey Lake Fault is a compound fracture zone, with displacements as large as 350 feet on individual breaks near the junction with the RC-SFS; it does not continue south of the RC-SFS.

Other faults of the WVFS lose displacement southward and die out before they reach the Rough Creek-Shawneetown Fault System.

Faults of the WVFS tend to merge and die out at depth. Bristol and Treworgy (1979) and Ault, Sullivan, and Tanner (1980) reported several instances of fault zones that are more complex in Pennsylvanian than in Mississippian rocks, and noted that some small faults die out downward; however, large faults appear to maintain displacement at least through the Mississippian section. Evidence from deeper structure, which comes from seismic profiling (Braile, Sexton, and Hinze, 1983) shows that the Albion-Ridgway and New Harmony Faults lose displacement at depth. Near-surface offsets of 200 to 300 feet diminish to less than the resolution of the profile (about 100 feet) below the Croixan (upper Cambrian) Eau Claire Formation. Prominent Precambrian reflectors exhibit large offsets—apparently due to faulting—but these do not connect with Wabash Valley faults in the Paleozoic strata.

One igneous intrusion has been reported in the WVFS: a dike trending N 10° E, encountered in the easternmost workings of the now-abandoned B. and W. Coal Company Mine (E 1/2 SE 1/4 NW 1/4, Sec. 18, T 9 S, R 9 E, Equality Quadrangle, Gallatin County). Associated with the intrusion was a fault with 4 feet of throw. Immediately to the east is the Ridgway Fault, a major normal fault with the east side downthrown approximately 150 feet. As is the case with dikes in the Cottage Grove Fault System, the coal was metamorphosed and mineralized along the igneous body in the B. and W. Mine.

Injection of magma evidently is responsible for Omaha Dome, a nearly circular uplift centered 4 miles west of the Ridgway Fault in Section 4, T 8 S, R 8 E, Gallatin County (fig. 9). Closure on the Omaha Dome decreases from more than 200 feet on the Herrin Coal to zero in Devonian and older strata. Igneous rocks have been struck in many wells: dikes in near-surface Pennsylvanian rocks, and sills or laccoliths at greater depth (Pullen, 1951). According to Howard Schwalb (personal communication, 1983), the sedimentary strata are progressively arched above a series of horizontal tabular intrusions in Devonian and Mississippian rocks. The igneous bodies may resemble a Christmas tree in cross section, with sills and laccoliths spreading away from a vertical central feeder.

Radiometric dating of samples of igneous rock from the Omaha Dome yielded two different ages—290 and 408 million years (Bikerman and Lidiak, 1982). The former age, regarded as a maximum age by Bikerman and Lidiak, is about 30 million years older than that obtained on peridotites from the Cottage Grove Fault System, while the latter age, older than the country rock, clearly is anomalous.

Origin The WVFS clearly is the product of horizontal extension of the earth's crust at right angles to the trends of the faults; that is, the region was pulled apart laterally from the west-northwest and east-southeast. As the strata ruptured, blocks subsided to varying degrees, producing grabens, horsts, and step-faults. These are classic gravity faults; they show no evidence of significant reverse, strike-slip, or differential uplifting movement.

The faults die out downward. Some of them may reach the basement, but do not necessarily penetrate it. In contrast, the Cottage Grove Fault System, with its ultrabasic intrusions, probably extends all the way to the mantle. The Rough Creek-Shawneetown Fault System also probably cuts the entire crust; it is difficult to conceive that faults of this magnitude do not.

The fact that the WVFS joins, but does not cross the Rough Creek-Shawneetown Fault System admits more than one interpretation. One is that the Rough Creek-Shawneetown Fault System is older; the WVFS extended itself southward until it met the Rough Creek-Shawneetown Fault System but did not bridge the latter because tensional stresses were relieved by slippage along pre-existing west-trending faults. A second possibility is that both fault systems developed at the same time. Yet another hypothesis is that the WVFS is older, and originally terminated north of the line where the Rough Creek-Shawneetown Fault System appeared. As the latter system developed, new shearing stresses were applied to the WVFS, causing several of the fractures to propagate themselves southward to the Rough Creek-Shawneetown Fault System. Little force is required to extend a crack once it has formed.

Because we have not seen the actual intersection of the two fault systems, we have no direct evidence as to which is older, but must apply indirect and theoretical considerations to determine relative ages of the faults.

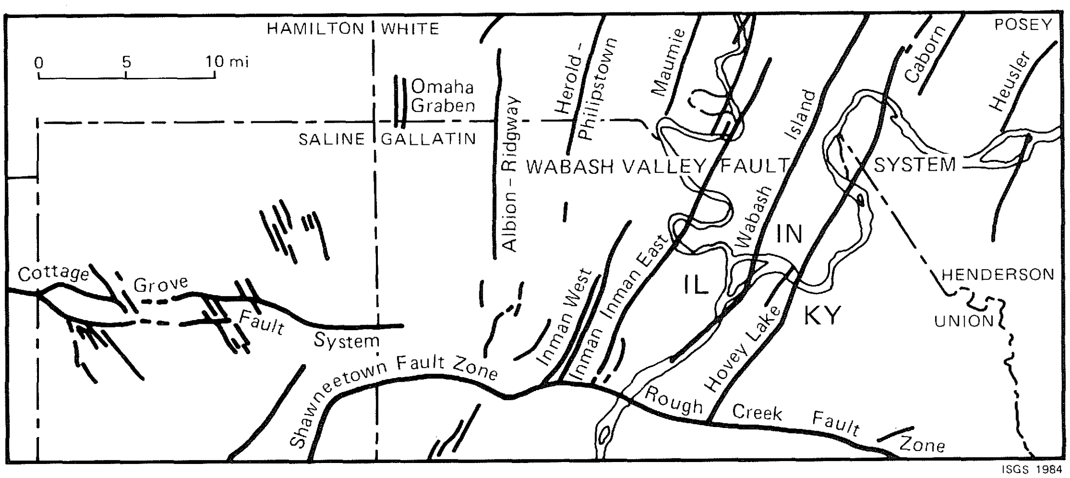


FIGURE 22. Fanlike or radiating pattern of normal faults north of Shawneetown Fault Zone.

Heyl (1972), Braile, Sexton, and Hinze (1983), and others have postulated that the WVFS is a northeastward extension of the Reelfoot Rift. Braile et al. (1984) interpreted seismic data as showing layered rocks—possibly thick Precambrian or early Cambrian sediments—in the proposed "southwest Indiana arm" of the Reelfoot Rift. No drill to date has reached deep enough to test this hypothesis. Braile et al.'s sections show apparent faults of large magnitude in the layered complex, but the orientation and distribution of these faults are unknown. More evidence will be needed before anyone can speak authoritatively on ancestral structure of the Wabash Valley.

Examination of a regional map of faults in southeastern Illinois and vicinity discloses an interesting pattern (fig. 22). North of the Rough Creek-Shawneetown Fault System and the Cottage Grove master fault, the faults are arranged like the fingers of a hand or an outstretched fan. If projected southward, all of these faults would intersect in the vicinity of Hicks Dome, south of the Shawneetown Fault Zone. The "fault fan" includes the following features, from west to east:

- Subsidiary faults in the Cottage Grove Fault System in western Saline County strike N 45° W.
- Subsidiary faults and peridotite dikes in eastern Saline County strike about N 25° W.
- The igneous dike near Cottage Grove strikes N 20° W.
- Two dikes north of Equality trend N 10° W.
- The Ridgway Fault runs due north.
- Inman Faults trend about N 20° E in their southern extent.
- Wabash Island Fault and others farther east strike about N 30° E.

All the faults in the "fan" are normal or gravity faults, produced by horizontal extension at right angles to the traces of the faults. The smooth transition in directional trend of faults in the "fan," from northwesterly to east-northeasterly, suggests that all of these faults were formed in a common stress field centered near Hicks Dome. This, in turn, suggests that the Wabash Valley and Cottage Grove Fault Systems formed in the same tectonic action.

Time of faulting Data that would confirm the last statement are difficult to obtain. No materials between late Pennsylvanian and Pliocene-Pleistocene age (Mounds Gravel) are known in the vicinity of the Wabash Valley Fault System. Direct evidence allows us only to say that the faults are post-late Pennsylvanian and pre-Pleistocene.

The igneous intrusion at the B. and W. Mine along the Ridgway Fault probably is the same age as the peridotite in the Cottage Grove Fault System. This assumption points to an early Permian age for at least the Ridgway Fault, if not the entire system.

Radiometric ages of igneous rocks from Omaha Dome reveal little about the time of faulting. In the first place, the dates themselves are questionable. In the second place, the Omaha Dome may not be genetically related to the WVFS, and dome and faults may have formed at different times.

To summarize, the age of the WVFS cannot be definitely determined, but most likely is early Permian, the same age as the Cottage Grove Fault System.

Fluorspar Area Fault Complex

As the name implies, the Fluorspar Area Fault Complex (FAFC) is a complicated system of structures centered in the Illinois-Kentucky fluorspar mining district (fig. 23). The FAFC lies immediately south of the Eagle Valley Syncline, mostly in Hardin and Pope Counties, Illinois, and in Crittenden and Livingston Counties, Kentucky. Its northernmost extremities reach the quadrangles we mapped in detail (plates 1 and 2).

The FAFC is not unified tectonically like the fault systems described previously. It consists of several structural elements formed at different times under different stress regimes:

- Hicks Dome and associated arch
- Faults concentric and radial to Hicks Dome
- Northwest-trending faults and dikes
- Northeast-trending block faults

Hicks Dome and associated arch The most striking feature of the FAFC is Hicks Dome, a nearly circular uplift 10 miles across in Hardin and eastern Pope Counties, Illinois. Middle Devonian rocks crop out at the center and are surrounded by Upper Devonian, Mississippian, and lower Pennsylvanian formations on the flanks. Dips decrease outward from about 20° near the center to less than 5° at the outer edge of the structure. The total uplift of surface rocks is about 4,000 feet.

Drilling at the apex of Hicks Dome revealed thick zones of brecciated sedimentary rock at depth. Sidewall core samples emitted unusually high radioactivity and were heavily mineralized with fluorite, apatite, metallic sulphides, and other minerals (Brown, Emery, and Meyer, 1954). Moreover, many explosion breccias or diatremes have been mapped at the surface on Hicks Dome. They take the form of vertical or steeply dipping pipes, dikelike bodies, and small stocks up to about 1,000 feet in diameter; they are composed of fragments of sedimentary and basic igneous rocks and sometimes crystals of hornblende and

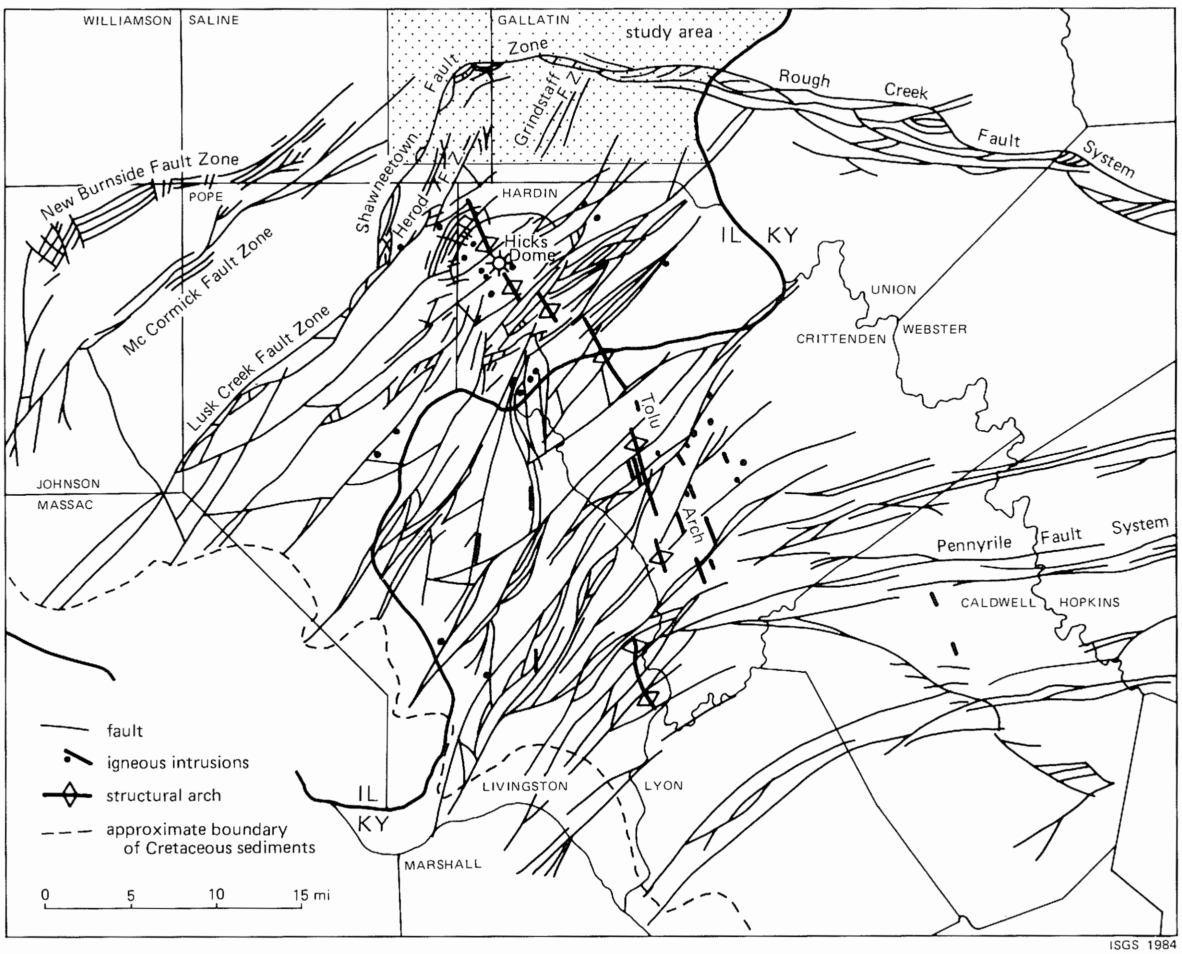


FIGURE 23. Fluorspar Area Fault Complex and associated structures (adapted from Trace, 1974; Schwalb and Potter, 1978; Treworgy, 1981; and Jacobson and Trask, 1983).

biotite, in a matrix of pulverized rock that may be replaced by carbonate or mineralized with fluorite and metallic sulfides and sulfates (Grogan and Bradbury, 1967).

The aeromagnetic survey of McGinnis and Bradbury (1964) showed no magnetic anomaly beneath Hicks Dome, although an intense magnetic high is centered about 6 miles to the northeast. No significant gravity anomaly is associated with the dome.

Most geologists today agree that Hicks Dome originated from explosive igneous activity. Rising magma may have encountered groundwater, producing subterranean explosions of steam, uplifting and shattering the bedrock (Brown et al., 1954; Heyl et al., 1965; Trace, 1974). The earlier theory of laccolithic intrusion is negated by gravity and magnetic data. Meteoritic impact has been suggested, but no supporting evidence has been advanced.

Hicks Dome lies along the axis of a broad northwest-trending arch that traverses the fluorspar district. In Kentucky this linear bulge is known as the Tolu Arch. The arch is greatly broken by northeast-trending block faults. A concentration of ultramafic intrusions along the arch suggests an origin by upwelling magma at depth (Trace and Amos, 1984).

Concentric and radial faults Baxter and Desborough (1965) and Baxter, Desborough, and Shaw (1967) mapped many faults concentric and radial to Hicks Dome. Concentric faults encircle the uplift from the south-southwest to the east-northeast and are concentrated in the outcrop belt of lower Chesterian rocks about 3 to 4 miles out from the center of the dome. They are vertical or steeply dipping faults and most are downthrown away from the center of the dome. Radiating faults also dip steeply and may be downthrown either to the right or the left side as viewed from the center of the dome. Displacements vary from a few tens of feet to a maximum of about 500 feet; most fall near the low end of this range.

These faults clearly developed contemporaneously with Hicks Dome. Most probably are tensional faults.

Northwest-trending faults and dikes Small northwest-trending faults and dikes of mica peridotite and lamprophyre are common along the northwest-trending arch that transects the fluorspar district (fig. 24). The faults dip vertically and are clean-cut, with little drag, gouge, or breccia. The presence of horizontal slickensides in mines and the absence of significant vertical offset indicate strike-slip movement. Dikes occupy faults and are cut by, and therefore older than, northeast-trending block faults. The igneous rock has been dated radiometrically as early Permian (Zartman et al., 1967).

Figure 24 shows that the northwest-trending dikes in the Cottage Grove Fault System line up with those in the fluorspar district and point toward Hicks Dome. Also shown are the ultramafic sills and laccolithic intrusions encountered in drill holes on the Omaha Dome, north of the Cottage Grove Fault System. All of these igneous rocks have similar petrology and radiometric ages, so they probably are all derived from the same parent magma. Therefore, Hicks Dome, the structural arch, the radial and concentric faults, and the ultrabasic intrusions probably all developed concurrently, in early Permian time.

Northeast-trending block faults The dominant trend of faulting in the FAFC is northeast-southwest. Northeast-trending fractures have by far the greatest areal extent and magnitude of displacement of any faults in the FAFC. These faults have attracted great economic interest because of the vein deposits of fluorite and other minerals found along them.

These northeast-trending block faults extend beyond the limits of the present fluorspar-producing region (fig. 23). Most die out within a few miles northeast of Hicks Dome, but several cross the axis of the Eagle Valley-Moorman Syncline. In our study area (Equality Quadrangle) the Grindstaff Fault Zone crosses the syncline and may reach the southern edge of the Shawneetown Fault Zone. Palmer (1976) mapped a northeastward extension of the Rock Creek Graben as possibly reaching the Rough Creek Fault System in the Grove Center Quadrangle, western Union County, Kentucky. On the southeast the FAFC curves gently eastward to merge with the Pennyrile Fault System. The FAFC disappears beneath the Cretaceous sediments of the Mississippi Embayment on the south and southwest. To the northwest, the McCormick and New Burnside Fault Zones apparently belong with the FAFC (Jacobson and Trask, 1983). The northeast-trending Lusk Creek Fault Zone joins the southwestern end of the Shawneetown Fault Zone in northeastern Pope County, Illinois.

Northeast-trending faults of the FAFC dip steeply. The vast majority of them are inclined more than 70°, and many are essentially vertical (Weller et al., 1920; Baxter, Desborough and Shaw, 1967; Trace, 1974; Hook, 1974). Only a few small antithetic faults dip as gently as 45° (Weller et al., 1920; Hook, 1974).

Most faults are normal, but several large ones display reverse movement. Among documented reverse faults are the Lusk Creek Fault Zone and the southwestern end of the Shawneetown Fault Zone and portions of the Hogthief Creek and Illinois Furnace Faults

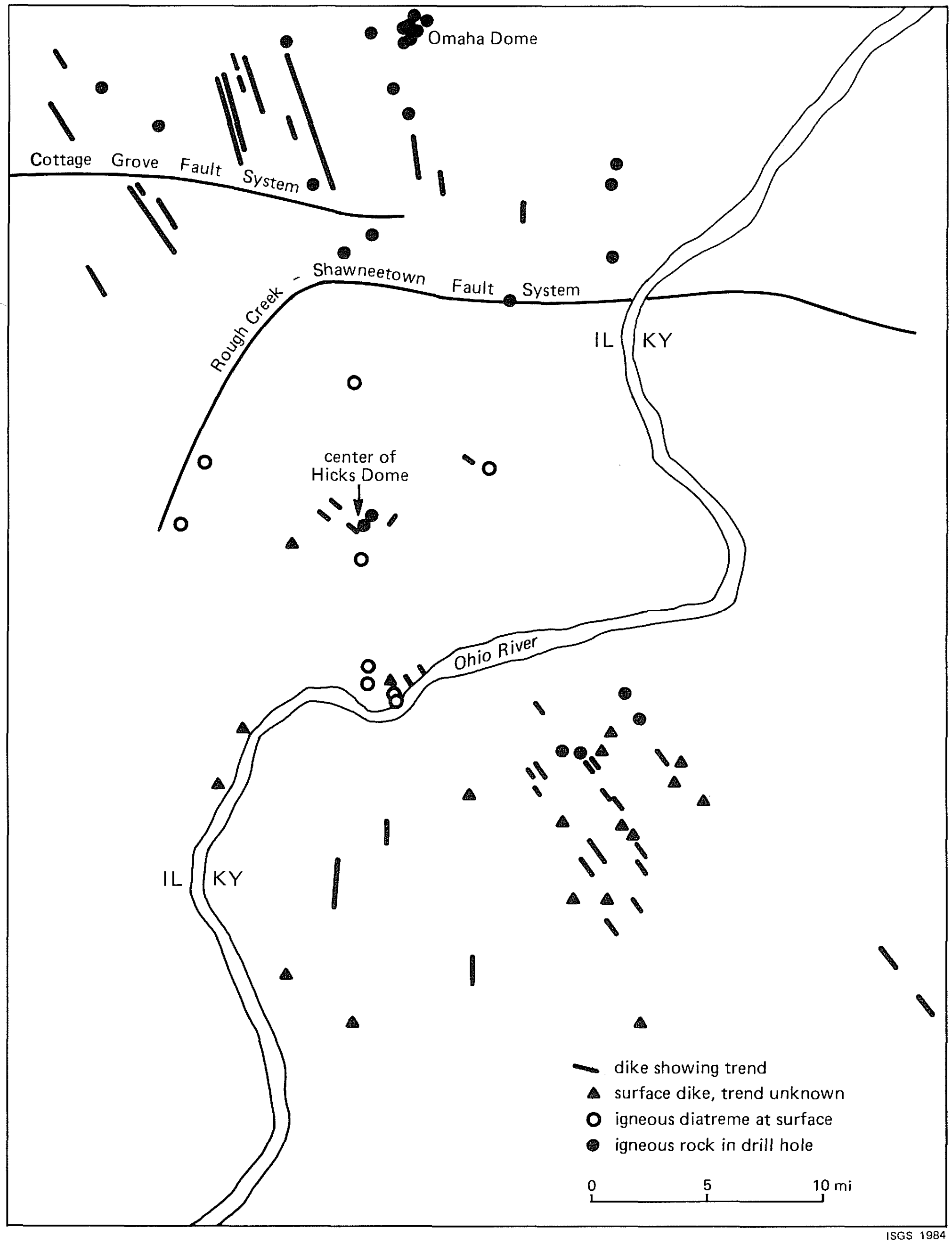


FIGURE 24. Igneous intrusions and diatremes in Illinois-Kentucky fluorspar district (modified from von Frese, Hinze, and Braile, 1980).

(Weller et al., 1920, 1952). Horizontal and obliquely plunging slickensides and mullion have been observed on many fault surfaces in fluorspar mines, indicating components of strike-slip movement. Right-lateral and left-lateral components appear to be about equally represented. Considering all available evidence, Trace and Amos (1984) concluded, along with most earlier researchers, that strike-slip displacement is subordinate to dip-slip in the FAFC.

Measured vertical displacements of northeast-trending faults range from inches to several thousand feet, but most faults have several tens to about 1,000 feet of throw. The largest known offset occurs in the southeast corner of the Smithland Quadrangle, Kentucky, where Fort Payne and Caseyville Formations are juxtaposed for a displacement of 2,400 to 3,000 feet (Amos, 1967).

Northeast-trending faults outline a complex series of upthrown and downthrown blocks. Many fault zones are broad and intricately branched, composed of numerous step faults and/or antithetic and synthetic intersecting fractures. Fault slices may be tilted and drag is well-developed. Many slices are broken by cross-faults (Hook, 1974). Some faults have sharply defined planes, but wide zones of gouge and breccia are the rule.

Vein deposits of ore minerals occupy many northeast-striking fault zones. In approximate descending order of abundance, vein minerals include calcite, fluorite, quartz, galena, sphalerite, ferroan dolomite, pyrite, marcasite, barite, chalcopyrite, and others. Some veins also contain oil or bitumen. Most geologists believe the deposits are epigenetic: that is, the ore elements were carried upward along faults and fissures in solution by water heated by deep-seated igneous activity (Trace, 1974).

This history of ore deposition is long and complex. Paragenesis varies from vein to vein; many show three or more stages of mineralization. Some veins are offset by faults, showing that tectonic movements continued during or after mineralization. Also, faults offset one another, and bear evidence (such as superimposed slickensides) of recurrent movement.

Thus, the northeast-trending block faults probably were active over a long period of time. Major movements were post-middle Pennsylvanian, and the movements continued after early Permian time, as demonstrated by offsets of peridotite dikes. However, tectonic activity may have begun while early Pennsylvanian sediments were being deposited. Potter (1957) described megabreccias and imbricate overthrusts in the Caseyville and Abbott Formation along the McCormick Fault Zone in Pope County. Breccias and overthrusts show clear evidence of soft sediment deformation, and are truncated and unconformably overlain by slightly younger Pennsylvanian sandstones. Findings of Jacobson and Trask (1983) also suggest early movements in the New Burnside Fault Zone. They mapped the zone as a series of northeast-trending high-angle faults, displaced by younger northwest strike-slip faults. If the strike-slip faults are early Permian, like those near Hicks Dome, then the northeast-striking faults are pre-Permian.

Evidence of Cretaceous and younger movements on northeast-trending block faults of the FAFC is somewhat ambiguous. Most faults apparently disappear under the cover of the Embayment, but Amos (1967 and 1974), Amos and Finch (1968), and Amos and Wolfe (1966) mapped faults offsetting Gulfian (upper Cretaceous) sediments near Paducah, Kentucky. Some of these juxtapose Paleozoic bedrock with Cretaceous Tuscaloosa and McNairy Formations; others have Cretaceous materials on both sides. Faults dip steeply and most show less than 100 feet of throw. In southern Illinois, Ross (1963 and 1964) attributed localized thickening in the subsurface of McNairy Formation and Wilcox Sand to tectonic movement in latest Cretaceous and Eocene time, respectively. He also reported steep dips and offset terraces in Mounds Gravel, suggesting Pliocene or younger faulting. Kolata, Treworgy, and Masters (1981), however, re-examined the subsurface information, including logs of recently drilled holes, and found no evidence for thickness or facies changes that can be attributed to tectonism. They also inspected many reported field exposures of disturbed Quaternary and Tertiary materials, and related all to stream-bank failure, solution collapse, and similar nonseismic causes.

In our own mapping, we observed several examples of undeformed loess and other Quaternary sediments overlying bedrock faults of the McCormick and Herod Fault Zones on the highwalls of strip mines. No other geologists, to our knowledge, have reported finding disturbed Quaternary materials in the FAFC.

To summarize, movement on northeast-trending block faults of the FAFC, at least in the northwestern part of the area, may have begun in early Pennsylvanian time. Major, recurrent slippage took place in Permian and early Mesozoic time; activity was winding down by late Cretaceous and earliest Tertiary time.

The block faulting probably was initiated by rifting or by regional horizontal extension toward the northwest and southeast. Later episodes involved components of reverse, strike-slip and oblique-slip faulting, mainly along pre-existing high-angle normal faults. These later movements probably were concurrent with vertical motion on the Rough Creek-Shawneetown Fault System.

We propose the following sequence of events in the evolution of the FAFC:

1. Extension northwest to southeast produced northeast-trending normal faults in the Pennsylvanian Period.
2. Magma was intruded along a northwest-trending arch in early Permian time. Peridotite was emplaced in northwest-trending fractures; deep-seated explosions created Hicks Dome and associated diatremes and radial and concentric faults.
3. Vertical movements on Rough Creek-Shawneetown Fault System reactivated northeast-trending block faults during late Permian and Mesozoic time. Recurrent mineralization took place along the block faults. The region was stabilizing by late in the Cretaceous Period.

Pennyrile Fault System

Schwalb (1975) applied the name Pennyrile Fault System (PFS) to an east-trending zone of fractures 25 to 40 miles south of and roughly parallel with the Rough Creek-Shawneetown Fault System in west-central Kentucky (fig. 9).

Extent and nature of faulting The PFS defines the southern edge of the Moorman Syncline; the Rough Creek-Shawneetown Fault System marks the northern edge. The PFS emerges eastward from the Fluorspar Area Fault Complex from which it cannot be clearly separated in Caldwell County. The width, complexity, and amount of displacement in the zone decrease eastward; the system dies out near Mammoth Cave in western Edmonson County.

Although the PFS as a whole trends nearly due east, most individual faults strike east-northeast and thus form an en echelon pattern (fig. 9). Individual fault sets are composed of subparallel fractures that tend to exhibit a braided or interwoven pattern in map view. The multitude of such fractures blurs the distinction between the PFS and adjacent fault zones, especially to the west.

No continuous master fault, such as is found in the Cottage Grove and Rough Creek Fault Systems, is present in the PFS.

The overall displacement of the PFS is down to the north. The aggregate throw may exceed 1,000 feet near the western end of the system; the offset decreases eastward. Vertical separation on individual faults ranges up to several hundred feet. Fault zones consist of series of horsts and grabens, within which the strata generally are horizontal or only gently tilted.

According to various geologic quadrangle maps and published reports (Schwalb, 1975), all the faults of the PFS are vertical and high-angle normal. Palmer (1969) measured attitudes of 21 fault surfaces in Hopkins and Christian Counties and recorded dips ranging from 52° to 90°. Slickensides are prominent on many of Palmer's faults, and invariably indicate only dip-slip movement. Most of the breaks are linear or only gently curved along strike. Palmer also remarked on the scarcity of drag features and on the scarcity of breccia. Even on faults with several hundred feet of throw the gouge zone rarely is wider than 1 or 2 feet.

Several sets of east-northeast-trending faults cross the Moorman Syncline in Hopkins, Muhlenberg, and southern McLean Counties. These faults obliquely link the Pennyrile and

Rough Creek Fault Systems. Like the Pennyrile faults, the faults that cross the syncline appear to be steeply dipping normal fractures with displacements of a few tens to several hundred feet.

Age and origin Schwalb (1982) noted that the Pennyrile Fault System approximately coincides with the southern edge of the Rough Creek Graben, which developed during Precambrian or early Cambrian time; however, no direct evidence of Cambrian faulting has been found. Strata displaced at the surface are of Mississippian and Pennsylvanian age, and drilling has revealed offsets in the Devonian. No Mesozoic or Tertiary deposits are present, and no deformation of Quarternary sediments along the fault system has been detected. Because the PFS blends into the Fluorspar Area Fault Complex, it is reasonable to infer that the two systems are contemporaneous: post-Pennsylvanian and mostly, if not entirely, pre-Gulfian (late Cretaceous).

Extensional tectonics are clearly indicated by the pattern of normal faults showing no evidence of reversed or strike-slip movement. A twisting component, however, is apparent from the en echelon arrangement of northeast- and north-northeast-trending fractures along an east-trending fault system. The pattern suggests that the tension was directed toward the northwest, but the line of faulting was controlled by an east-trending feature—the buried southern wall of the Rough Creek Graben.

We propose that the PFS marks the southern edge of the elongate rectangular crustal block that rose and fell to create the Rough Creek-Shawneetown Fault System. The western and eastern ends of this block are marked, respectively, by the FAFC and by the southeastward-trending end of the Rough Creek-Shawneetown Fault System in Grayson County, Kentucky (fig. 25). Dimensions of this rectangle are approximately 150 miles east to west,

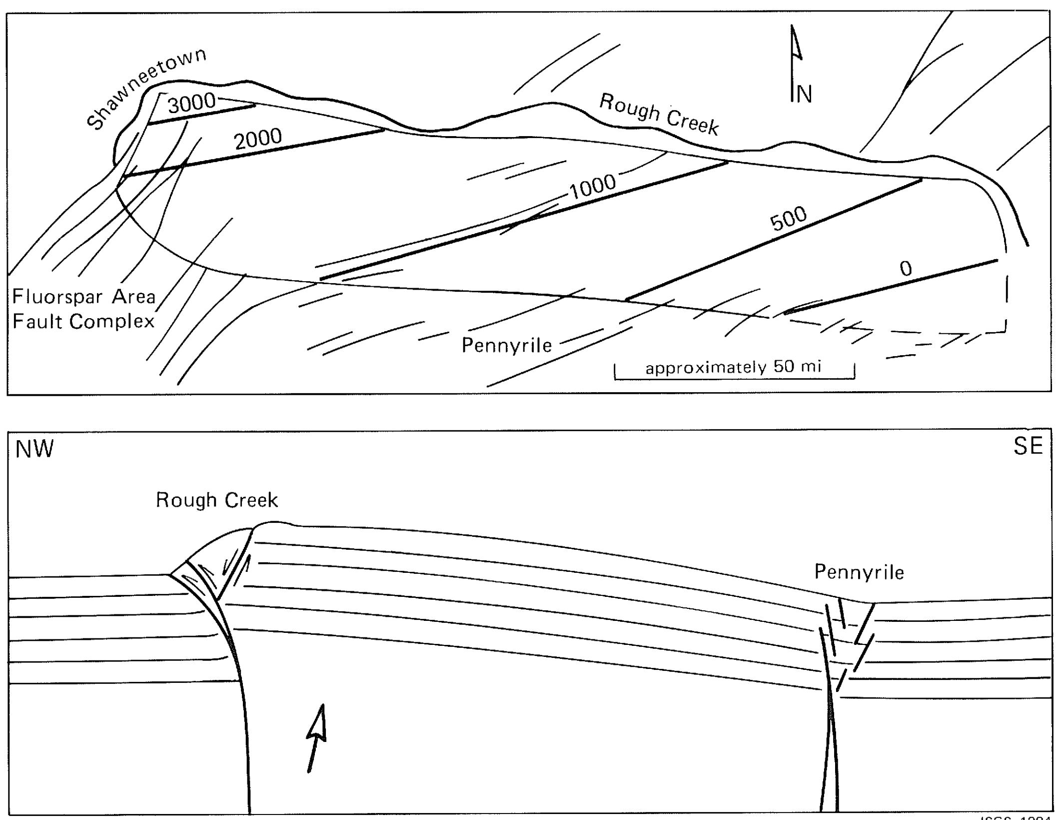


FIGURE 25. Development of Rough Creek and Pennyrile Fault Systems through rocking motion of major crustal block. Top: approximate inferred outline of fundamental block is shown in map view; greatest movement of the block occurred at the northwest in vicinity of Cave Hill. Bottom: this schematic cross section (approximately parallel to the longest dimension of the block) illustrates the situation at time of maximum uplift.

and 25 to 40 miles north to south. The greatest vertical movements, at least 3,500 feet, took place at the northwestern corner of the block, where the Shawneetown Fault Zone abruptly bends to the south-southwest. Relative offset diminished eastward along the Rough Creek-Shawneetown Fault System; the termination of the zone in Grayson County marks an area of little or no movement. Although the southern margin of the block experienced much less displacement than did the northern edge, offsets were still greater to the southwest (Fluorspar Area Fault Complex) than to the southeast.

The great crustal block apparently rocked up and down, like an obliquely hinged trap door, with the hinges at the east and southeast and the greatest opening at the north and northwest. The Pennyrile Fault System developed when the sedimentary strata draped over the hinged block failed under flexure. The northeast-trending faults that cross the Moorman Syncline are essentially parallel to the hinge line (fig. 25) and may reflect bending of the rectangular block as it rocked up and down.

The nature of the movements, if not their cause, can be defined rather clearly. When the action began, this great crustal block was already bounded on three sides by ancient zones of weakness—the northern and southern walls of the Rough Creek Graben, and the Reelfoot Rift on the west. Only the eastern and southeastern sides, buttressed against the Lexington and Nashville Domes, had not experienced prior movement. Some force from below—deep in the crust or even in the mantle—pushed upward at the northwest corner of the block, raising it at least 3,500 feet, and then allowed it to settle back down. The block remained hinged along its southeastern corner, where no faults appear, but elsewhere the movements were sufficient to break the sedimentary strata, produce the RC-SFS and PFS, and reactivate existing fractures in the FAFC.

TECTONIC HISTORY

The tectonic evolution of the study area began in late Precambrian or early Cambrian time, when tensional movement produced the Reelfoot and Rough Creek Grabens (fig. 1). This rifting accompanied the breakup of the Proterozoic supercontinent (Burke and Dewey, 1973). The floors of the two grabens sank several thousand feet below sea level as the earth's crust was stretched. Adjoining upland areas were worn down, furnishing vast quantities of sediments to the troughs. As the grabens filled, the weight of detritus probably triggered renewed faulting; but by the end of Cambrian time tectonism had ceased, the grabens were mostly filled, and the entire Illinois Basin lay under a shallow sea.

Renewed intermittent movements took place here and there during the Ordovician, Silurian, Devonian, Mississippian, and Pennsylvanian Periods. Major tectonism returned to southern Illinois in the late Paleozoic, concurrent with the Appalachian and Ouachita Orogenies. The first episode, in late Pennsylvanian and/or early Permian time, produced the Cottage Grove and Wabash Valley Fault Systems and part of the Fluorspar Area Fault Complex (fig. 26). This action took the form of rifting along the southeastern side of the Reelfoot Graben. Northeast-trending high-angle normal faults in the FAFC and WVFS developed in response to northwest-southeast horizontal stretching of the earth's crust interrupted by the buried northern scarp of the Rough Creek Graben. Extension was greater south of this ancient fracture zone than north of it. In other words, the rocks on both sides of the scarp moved westward, but the block south of the scarp moved farther west than the north block (fig. 26). Right-lateral shear thus developed, and reactivated the Cambrian graben fault, forming the Cottage Grove Fault System.

Conceivably these movements may have produced a corresponding left-lateral shear to the east, along the Rough Creek-Shawneetown Fault System. If such strike-slip faulting took place, it was of small magnitude, and most, if not all, traces of it subsequently were erased by the much larger vertical displacement along the RC-SFS.

The pattern, as we believe it developed, is not unlike that seen on mid-oceanic ridges—a line of rifting or spreading, offset by strike-slip transform faults that trend perpendicular to the rifts. In this analogy the Wabash Valley Fault System and Fluorspar Area Fault Complex represent rift zones and the Cottage Grove Fault System is a transform fault.

Shortly afterward, molten magma welled upward along a north-northwest-trending arch in the fluorspar region. Tensional stresses temporarily aligned themselves north-northwest, allowing igneous material to intrude north- and northwest-trending fractures, including those in the eastern part of the Cottage Grove Fault System and in the Ridgway Fault. Omaha Dome was produced by laccolithic intrusions. Tremendous subterranean explosions of steam created Hicks Dome and associated breccia pipes; radial and concentric faults developed either during original upheaval or subsequent collapse of Hicks Dome.

After the magma had solidified in early Permian time, extension may have been renewed along the Reelfoot Rift, rejuvenating Fluorspar Area Fault Complex faults so that they offset dikes. This step, however, is not essential to our tectonic hypothesis.

Some time during or after the early Permian, the Rough Creek Graben was uplifted by deep-seated forces. On the north side, most slippage took place along a single high-angle south-dipping fault, the front fault of the Rough Creek-Shawneetown Fault System. Lesser hinge-type movements on the south side of the inverted graben produced the Pennyrile Fault System. In the fluorspar district, northeast-trending faults were reactivated, and probably new faults were formed. Most movements were normal but some were reverse; some blocks rotated, twisted, or slipped laterally. Uplift reached at least 3,500 feet at the northwest corner of the block. The upraised block must have been subjected to erosion, shedding detritus to its flanks and profoundly influencing sedimentation; however, none of these sediments seems to have survived to the present.

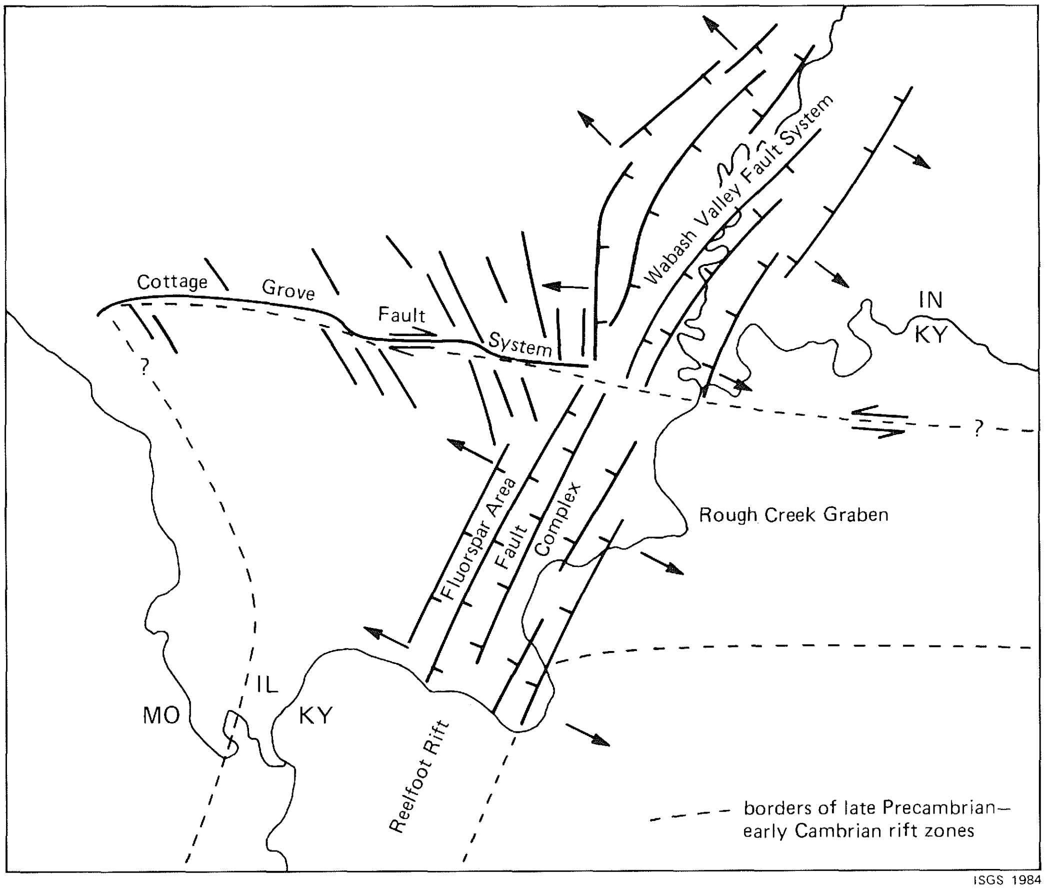


FIGURE 26. Tectonic events of late Pennsylvanian-early Permian time. Approximately a mile of horizontal extension in Reelfoot Rift area created northeast-trending normal faults in Fluorspar Area Fault Complex. This rift was interrupted at the northern edge of the Rough Creek Graben; a smaller amount of extension farther northeast formed the Wabash Valley Fault System. The relative westward movement, which was greater south of the western part of the Rough Creek line than it was north of that line, set up a right-lateral stress that produced the Cottage Grove Fault System. A complementary left-lateral system might have developed eastward along the Rough Creek line, but no evidence for such a system can be found. If a strike-slip fault developed, it was obliterated by later up-and-down movement along the Rough Creek-Shawneetown Fault System.

Later, the uplifted graben-block fell back to more or less its original position. As they sank, the rocks along the Rough Creek-Shawneetown Fault System bent sharply, forming the north limb of the Eagle Valley-Moorman Syncline. Many secondary faults developed; slices of Devonian and Mississippian rocks became trapped along the fault zone far above their original positions. These blocks rotated in place, under the influence of drag, until their strata dipped steeply southward or even were overturned.

This episode rejuvenated the Pennyrile Fault System and the Fluorspar Area Fault Complex. During the later stages of faulting, hydrothermal solutions, heated by magma at great depth and charged with fluorine, sulfur, metallic ions, and other elements, moved upward along northeast-trending fractures in the FAFC. These minerals precipitated or replaced carbonates at favorable spots, mostly in the hard, strong upper Valmeyeran and lower Chesterian strata. There were many overlapping events of mineralization, occasionally interrupted by renewed movements on the faults that served as conduits for the hydrothermal fluids.

Strunk (1984) proposed an alternate tectonic history for the region. Strunk worked with us throughout our study, and accepts our interpretation of the origin of the Rough Creek-Shawneetown Fault System. However, he hypothesized that the Cottage Grove and Rough Creek-Shawneetown Fault System developed together during the late Pennsylvanian-early Permian Periods and prior to the rifting that produced the Wabash Valley and Fluorspar Complex Faults. Strunk suggested that continental collision along the Appalachian and Ouachita foldbelts induced right-lateral slippage along the Cottage Grove-Shawneetown-Rough Creek Faults. At the same time, upwelling magma formed dikes, diatremes, and Hicks Dome, and lifted the southern block of the Rough Creek-Shawneetown Fault System. The block was held up until Jurassic time, when the continents began to rift apart along the mid-Atlantic ridge. This relaxed compression on the southern block of the Rough Creek-Shawneetown Fault System, and allowed it to drop back down. At the same time, the Wabash Valley Fault System and northeast-trending faults in the Fluorspar Complex were created by NW-SE horizontal extension.

We cannot refute this scenario with direct geologic evidence. The timing of many of the movements remains obscure. Only the timing of igneous activity and movement along the Cottage Grove Fault System appears well established. However, Strunk's theory seems to require that the Cottage Grove and Shawneetown Fault Zones be linked, at least at depth. It also does not account well for reverse and strike-slip movements on northeast-striking faults of the Fluorspar Complex. If these faults developed under regional extension, only normal faults should be found. For these reasons, we prefer our own scenario, although Strunk's has merit in relation to global tectonics.

Tectonism probably ceased gradually in the region. Some faults were still active early in late Cretaceous time when terrestrial sediments began to accumulate in the Mississippi Embayment. Intermittent slippage may have even continued into the Tertiary Period, but any such late movements certainly were minor in comparison with those that produced the great faults cutting Paleozoic bedrock.

MODERN STRESS FIELD AND SEISMICITY

Thus far in this report we have considered the ancient stress fields that formed the Rough Creek-Shawneetown and other fault systems of southeastern Illinois and vicinity. Recently acquired evidence indicates that the region today is under a stress field of different orientation than any that prevailed during Mesozoic and earlier times. In this chapter we shall examine the modern stress field and patterns of seismicity in relation to the fault systems that we have discussed.

Modern stress field

Several independent lines of evidence show that the study area today is subjected to a stress field of horizontal compression oriented east-west or ENE-WSW (fig. 27). This compressional field, furthermore, prevails throughout the northeastern United States and in the New Madrid Seismic Zone.

Focal-plane solutions The nearest quake for which focal-plane data are available is the Broughton, Illinois tremor of November 9, 1968 (fig. 27). This event registered a magnitude of 5.3 and damaged a number of brick walls, chimneys, tombstones, and similar structures near the epicenter, which was fixed at latitude 37°96′ N Long. 88°46′ W, approximately 15 miles northwest of Equality. The focal depth was calculated at 19 km (about 12 miles). Gordon et al. (1970) crudely calculated the focal mechanism by noting the sense of rotation of gravestones and other heavy objects in relation to their distance and direction from the epicenter. They concluded that the maximum compressive stress was aligned east-west and that the tensional axis was vertical. Focal-plane solutions, based on seismograms, confirm these results (Stauder and Nuttli, 1970). They show one nodal plane striking N 15° E and dipping 45° west, and a second striking N 1° W and dipping

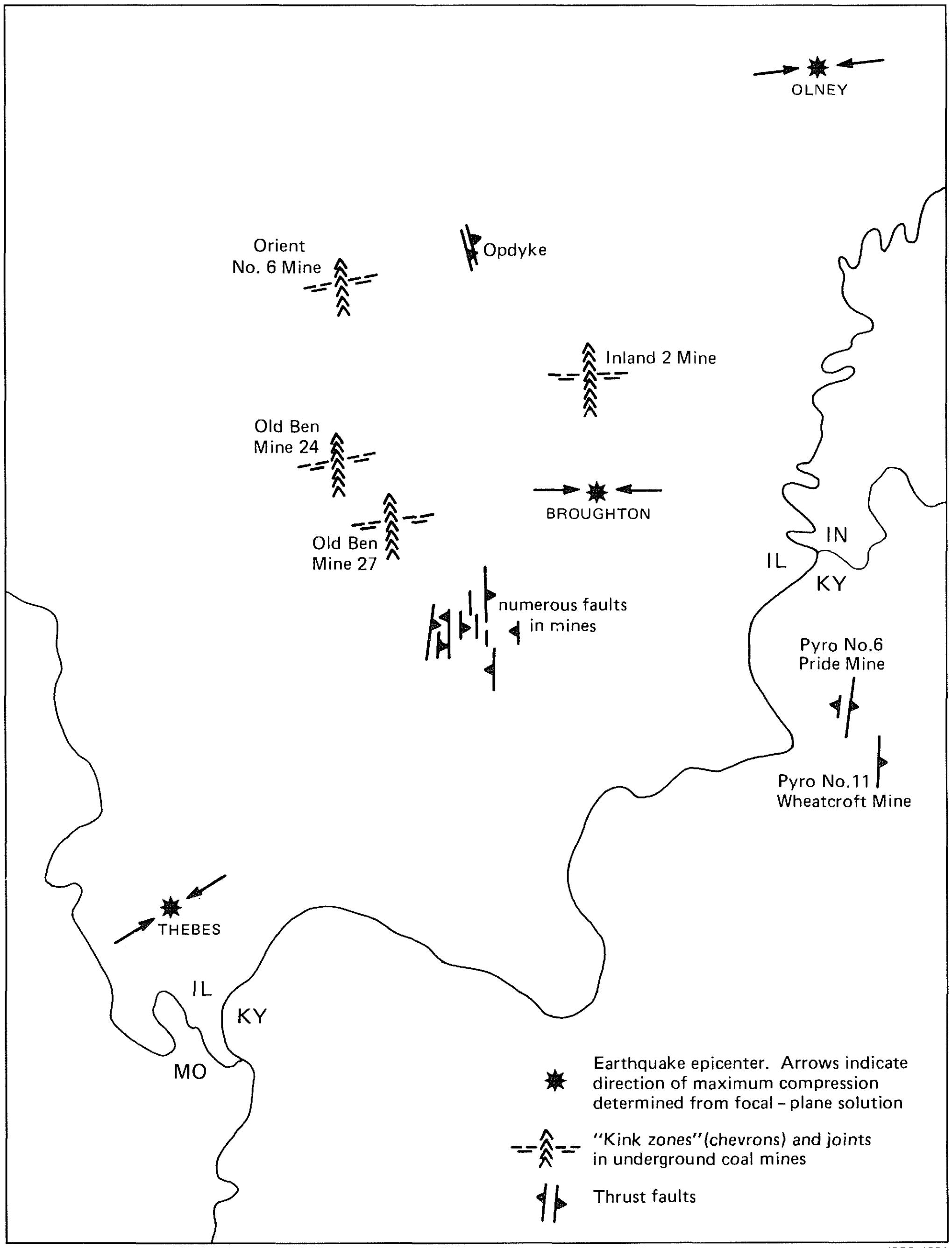


FIGURE 27. Features and measurements indicative of modern stress field.

47° east, signifying nearly pure dip-slip reverse faulting in response to horizontal east-west compression.

Herrmann (1979) gave focal-plane solutions for three additional earthquakes in Illinois, and two out of three indicated maximum compression oriented east-west to ENE-WSW, as found for the Broughton quake. The axis of compression trended N 83°E for the Olney quake of April 3, 1974, and N 59° E for the Thebes quake of August 14, 1965 (fig. 27). The epicenters of these quakes were located about 65 miles north and 75 miles west-southwest, respectively, from Shawneetown. In both cases the resulting movement apparently was strike-slip along a fault trending about 45° from the direction of compression. The third earthquake, nearly 300 miles north of the study area in Lee County, showed maximum compression oriented N 38° E.

A tremor of magnitude 3.8, centered northwest of Memphis, Tennessee, was the result of east-northeasterly compressional stress (Arch Johnston, personal communication, 1982).

Hydrofracturing experiment Haimson (1974) reported results of an experiment designed to measure in situ stresses in boreholes. At an unspecified location in Illinois—Zoback and Zoback (1980) stated it was near Hillsboro, in the west-central part of the state—the researchers drilled five holes, ranging from 298 to 338 feet deep. A portion of each borehole was sealed with rubber packers, then water was pumped into the sealed interval at high pressure to fracture the rock. This procedure, known as hydrofracturing ("fracking"), is widely used in the oil industry to increase porosity and stimulate production from tight reservoirs. After fracking the holes, Haimson and colleagues inserted and inflated soft rubber impression packers that retained impressions of fractures in the walls of the well. When the impression packers were withdrawn, the orientations of the fractures were measured. The average for five holes was N 62° E, with a range of N 49 to 72° E, indicating a maximum compressive stress trending N 62° E.

In situ stress measurements Instrumental measurements of in situ stresses are available from several coal mines and boreholes in Illinois. At the Inland Steel Coal Company's No. 2 Mine in Hamilton County, strain gauges inserted into boreholes angled upward 15 feet ahead of the working face showed the axis of compression to be N 87° E (Blevins, 1982). Strain gauges applied to drill cores from boreholes in southeastern Franklin County showed maximum compression at N 76° E (Yoginder P. Chugh, personal communication, 1984). Stress tests at two mines in west-central Illinois also reportedly indicated NE-SW or ENE-WSW compression; but details are currently lacking.

None of the results available to date was obtained by overcoring, which is the most reliable method for measuring in situ stress; nevertheless, the data are quite consistent.

Ground failure in mines Workers in underground coal mines in southern Illinois have noted for years that mine roof is considerably more prone to failure on north-south than on east-west headings. The effect appears to become more severe as mining becomes deeper. Typically, failure begins a short distance back from the working face. Rock layers in the immediate roof buckle downward and snap, either near the center of the entry or along one side. This sag, which Krausse et al. (1979) termed a "kink zone," propagates north-south, or slightly west of north, with successive failure of layers higher in the roof. If left untended, "kink zones" may produce major roof falls. "Kinks" develop most strongly in brittle, thinly laminated rocks such as shale or siltstone. Their progress appears to be unrelated to local geologic setting or method and pattern of mining.

A failure similar to a "kink zone" can result from simply driving a mine opening too wide, so that beam strength of the roof is insufficient to support overburden. Such failure, however, would be independent of the direction of mining. Mapping of hundreds of kink zones in numerous mines of Illinois confirms their strongly preferred north-south alignment.

The compressional origin of kink zones was clearly visible in the Inland No. 2 Mine. Many kinks showed actual horizontal convergence; broken rock layers were pushed together so that they overlapped. Striations trending east-west were observed along these kinks. In an attempt to relieve stress, the miners cut vertical slots 6 inches wide in the roof ahead of the face. These slots narrowed 1¼ to 1½ inches within 24 hours after cutting. When stress measurements confirmed visual observations, Inland Steel changed the direction of mining from due north to NE-SW and NW-SE. This change brought markedly improved roof stability (Blevins, 1982).

Joints Extremely regular and systematic sets of planar, vertical joints are characteristic of certain lithologies that overlie coal seams in Illinois. These cracks are best developed in black, hard fissile shales that overlie the Springfield and Herrin Coals in large regions of the state. They are also well-developed in firm, gray silty shales and siltstones that locally overlie the same coals. Joints occur in sandstone and limestone, but are widely spaced and inconspicuous. Weak shales and mudstones generally lack joints.

In most of Illinois, the primary orientation of joints in roof shale is N 60° E to N 75° E, in most of Illinois. A secondary set, perpendicular to the primary set, is developed in some mines. In southeasternmost Illinois the primary fractures trend N 75° to 90° E. Exceptions to this pattern only occur close to major faults, where fracturing is clearly related to faulting.

The Inland No. 2 Mine has especially prominent joints. Some of them are open fractures 1/8 inch or wider; others are filled with calcite or clay. In some cases these fractures are concentrated in narrow zones, up to a foot wide, in which the coal as well as the shale is almost pulverized. None of them, however, displays any offset, slickensides, or other evidence of shearing movement. The average trend is N 84° E—parallel to measured maximum compressive stress at the mine (Blevins, 1982).

Ault et al. (1985) report that in western Indiana, joints in Mississippian and Pennsylvanian bedrock consistently trend ENE, as in Illinois. Joints in southwesternmost Indiana mostly strike NNE, but this change could reflect proximity to the Wabash Valley Fault System.

These joints clearly are tensional features. Their orientation, parallel with maximum and perpendicular to minimum horizontal compressive stress, is consistent with the modern stress regime. Thus, at least some joints may be modern features. Foote (1982) and Engelder (1982), in previous studies, reached the same conclusion as we do.

North-trending thrust faults Numerous small, low-angle reverse faults have been mapped and described at coal mines in southeastern Illinois and western Kentucky (Nelson and Lumm, 1984). The northerly strike of these faults indicates that they are the product of east-west horizontal compression. Figure 27 shows the mapped distribution of these thrust faults. The ones in Kentucky lie on the southern limb of the Moorman Syncline south of the Rough Creek Fault System. Numerous thrust faults in Saline and Williamson Counties, Illinois lie just south of or within the Cottage Grove Fault System. Thrust faults near Opdyke, Jefferson County, are far from any other known tectonic fault zone. Since those reverse faults do not fit any known ancient stress field, but do match the modern one, they may be relatively recent structures.

Seismicity

Figure 28 is a map showing epicenters of 488 earthquakes that occurred in the Mississippi valley from 1811 through 1974. The New Madrid Seismic Zone is immediately evident. It is the zone of intense seismicity extending southeastward from the southern tip of Illinois into northeastern Arkansas. Elsewhere in the region, earthquakes are scattered and show no preferred alignment or concentration that can be related to geologic structure.

Herrmann and Canas (1978) and Herrmann (1979 and 1984) discussed the seismicity of the New Madrid Seismic Zone. According to these articles, focal mechanisms of most earthquakes in the New Madrid region are consistent with reverse or strike-slip movement on faults subjected to east-west horizontal compression. This is the same stress regime that

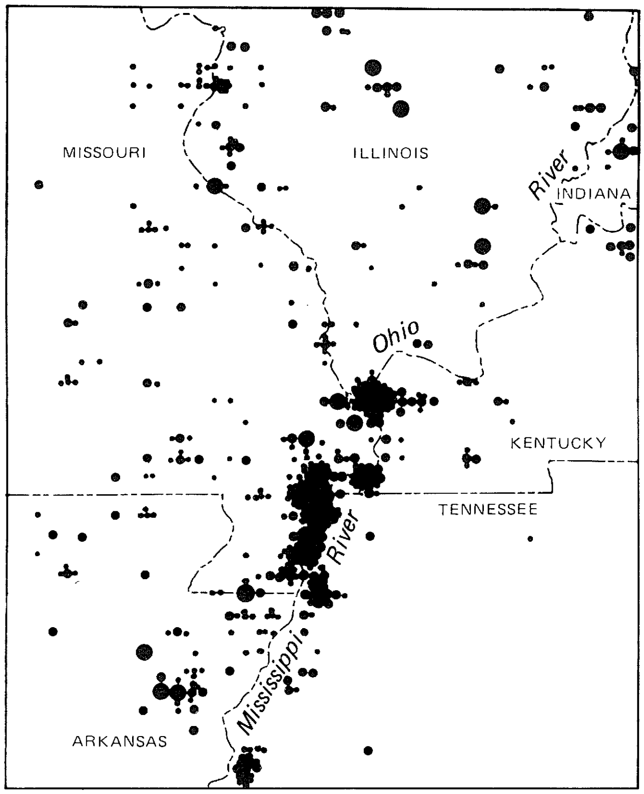


FIGURE 28. Epicenters of 488 earthquakes (magnitude 3.0 and greater) that occurred in the Mississippi Valley from 1811 through mid-1974. New Madrid seismic zone is clearly indicated (Stauder, 1982). Size of dot indicates strength of quake.

prevails in Illinois, as well as in most of the northeastern United States (Sbar and Sykes, 1973; Zoback and Zoback, 1980).

If the entire region is subject to the same stress regime, why is intense seismic activity apparently limited to the New Madrid Seismic Zone? No definitive answer can be given, but several suggestions have been made.

- The Reelfoot Rift is intensively fractured, and some of these faults have the proper orientation to reactivate under current stress conditions.
- The central axis of the rift seems to have experienced recurrent tectonic and igneous activity throughout Phanerozoic time, and these processes may have served to weaken the crust there.
- Radiogenic heat production and consequent thermal stress may be greater in the rift than elsewhere (McKeown, 1984).
- The Mississippi Embayment is still subsiding; this subsidence may place additional stress on the rocks.

In sum, the rocks in the New Madrid Zone probably are weaker than rocks elsewhere; it is also possible that stresses are more intense in the New Madrid Zone, but no data on this subject are available.

Southeastern Illinois and vicinity, if not as violently active as the New Madrid area, still receives its share of small to moderate (magnitude 5–6) earthquakes. Blame for these tremors is popularly placed on the faults that riddle the region. One must recall, however, that stresses, not faults, produce earthquakes. When placed under sufficient stress, rocks will fail at their weakest point. Pre-existing fractures or faults can provide the locus of failure, but only if two conditions are met: (1) the faults must have the proper orientation with respect to the applied force, and (2) the fault zone must actually be weaker than the surrounding rock.

Under a regime of horizontal and east-west maximum compression, fractures having the following orientations are prone to slip (fig. 29):

1. Fractures striking north-south and inclined approximately 30° to horizontal, dipping either east or west. These represent conjugate shear fractures on either side of the horizontal plane, and can undergo reverse or thrust faulting.
2. Vertical or steeply dipping fractures striking approximately N 60° E and N 60° W. These represent conjugate shear fractures on either side of a vertical plane, and can undergo strike-slip motion.
3. Vertical or steeply dipping fractures trending east-west. These are placed in relative tension and can undergo normal, dip-slip faulting, but only if the north-south confining force is low or negative (tensional), and/or if a differential vertical force, of uplift or subsidence, is also applied to the opposite blocks of the fault.

On faults having other orientations, the component of stress normal to the fault plane will raise the frictional resistence to movement above the value of the component of shearing stress, and the fault will not slip.

The Rough Creek-Shawneetown Fault System and the master fault of the Cottage Grove Fault System fit case 3 above; that is, it is possible that they may undergo normal movement under east-west compression. However, we have no evidence that the additional conditions necessary to produce slippage (as discussed under case 3) are met. The north-south confining force and the friction along the faults may be too great to allow slippage under currently prevailing conditions of stress.

Faults in the Wabash Valley Fault System strike mainly north-south to N 30° E. Steeply inclined normal faults, they formed under a stress regime nearly opposite to the present one. Therefore, the probability that slippage and earthquakes may originate in the Wabash Valley Fault System appears to be low.

The same considerations apply to the westernmost end of the Shawneetown Fault Zone, which trends approximately N 20° E.

The Fluorspar Area Fault Complex contains faults having a great variety of orientations, but steeply dipping fractures trending NE-SW dominate. Some of these are candidates for

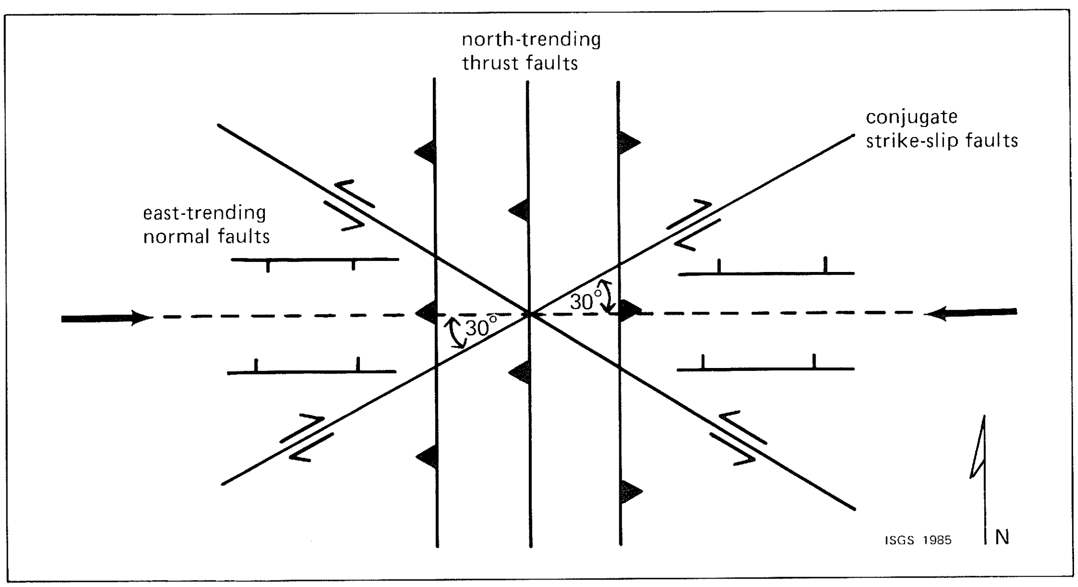


FIGURE 29. Diagram (map view) illustrating faults that may be formed, or could be re-activated, in a stress field with the principal compressive stress horizontal and oriented east-west.

strike-slip (right lateral) movement under case 2, and a few might be capable of normal slippage (case 3). Yet few earthquakes within the FAFC have been detected. And as discussed earlier, although many northeast-trending faults bear obliquely dipping slickensides, little evidence of pure strike-slip movement along these faults has been observed in mines.

One recent earthquake must be mentioned. The quake occurred June 29, 1984, in southeastern Saline County, Illinois. The epicenter was placed at latitude 37°71′ N, longitude 88°48′ W, which lies in the west half of Section 30, T 9 S, R 7 E, Rudement Quadrangle. The body-wave magnitude was 3.8 and the focal depth very shallow, only 1.6 km (1.0 mile). Preliminary focal analysis by Dr. Otto Nuttli of Saint Louis University (personal communication, 1984) indicates slippage along a high-angle normal fault striking approximately ENE. The epicenter is plotted approximately 1½ miles northwest of our mapped subsurface trace of the McCormick Fault, a high-angle fault trending N 35° E. This is not a precise match, but does suggest that the quake was initiated by movement along a segment of the McCormick Fault. The June 29 earthquake apparently is an example of movement under case 3.

The Pennyrile Fault Zone contains normal faults striking east-west to ENE-WSW, and thus also has potential for slippage under case 3. No earthquakes, however, have been reported along the Pennyrile Fault Zone.

To complete our assessment of seismic potential of faults in the study area, we must consider the relative strength of rocks along the fault zones. Full analysis would require mechanical testing of rock samples from all depths along the various faults. Such information is not available, but a few generalizations are possible. Northeast-trending block faults in the Fluorspar Area Fault Complex are extensively mineralized. Mineralization probably serves in many cases to cement or heal the fracture zones, locking them against further movement. Accumulations of barite and other minerals also have been reported in places along the Rough Creek-Shawneetown Fault Zone (Palmer, 1976). We have observed in many places very hard, shattered and recemented or recrystallized sandstone along the Shawneetown Fault Zone. Such material may be very resistant to renewed slippage in the fault zone. Yet in other places, breccia or gouge of pulverized shale and other weak rocks undoubtedly are present, and could admit new movements in the fault zone.

The small north-trending thrust faults, which we have observed in coal mines, clearly fit case 1. We believe that these faults have formed, and may continue to develop, in the current stress regime. The earthquake in 1968 at Broughton evidently took place along such a fault. The rocks observed to be faulted (coal, shale, and underclay) are characterized by low tensile and compressive strengths. Therefore, we postulate that the modern compressive stress is in many cases producing new faults, in preference to re-activating old ones. That is to say, the amount of force required to create new fractures may be less than that needed to break mineralized zones or re-cemented breccia along Paleozoic and Mesozoic faults. This may tend to dissipate seismic activity across a broad area instead of concentrating it along a few large faults, as apparently is happening in the New Madrid Seismic Zone.

We conclude that some faults in southeastern Illinois and vicinity could be re-activated under the present stress regime of east-west compression. A few earthquakes, such as the one of June 1984 in the Rudement Quadrangle, may be the product of such renewed slippage. However, for the most part, seismic activity in southern Illinois probably is related to slippage along new faults, primarily north-trending reverse faults. Therefore, the seismic risk along major bedrock faults in the region probably is not much greater than the risk away from such mapped faults.

Much additional research into the nature and magnitude of the stress field, the rate of strain, and the mechanical properties of rocks in faulted and unfaulted areas will be required to complete the picture. Also, we have not considered the hazards posed to manmade structures in Illinois from major (magnitude 6–8) earthquakes originating in the New Madrid Zone. Such assessment will require input from many fields besides that of structural geology.

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