

# **Precambrian and Paleozoic Geology and Ore Deposits in the Midcontinent Region**

**Rosiclare, Illinois to Ironton and Viburnum, Missouri  
June 30–July 8, 1989**

**Field Trip Guidebook T147**

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This field excursion starts and ends in St. Louis, Missouri. Established as a fur trading post in 1764 by French trader Pierre Laclède, St. Louis thrived because of its excellent location where the Missouri River flows into the Mississippi. The city is named after the French King Louis IX, and its early culture was determined mostly by the French. Today, with a population of about 2 million, St. Louis is one of the larger cities in the United States.

The field excursion will examine the igneous and sedimentary rocks and associated ore deposits in the midcontinental United States. The Ozark dome in south central Missouri and the Illinois basin are the major structures in the field trip area. The St. Francois Mountains, which constitute the highest level of the Ozark dome, have excellent exposures of Middle Proterozoic granites and rhyolites, representative of extensive buried terranes of similar rocks. The iron deposits at Iron Mountain and Pilot Knob are in rhyolites and associated ash-flow tuffs; they are part of a major Precambrian iron metallogenic province containing more than 30 deposits of both historical and potential future importance. The Sn-W-Ag deposits in the Silver Mine District are in granite. The Iron Mountain and Pilot Knob deposits were visited by attendees of the 16th International Geological Congress in 1933, the last time the United States hosted the Congress.

Cambrian-Ordovician sedimentary rocks, consisting of dolomites, sandstones, and shales, were deposited in a shallow sea surrounding the St. Francois Mountains, which at that time were islands. The Cambrian

Bonneterre Formation exhibits a variety of sedimentary facies that reflect its depositional environments. The Pb-Zn-Cu ore deposits of the Southeast Missouri Lead District, including the Old Lead Belt and the Viburnum Trend, occur along the flanks of the St. Francois Mountains and are largely in the Bonneterre Formation, the first carbonate formation above the Precambrian crystalline basement. The ore deposits are underlain by the permeable Cambrian Lamotte Formation, a sandstone and conglomerate that locally contains ore deposits, which are overlain by the relatively impermeable Cambrian Davis Shale.

The Illinois basin, east and northeast of the Ozark dome, contains Paleozoic sedimentary rocks. The Illinois-Kentucky Fluorspar District is in the southern portion of the basin, and the ore deposits are largely in Mississippian limestones.

This field excursion consists of the following three parts:

- T147A: The Illinois-Kentucky Fluorspar Mining District, by James W. Baxter and James C. Bradbury;
- T147B: Precambrian Rocks and Ore Deposits in the St. Francois Mountains, Southeast Missouri by Eva. B. Kisvarsanyi; and
- T147C: 1) The Southeast Missouri Lead District, by Richard D. Hagni with a  
2) Field Trip Guide to the Upper Cambrian Lamotte, Bonneterre, and Davis Formations, by Paul E. Gerdemann and Jay M. Gregg.

**PRECAMBRIAN AND PALEOZOIC GEOLOGY AND ORE DEPOSITS  
OF THE MIDCONTINENT AREA**

The Illinois-Kentucky Fluorspar Mining District

**Saturday, July 1, 1989**

FIRST DAY

Itinerary

- 06:30 - 07:45 Breakfast, Park Terrace  
Hilton Hotel, St. Louis, MO;  
load bus.
- 07:45 - 09:45 Tour of Mississippi  
River Front, Arch, Old Court  
House.
- 09:45 - 09:55 Meet bus below arch and  
depart.
- 09:55 - 12:30 Interstate 64 East to  
Interstate 57, I57 South to  
Interstate 24, I24 east to IL.  
Rt. 146, Rt. 146 East to
- 12:30 - 13:00 **LUNCH** Dixon Springs State  
Park.
- 13:00 - 13:10 Load bus and proceed to  
Intersection of Rts. 146 and  
145.
- 13:10 - 13:30 **STOP 1**, Lusk Creek Fault  
Zone.
- 13:30 - 13:55 North on IL Rt. 145 to  
Eddyville, turn right (south on  
Eddyville-Golconda road,  
continue 4 km (2.46 miles) to  
Clay Diggings entrance just  
before Lusk Creek bridge.
- 13:55 - 14:40 **STOP 2**, Clay Diggings  
Mine.
- 14:40 - 15:15 Continue on Eddyville  
Road to Il Rt. 146, left  
(north) on Rt. 146 to IL Rt.  
34, left (north) on Rt. 34, 7.7  
km (4.6 miles), to Hicks Branch  
Road, follow Hicks Branch Road  
bearing left at first inter-  
section and right at next to  
arrive at
- 15:15 - 17:30 **STOP 3**, Hicks Dome
- 17:30 - 18:00 Return to Rt. 34, turn  
right (north) to Il Rt. 145,  
turn right (north) to U.S. Rt.  
45, continue through Harrisburg  
to village of Muddy and the  
Gateway Inn.
- 19:00 - 20:00 Dinner at Gateway Inn.
- 20:00 - 21:00 Presentation by W. John  
Nelson, ISGS, "Structural Set-  
ting of the Illinois-Kentucky  
Fluorspar Mining District,  
discussion.

**Sunday, July 2, 1989**

SECOND DAY

Itinerary

- 06:30 - 07:45 Breakfast and load bus.
- 07:45 - 08:15 IL Rt. 45 south to  
Harrisburg and IL Rt. 13, left  
(east) on Rt. 13, to IL. Rt.  
142, turn right (south) to  
Equality, from Equality go  
south 3.2 km (2 miles) to foot  
of Wildcat Hills via country  
road, then west 0.3 km (.2 mi)  
past turnoff to Glen O. Jones  
Lake.
- 08:15 - 09:15 **STOP 4**, Horseshoe Quarry
- 09:15 - 10:00 Return to IL Rt. 13,  
turn right (east) to Il Rt. 1,  
turn right (south) on Rt. 1 to  
junction with IL Rt. 146, con-  
tinue on Rt. 1 for 0.4 km (.25  
miles) to quarry road, turn  
left (east) and go 0.5 km (0.3  
miles) to quarry entrance.
- 10:00 - 11:00 **STOP 5**, Rigsby and  
Barnard Quarry
- 11:00 - 11:10 Return to Rt. 1, turn  
left (south), go 2.6 km (1.65  
miles to warning light, turn  
left (east) and park.
- 11:10 - 11:30 Visit Rock Shop.
- 11:30 - 11:35 Continue east 1.2 Km  
(0.75 miles) to
- 11:35 - 12:25 **STOP 6**, Cave in Rock  
State Park, **LUNCH**.
- 12:25 - 13:25 Return to warning light  
in Cave in Rock, turn left  
(south) and take ferry across  
Ohio River. Follow KY Rt 91 to  
Marion, KY, U.S. Rt. 641 South  
to KY Rt. 70 West, continue on  
Rt. 70 West to
- 13:25 - 14:25 **STOP 7**, Pigmy Mine.
- 14:25 - 15:35 KY Rt. 70 East to U.S.  
Rt. 641, left (north) on Rt.  
641 to Marion and Rt. 91, Rt.  
91 north to Cave in Rock  
Ferry, cross Ohio River. IL  
Rt. 1 north to IL Rt. 146,  
turn left (west) on Rt. 146 to  
access road for
- 15:35 - 16:35 **STOP 8**, Hastie Brothers  
Mining and Trucking Company.  
Spar Mountain area,
- 16:35 - 17:30 Return to Rt. 146 and  
turn left (east) to return to  
Rt. 1., turn left (north)

on Rt. 1 to IL. Rt. 13, left (west) on Rt. 13 to Harrisburg and U.S. Rt. 45, right (north) on Rt. 45 to Gateway Inn.

19:00 - 20:00 Dinner at Gateway Inn.  
20:00 - 21:00 Presentation (to be announced), discussion.

### Monday, July 3, 1989

#### THIRD DAY

#### Itinerary

06:45 - 07:45 Breakfast and load bus.  
07:45 - 08:30 U.S. Rt 45 south to IL. Rt. 34, Rt. 34 south to Rosiclare, follow road past hospital and through Fairview subdivision to gravel road across floodplain of the Ohio River, continue to first private lane (on right) beyond Mud Creek and to  
08:30 - 09:30 **STOP 9**, Soward Breccia.  
09:30 - 09:45 Return to Rosiclare and  
09:45 - 10:05 **STOP 10**, American Minerals Company (former site of Rosiclare workings of the Aluminum Company of America.  
10:05 - 10:15 Drive-by, Rosiclare Lead and Fluorspar Mining Company (former plant) enroute to  
10:15 - 11:30 **STOP 11**, Ozark Mahoning Company, Rosiclare mill.  
11:30 - 11:50 Return to Rt. 34, right (north) on Rt. 34 to junction with Rt. 146, Rt. 146 to  
11:50 - 12:30 **LUNCH**, Ohio River Recreational Area, located near Golconda, LUNCH.  
12:30 - 18:00 To Lesterville, MO.

### **ILLINOIS-KENTUCKY FLUORSPAR MINING DISTRICT**

James W. Baxter and James C. Bradbury  
Illinois State Geological Survey, Champaign

#### **INTRODUCTION**

The Illinois-Kentucky fluorspar Mining District (fig.1), comprising about 2,600 km<sup>2</sup> (1000 mi<sup>2</sup>) within the Illinois Basin, lies north and south of the Ohio River within a complexly faulted portion of the Shawnee Hills section of the Interior Low Plateau

Physiographic Province. The Shawnee Hills extend across the southern tip of Illinois as a "spur" of the Ozarks bordered, on the south, by sediments of the Mississippi Embayment of the Coastal Plain Province and, on the north, by the Mt. Vernon Hill Country of the Till Plains Section of the Central Lowlands Province (Willman et al, 1975).

In Illinois, the mining and processing of the larger and more extensive ore bodies have been centered around the villages of Rosiclare and Cave in Rock in Hardin County; outlying occurrences extend the district into eastern and southeastern Pope County. South of the Ohio in Kentucky, where the deposits are generally smaller and production has been more scattered, prominent centers of activity have been near Marion and Mexico, in Crittenden County; near Salem, in Livingston County; and southeast of Fredonia, in Caldwell County. The locations of most mines in Illinois and in Kentucky are shown (fig. 1).

The deposits are essentially of three types: 1) fissure-filling veins in rocks of Mississippian (Lower Carboniferous) age, along faults with typical vertical displacements of 30-150 m (100 to 500 ft); 2) flat-lying, strata-bound, replacement or "bedded" deposits at favorable horizons in limestone of late Valmeyeran (middle Mississippian) to early Chesterian (late Mississippian) age and localized along fractures or minor faults of little displacement; and 3) residual deposits formed by surficial weathering of a vein or bedded occurrence, solution of limestone host rock and the accumulation of the more resistant ore minerals. Some relatively narrow veins, generally located along faults of small displacement, about 8 m (25 ft), have replacement ore that extends laterally, replacing favorable limestone beds in the wall rock. Mixed deposits of this type are characteristic of many orebodies in Illinois and Kentucky, but extensive replacement ore is rare south of the Ohio River. Residual deposits may give way to unaltered ore bodies at depth. The distribution of fluorspar deposits, igneous rocks, and major structural features in the Illinois-Kentucky district are shown in figure 2.

The Illinois-Kentucky Fluorspar District has accounted for more than 75 percent of fluorspar produced the U.S. (1880-1987). According to U.S. Bureau of mines estimates, (Anonomous, 1988), domestic production in 1987 was about 80,000 short tons (over 90% from Illinois) compared to record shipments of over 300,000 tons reported in 1943. Approximately 550,000 short tons were imported in 1987 against reported consumption of 600,000 and apparent consumption of 647,000. About 3,000 short tons were exported.



FIGURE 1 Illinois-Kentucky Fluorspar Mining District, showing location of most Mines. Modified from Grogan and Bradbury, (1968, fig. 1).

At present (November 1988), Ozark-Mahoning Company, a subsidiary of Pennwalt Corporation, is the sole continuous producer in the district with two mines operating in bedded deposits of the Harris Creek District, 8 miles northwest of Cave in Rock, and a mill in Rosiclare. Hastie Brothers Mining and Trucking Company makes occasional sales, largely from open-pit operations in the vicinity of the former Benzon (later Austin Group) Mines in the Cave in Rock District. Recent Hastie sales have been from pockets of ore uncovered as an overlying sandstone is being stripped away, crushed, and prepared for use as skid-resistant aggregate in bituminous road surfaces. No mining is currently reported in Kentucky.

#### HISTORY OF MINING

The fluorspar deposits of southern Illinois and adjacent portions of western

Kentucky were known by prehistoric to early historic Amerindian tribes that populated the Mississippi River Drainage Basin and portions of the southeastern part of North America. These people built and left, as mementos of their passing, the burial mounds and other earthworks from which their name, Mound Builders, is derived. Crude carvings, executed in fluorspar, have been found in many archeological excavations over a wide area. The turtle, a symbol of long life and good fortune, was a favored subject according to some accounts (Hatmaker and Davis, 1938).

An early mention of the occurrence of the mineral fluorite ( $\text{CaF}_2$ ) in Illinois, or of "fluate of lime" as it was then called, was recorded in 1818 (Schoolcraft, 1819) but it was the lead content of the fluorspar-bearing deposits that first attracted the economic interest of early frontiersmen and pioneers migrating westward along the Ohio River. Galena ( $\text{PbS}$ ), which along with sphalerite

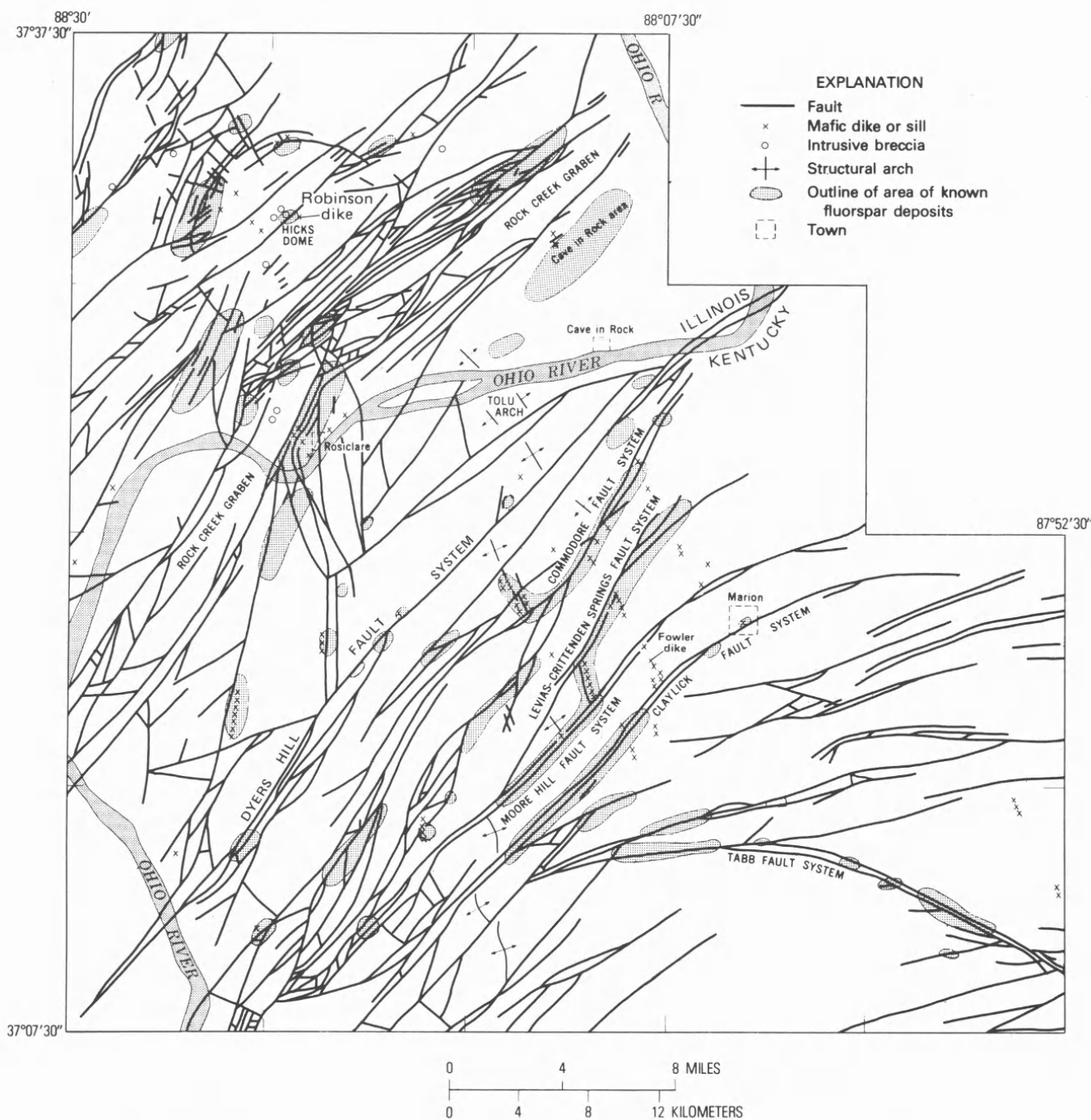
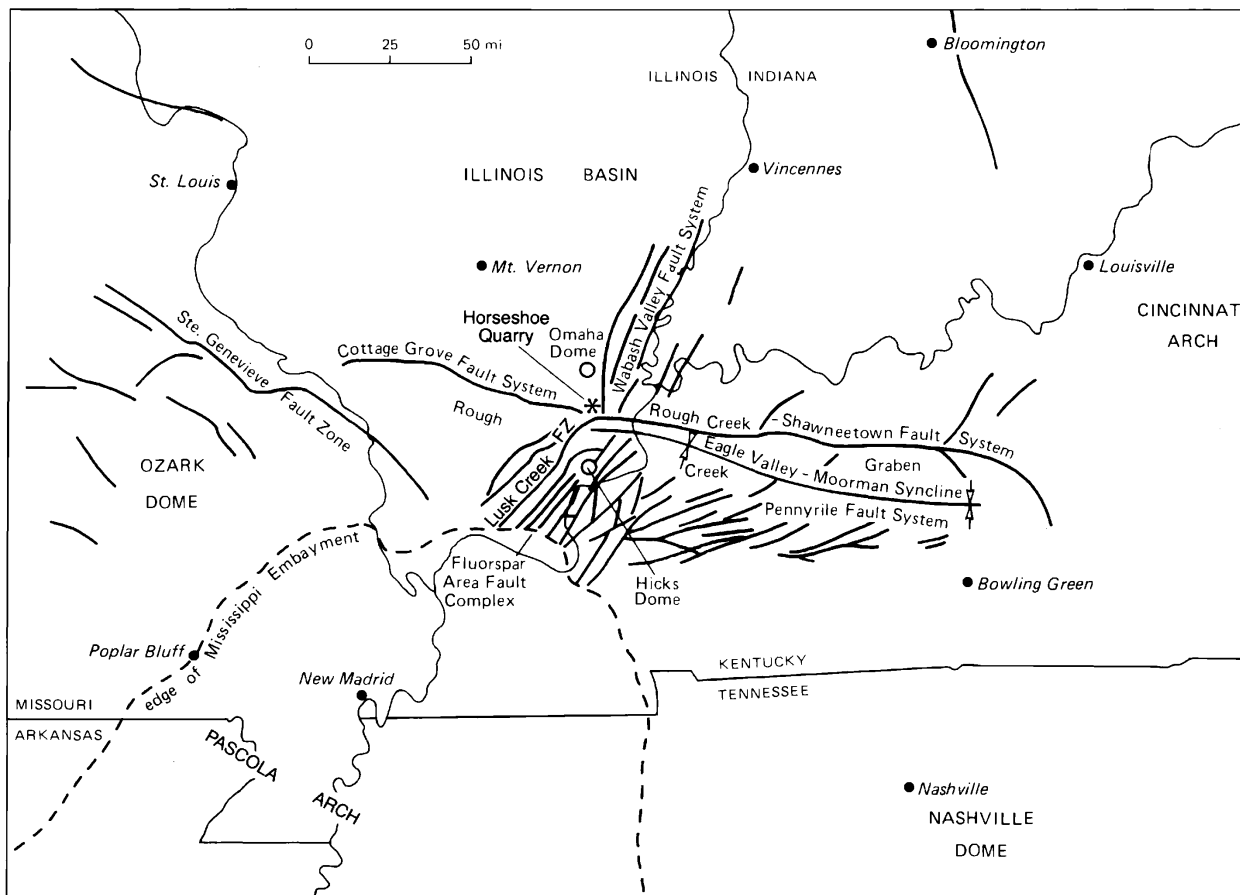


FIGURE 2 Major structural features, igneous rocks, and distribution of known fluorspar deposits, Illinois-Kentucky Fluorspar District. From Trace and Amos (1984, fig. 5).

(ZnS) and barite ( $BaSO_4$ ) are important byproducts of fluorspar mining, was probably first observed in Illinois at Lead Hill at the southwest end of the present Cave in Rock District (figs. 1 and 3), where some exploration and small-scale mining activities for lead probably took place as early as 1820 (Schoolcraft, 1825; Weller et al, 1952).

The first concerted mining venture along the lower reaches of the Ohio occurred near Marion, Crittenden County, Kentucky in 1835;

an enterprise headed by Andrew "Old Hickory" Jackson, U.S. General (War of 1812, Battle of New Orleans) and seventh president (1829-1837) of the United States (Bain, 1905). This mining probably took place in the vicinity of the Columbia Mine (fig. 1) and sought to exploit galena-rich deposits for their contained silver values. After 1835, prior to the Civil War, other primitive attempts to mine lead were made notably in Livingston County, near Smithland. During



ISGS 1984

FIGURE 3 Regional tectonic setting of the Illinois-Kentucky Fluorspar District. Modified from Nelson and Lumm, (1987, fig 2).

the early 1870's, prospecting and mining in Kentucky were resumed, chiefly in Crittenden County. The first shipments of Kentucky fluorspar were made from the Yandell Mine (fig. 1) near Mexico in that county, in 1873.

Serious mining in Illinois was not undertaken until 1842 when operations to recover disseminated "lumps" of lead (galena), found scattered throughout "fluor spar gangue" in vein deposits, were begun in what became the Rosiclare District (Hatmaker and Davis, 1938; Weller et al, 1952). Mining and local smelting of lead continued more or less continuously in the Rosiclare District until after the American Civil War, with growing appreciation of the potential marketability of the fluorspar. Shipments of fluorspar did not begin until about 1870.

Most of the fluorspar produced prior to 1887 was used in the manufacture of glass, enamels, and hydrofluoric acid although its value in metallurgy was recognized. As early as 1866, fluorspar was used in smelting the southern Illinois lead ores "where the sulphuret of zinc occurs with the galena, rendering smelting operations more difficult"

(Norwood, 1866). The value of fluorspar in the smelting of iron ore was also recognized early. A circa 1880 advertisement of the Pell Mining Co, Rose Clare, Hardin County, Illinois read in part:

"Gentlemen: Your close attention is earnestly invited to this new and powerful flux, endorsed by all chemists as the most searching and most favorable mineral ever discovered for the reduction and purification of metals. Our mines produce it in its purest state and without adulteration, and as it is only manufactured so as to be in the best condition for your use, we respectfully ask you to give it a try. Fluor Spar, when exposed to heat, sends forth fumes of the most powerful fluxing, searching, purifying kind known to science, and these fumes, coming into contact with the silicates and impurities in metals, drives them out. Phosphorus and sulphur, that **bugbear** to

all metals, is volatilized at once and passes off, leaving a clean clear residue which flows without hindrance or obstruction until the last ounce of metal contained in the charge is withdrawn. A few pounds added to last heat in cupola will drop out slag perfectly clean, requiring no hand work to prepare furnace for the next run. The effect is **truly marvelous** and this flux is certainly the **most valued friend** the iron manufacturer ever possessed."

Introduction of the basic open-hearth steel furnace in 1888 created further demand for fluorspar. Production from the district (Hatmaker and Davis, 1938) increased from 5,000 short tons in 1887 to more than 55,000 in 1905. Kentucky mines, despite a comparatively slow start (only 6,000 short tons prior to 1898), consistently out-produced those in southern Illinois during 7 consecutive years (1898-1904).

From time to time in the early years, trial shipments of zinc were made (Bain, 1905). With an increase in zinc prices in 1899, a period of active prospecting for zinc ore was begun, centered in Kentucky. The discovery of the Old Jim Mine near Marion in Kentucky stimulated the search for zinc throughout the district and as a result the size and purity of the fluorspar deposits became appreciated for the first time (Bain, 1905). A few mines in Kentucky have produced zinc only. In addition to the Old Jim, these include the Hutson, Nine Acres, and Hickory Cane Mines (Trace and Amos, 1984).

Prior to World War I, the vast majority of Illinois fluorspar production came from the large, vertically and laterally extensive ore veins at Rosiclare: the Rosiclare, Fairview, Blue Diggings, Goodhope, and Annex-Extension Mines; but many outlying occurrences had been prospected and some were mined (Weller et al, 1920). In 1918, Illinois-Kentucky production exceeded 220,000 short tons, equal to 84 percent of domestic production (Hatmaker and Davis, 1938). Most of the rest came from Colorado and 4.55 percent of consumption was imported.

The bedded fluorspar deposits of the Cave in Rock District were known from an early date, especially from surface exposures in the vicinity of Lead Hill, an isolated prominence at the southwest end of the district (fig. 1). However, little development occurred until armament requirements and the loss of foreign imports (25 percent of U.S. consumption from 1910-1913), redirected attention to Lead Hill and in 1918 led to the

recognition of rich extensions of ore trends and then to mining along the Spar Mountain Escarpment to the northeast (Benzon area, particularly the Cleveland, Defender, and Lead Mines, the present site of Hastie Brothers Mining and Trucking Company).

The years between World War I and World War II, including the period of the worldwide Great Depression, are significant. U. S. domestic shipments of fluorspar remained fairly stable, ranging between 112,000 and 165,000 short tons annually, averaging about 129,000 short tons from 1922 to 1929. The introduction of froth flotation in 1929 stimulated the production of acid-grade spar, used in the production of hydrofluoric acid, and allowed processing of siliceous ores from the outlying deposits in the Illinois-Kentucky District. Froth flotation was also applied to less pure deposits of the western U.S., especially Colorado. With the discovery of the extensive, interconnected ore bodies of the Cave in Rock District and the installation of such mines as Victory (1928), Crystal (1929), and W. L. Davis-Deardorff (1937) (fig. 1); the increased demand for fluorspar for use in the processing of both steel and aluminum, during and just before U.S. involvement in World War II, were met.

The major source of domestic fluorspar in the post-war years has been from the bedded deposits of the Cave in Rock District, with contributions from small- to moderate-sized vein deposits lying outside the Rosiclare District. The Minerva No. 1 Mine, located northeast and downdip from the Crystal, Deardorff, and Mahoning Mines was opened in 1943, following four years of development work. The hoisting shaft, 200 m (645 ft) deep, is the deepest in the Cave in Rock District.

The Rosiclare Lead and Fluorspar Company completed the first heavy-media plant in the Illinois-Kentucky Fluorspar District in Rosiclare, during February, 1944. Heavy-media separation had certain metallurgical advantages over the jigging methods previously employed and cut milling costs, and its use rapidly spread throughout the industry. Rosiclare Lead and Fluorspar Mining Company ceased operation on the Rosiclare vein in 1954 and Alcoa abandoned the Goodhope, Blue Diggings and associated veins in 1965, thus allowing the entire Rosiclare vein system to flood.

Competition from low-cost Mexican and European ore had escalated. Importation of acid-grade spar increased almost 700% from 20,000 tons in 1949 to 156,000 tons in 1954, in part due to tariff concessions made to foreign producers in 1951. Domestic producers sought relief through higher tariffs, the

imposition of import quotas, and government price support. Some relief came by means of a government stockpiling program, but by 1958, 73% of acid-grade spar used in the U.S. was imported and prices of lower grade spar products were severely depressed.

Most of the credit for the viability of the district and the ability to compete with low-cost foreign ore goes to the industry. Ozark-Mahoning and the Minerva Company carried out vigorous exploration projects guided by an understanding of the geology of the district. Both companies were excellent ore-finders and skilled at cost cutting. The bedded deposits of the Cave in Rock District were large and amenable to the use of modified room and pillar mining methods and the introduction of efficient, rubber-tired, diesel equipment. Prior to 1955, the actual mining of Ozark-Mahoning properties was let to local mining contractors, in particular, J. W. Patton and Sons and KMD Mining Company. Since that time, all mining operations have been carried out by Ozark-Mahoning, allowing close control of mining costs and added competitiveness.

In 1952, Minerva purchased Crystal Mining Company, Victory Fluorspar Mining Company, and the properties of the Yingling Mining Company, greatly expanding their scope of operations. In 1971, Minerva leased the Lafayette Mine near Mexico, Kentucky from U.S. Steel, dismantled the mill and brought the heavy media plant to the Minerva Mine site, increasing their capacity to handle ore, not only from Mine No. 1, but also from their outlying vein mines: the Fairbairn, Gaskins, and Spivey. The Lafayette Mine was the largest and most productive of the mines along the Tabb Fault System and, with the Dyers Hill Mine one of the largest producers of fluorspar in Kentucky.

Minerva holdings were sold to Allied Chemical Company in 1975 and subsequently were acquired by Seaforth Mineral and Ores Company in 1980. Since 1982 when Inverness Mining Company, the mining subsidiary of Seaforth, ceased its operations; Ozark-Mahoning Company has become the sole remaining major producer of fluorspar in the U.S., accounting for about 90 percent of domestic consumption. At present, (November, 1988) Ozark-Mahoning production is from from the Annabel Lee and Denton Mines (fig. 1) in the relatively newly developed Harris Creek District located about 3.8 miles (6.1 km) northwest of Minerva No. 1 Mine and on the north side of the Rock Creek Graben where it mirrors, on a smaller scale, the Cave in Rock District on the south side of the graben. The possibility of deep, bedded deposits within the graben has not been adequately tested.

## TECTONIC HISTORY

The Illinois-Kentucky Fluorspar Mining District is located near the southern end of the Illinois Basin, which is an intracratonic basin that developed during middle to late Paleozoic time. This southern portion of the Illinois Basin is bordered on the west by the Ozark Uplift, on the south by the buried Pascola Arch, and on the southeast by the Nashville Dome and Cincinnati Arch (fig. 3).

Early basin history is related to late Precambrian to middle Cambrian rifting and later basin evolution involves late Paleozoic to late Cretaceous rift reactivation. The ore deposits are situated astride a rather low, northwest-trending anticline, the Tolu Arch, with closure near the village of Tolu in Crittenden County, Kentucky (fig. 2). Hicks Dome, a cryptoexplosion structure with approximately 1220 meters (4000 feet) of structural relief, is located near the northwestern end of the Tolu Arch in Hardin County, Illinois (fig. 2). Hicks Dome and the Tolu Arch, the larger fluorspar district domal anticline (or "fluorspar arch"), are located at the intersection of the Reelfoot Rift and its east-trending extension into Kentucky, the Rough Creek Graben (fig. 4). These two structures, along with an inferred Southern Indiana arm (Braile et al, 1982, 1984), constitute the New Madrid Rift System in southern Illinois and western Kentucky. On the present bedrock surface, the north and northwest boundaries of this system are marked by the Rough Creek-Shawneetown Fault System and the Lusk Creek Fault Zone respectively (fig. 3). The southern boundary in

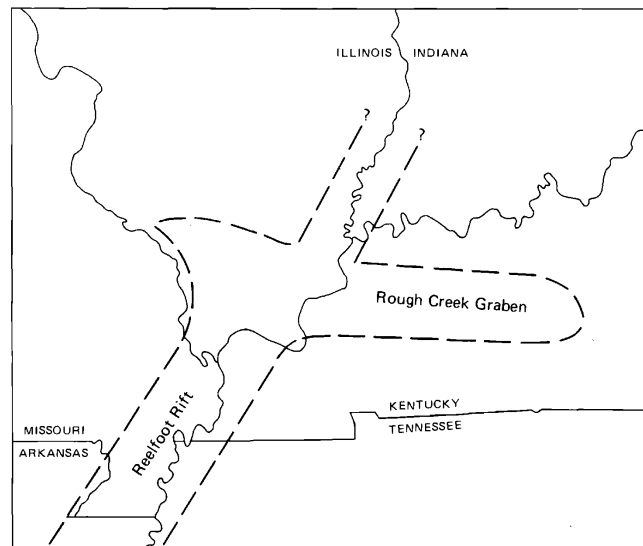


FIGURE 4 Precambrian rift zones in the northern Mississippi Embayment. From Nelson and Lumm, (1987, fig. 1).

Kentucky is less clearly defined, but it is believed to partially coincide with the Pennyrile Fault System (fig. 3). At the intersection of the Shawneetown and Lusk Creek Fault Zones, the rift is 70-80 km (45-50 mi) wide; Hicks Dome is located about 11 km (7 mi) due east of the intersection.

The Reelfoot Rift (Ervin and McGinnis 1975) and the Rough Creek Graben (Soderberg and Keller, 1981), are thought to be parts of a system of "failed rifts" that developed in response to extensional forces initiated by late Precambrian crustal uplift. The nature and ultimate cause of the rifting is highly debatable. One suggestion (Braile et al, 1984) is that it was related to upwelling and interjection of anomalous low-density mantle material in the lower part of the crust and corresponded closely in time to the postulated break-up of a Precambrian supercontinent (Bond et al, 1984), splitting much of what is now North America from a southern land mass. As it is postulated, this split resulted in a continental margin along which the Appalachian and Ouachita geosynclines later developed. The crustal "underplating" responsible for the Reelfoot Rift would have occurred along a zone of crustal weakness created by the tensional forces related to the continental separation.

According to the above scenario, the uplifted Precambrian surface, with axial rift or graben, initially underwent widespread erosion, but near the end of the Precambrian or in the early Cambrian, the axial graben began to subside and receive sediments, the first probably terrestrial. However, since intrusive or volcanic rocks are characteristic of the early history of rifts, such rock types may be present in the deep and undrilled portions of the rift system.

The relaxation of rifting forces in the early Cambrian initiated isostatic readjustment of uplifted anomalous mantle material, with respect to the lighter crust, and crustal subsidence within the fault-bounded troughs. With marine transgression, these troughs became arms of the sea that began rapid accumulation of clastic sediments. Through middle Cambrian time, areas adjacent to the rift complex remained upland and were eroded, while the oldest sediments associated with the Illinois Basin, as it is presently defined, were deposited in the troughs. The age and composition of pre-late Cambrian (pre-Mt. Simon) sediments in the rift area are poorly known but, where penetrated, they consist of arkosic sandstone, shaly limestones and dark basinal shales (Schwalb, 1982; Houseknecht and Weaverling, 1983; Howe and Thompson, 1984, Nelson and Lumm, 1984; Nelson and Kolata, in press). A generalized

stratigraphic column to basement for the southern part of the Illinois Basin is shown in figure 5.

Trough subsidence; accommodated by normal, basement-involved faulting; was largely restricted to the trough margins and continued until the late Cambrian. By that time, extension within the rift area had given way to slow subsidence, accompanied by widespread cratonic downwarping, that lasted through the Paleozoic. A major marine transgression led to deposition of pre-Knox clastics beginning with the late Cambrian Mt. Simon (Lamotte) Sandstone, across nearly the entire Illinois Basin area. The Cambro-Ordovician depocenter remained within the Reelfoot Rift south of the present "bootheel" of Missouri but this "Reelfoot Basin" extended into southern Illinois (Schwalb, 1969). Sargent (in press) indicates that more than 2,700 m (9,000 ft) of Mt. Simon (Lamotte) and older sediments accumulated in the deepest part of the trough in southeast Illinois and in an adjacent portion of Kentucky. Subsidence during the remainder of the Paleozoic was accentuated by periodic uplift within and adjacent to the developing Illinois Basin. By Devonian time the basin depocenter had migrated to southern Illinois. Basinal deformation corresponded to compressional stress and was related to Taconic, Acadian, and especially the Ouachita and Alleghenian orogenies (Nelson and Kolata, in press).

Near the end of the Paleozoic Era (late Pennsylvanian-early Permian), the African and South American plates collided with the North American plate forming the supercontinent, Pangea. According to Nelson and Kolata, the compressional stresses caused high-angle, reverse faulting along the Rough Creek-Shawneetown Fault System and the Lusk Creek Fault Zone. It now appears probable that the Tolu Arch, within the rift system at the juncture of the Reelfoot and Rough Creek segments, was uplifted at about this time and; along northwest trending, tensional fractures; intruded with a swarm of mafic dikes that yield an early Permian date (Zartman et al, 1967; Nelson and Lumm, 1984). Dikes in the Cottage Grove Fault System, as much as ten miles north of the Shawneetown Fault Zone, occupy tensional fractures, radiate away from the Tolu Arch and Hicks Dome, and are of the same age and composition as the dikes found in the fluorspar district.

The Permian date of known igneous activity has led some authors (Nelson and Lumm, 1987) to suggest an early Permian age for the origin of Hicks Dome. However, a lead-alpha date of 90-100 Ma obtained on the mineral brockite (thorium-bearing phosphate) from near the surface at Hicks Dome (Heyl and

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
		DESMOINESIAN	Kewanee	Modesto		375 - 475
				Carbondale		350 - 400
			Spoon		350 - 400	
		AOKAN	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
				Gassy Knob Chert		200 - 550
			Bailey Ls.		200 - 450	
	SILURIAN	NIAGARAN		three formations		150 - 350
	ORDOVICIAN	ALEXANDRIAN		undifferentiated		200 - 425
		CININNATIAN	Maquoketa	undifferentiated		15 - 130
		CHAMPLAINIAN	Galena	undifferentiated		500 - 600
				Platteville		500 - 600
Ancell			Joachim		250 - 950	
		Dutchtown		50 - 200		
		St. Peter		50 - 200		
		Everton Dolomite		50 - 600?		
CANADIAN			undifferentiated		1800 - 3600	
CAMBRIAN		CROIXAN	Knox Dolomite Megagroup	Eminence Dolomite		350 - 900
				Potosi Dolomite		800 - 1000
				Franconia Ss.		900 - 1350
	Eau Claire Dolomite				800 - 2700	
	MIDDLE AND LOWER?	Potsdam Sandstone Megagroup		Mt. Simon Ss.		0 - 700?
			pre - Mt. Simon (Mermet Ss., Rome, Conasauga?)		564 +	
PRECAMBRIAN					ISGS 1984	

FIGURE 5 Generalized stratigraphic column for the Illinois-Kentucky Fluorspar District. From Nelson and Lumm (1987, fig. 4).

Brock, 1961) indicates that the thorium-rare earth mineralization associated with the gaseous cryptoexplosive event at the intersection of the Reelfoot Rift and the Rough Creek Graben may be considerably younger than the mafic dikes. However, Ruiz et al (1988) point out that lead-alpha age determinations are fraught with uncertainty and raise the possibility that the 100 Ma date on brockite (originally reported as on monazite, not monzonite as indicated by Ruiz et al), could conceivably be as much 100 Ma too young. They have compared the isotopic evolution of strontium in biotites from 290 Ma alkalic rocks from the fluorspar district (Zartman et al, 1967) to observed isotopic composition of fluorite from the Cave in Rock District. These data indicate that, 200 Ma ago (ca Jurassic-Triassic), the biotites evolved strontium isotope ratios similar to the isotopic composition of those of fluorspar from the Cave in Rock District. They suggest that the similarity was achieved by means of incongruent dissolution of the older biotites by heated solutions, the origin of which they relate to the later igneous activity at Hicks Dome. If one can assume that the fluorine, thorium, beryllium and rare earth elements at Hicks Dome were derived from the mantle as part of the gaseous emanation responsible for the event; it is reasonable to suspect that the uplift and brecciation were related to crustal weakening and igneous activity that were connected in time to post-early Permian reactivation of the rift.

The breakup of Pangea could have reintroduced extension to the stress regime acting on the rift system and renewed movement along the faults. Rift reactivation normally promotes alkaline igneous activity (Burke and Dewey, 1973). Crustal extension and rift reactivation may have resulted in the interjection of mantle material into the lower crust, doming within the rift, intrusion of alkaline igneous rocks at great depth, and closing of the Illinois Basin to the south by the uplift of the Pascola Arch (fig. 3). However, timing of structural events related to rift reactivation and to the fluorspar district are poorly constrained; but multiple movements have obviously occurred on many faults.

It has been postulated that uplift of the Pascola Arch was initiated as early as Devonian time, as part of a larger structure, the Ozark Arch, that connected the Ozark Uplift (Ozark Dome) and the Nashville Dome (Tikrity, 1968; Ervin and McGinnis, 1975). Schwalb (1969) felt that the Pascola Arch was emergent in early Pennsylvanian. Recent review of all the evidence (Kolata and Nelson, in press) led to the suggestion that the Pascola

Arch is post-Middle Pennsylvanian and pre-late Cretaceous and most likely appeared either in the late Permian, thrust up along reverse faults, or in the early Mesozoic (Jurassic-Triassic) by igneous doming due to incipient rifting along a reactivated Reelfoot Rift. Of these alternatives, Kolata and Nelson prefer the latter explanation. Some authors, however, claim that the early and middle Mesozoic was a time of emergence and relative quiescence throughout the Midcontinent (Moore, 1970; Ervin and McGinnis, 1975). Moody (1949) concluded that magma invaded the northern coastal plain during two separate Mesozoic time intervals; the first, as early as Triassic, being basaltic; the later, in the mid-Upper Cretaceous, both alkaline and basaltic.

Whatever the timing of post-Appalachian crustal deformation, it is likely that the Hicks Dome explosive events, with their unique geochemical signature: fluorine, lead, zinc, barium, thorium, beryllium, titanium, niobium, and rare earth elements; were related to reactivation of the New Madrid Rift System and to deep-seated igneous activity with major contribution of material derived from the mantle.

Northeast-southwest trending, mineralized faults of the Illinois Kentucky Fluorspar District are associated with a series of grabens that offset the axis of the Tolu Arch and individual fluorspar area faults offset and are younger than the northwest trending Permian dikes (fig. 2). This block faulting is mostly of post-early Permian and pre-late Cretaceous age, but field evidence of some post-Cretaceous movement has been cited. (Rhoades and Mistler, 1941; Amos, 1967). However, the brittle and easily cleavable fluorite in the major veins has shown little evidence of crushing such as would accompany significant post-vein fault movements. The occurrences of crushed ore that have been reported and cited as evidence of post-mineralization movement are associated with the Lusk Creek Fault Zone and the Interstate Fault Zone. The Lusk Creek Fault Zone forms the northeast boundary of the Dixon Springs Graben and the name Interstate Fault Zone has been applied to a very complexly faulted portion of the system of faults forming the northeast boundary of the Rock Creek Graben.

#### IGNEOUS INTRUSIVE ROCKS

Igneous intrusive rocks in the Illinois-Kentucky Fluorspar District (fig. 2) consist mainly of alkalic, ultramafic dikes and a few sills. Intrusive breccias are found in the Illinois part of the district. To the north of the mining district, ultramafic dikes have

been encountered in coal mines and in exploration borings north of the Shawneetown Fault Zone in Gallatin, Saline, and Williamson Counties. Exploratory drilling for oil on the Omaha Dome in Gallatin County revealed ultramafic dikes and sills. The sills are believed to be the cause of the domal uplift. Omaha Dome has 46-61 m (150-200 feet) of closure on Mississippian strata (Bristol, 1975). A well drilled near the apex cut numerous sills within post-Devonian rocks and encountered the top of Middle Devonian carbonate at the same elevation at which it is recorded in nearby wells off the dome. Total thickness of sills encountered in the Omaha Dome drilling approximately equals the structural relief in post-Devonian strata (Nelson, in press).

The ultramafic dikes in southern Illinois and western Kentucky are generally narrow, rarely more than 5 meters (15 feet) wide. One, located outside the fluorspar district in a coal mine in Saline County, was said by Cady (1919) to be 100 m (300 ft) wide. The thicknesses of the few sills that have been observed are generally about 0.3 m (1 ft) or less. The ultramafic occurrences are most difficult to find in outcrop because of their extreme vulnerability to weathering.

Megascopically, the ultramafic rocks are generally porphyritic, with a fine- to medium-grained groundmass; the intensively altered varieties, may appear to be simply fine-grained, dense rocks. Color ranges from dark gray and dark greenish gray to lighter shades of gray and greenish gray, the more altered varieties being lighter colored. Phlogopite and serpentine are the most commonly observed phenocrysts, but pyroxene phenocrysts may be recognized in some rocks. Petrographically, the dikes and sills have been identified as mica peridotite, and lamprophyre (Clegg and Bradbury, 1956; Koenig, 1956). Alnoite was reported by Lewis and Mitchell (1987) from drilling chips from a relatively recent oil test on the Omaha Dome. Characteristic minerals in thin sections were melilite, monticellite, phlogopite, diopside, titanium andradite, and primary carbonates (R. D. Lewis, pers. comm., 1987). Earlier igneous chips from drilling samples from the Omaha Dome area lacked any evidence of melilite and were identified as mica peridotite (English and Grogan, 1948).

The mica peridotite in thin section contains phenocrysts of phlogopite, olivine (partly serpentinized) and serpentine pseudomorphs after both olivine and pyroxene. Colorless clinopyroxene is present as small crystals in the groundmass. The balance of the groundmass consists of mica, chlorite, secondary carbonate, and various other

alteration products. Carbonate also replaces the phenocrysts to various degrees. Accessory minerals include apatite, perovskite, magnetite and ilmenite. Yellow garnet was reported in the Omaha Dome intrusive (English and Grogan, 1948) and in the Absher Dike in Williamson County (Clegg, 1955).

The term lamprophyre is applied to dikes that contain no evidence of olivine or of serpentine pseudomorphs after olivine. Most of the lamprophyres have suffered replacement by carbonate to the extent that the identity of the primary minerals is largely a matter of conjecture. In the most extreme examples, apatite remains as the only evidence of igneous origin.

Many of the rocks termed lamprophyres may actually be altered peridotite. However, a few occurrences provide evidence that some of the ultramafic dikes can not be such altered peridotites. For example, the Golconda Dike (near Golconda, IL) was described by Johanssen (1905) as containing phenocrysts of serpentine after pyroxene but none after olivine and was classified as a pyroxene lamprophyre. The Downeys Bluff Sill, near Rosiclare, contains phenocrysts of phlogopite and relatively fresh augite in a carbonate groundmass. While it is conceivable that the secondary carbonate has completely obliterated evidence of any preexisting olivine, the relatively large size of the phenocrysts of augite is atypical of mica peridotites and suggests that the Downeys Bluff Sill is a lamprophyre. In addition, an X-ray diffractogram of a sample of the Downeys Bluff Sill revealed a few percent of analcime, a mineral one would not expect in a mica peridotite.

Intrusive breccias are confined to the Illinois portion of the Illinois-Kentucky Fluorspar District. A cluster of dikes and other breccia bodies are found at Hicks Dome, and individual diatremes are found at five other localities, at distances of 8 to 11 km (5 to 7 mi) from the center of the dome. Hicks Dome breccias have been classified as shatter breccias, vent breccias, and some as carbonatitic breccias (Bradbury and Baxter, in press). The shatter breccias consist of angular to sub-rounded clasts of host rock in a matrix of finely comminuted host rock and secondary quartz or carbonate. The clasts appear to have experienced little if any vertical displacement. The shatter breccias are believed to have formed chiefly by in-place shattering caused by a sudden reduction in confining pressure. Stretching of the strata during vertical domal uplift may have provided the required tensile stress. A slight rounding of the corners of some clasts suggests that there may have been some entrainment of the fine rock particles

of the matrix by an upward streaming gas.

Two undoubted vent breccias at Hicks Dome are bodies of unknown shape and dimensions. The included sedimentary rock fragments are of mixed lithologies, indicating significant vertical displacement. Both bodies were found in the topographically high central portion of the dome, inside the encircling outcrop of New Albany Shale. One, the Pankey Breccia, is expressed as a knob, 60 X 90 m (200 X 300 ft) in plan, covered with abundant blocks of breccia. This breccia field is located near the northeast edge of the central area and at the highest topographic point. The breccia, is greater than 90 percent silica and is composed of clasts of chert and some silicified limestone in a matrix that appears to be finely comminuted host rock and secondary quartz. No igneous component has been seen. Barite occurs in the breccia at the south end of the field.

The other vent breccia, intersected by the Hamp well, drilled by the St. Joseph Lead Company at the approximate center of Hicks Dome, was encountered at a depth of 488 m (1600 ft), continued to the bottom of the hole at a depth of 698 m (2944 ft), and was described by Brown et al (1954) as "a confused breccia zone". The oldest formation boundary that could be identified with any degree of confidence was the contact of the Ordovician Decorah-Plattin and Joachim Formations at a depth of 553 m (1815 ft). Below this "intense brecciation....confused (the identification of) lithologic units throughout the (lower) 1100 feet (335 meters) of the hole". As determined from rotary drill cuttings, the Hamp well breccia consisted of broken fragments of host sedimentary strata. The only material of possible igneous origin, "three brown, altered, fragments, possibly basic igneous," were noted in thin sections of side-wall cores. The breccia matrix appeared to be largely comminuted host rock and secondary quartz, although in the more heavily mineralized intervals, fine-grained fluorite served as a breccia cement. Considerable vertical displacement of rock fragments was recorded: "Pieces resembling Maquoketa Shale were found 1000 feet (305 meters) below the base of that formation" and St. Peter-type sand was found to cover more than twice its normal range".

Carbonatitic breccia, discovered at three sites, consists of igneous and sedimentary fragments in reactive carbonate matrix or in an incoherent, weathered residuum that is presumed to have had a carbonate matrix. The Grant Intrusive, about 2.7 km (1.7 mi) southwest of the center of Hicks Dome, is characterized by rather large crystals of biotite and hornblende (1 cm or more across),

fairly numerous lapilli, fragments of igneous and sedimentary rock, and a carbonate matrix that is largely dolomite. Other recognizable mineral grains include apatite, and an occasional green pyroxene. Many mineral grains are partly to completely replaced by serpentine and/or carbonate. Igneous rock fragments in the Grant Intrusive include aegerine syenite up to 5 cm across, but other fragments are replaced by carbonate to the extent that only remnants of feldspar attest to their igneous origin. Siliceous fragments of sedimentary rock show greenish-white, reaction rims that include carbonate minerals, scattered grains of epidote, and an opaque, unidentified substance.

A second carbonatitic breccia, a 60 cm (24-inch) wide dike, occurs within the outcrop of New Albany Shale on the south side of the dome. It contains both sedimentary and igneous rock and mineral fragments in a matrix of fine-grained dark brown siderite. A 90 cm (36-inch) wide, deeply weathered dike, 5 meters (15 feet) east of the sideritic dike, consists of a soft mass of weathering products containing abundant flakes of mica. The intensely weathered condition of the rock provides very little evidence of its original character. However, the presence of abundant phlogopite, apatite and feldspathic rock fragments indicates a genetic relationship to the near-by sideritic breccia dike. The extensive disintegration of the weathered dike suggests a carbonate matrix other than siderite.

Other intrusive breccias in the Illinois Fluorspar District include the Soward Breccia (field trip stop 9), 11 km (7 mi) south of Hicks Dome; Sparks Hill Breccia, 9.7 km (6 mi) east of Hicks Dome; and three occurrences in the vicinity of Herod IL, at distances of 7 km (4.5 mi) north, 7 km (4.5 mi) northwest, and 9.6 km (6 mi) west northwest of Hicks Dome. The latter, along with the Soward and Sparks Hill occurrences, are best described as metamict or diatrema breccias and are composed of fragments of igneous and sedimentary rocks and minerals in a matrix of comminuted rock and carbonates. The occurrence 7 km northwest of the dome consists of boulders and small intermittent outcrops of altered and broken sedimentary rock that extend up a ravine for a distance of about 183 m (600 ft) to an area of cobbles of dark green, fine-grained, igneous rock at the upper end of the ravine. The dark green cobbles contain fragments of metamorphosed rock and crystals of hornblende and biotite. In thin section, the matrix appears to be very finely crystalline silicates and contains a profusion of tiny (1 X 10 micrometer) needles of aegerine that tend to cluster around many of the rock

and mineral inclusions. Nepheline and feldspar can also be identified in the matrix. Many of the rock inclusions show extensive resorption and/or recrystallization. Some features of the rock suggest crystallization followed by remobilization. A chemical analysis of the dark green rock showed 9 percent Na<sub>2</sub>O. This rock has tentatively been termed a tinguaitite because of the profusion of aegerine needles in the matrix. None of the igneous rock was found in place, and its relationship to the breccia cannot be determined. It may have been intruded into the brecciated sediments or could have been brought up in a single block or in multiple blocks along with the breccia.

#### **Age of Intrusion**

K-Ar and Rb-Sr age determinations on biotite and hornblende from the Downeys Bluff Sill and the Grant Intrusive (Zartman et al, 1967) and on the Omaha Dome alnoite (Nelson and Lumm, 1984; Lewis and Mitchell, 1987) indicate that ultramafic intrusion took place in the fluorspar district during the early Permian. However, evidence that the Hicks Dome explosive events were separated in time from this intrusion of ultramafic rocks must also be considered. As stated previously, Ruiz et al (1988) have strontium isotope data that led them to suggest that post-Permian igneous activity occurred at Hicks Dome about 200 Ma ago (Jurassic-Triassic).

#### **STRATIGRAPHIC SETTING**

Paleozoic rocks ranging in age from lower Devonian (Clear Creek Chert) to Pennsylvanian (fig. 6) crop out in the Illinois-Kentucky Fluorspar District. The thicknesses cited below refer to the fluorspar district. The stratigraphic nomenclature shown is that of the Illinois State Geological Survey (Willman et al, 1975) and differs in some details from that of the Kentucky Geological Survey and the U.S. Geological Survey.

#### **Devonian Formations**

Rocks of the Devonian System are exposed only at Hicks Dome where Lower and Middle Devonian carbonate formations are encircled by a belt of Devonian-Mississippian shale of the New Albany Group. Lower Devonian Clear Creek Chert and Middle Devonian Grand Tower and Lingle Limestones are probably present but poorly exposed and largely reduced to a rubble of chert except where seen in vent-type breccia bodies. The total thickness of Devonian carbonates exposed at Hicks Dome is difficult to judge but, in the fluorspar

district, 120-137 m (395-450 ft) are assigned to these strata.

#### **Devonian-Mississippian New Albany Group**

The New Albany Shale, composed of dark gray to black, carbonaceous, silty shale, is approximately 120 m (395 ft) thick. The New Albany is mostly of late Devonian age but these black shales are known to be time-transgressive and an undetermined thickness exposed at Hicks Dome is Kinderhookian in age. The black shale is overlain by a few cm of gray, calcareous siltstone or silty limestone, probably equivalent to part of the Chouteau (Kinderhookian) Limestone.

#### **Mississippian Formations**

The fluorspar district is mainly underlain by Mississippian rocks that attain almost 915 m (3,000 ft) in thickness. Strata of the Mississippian System are the primary host for both bedding-replacement and fissure vein fluorspar deposits in the Illinois-Kentucky Fluorspar District.

**Valmeyeran Series.** The lower unit of the Valmeyeran, the Springville Shale, consists of 3-5 m (10-25 ft) of mostly gray and greenish gray shales. These strata represent a long period of limited sedimentation within a starved basin (Lineback, 1966) that existed in the southern part of the Illinois Basin during the early Valmeyeran (Osagean in Kentucky). The Springville is overlain by siltstone and cherty limestone of the Ft. Payne Formation, the basinal equivalent to the Borden Siltstone of Indiana and of the deltaic tongue of the Borden that prograded westward across the central portion of the Illinois Basin. The Fort Payne, 68-195 m (120-640 ft) thick, records the early history of differential infilling of the starved basin. Fine silt and carbonate material was carried into the deeper portion of the basin from shelf areas that expanded as carbonate production and downslope transport proceeded.

The Fort Payne is overlain by the Ullin Limestone with complementary changes in thickness. The Kentucky Geological Survey considers the Ullin to be a facies of the Fort Payne. As the starved basin continued to fill and the influx of silt diminished, crinoid and bryozoan colonies became established in the shelf areas and the fossilized debris from these organisms, swept into the infilling basin, constitute the Ullin Limestone. The Ullin consists of medium- to thick-bedded, fossil-fragmental limestone composed mostly of crinoid ossicles and bryozoan debris either cemented by syntaxial

SYSTEM	SERIES	FORMATION	MEMBER	LITHOLOGY	THICKNESS (FT.)	LITHOLOGIC DESCRIPTION	RANGE OF DEPOSITS		
							VEINS	BEDDED	
		PENNSYLVANIAN			600-900	Sandstone, shale, thin coals			
MISSISSIPPIAN	CHESTERIAN	KINKAID			0-80	Gray, cherty limestone; shale			
		DEGONIA			0-30	Shale and thin-bedded sandstone			
		CLORE			100-120	Shale; limestone; thin-bedded sandstone			
		PALESTINE			50-60	Sandstone; silty shale			
		MENARD			100-130	Fine-grained limestone; shale			
		WALTERSBURG			15-50	Shale; shaly sandstone			
		VIENNA			10-20	Limestone; shaly limestone			
		TAR SPRINGS			90-110	Sandstone; shale; thin coal			
		GLEN DEAN			40-70	Fossiliferous, partly oolitic limestone; shale			
		HARDINSBURG			90-115	Sandstone; shale			
		HANEY				Fossiliferous limestone			
		FRAILEYS			105-140	Shale; thin limestone			
		BEECH CREEK				Silty limestone			
		CYPRESS			80-110	Sandstone; shale			
	RIDENHOWER			25-65	Shale; shaly sandstone				
	BETHEL			80-100	Sandstone				
	DOWNEYS BLUFF			25-40	Crinoidal, locally oolitic limestone				
	YANKEETOWN			30-45	Shale; siltstone (Yankeetown); limestone; shale (Shettersville)				
	RENAULT	Shettersville		15-35	Light-colored oolitic limestone (Levias)				
	AUX VASES	Rosiclare		15-35	Calcareous sandstone, shale at base				
	STE. GENEVIEVE	Spar Mtn.		120-160	Light-colored, largely oolitic limestone; sandstone lenses				
			ST. LOUIS			350-400	Fine-grained, cherty limestone		
		VALMEYERAN	SALEM			500±	Dark-colored, fine-grained limestone; foraminiferal calcarenite		
			ULLIN			125-360	Crinoidal, bryozoan limestone; dark-gray, fine-grained limestone		
			FORT PAYNE			225-640	Siltstone; silty, cherty limestone		
	DEVONIAN-MISSISSIPPIAN		SPRINGVILLE				Gray and greenish gray shale		
			NEW ALBANY GROUP			395±	Gray to black shale		
	DEVONIAN		LINGLE						
		GRAND TOWER			250±	Limestone and chert			
		CLEAR CREEK							

FIGURE 6 Formations exposed in the Illinois-Kentucky Fluorspar District. From Grogan and Bradbury (1968, fig. 2).

sparry calcite in optical continuity with the crinoid ossicles or within a micrite matrix. The Ullin is 38-110 m (125-360 ft) thick.

With carbonate infilling, a shallow water carbonate environment was established and continued throughout the duration of the Valmeyeran until the introduction of the terrigenous clastics and cyclical deposition that characterize strata of the Chesterian Series. The Salem Limestone, overlying the Ullin, is about 240 m (500 feet) thick. A lower 78 m (260 ft) thick, consists of fossil-fragmental limestone that resembles the Ullin but has intercalated dark, fine-grained limestone that is partly silty, dolomitic, and/or cherty. This part of the Salem is assigned to the Warsaw Formation by the Kentucky Geological Survey. Foraminiferids diagnostic of the type Salem of Indiana occur in beds near the top. A middle portion of the Salem, 30-40 m (100-120 ft) thick, is predominately pseudo-oolitic to oolitic, biocalcarenite. In Kentucky the name Salem is restricted to this unit.

The upper part of the Salem as now recognized in Illinois, is 40-50 m (120-150 ft) thick and consists of dark gray to nearly black limestone that is mostly fine-grained with occasional pseudo-oolitic stringers. In Kentucky, this unit is assigned to a lower member of the St. Louis.

The St. Louis Limestone, as recognized in Illinois, is typically cherty and fine-grained to sublithographic. In the fluorspar mining district, a lower part, about 30 m (100 ft) thick, is light- to medium-gray, mostly finely crystalline limestone and equivalent to an upper portion of the lower member of the St. Louis in Kentucky. This is overlain by about 40 m (120 ft) consisting of fine- to medium-grained, bryozoan-rich limestone assigned to the upper member of the St. Louis in Kentucky. An upper portion, about 50 m (160 ft) thick is similar but has some prominent interbedded oolite and dolomitic limestone, transitional to the overlying Ste. Genevieve. The St. Louis has a total thickness of 106-120 m (350-400 ft).

The Ste. Genevieve Limestone, about 50 m (160 ft) thick, is typically composed of medium-grained, oolitic calcarenite with some interbedded fine-grained, dolomitic limestone and one or more sandy stringers. The most conspicuous sandstone, the Spar Mountain Sandstone Member serves as a means of subdividing the formation. The occurrence of sandstones and shales, signaling the introduction of Chesterian sedimentation, played a leading role in the stratigraphic localization of the bedded fluorspar deposits in beds of late Valmeyeran and early Chesterian age, serving as aquatards that trapped

the upward migrating of ore fluids, promoting mineral deposition (fig. 6).

The Fredonia Member of the Ste. Genevieve, lower Fredonia in Kentucky, is 18-24 m (60-80 ft) thick and contains prominent layers of light gray oolite in thick, cross-bedded units. In the Illinois portion of the fluorspar district, the Fredonia Member is mostly free of chert.

The Spar Mountain Sandstone Member, the sub-Rosiclare sandstone prominent in the Cave in Rock District, is 0-5 m (0-15 ft) thick, consists of gray to greenish gray calcareous sandstone or sandy limestone and is one of two or three pre-Aux Vases sandstone or sandy limestone zones in the Ste. Genevieve.

The upper 15-18 m (50-60 ft) of the Ste Genevieve represents two members that are not everywhere differentiated. These are the Karnak and Joppa Members, that collectively equate to an upper portion of the Fredonia of Kentucky. The Karnak and Joppa Members are approximately equal in thickness; the Karnak is commonly more oolitic and the Joppa has conspicuous shale in thin interbeds and in partings along bedding planes. The Joppa is overlain by Aux Vases (Rosiclare) Sandstone.

The Aux Vases Sandstone is 5-12 m (15-35 ft) thick and consists of fine-grained, gray or greenish, calcareous sandstone or siltstone, and some interbedded limestone. The sandstone is commonly cross-bedded and, in some cases, ripple-marked. A foot or so of sandy, micaceous, greenish gray shale is locally present at the base of the Aux Vases formation, especially in the Cave in Rock District. The Aux Vases is overlain by the Levias Member of the Renault Limestone, the Levias Member of the Ste. Genevieve as that formation is recognized in Kentucky.

The Renault Limestone has two members, in ascending order, the Levias and Shetlerville. The Levias Member, 8-11 m (25-35 ft) thick, consists of light gray, medium-grained limestone that is partly oolitic, and of medium gray, fine-grained limestone. Pink calcite crystals are diagnostic. The Levias is the uppermost unit of Valmeyeran age in the fluorspar district; the Shetlerville Member of the Renault is Chesterian.

**Chesterian Series.** The Chester is about 400 m (1200 ft) thick in the fluorspar district. The Shetlerville Member of the Renault being the lowermost unit of the Chesterian Series. The total thickness of the Shetlerville Member is about 8 m (25 ft). A lower part, 1-5 m (2-14 ft) thick is somewhat argillaceous, coarsely crystalline, silty limestone. The more impure beds in the lower part locally grade to siltstone. The upper 3-7 m (10-20 ft) of the Shetlerville

consists of fairly pure, partly oolitic, medium-grained to sublithographic limestone, with minor amounts of interbedded gray shale. The Shetlerville, a lower part of the Renault in Kentucky, is overlain by the Yankeetown Shale.

The Yankeetown Shale is 5-10 m (15-30 ft) thick and consists of calcareous, greenish gray to red, fossiliferous shale; dark gray, fossiliferous shale; greenish gray, red mottled, silty, argillaceous dolomite or dolomitic siltstone; and buff or greenish gray, medium- to coarse-grained, fossiliferous limestone. The Yankeetown, also a part of the Renault in Kentucky, is overlain by the Downeys Bluff Limestone.

The Downeys Bluff Limestone, uppermost Renault in Kentucky, is 7-12 m (25-40 ft) thick and consists of medium-bedded, gray to brownish gray, fossiliferous limestone. Oolites are common and locally abundant. Gray and/or pink chert is often present, in the upper part of the formation. Some beds are dolomitic and interbedded, light gray, calcareous shale may be present. A variable thickness of greenish gray or reddish gray shale occurs locally at the top of the formation although at many places it is removed by pre-Bethel erosion. The Downeys Bluff is overlain by the Bethel Sandstone.

Lithofacies of the Chesterian Series, beginning with the Bethel Sandstone, show a cyclical alternation of sandstone, shale and limestone and commonly grade laterally, one into the other (Treworgy, in press). Within the fluorspar district, the formations and many members are laterally persistent but the siliciclastic formations exhibit lateral intertonguing of sandstone and shale. Sandstones of the Chesterian Series (the Bethel, Cypress, Hardinsburg, Tar Springs, Waltersburg, Palestine, and Degonia) are generally blanket sands that show gradational contacts with an underlying limestone unit or, locally, they may be channel sands with erosional basal contacts. Siliciclastics, presumably eroded from the eastern Canadian Shield, entered the basin area from the northeast via a major river system, the Michigan River (Swann, 1963). According to Swann, the Michigan River Delta system shifted position from northwest to southeast by as much as 320 km (200 mi).

Limestone units of the the Golconda Group and the Glen Dean and Vienna Limestones are generally similar in lithologic aspect to the older Chesterian carbonates and composed of light- to medium-brownish gray, medium-grained limestone. The younger limestone units (Menard, Clore and Kinkaid tend to be darker colored and are generally finer grained.

About half of the 400 m (1200 ft) thickness of the Chesterian in the fluorspar district is shale interbedded within sandstone or limestone formations. A middle portion of the Golconda Group, the Fraileys Formation, is predominately shale.

#### **Pennsylvanian Formations.**

The Chesterian Series is separated from the overlying Pennsylvanian by a major, erosional unconformity. The basal formation, the Caseyville, is characterized by cross-bedded to massive quartz-arenitic sandstone that contains abundant granules and pebbles of quartz. The Caseyville also contains gray to black silty shale and siltstone and thin and lenticular coal beds. The overlying Abbott (Tradewater) Formation consists of shale, siltstone, and micaceous subgraywacke; with rare quartz-pebble granules, lenticular coal beds and thin shaly limestones. Maximum total thickness of Pennsylvanian within the fluorspar district is roughly 300 m (1000 ft).

#### **MINERAL DEPOSITS**

The following is a brief resume of information on fluorspar, lead, zinc, and barite deposits of the Illinois-Kentucky Fluorspar District. Published articles that give more detailed accounts for Illinois include: Weller et al (1952), Brecke (1962, 1983), Baxter et al (1963, 1967, 1973), Baxter and Desborough (1965), Bradbury et al (1968), Heyl (1983); and for Kentucky: Oesterling (1952), Klepser (1954) Thurston and Hardin (1954), Trace (1954 a, b; 1974), Hardin (1955), Hardin and Trace (1959), Hook (1974), and Trace and Amos (1984). A more general treatment of the district as a whole may be found in Grogan and Bradbury (1968).

#### **Vein Deposits**

In the veins, best exemplified by deposits formerly worked at the village of Rosiclare (fig. 7), the chief minerals are fluorite and calcite. Sphalerite and galena are locally abundant but in most deposits are present only in small amounts at the vein margins. Barite occurs in some areas, mostly in the central part of a vein or in narrow fissures next to the veins. However, as noted previously, some mines in Kentucky produced zinc only and a few mines, also mainly in Kentucky, have produced only barite or have produced substantial amounts of barite; these include the Mico, Ainsworth, part of the Pigmy, part of the Wright, and part of the Damron (Anderson et al, 1982: Trace and

Amos, 1984).

The fluorspar, lead, zinc and barite vein orebodies are found mainly along north- and northeast-trending faults of but moderate displacement. Although some fissure-vein ore deposits in the Rosiclare District were as wide as 14m (45 ft), fissure-veins average 1-3 m (3-10 ft) in width (Heyl, 1983). Mined ore shoots commonly range in strike-length from 60-120 m (200-400 ft), but greater lengths were common in the Rosiclare mines and at the Dyer Hill Mine in Kentucky. Most ore shoots are 30 to 60 m (100-200 ft) deep but some extend downward for nearly 250 m (800ft).

Faults of moderate displacement, 8 to 150 m (25 to 500 ft), evidently provide avenues for the movement of mineralizing fluids and open fissures for mineral deposition. Faults of lesser displacement apparently failed to develop sufficient open space along fault

planes and those of greater displacement had excessive development of gouge and other fault material that decreased the amount of open space.

The widest and most extensive vein deposits have been found where the fault walls are formed by competent Ste. Genevieve and/or St. Louis Limestones (fig. 6). In the Rosiclare District, the massive Bethel Sandstone and the Cypress Sandstone are also associated with productive parts of the veins. However, some commercial veins have been found where the wallrocks are made up of younger strata of Chesterian age, with little known mineralization at deeper levels in older and presumably more favorable rocks.

### Bedding-replacement Deposits

The bedding-replacement deposits are located on either side of a major northeast trending structural element, the Rock Creek Graben (fig. 2). In the older and more noted Cave in Rock District, southeast of the graben, the ore deposits follow the course of a group of fractures and minor faults that trend N45° to N60°E and N30° to N85°W (fig. 8). The northeast-southwest trending fractures dip toward the faults of the Rock Creek Graben. It has been commonly assumed that the faults bounding the graben served as part of the plumbing system that carried the ore solutions responsible for the emplacement of the deposits. The wider and more persistent orebodies follow northeast-southwest trends, parallel to the graben. According to Heyl (1983), the bedding-replacement deposits in Illinois and Kentucky are commonly 15-60 m (50-200 ft) wide and 1.5-6 m (5-20 ft) thick; the length is variable, from 60 m (200 ft) to 3 km (2mi). The ore ranges from 20 to 35 percent CaF<sub>2</sub> and commonly contains about 4 percent zinc as sphalerite, and locally, silver-bearing galena. Sphalerite and galena are relatively more abundant and calcite less abundant in bedded deposits than in the veins. The orebody mined at Minerva No. 1 Mine reportedly contains more zinc toward the northeast. Minor copper ore values (chalcopryrite) have been recovered from the metallic concentrates produced from the Annabel Lee Mine in some recent years. Barite, practically absent in some bedded orebodies, is abundant around the margin of others. In some instances, barite can be recovered as a by-product but only when economic conditions are favorable.

Fluorite commonly occurs in alternating coarse (light-colored) and fine-grained (dark-colored) layers in what is called banded or, by the miner's term, "coon tail" ore. Sphalerite, where abundant, replaces

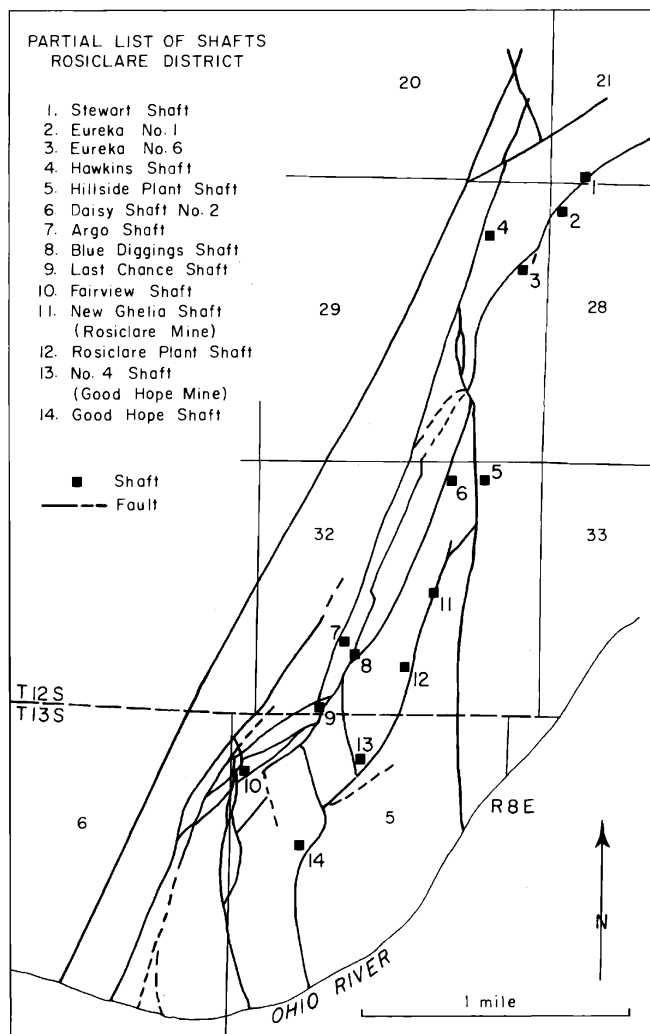


FIGURE 7 Faults and mine shafts in the Rosiclare District. Modified from Baxter and Desborough (1965, Plate 1).

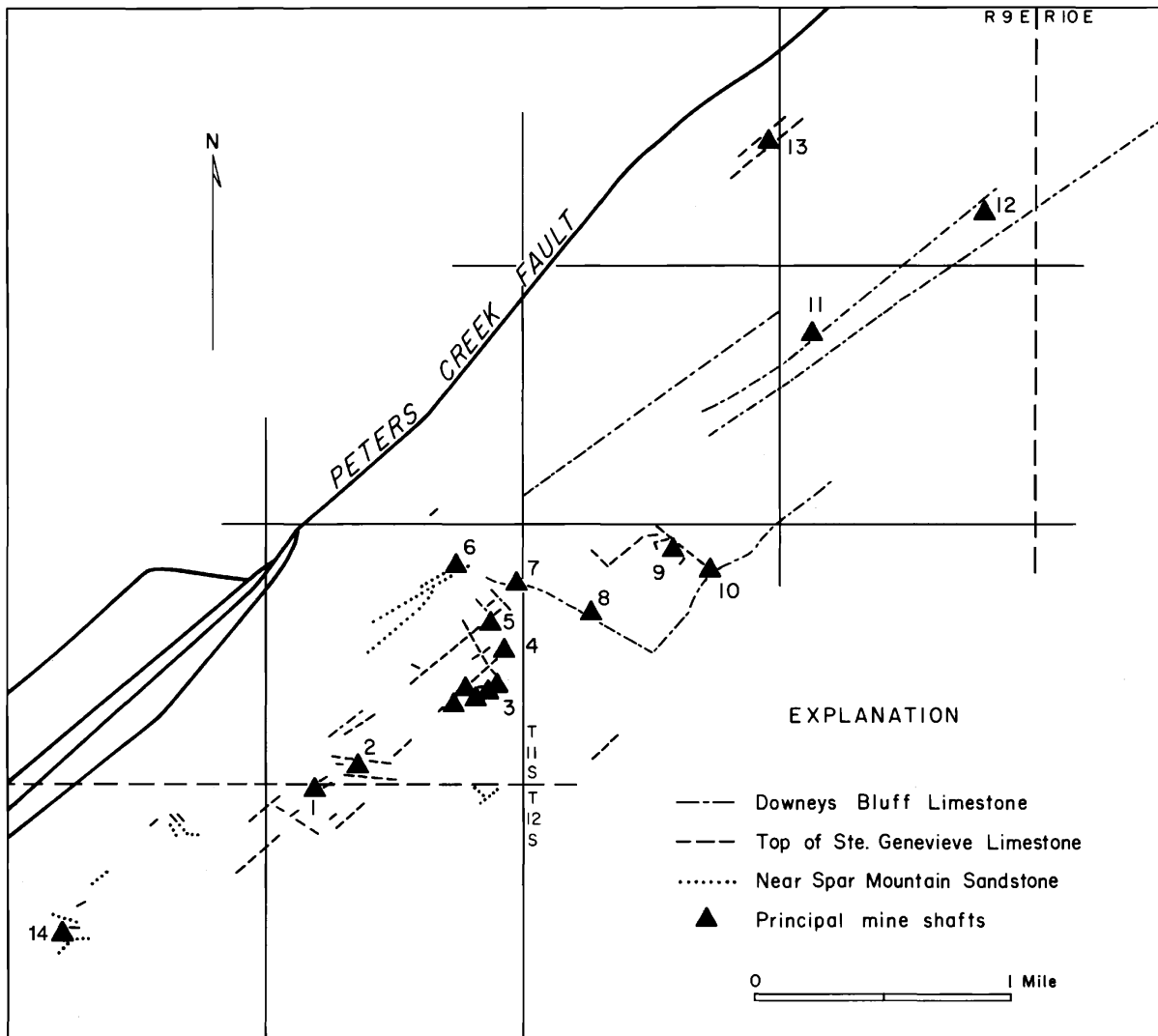


FIGURE 8 Cave in Rock Fluorspar District, Hardin County Illinois: ore deposits and mineralized trends. From Grogan and Bradbury, (1968, fig. 11). 1. Addison shaft, Victory Mine. 2. Carlos Shaft, Victory Mine. 3. Crystal Mine shafts. 4. Crystal shaft No. 3. 5. Crystal shaft No. 4. 6. Davis-Deardorff Mine. 7. W. L. Davis No. 2 Mine. 8. A. L. Davis Mine. 9. West Green Mine. 10. East Green Mine. 11. Oxford Mine. 12. Minerva No. 1 Mine. 13. Hill-Ledford Mine. 14. Lead Hill mines.

the fine-grained fluorite in banded ore and galena occurs in coarse-grained fluorite layers in masses up to 8 cm (3 in) across. Brecke (1962, 1983) has invoked a solution penetration or "diffusion" mechanism for the origin of banded ore. The alternative and older theory is that such textures are the result of replacement of original sedimentary layering in the host rock.

The restriction of replacement deposits to certain favorable stratigraphic levels (fig. 6) indicates that these beds are particularly suited for replacement processes. The three favored ore horizons are, in ascending order: 1) sub-Rosiclare ore, below the Spar Mountain Sandstone Member of the Ste. Genevieve Limestone or at the level of the Spar Mount-

ain were the sandstone is missing, 2) Rosiclare ore, in the upper part of the Joppa Member of the Ste. Genevieve and 3) Bethel ore in the upper part of the Downeys Bluff Limestone. Grogan and Bradbury (1968) list features common to the three major mineralized levels. All are limestones, the uppermost two are overlain by sandstones that are shaly at the base and could have acted as aquatards, and each favored interval may have been exposed to erosion or reworking during a depositional hiatus marking a minor marine regression.

Less extensive deposits have been found in the Karnak Member of the Ste. Genevieve, "lower Rosiclare ore" and in the upper part of the Levias Member of the Renault. Notable

features of the bedded deposits listed by Heyl (1983) and discussed in more detail by Grogan and Bradbury (1968) are: 1) the feeding faults or fractures, 2) solution thinning of the limestone host rock toward the center of the ore bodies and slumping of the overlying sandstone roof rocks, 3) solution V's (or Y's when considered in association with the feeding fractures), 4) the shale cap with very irregular, mostly massive "vein ore" beneath the cap and 5) the observed zonation of sphalerite away from the main fracture.

Brecke (1962, 1983) describes local areas of intense brecciation, pipe-like in form, one per ore body, and of large dimensions. "The horizontal dimensions may be 200 to 300 feet (61 to 91.5 m) in diameter and a vertical dimension in excess of 500 feet (152 m). The pipes cross several stratigraphic units, the lower limits are unknown." One such pipe was mineralized from the top of the Cypress Sandstone to top of the St. Louis Limestone. Brecke's breccia pipe concept has mineralizing fluids rising from depth, through the breccia pipes, and migrating up dip to the southwest.

#### Hicks Dome Mineralization

The nature of mineralization at Hicks Dome is known from outcrop studies, trenching, and from a test well drilled near the center of the dome (Brown et al., 1954). Centrally located outcrops of breccia have minor amounts of barite (most common), fluorite and, in some instances, traces of sphalerite and galena. A rare, light green variety of fluorite was obtained from the Rose Mine (fig. 9) on the southeast flank of the dome within the central area of Devonian carbonate bedrock. Rare mineral species encountered at or near the surface from breccia bodies include a mineral first reported as monazite (Trace, 1960) but later identified as brockite, a calcium thorium phosphate (A.V. Heyl, pers. comm.); florencite, a cerium aluminum phosphate (Trace, 1960) and rare bertrandite, a beryllium silicate (Baxter and Bradbury, 1980).

Dark purple fluorite, galena, sphalerite, and barite are associated with thorium and rare earth elements in breccia cuttings from the test well and occur with abnormally high amounts of beryllium and niobium. Heyl (1983) describes the lowermost 488 m (1,600 ft) of the Hamp Well as "composed of a strongly mineralized breccia (largely micro-breccia) with some alkalic igneous rock fragments and a matrix of purple fluorite, barite, ferroan dolomite, silica, calcite, serpentine, chlorite, titanite, biotite,

magnetite, ilmenite, leucosene, marcasite, fluorapatite, garnet, perovskite, sphalerite, galena, brockite, florencite, bertrandite, pyrite, brookite, rutile, and xenotime". Heyl points out that these minerals, "plus fragments of felsic syenites and peridotite penetrated in the well are typical of mantle derived igneous rocks" and suggest that the large probable pluton, that lifted the Tolu Arch, "was a felsic syenite intruded by ultramafic dikes and kimberlites from the mantle".

#### Constraints on Origin of Mineralizing Fluids

Studies carried out on fluid inclusions in fluorite and associated minerals from the bedded deposits of the Cave in Rock District indicate that most of the fluorite there was deposited within a temperature range of 140°-150° C (Cunningham and Heyl, 1980; Richardson and Pinckney, 1984). Chemical analyses and stable isotope data from the inclusion fluids have led investigators to favor basinal brines as the mineralizing fluids (Hall and Friedman, 1963; Ruiz et al, 1988). However, Hall and Friedman suggest that a magmatic component was added from Hicks Dome igneous activity, whereas Ruiz et al postulate either a magmatic component or a deep circulation into either older sediments or basement rocks. Both studies conclude, and it is generally agreed, that basin brine alone is not an adequate source of fluorine.

Much of the fluorite from the Hamp well breccia at Hicks Dome is a fine-grained, nearly opaque, dark purple variety that is intimately associated with rare earths and beryllium minerals (Brown et al, 1954; Hall and Heyl, 1968; Bradbury and Baxter, in press). However, coarse-grained, translucent fluorite, similar to that found in the vein and replacement deposits of the mining district are also found at Hicks Dome; in the upper part of the Hamp well, at the Rose mine and in minor occurrences at other scattered locales near Hicks Dome. This light colored fluorite does not show the association with exotic elements and partial analyses of fluid inclusions from rare, light-green fluorite from the Rose Mine (Hall and Friedman, 1963) revealed a soluble salt content and deuterium concentration similar to fluid inclusion data from the Cave in Rock District.

Fluid inclusion homogenization temperatures of 175° C, were obtained with light-colored fluorite and barite from near the top of the subsurface breccia at Hicks Dome, at a depth of about 450 m (1475 ft) in the Hamp hole. Barite from a depth of 713 m (2338 ft) in the hole gave a temperature of 220°-270° C. (Cunningham and Heyl, 1980). Thus, the

light-colored fluorite at Hicks Dome appears to have formed under conditions that were transitional between those of the Cave in Rock fluorite and the more intense conditions of mineralization at Hicks Dome, but more like those of the Cave in Rock fluorite.

Trace elements studies of Hall and Heyl (1968) showed that the silver content of galena progressively decreased from 1000 ppm at Hicks Dome to 20 ppm in Kentucky. They also report that galena from Hicks Dome is less radiogenic than that elsewhere in the district, with  $^{206}\text{Pb}/^{204}\text{Pb}$  progressively increasing outward. This evidence appears to indicate a relationship between Hicks Dome igneous activity and the fluorite, zinc, lead and barite deposits in the major orebodies of the Illinois-Kentucky district. Interaction between basinal brines and solutions from a deep magmatic source, appears to provide the most suitable mineralizing fluid for mineral deposition at Hicks Dome and in the Cave in Rock District.

#### **Age of Mineralization**

The age of mineralization in the Illinois-Kentucky Fluorspar District is uncertain. On stratigraphic evidence alone, it is post-Pennsylvanian and pre-Pleistocene. On the basis of radiometric dating of the ultramafic igneous intrusions with which the mineralization is often considered to be connected, it is at least as young as Permian, the age of ultramafic intrusions in the Rosiclare district, the Grant carbonatitic breccia (Zartman et al, 1967) and, by inference, the age of the Tolu Arch. The ages of other tectonic events, such as the igneous activity and intense brecciation at Hicks Dome and the extensive northeast-trending block faulting that provided channelways for the mineralizing fluids and loci for mineral deposition, must also be considered.

If the fluorine content of basinal brines is insufficient to account for the amount of fluorite deposited, the relationship between possible post-early Permian igneous activity at Hicks Dome and the fluorspar deposits of the greater Illinois-Kentucky district is important. Rough zonation of the silver content of galena and the isotopic ratios of lead in galena suggests that some sort of relationship exists. The strontium isotope data of Ruiz et al (1988) is indicative of igneous activity at Hicks Dome as recently as 200 Ma (early Mesozoic, Jurassic-Triassic).

Mineralized northeast-southwest trending faults of the fluorspar district offset the axis of the Tolu Arch, cut and offset early Permian-aged, northwest-southeast trending, ultramafic dikes and are therefore younger

than those features. This block faulting was perhaps related to collapse of the Tolu Arch at the time, or shortly after, the explosive events at Hicks Dome.

#### **STOP DESCRIPTIONS**

##### **Stop 1 - Junction, Illinois Routes 145 and 146, near Dixon Springs State Park. LUSK CREEK FAULT ZONE, DIXON SPRINGS GRABEN, STRUCTURE**

**Location:** Cen. of N. line, NE, SW, SW, sec. 16, T. 13 S., R. 5 E., Glendale 7.5-minute Quadrangle, Pope County, IL just east of the intersection of IL Rts. 145 and 146, at Dixon Springs State Park.

**Stop Leaders:** W. John Nelson, James C. Bradbury and James W. Baxter (Illinois State Geological Survey).

The Lusk Creek Fault Zone (see handout) is a complex structure that extends from the northeast corner of Pope County to the Cache Valley in Massac County, Illinois, where it is obscured by embayment sediments. The Lusk Creek Fault Zone apparently marks the northwestern edge of the Reelfoot Rift, which formed in late Precambrian or early Cambrian and was at times reactivated after the Pennsylvanian Period. It forms the northwest boundary of the Dixon Springs Graben, one of two major grabens in the Illinois portion of the Illinois-Kentucky Fluorspar District. The Lusk Creek Fault Zone is a southwestward extension of, and shares structural style with (Nelson, 1987 and Stop 4, this guidebook), the Rough Creek-Shawneetown Fault System. The latter marks the northernmost extent of the Rough Creek Graben, an eastward extension of the New Madrid Rift System from southeastern Illinois unto Kentucky (Nelson and Lumm, 1987). The Lusk Creek Fault Zone, like the Rough Creek-Shawneetown Fault System, at least locally displays sheared wedges of much older rocks trapped in the fault zone, suggesting that there have been two separate episodes of dip-slip faulting (Nelson, 1986). Recent ISGS mapping has revealed strata as old as Ste. Genevieve (late Valmeyeran) trapped between upper Chester and/or Pennsylvanian strata that form the hanging and footwalls of the fault zone (Joseph A. Devera and W. John Nelson, pers. comm., 1988). The Lusk Creek Fault Zone marks the westernmost extent of mineralization of any note in the Illinois portion of the fluorspar district. Among these long inactive areas of known mineralization (Weller et al, 1952), are mine sites with picturesque placenames such as Rock Candy Mountain, Lost 40, and Clay Diggings, all shown on figure 3.

**STOP 2 - Clay Diggings Mine**  
**LUSK CREEK FAULT ZONE, ABANDONED**  
**FLUORSPAR MINE, OLD LIMESTONE**  
**QUARRY, CLAY DIGGINGS.**

**Location:** NW NE, SE, sec. 16, T. 12 S., R. 6 E., Pope County, IL, gated access road, approximately 950 feet northwest of bridge over Lusk Creek.

**Stop Leaders:** W. John Nelson and James W. Baxter (Illinois State Geological Survey).

Abandoned Clay Diggings (see handout) and vicinity have afforded sites for limestone quarrying, clay mining, and several shafts sunk in the Lusk Creek Fault Zone following narrow veins with fluorspar, galena, and sphalerite. Production from the veins is believed to have been small. A limestone quarry was worked in the 1930's. Bluish to white halloysite clay is reported to have been mined in the 1860's, probably for use in making ceramic articles such as pottery or stoneware. Fragments of clay were at one time observable on waste dumps (Weller et al, 1952).

The Lusk Creek Fault Zone is about 140 m (450 feet) wide at the Clay Diggings and occupied mainly by quartzitic sandstone of Pennsylvanian age and Kinkaid Limestone. The limestone exposed in the old quarry is unusually thick and massive for the Kinkaid and has been referred to the Ste. Genevieve by some geologists (W. John Nelson, pers. comm., 1988), a wedge of old rock trapped well up in the fault zone. The total displacement along the Lusk Creek Fault Zone at Clay Diggings, disregarding the slice that is possibly Ste. Genevieve, is probably 500 feet or more with downthrow to the southeast. The presence of Ste. Genevieve would indicate differential movement in excess of 500 m (1500 feet) and recurrent faulting that cut off and left the Ste. Genevieve high in the fault zone.

Calcite, fluorite, galena and sphalerite mineralization is known at Clay Diggings and with the halloysite were prospected and worked by a series of shafts up to 27 m (84 feet deep). At a depth of 13 m (40 feet), a vein dipping steeply to the southeast consisted of about 1 m (3.5-4.0 feet) of fluorspar on the northwest and 2.5 m (8 feet) of halloysite on the southeast.

Two other mines operated in past years within the Lusk Creek Fault Zone. The Lost 40 property, located about 3.7 km (2.3 miles) to the northeast of here was prospected for many years with mining being attempted from time to time. The Lost 40 Mine, opened in 1940, was the most ambitious effort undertaken. Worked to a depth of about 30 m (100 ft), the deposit followed a vein between walls that consist of quartzitic sandstone and clay,

strata of Upper Chesterian and Caseyville age. Some of the ore was of fairly high purity, much was more or less siliceous. At one time galena was fairly abundant in exposures on the property, but only trace amounts of sphalerite were reported (Weller et al, 1952).

The Rock Candy Mountain Mine is located an additional 3.8 km (2.5 miles) northeast of the Lost Forty Mine, within the structurally complex system of faults at the junction of the Shawneetown Fault Zone, the Lusk Creek Fault Zone, and the Herod Fault Zone. Rocks are extremely broken up into narrow segments that are complexly displaced with respect to each other. The Rock Candy Mine is one of but a few that have produced fluorspar from a vein with Pennsylvanian sandstone in the wall. The ore taken from this mine was high in silica and low in galena and sphalerite (Weller et al, 1952).

**Stop 3 - Hicks Dome and Vicinity**  
**HICKS DOME, SHATTER BRECCIAS, VENT**  
**BRECCIAS, CARBONATITIC BRECCIAS**

**Location:** Centered in Sec. 30, T. 11 S., R. 8 E., Karbers Ridge and Herod 7.5-minute Quadrangles, Hardin County, IL.

**Stop Leaders:** Joe Porter (Carroll and Associates) and James C. Bradbury and James W. Baxter (Illinois State Geological Survey).

Hicks Dome is an exposed structural high approximately 13 km (8 mi) wide in a northwest-southeast direction and truncated on the southeast side by northeast-trending faults. The configuration of the dome is best shown by the central portion where outward-dipping strata describe an oval pattern with the long axis in a northwest-southeast direction (fig. 9). The definitive topographic feature identifiable as Hicks Dome, is a central hill about 1200 m (3960 feet) wide. The hill, at the apex of the dome, is underlain by Lower and Middle Devonian limestone and chert. A topographically lower belt of New Albany Shale surrounds the central area and is succeeded by an encircling ridge of lower Valmeyeran (middle Mississippian, Lower Carboniferous) Fort Payne Formation, a succession of siliceous limestone and chert. The Fort Payne is overlain by a thick sequence of Valmeyeran limestones.

Hicks Dome is cut by numerous bodies of breccia and one ultramafic dike. The dike is exposed as a micaceous residuum in an old prospect pit on the east side of the dome. A shallow exploration trench a short distance west of the pit intersected a 30 cm (12 in) wide dike with a N57°E strike. The residuum contains abundant phlogopite flakes up to 1 cm across, scattered apatite crystals up to 2 mm in length, and minor brown hornblende



collar of the Hamp hole, the discovery well of the breccia under Hicks Dome, lies 60 m (200 ft) east of the exploration trench. The Hamp well breccia, a vent breccia, is described in the section on Intrusive Rocks. Some breccia bodies that will be examined (see handout) are described here.

**Substop A.** The Pankey Breccia underlies a knob covered by abundant blocks of siliceous breccia near the northeast edge of the central Devonian area. The breccia is intensely silicified, analyzing more than 90 percent silica. Individual blocks may be composed of either hard dense breccia or of porous breccia in which rock fragments appear to be welded together by a fine-grained, drusy quartz. Rather abundant barite can be found in the breccia near the south end of the exposure area. The original clast lithologies in the Pankey Breccia cannot be satisfactorily distinguished in hand specimen because of the intense silicification. In thin section, remnant textures suggest a mixture of Lower Devonian Clear Creek Chert and Middle Devonian Dutch Creek and Grand Tower Limestones. Because of this mixing of lithologies, the Pankey is classified as a vent breccia.

**Substop B.** Shatter breccia dikes in the Fort Payne are strongly silicified and generally more resistant to erosion than the country rock. Where exposed the larger ones stand as much as 1 m (3 feet) or more above ground surface. All are composed of clasts of the immediate wall rock in a matrix of finely comminuted wall rock and secondary quartz. This stop will provide the opportunity to see one of these dikes.

**Substop C.** Shatter breccias in the New Albany Shale, like those in the Fort Payne, consist of clasts of wall rock and a matrix containing finely comminuted wall rock. Unlike the Fort Payne dikes, some of the shale dikes contain calcite rather than quartz as a cementing material. The breccia dike at this location, exposed in a small stream just north of a bridge on the south side of Hicks Dome, is essentially a shale breccia cemented by coarse calcite and is sparingly mineralized with barite.

#### Stop 4 - Horseshoe Quarry

##### **HORSESHOE UPHEAVAL, ROUGH CREEK-SHAWNEETOWN FAULT SYSTEM NEW ALBANY SHALE FT. PAYNE CHERT, STRUCTURAL STYLE**

**Location:** SW, NW, NE, Sec. 36, T.9S., R.7E.; Rudement and Equality 7.5-minute Quadrangles, Saline County, IL. (fig 10.)

**Stop Leaders:** W. John Nelson (Illinois State Geological Survey) and Mark P. Fischer (University of Tennessee, Knoxville).

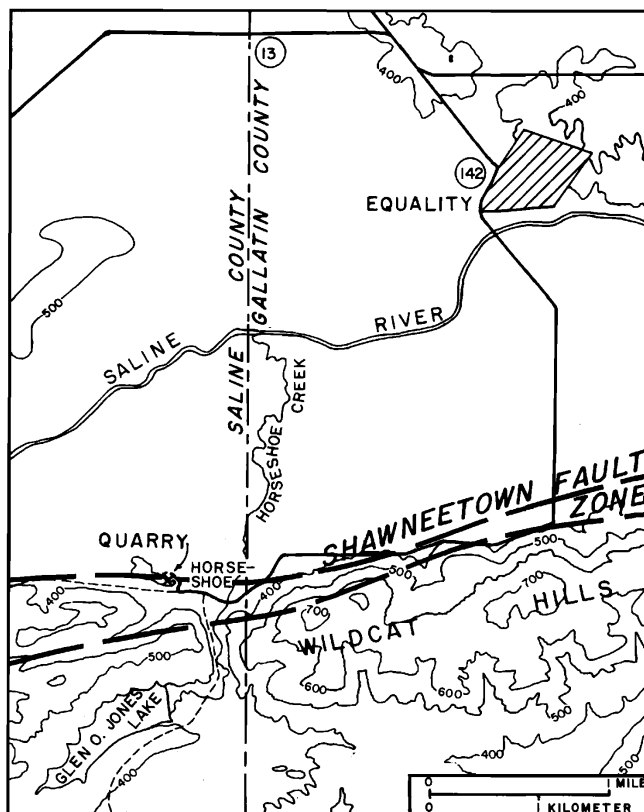


FIGURE 10 Horseshoe Quarry and environs. From Nelson (1987, fig. 2).

Steeply tilted, deformed lower Mississippian and uppermost Devonian strata exposed in this quarry are upthrown approximately 1050 m (3500 ft) within the Shawneetown Fault Zone (fig. 11). This exposure reveals the structural style of one of the greatest fault systems in the central U.S. The Shawneetown Fault Zone is the western portion of the Rough Creek-Shawneetown Fault System, which extends 200 km (125 miles) from a point in Pope County, Illinois, 21 km (13 miles) southwest of Horseshoe, to Grayson County Kentucky. Its history is long and complex (Nelson, 1987; also see section on tectonic history in this guidebook). The Rough Creek-Shawneetown Fault System, as exposed and based on stratigraphic evidence, developed in post-Pennsylvanian to pre-late Cretaceous time along a major zone of crustal weakness that has persisted from the late-Precambrian time to the present. The ancestral Rough Creek-Shawneetown Fault System formed the northern boundary of the Rough Creek Graben that, along with the Reelfoot Rift, constitutes the New Madrid Rift System (figs. 3, 4). This ancient rift complex is interpreted as an aulacogen produced by the breakup of a super continent near the end of Precambrian time (Braile et al, 1984).

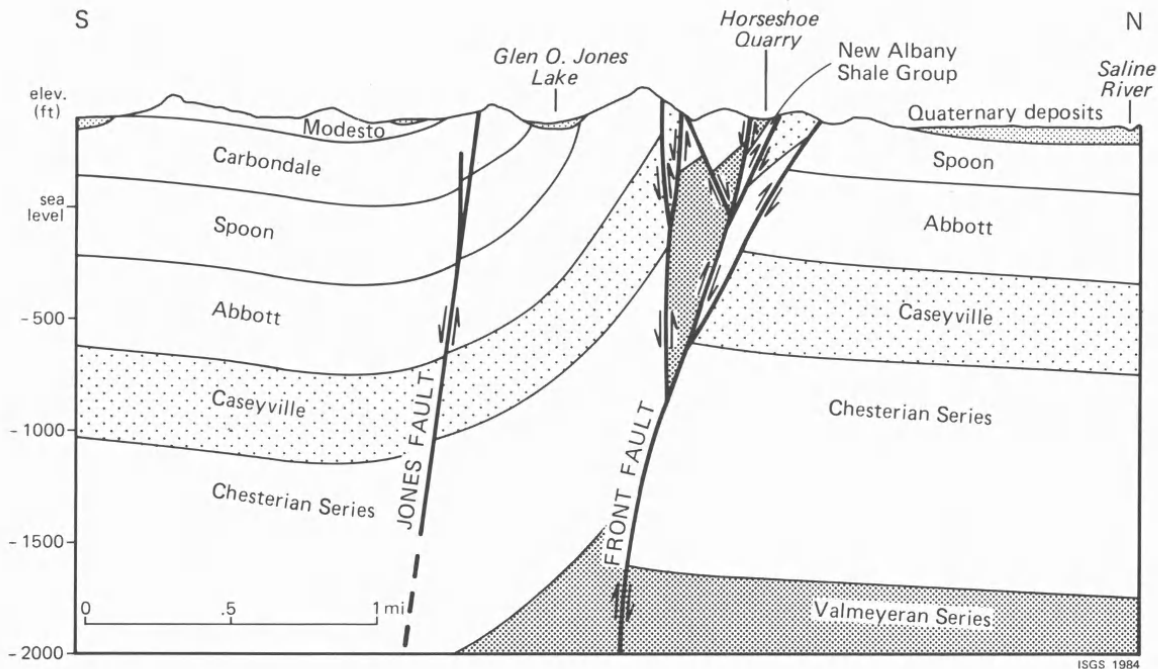


FIGURE 11 Cross section of Rough Creek-Shawneetown Fault System through Horseshoe Quarry. From Nelson (1987).

The Rough Creek-Shawneetown Fault System was reactivated from time to time throughout the Paleozoic, but it is likely that the observable faults developed in Permian time, coincident with the Appalachian orogeny (Nelson and Lumm, 1984). Conflicting ideas to explain the origin of the the Rough Creek-Shawneetown Fault Zone include: 1) strike-slip faulting (Heyl, 1972), and 2) thrusting movements related to horizontal compression from the south (Weller 1940; Smith and Palmer, 1981). Nelson (1987) states that the major movements were dip-slip and that they were related to reactivation of the rift. The peculiar structure of the fault zone requires at least two separate episodes of dip-slip faulting (fig. 12). Narrow slivers of old rock trapped between younger rock are a characteristic feature of the Rough Creek-Shawneetown Fault System. The Horseshoe Quarry provides a spectacular example; the rocks seen here are the oldest found in the fault zone.

The stone that was quarried at Horseshoe is deeply weathered chert of the Fort Payne Formation of early Valmeyeran (middle Mississippian, Lower Carboniferous) age. The Fort Payne Formation is composed of thin-bedded, very silty, highly silicified dark limestone interbedded with calcareous siltstone and dark gray siliceous shale. The Fort Payne represents an early depositional episode in the filling of a relatively deep starved basin that existed in the southern

portion of the Illinois Basin during early Mississippian time. The Fort Payne overlies the Springville shale, distal bottomset beds of The Borden Delta (Lineback, 1966), a southwestern portion of the Catskill-Pocono deltaic complex that prograded westward in during late Devonian and early to middle Mississippian time. The Springville Shale was visible at one time in the quarry. The New Albany Shale, part of the extensive body of Upper Devonian-Lower Mississippian black Shale (Chattanooga, Ohio, and Sunbury) can be seen on the north wall of a narrow trench that cuts through the hill just north of the Fort Payne exposures.

Fischer (1987,1988) has mapped Horseshoe Quarry structures in detail, recognizing two structural domains within the Fort Payne exposures. In the unfolded domain, which covers most of the quarry, bedding attitudes average  $N87^{\circ}W/65^{\circ}S.$ , close to the attitude of the adjacent major faults. In the folded domain, exposed in the northeastern part of the quarry, two anticline-syncline pairs having amplitudes of 1.5-5 m (5-17 feet) are present, along with numerous smaller parasitic folds. Both flexural slip and flexural flow folds are involved. The mean plunge and trend of the fold axes is  $58^{\circ}N. 45^{\circ}W.$  This fold geometry indicates that the folded domain was subjected to oblique, left lateral/compressional stress. Just how this fits into the regional stress regimes is uncertain.

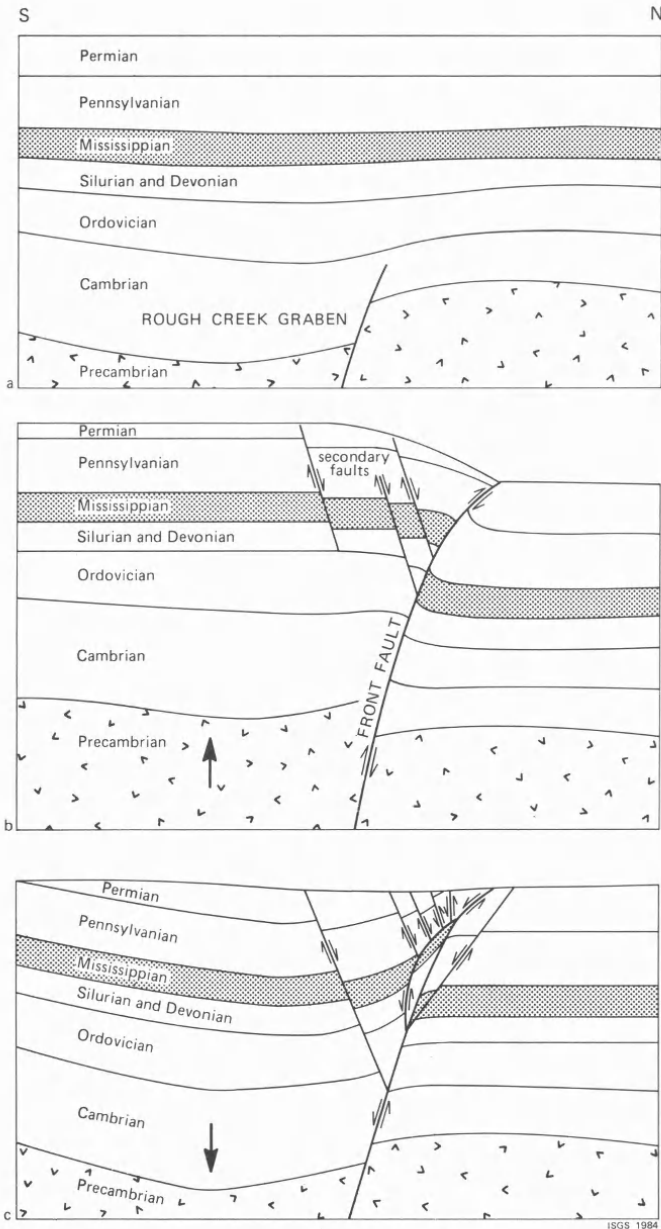


FIGURE 12 Proposed origin of the Rough Creek-Shawneetown Fault System and sequence of events. From Nelson (1987, fig. 4).

Nelson (1987) summarizes the events at Horseshoe and the relationships to adjacent structure as follows:

"The structure at Horseshoe testifies to recurrent post-Pennsylvanian movement on the Rough Creek-Shawneetown Fault System. First, the southern block was raised approximately 3,500 ft (2,000 m), placing New Albany Shale of the southern block against middle Pennsylvanian rocks of the northern block. Then the south-southern block began to drop back down, shearing off a wedge of Fort

Payne-New Albany within the fault zone. Other slices of rock were cut off in the same way. The major part of the southern block slid down past the isolated fault slivers, which were jammed in place. At the same time, strong drag on the downward-slipping block rotated the fault slices and formed the north limb of the Eagle Valley Syncline. The southern block eventually returned to nearly its origin position; coal beds along the axis of the Eagle Valley Syncline lie at nearly the same elevation as the same coals north of the Shawneetown Fault Zone. The northern block was relatively passive throughout all this activity. Fault slices such as the one at Horseshoe remain more than 3,000 ft (1,000 m) above their starting position."

**Stop - 5 Rigsby and Barnard Quarry**  
**STE. GENEVIEVE LIMESTONE, AUX VASES SANDSTONE, RENAULT LIMESTONE, YANKEETOWN SHALE, DOWNEYS BLUFF LIMESTONE, BETHEL SANDSTONE**

**Location:** Center north line, sec 12, T. 12 S., R. 9 E., Cave in Rock 7.5-minute Quadrangle, Hardin County, Illinois, 2.4 km (1.5 mi) north of Cave in Rock.

**Stop Leader:** James W. Baxter (Illinois State Geological Survey).

This quarry affords the opportunity to examine that part of the stratigraphic section that serves as host rock for the bedding-replacement deposits of the Cave in Rock District, 3.2 km (2 miles) to the northwest of the quarry. An almost continuous section from near the base of the Ste. Genevieve to the Bethel Sandstone is exposed (see handout). Minor veinlets of fluorspar are occasionally encountered in the quarry.

A lower portion of the quarry has conspicuous layers of massive, light-gray oolite of the Fredonia Member of the Ste. Genevieve. The Spar Mountain Sandstone, the lowermost level of major replacement in the Cave in Rock District has not been definitely identified in the quarry ledges, but may be represented by an inconspicuous, somewhat sandy, 70 cm (28 inch) bed approximately 14 m (46 feet) below the base of the Aux Vases.

The Aux Vases Sandstone, overlying the Ste. Genevieve, is prominent high on the main, upper level, quarry face. The basal shale of the Aux Vases, that presumably served as an aquatard promoting mineral deposition is not as conspicuous as it is at some localities in the Cave in Rock District.

The Renault, Yankeetown, and Downeys Bluff, are exposed with varying degrees of completeness in the sloping hillside above the

quarry. Bethel Sandstone caps the hill. The uppermost level of replacement deposits, commonly referred to as "Bethel ore", is hosted by the Downeys Bluff.

#### **Stop - 6 Cave in Rock State Park**

##### **CAVE IN ROCK: FERRY, CAVERN, PARK, VILLAGE, ROCK SHOPS**

**Location:** NW, SW, SE, sec. 13, T. 12S, R. 9E, Cave in Rock 7.5-minute Quadrangle, Hardin County, IL.

**Stop Leader:** James W. Baxter (Illinois State Geological Survey).

Transportation between the Illinois and Kentucky portions of the Illinois-Kentucky Fluorspar District has been facilitated by use of the Cave in Rock Ferry, at least since 1909. The first ferry with motorized propulsion was used in 1913. Early river crossings carried one mule-drawn wagon; the mules, unhitched from the wagon and tied behind a skiff towed by the ferry flat, swam across the river. Use of the Cave in Rock ferry shortens the distance to many points to the south, saving 22.4 km (13.9 miles) going from Cave in Rock to Paducah KY.

The village of Cave in Rock was settled late in the 18th century. Early settlers of this region came from the eastern seaboard and nearby states of Kentucky and Tennessee to till the fertile lands of extreme southern Illinois. Germans, English, Irish, and colonial Americans came down the Ohio, past the frontier settlement at Shawneetown. Old Shawneetown, located 32 km (20 mile) north of Cave in Rock on the Ohio River, was first established in 1810 as a Shawnee Indian trading post and during the period of westward migration became a center of commerce boasting the first bank in the Illinois territory. It is said that the directors of the bank at one time, in their wisdom, refused a loan for a commercial development near Fort Chicago, on the shores of Lake Michigan, because it "was too far from Shawneetown to ever amount to anything".

The area of Illinois adjacent to the Ohio River is referred to as "Egypt" or "Little Egypt" although these names were probably originally applied only to the southernmost tier of counties underlain by Mississippi Embayment sediments. That area probably reminded travelers of the fertile alluvial plain and delta of the Nile and inspired such southern Illinois placenames as Cairo, Thebes, Karnak, and Dongola. Another apocryphal explanation lies in an account of late spring and early fall frosts to the north, which shortened the growing season and forced people to come south for corn and wheat, "going down to Egypt" as did the biblical sons of Jacob.

Cave in Rock State Park was opened in 1929 and is one of many within the Illinois state park system. Trees within the the park include, catalpa, locust, shag hickory, oak, ash, sycamore, cypress, sugar maple, and elm. Wide-spread karst topography has developed in the Cave in Rock area, on limestone strata of the Valmeyeran (middle Mississippian, Lower Carboniferous) Series. The soil is partly loess-derived. The main attraction within the park is Cave in Rock; a small, natural, limestone cavern in the bluff of the Ohio. Some recent improvements on the grounds that serve to make this attraction more accessible to the public, include the construction of an eight-unit lodge and restaurant.

Cave in Rock, the cavern, has a long and colorful history. Position, accessibility, and ease of defense has made this small cavern ideal for a long succession of illicit or at best questionable enterprises "when the west was young". First described by the French in the early 18th century, "Caverne dans le Roc" became a hideout for outlaw gangs and river pirates just after the end of the Revolutionary War. Riverboats traveling down the Ohio became easy prey. At other times the cave harbored such other nefarious establishments as Samuel Mason's "Liquor Vault and House of Entertainment" and a gang of counterfeiters occupied the cave for a period prior to 1831. After the undesirable elements or "river rats" were removed, Cave in Rock served as a shelter for westward-bound pioneers traveling along the Ohio and, during the mid 19th century, as a storage place for potatoes awaiting shipment downriver.

The limestone cavern is developed in the St. Louis Limestone within a portion of that formation transitional to the overlying Ste. Genevieve Limestone. Within the transition, light colored, cherty, fine-grained limestone and fine- to medium-grained bryozoan limestone are interbedded with oolitic and/or pseudo-oolitic lithologies typical of the Ste. Genevieve. Ample time will be allowed to visit the cavern and time will be afforded for a short stop in Cave in Rock to visit a local main street rock shop and purchase specimens.

#### **Stop 7 - Pigmy Mine Area**

##### **TABB FAULT ZONE, ABANDONED UNDERGROUND FLUORSPAR MINE, OLD BARITE OPEN CUT, STRIKE-SLIP MOVEMENT ON FAULTS.**

**Location:** Carter coordinate section 10-1-17, Fredonia 7.5-minute Quadrangle, just south of Mexico, Crittenden County, KY.

**Stop Leader:** Warren Anderson, (Kentucky Geological Survey)



FIGURE 13 Tabb Fault Zone exposed in Pigmy Mine area open cut, Hardinsburg Sandstone on right and St. Louis Limestone on left, looking northwest, 1980 (courtesy of Kentucky Geological Survey).

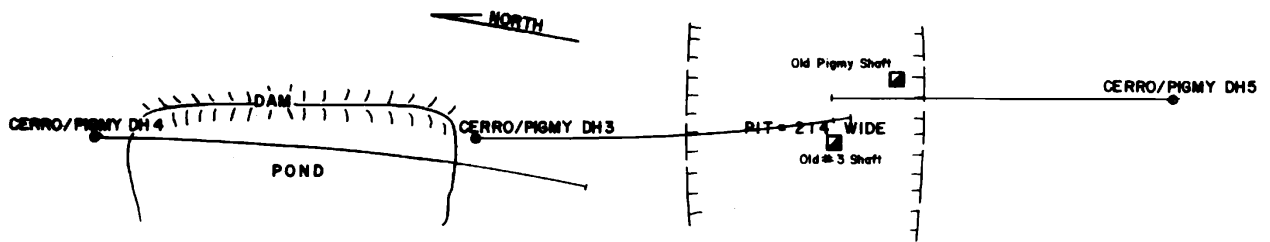
The following observations on the history and geological conditions at the Pigmy mine and open cut are largely abstracted from a report on the barite deposits of Kentucky (Anderson et al, 1982).

The name "Pigmy Mine" refers to a series of shafts and open cuts that are present for about 610 m (2,000 feet) along the Tabb Fault Zone at the southern boundary of the Mexico Graben. All the mine workings are abandoned and caved; many of the shafts were destroyed during open-cut mining operations in the 1960's. The Pigmy Mine has probably produced more than 136,000 metric (150,000 short) tons of fluorspar concentrate since the early 1900's. Most of the mining was for vein deposits from shafts as deep as 100 m (325 feet). A small but significant recovery of lead was also accomplished.

Barite was not common in the underground ore; overall barite content from underground was less than 5 percent. From 1959 to 1964, about 13,600 metric (15,000 short) tons of barite were produced from an open cut by the J. Willis Crider Fluorspar Company (fig. 13). Several thousand tons of metallurgical-grade fluorspar were also produced using a log washer at the mine site and a jig mill at

nearby Mexico, Kentucky. Mining was done by drag line along an almost continuous open cut running for approximately 460 m (1500 feet) along the Tabb Fault Zone. The ore occurred as a residuum or "gravel" deposit that consisted of bladed, white barite; clear, brown, and purple fluorite; chert and sandstone fragments; and red clay. Barite made up 20 to 30 percent of the total residuum, but was more abundant near the surface; fluorite became more abundant with depth.

The Tabb Fault Zone is here about 60 to 90 m (200 to 300 feet) wide and consists of a series of steeply dipping subparallel normal faults that trend about N75°E. In some places the total vertical displacement of about 366 m (1200 feet) is distributed among only 2 or 3 faults. At other places, the displacement is spread across the system, more or less evenly, among numerous closely spaced faults. Locally in the open cut, there are three east northeast-trending faults. The hanging wall of the northernmost bounding fault has the Menard Limestone at the surface and against the Hardinsburg Sandstone, indicating about 100-120 m (350-400 feet) of vertical displacement. The middle fault has Hardinsburg Sandstone



PLAN VIEW

CROSS SECTION

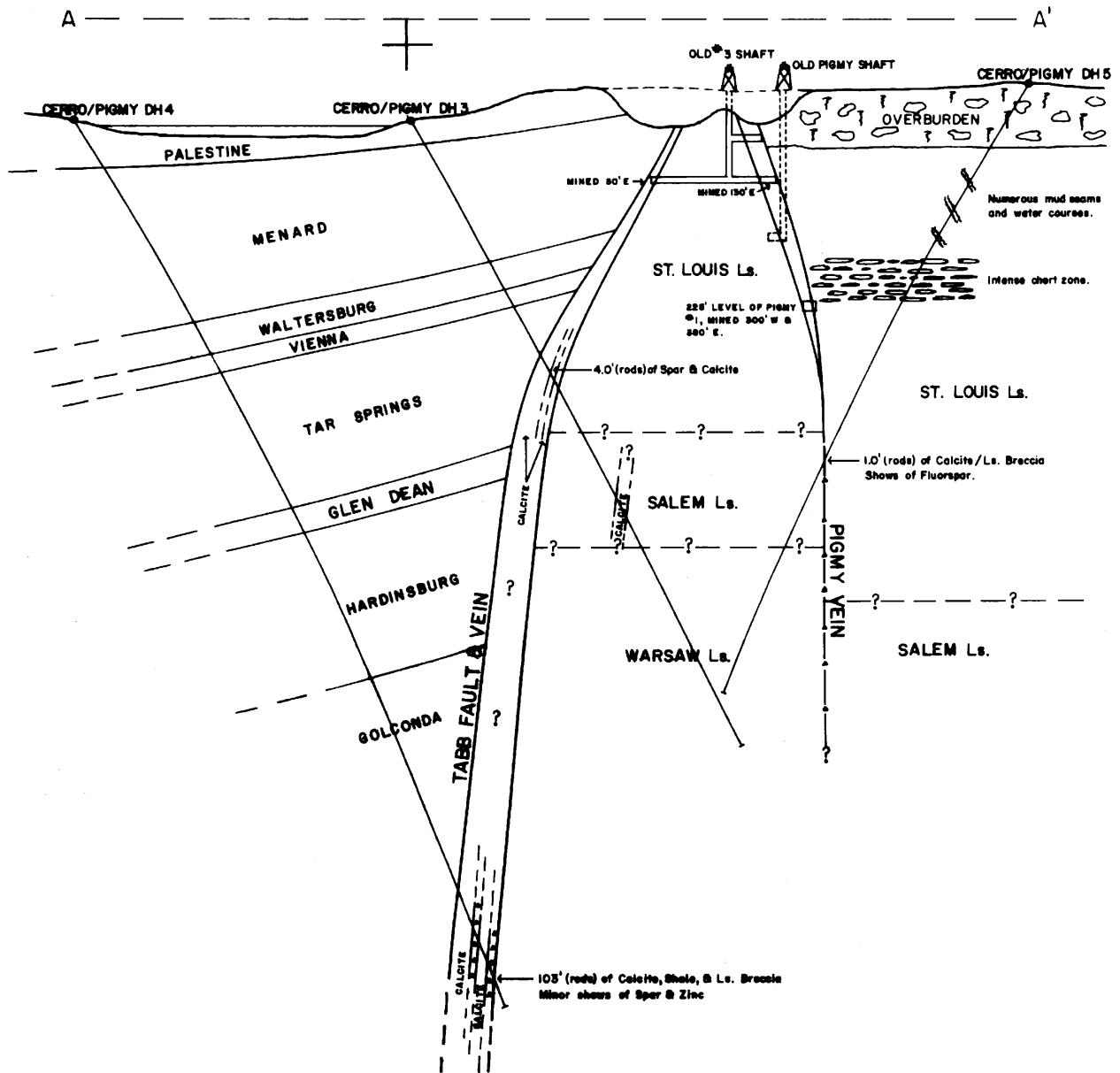


FIGURE 14 Plan view and cross section of Pigmy Mine (Courtesy of F. Boyce Moodie III).

against an upper portion of the St. Louis, as much as 245-275 m (800-900 feet) vertical displacement. The southernmost fault has St. Louis Limestone in both walls. In these cases the north side of each fault is down, indicating that the fault system is a series of step faults. However, core drilling under the open cut in the 1970's suggests that at least locally, where the fault zone consists essentially of two bounding faults, the south-bounding fault is downthrown 30 m (100 feet) or less to the south making a horst of the central slice of St. Louis Limestone (fig. 14).

The Pigmy open cut provides an excellent opportunity to examine the structural style of a major mineralized fault zone with step faults marking the southeast side of a fluorspar district graben structure. Well developed horizontal slickensides provide evidence of strike-slip movement on the faults. The relative importance of dip-slip vs strike-slip for some of the structures in the district are a matter of some controversy.

**Stop 8 - Hastie Brothers Fluorspar and Trucking Company  
SPAR MOUNTAIN, BEDDED FLUORSPAR,  
ROSICLARE SANDSTONE, ROSICLARE  
ORE.**

**Location:** NE, NE, sec. 4, T. 12 S. R. 9 E, Saline Mines 7.5-minute Quadrangle, 6 km (4 mi) northwest of Cave in Rock, Hardin County, IL.

**Stop Leaders:** Robert Hastie (Hastie Bros. Mining and Trucking Company), James C. Bradbury and James W. Baxter (Illinois State Geological Survey).

Earliest mining in the Illinois-Kentucky Fluorspar Mining District probably occurred around Lead Hill, a small isolated hill approximately 0.8 km (0.5 mi) west of this site, perhaps as early as 1818. Although there was some prospecting and mining carried out at Lead Hill just after that time, there was little real development of those properties until just before and during U. S. involvement in World War I. In 1934, the Lead Hill group of mines was acquired by Fluorspar Products Company, and most of the production recorded for the group came after that time.

War-time requirements also focused attention on some moderate-sized ore bodies along the south facing slopes of Spar Mountain. Mining by the Spar Mountain Company began in 1919 and continued until 1925 when succeeded by the Benzon Fluorspar Company which continued operations until 1939. Mining at Spar Mountain was by means of adits driven into a sandstone-capped bluff, shallow

shafts, or by open-pit methods where thickness of overburden allowed. In 1930, this group of mines produced 25,995 short tons of crude ore and was the largest shipper of fluorspar in the U.S. (Weller et al, 1952). Mineralized trends in the Spar Mountain area are principally NE and NW. The ore occurs in nearly flat-lying replacement orebodies extending laterally from narrow, vertical fissure veins. The ore is typically banded, parallel to bedding. Banded or "coontail ore" shows multiple banding of coarse-grained fluorite alternating with fine-grained fluorite mixed with unreplaced rock. Massive ore, such as occurs in the vertical fissure vein deposits, also may be found occupying space between the banded ore and the cap rock. The thickness of ore in the various ore bodies apparently ranged from 1 to 2.5 m (3.5 to 8 feet). Most of the ore was found in the upper 3 m (10 feet) of the Ste. Genevieve Limestone but some ore was found at lower levels, down to and including sub-Rosiclare ore. The Hastie Bros. Mining and Trucking Company, in recent years, has mined ore left in the ground or in support of pillars in abandoned underground mines. From time to time they have ore exposed in some parts of their workings. They are now also engaged in quarrying the Rosiclare Sandstone and the production of stone "chips" used as a skid-resistant aggregate for surface application in the construction of bituminous highways. In the course of this endeavor, they still occasionally uncover runs of ore. Depending on the availability of exposures, we hope to be able to see an example of replacement at or near the contact of the Ste. Genevieve Limestone and the overlying Rosiclare Sandstone. Deeper ore horizons may also be exposed.

**Stop 9 - Soward Breccia  
DIATREME, METAMICT BRECCIA,**

**Location:** NW, SE, sec. 31, T. 12 S., R. 8 E., Rosiclare 7.5-minute Quadrangle, 2.4 km (1.5 mi) west of Rosiclare, Hardin County, IL

**Stop Leaders:** Eric Livingston (Ozark-Mahoning Company), James C. Bradbury and James W. Baxter (Illinois State Geological Survey).

The Soward Breccia is exposed somewhat intermittently over an area of about 325 m<sup>2</sup> (3500 ft<sup>2</sup>) on the southeast side of a steep hill where it has been intruded into strata of late Chesterian age (Kinkaid Limestone). The breccia is composed of fragments of igneous and sedimentary rocks and minerals. Replacement by carbonate, affecting both clasts and matrix, has been extensive. No ferromagnesian minerals can be recognized. Feldspar has largely escaped replacement by

carbonate and is relatively common either as mineral fragments or in feldspathic rock fragments. In some rock fragments the feldspar shows radial extinction, a suggestion of recrystallization. Some clasts, apparently sedimentary rock fragments, show reaction rims. Lapilli have been reported in the Soward Breccia, but have not been detected in material examined at the ISGS. Although breccia bodies such as the Soward, Sparks Hill, Grant, and those in the vicinity of Herod, IL (see section on Igneous Intrusions) are often referred to as "explosive" breccias and related to events at Hicks Dome, these relatively small bodies are emplaced without major disturbance of the country rock, with no arching of strata, and usually at sites removed from faults. Since extensive carbonatization masks much of the mineralogical evidence that would aid in deciphering the emplacement history of the Soward Breccia, for the present at least, it seems best to refer to breccias of the Soward type simply as polymict breccias. At this stop we will see the Soward Breccia not only in outcrops but also in sections of core made available by Ozark-Mahoning Company.

**Stop 10 - American Metals, Inc.  
MANGANESE ORE PROCESSING, FORMER  
ALCOA FLUORSPAR ORE PROCESSING  
PLANT.**

**Location:** NE, NE, SW Sec. 5, T. 13 S., R. 8 E., Rosiclare 7.5-minute Quadrangle, in Rosiclare, Hardin County, IL

**Stop Leaders:** Robert Stone (American Metals, Inc.) and James C. Bradbury (ISGS).

American Metals, Inc. processes manganese ore imported from around the world for use in livestock feed, fertilizer, face brick and other industrial uses. In addition to manganese from such places as Australia and South Africa, we may find in the materials yard a small pile of barite from China, another example of carrying coals to Newcastle. During a short stop, Mr. Stone will give an overview of this operation. American Metals utilizes the former Alcoa fluorspar processing plant, located in the historically important Rosiclare District.

Mining of veins in the Rosiclare District began in 1842, seven years later than the first significant mining in Kentucky. Lead was the sole target of mining for about 30 years. The first fluorspar was ground and shipped in 1870. The emphasis began to shift from lead to fluorspar in the late 1870's and early 1880's. The first production of open-hearth steel in the U.S. took place in 1888, and the importance of fluorspar grew with the expansion of the steel industry.

Alcoa began operation in the Rosiclare

District when the company purchased the Fairview Fluorspar Company in 1924. Alcoa's froth flotation plant, the first in the Illinois-Kentucky Fluorspar District, was built in 1929. Alcoa was, at one time, the largest producer of finished fluorspar in the U.S. but ceased mining at Rosiclare in 1965, while continuing to mill stockpiled and custom ore until operations ceased in 1968.

The abandoned plant of the Rosiclare Lead and Fluorspar Mining Company, another former major producer in the Rosiclare area, can be seen along the road that we travel through the town of Rosiclare. Rosiclare Lead and Fluorspar Mining Company ceased operations in 1954.

**Stop 11 - Ozark-Mahoning Fluorspar Mill  
ORE PROCESSING, FLOTATION, PRODUCT  
HANDLING**

**Location:** NW, SE, NE, sec. 32, T. 12 S. R. 8 E., Rosiclare 7.5-minute Quadrangle, at Rosiclare, Hardin County, IL.

**Stop leaders:** Vic Evans and C. B. Rash (Ozark-Mahoning Company).

Much of the early history of Ozark-Mahoning activities in the Illinois-Kentucky Fluorspar District in the following brief discussion was extracted from an article in the Hardin County Independent of October 9, 1969, marking the 30th anniversary of the first crude ore processed from the W. L. Davis Mine.

The Ozark-Mahoning Company was originally formed under the name of the Mahoning Mining Company, as a wholly owned subsidiary of the Youngstown Sheet and Tube Company of Youngstown, Ohio. In 1946, the Mahoning Mining Company was separated from Youngstown Sheet and Tube and merged with the Ozark Chemical Company of Tulsa, Oklahoma. In December 1946, the Illinois-based operations were designated as the Mining Division of the Company. Ozark-Mahoning is now a subsidiary of Pennwalt Corporation.

In November 1938, construction of the concentration plant to process ore from Ozark-Mahoning's mines was started at Rosiclare, Illinois. The first exploration work conducted by Ozark-Mahoning for fluorspar had begun in December, 1936 and a large reserve of fluorspar was developed on the W. L. Davis property located north of Cave in Rock. In July 1937 the company began sinking a shaft to obtain samples for mill tests. It was determined that the fluorspar, zinc, and lead could be successfully separated by a flotation process and mill construction began. The concentration plant started operations by milling tailings which were hauled from the old Benzon mill, located near Cave in Rock (site of our Stop 7). The

first crude ore from a Mahoning mine, the W. L. Davis, was processed in August, 1939. Increased demands, during and after World War II, lead to expansions in 1942, 1946, and 1949. In 1960, the company completed the construction of a heavy-media separation plant near the mines north of Cave in Rock where they made a practice of hauling low-grade ores for upgrading to feed for the mill at Rosiclare.

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PRECAMBRIAN ROCKS AND ORE DEPOSITS IN THE ST. FRANCOIS  
MOUNTAINS, SOUTHEAST MISSOURI -- A MIDDLE PROTEROZOIC TERRANE  
OF GRANITE RING COMPLEXES AND ASSOCIATED RHYOLITES

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## INTRODUCTION

The St. Francois Mountains constitute the exposed portion of an extensive Precambrian terrane of anorogenic, granite ring complexes and associated rhyolites that underlie most of southeastern Missouri (figure 1). This igneous terrane is of regional interest not only because it is a splendid example of an unmetamorphosed, Middle Proterozoic granite-rhyolite terrane, but also because it forms the only extensive outcrops of rocks whose ages range from 1.48 to 1.45 Ga in the United States midcontinent (Bickford and others, 1981).

The Precambrian terrane has been deeply eroded and dissected, resulting in a rugged topography and the unroofing of granite. Upper Cambrian marine sedimentary rocks are in nonconformable contact with the underlying igneous rocks. Near the crest of the Ozark dome, the dominant regional structure, the Precambrian outcrops of the St. Francois Mountains represent a structural and topographic high. The granite ring complexes correspond to the deeply eroded root region of a formerly more extensive volcanic terrane comprising several calderas, cauldron subsidence structures, ring intrusions, and resurgent cauldrons with central plutons (Kisvarsanyi, 1981). These volcano-tectonic features are comparable to some of the classic ring complexes of the world, such as the "younger" granites in Nigeria and Glen Coe in Scotland.

The igneous terrane is characterized by the predominance of silicic over mafic rocks, and by alkaline-intermediate rocks (trachytes). Its distinctive ore deposits include volcanic-hosted magnetite-hematite-apatite (e.g., Iron Mountain, Pilot Knob, Pea Ridge); hypo-xenothermal vein deposits of tungsten, silver, and lead (Silver Mine district); and vein and replacement deposits of manganese.

The outcrops of the Precambrian rocks, the network of major roads in the St. Francois Mountains, and the scheduled stops are shown in figure 1. The Precambrian rock units compiled by Pratt

and others (1979) are shown in Table 1. The stops featured in this excursion guide are described in the context of self-guiding, detailed road logs amounting to a cumulative total distance of 253 km through the area (Kisvarsanyi and others, 1981).

## PRECAMBRIAN GEOLOGIC RELATIONSHIPS

The volcanic superstructure of the St. Francois terrane has been largely removed by pre-Paleozoic erosion, but as much as 1,700 m of rhyolite ash-flow tuffs are preserved locally. The thickest succession of volcanic rocks mapped in the St. Francois Mountains is in the area of the Taum Sauk caldera (Berry and Bickford, 1972).

The volcanic rocks are predominantly rhyolite ash-flow tuffs containing very high  $\text{SiO}_2$ ,  $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ,  $\text{Fe}/\text{Mg}$ , and F, and low  $\text{CaO}$ ,  $\text{MgO}$ , and  $\text{Al}_2\text{O}_3$  (Kisvarsanyi, 1972). They are characterized by perthitic alkali feldspar phenocrysts and iron-rich mafic minerals, including fayalite, ferrosilite, and ferrohastingsite. Some of the rocks are transitional to comendites but the agpaitic index is always less than one (Kisvarsanyi, 1981). Intermediate and mafic rocks are notably rare and of small volume. They are chiefly trachyte and trachyandesite (Anderson, 1970; Kisvarsanyi, 1981), and the suite is distinguished from those of calc-alkaline petrogenetic provinces of subduction zones and compressional tectonic regimes by the absence of andesites.

The granitoids in the St. Francois Mountains are classified into three distinct types distinguished by composition and mode of occurrence (Kisvarsanyi, 1981): (a) subvolcanic massifs, (b) ring intrusions, and (c) central plutons. The subvolcanic massifs are comagmatic with the rhyolites and are their intrusive equivalents. They are typical epizonal rocks having granophyric texture and perthitic alkali feldspar; biotite is the



TABLE 1 Precambrian Rock Units in the St. Francois Mountains

St. Francois Mountains Volcanic Supergroup	St. Francois Mountains Intrusive Suite	
	Hypabyssal Rocks ***	Plutonic Rocks ***
Taum Sauk Group*		
Johnson Shut-ins Rhyolite		Graniteville Granite
Taum Sauk Rhyolite		
Royal Gorge Rhyolite		
Bell Mountain Rhyolite	Buford Granite Porphyry	
Wildcat Mountain Rhyolite	Munger Granite Porphyry	
Russell Mountain Rhyolite	Carver Creek Granite Porphyry	
Lindsey Mountain Rhyolite		
Ironton Rhyolite		
Buck Mountain Shut-ins Formation		
Pond Ridge Rhyolite		
Cedar Bluff Rhyolite		
Shepherd Mountain Rhyolite		
Butler Hill Group**		
Pilot Knob Felsite		Silvermine-Knoblick Granites
Grassy Mountain Ignimbrite	Brown Mountain Rhyolite Porphyry	Slabtown-Stono Granites
Lake Killarney Formation		Butler Hill-Breadtray Granites

\* Volcanic units defined by Berry (1976).

\*\* Volcanic units defined by Sides (1976).

\*\*\* Formal names from Tolman and Robertson (1969).

characteristic mafic mineral and magnetite is ubiquitous. Near the contact with the intruded rhyolites, the subvolcanic massifs consist almost entirely of fine-grained granophyre; at depth, they grade into medium- to coarse-grained rapakivis. The Butler Hill and Breadtray Granites (Table 2) are representative of the rapakivi and granophyre phases, respectively, of the subvolcanic massifs in the St. Francois Mountains.

The ring intrusions are intermediate- to high-silica rocks whose emplacement was controlled by ring fractures related to caldera collapse and cauldron subsidence. The suite of rocks associated with the ring structures ranges from trachyandesite, through trachyte and syenite, to amphibole-biotite granite; porphyritic textures are common. The Knoblick, Slabtown, and Silvermine Granites (Table 2) are representative of the ring intrusions in the St. Francois Mountains.

The central plutons in southeast Missouri are typically high-silica, two-mica granites having distinctive accessory minerals and trace element suite (Kisvarsanyi, 1981). Their accessory minerals include fluorite, topaz, apatite, spinel, allanite, sphene, and cassiterite. Because of their relative enrichment in tin, lithium, beryllium, rubidium, barium, yttrium, niobium, and fluorine, they have been described as "tin granites" (Kisvarsanyi, 1981). They are also classed as HHP (high heat production) granites because of high uranium and thorium contents. The Graniteville Granite (Table 2) is representative of an HHP pluton in outcrop, but 14 others have been identified from drill cores in the region. These plutons are inferred to have been emplaced in resurgent cauldrons, are circular to oval in plan, and have distinctive negative magnetic anomalies of comparable shape and size associated with them.

TABLE 2 Chemical Analyses of the Principal Rock Types  
in the St. Francois Terrane

Wt %	Grassy Mountain Ignimbrite	Butler Hill Granite	Breadtray Granite	Knoblick Granite	Silver- Mine Granite	Slabtown Granite	Granite- ville Granite
SiO <sub>2</sub>	76.35	75.50	76.59	66.55	69.70	72.55	76.44
Al <sub>2</sub> O <sub>3</sub>	11.63	12.74	12.10	15.52	14.80	13.09	12.48
Fe <sub>2</sub> O <sub>3</sub>	1.24	0.46	0.64	1.57	1.26	1.80	0.44
FeO	1.27	1.12	0.51	2.88	1.80	1.47	0.45
MgO	0.12	0.19	0.14	1.28	0.76	0.39	0.05
CaO	0.39	0.63	0.53	3.04	1.75	0.80	0.95
Na <sub>2</sub> O	3.53	3.43	3.25	4.34	4.18	4.18	3.67
K <sub>2</sub> O	4.50	4.66	5.38	3.18	3.92	4.51	4.84
H <sub>2</sub> O <sup>+</sup>	0.35	0.68	0.37	0.74	0.76	0.51	0.13
H <sub>2</sub> O <sup>-</sup>	0.04	0.13	0.13	0.11	0.13	0.11	0.05
TiO <sub>2</sub>	0.16	0.14	0.11	0.48	0.40	0.40	0.07
P <sub>2</sub> O <sub>5</sub>	0.00	0.04	0.02	0.16	0.14	0.06	0.00
MnO	0.08	0.05	0.02	0.08	0.07	0.04	0.00
F	0.10	0.13	0.26	0.07	0.07	0.00	0.41
Total	99.76	99.90	100.05	100.00	99.74	99.91	99.98

Source of chemical analyses: Kisvarsanyi, (1972).

#### EXCURSION STOPS IN THE ST. FRANCOIS MOUNTAINS

In this guide the excursion stops are designated by two numbers, the first for the day, the second for the stop. Thus, 2-3 means the third stop on the second day. The stops are shown in figure 1.

#### FIRST DAY

ROUTE: Potosi - Bonne Terre - Farmington - Knob Lick - Fredericktown - Silver Mine - Ironton - Pilot Knob - Graniteville - Potosi (figure 1).

#### Stop 1-1: Roadcuts in Butler Hill Granite

This stop is 8.5 km south of Farmington on Highway 67, near the eastern boundary of the Precambrian outcrop area (figure 1).

The Butler Hill Granite and its granophyric roof facies, the Breadtray Granite, are the most extensively exposed granites in the St. Francois Mountains. They constitute an epizonal, subvolcanic massif that produced a comagmatic suite of rhyolite ash-flow tuffs, the Grassy Mountain Ignimbrite (Table 1), now largely removed by erosion. Roof pendants of rhyolite are locally preserved within the massif and along its southwestern periphery.

The Butler Hill Granite at this locality has well-developed rapakivi texture: ovoidal, pink alkali feldspars (orthoclase-microphertite) up to 3 cm in diameter are mantled by a thin white rim of oligoclase. The granite has prominent joint sets; it is intruded by an aplite dike that follows the major joint directions and branches out into fractures. The dike is exposed in the west roadcut.

The erosional contact between Butler Hill Granite and the basal Paleozoic strata is well exposed in the cuts on both sides of the road. The granite is weathered on top and is overlain by dark-maroon, shaly regolith derived from the weathering of the granite. Buff-colored shale and arkosic Lamotte Sandstone rest on top, lapping onto the Precambrian surface.

#### Stop 1-2: Knob Lick Mountain Section: Intrusive Contact of Granite with Rhyolite

In the entire Precambrian outcrop area of the St. Francois Mountains, the Knob Lick quarry affords the best exposure illustrating the intrusive relationship of granite into rhyolite. The granite, mapped as Knoblick Granite (Pratt and others, 1979), is representative of the ring intrusions in the St. Francois Mountains.

Rhyolite ash-flow tuffs are exposed at the top of Knob Lick Mountain and along its southern slope. This area of rhyolite is a



assimilated basaltic xenoliths and some are basic segregations in the granite. Xenoliths of mica schist, possibly brought up from the metamorphic basement by intrusion of the pluton, have been reported (Davis, 1969).

The dense, aphanitic rhyolite in the quarry is overlain by a porphyritic unit, the Grassy Mountain Ignimbrite, forming most of the prominent outcrops on the southern slope of Knob Lick Mountain. The somewhat bleached and recrystallized ignimbrite suggests that the intrusive contact of Knoblick Granite may not be far below. A north-south section across Knob Lick Mountain shows the relationship of these volcanic units and the granite (figure 2c). Both aphanitic and porphyritic rhyolites are intruded by a 3- to 6-m wide dike of porphyritic Knoblick Granite (figure 2a).

The different weathering characteristics of granite and rhyolite, resulting in strikingly different topographic expressions, are displayed in a panoramic view from the upper southern slope of Knob Lick Mountain, immediately south of the lookout tower and parking area. The large area of relatively low topographic relief to the southwest, called The Flatwoods, is underlain by Butler Hill and Breadtray Granites; hills and knobs in the distance are formed by rhyolite. Granite areas in the St. Francois Mountains tend to be gently rolling, whereas erosion-resistant volcanic rocks are commonly expressed as knobs or areas of dramatic high relief. The highest point in the State of Missouri, 532-m Taum Sauk Mountain, is within the most extensive outcrop and thickest section of volcanic rocks in the St. Francois Mountains.

#### Stop 1-3: Roadcuts in Slabtown Granite

Slabtown Granite is exposed in the large cuts on both sides of Highway 67 (figure 1). The Slabtown Granite forms numerous small outcrops overlapped by Lamotte Sandstone, in the southeastern part of the igneous outcrop area. Drillholes between the isolated outcrops encountered Slabtown Granite at depths of less than 30 m to over 90 m, suggesting moderate topographic relief on its erosional surface. The Slabtown Granite is part of a multiple ring intrusion, formed by the Knoblick, Slabtown, and Silvermine Granites, along the eastern boundary of the Butler Hill caldera (Pratt and others, 1979; Kisvarsanyi, 1981; Sides and others, 1981). The roadcuts at this locality

expose typical Slabtown Granite: fine-grained amphibole granite consisting of about 55 percent orthoclase-microperthite, 12 percent albite-oligoclase, 20 percent quartz, 10 percent fibrous, blue-green amphibole mostly altered to chlorite, and 3 percent magnetite. Slabtown Granite commonly exhibits granophyric texture. A chemical analysis of Slabtown Granite is shown in Table 2.

In these cuts, Slabtown Granite is intruded by small mafic dikes. Near the north end of the cut, a dike swarm is exposed on both sides of the road. Thirty or more nearly vertical basalt dikes, most of them less than 8 cm wide, have intruded joints and fractures of a 7.5-m wide, sheared interval of granite.

Enroute to Stop 4, Highway 67 passes through the western part of the historic Mine La Motte-Fredericktown subdistrict of the Southeast Missouri Lead district. The subdistrict includes some of the oldest lead-mining areas in Missouri, and was responsible for the district's only important cobalt-nickel production. Surface lead was discovered at Mine La Motte in 1720 and first mined in 1723. The Catherine Mines, located just west of Highway 67, opened in the late 1860's and operated intermittently for nearly 90 years. This tract produced an estimated 55,000 tons of lead from the sandy dolomites in the lower part of the Bonnetterre Formation.

#### Stop 1-4: Roadcuts in Grassy Mountain Ignimbrite

At Stop 4, along Highway 72 (figure 1), the Grassy Mountain Ignimbrite, a massive Precambrian rhyolite porphyry with well-developed joint sets is exposed on both sides of the road. A 1.2- to 1.5-m wide diabase dike has intruded the rhyolite along one of the prominent northeast-trending (N 15° E) joints and is exposed on both sides of the road. On the south side the dike is terminated at the Precambrian surface and is truncated by the overlying basal boulder conglomerate; on the north side the boulder bed is absent and the dike is exposed at the surface, on top of the roadcut. The dike is deeply weathered in the southern cut and in the upper portion of the northern cut, but is relatively fresh near the road level in the northern cut. The dike contacts are sharp, but fractured and sheared, with calcite and quartz filling narrow fractures along the sheared contact with the rhyolite. Near the west end of the cut, on the south side,



Granite; it is one of the best granite shut-ins in the region. Shut-ins are regionally unique physiographic features in the St. Francois Mountains but are more commonly developed where streams flow over volcanic rock.

Silvermine Granite, exposed in the bluffs along the St. Francis River (figure 3), is part of a multiple ring intrusion formed by the Knoblick, Slabtown, and Silvermine Granites emplaced along the margins of the Butler Hill caldera (Sides and others, 1981). The rock is a medium-grained amphibole-biotite granite averaging 40 percent orthoclase-microperthite, 30 percent sodic oligoclase, 20 percent quartz, and 10 percent mafic minerals. Chemically, Silvermine Granite is intermediate between less silicic Knoblick Granite and more silicic Slabtown Granite (Table 2).

The Einstein Mine (figure 3) is but one of several mines and prospects that began operations in the 1870's to produce silver from argentiferous galena in quartz veins cutting Silvermine Granite. The deposits have been described in detail by Tolman (1933) and Lowell (1975). There were two distinct periods of mining in the Silver Mine area: 1877 to 1894, and 1916 to 1946. During the earlier period, an estimated 50 tons of lead and 3,000 ounces of silver were produced; during the latter, an estimated 120 short tons of tungsten concentrates were produced, largely by high-grading the old dumps, and from shallow surface diggings. The remains of the dam, constructed in 1879, can be seen upstream from the mine dumps. Foundation remnants on the west hillslope south of the dam are all that remain of the large mill constructed during the silver- and tungsten-mining periods.

Of the several quartz veins mined and prospected in the area, vein no. 1, the Einstein, was the most productive; it accounted for the bulk of the early silver and lead production. It was entered by the River Tunnel, the entrance to which is about 15 m above the river. (Caution: Entry through this old adit is dangerous and should not be attempted!) The vein strikes N 80° E and dips 35° S; it pinches and swells, having a maximum width of not over 2 m and an ore zone as much as 65 cm wide (Tolman, 1933). A pinched outcrop of the vein, where it is less than 5 cm wide, is visible above a small mine opening in the hillside, about 15 m uphill from the River Tunnel. Near the contacts the intruded granite is intensely greisenized.

The high-temperature, pneumatolytic mineral assemblage at Silver Mine includes argentiferous galena, wolframite, arsenopyrite, sphalerite, cassiterite, chalcopyrite, covellite, hematite, stolzite, and scheelite. Quartz, topaz, sericite, fluorite, zinnwaldite, chlorite, and garnet are among the gangue minerals. Persistent search on the dump downhill from the mine may turn up good specimens. Hagni (1984) identified argentiferous tennantite, antimonpearcite, and berryite among the sulfides.

Numerous intermediate to mafic dikes older than the quartz veins have been mapped in the Silver Mine area. One of these is well exposed on the east side of the St. Francis River, just below the dam. The dike is about 1.5 m wide, strikes N 65° E, and is nearly vertical. Its borders against Silvermine Granite are chilled, but its central part is coarser grained. The rock contains a few small plagioclase phenocrysts in a groundmass of andesine and augite with intergranular texture. Euhedral magnetite and pyrite are abundantly disseminated through the groundmass, and there is a small amount of interstitial quartz.

#### Stop 1-6: Stouts Creek Shut-ins

Beginning about 3.2 km east of Ironton on Highway 72 (figure 1), massive rhyolite ash-flow tuffs are extensively exposed. The road passes through Stouts Creek Shut-ins, one of the better known geomorphic features developed in volcanic rocks in the St. Francois Mountains region. Below the shut-ins and immediately south of the road, Lake Killarney is one of Missouri's older impoundments and a favorite vacation spot.

At the upper end of the shut-ins, immediately northwest of the bridge across Stouts Creek, is the site of the Tong-Ashebran furnace. Built in 1816, this was the first iron furnace in Missouri and produced charcoal iron from hematite ore mined nearby and on Shepherd Mountain, 5.6 km northwest. Production ceased about 1819.

For a distance of about 1.8 km, the roadcuts and massive cliffs on the north side of the road expose the Lake Killarney composite ash-flow tuff and the Grassy Mountain Ignimbrite, as mapped by Sides (1976). The contact between the Lake Killarney and the overlying Grassy Mountain units is not exposed, but a coarse breccia of the Lake Killarney, containing diverse lithic clasts in a fine-grained groundmass

showing faint flow lines, is well exposed near the Lake Killarney sign. Farther east, most of the cuts expose Grassy Mountain Ignimbrite.

The Grassy Mountain Ignimbrite, a wide-spread and uniform volcanic unit in the St. Francois Mountains (Sides, 1976; Pratt and others, 1979), is characterized by abundant quartz phenocrysts, and collapsed pumice fragments that produce striking compaction foliation, manifested as prominent, discontinuous banding. It is considered to be the major collapse ash flow of the Butler Hill caldera (Sides and others, 1981). In these cuts, compaction foliation is nearly vertical and dips steeply to the west-southwest. The chemical similarity of Grassy Mountain Ignimbrite and the Butler Hill and Breadtray Granites is illustrated in Table 2. They represent compositions corresponding to alkali rhyolites and alkali granites, respectively.

#### Stop 1-7: Elephant Rocks: A Granite Tor in Graniteville Granite

This site is a classic example of a granite tor. It displays giant boulders, or core-stones, that resemble a herd of sitting elephants. The boulders are of Graniteville Granite, representative of the HHP plutons, and one of three principal granite types recognized in the St. Francois terrane (Kisvarsanyi, 1981). The granite is exposed on the margin of one of the resurgent cauldron subsidence structures in the region. The site was designated a State of Missouri Geologic Natural Area in 1978.

The prime scenic and geologic attractions of the park are the giant, picturesque residual boulders ("elephant rocks") of Graniteville Granite. The boulders are the result of a two-stage process: spheroidal weathering of block-jointed granite by circulating groundwater, followed by erosional stripping of the weathered fines.

The outcrop of Graniteville Granite is restricted to three small areas along the eastern and southeastern boundaries of a sediment-filled depression, the Belleview Valley (figure 1). Morphologically the valley is square, bounded by straight topographic escarpments, which are especially pronounced along its northwestern and northeastern sides. Belleview Valley is considered to be a fault-bounded, down-dropped Precambrian structural block; the topographic

escarpments are the results of erosion along nearly vertical faults. The square-shaped Belleview Valley is a prominent feature on satellite imagery of the region (Kisvarsanyi and Kisvarsanyi, 1976).

Looking northwest from the lookout point in the park, Belleview Valley appears to be a gently rolling, bowl-shaped depression surrounded on the horizon by higher hills of rhyolite. Drillholes indicate that Graniteville Granite underlies the sedimentary rocks in Belleview Valley (Kisvarsanyi, 1981). Aeromagnetic maps show the pluton as an oval magnetic low coincident with Belleview Valley (Cordell, 1979).

The Graniteville Granite is a medium- to coarse-grained, muscovite-biotite alkali granite averaging 55 percent alkali feldspar, 40 percent quartz, and less than 5 percent mafic minerals. In this rock, the common alkali feldspar is typically microcline-microperthite, but albite and orthoclase-microperthite are also present. Both primary and secondary muscovite (sericite) occur. The rock contains a varied suite of accessory minerals, including abundant fluorite, zircon, and magnetite; cassiterite and molybdenite are less common. Locally, the granite contains complex pegmatites with topaz, beryl, muscovite, fluorite, rutile, cassiterite, and sulfide minerals. Anomalously high levels of Sn, Be, Y, Nb, and F in Graniteville Granite led to its identification as a tin-granite pluton, the only one exposed, in the St. Francois terrane (Kisvarsanyi, 1981). The granite is classified as an HHP pluton because of abnormally high uranium and thorium contents. A chemical analysis of Graniteville Granite is shown in Table 2.

Graniteville Granite, known commercially as "Missouri Red," has been quarried in the area since 1869. By the turn of the century, building-, paving- and monumental-stone were being produced from several quarries. Blocks of Graniteville Granite were used as paving and curbing stone in St. Louis city streets. Buildings and monuments from San Francisco, California to Pittsfield, Massachusetts bear witness to the popularity and widespread use of this beautiful rock as a construction and monumental stone. Many older homes and commercial buildings in the area are also constructed from Graniteville Granite. Today only one quarry, 0.8 km northeast of Elephant Rocks State Park survives as an intermittent producer of monumental stone.

SECOND DAY

ROUTE: Potosi - Graniteville - Iron Mountain - Pilot Knob - Taum Sauk Power Plant - Johnson Shut-ins - Graniteville - Potosi (figure 1)

Stops 2-1 and 2-2: Pilot Knob and Iron Mountain Mines

About 7.2 km southeast of Graniteville, just east of Missouri Highway 21, is the historic town of Pilot Knob, at the foot of the Precambrian knob of the same name. The Civil War Battle of Pilot Knob took place here on September 27, 1864. The earthwork remnant of Fort Davidson, built by Union troops to protect the terminus of the St. Louis and Iron Mountain Railroad, and the iron mines on Pilot Knob and at Iron Mountain, is a feature of this State Historic Site.

The Precambrian rocks of southeastern Missouri have been a major source of iron ore in the State for more than 150 years. During the early period of mining, only near-surface deposits in the St. Francois Mountains like at Iron Mountain and Pilot Knob were worked. Aeromagnetic surveys between 1946 and 1968 disclosed several prominent magnetic highs in areas where thick sections of Paleozoic sedimentary rocks cover the Precambrian basement. Subsequent drilling has delineated several magnetic ore bodies at depth; the Pea Ridge, Bourbon, Kratz Spring, Camels Hump, Boss, and Pilot Knob (lower) deposits were discovered by drilling (figure 4). The Boss deposit is of particular interest, because it is a copper-iron ore body.

The magnetite-hematite deposits of southeast Missouri constitute a Precambrian iron metallogenic province (Kisvarsanyi and Proctor, 1967) and are classified as Kiruna-type deposits on the basis of their association with acid and intermediate volcanic rocks, low titanium content of the ores, and the ubiquitous presence of apatite and, in some cases, monazite as gangue minerals. The deposits are believed to be derived from iron- and alkali-enriched fluids alternately emplaced as magmatic injections and late-stage magmatic differentiates with pegmatitic and hydrothermal end phases. The deposits display a wide variety of features ranging from magmatic injection through hydrothermal veins and disseminations, contact metasomatic replacements to volcanic exhalative impregnations. Because of the wide range of features, various theories have been advocated for the

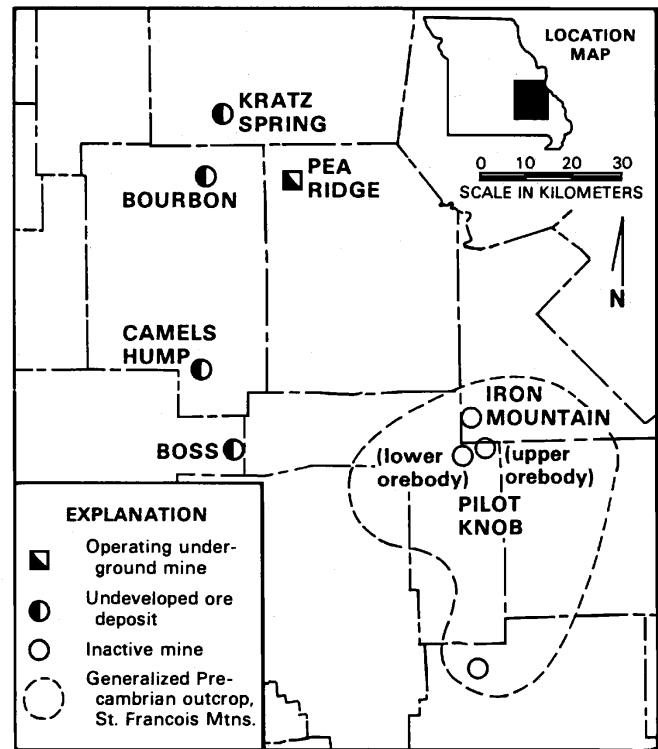


FIGURE 4 Precambrian iron-oxide-rich deposits in the Southeast Missouri metallogenic region. Adapted from Snyder (1969).

genesis of the ore bodies (see Snyder, 1969, and Ryan, 1981, for a review of some of the theories).

The discovery in 1975 of the giant Olympic Dam deposit in South Australia (Roberts and Hudson, 1983) inspired the development of new exploration concepts pertaining to the iron-oxide-rich Middle Proterozoic ore deposits of Southeast Missouri. Hauck and Kendall (1984) developed an exploration model for an Olympic Dam-type deposit in the region and suggested the genetic similarity between the Precambrian iron ores of the Kiruna district, Southeast Missouri, and South Australia. Sims and others (1987) noted many analogies between the regional geologic settings of the metallogenic regions of southeast Missouri and south Australia, and concluded that the St. Francois terrane is generally favorable for hosting Olympic Dam-type copper-uranium-gold deposits. The discovery of gold and tellurides in the Boss deposit (Hagni and Brandon, 1988) enhances the similarities between the respective mineralizations. Similar results are indicated by current research at the Pea Ridge mine. As a result of the new developments, the U. S. Geological Survey and the Missouri Geological Survey are collaborating in a comprehensive, 5-year

research to study in detail all the known Precambrian ore bodies in the region.

The Pilot Knob deposits (upper and lower ore bodies) and the Iron Mountain deposit are part of the Precambrian iron metallogenic province. Near-surface deposits in this immediate area - the Iron Mountain, Pilot Knob (upper ore body), and numerous smaller deposits - yielded magnetite and hematite ores amounting to nearly 11 million tons. Most productive of these early mines was Iron Mountain which yielded about 9 million tons of ore between 1843 and 1966 and was operated more or less continuously for 123 years.

The upper ore body at Pilot Knob consisted entirely of hematite in porous and permeable Precambrian bedded tuffs. Many authorities support a hydrothermal-replacement origin for the deposit; others favor a syngenetic hypothesis. The deposit was worked intermittently between 1835 and the 1920's, and yielded a total of 1.6 million tons of ore. The big cut at the top of the mountain, a memento of the early open-pit operations, is clearly visible as a "notch" from the highway. The geology and history of the Pilot Knob hematite deposit are described in detail by Ryan (1981).

The lower ore body at Pilot Knob was discovered by drilling a magnetic high in the valley just west of Pilot Knob Mountain. The ore body is a roughly tabular mass of magnetite concordant with the enclosing rhyolite ash-flow tuffs. Matrix and disseminated magnetite were emplaced by injection and hydrothermal replacement, respectively (Wracher, 1976). Ore depth ranged from 122 meters to 457 meters below the surface. The mine was permanently shut down in 1980 after yielding more than 19 million tons of ore in 12 years of operation. Remnants of the integrated mine, mill, and pellet plant are still to be seen east of the highway, at the foot of Pilot Knob.

The historic Iron Mountain mine is about 8 km north of Pilot Knob (figure 1). Three types of ore occurred at Iron Mountain: boulder ore, vein ore, and conglomerate ore. The boulder ore, the first type to be discovered and mined, consisted of hematite boulders embedded in surface residual clays. The vein ore occurred as several massive veins in Precambrian volcanic rocks, and was mined at first by open-pit methods from the Big Cut and Hayes Cut. Later, when magnetic surveys and exploratory drilling disclosed the deeper, vein-type ore bodies (Main Ore Body, Northwest Ore Body), underground methods

were also employed. The conglomerate ore, worked mostly by underground methods, occurred in the basal conglomerate between the Precambrian rocks and the overlying Upper Cambrian sediments. By far the greatest production was from the vein deposits. Both the boulder ore and the conglomerate ore were derived from erosion of a primary, vein-type ore body. The geology of the Iron Mountain deposit is described in detail by Murphy and Ohle (1968).

#### Stop 2-3: Taum Sauk Mountain Section

One of the most spectacular geologic sites in the state, the three-dimensional cut around Union Electric Company's power plant displays the erosional unconformity between Precambrian rhyolite and overlying Upper Cambrian sedimentary rocks. Both a buried rhyolite knob and a partially exhumed rhyolite knob can be observed in the 33-m-high cut. The site is within the thickest section of volcanic rocks in the St. Francois Mountains, and is part of the Taum Sauk caldera (Berry and Bickford, 1972).

The U-shaped cut at the power station exposes massive Precambrian ash-flow tuff, the Taum Sauk Rhyolite (Table 1) overlain by Upper Cambrian sedimentary rocks. The Taum Sauk Rhyolite is considered to be the major collapse ash-flow of the Taum Sauk caldera (Sides and others, 1981). The cut stands some 33 m above the tailrace and reveals a spectacular three-dimensional cross section of the Precambrian-Paleozoic erosional unconformity. Weathering has produced a few tens of feet of relief on the rhyolite surface. In the north face of the cut, the rhyolite knob is exposed at the ground surface, the overlying sediments having been removed by erosion. In the east and south faces of the cut, the knob is still buried by sediments.

The rhyolite is overlain by beds of shaly and arkosic dolomite, a sequence of alternating stromatolitic and burrowed carbonate muds assigned by Howe (1968) to the upper Davis Formation and the Derby-Doerun Dolomite. The dolomite laps onto the Precambrian surface from the west and has a maximum dip of 25 degrees. The steep dips are attributed to differential compaction of unconsolidated sediments deposited over the uneven rhyolite surface. The combined effects of carbonate solution, dolomitization, and compaction of argillaceous layers caused a loss of volume in the sedimentary beds; some relative movement of the sediments with respect to the rhyolite knob may have occurred.

Stop 2-4: Johnson Shut-ins Sequence of Rhyolite Ash-Flow Tuffs

Johnson Shut-ins is an excellent example of the regionally unique geomorphic features called shut-ins. Shut-ins are narrow, constricted gorges and valleys where a stream has cut through resistant igneous rocks. Upstream and downstream from a shut-in, a relatively wide and open valley is developed on less resistant sedimentary rocks.

At Johnson Shut-ins State Park a 1.6-km-long segment of the East Fork of the

Black River cuts through a thick sequence of Precambrian rhyolites. Stream erosion in the shut-ins is controlled by three important vertical joint sets in the rhyolites: northeast, southeast, and east. These are the principal directions of joint sets characteristic of all Precambrian outcrops in the region.

A 650-m thick sequence of rhyolitic ignimbrites and intercalated volcanoclastic sediments is well exposed in the shut-ins; the rocks display well-preserved volcanic-rock textures and constitute the best easily accessible section of such rocks in the St. Francois Mountains.

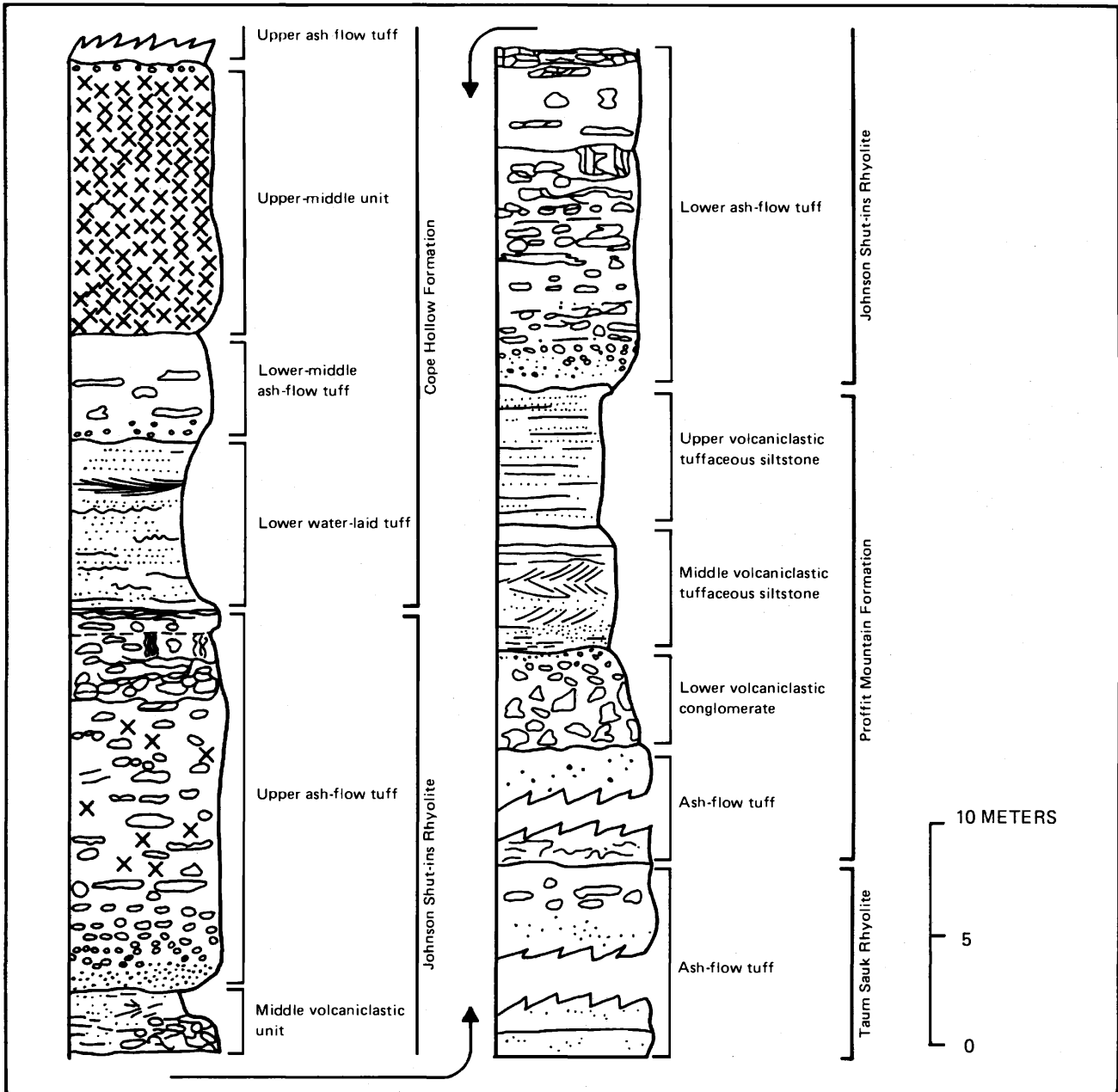


FIGURE 5 Measured stratigraphic section of Middle Proterozoic volcanic rocks in the Johnson Shut-ins area, STOP 2-4. Adapted from Blades and Bickford (1976).

The Johnson Shut-Ins Rhyolite (Table 1), a composite series of ash-flow tuffs and water-laid tuffs (figure 5), is well exposed in the shut-ins (Blades and Bickford, 1976). The ash-flow tuffs are dark gray to red in color and display fiamme, pisolites, and lithic fragments indicative of pyroclastic origin. Lithophysal units in the sequence have quartz-, feldspar-, and calcite-filled lithophysae.

Several volcanoclastic sedimentary units are interbedded with the ash-flow tuffs (figure 5). A uniform, gray, fine-grained water-laid tuff with ripple marks, cross-bedding, and finely graded bedding is exposed directly across the river from the observation platform.

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# THE SOUTHEAST MISSOURI LEAD DISTRICT

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## INTRODUCTION

### Location

The Southeast Missouri Lead District consists of five mining subdistricts in southeastern Missouri, which are distributed around the core of the St. Francois Mountains. The location of the subdistricts is shown in Figure 1 in the following section by Gerdemann and Gregg. All of the ore produced in the district currently comes from the Viburnum Trend subdistrict. The subdistrict comprises 10 mines, 8 of which are operating at the present time (one has been mined out and another mine is temporarily shut down). The mines are aligned approximately north-south over a distance of about 45 miles (72.4 km). The Trend extends from about 5 miles (8 km) north of the small town of Viburnum to more than 15 miles (24 km) south of the town of Bunker.

Prior to 1964 the principal production came from the Old Lead Belt subdistrict, which is about 30 miles east-northeast of the northern end of the Viburnum Trend. The subdistrict was operated by St. Joe (now Doe Run Company) as three divisions (north to south): 1) Bonne Terre, 2) Leadwood-Desloge, and 3) Federal Mines-Flat River.

The first discovery of lead in southeast Missouri was in the Fredericktown subdistrict, located about 15 miles (24 km) southeast of the old Lead Belt, and where mining continued until 1961. The old Madison mine was dewatered in 1979 by the Anschutz Mining Corporation to extract cobalt, copper, and nickel (Brooke, 1981), but production did not commence due to the subsequent decline in the price of cobalt. The Higdon deposit, located about 10 miles northeast of Fredericktown, was discovered by National Lead Company in 1956. Although joint plans with the Bunker Hill Mining Company (Bunker Hill bought out the NL Industries interests in 1976 and subsequently became a subsidiary of Gulf Resources and Chemical Corporation in 1968) for development were announced in 1964 and two shafts

were drilled in 1967, the deposit has not been mined due to its small size.

The Indian Creek subdistrict is located northwest of the old Lead Belt and north-northeast of the Viburnum Trend. The district comprised two mines, the Indian Creek and Goose Creek mines, was discovered in 1948 and operated by St. Joe Minerals until 1982.

The old Annapolis subdistrict is about 22 miles (35.4 km) east of the southernmost Viburnum Trend and about 20 miles (32.2 km) southwest of the Fredericktown subdistrict. The subdistrict consisted of a single mine that exploited small ore deposits and was closed in 1931.

The Doe Run Company has filed mineral lease applications with the Bureau of Land Management for an area within the Mark Twain National Forest about 8 to 12 miles (12.9-19.3 km) south of the town of Winona. The United States Forest Service is currently reviewing public comments on an October, 1987 draft environmental impact statement for the area. Pay holes have been drilled in the Winona area, which is about 30 to 35 miles (48.3-56.3 km) south of the Viburnum Trend.

### Discovery and Development

Lead was first discovered in surface exposures in the Southeast Missouri Lead District, in 1720, at the present site of Mine La Motte, in the Fredericktown subdistrict, by Philip Renault, who was leading a French expedition, although the deposits were known to the Indians before the 18th century. The ore deposits in the Leadwood-Desloge and Federal Mines-Flat River portions of the old Lead Belt subdistrict also were discovered in outcrops. The discovery of the Bonne Terre portion of the old Lead Belt, however, was due to diamond drilling, the first place in the world where diamond drilling was applied to metal exploration (Ohle, 1982; Ohle and Gerdemann, in press). The principal production until 1964 came from the old Lead Belt where

mining by the St. Joe Lead Company (now Doe Run Company) continued until 1972. Much of the land in the subdistrict has been donated to the State of Missouri to form St. Joe State Park and a Missouri Mines State Historic Site that were dedicated by the Missouri Division of Parks and Historic Preservation on May 8, 1988.

As reserves in the old Lead Belt diminished, St. Joe embarked in 1940 upon an expanded exploratory drilling program that was based upon the recognition that the ore deposits in the old Lead Belt were associated with Precambrian knobs, Lamotte sandstone pinchouts, and Bonneterre reef facies. After drilling 1,000 holes the first pay hole was drilled near a buried Precambrian knob at Indian Creek in 1947. The subsequent definition of the ore bodies at Indian Creek attracted other exploration companies to Missouri and resulted in the eventual discovery of the Viburnum Trend.

The Precambrian exposure known as Czar Knob drew attention to the Viburnum area, but the first ore hole, drilled by St. Joe in 1955 into what was to become the Viburnum 27 mine, was in the vicinity of a nearby buried knob. At about the same time that St. Joe was exploring the Viburnum area, Ozark Lead (Kennecott) had been independently exploring to the south around Eminence, where they were attracted by the presence of the Precambrian knobs that constitute the Eminence high and a geologic setting similar to that of the Old Lead Belt. After drilling 24 barren holes, Ozark Lead's first near-ore hole was drilled in 1957 northwest of Ellington near the Reynolds-Shannon County line (G. Kisvarsanyi, personal communication, 1981). With the discovery of ore by St. Joe at Fletcher in 1958, it became evident that additional deposits might be discovered between the Viburnum and Ozark Lead deposits. Most of the principal deposits were drilled out during the next four years.

Mining in the Viburnum Trend began at the Viburnum No. 27 mine in 1960. Eight mines are currently producing from the Viburnum Trend: Nos. 29, 28, 35 (Casteel), Buick, Magmont, West Fork, Fletcher, and Sweetwater. The Viburnum No. 27 deposit has been mined out and the mine closed in 1978. The most recent mines to be opened were the Viburnum No. 35 in 1983 and the West Fork mine in 1985. The Sweetwater mine (formerly Ozark Lead mine; Frank B. Milliken mine) was closed recently has been reopening by ASARCO. An ore deposit to the southwest of Sweetwater, the Blair Creek deposit, is owned by Ozark Lead but is undeveloped.

## Production

The Southeast Missouri Lead District has been the largest producer of lead in the United States since 1907; the world's largest lead producer since 1970 (15 percent of world production). Production reached a peak in 1982, when the district produced 523,003 short tons of lead metal that amounted to 92.5 percent of United States lead production (U.S. Bureau of Mines Mineral Industry Surveys, 1983). Over-supplies of lead, the decline in the price of lead, and labor problems reduced production in subsequent years and 352,630 short tons of recoverable lead metal were produced in 1986 (Missouri Department of Natural Resources, 1987). The district is third in zinc production in the United States. It yielded 41,799 tons of zinc metal in 1986, which constituted 19 percent of United States mine output (U.S. Bureau of Mines Mineral Industry Surveys, 1987). The district placed Missouri fifth among copper-producing states in the United States; 21,121 tons of copper metal were produced in 1986. Viburnum Trend silver occurs only in solid solution within the base metal sulfides, but the recovery of 1.3 million troy ounces in 1986 ranked Missouri 7th among silver-producing states in the United States. The value of these four metals in 1986 amounted to about 223 million dollars. Very small amounts (less than 0.1 percent) of cobalt and nickel are present in the ores of the Southeast Missouri Lead District. Because large tonnages of ore are present, the district contains the second largest cobalt reserve in the United States, about 120 million pounds of cobalt metal (Hagni, 1983b).

Total production from the Viburnum Trend from 1960 through 1984 was over 123 million tons of ore, yielding about 7.7 million tons of lead, over one million tons of zinc, about 181,000 tons of copper, and nearly 33 million troy ounces of silver (Wharton, 1986). The figures from that source calculate to an average grade of 5.8 percent lead, 0.8 percent zinc, 0.14 percent copper, and about a quarter of an ounce silver per ton of ore, although the results for copper and silver are low, due to the lack of metal data for some years. The cumulative value of the four metals recovered during those 25 years was about 5.1 billion dollars.

Total production from the older subdistrict has been summarized by Wharton (1981). The old Lead Belt subdistrict, from 1865 to 1972, produced 8.5 million tons of lead metal. From 1915 to 1972, 228 million tons of ore, with an average grade of 2.8

percent lead were produced in that subdistrict. Production from the Indian Creek subdistrict was nearly 15 million tons of ore, with a grade of about 2.5 percent lead. Production in terms of lead metal was about 0.6 millions tons from the Fredericktown subdistrict and 20,000 tons from the Annapolis subdistrict.

#### Mining

The ore deposits in the lead district are mined by open stope, room and pillar system. Blast holes are drilled with rotary-percussion drill jumbos. Large front-end loaders are used as 10-ton load-haul-dump units. For longer hauls 40- to 50-ton trucks are used. Sublevel rail haulage is used at Buick and Milliken. Most primary crushers are located underground below the main mining level, which is 600 to 1200 feet (966 to 1931 km) below the surface at mines in the Trend. Weakly (1982) has described the ore-moving methods used in most mines in the Viburnum Trend.

#### Beneficiation

The Viburnum, Fletcher, Brushy Creek, Magmont, and West Fork mills in the Viburnum Trend are designed to produce three concentrate products: lead, zinc, and copper. At the Buick and Milliken mills only lead-copper and zinc concentrates were produced; at Indian Creek only lead and copper concentrates were produced in the later years.

The ores are reduced by crushing and grinding to produce heads that are 50-60 percent minus 200 mesh. Bulk flotation in the lead circuit uses isopropyl xanthate as the flotation reagent to collect both galena and chalcopryrite particles. Dolomite, sphalerite, marcasite, and pyrite constitute the tailings. Tailings from the lead rougher cells are fed to the zinc flotation circuit, where copper sulfate is the conditioner for sphalerite flotation. In mills that make copper concentrates, the concentrates from the lead rougher circuit pass to the lead cleaner circuit and then to lead-copper separation, where a combination of sulfur dioxide and starch inhibits galena flotation and allows chalcopryrite to float. The concentrator at Buick has been discussed by Randall and Arterburn (1970). The wide variety of beneficiation problems to which ore microscopy and process mineralogy have been applied were summarized by Hagni (1983c). These involved incomplete separations of 1) sphalerite, pyrite, and marcasite from lead concentrates; 2) dolomite and siegenite from the zinc concentr-

ates; 3) galena and siegenite from copper concentrates; and 4) galena, sphalerite, and chalcopryrite from the final tailings.

#### Sintering

The lead concentrates are sintered into a feed for the lead blast furnace to remove part of the sulfur and to agglomerate the concentrate. Reflected light microscope studies of the lead sinters (Dressel et al., 1975; Pignolet-Brandom et al., 1987) show that they consist principally of lead silicate, lead-zinc silicate, lead-zinc-bearing calcium silicate (wollastonite), and an iron-zinc spinel.

#### Smelting

The lead concentrates from the Viburnum Trend are treated principally at three lead smelters: the Doe Run Buick smelter located only 2.5 miles (4 km) from the Buick mill area, the ASARCO Glover plant located in the small town of Glover 22 miles (35.4 km) east of the Viburnum Trend, and the Doe Run Herculaneum plant located on the Mississippi River at Herculaneum, south of St. Louis, and about 50 miles (80.5 km) northeast of the Viburnum Trend.

Most zinc concentrates from the Viburnum Trend are shipped by rail to the AMAX zinc smelter at Sauget, Illinois, about 70 mi to the northeast, or to St. Joe's National Zinc Division smelter at Bartlesville, Oklahoma.

Much of the copper concentrates, because of their lead content, are have been sent to Japan and Europe for smelting. Recently, some of the copper concentrates with low lead content have been smelted domestically.

Deleterious "slick" dross formed at the surface of the dressing furnaces at the Herculaneum, Missouri smelter examined by reflected light microscopy has been found to differ mineralogically from that of normal dross (Pignolet-Brandom et al., 1988).

#### Environmental Concerns and Forest Lands

The limited surface disturbance associated with the development of the mines in the Viburnum Trend is one of the industry's best examples of the compatibility of mining with other land uses. Visitors to the Viburnum Trend have commonly asked where the mines are located because most of the mines are concealed from main highways and blend into their natural surroundings.

The royalties on ore mined from the U.S. Forest Service (Mark Twain National Forest) lands are an important source of revenues. They are levied on the concentrates; the

annual receipts vary with the fluctuating price of those concentrates. They reached nearly 14 million dollars in 1980, and in fiscal 1985 they amounted to 3.08 million dollars (Missouri Geol. Surv., 1983). The annual rent and royalty payments usually range from 60 to 90 percent of the total Mark Twain National Forest revenues. Of this revenue, 25 percent is returned to the governments of those counties within the National Forest; the amounts in proportion to their federal acreages. The counties also receive revenue called "payments in lieu of taxes" (PILT), which is designed to reimburse the counties for their loss of property taxes; this totaled \$718,434 in 1985.

#### GEOLOGY (STRATIGRAPHY AND STRUCTURE)

The ore deposits of the Southeast Missouri Lead District are contained in Cambrian sedimentary rocks along the flanks of the St. Francois Mountains. The Precambrian rocks in the uplift were eroded to high relief and formed islands in the Paleozoic seas, where they strongly affected sedimentary facies, especially those in the Cambrian Bonneterre Formation, the host for the largest lead-zinc ore deposits. The Precambrian rocks are mostly acid intrusives and extrusive ash-flow tuffs or ignimbrites, rhyolite flows, and ash-fall tuffs. Although minor lead-zinc mineralization is locally present in the Precambrian rocks, they contain no lead-zinc-bearing ores, except at Silver Mine, Missouri.

The Paleozoic sedimentary rocks of the district are mostly dolomitized limestones together with a basal sandstone and interbedded thin shale units (Figure 1). The Cambrian Lamotte Sandstone forms the basal sedimentary unit; its pinchout around basement knobs is believed to have been an important factor affecting localization of the ore bodies. Ore deposits in the Fredericktown subdistrict commonly are localized in that portion of the lowest Bonneterre that immediately overlies the Lamotte pinchout. Locally the Lamotte itself may contain ore deposits in the old Lead Belt, Indian Creek, and Fredericktown subdistricts. The Lamotte typically grades upward from a basal conglomerate into a sandstone. At the Hayden Creek mine, in the old Lead Belt, ore was mined from the Lamotte conglomerate (Ohle, 1952). The Lamotte Formation reaches a maximum thickness of 500 feet (152 m) and pinches out against Precambrian knobs.

#### The Cambrian Bonneterre Formation

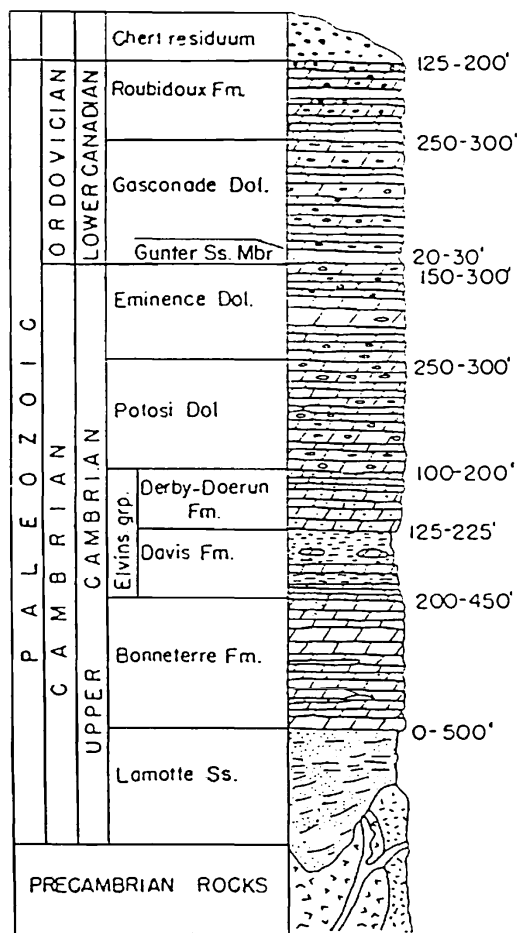


FIGURE 1 Stratigraphic Column, Southeast Missouri.

overlies the Lamotte and forms a gradational contact in the form of a sandy carbonate called the "sandy transition." The Bonneterre Formation consists mostly of various carbonate facies developed in relation to the Precambrian highland. A barrier-type reef grew during lower Bonneterre time forming a horseshoe-shaped (areally) reef along the east, north, and west flanks of the St. Francois Precambrian highland (Gerdemann and Myers, 1972; Larsen, 1977; G. Kisvarsanyi, 1982; Gerdemann and Gregg, 1986 and this guidebook). The carbonates of the reef complex are mostly digitate stromatolites and reef-associated tan, crystalline calcarenites. The backreef facies surrounds the main area of Precambrian knobs of the St. Francois Mountains and extends southward for a considerable distance (Howe, 1968). It comprises burrowed carbonate muds and planar stromatolites. The forereef facies is a gray or brown shaly lime mudstone. Carbonates of the succeeding middle and

upper Bonneterre Formation are those of a normal offshore shelf facies. Most of the major lead and lead-zinc ore deposits of the Southeast Missouri Lead District occur in the Bonneterre Formation. Ore deposits in the Old Lead Belt, Fredericktown, Indian Creek, and Annapolis subdistricts were contained primarily in the lower third of the Bonneterre Formation; those in the Viburnum Trend are located mostly within the middle third of the formation. The Bonneterre limestones are largely dolomitized in the vicinity of the ore deposits and throughout most of the backreef facies. The Bonneterre Formation averages about 240-250 feet (73-76 m) thick.

The individual units within the Bonneterre Formation can be correlated between mines (Larsen, 1979). Two distinctive marker horizons in the calcarenites of the middle third of the Bonneterre Formation are the False Davis and the gray beds. The False Davis unit occurs above the highest ore and probably formed an impermeable top for much of the ore fluids. The gray beds served especially as the focus for solution thinning and the formation of breccias in the lower portions of many ore bodies.

The Davis Formation, which conformably overlies the Bonneterre Formation, comprises interbedded shales and carbonates. It is believed to have played an important role in controlling paths of ore fluids, by forming an impermeable barrier to their upward and lateral migration and thus preventing mineralization of younger stratigraphic units. The Davis shale has a relatively high potash content (10-11 percent), a feature that has been suggested by Desborough et al. (1983) to indicate that it may be largely tuffaceous; its thickness is 125-225 feet (38-68.6 m).

The remaining stratigraphic units, where present, are mainly dolomites together with some sandstones. The Cambrian Eminence Dolomite and the Ordovician Gasconade Dolomite are the principal bedrock formations in the Viburnum Trend; however, an insoluble residue of red clay and chert formed from these dolomitic formations commonly is present as a residuum overlying the bedrock in that subdistrict. Large blocks of sandstone float from the Ordovician Roubidoux Formation occur on the crests of some hills in the Viburnum Trend; brownish dolomite of the Cambrian Potosi formation, which contains abundant drusy quartz, crops out in some valleys in the Trend.

The structural attitude of the Paleozoic sedimentary formations is horizontal to gently dipping away from the St. Francois

Mountains, except locally, where modified by post-depositional faulting. The Ste. Genevieve and Simms Mountain fault zones, along the northeast flank of the St. Francois Uplift, are present in the vicinity of the Old Lead Belt and may have been a factor in ore localization in that subdistrict (Snyder and Gerdemann, 1968). At the north edge of the district, roughly along the 38th parallel, a series of structures, variously interpreted to have formed by cryptovolcanic or extraterrestrial impact origin, and other structures are considered to be related and called the 38th parallel lineament (Snyder and Gerdemann, 1965).

No major north-trending fault or fault zone has been discovered to coincide with the north-south alignment of the Viburnum Trend. At the Magmont mine, however, a fault that shows strike-slip movement in the Bonneterre Formation and that trends N. 5° W. has been penetrated by drilling into the basement. Where penetrated, it exhibits high-temperature alteration and contains copper and iron mineralization (Sweeney, pers. comm., 1983). Apparently it is a Precambrian fault that has undergone subsequent rejuvenation. The northeasterly-trending Conway Fault at the Viburnum 28 mine is locally associated with unusually rich ore (Pettus and Dunn, 1986). Many faults in the lead district postdate mineralization.

The northeast-trending New Madrid fault zone, which is about 40 miles (64.4 km) south of known ore deposits in the Fredericktown subdistrict, has recently been recognized to represent an ancient rift zone that probably involved igneous activity over a long period (Hildenbrand et al., 1977). Along the fault zone, geophysical evidence indicates there are numerous igneous intrusions, which appear to be mafic to ultramafic in composition. It has been suggested that faults trending northwesterly from the New Madrid zone toward the Southeast Missouri Lead District represent ancient transform faults (Horrall et al., 1983) and that they may have localized distribution of some of the ore fluids. If older igneous intrusions exist in the New Madrid zone they could have provided possible sources for some of the copper, cobalt, and nickel in Southeast ores (Horrall et al., 1983).

Paleozoic and post-Paleozoic cryptoexplosive pipe-like structures are present, especially to the east of the old Lead Belt in the vicinity of Avon, Missouri (Kidwell, 1947). The fact that some structures of this type have vented into the lower Bonneterre Formation at the time of

its deposition has suggested that there was a higher geothermal gradient during Bonnetterre time and that perhaps metals such as copper, cobalt, and nickel were contributed to the basinal lead-zinc-bearing brines from that source (E. Kisvarsanyi, 1983).

#### ORE DEPOSITS

The forms of individual ore deposits and their controlling structures in the Southeast Missouri Lead district are diverse. The most important structural control for deposits in the Viburnum Trend is that of solution collapse breccias, which are best developed within the Trend at the Buick, Magmont, and Milliken mines. At Buick and Magmont the principal ore bodies are contained in two or three north-trending breccias (Rogers and Davis, 1977; Sweeney et al., 1977; Bradley, 1986); at Milliken the ore bodies are associated with a single northwest-trending solution collapse breccia and with associated offset structures (Mouat and Clendenin, 1977). Ore bodies at Buick and Magmont are about 120-200 feet (36.6-61 m) wide (east-west), 30-60 feet (9.15-18.3 m) thick (vertical dimension), and are one to four miles (1.6-6.4 km) long (north-south) and extend across property lines. The east and west flanks of the breccia structures at Buick and Magmont typically dip away from the centers of those structures. The principal factor in their development was the solution thinning of certain beds in the Bonnetterre Formation. At the Magmont mine much of this dissolution was in the silty marker bed (synonymous with gray beds). At the Milliken mine the most significant dissolution took place in the Q-1 horizon, the lowest unit in the middle third of the Bonnetterre Formation and which occurs immediately above the reef rocks of the lower third in that formation.

Control by solution collapse breccias is less well developed at other mines in the Viburnum Trend, but a breccia structure can be traced with difficulty throughout the length of the Brushy Creek and Fletcher mines (Paarlberg, pers. comm., 1982), to the south of Buick and Magmont. To the north, solution breccia control is evident in part of the Viburnum No. 28 mine (Pettus and Dunn, 1986). Where the breccia is less well developed the ore bodies have more extensive lateral dimensions. For example, the ore body at Fletcher is 2000 feet (610 m) or more in width. Gerdemann (in Ohle, 1985) has estimated that half the ore occurs in breccias in parts of the Viburnum Trend, and that 10-15 percent is contained in breccias in the subdistrict as a whole. In contrast

to most of the mines in the Viburnum Trend, about half the ore at the Viburnum 28 mine is in the upper portion of the reef (Pettus and Dunn, 1986).

The ore-bearing breccia structures have formed largely as a result of dissolution by the ore fluid itself, but the causes for their initial development and for their locations are not well understood. One interpretation involves the total dissolution of local evaporites (Rogers and Davis, 1977). The fact that the breccias at the base of the breccia piles have a "swirly" texture has suggested that they may be of sedimentary origin and that the solution collapse breccias developed as an upward extension of earlier sedimentary slide breccias. At the Magmont and Buick mines, a small ridge about 10 feet high, west of the breccias, perhaps provided a sufficiently steep slope to locally initiate such slide breccias. At the Sweetwater mine, (Larsen et al., 1979) have found evidence that the solution collapse structure developed over the toe of a submarine slide, which is interpreted to have been generated by oversteepened slopes associated with the Eminence Precambrian high to the southwest of the ore deposit. An interpretation favored by some (e.g., Ohle, 1985) is that the rigid reef acted as a fulcrum during compaction of surrounding, more compressible sediments to cause fracturing of the overlying Bonnetterre beds. Ohle (1985) also has suggested that chemical brecciation may have been a contributing factor in addition to solution collapse and gravity shattering.

A recent development is the mining of a linear breccia ore body, the Magmont West mine, which is about two miles west of the main Viburnum Trend, and is reached by a drift from the main Magmont mine (Bradley, 1986). The ore body averages about 200 feet (61 m) wide and has been mined for a length of greater than 4,000 feet (1220 m). In contrast to other deposits in the Viburnum Trend, the ore at Magmont West occurs mostly in the False Davis and it contains about three times as much zinc.

Other ore bodies are mostly in submarine slide structures. The deposit at the Viburnum No. 27 mine, and possibly part of the West ore body at Magmont, appear to be examples of ore control by slide breccia. The ore bodies at Viburnum 27 are about 250-500 feet (76-152 m) wide, 50 feet (15.2 m) thick, and extend 2000 to 3000 feet (610-915 m) from the ridge (Grundmann, 1977). Submarine slide breccias were first described by Snyder and Odell (1958) as a form of ore control for deposits in the old Lead Belt, but they accounted for less than

2 percent of the ore in that subdistrict (Ohle, 1985).

Blanket-shaped ore bodies, a relatively new development in the Viburnum Trend, are thin (less than 30 feet or 9.15 m thick) and laterally extensive (up to 2000 feet or 610 m east-west). They are located to the east of the high breccia ore bodies and are perched on tongues of reef rock that pinch out westward and are stratigraphically higher than the main reef (Mugel and Hagni, 1984). The Magmont East ore body at Magmont and the Blanket ore body at Buick are examples of this type of deposit.

In the old Lead Belt, where the ores occurred mainly in the lower third of the Bonnetterre Formation, the ore bodies formed in close association with northeast-trending quartz-sand and calcarenite bars or ridges and superposed algal reef structures (Ohle and Brown, 1954).

In the Indian Creek subdistrict the ore body occurs along the northwest side of a Precambrian ridge, and it pitches downward to the northeast. In the southwest portion (Indian Creek mine), the ore is closely associated with a reef structure in the lower Bonnetterre, an isolated reef localized by the Precambrian ridge. In the northeast portion (Goose Creek mine), the reef pinches out and ore drops down to the Lamotte Sandstone where it occurs primarily in disseminated spots very similar to the ore from Laisvall, Sweden.

The most common deposits in the Fredericktown subdistrict are contact ores, which are localized in that portion of the lower Bonnetterre Formation immediately overlying the pinchout of the Lamotte Formation (James, 1952). Such deposits are circular to horseshoe-shaped in plan. The ore body at the old Missouri Cobalt mine (later part of the Madison mine) was 200 feet (61 m) wide, 20 feet (6.1 m) thick, and 4000 feet (1220 m) long. It occurred 400 to 425 feet (122-130 m) from the surface and formed a horseshoe-shaped pattern open to the north. Other deposits in this subdistrict were associated with solution collapse breccias. A stratigraphically higher zone of mineralization, at the level of the False Davis, has been investigated by recent drilling at the Madison mine (Pignolet-Brandom and Hagni, 1985b).

#### MINERALOGY AND PARAGENESIS

The major sulfide minerals found in the Southeast Missouri lead deposits are galena, sphalerite, chalcopyrite, marcasite and pyrite. All five can occur as euhedral crystals in open spaces of breccias,

hostrock dissolution vugs, bedding planes, fractures, etc., or as disseminated to massive replacements of hostrock dolomite and shaly dolomite. All of the sulfide minerals have been repetitively deposited and periods of sulfide dissolution occur between some generations of sulfide deposition. The earliest generations of galena crystals are octahedral, whereas late galena crystals are cubic with rare octahedral modifications. The largest cubes, about 10 inches (25.4 cm) on a side, appear to have been deposited very slowly from dilute solutions. Rarely, rapid sulfide deposition led to development of colloform and even spherical galena forms.

Sphalerite commonly occurs as small disseminated crystals replacing hostrock dolomite, but it also occurs in massive ores and in small, late, euhedral crystals in vugs. At least four generations of sphalerite deposition can be distinguished by their colors.

Much of the early chalcopyrite exhibits massive to colloform textures suggesting that it was rapidly deposited. Small amounts of late chalcopyrite crystals may be found in some vugs. The iron sulfides, marcasite and pyrite, are abundant in the ores and the iron content may be nearly as high as the lead content in some ores. Pyrite occurs most commonly as small, early, disseminated crystals, and it occurs together with marcasite in later, colloform iron sulfide masses. Marcasite occurs as crystal coatings on other sulfides, especially galena, as colloform masses, and as intergrowths with quartz at the fringes of many ore deposits.

The principal gangue minerals, in addition to pyrite and marcasite, are dolomite, calcite, and quartz. Dolomite occurs most abundantly as a replacement of the original limestone host rock, but it was also subsequently deposited as crystals, especially those that line small vugs in the ores and host rock. Dolomite was deposited during four principal periods (Voss and Hagni, 1985; Voss, Hagni, and Gregg, in press). Calcite was deposited after most sulfide deposition had ceased, although marcasite, chalcopyrite, pyrite, and bravoite crystals are enclosed in some calcite crystals, where they outline the surfaces of the earlier scalenohedral calcite and mark a hiatus in calcite deposition. Quartz is abundant at some mines, where it was deposited partly as small crystals in vugs and partly as jasperoidal replacements of the hostrock carbonate. Dickite was deposited in association with the ore deposits; where it

is adjacent to sulfide crystals it appears to be a late mineral. Rare inclusions of a calcium sulfate mineral occur within octahedral galena (Mark Marikos, pers. comm., 1988).

Examination of the sparry dolomite by cathodoluminescence microscopy has revealed the presence of four growth zones with marked variations in the intensity of cathodoluminescence produced by differences in Mn:Fe ratios (Voss and Hagni, 1985). The four zones are: 1) an early cathodoluminescent non-banded zone, 2) a non-cathodoluminescent zone, 3) a strongly banded zone comprising alternating brightly cathodoluminescent and non-cathodoluminescent dolomite, and 4) a dull to non-cathodoluminescent zone. The four growth zones are detectable in sparry dolomite crystals in the ores throughout the 45 mile (72.4 km) length of the Trend and establish a "dolomite stratigraphy." Sparry dolomite crystals elsewhere in Missouri and Arkansas possess the same four growth zones (Gregg, 1985; Rowan, 1986).

Additional opaque minerals which were deposited locally or in minor amounts include siegenite, bravoite, fletcherite, carrollite, millerite, bornite, chalcocite, digenite, djurleite, anilite, polydymite, vaesite, gersdorffite, tennantite, arsenopyrite, pyrrhotite, magnetite, enargite, covellite, and blaubleibender covellite. Most siegenite occurs in close association with chalcopyrite, and forms crystal coatings and partial replacements of that copper-iron sulfide mineral. Bravoite occurs mostly as disseminated, compositionally zoned, pyritohedral crystals, and less commonly forms thin layers in colloform marcasite-pyrite masses. The remaining minor minerals occur primarily either in bornite pods or in cobalt-nickel-rich areas.

Small (about ten feet or 3 m wide and one foot or 0.3 m or less thick) pods of bornite-chalcopyrite ore are locally present. Their ore textures and paragenetic sequence have been discussed by Hagni (1986; 1988). The bornite exhibits exsolution, colloform, and replacement textures chalcopyrite. Other minerals present in smaller amounts are fletcherite, nickelian carrollite, gersdorffite, tennantite, enargite, cobaltian pyrite, chalcocite, digenite, djurleite, anilite, covellite, and blaubleibender covellite. Djurleite crystals as large as two centimeters occur at Milliken and represent one of the few such occurrences in the world. The bornite pods were among the earliest of the ores to be deposited and may mark local hotspots of early ore deposition.

Rarely, small acicular millerite crystals were deposited in vugs. They are especially well known from the cobalt-nickel-rich zone along the east side of the west ore body at the Buick mine. They are commonly altered to polydymite, vaesite, and siegenite. A different type of millerite occurrence is that associated with colloform gersdorffite, polydymite, vaesite, tennantite, enargite, and chalcopyrite recently discovered in the Magmont West orebody (Pignolet-Brandom and Hagni, 1986b).

Although the general paragenetic sequence of the Viburnum ores is chalcopyrite, sphalerite, octahedral galena, chalcopyrite, siegenite, pyrite, marcasite, dolomite, cubic galena, and quartz, but there are many repetitions of deposition and dissolution (Hagni and Trancynger, 1977; Hagni (1986a).

## GEOCHEMISTRY

### Fluid Inclusions

Fluid inclusion homogenization temperatures for sphalerite range from 137 to 82°C (Roedder, 1977; Hagni, 1983a). Early yellow sphalerite was deposited during declining temperatures (137 to 82°C); brown sphalerite formed during a period of more constant temperature (mainly 125 to 110°C) (Hagni, 1983a). Temperatures determined for quartz (120 to 94°C) are similar to those for sphalerite; calcite was deposited from fluids at lower temperatures (70 to 48°C) (Hagni, 1983a). Homogenization measurements for dolomite give elevated temperatures (about 90-120°C) for dolomite within and outside the lead district in Missouri indicating that the fluids which deposited dolomite and presumably the sulfide minerals were very widely distributed and effectively penetrated the rocks of the region (Leach, 1983; Rowan, pers. comm., 1986).

Salinity determinations for fluid inclusions in sphalerite indicate that the ore depositing fluid was a brine (mostly 22 to 26 percent NaCl equivalent) (Roedder, 1977). Late calcite was deposited from fluids whose salinity had diminished to about 12 to 2 percent NaCl equivalent.

### Trace Elements

The trace element content of sulfide minerals in the Southeast Missouri Lead district has recently been summarized and compared to other Mississippi Valley-type deposits (Hagni, 1983b). The Southeast Missouri Lead District differs significantly from other MVT deposits in the abundance of certain minor and trace elements. Galena

has an average content of 85 ppm silver (smelter recoveries show 31 ppm), 340 ppm arsenic, 171 ppm antimony, and 50 ppm bismuth. The silver content of sphalerite (434 ppm) is about ten times greater than that of galena, and orders of magnitude greater than that of sphalerite from other MVT districts that average 2-20 ppm. The amounts of cobalt (490 ppm) and nickel (391 ppm) also are much greater in sphalerite than that from other MVT deposits (0.2 - 15 ppm Co; 2 - 42 ppm Ni). The average cadmium content (8571 ppm) in sphalerite in the district also is greater (two to nearly five times) than in sphalerite elsewhere in the Mississippi Valley. The average germanium (114 ppm) and gallium contents (155 ppm) are similar to those MVT deposits elsewhere in the world.

The iron content for sphalerite from the district averages 8.3%, but it varies significantly for sphalerite crystals deposited at different times. Cadmium also varies from 1.3% for one type of early black sphalerite to 0.28% for late yellow sphalerite. Indium and thallium have been detected in concentrates.

Chalcopyrite contains an average of 38 ppm silver, 234 ppm molybdenum, 257 ppm bismuth, 272 ppm cadmium, and 33 ppm nickel. Isotopic Compositions

The lead isotope ratios for galena from the Southeast Missouri Lead district are anomalous J-types that give dates for ore deposition in the future. Prolonged differential leaching of a lead-uranium-rich source was suggested by Pelissonnier (1983) to explain such leads. Comparison of lead isotopes in the ore with those in residues from rocks in the district suggested that the lead originated from the Lamotte (Doe and Delevaux, 1972), but Doe et al. (1983) has also subsequently considered the Precambrian as a possible source. Cubic galena is more radiogenic than earlier deposited octahedral galena. Ion probe examinations of single galena crystals show a progressive outward increase in radiogenic lead in single galena crystals (Hart et al., 1981, 1983).

Sulfur isotopes in the ore minerals give wide ranges of ratios (Brown, 1967). Although earlier analyses of sulfur isotope ratios in galena appeared to indicate that they varied systematically with lead isotope ratios, the lighter ratios are associated with the more radiogenic lead ratios (Sverjensky et al., 1979), additional study shows a lack of detailed correlation and suggests that lead and sulfur have different sources (Deloule et al., 1986).

Carbon and oxygen isotope ratios show

differences between early host rock dolomite and the four CL zones within the hydrothermal dolomite crystals that have been interpreted to indicate mixing of three brines (Frank and Lohmann, 1986).

Strontium isotope ratios for calcite are higher (about 0.711 to 0.712) than dolomite (about 0.709 to 0.710) and they increase outward within late zoned calcite crystals (Chadhuri et al., 1983).

#### GENESIS OF THE ORE DEPOSITS

The genesis of the Southeast Missouri lead ores has been controversial. The evidence from fluid inclusions in sphalerite and sparry dolomite that the ore fluids were warm (82 - 137°C) and very salty fluids, has led to the currently popular view that the ore fluids were connate brines derived from adjacent sedimentary basins, such as the Ouachita and Arkoma basins, south and southwest of the district, in Arkansas and Oklahoma (Leach, 1979; Sharp, 1978; Rothbard, 1983; Leach and Rowan, 1986). The force that moved basinal brines to the depositional sites of the MVT ore deposits has commonly been thought to be that of sediment compaction during basin subsidence (Sharp, 1978; Cathles and Smith (1983), but recent studies using numerical modeling have appealed to gravity-driven groundwater flow due to topographic uplift and elevation of the source areas (Bethke, 1986; Garvin, 1985).

Within the Viburnum Trend the ore fluids have been interpreted to have originated in the vicinity of the Magmont and Buick mines and with a second source from the south (Hagni, 1983a). These directions of ore fluid movement are indicated by 1) mineral asymmetry; 2) cobalt and nickel contents of the ores; 3) ratios of cobalt to nickel; 4) cadmium contents in sphalerite; 5) silver contents in cubic galena; 6) ratios of other metals; 7) proportions of quartz and iron sulfides; and 8) distribution of ore grades throughout the Trend. This overall pattern of fluid movement is more complicated, however, as shown by evidence for vertical movement and by the presence of multiple sites of early ore deposition marked by the bornite pods.

Metal solubility and transport have been variously attributed to bisulfide complexing, chloride complexing due to the high chlorine content of the fluid inclusions and organic complexing (Giordano and Barnes, 1981; Giordano, 1985) because of the presence of organic matter in most MVT deposits. Four types of petroliferous materials have been recognized in the

Viburnum Trend (Niewendorp, 1987). One of these, a coal-like bitumen appears to have been mobilized by the introduction of the hydrothermal fluids (Marikos et al., 1986) and contains paragenetically late very fine-grained dendritic galena, chalcopyrite, and pyrite (Niewendorp, 1987). Spirakis (1986) has noted that sulfur transported in the form of metastable, partly oxidized species could be readily reduced by organic carbon to provide minus two-valent and minus one-valent sulfur for sulfide and disulfide precipitation. Whether the metals and sulfur were carried together in a single fluid or separately in two different fluids (Jackson and Beales, 1967) is an unresolved problem. The alteration of potash feldspar to kaolinite suggested to Sverjensky (1984) that the pH of the ore fluids must have been acid. Anderson (1983) and Anderson and Garven (1987) have suggested that the ore fluids become acid at the site of ore deposition by the release of hydrogen in the reaction of hydrogen sulfide to form the sulfide minerals. Researchers have appealed to various sources from which to derive part or all of the metals, including the Bonneterre Formation, Lamotte Formation (Doe and Delevaux, 1972), Precambrian basement (G. Kisvarsanyi, 1977), mafic to ultramafic rocks within the Bonneterre Formation (E. Kisvarsanyi, 1983), and Davis shale (Panno et al., 1988).

The age of mineralization for the lead ores has been thought to be late Paleozoic based upon the time of expulsion from the Ouachita Basin (Sharp, 1978), studies of very weak remnant magnetism of some ores and the alignment of their paleomagnetic pole positions (Wu and Beales, 1981), and K/Ar dating of post-galena illite clays in the Lamotte Formation (Rothbard, 1983). Rb-Sr isotopic analyses of sedimentary or diagenetic glauconite pellets in the Bonneterre Formation whose isotope compositions are believed to have been reset by the introduction of the ore fluids give dates that are Late Devonian or Early Carboniferous (359 Ma) (Stein and Kish, 1985).

The recent recognition of the role of high heat production (HHP) Variscan-age granites in the origin of some ore deposits in the Cornwall tin district raises the question as to whether the Precambrian granites could have had a similar relationship to the lead-bearing fluids in southeast Missouri. The high content of heat-producing radioactive elements in the Cornish granite have been found to provide significant amounts of heat by radioactive decay long after their final solidification (Halls, 1985). Some of the Precambrian

granites exposed in the St. Francois Mountains, such as the Graniteville granite, have unusually high uranium (14 ppm) and thorium (42 ppm) contents that could have provided heat that promoted the development of groundwater circulation cells with associated leaching of lead and other metals from the Precambrian and Paleozoic sedimentary rocks in the general vicinity of the present ore deposits in the Southeast Missouri Lead District. Tin granites similar to the Graniteville granite have wide distribution in the covered Precambrian basement in Missouri (E. Kisvarsanyi, 1981).

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FIELD TRIP GUIDE TO THE UPPER CAMBRIAN LAMOTTE, BONNETERRE,  
AND DAVIS FORMATIONS, ST. FRANCOIS MTS. AREA, MISSOURI

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## INTRODUCTION

This field trip was prepared using notes from the extensive field studies, conducted in the St. Francois Mountains region, by the senior author and others. These studies were part of the exploration effort undertaken by St. Joe Minerals Corporation, during the 1950s, that eventually lead to the discovery of the Viburnum Trend lead-zinc district. This trip will serve to introduce geologists to many aspects of the sedimentary and economic geology of the St. Francois Mountains region (Fig. 1).

The trip is designated to take one full day. If two days are allowed, a more leisurely pace can be taken and several other points of geological interest, shown on the field trip map (Fig. 2), may be visited (e.g., Silver Mines and Elephant Rocks state parks).

Several references will serve to introduce the geologist to the southeast Missouri mineral districts (Gerdemann and Myers, 1972; Thacker and Anderson, 1977). Anderson and Macqueen (1982) present a general overview of the origin of Mississippi Valley-type sulfide mineralization.

## ROAD LOG

### Stop 1.

From Hwy 21-Hwy M intersection go 6.5 mi (10.4 km) east on Hwy M to outcrops on both sides of the road (Fig. 2). Bonneterre Dolomite, digitate algal stromatolite "reef" facies. This facies is not an "ecologic reef" in the sense of Dunham (1970) but is better termed a "bioherm" or "stratigraphic reef". Definition of the reef as a control on the distribution of mineralization in the "Old Lead Belt" lead to the discovery of the Viburnum Trend (see Gerdemann and Myers, 1972). This exposure contains well developed digitate stromatolites, interstromatolitic grainstones, and bioturbated beds. Also present are "roll structures" which are described by Ohle and

Brown (1954) from exposures in underground mines. These structures are individual mines built of digitate stromatolites.

The rock at this outcrop is now completely dolomitized. Galena was mined in the Bonneterre about 1 mile (1.6 km) to the northwest of this road cut in the old Irondale Mine on the bank of the Big River.

### Stop. 2

From Hwy M-Hwy 8 intersection go 1 mile (1.6 km) east on Hwy 8, outcrops on both sides of the road. Upper part of the Bonneterre Dolomite containing interbedded oolitic grainstones, some with cross-bedding. An unconformable contact with the overlying Davis Formation is visible near the top of the outcrop on the south side of the road (Kurtz, 1986).

### Stop 3.

From stop 2 continue east on Hwy 8 for 1 mi (1.6 km), outcrops on both sides of the road. Interbedded dolomites and shales of the Davis Formation which overlies the Bonneterre. Note the large concretion-like "boulders". These are dolomitized algal bioherms. The Davis represents a transgressive offshore or "basial" facies. The water was probably never much deeper than the photosynthetic limit (about 40 m), as is evidenced by fossil algal and faunal remains. Note the ripple marks at the west end of the outcrop (north side of the road). Saddle dolomite, sphalerite, and galena crystals can be found in the road cut, indicating that these rocks were exposed to mineralizing fluids.

### Stop 4.

From stop 2 go about 0.5 mi (0.8 km) east and turn right off of Hwy 8 and go 0.1 mi (160 m) to stop sign (first intersection). Turn right and go 0.7 mi (1.1 km) and turn left at crest of the hill onto Mitchel Rd. Go 1.5 mi (2.4 km) and turn left at Davis Crossing Rd. Go 2.9 mi (4.6 km) and turn right (southwest) on to

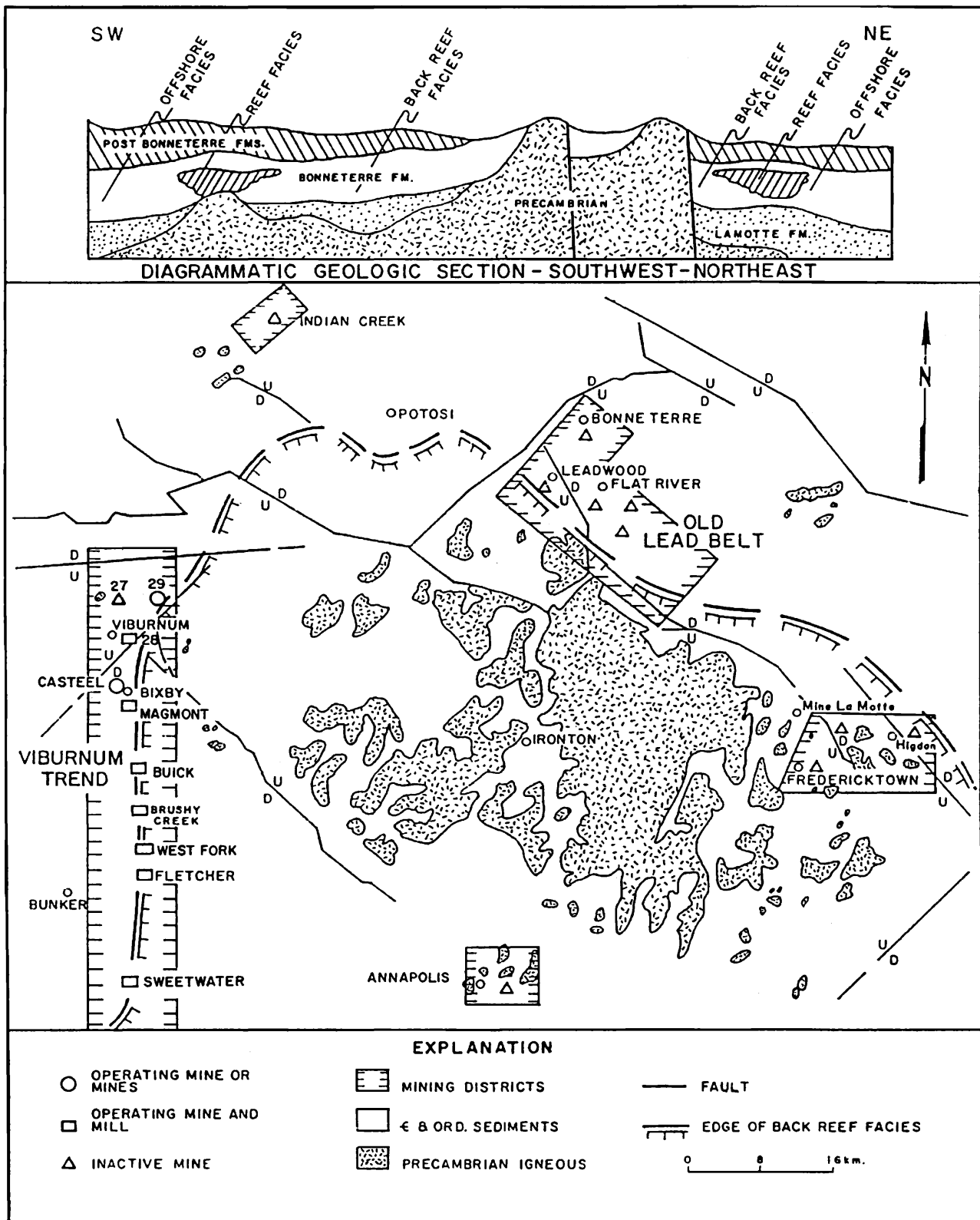


FIGURE 1 Map of St. Francois Mountains region showing mining districts, locations of mines and distribution of major Bonneterre facies. Diagrammatic section across the St. Francois Mts. showing facies relationships in the subsurface.

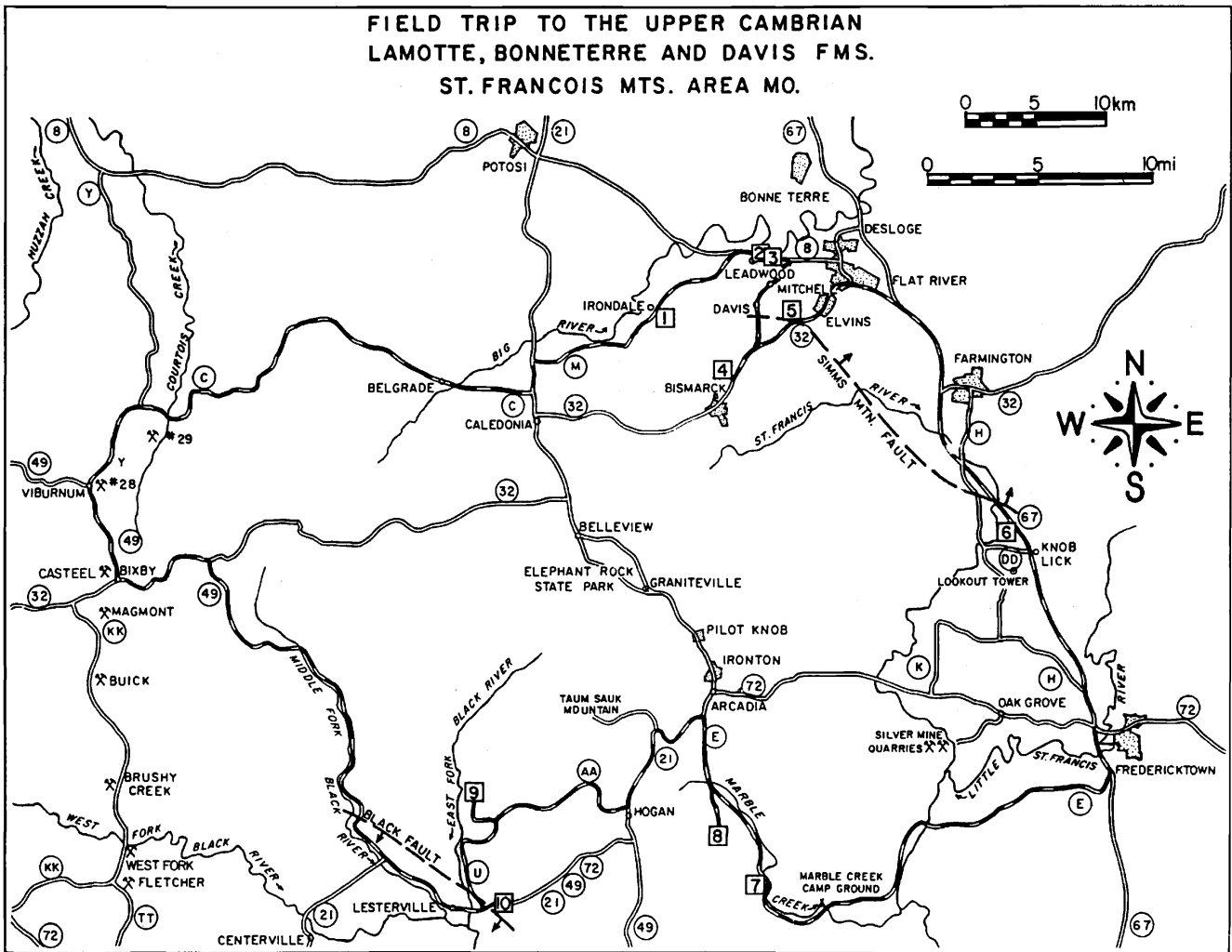


FIGURE 2 Road map of the field trip area.

Hwy 32. Go 2.4 mi (2.2 km) on Hwy 32 to intersection with County Rd. 32-B, the outcrop is on the right. This outcrop shows the conformable contact between the Bonneterre and the underlying Lamotte Sandstone. The rocks are dolomitic, arkosic sandstone and sandy dolomite, with cross-bedding, minor faulting, fracturing and vuggy weathering patterns.

**Stop 5.**

Turn around and go back (northeast) on Hwy 32 1.9 mi (3 km) to outcrop on the right. Lamotte Sandstone with arkose, quartz arenite, conglomerate, and shale facies. Note the cross bedding and channel cuts in parts of the exposure. The Lamotte Sandstone is regarded as a regional aquifer which transported the warm mineralizing brines from the basin to the sites of sulfide ore deposition in southeastern

Missouri (see Gregg, 1985). This outcrop is cut by several faults (Fig. 2) which are part of the Simms Mountain Fault system. The main trace of the fault is to the immediate northeast of the outcrop. There is about 800 feet of throw on the the fault at this location with the downthrown side to the northeast. The Upper Cambrian Derby-Doerun Formation crops out on the northwest side of the road just to the northwest of the Lamotte outcrop.

**Stop 6.**

Take Hwy 67 south to Farmington (see Fig. 3). (Note: 4.7 mi (7.5 km) wouth of the Hwy 67-Hwy W intersection the Simms Mountain Fault cuts across the road). At 5.6 mi (9 km) south of Hwy W intersection outcrop on right (west) side of Hwy 67. Thin-bedded Lamotte Sandstone overlying Precambrian igneous rocks.



Precambrian igneous highs and the overlying sediments exist in the subsurface as observed underground in the Viburnum trend mines. Pinch outs of the Lamotte Sandstone aquifer and the overlying carbonates where they overlapped Precambrian highs are believed to have formed "traps" where sulfide ores precipitated (see Grundmann, 1977).

#### Stop 10.

From the power plant go back on Hwy AA 2.1 mi (3.4 km) to Hwy U intersection. Turn right (south) on Hwy U and go 6.6 mi (10.6 km) to Hwy 21-49-72 intersection. Turn left (east) and go 0.5 mi (0.8 km) to outcrop on the left. Lower Davis Formation "white rock" facies. Note planar stromatolites, rip-up clasts and other shallow subtidal and intertidal features. These features are similar to those in the underlying Bonneterre "white rock" and contrast with the deeper water Davis shale facies observed at Stop 3.

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