SOCIETY OF ECONOMIC GEOLOGISTS

SEDIMENT-HOSTED Pb-Zn-Ba DEPOSITS OF THE MIDCONTINENT

Pre-Meeting Field Trip No. 1

November 3-8, 1986

In conjunction with

1986 Annual Meeting of the Geological Society of America

San Antonio, Texas

November 10-14, 1986

Society of Economic Geologists

SEDIMENT-HOSTED Pb-Zn-Ba DEPOSITS OF THE MIDCONTINENT

Pre-Meeting Field Trip No. 1

November 3-8, 1986

In conjunction with

1986 Annual Meeting of the Geological Society of America

San Antonio, Texas

November 10-14, 1986

Prepared for
publication by the
Missouri Department of
Natural Resources
Division of Geology
and Land Survey
P.O. Box 250
Rolla, Missouri 65401

Richard D. Hagni
Milton F. Bradley
Robert G. Dunn, Jr.
Paul E. Gerdemann
Jay M. Gregg
Timothy D. Masters
Charles G. Stone
Heyward M. Wharton

TABLE OF CONTENTS

ITINERARY

SOCIETY OF ECONOMIC GEOLOGISTS FIELD TRIP

SEDIMENT-HOSTED Pb-Zn-Ba DEPOSITS OF THE MIDCONTINENT

November 3-8, 1986

Part A: Ouachita Shale-Hosted Mineralization

November 3 (Mon.)

4:00-6:00 p.m.:	For early arrivers: Big Fork Chert surface Redox level exposed in cut behind the Vapors Lounge, or walk through Hot Springs Geothermal Field and observe Arkansas Novaculite.
7:30 p.m.:	Dinner reservations at the Arlington or place of choice (cost not included in the trip).
9:00-9:30 p.m.:	Ouachita Stratigraphy and Structural Deformation Events, Callahan Mining Corporation project and preview of following day's field stops.

November 4 (Tues.) 6:30-7:15 a.m.: Breakfast, with departure at 7:45.

9:00 a.m.:	Arrive at Caddo Gap roadcut to examine the Arkansas Novaculite (Upper Calcareous Chert Member, Middle Shale Member, and Lower Massive Chert Member — all well exposed).
9:30 a.m.:	Depart Caddo Gap.
10:00 a.m.:	Arrive at Dempsey-Cogburn barite mine and inspect soft-sediment deformation and pyritic breccia in top of Arkansas Novaculite and chert and the barite mineralization in the Basal Stanley Flysch.
10:45 a.m.:	Depart Dempsey-Cogburn area. Depart for lunch.
11:30 a.m.:	Arrive at Mosquito Gap, Missouri Mountain red slate quarry.
12:00 p.m.:	Lunch at Mosquito Gap.
12:30 p.m.:	Depart Mosquito Gap.
1:00 p.m.:	Arrive at Callahan's Macks Creek Prospect; 15 minute walk up creek through Polk Creek Cherty Shale and Limestone turbidite into the Big Fork Chert. Observe the massive hydromorphic Fe-Mn seep in creek, with Fe-Mn zonation and gossanous chert at the origin in prospect pits. Observe ferricrete in dry creek bed up drainage. The -80 mesh fraction of stream sediment in this creek assays up to 2.5 percent Zn. Display Callahan's Macks Prospect and planned drilling.
2:30 p.m.:	Depart Macks Creek.
3:30 p.m.:	Arrive at Manfred Melange (sedimentary melange in Womble Formation containing Blakely Sandstone fragments. Display Callahan's Polk Creek drill hole cross section and regional map.
4:30 p.m.:	Depart Manfred Melange.
4:50 p.m.:	Arrive at Mill Creek; 15 minute hike to observe Womble Formation-Big Fork Chert transitional zone and favorable SEDEX lithologies containing pyritic limestone turbidite, carbonaceous shale-chert, soft-sediment deformation, and fragmental rocks.
5:30 p.m.:	Depart Mill Creek.
6:30 p.m.:	Arrive at Arlington, Hot Springs.
8:30-9:30 p.m.:	Callahan and Exxon Core displayed.

November 5 (Weds.) 7:00 a.m.: Breakfast

7:45-8:00 a.m.: Check-out and depart hotel.
8:30 a.m.: Geomex Quartz mine to observe Blakely Sandstone debris flows.
10:00 a.m.: Depart Geomex.
10:45 a.m.: Arrive Chamberlain Creek Barite mine.
11:30 a.m.: Depart Chamberlain Creek for Hot Springs.
12:00 p.m.: Lunch in Hot Springs.
12:45 p.m.: Departure to Viburnum, Missouri.
6:00 p.m.: Arrive Viburnum Inn, Missouri.

Part B: Missouri Carbonate-Hosted Ores

November 6 (Thurs.) 6:30 a.m.: Breakfast at Viburnum Inn.

7:30 a.m.: Depart Viburnum Inn.
7:45 a.m.: Arrive at St. Joe Minerals Corporation's Viburnum 28 lead-zinc mine, Viburnum, Missouri or Cominco American's lead-zinc mine at Bixby, Missouri.
8:00-11:30 a.m.: Underground tour at Viburnum 28 or Magmont mines. The participants will split into two groups. One group will visit the Viburnum 28 mine; the other, the Buick mine.
11:30-12:30 p.m.: Tour of Viburnum or Magmont mill and flotation plant.
12:30-1:45 p.m.: Lunch at Viburnum Inn.
1:45-5:00 p.m.: Visit St. Joe Minerals Corporation Geological Research Laboratory, Viburnum, Missouri.
6:00 p.m.: Dinner at Viburnum Inn, Viburnum.
7:30 p.m.: Evening presentation by Paul E. Gerdemann, Chief Geologist, St. Joe Minerals Corporation, on the Geology of the Viburnum Trend.

November 7 (Fri.) 7:00 a.m.: Breakfast at Viburnum Inn, Viburnum

8:00 a.m.: Depart Viburnum Inn.
8:00-12:00 a.m.: Outcrops of Bonneterre and Davis formations showing reef, grainstone, offshore, arkosic and backreef facies, and Lamotte Formation.
12:00-1:00 p.m.: Sack lunch.
1:00-5:00 p.m.: Outcrops of Bonneterre and Davis Formations showing backreef facies, steep initial dips off Precambrian highs, faulting, and Precambrian welded tuffs with lithophysae.
6:00 p.m.: Dinner at Viburnum Inn, Viburnum.

November 8 (Sat.) 7:00 a.m.: Breakfast at Viburnum Inn, Viburnum.

8:00 a.m.: Depart Viburnum Inn.
8:30-9:30 a.m.: Outcrops of barite ore in bedrock.
9:30 a.m.: Arrive at barite mine, Washington County Barite District.
9:30-12:00 a.m.: Visit open pit mine, washer, and flotation plant.
12:00-1:00 p.m.: Lunch at De Soto, Missouri
1:00-3:00 p.m.: Drive to St. Louis, Missouri. Arrive St. Louis, Lambert airport.

ACKNOWLEDGMENTS

We thank the mining companies whose operations are to be visited and whose drill core is to be available for examination during this field trip and we acknowledge their cooperation: St. Joe Minerals Corporation, Cominco, American, Inc., IMCO Services (Division of Halliburton Company), Callahan Mining Corporation, and Exxon Corporation. The descriptions for some of the stops in Arkansas were modified from earlier descriptions by Marjorie S. Erickson, Barbara Chazin, A. Wallace Mitchell, and Samuel A. Bowring. Finally, we thank Heyward M. Wharton, Missouri Department of Natural Resources, Division of Geology and Land Survey, for reviewing the manuscript and for many valuable suggestions.

SOUTHEAST MISSOURI LEAD DISTRICT

by
Richard D. Hagni

Department of Geology and Geophysics
University of Missouri-Rolla
Rolla, Missouri 65401

IMPORTANCE, PRODUCTION, AND GRADE

The Southeast Missouri Lead district, the world's largest producer of lead since 1970 (15 percent of world production), has been the largest producer of lead in the United States since 1907, except for 1962, when production was reduced by a prolonged labor strike. Production has declined slightly but steadily since 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). The decline in the price of lead and labor problems reduced production in subsequent years and 405,965 short tons of recoverable lead metal were produced in 1985 (Missouri Department of Natural Resources, 1986). The district is second in zinc production in the United States. It yielded 70,196 tons of zinc metal in 1982, which constituted 21 percent of United States mine output (U.S. Bureau of Mines Mineral Industry Surveys, 1983). Because the price of zinc is much higher than lead, it has been mined selectively during the past year, and the 54,388 tons of recoverable zinc metal produced in 1985 constituted about 23 percent of United States mine output (Missouri Department of Natural Resources, 1986). The district placed Missouri fifth or sixth among copper-producing states in the United States; 8754 tons of copper metal were produced in 1982 and an estimated 14,227 tons in 1985. The silver in the district occurs only in solid solution in the base metal sulfides, but is recovered from those minerals and ranked Missouri fifth among silver-producing states in the United States. In 1982, 2.24 million troy ounces, accounting for 6 percent of domestic silver production, were recovered; in 1985, 1.6 million troy ounces, accounting for 4.5 percent, were recovered and placed Missouri fifth among silver-producing states. The value of these four metals in 1985 amounted to about 230 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 1 million tons of zinc, about 181,000 tons of copper, and nearly 33 million troy ounces of silver (Wharton, 1986). The figures from the 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 million tons from the Fredericktown subdistrict and 20,000 tons from the Annapolis subdistrict.

The Viburnum No. 28 mine accounted for between 7 and 8 percent of United States lead production in 1985 (Harold Myers, personal communication); the Magmont mine, for 18.5 percent (Milton Bradley, personal communication).

LOCATION, SUBDISTRICTS, CURRENT PRODUCING MINES, AND MINING HISTORY

The Southeast Missouri Lead district consists of several mining subdistricts in southeastern Missouri, around the core of the St. Francois Mountains. Figure 1, taken from Wharton (1975), shows the location of the subdistricts. The most recently discovered deposits occur in the Viburnum Trend, currently the only producer in the district. The Viburnum Trend comprises ten mines aligned approximately north-south over a distance of about 45 mi; it extends from about 5 mi north of the town of Viburnum to more than 15 mi south of the town of Bunker.

The mines constituting the Viburnum Trend (north to south) together with ownership and start-up dates, are the following:

- Viburnum No. 29 mine — St. Joe Minerals Corporation — November 1964
- Viburnum No. 27 mine — St. Joe Minerals Corporation — July 1960
- Viburnum No. 28 mine — St. Joe Minerals Corporation — January 1962
- Viburnum No. 35 mine — St. Joe Minerals Corporation — August 1983
- Magmont mine — Cominco American (operator) and Dresser Minerals — June 1968
- Buick mine — AMAX (operator) and Homestake Mining Company — February 1969
- Brushy Creek mine — St. Joe Minerals Corporation — November 1973
- West Fork mine — ASARCO Incorporated — September 1985
- Fletcher mine — St. Joe Minerals Corporation — February 1967
- Frank R. Milliken mine — Ozark Lead Company (Kennecott Copper) — June 1969

Mining in the Viburnum Trend began at the Viburnum No. 27 mine in July 1960. Five mines are currently producing from the Viburnum Trend: Nos. 29, 28, 35, Magmont, and Fletcher. The Viburnum No. 27 deposit has been mined out and the mine closed in September 1978. Viburnum No. 35 began production in August 1983. Production began in September 1985 at the West Fork mine, where two shafts were sunk in 1980. Underground development at West Fork was suspended in October 1982, but resumed in October 1983. The West Fork mill was completed in June 1983. The Milliken mine (formerly called Ozark Lead mine) is closed due to labor problems and economic conditions. A new shaft, the Ozark Lead Company's No. 6 shaft, was drilled at this mine in September 1980 to intersect an ore body that is separate from the Milliken ore body. The steel liner of the shaft ruptured and caused serious water problems. An ore deposit to the southwest of Milliken, the Blair Creek deposit, is owned by Ozark Lead but is undeveloped.

Until 1964 the principal production came from the old Lead Belt subdistrict, which is about 30 mi east-northeast of the northern end of the Viburnum Trend. The subdistrict was operated by St. Joe as three divisions (north to south): 1) Bonne Terre, 2) Leadwood-Desloge, and 3) Federal Mines-Flat River. The St. Joe Lead Company (now St. Joe Minerals Corporation) was formed in 1864 to mine deposits in the Bonne Terre area and by 1933 had become the sole operator in the old Lead Belt subdistrict, which is mined out, the last operations having been in October 1972. Much of the land has been donated to the State of Missouri to form St. Joe State Park and a Missouri Mines State Historical Site.

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. Although mining had ceased in the Fredericktown subdistrict by 1961, Anschutz Mining Corporation announced in 1979 that it would dewater the old Madison mine to extract the remaining ore reserves for cobalt, copper, and nickel (Brooke, 1981). However, the subsequent decline in the price of cobalt caused Anschutz to suspend developing

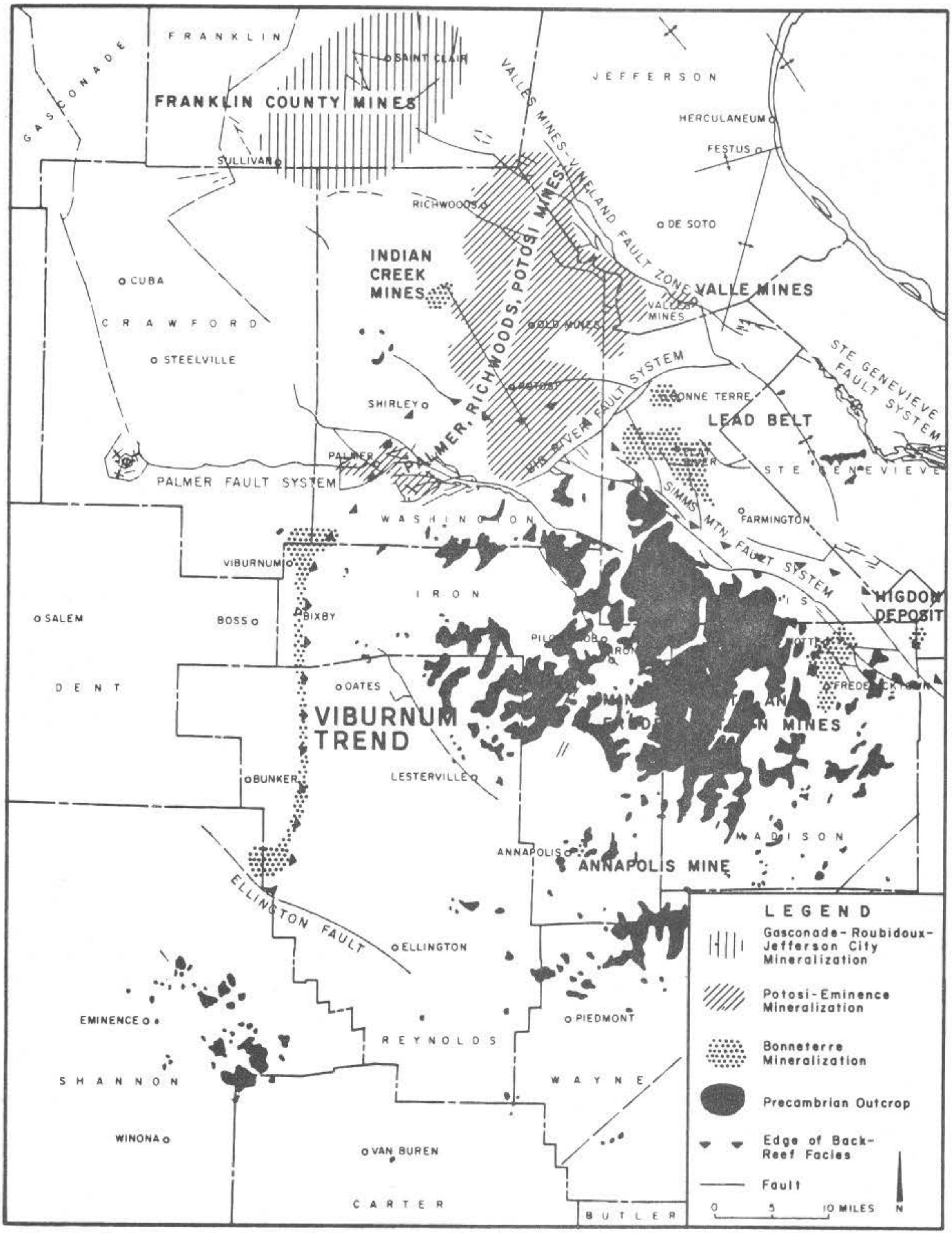


Figure 1

Map of Southeast Missouri Lead district.

the Madison mining project and recently made an agreement with Falconbridge, Ltd. for more drilling on their properties. Discovery of the Higdon deposit, about 10 mi northeast of Fredericktown, was announced by National Lead Company in 1956. A joint venture with Bunker Hill Mining Company was formed and plans for development were announced in 1964. Two drilled shafts were completed in 1967, but both shafts are now sealed. Bunker Hill bought out the NL Industries interests in 1976 and subsequently became a subsidiary of Gulf Resources and Chemical Corporation in 1968. The small size of the Higdon deposit, compared to deposits in the Viburnum Trend, has delayed further development.

St. Joe discovered the Indian Creek subdistrict, by drilling, in April 1948 as a result of efforts to discover additional lead reserves to replace those of the old Lead Belt, which were nearly exhausted. It is separate from and lies north of the main areas of lead-zinc mineralization in the lead district. The interesting factors that led to the discovery of the ore deposits at Indian Creek are related in an in-house memorandum by Richard E. Wagner, and in a paper by Ohle and Gerdemann (in press). These include 1) the decision by St. Joe in 1944 to explore for lead ore outside the old Lead Belt, where the reserves were declining; 2) leases that included land in which St. Joe was not interested; 3) a driller's attempt to wedge past a stuck drill bit; and 4) the decision to do additional optioning and drilling based on trace mineralization. Discovery of the Indian Creek subdistrict was important because it indicated that sizable lead deposits were not limited to the old Lead Belt and Fredericktown subdistricts and because it directed exploration efforts to other Precambrian knobs, including Czar Knob, and led to the discovery of nearby ore at what are now St. Joe's Viburnum mines. The Indian Creek subdistrict comprises two mines, the Indian Creek (two shafts: Nos. 23 and 24) and Goose Creek (No. 32) mines. They are northwest of the old Lead Belt and north-northeast of the Viburnum Trend, and were operated by St. Joe Minerals until April 1982.

The old Annapolis mine, which is far from other known mineralization trends, is about 22 mi east of the southernmost Viburnum Trend and about 20 mi southwest of the Fredericktown subdistrict. The mine exploited small ore deposits, which were mostly mined out by 1931, when the mine was closed.

GEOLOGY
(Stratigraphy and Structure)

The ore deposits of the Southeast Missouri Lead District are 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 silicic 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 (fig. 2). 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 ft and pinches out against Precambrian knobs.

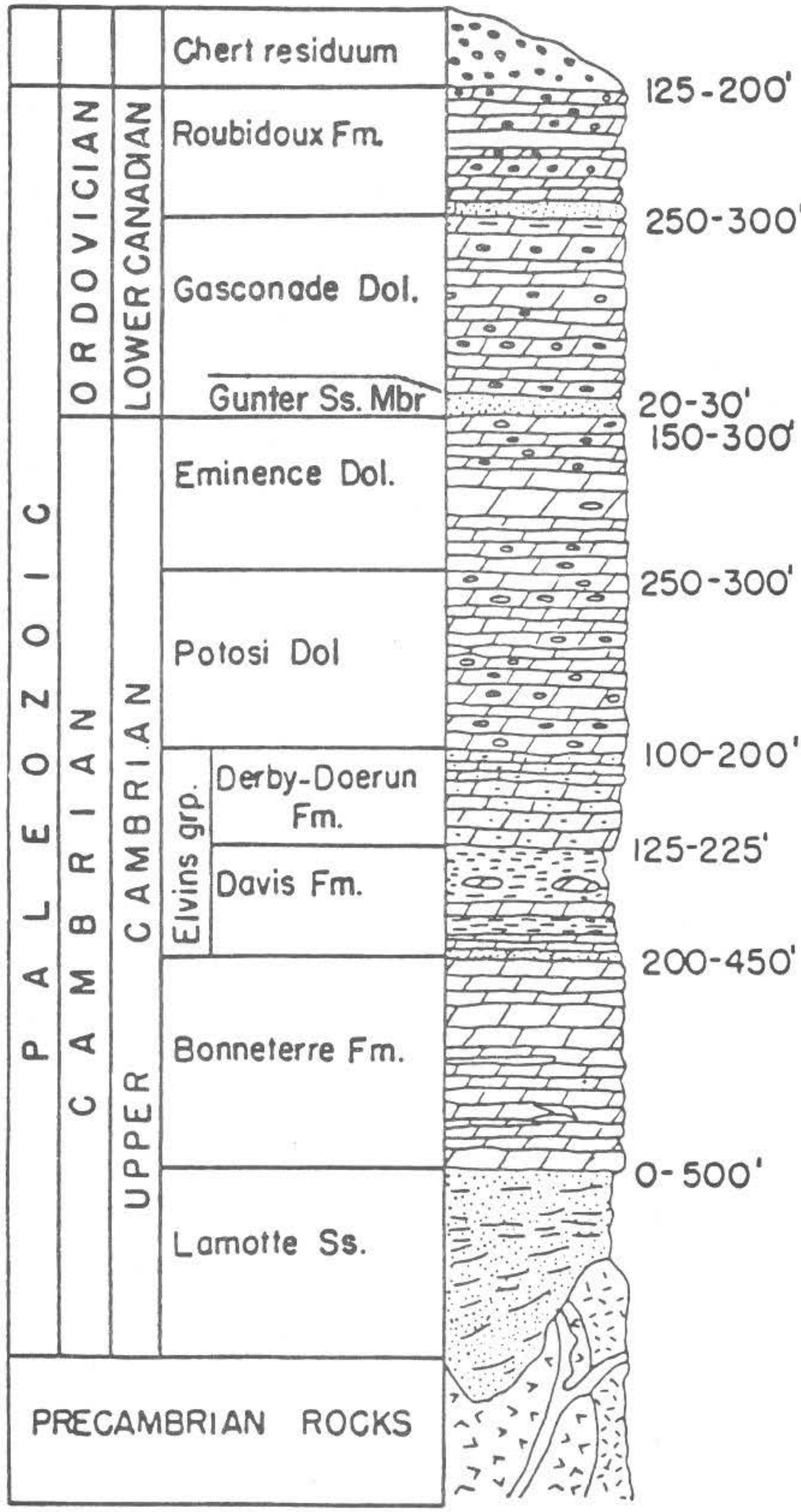


Figure 2. Stratigraphic Column for Southeast Missouri.

The Cambrian Bonneterre Formation overlies the Lamotte and forms a gradational contact in the form of a sandy carbonate called the "sandy transition." The Bonneterre Formation is mostly 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, 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 primarily in the lower third of the Bonneterre Formation; those in the Viburnum Trend are in 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 ft thick.

Correlation between mines of individual units within the Bonneterre Formation has been discussed by Larsen (1979). Two distinctive marker horizons in the calcarenites of the middle third of the Bonneterre Formation are called the False Davis and the gray beds at the Buick and other mines. The False Davis unit is just above the highest ore and probably formed an impermeable top for much of the ore fluids. The gray beds are in the lower portions of the ore bodies and were involved in solution thinning to form the host breccias.

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 relatively high potash content (10-11 percent) of the Davis shale suggested to Desborough et al. (1983) that the Davis may be largely tuffaceous; its thickness is 125-225 ft.

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 chert residue 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 are on the crests of some hills in the Viburnum Trend; brownish dolomite of the Cambrian Potosi formation, which contains abundant drusy quartz, is 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 in the vicinity of the old Lead Belt and may have been a factor in ore localization in that subdistrict (Snyder and Gerdemann, 1968).

The latter authors (1965) suggested that a series of structures having numerous similar features, aligned east-west across southern Illinois, Missouri, and eastern Kansas, are related and represent a basement zone of weakness associated with basic igneous rocks. These structures have been collectively called the "38th parallel lineament" because of their near alignment along that parallel. Perhaps it should be pointed out, however, that two of them, the Crooked Creek and Decaturville structures, both in Missouri, are variously classified as cryptovolcanic or extraterrestrial-impact structures. The lineament, so designated, is at the northern edge of the Southeast Missouri Lead District.

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 (Peter H. Sweeney, personal communication). 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, this guidebook). Many faults in the lead district postdate mineralization.

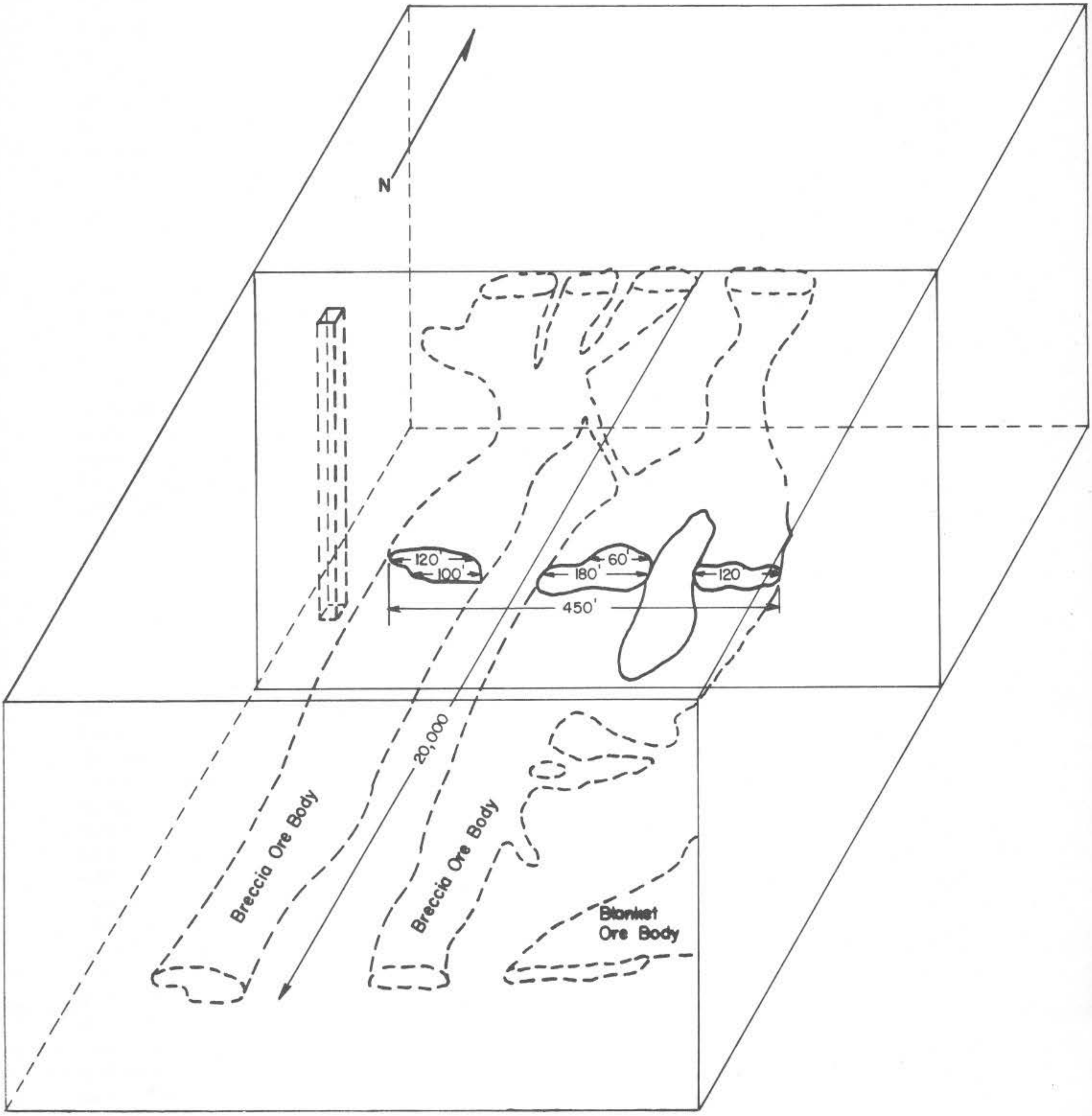
The northeast-trending New Madrid fault zone, which is about 30 mi south of known ore deposits in the Fredericktown subdistrict, has recently been recognized to represent an ancient rift zone that probably involved igneous activity over a long period (Hildenbrand, 1977). Along the fault zone, geophysical 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 district 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 depositon has suggested that there was a higher geothermal gradient at that time and that perhaps metals such as copper, cobalt, and nickel were added to the basinal lead-zinc-bearing brines from that source (E. Kisvarsanyi, 1983).

FORMS OF INDIVIDUAL ORE DEPOSITS AND CONTROLLING STRUCTURES

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 in 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, this guidebook); 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 ft wide (east-west), 30-60 ft thick (vertical dimension), and are 1 to 4 mi long (north-south) and extend across property lines. Figure 3 is a block diagram of ore bodies at the Buick mine. The east and west flanks of the breccia structures at Buick and Magmont typically dip away from the centers of those structures. Evidence of reverse throw along the bounding faults indicate that compressional forces may have been involved in the development of these structures. The principal factor in their development, however, was the solution thinning of certain beds in the Bonneterre Formation. At the Magmont mine much of this dissolution was in the silty marker bed (equivalent to the gray beds at the Buick mine). At the Milliken mine the most significant dissolution was in the Q-1 horizon, the lowest unit in the middle third of the Bonneterre Formation, which is immediately above the reef rocks in the lower third in that formation.

Figure 3. BLOCK DIAGRAM OF ORE BODIES AT BUICK MINE



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 (Norman Paarlberg, personal communication), 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, this guidebook). Where the breccia is less well developed the ore bodies have more extensive lateral dimensions. For example, the ore body at Fletcher is 2000 ft or more in width. Some of the structures formerly described as "basin," "graben," and "rift" deposits in the older subdistricts probably were similar to the solution collapse breccias in the Viburnum Trend. Gerdemann (in Ohle, 1985) has estimated that half the ore is 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, this guidebook).

The breccia structures being mined today developed largely by ore fluid dissolution, but the causes of their initial development and of their locations are not fully known. Answers to these questions are not only of academic interest but are also important to discovery of additional deposits with similar structural control. 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 ft high, west of the breccias, perhaps provided a sufficiently steep slope to locally initiate such slide breccias. At the Milliken mine, there is evidence that the solution collapse structure developed over the toe of a submarine slide (Larsen et al., 1979), which is interpreted to have been generated by oversteepened slopes associated with the Eminence Precambrian high to the southwest of the ore deposit and possibly to have been triggered by movement along the Ellington fault, which is also located to the southwest. 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 Bonneterre beds. Ohle (1985) has suggested that tectonic squeezing may have been an early process that acted before solution collapse in development of the principal breccias in the Viburnum Trend. He also supported the hypothesis of chemical brecciation as a contributing factor in addition to solution collapse and gravity shattering. Chemical brecciation is a proposed geological analogue of the alkali-chert and alkali-carbonate reactions that are well known to the concrete industry because they cause aggregate fragments to fracture and weaken concrete. The process was first suggested by Sawkins (1969) for the development of chert breccias in the Tri-State District.

A recent development is the mining of a linear breccia ore body in the Magmont West mine, which is about 2 mi west of the main Viburnum Trend, and is reached by a drift from the main Magmont mine (Bradley, this guidebook). The ore occurs mostly in the False Davis and contains about three times as much zinc as the average Viburnum Trend deposit.

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, appears to be examples of ore control by slide breccia. The ore bodies at Viburnum 27 are about 250-500 ft wide, 50 ft thick, and extend 2000 to 3000 ft 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 ft thick) and laterally extensive (up to 2000 ft east-west). They are 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, 1983; Mugel and Hagni, 1984). An underlying Precambrian high and minor fracturing appear to have been important factors in the plumbing system for the development of these deposits. 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 Bonneterre 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 is 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 Bonneterre, 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 Bonneterre Formation immediately overlying the pinchout of the Lamotte Formation (James, 1952). Such deposits are circular to horseshoe-shaped areally. For an example of the dimensions of such a deposit, the ore body at the old Missouri Cobalt mine (later part of the Madison mine), was 200 ft wide, 20 ft thick, and 4000 ft long. It was 400 to 425 ft 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 deposited 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, host rock dissolution vugs, bedding planes, fractures, etc., or as disseminated to massive replacements of host rock dolomite and shaly dolomite. All 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 in. on a side, apparently were deposited very slowly from dilute solutions. Rarely, rapid sulfide deposition led to development of colloform and even spherical galena forms (Rickman, 1981).

Sphalerite commonly occurs as small disseminated crystals replacing host rock 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, a fact that suggests that it has been 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 in the host rock, but it was also subsequently deposited as crystals, especially those that line small vugs in the ores and host rock. The principal time of deposition of the later dolomite was between the periods of deposition of octahedral and cubic galena. 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 host rock carbonate. Dickite was deposited in association with the ore deposits; where it is adjacent to sulfide crystals it appears to be a late mineral.

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, composiitonally zoned pyritohedral crystals, and less commonly forms thin layers in colloform marcasite-pyrite masses. The remainining minor minerals occur primarily either in bornite pods or in cobalt-nich-rich areas.

A few small (about 10 ft wide and 1 ft or less thick) pods of bornite ore have been discovered at some mines in the Viburnum Trend (Kastler, 1972; Woolverton, 1975; Horrall, 1982; Hagni, 1986a, 1986b, 1986c; Pignolet-Brandom and Hagni, 1986a). The ore textures and paragenetic relationships of the minerals in the bornite pods have recently been discussed by Hagni (1986a). The bornite exhibits a variety of textures with chalcopyrite. Exsolution textures are prevalent in the bornite ores from the Fletcher mine, a fact that suggests temperatures of deposition of 200°C or more. Banded colloform textures at the Viburnum 28 mine suggest rapid deposition. Replacement textures in which bornite has replace chalcopyrite are common at the Milliken mine and at the margins of the pods at the Fletcher mine. The thiospinel phase present in these pods is fletcherite at the Fletcher mine (Craig and Carpenter, 1977) and nickelean carrollite at the Milliken mine (Jessey, 1981a). Gersdorffite crystals were deposited early in bornite pods at the Fletcher mine and are successively altered to tennantite and then enargite (Hagni, 1986). Distinctly zoned crystals of cobaltian pyrite represent an early deposited phase that is replaced by the copper-iron sulfide minerals (Pignolet-Brandom and Hagni, 1986). At Milliken, the bornite pods have local thin veinlets containing chalcocite, digenite, djurleite, anilite, covellite, and blaubleibender covellite (Robin W. Potter, personal communication). 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 hot spots of early ore deposition.

Acicular millerite crystals deposited locally in vugs represent a different type of minor mineral occurrence. They are especially well known from the cobalt-nickel-rich zone along the east side of the west ore body at the Buick mine. The millerite needles probably were deposited from ore fluids of somewhat different composition than those that deposited galena and sphalerite (Hagni, 1983a). Millerite, which is widely distributed in very minor quantities throughout the region outside the lead district, was deposited on octahedral galena crystals and enclosed by later, cubic galena crystals. The millerite needles are commonly altered to polydymite pseudomorphs and coated by tiny vaesite cubes. Continued alteration of millerite forms siegenite pseudomorphs (Hagni, 1986a).

Since early study of the paragenetic sequence of the Magmont ores (Hagni and Trancynger, 1977) that sequence has been the subject of a number of studies, particularly at the University of Missouri-Rolla (Trancynger, 1975; Jessey, 1981; Rickman, 1981; Horrall, 1982; Pignolet and Hagni, 1983; Pignolet-Brandom and Hagni, 1986a) and have recently been reviewed by Hagni (1986a). Results of these studies indicate the general paragenetic sequence and many of the repetitions of deposition and dissolution are present at all the mines; these results also suggest that the ore fluids were largely capable of traversing the entire trend and suggest that most of the sequence of ore fluids traversed that trend. Support for this idea also comes from the fact that certain bands in gangue dolomite crystals can be traced by cathodoluminescence throughout the Viburnum Trend (Voss and Hagni, 1985). All the ore minerals were deposited during more than one period, many exhibit oscillations of deposition within a given period, the rates of deposition varied with time, and at times the earlier deposited minerals were partly or completely removed by dissolution. Some of the later deposited sulfides may have derived some of their constituents from the dissolution of earlier deposited sulfides. Evidence for this is found where high-grade cubic galena ores occur next to areas of leached octahedral galena (Norman Paarlberg, personal communication).

Unusual colloform cobalt and nickel ores deposited in the sequence millerite, polydymite, vaesite, tennantite, enargite, gersdorffite, chalcopyrite have recently been discovered in the Magmont West ore body (Pignolet-Brandom and Hagni, 1986b).

CATHODOLUMINESCENCE MICROSCOPY

Recent cathodoluminescence microscopy studies of gangue dolomite cements in the Viburnum Trend and surrounding region have provided some important information about the character of the ore-depositing fluids. Rickman (1981) discovered that four growth zones could be distinguished in single sparry dolomite cyrstals in the ores at the Milliken mine, due to the presence of marked variations in the intensity of cathodoluminescence produced by differences in Mn:Fe ratios. 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.

Subsequent cathodoluminescence microscopy studies of the Viburnum Trend dolomites by Voss and Hagni (1985) revealed that the four growth zones were detectable in sparry dolomite crystals in the ores throughout the 45-mi length of the Trend and established a "dolomite stratigraphy" similar to that discovered by Ebers and Kopp (1979) in Tennessee zinc ores and to that discovered by McLimans et al. (1980) for growth bands in sphalerite in the Wisconsin-Illinois zinc-lead district. Further cathodoluminescence study of sparry dolomite cyrstals elsewhere in Missouri and Arkansas by Gregg (1985), Rowan (in press), and Farr (1986) have shown that dolomites outside the district also possess the same four growth zones, which can be recognized for a distance of 350 km southwest of the Viburnum Trend, to the margins of the Tri-State and Northern Arkansas zinc districts. These observations indicate that the ore fluids have traversed a large portion of Missouri and Arkansas. Using the cathodoluminescence character of the four dolomite growth zones, Lohmann (in press) and Rowan (in press) have examined the variations in isotopic composition, fluid-inclusion-filling temperatures, and salinities of the dolomite-depositing fluids as a function of time.

During the course of cathodoluminescence microscopic study of the Viburnum Trend dolomites, it was noted by Gregg and Hagni (in press, a,b) that some dolomite crystals possess crystal faces that are not expressed by external morphology. Such crystal faces, which have been identified and indexed by universal stage techniques, are interpreted to have formed as a result of the high metal content of the depositing fluids and are believed to be potential guides to ore.

Cathodoluminescence microscopy has been used to detect breccias, termed ghost breccias, that were otherwise unrecognizable in some Mississippi Valley-type deposits (Kopp, 1981; Ohle, 1985).

FLUID INCLUSIONS

Fluid inclusion homogenization temperatures for sphalerite range from 137° to 82°C (Roedder, 1977; Hagni, 1983a), although the earliest black sphalerite has not been measured and presumably formed at a slightly higher temperature, perhaps about 180°-140°C. Early yellow sphalerite was deposited during declining temperatures (137° to 82°C); brown sphalerite, 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).

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). By the time calcite was deposited the salinity of the fluids was only about 12 to 2 percent NaCl equivalent.

Recent measurements of filling temperatures for tiny fluid inclusions in dolomite indicate that "hydrothermal" dolomite is not limited to the lead district but is widely distributed in Missouri (Leach, 1983; Rowan, in press). This conclusion suggests that the fluids that deposited dolomite were widely distributed and effectively penetrated the rocks of the region.

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 information in this section is summarized from that source. An average of 318 spectrographic analyses of galena from the Southeast Missouri Lead district shows a content of 85 ppm silver, a figure that may be somewhat high, inasmuch as about one ounce of silver per ton of galena concentrate (31 ppm) is commonly recovered at the smelters. Galena also contains small amounts of arsenic (340 ppm), antimony (171 ppm), and bismuth (50 ppm).

It is interesting to note that, in contrast to most districts (e.g., Tri-State, Southern Illinois-Kentucky), the silver content of sphalerite (434 ppm) in the Southeast Missouri district is about ten times greater than that of galena. However, because the district produces so much more lead than zinc concentrates, nearly as much silver is recovered from the former as from the latter. Sphalerite in other districts in the Mississippi Valley have average silver contents between 2 and 20 ppm. This feature, together with other mineralogical and chemical aspects, sets the Southeast Missouri Lead district apart from other districts of this type in the Mississippi Valley.

Cobalt (490 ppm) and nickel (391 ppm) contents are much greater in sphalerite in the district than in sphalerite elsewhere in the Mississippi Valley (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 in Mississippi Valley-type deposits elsewhere in the world.

The iron content of sphalerite in the district averages 8.3 percent, but it varies significantly in sphalerite crystals deposited at different times. There are other significant trace element variations between different generations of sphalerite in the district. For example, the cadmium content ranges from an average of 1.3 percent for one type of early black sphalerite to 0.28 percent for late yellow sphalerite. Indium and thallium have been detected in concentrates.

The average trace element contents in chalcopyrite are 38 ppm silver, 234 ppm molybdenum, 257 ppm bismuth, 272 ppm cadmium, and 33 ppm nickel.

Trace element concentrations have been discovered to vary significantly from the center to the periphery of galena crystals (Bhatia and Hagni, 1980; Bhatia and Blackburn, 1986). Silver, gallium, germanium, and indium concentrations increase in that manner, whereas arsenic decreases.

Gangue iron sulfides have not been thoroughly studied for their trace element content, but some analyses indicate an average of about 50 ppm silver and a maximum that is nearly an order of magnitude greater.

The rare-earth element patterns determined by Graf (1983) for coarsely crystalline dolomite and calcite (La/Sm 0.26-3.0) show that they are significantly depleted relative to host rock dolomite (La/Sm 5.1-8.7). He has suggested that such depletion may have resulted from ore-fluid interaction with ferromagnesian minerals in Precambrian basement rocks.

Chlorine and bromine contents, probably in fluid inclusions, of Bonneterre host rock dolomite adjacent to the ore deposits at the Buick mine are enriched (500-1000 ppm and 4-7 ppm, respectively) over background concentrations (400 and 2 ppm) (Panno et al., 1983).

ISOTOPE COMPOSITIONS

The lead isotope content of galena in the Southeast Missouri Lead district belongs to the J-type, an anomalous type that gives dates for ore deposition in the future. Differential leaching, over a long period, of a lead-uranium-rich source, such as the Precambrian basement, has been suggested as a mechanism to explain anomalous J-type lead (Pelissonnier, 1983). A comparison of lead isotopes in the ore with those in residues from rocks in the Precambrian basement, and in the Lamotte, Bonneterre, and Davis Formations suggested that the lead originated from the Lamotte (Doe and Delevaux, 1972), but Doe has also considered the Precambrian and the Bonneterre as possible sources in subsequent oral presentations. 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). Sulfur isotope ratios appear to vary systematically with variations in lead isotope ratios, the lighter ratios are associated with the more radiogenic lead ratios (Sverjensky et al., 1979). They have cited these data as evidence that the ore fluids contained both lead and sulfur, in contrast to a model in which the two constituents originated from different sources and combined as a result of mixing at the site of deposition.

Carbon and oxygen isotopic study of dolomite from the Milliken mine has shown that the dolomite crystals introduced with the ore fluids (-8.0 ^{18}O, -0.5 $^{13}CPDB$) can be distinguished from early host rock dolomite (-6.0 ^{18}O +2.0 $^{13}CPDB$) (Braunsdorf and Lohmann, 1983). Isotope variations between and within different zones in the hydrothermal dolomite crystals have been interpreted to indicate that much of their deposition occurred during mixing of two brines and that the mixing followed the introduction of a brine that deposited the main ores. Carbon and oxygen isotope studies of calcite and dolomite from the Magmont mine have been interpreted to indicate a changing fluid composition during the late stages of mineralization (Hannah and Stein, 1984).

Strontium isotope ratios for carbonates from the Brushy Creek mine show that calcite has higher ratios (about 0.711 to 0.712) than dolomite (about 0.709 to 0.710) and that the ratios increase outward with time for late zoned calcite crystals (Chadhuri et al., 1983). These systematic variations have been suggested to result either from strontium released from the alteration of different minerals in the source area at different times or from strontium derived from more than one source. Subsequent analyses of five cubic galena crystals from the Viburnum 27 mine contained 0.22 to 0.60 ppm strontium and 0.01 to 0.44 ppm rubidium; a galena cube from the Washington County Barite district contained 0.12 ppm strontium and 0.02 ppm rubidium (Lange et al., 1983). Strontium isotope ratios for barite from the latter district ranged from 0.710 to 0.712, contrasted to those of the dolomitic host rock that ranged from 0.708 to 0.709.

MINERAL AND METAL ZONING, MINERAL ASYMMETRY, AND POSSIBLE DIRECTIONS OF ORE FLUID FLOW

Several aspects of metal zoning, distributions of certain minerals, and asymmetrical mineral overgrowths in the Viburnum Trend have recently been summarized to indicate possible directions of ore fluid flow in the subdistrict (Hagni, 1983a). These data appear to indicate that in the Trend a major source of ore fluids was in the vicinity of the Magmont and Buick mines and that an important horizontal component of fluid movement was north and south from that source. These general directions were indicated by a study of mineral asymmetry; they are supported by 1) relative amounts of cobalt and nickel in the ores, 2) ratios of cobalt to nickel, 3) cadmium contents in sphalerite, 4) silver contents in cubic galena, 5) ratios of other metals, and 6) by distribution of ore grades throughout the Trend. These directions are further supported by the fact that iron sulfides and quartz are much more abundant at Magmont, and to a lesser extent at Buick, than in the mines north and south. The greatest contents of cobalt and nickel are in ores in the Magmont and Buick mines. The lowest nickel-cobalt ratio is in ores in the Buick mine. Incomplete data on the cadmium content of sphalerite suggest that it may be highest at Buick. Many analyses in the Trend indicate that the silver content of cubic galena is highest at Buick. It is apparent to even casual visitors to mines in the Trend that the ore grades at the Buick and Magmont mines exceed those at most others. Studies at one mine, the Buick mine, show progressive variations in cobalt and nickel contents and in the ratios of the two elements, factors that support a southerly direction of flow (Jessey, 1981a). These same factors suggest a second source of ore fluids, south of the Milliken mine (Hagni, 1983a). The fact that sparry dolomite is must abundant at the south end of the Viburnum Trend and becomes progressively less abundant northward (Voss and Hagni, 1985) may indicate that dolomite-depositing solutions moved south to north or that dolomite was antipathetic to sulfide deposition, a possibility suggested by dolomite deposition principally during a hiatus in sulfide deposition.

The importance of the vertical component of ore-fluid flow in the district is shown by indications that an important portion of the fluids moved upward into the Bonneterre from Lamotte pinchouts. It also is shown by vertical distribution of constituents; early formed massive chalcopyrite is lower in the ore bodies than late-deposited quartz, iron sulfides, and late chalcopyrite, which form upper and outer fringes of the deposits. It is shown by the presence of rare vertical veins that fed horizontal ore layers at their upper ends, where the fluids spread laterally into favorable sedimentary beds; such features are shown by copper mineralization at Milliken and by lead mineralization in the Magmont East ore body at Magmont.

In the old Lead Belt, copper-bearing ores were deposited most abundantly along the north and east edges of the subdistrict (Davis, 1960). Most of the copper was deposited early, a factor that suggests that the source of the fluids that deposited the ores in that subdistrict was to the north and the east. Zinc is most abundant in the central part of the southern portion of the subdistrict, where it is associated with the best lead grades. At Indian Creek the ores are principally on the northwest side of the Precambrian knob and the copper-rich portions are to the north, facts that suggest that the source of the ore fluids was to the northwest in this subdistrict. The high cobalt and nickel contents of ores at the Madison mine suggest the ores may occur near a source to the south. In the Viburnum Trend, some mines, such as Viburnum 27 (Grundmann, 1977) show copper concentrations to the west, but others, such as the Magmont C-level, show copper concentrations to the East (Stein, 1980). Most of the metal zonations in the district seem to indicate that the principal direction of the horizontal component of ore fluid flow was toward the central Precambrian high.

Metal zoning in a mine can be varied and indistinct. A common pattern, such as at the Buick and Magmont mines, is that in which copper occurs low, zinc higher, and quartz and iron sulfides form an upper and outer fringe. Throughout the entire length of the Buick mine, the West ore body contains a cobalt-nickel-rich zone along its eastern side.

AGE OF MINERALIZATION

The age of mineralization of the lead ores is still uncertain. Geological evidence indicates deposition after consolidation and brecciation of the Cambrian Bonneterre host rocks. The fact that fragments of the Davis Formation are locally cemented by ore indicates that some, and probably all, of the mineralization postdated deposition of the Davis Formation. Studies of very weak remnant magnetism of some ores indicate an alignment of paleomagnetic pole positions that correspond to the Late Pennsylvanian to Early Permian (Wu and Beales, 1981). A late Paleozoic age would be expected if the Ouachita Basin was the source of the ore fluids (Sharp, 1978). Lead istopes can not be used with a single-stage model to date the mineralization, because they give anomalous ratios. K/AR dating for post-galena illite clays in the Lamotte Sandstone indicate Early to Middle Permian ages and indicate that the ore fluids passed through the Lamotte before that time (Rothbard, 1983). Rb-Sr isotopic analyses of sedimentary or diagenetic glauconite pellets in the Bonneterre Formation yield dates younger than the host rocks. These analyses have been interpreted by Stein and Kish (1985) and Posey et al. (1983) to indicate that the glauconite isotope compositions may have been reset by introduction of the hydrothermal fluids during the Late Devonian or Early Carboniferous (359 Ma).

Rb-Sr age dating of galena from the Viburnum 27 mine have been interpreted to indicate an Early Devonian age (Lange et al., 1983), but the interpretation has been questioned on the basis of fluid mixing and for other reasons (Ruiz et al., 1985).

Although the mineralogy and structural controls at the Gortdrum Cu-Ag-U deposit in Ireland differs from that of typical Mississippi Valley-type deposits, it has been speculated that the U-Pb (340 Ma) and Pb-Pb isotope dates are representative of the Irish MVT deposits, that the dates are close to those for the Viburnum Trend and the Selwyn Basin in Canada (370 Ma), and that the deposits in all three districts are related to a major tectonothermal event that occurred in the Late Carboniferous, during closing of the proto-Atlantic (Duane et al., 1986).

GENESIS OF THE ORE DEPOSITS

As with all Mississippi Valley-type deposits, genesis of Southeast Missouri lead ores has been controversial. The fact that the deposits are near the surface, consist of simple minerals, and are not directly associated with igneous activity led to early interpretations that the metals were leached from host rocks by downward and laterally migrating cold meteoric groundwaters and deposited in favorable rock openings, essentially a hypothesis of lateral secretion. The incapacity of cold meteoric fluids to carry significant metal contents and the fact that such fluids are typically oxidizing led some to believe that magmatic hydrothermal (telethermal) fluids from undisclosed igneous sources distal from the deposits were responsible for their development. However, eventual acceptance of fluid inclusions as valid samples of the depositing fluids, together with evidence for heated and very salty fluids, led to the currently popular view that the ore fluids were connate brines derived from adjacent sedimentary basins. The Ouachita and Arkoma basins, south and southwest of the district, in Arkansas and Oklahoma, have been suggested as possible sources (Leach, 1979; Sharp, 1978; Rothbard, 1983). The fact that the fluid inclusions in sphalerite indicate somewhat higher temperatures (82°-137°C) than that expected for fluids from possible source basins has suggested to some workers that small additions of heat and perhaps metals from a magmatic source may have been involved.

The force that moved basinal brines to the depositional sites of Mississippi Valley-type ore deposits has been the subject of recent research. Although sediment compaction during basin subsidence has commonly been believed to have provided the force to push the fluids up-dip, episodic dewatering from overpressuring has recently been advocated by Sharp (1978) and Cathles and Smith (1983). Numerical modeling suggested that gravity-driven groundwater flow due to topographic uplift and elevation of the Pascola arch in post-Early Permian to pre-Late Cretaceous time was a viable alternative for moving ore fluids to the depositional sites of ores in the Wisconsin-Illinois Zinc-Lead district (Bethke, 1986). Similar modeling has indicated that gravity-driven brine flow from southwest to northeast could account for fluid movement to the depositional sites of the zinc-lead ores at Pine Point, Northwest Territories (Garvin, 1985). Bethke (1986) notes, however, that compaction-driven flow may be the dominant ore-forming process for ore districts associated with the Ouachita basin, because the latter has much more shale than the Illinois basin and its rate of subsidence was more rapid.

The fact that ore deposits of the Southeast Missouri Lead district and Liasvall, Sweden differ from most other Mississippi Valley-type deposits in their high lead-zinc ratios has been a problem for many investigators. Some workers (Bjorlykke and Sangster, 1981; Sangster, 1983) believe that the deposits in those two districts represent a subtype and that their genesis is related to groundwater transport with precipitation, at the interface with marine water. It has recently been proposed that the high lead contents resulted from the smaller capacity for reactions of oil-field brine waters with rock in sandstone aquifers than in carbonate aquifers (Sverjensky, 1984).

An important unsolved problem is whether the metals and sulfur were carried in two different fluids, with sulfide precipitation resulting from mixing of the two fluids (essentially the Jackson and Beales (1967) model), or whether both were carried in the same fluid. In addition to the isotope evidence noted earlier, another feature that has been cited to argue against a mixing model is that the sulfides should show abundant evidence of rapid deposition and that they should be fine grained in contrast to the large well-formed crystals of much of the ore.

Metal solubility and transport have commonly been attributed to chloride complexing because of the high chlorine content of the fluid inclusions and because of the increased solubility of many metals in a sodium chloride brine. Attention has recently concentrated on the possible role of organic complexing (Giordano and Barnes, 1981; Giordano, 1985). One form of organic matter present at the Magmont mine, bitumen, appears to have formed very late in the paragenetic sequence, after most of the sulfide minerals had been deposited (Marikos, 1986). By considering the full mineral assemblage, it has been difficult to fix closely the chemical character of the ore fluids that formed Mississippi Valley-type ore deposits (Barton, 1983). Anderson (1983) discussed possible chemical parameters of the ore-depositing fluids. It has been argued by Stormo and Sverjensky (1983) and Sverjensky (1984) that the pH of the ore fluids must have been acid (pH=4), as indicated by alteration of potash feldspar to kaolinite.

Equally uncertain is the source of the metals. Many have argued, because of trace amounts of lead in the Bonneterre Formation, that the metals may have been leached from that formation. As noted earlier, the lead isotope content suggests the Lamotte as the source. Because there are metals in the Precambrian basement, in the form of scant ore deposits or as trace lead in feldspars, others (e.g., G. Kisvarsanyi, 1977) have suggested that the basement may have supplied some metals to the brines.

A recent conference at St. Austell, Cornwall, England has served to focus attention upon the capability of granites with a high content of heat-producing radioactive elements to provide significant amounts of heat by radioactive decay long after their final solidification (Halls, 1985). Granites of Variscan age in the Cornwall tin district have high uranium and thorium contents and are called "high heat-production granites"; they have supplied heat to groundwaters that for a long time have promoted development of groundwater circulation cells. Numerical modeling and the presence of modern hydrothermal brines in some Cornish mines indicate that groundwater temperatures of about 50°C may develop by this process. Other factors, such as a sizable overburden and additional heat contributed from some regional thermal source, can elevate that temperature to as much as 200°C (e.g., Fehn, 1985). These deeply circulating and heated groundwaters leached metals such as uranium from the granitic rocks in the Cornwall district and precipitated them at higher levels, on cooling from Pennsylvanian to Pleistocene times. Although this model has been applied to the origin of the uranium and kaolinite deposits in the Cornwall district, and to SEDEX deposits (Russell, 1986), the possible application of such a model to Mississippi Valley-type deposits also can be considered. 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). Such a model appears to find some support in the widespread alteration of the basement rocks (chloritic alteration of the mafic minerals and turbid feldspars) and in the oxygen isotope ratios (high O^{18} and deuterium) (Wenner and Taylor, 1972). The presence of greater amounts of cobalt and nickel in the Fredericktown subdistrict, where potential source rocks, diabase dikes and sills, are most abundant, may constitute further support for the application of this model to the Southeast Missouri district. The presence of volcanics within the Bonneterre Formation indicates that there was an additional heat contribution at least in early Paleozoic time. Erickson et al. (1978) have argued against the Precambrian volcanic and granitic rocks and locally derived Precambrian detritus in the basal Cambrian Lamotte Sandstone as sources for the Southeast Missouri ores, because those rocks contain less than 5 ppm of Cu, Ni, and Co, and only about 20 ppm Pb. Whether the Precambrian served as an important source for the metals and whether such circulation cells existed are subjects for further investigation.

EXPLORATION

Although ore deposits in the old Lead Belt and Fredericktown areas were discovered in outcrops of lead mineralization, drilling, closely guided by geologic features, has been the principal means of exploration elsewhere in the district. Ohle (1982) and Ohle and Gerdemann (in press) have summarized the exploration history involved in the Southeast Missouri district. The discovery of the Bonne Terre portion of the old Lead Belt represented the first place in the world where diamond drilling was applied to metal exploration. The growing realization of diminishing reserves in the old Lead Belt was the principal impetus toward exploration outside that subdistrict. In 1940-1941, St. Joe embarked upon an expanded drilling program based on three geological models. One model, that the Precambrian knobs were favorable loci for ore deposits, had been especially evident in the Fredericktown subdistrict and the Doe Run area in the old Lead Belt. Four small Precambrian knobs, which are shown on the State of Missouri geological map, drew attention to the general vicinity of Indian Creek. It was near a buried Precambrian knob, after drilling 1000 holes (churn drilled through the cherty dolomite formations into the Davis and cased and then diamond drilled through the non-cherty Bonneterre to the top of the Lamotte), that the first pay hole was drilled in 1947 at Indian Creek. An interesting quirk of exploration history is that this was to be the last exploration hole and the hole was incorrectly spotted in a stream valley that was not the one intended. Discovery of the Indian Creek deposits by St. Joe attracted other exploration companies and led eventually to the exploration boom in Missouri in the 1950's.

Early in the 1950's drilling concentrated in the vicinity of Czar Knob, around a nearby buried Precambrian knob. Czar Knob was known from surface outcrops of Precambrian rocks, in an area normally occupied by sedimentary rocks belonging to the Eminence and Potosi Dolomites, all of which were shown in this area on the State Geological map. The first ore hole in the Viburnum trend was drilled in September 1955, by St. Joe near the buried knob and near the present shaft at the Viburnum 27 mine. Another of the interesting quirks of exploration history is that the discovery of ore at Viburnum 27 was the result of drilling almost exactly at the location of a core shed of a company that had abandoned the property.

Some of the subsequent drilling in 1956-1957 and even later was concentrated on the area between the discovery at Viburnum and the old Annapolis subdistrict to the southeast. This exploration was predicated on the erroneous idea that the Black fault might have been an important structural control for the deposits known at that time. The fact that the Black fault trended northwestward parallel to the Ste. Genevieve fault system in the old Lead Belt supported that exploration concept. Another idea, that a Precambrian ridge might trend southeast from the Czar knob area to connect with a small Precambrian outcrop southeast of Bixby, was erroneous but did lead to the discovery of the Viburnum 28 mine (Wharton, 1986, personal communication).

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 (Geza Kisvarsanyi, personal communication).

For some time it was not realized that the discoveries at Viburnum and by Ozark Lead were actually the termini of a 45-mi-long trend of ore deposits. With the discovery of ore by St. Joe at Fletcher in 1958, it became evident that additional deposits might be discovered between Viburnum and Ozark Lead. The earlier idea of a trend toward Annapolis was largely discarded, and at least a dozen companies actively began exploring the developing Trend. Because much of the land involved was U.S. Forest Service Lands and because the land that could be leased from that agency by a company at any time was restricted to 20,480 acres, the process of land evaluation was slowed sufficiently to prevent any one company from acquiring all the deposits eventually discovered in the Viburnum Trend.

During the next four years, when the principal ore bodies were drilled out, exploration was aided by several factors. One was the use of magnetic and gravimetric methods to gain knowledge of basement topography, and thereby determine Precambrian highs and areas where Lamotte pinchouts may have channeled ore fluids up into the Bonneterre. Data obtained by geophysical methods were also partly the result of lithologic variations in the Precambrian basement. Spector and Pichette (1983) discussed the application of aeromagnetics to lead exploration in southeast Missouri.

Aerial photography was used to assess drilling density by competing companies and formed a guide to further exploration. Much of the earliest drilling was on 1000-ft centers. Near ore intersections additional drilling on 500-ft centers served to outline ore bodies. The reduced spacing was an indication of mineral discoveries. Eventually, before mining, holes were commonly placed in the centers of the 500-ft squares. Despite the close-spaced drilling, much higher and lower grades are locally encountered in development drilling and mining than were anticipated from earlier drilling.

Exploration in the Viburnum Trend also was greatly aided by increased understanding of the control of ore deposition by sedimentary facies of the Bonneterre Formation. This understanding began in 1949 with Harlan Johnson's recognition that the snurly or fingered Bonneterre rock is algal reef. Subsequently, it was gradually recognized that the so-called "white rock" is a backreef facies, that the shaly limestone are forereef facies, and that the ore deposits are largely confined to dolomitic calcarenites in the Bonneterre above the reef. Exploratory drill sites could therefore be limited to an area between the white rock front to the east and the limestone to the west. The role of the Precambrian basement configuration and related Lamotte pinchouts and Bonneterre depositional facies in discovery of the Viburnum Trend deposits is an important case history in exploration geology.

In the Viburnum trend, applied mineralogy and geology are currently as important as during the period of discovery. At all the mines one or more geologists are involved in grade control, reserve determination, exploration, and rock mechanics. A recent presentation by Brumbaugh (1983) treated the role of mine geologists at the Buick mine. A cooperative program of mapping and resource appraisal by the U.S. Geological Survey and the Missouri Geological Survey has produced numerous maps that should aid future exploration in the region (Pratt et al., 1983).

MINING

All 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 1000 to 1200 ft below the surface at mines in the Trend, except at Viburnum, where it is 600 ft. A recent paper by Weakly (1982) describes in detail the ore moving methods for most mines in the Viburnum Trend.

BENEFICIATION

The St. Joe and Magmont 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 chalcopyrite particles. Dolomite, sphalerite, marcasite, and pryite 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 chalcopyrite to float. The concentrator at Buick has been discussed by Randall and Arterburn (1970); its capacity exceeds 100,000 short tons of recoverable lead per year (Missouri Department of Natural Resources, 1983).

MINERALOGY APPLIED TO BENEFICIATION

In the Viburnum Trend, the wide variety of beneficiation problems that applied mineralogy and ore microscopy have benefited were recently summarized by Hagni (1983c). Some of these involved incomplete separations of 1) sphalerite, pyrite, and marcasite from lead concentrates; 2) dolomite and siegenite from the zinc concentrates; 3) galena and siegenite from copper concentrates; and 4) galena, sphalerite, and chalcopyrite from the final tailings.

Some of the more interesting applications of ore microscopy have involved the detection of locked particles. Binary locked sphalerite-dolomite in all zinc concentrates from the lead district has required either sulfuric acid treatment of the final concentrates or regrinding and reflotation to reduce their magnesium content (from about 1.2 percent to less than 0.6 percent). At the electrolytic refineries magnesium is a deleterious constituent of the concentrates. Binary locked sphalerite-siegenite in the zinc concentrates from some ore bodies has resulted in their cobalt and nickel contents exceeding that acceptable (0.13 percent cobalt or 0.25 percent cobalt and nickel) at the electrolytic refineries.

Other applications of ore microscopy have involved detection of free particles that should not be present. Small, free galena particles in the copper concentrates until recently have caused all copper concentrates produced in the lead district to be shipped overseas. The lead content of some of the copper concentrates has recently been reduced by increased agitation with Denver attrition machines during conditioning before copper-lead separation (James A. Jones, personal communication). Free iron sulfide particles can be observed in lead concentrates when the on-stream X-ray analyzer has misread some of the iron in the heads as lead and automatically increased the isopropyl xanthate content in the lead circuit (Robert D. Deister, personal communication). Small amounts of lead, zinc, and copper are lost to the tailings; ore microscopy can show that these metals are largely present as free particles.

An especially interesting beneficiation problem is that which involves efforts to recover cobalt and nickel from the ores. Cobalt and nickel concentrates have been produced only at the Madison mine, where the average amounts of these metals are about an order of magnitude greater than elsewhere in the district, and during a time (World War II) when United States government support was available. The beneficiation difficulties result from 1) siegenite grains in locked particles with chalcopyrite,

pyrite, bravoite, and other minerals, 2) free siegenite which has flotation properties similar to those of chalcopyrite, and 3) the presence of cobalt and nickel in other phases, such as bravoite, carrollite, polydymite, etc. Recent research by the U.S. Bureau of Mines on this problem has been summarized by Clifford and Higley (1978). Pignolet and Hagni (1984) conducted ore microscope and electron probe studies of the Madison ores. Although the amounts of cobalt and nickel are much less elsewhere in the district, current research by the Bureau of Mines involves efforts to recover cobalt from copper concentrates at Magmont (Frank H. Sharp, personal communication) and from mill tailings in the district (Cornell et al., 1986).

Anschutz Mining Corporation dewatered the Madison mine in the late 1970's to evaluate the remaining reserves for their cobalt and nickel contents; Falconbridge recently optioned the property to continue the evaluation. Cobalt and nickel averaged about 0.23 and 0.29 percent, respectively, in the ore produced from the Madison mine from 1944 to 1961 (Brooke, 1981); ores from the Fredericktown subdistrict contained about ten times that present in the average ores from the Viburnum Trend (Hagni, 1983b). Ore microscope examination of the drill core from exploration on the Madison property and concentrates previously produced from the mine show that cobalt and nickel occur in two deposits that differ in stratigraphic positions, mineralogy, and potential beneficiation problems (Pignolet-Brandom and Hagni, 1983; Pignolet-Brandom and Hagni, 1985a). Ores previously mined at Madison came from the lower portion of the Bonneterre Formation where it is transitional with the underlying Lamotte Sandstone; they were lead-copper ores in which cobalt and nickel were present, principally as siegenite. Previous and potential beneficiation problems with these ores result primarily from intergrowths of siegenite with chalcopyrite. Cobalt and nickel mineralization that was recently investigated in the upper portion of the Bonneterre Formation contain abundant bravoite and siegenite and has only small amounts of chalcopyrite and galena. Potential beneficiation problems with these ores are expected to involve dilution of the concentrate grade by pyrite and marcasite.

Ore microscope studies of concentrates prepared from broken ore after blasting and allowed to remain underground for periods of several months show that in the concentrates galena has thin oxidation coatings of cerrusite and goethite and that chalcopyrite has similar coatings of covellite. Such coatings cause poor flotation recoveries (Schroer et al., in press).

SINTERING AND MINERALOGY APPLIED TO LEAD SMELTERS

The lead concentrates are sintered into a feed for the lead blast furnace to remove part of the sulfur and to agglomerate the concentrate. A reflected light microscope study by the U.S. Bureau of Mines (Dressel et al., 1975) illustrates the usefulness of applied mineralogy in the study of phases in a lead smelter. Although most workers previously believed lead oxide and lead sulfate formed the principal phases constituting the lead sinter, these phases were only found in limited amounts. Lead sinters from AMAX's Buick smelter, ASARCO's Glover smelter, and St. Joe's Herculaneum smelter were discovered by ore microscopy and electron probe analyses to consist of four principal phases in decreasing order of abundance: 1) lead silicate, 2) lead-zinc silicate, 3) lead-zinc-bearing calcium silicate (wollastonite), and 4) an iron-zinc spinel.

SMELTING

The lead concentrates from the Viburnum Trend are treated principally at three lead smelters. The Homestake Buick smelter, which can produce more than 140,000 short tons per year of pig lead (Missouri Department of Natural Resources, 1983a) is 2.5 mi from the mine-mill area. The ASARCO Glover plant, which can produce more than 110,000 tons per year of pig lead, is in the small town of Glover, 22 mi east of the Viburnum Trend. The St. Joe Herculaneum plant was modernized and expanded in 1967 to produce more than 230,000 tons of pig lead per year. It is located on the Mississippi River at Herculaneum, south of St. Louis, and about 50 mi northeast of the Viburnum Trend.

The Buick smelter, which began production in 1968, processed lead concentrates in three steps: 1) sinter plant, 2) blast furnace, and 3) refinery. The purpose of the up-draft sinter plant is to get rid of part (about 72 percent) of the sulfur (produces SO_2, which goes to the sulfuric acid plant) and to aggregate the lead concentrate for feeding the blast furnace. The feed to the sinter plant consists of approximately 28 percent lead concentrate, 50 percent fines from the sinter output, 16 percent blast furnace slag, 5 percent dross, 0.5 percent quartz sand, and a trace of pyrite. The reason for the large recirculation of the sinter fines is that excessive fines in the blast furnace feed produce problems partly by being blown back. More importantly, the fines fill pore spaces and thereby reduce air circulation which can cause incomplete melting of the blast furnace feed. Coke is added to the sinter to form the feed to the two blast furnaces. Products continuously tapped from the blast furnace are molten lead bullion, molten slag, and SO_2 (goes to the bag house). The lead bullion is treated successively in the refinery in 1) drossing kettles to produce a lead bullion and a copper-bearing dross, 2) sodium process kettles to produce lead metal and a copper matte, 3) decopperizing kettles, where pyrite is added to extract the last of the copper and sulfur, 4) desilvering kettles where zinc is added to alloy with silver, and 5) dezincing kettles where NaOH and KNO_3 are added to extract the zinc. The refined lead is 99.99 percent pure and poured into 100 pound pigs and 2000 pound blocks.

The lead content of the blood of the workers at the Buick smelter is closely monitored and kept at safe levels by temporarily assigning workers to low-lead areas if necessary.

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 sent abroad for smelting. Some of those with low lead content are smelted domestically.

MINERALOGY APPLIED TO SMELTING

Small amounts of pyrite, which is a fluxing and reducing agent, are used in smelting the Viburnum Trend lead concentrates. Pea Ridge formerly produced about 10,000 tons of byproduct pyrite concentrate annually, much of which was consumed in smelting in the Viburnum Trend and at Herculaneum. The Pea Ridge pyrite, however, contains about 0.05 percent nickel, which is a detrimental constituent in the reverberatory furnace, where it forms high melting point alloys. An ore miscroscope study of pyrite-rich portions of Pea Ridge iron ores and of the pyrite concentrates identified the nickel-bearing phase (Hagni, 1981, 1983). If the nickel were carried, as expected, in solid solution as the mineral bravoite, there would be no hope for reducing the nickel content of the pyrite concentrates. On the other hand, if a separate nickel-bearing mineral is present it might be possible to separate that phase from the iron sulfide concentrates, reduce their nickel content, and market a greater amount of the pyrite concentrates. Ore microscope examination showed that no bravoite is present in the Pea Ridge pyrite concentrates. The nickel occurs as a separate phase, identified as melonite ($NiTe_2$) by quantitative measurements of its very low hardness (Vickers hardness number 100) and quantitative measurements of its very high reflectance (65 percent), together with its distinctive anisotropism showing colors of grayish purple to yellowish brown. Its identity was subsequently further confirmed by scanning electron microscopy with energy dispersive spectroscopic analyses. Because the nickel content is present as a separate phase, rather than in solid solution in the pyrite, and because the melonite forms rather coarse grains and veins showing simple locking with the pyrite, it appears that much of the nickel could be separated by flotation to reduce its content in the pyrite concentrate.

Pea Ridge pyrite also contains about 0.5 percent cobalt, and the pyrite concentrate is currently being examined by ore microscopy to identify the cobalt-bearing mineral.

The formation of deleterious "slick" dross at the surface of the drossing furnaces at the Herculaneum, Missouri smelter has recently been examined by reflected light microscopy (Pignolet-Brandom et al., 1986b). Phases identified by microscopy and electron microprobe analyses included galena, metallic copper, Cu_2S, NiAs, $Ni_4Pb_3S_3$, and Pb-Cu sulfides with variable compositions. Other pyrometallurgical products examined by reflected light microscopy and probe analysis in that study included lead sinter, lead blast furnace slag, copper dross, and dust particles.

ENVIRONMENT AND FOREST LANDS

The development of the mines in the Viburnum Trend, with their limited surface disturbance, is one of the industry's best examples of the compatibility of mining with other land uses. Missouri visitors who have driven through the heart of the Viburnum Trend commonly ask this writer where the mines are located. Most of them are concealed from main highways and blend into their natural surroundings, so that the casual visitor is hardly aware of them.

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. In fiscal 1982, they amounted to 5.26 million dollars; in 1985 they were 3.08 million dollars, and they reached nearly 14 million dollars in 1980 (Missouri Geological Survey, 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), and which is designed to reimburse the counties for their loss of property taxes; this totaled $224,857 in fiscal 1982, $718,434 in 1985.

REFERENCES CITED

Anderson, G.M., 1983, Some geochemical aspects of sulfide precipitation in carbonate rocks, *in* Kisvarsanyi, G., Grant, S.K., Pratt, W.P., and Koenig, J.W., eds., International Conference on Mississippi Valley Type Lead-Zinc Deposits, p. 61-76.

Ault, W.U., and Kulp, J.L., 1960, Lead isotopes and ore deposition in the S.E. Missouri Lead District: Economic Geology, v. 55, p. 73-100.

Barton, Paul B., Jr., 1983, High-temperature calculations applied to ore deposits, Chapter 14, Mineral-fluid equilibria in hydrothermal systems: Society of Economic Geologists short course book, preliminary edition, Indianapolis, Indiana, 10 p.

Bethke, Craig M., 1986, Hydrologic constraints on the genesis of the Upper Mississippi Valley Mineral District from Illinois basin brines: Economic Geology, v. 81, p. 238-249.

Bhatia, D.M.S., and Blackburn, W.H., 1986, Trace element variations in galena crystals— Mississippi Valley-type deposits: AIME-SME Transactions.

Bhatia, D.M.S., and Hagni, Richard D., 1980, Laser probe determinations of trace element concentrations in sulfide minerals from the Magmont mine, Viburnum Trend, southeast Missouri: AIME-SME Transactions, v. 268, p. 1847-1855.

Bjorlykke, A., and Sangster, D.F., 1981, An overview of sandstone lead deposits and their relation to red-bed copper and carbonate-hosted lead-zinc deposits: Economic Geologists, 75th Anniversary Volume, p. 179-213.

Bradley, Milton F., 1986, Magmont-West mine (Cominco American Incorporated & Dresser Industries), Viburnum Trend, southeast Missouri, in this guidebook.

Braunsdorf, N.R., and Lohmann, K.C., 1983, Isotopic trends in gangue carbonates from the Viburnum Trend, Ozark Lead mine, S.E. Missouri (abstract): Geological Society of America, 96th Annual Meeting, Indianapolis, Indiana, p. 532.

Brooke, G.L., 1981, Madison Cobalt mine, Madison County, Missouri: AIME-SME Preprint 82-324, Denver, Colorado, November 18-20, 3 p.

Brown, John S., 1967, Isotopic zoning of lead and sulfur in southeast Missouri: Economic Geology, Monograph 3, p. 410-426.

Brumbaugh, R.L., 1983, Mine geology and its relationship to operation, exploration, and research (abstract): Fall Meeting, Society of Mining Engineers, AIME, Salt Lake City, Utah, p. 22.

Chadhuri, S., Clauer, N., and Ramakrishnan, S., 1983, Strontium isotopic composition of gangue carbonate minerals in the lead-zinc sulfide deposits at the Brushy Creek mine, Viburnum Trend, southeast Missouri, *in* Kisvarsanyi, G., Grant, S.K., Pratt, W.P., and Koenig, J.W., eds., International Conference on Mississippi Valley Type Lead-Zinc Deposits, p. 140-144.

Clifford, R.K., and Higley, L.W., Jr., 1978, Cobalt and nickel recovery from Missouri Lead Belt chalcopyrite concentrates: U.S. Bureau of Mines, Report of Investigations 8321, 14 p.

Cornell, W.L., Holtgrefe, D.C., and O'Connor, W.K., 1986, Ore microscopy in support of applied beneficiation research to recover cobalt from Missouri lead ores (abstract): Society of Mining Engineers of American Institute of Mining, Metallurgical, and Petroleum Engineers Annual Fall meeting, St. Louis, Missouri.

Craig, James R., and Carpenter, Alden B., 1977, Fletcherite, $Cu(Ni,Co)_2S_4$, a new thiospinel from the Viburnum Trend (New Lead Belt) Missouri: Economic Geology, v. 72, p. 480-486.

Cathles, L.M., and Smith, A.T., 1983, Thermal constraints on the formation of Mississippi Valley-type lead-zinc deposits and their implications for episodic basin dewatering and deposit genesis: Economic Geology, v. 78, p. 983-1002.

Davis, J.H., 1960, Mineralization in the Southeast Missouri Lead District: Ph.D. dissertation, University of Wisconsin, 68 p.

Desborough, G.A., Connor, J.J., Elrick, Maya, 1983, Silicates of the Davis Formation (Upper Cambrian) in Missouri — reconstituted volcanic ash? (abstract): 96th Annual Meeting, Geological Society of America, Indianapolis, Indiana, p. 557.

Doe, B.R., and Delevaux, M.H., 1972, Source of lead in southeast Missouri galena ores: Economic Geology, v. 67, p. 409-425.

Dressel, W.M., Cole, E.R., Jr., Barnard, P.G., and Clinton, W.C., 1975, Composition of lead sinter: U.S. Bureau of Mines, Report of Investigations 8059, 34 p.

Duane, M.J., Welke, H.J., and Allsopp, H.L., 1986, U-Be age for some base-metal sulfide deposits in Ireland: genetic implications for Mississippi Valley-type mineralization: Geology, v. 14, p. 477-490.

Ebers, M.L., and Kopp, O.C., 1979, Cathodoluminescent microstratigraphy in gangue dolomite, the Mascot-Jefferson City District, Tennessee: Economic Geology, v. 74, p. 908-918.

Erickson, R.L., et al., 1978, Generalized geologic and summary geochemical maps of the Rolla 1° x 2° quadrangle: Miscellaneous Field Studies Map MF-1004A, Folio of the Rolla 1° x 2° quadrangle, Missouri, United States Geological Survey.

Erickson, R.L., Mosier, E.L., Viets, J.G., Odland, S.K., and Erickson, M.S., 1983, Subsurface geochemical exploration in carbonate terrane — Midcontinent, U.S.A., *in* Kisvarsanyi, G., Grant, S.K., Pratt, W.P., and Koenig, J.W., eds., International Conference on Mississippi Valley Type Lead-Zinc Deposits, p. 575-583.

Farr, M.R., 1986, Regional isotopic variation in Bonneterre Formation cements: Implication for brine migration pathways and sources (abs.), *in* Gregg, Jay M., and Hagni, Richard D., eds., Symposium on the Bonneterre Formation (Cambrian), southeastern Missouri: Stratigraphy, sedimentology, diagenesis, geochemistry, and economic geology: University of Missouri-Rolla, Rolla, Missouri, p. 8.

Fehn, U., 1985, Post-magmatic convection related to high heat production in granites of southwest England: A theoretical study, *in* Halls, C., ed., High heat production (HHP) granites, hydrothermal circulation and ore genesis: The Institution of Mining and Metallurgy, London, England, p. 113-133.

Garvin, Grant, 1985, The role of regional fluid flow in the genesis of the Pine Point deposit, Western Canada Sedimentary basin: Economic Geology, v. 80, p. 307-324.

Gerdemann, P.E., and Myers, H.E., 1972, Relationships of carbonate facies patterns to ore deposition and to ore genesis in the Southeast Missouri Lead District: Economic Geology, v. 67, p. 426-433.

Giordano, T.H., 1985, A preliminary evaluation of organic ligands and metal-organic complexing in Mississippi Valley-type ore solutions: Economic Geology, v. 80, p. 96-106.

____________, and Barnes, H.L., 1981, Lead transport in Mississippi Valley-type ore solutions: Economic Geology, v. 76, p. 2200-2211.

Graf, Joseph L., Jr., 1983, Rare earth elements in carbonate rocks and minerals from the Viburnum Trend, southeast Missouri, *in* Kisvarsanyi, G., Grant, S.K., Pratt, W.P., and Koenig, J.W., eds., International Conference on Mississippi Valley Type Lead-Zinc Deposits, p. 131-139.

Gregg, Jay M., 1985, Regional epigenetic dolomitization in the Bonneterre Dolomite (Cambrian), southeastern Missouri: Geology, v. 13, p. 503-506.

__________, and Hagni, Richard D., (in press), Irregular cathodoluminescent banding in late dolomite cements: Evidence for complex faceting and metalliferous brines: Geological Society of America Bulletin.

__________, and Hagni, Richard D., in press, The use of cathodoluminescence microscopy to reveal hidden crystal faces in gangue dolomite cements, Viburnum Trend, southeast Missouri, *in* Hagni, Richard D., ed., Process Mineralogy VI: AIME, New York, New York.

Grundmann, William H., Jr., 1977, Geology of the Viburnum No. 27 mine, Viburnum Trend, southeast Missouri: Economic Geology, v. 72, p. 349-364.

Hagni, Richard D., 1983a, Ore microscopy, paragenetic sequence, trace element contact, and fluid inclusion studies of the copper-lead-zinc deposits of the Southeast Missouri Lead District, *in* Kisvarsanyi, G., Grant, S.K., Pratt, W.P., Koenig, J.W., eds., International Conference on Mississippi Valley Type Lead-Zinc Deposits, Proceedings Volume, University of Missouri-Rolla, Rolla, Missouri, p. 243-256.

__________, 1983b, Minor elements in Mississippi Valley-type ore deposits, *in* Shanks, W.C., III, ed., Cameron Volume on Unconventional Mineral Deposits, Chapter 7: Society of Economic Geologists-Society of Mining Engineers, AIME, New York, p. 71-88.

__________, 1983c, Applications of the ore microscope to ore dressing problems in the Viburnum Trend, southeast Missouri, U.S.A., *in* de Villiers, J.P.R., and Cawthorn, P.A., eds., ICAM 81: Proceedings of the First International Congress on Applied Mineralogy, Special Publication No. 7, The Geological Society of South Africa, Marshalltown, South Africa, p. 209-215.

__________, 1986a, Paragenetic sequence of the lead-zinc-copper-cobalt-nickel ores of the Southeast Missouri Lead District, U.S.A., *in* Craig, J.R., Hagni, R.D., Kiesl, W., Lange, I.M., Petrovskaya, N.V., Shadlun, T.N., Udubasa, G., and Augustithis, S.S., eds., Mineral paragenesis, p. 90-132.

__________, 1986b, Ore microscopy and paragenetic sequence of the ores of the Southeast Missouri Lead District: International Mineralogical Association, 14th General Meeting, Abstracts with Program, Stanford University, Stanford, California, p. 118.

__________, 1986c, Ore microscopy and mineral paragenetic sequence of the early bornite ores in the Viburnum Trend, southeast Missouri (abs.): Seventh International Association on the Genesis of Ore Deposits Symposium, Lulea, Sweden.

__________, and Trancynger, Thomas C., 1977, Sequence of deposition of the ore minerals at the Magmont mine: Economic Geology, v. 72, p. 451-464.

Halls, C., ed., 1985, High heat production (HHP) granites, hydrothermal circulation and ore genesis: The Institution of Mining and Metallurgy, London, England, 593 p.

Hannah, Judith L., and Stein, Holly J., 1984, Evidence for changing ore fluid composition, stable isotope analyses of secondary carbonates, Bonneterre Formation, Missouri: Economic Geology, v. 79, p. 1930-1935.

Hart, S.R., Shimizu, N., and Sverjensky, D.A., 1981, Lead isotope zoning in galena: An ion microprobe study of a galena crystal from the Buick mine, southeast Missouri: Economic Geology, v. 76, p. 1873-1879.

Hart, Stanley R., Shimizu, Noburmichi, and Sverjensky, Dimitri A., 1983, Toward an ore fluid lead isotope "stratigraphy" for galenas from the Viburnum Trend, S.E. Missouri, *in* Kisvarsanyi, G., Grant, S.K., Pratt, W.P., and Koenig, J.W., eds., International Conference on Mississippi Valley Type Lead-Zinc Deposits, p. 257-270.

Hildenbrand, T.G., Kane, M.F., and Stauder, W., 1977, Magnetic and gravity anomalies in the Northern Mississippi embayment and their special relation to seismicity: U.S. Geological Survey Miscellaneous Field Studies Map MF-914.

Horrall, K.B., 1982, Mineralogical, textural, and paragenetic studies of selected ore deposits of the Southeast Missouri Lead-Zinc-Copper District and their genetic implications: Ph.D. dissertation, University of Missouri-Rolla, 650 p.

__________, Hagni, R.D., and Kisvarsanyi, G., 1983, Mineralogical, textural, and paragenetic studies of selected ore deposits of the Southeast Missouri Lead-Zinc-Copper District and their genetic implications, *in* Kisvarsanyi, G., Grant, S.K., Pratt, W.P., and Koenig, J.W., eds., International Conference on Mississippi Valley Type Lead-Zinc Deposits, p. 289-316.

Howe, W.B., 1968, Planar stromatolite and burrowed carbonate mud facies in Cambrian strata of the St. Francois Mountain area: Missouri Geological Survey and Water Resources, Report of Investigations 41, 113 p.

Jackson, S.A., and Beales, F.W., 1967, An aspect of sedimentary basin evolution: The concentration of Mississippi Valley-type ores during late stages of diagenesis: Canadian Petroleum Geologists Bulletin, v. 15, p. 383-433.

James, J.A., 1952, Structural environments of the lead deposits in the Southeastern Missouri Mining District: Economic Geology, v. 47, p. 650-660.

Jessey, David R., 1981a, An investigation of the nickel-cobalt occurrence in the Southeast Missouri Mining District: Ph.D. dissertation, University of Missouri-Rolla, 225 p.

__________, 1981b, Mineralogical and compositional variations of the nickel-cobalt mineralization in the Southeast Missouri Mining District, *in* Hausen, D.M., and Park, W.C., eds., Process mineralogy: Extractive metallurgy, mineral exploration, energy resources: AIME, New York, p. 159-177.

__________, 1983, The occurrence of nickel and cobalt in the Southeast Missouri Mining District, *in* Kisvarsanyi, G., Grant, S.K., Pratt, W.P., and Koenig, J.W., eds., International Conference on Mississippi Valley Type Lead-Zinc Deposits, p. 145-154.

Kastler, E.J., 1972, Mineralization of the Fletcher Lead-Zinc mine in southeast Missouri: M.S. thesis, University of Missouri, 118 p.

Kidwell, A.L., 1947, Post-Devonian igneous activity in southeastern Missouri: Missouri Geological Survey and Water Resources, Report of Investigations 4, 83 p.

Kisvarsanyi, Eva B., 1981, Geology of the Precambrian St. Francois Terrane, southeastern Missouri: Missouri Department of Natural Resources, Division of Geology and Land Survey, Report of Investigations 64, 58 p.

__________, 1983, The Bee Fork volcanic center and its relationship to the Southeast Missouri Lead-Zinc District (abstract): Geological Society of America, 96th Annual Meeting, Indianapolis, Indiana, p. 614.

Kisvarsanyi, Geza, 1977, The role of the Precambrian igneous basement in the formation of the stratabound lead-zinc-copper deposits in southeast Missouri: Economic Geology, v. 72, p. 435-442.

__________, 1982, Regional depositional facies of the Cambrian Bonneterre Formation, Rolla 1° x 2° Quadrangle, Missouri: U.S. Geological Survey, Miscellaneous Field Studies Map MF-1002-I.

Kopp, Otto, 1981, Cathodoluminescence petrography, available tool for teaching and research: Journal of Geological Education, v. 29, p. 108-113.

Lange, S., Chadhuri, S., and Clauer, N., 1983, Strontium isotopic evidence for the origin of barites and sulfides from the Mississippi Valley-type ore deposits in southeast Missouri: Economic Geology, v. 78, p. 1255-1261.

Larsen, Kenneth G., 1977, Sedimentology of the Bonneterre Formation, southeast Missouri: Economic Geology, v. 72, p. 408-419.

__________, 1979, Stratigraphic and facies nomenclature of the Viburnum Trend, southeast Missouri, *in* Paarlberg, N., ed., The 26th Annual Field Trip Guidebook, Association of Missouri Geologists, p. 15-19.

__________, Clendenin, C.W., Mouat, M.M., Walker, W.T., and Taylor, D.R., 1979, Frank R. Milliken mine of Ozark Lead Company, New Lead Belt, southeast Missouri, *in* Paarlberg, N., ed., The 26th Annual Field Trip Guidebook: Association of Missouri Geologists, p. 48-60.

Leach, David L., 1979, Temperature and salinity of the fluids responsible for minor occurrences of sphalerite in the Ozark region of Missouri: Economic Geology, v. 74, p. 931-937.

__________, 1983, Evidence for ore fluid migration in the Bonneterre Formation, southeast Missouri (abstract): 96th Annual Meeting, Geological Society of America, Indianapolis, Indiana, p. 625.

Lohmann, Kyger C., in press, Integration of cathodoluminescence and geochemical approaches in studies of carbonate diagenesis, *in* Hagni, Richard D., ed., Process mineralogy VI: AIME, New York, New York.

Lyle, John R., 1977, Petrography and carbonate diagenesis of the Bonneterre Formation in the Viburnum Trend area, southeast Missouri: Economic Geology, v. 72, p. 420-434.

Marikos, Mark A., 1986, Relation of bitumen to ore in the Magmont West orebody, Viburnum Trend, Missouri, *in* Dean, Walter E., ed., Proceedings of the Denver Region Exploration Geologists Society Symposium, Organics and Ore Deposits, Wheat Ridge, Colorado, p. 157-164.

McLimons, Roger K., Barnes, Hugh L., and Ohmoto, H., 1980, Sphalerite stratigraphy of the Upper Mississippi Valley Zinc-Lead District, southwest Wisconsin: Economic Geology, v. 75, p. 351-361.

Mineral Industry Surveys, 1983, The mineral industry of Missouri in 1982: U.S. Bureau of Mines and Missouri Department of Natural Resources, Division of Geology and Land Survey, 3 p.

__________, 1984, The mineral industry of Missouri in 1983: preliminary data: U.S. Bureau of Mines and Missouri Department of Natural Resources, Division of Geology and Land Survey, 3 p.

Missouri Department of Natural Resources, Division of Geology & Land Survey, 1983a, Design capacities of lead mines, mills, and smelters and iron ore pellet plants in southeast Missouri in 1981-1982, and annual mine production of lead and the coproduct metals in Missouri, 1 p.

__________, 1983b, Lead-zinc-copper-silver production and royalties from Mark Twain National Forest mining leases compared to total Missouri mine production (short tons) in 1981 to 1982, 1 p.

__________, 1986, Design capacities of lead mines, mills and smelters and iron ore pellet plants in southeast Missouri in 1984-1985, and annual mine production of lead and the coproduct metals in Missouri, 1 p.

Mouat, M.M., and Clendenin, C.W., 1977, Geology of the Ozark Lead Company mine, Viburnum Trend, southeast Missouri: Economic Geologists, v. 72, p. 398-407.

Mugel, Douglas N., 1983, Geology of the Blanket Lead-Zinc Deposit, Buick mine, Viburnum Trend, southeast Missouri: M.S. thesis, University of Missouri-Rolla, Rolla, Missouri, 155 p.

__________, and Hagni, Richard D., 1984, Mineralogy and geology of the Blanket Lead-Zinc Deposit, Buick mine, Viburnum Trend, southeast Missouri, *in* Park, W.C., Hausen, D.H., Hagni, R.D., eds., Applied Mineralogy: Proceedings of the Second International Congress on Applied Mineralogy in the Minerals Industry: AIME, New York, New York, p. 965-986.

Ohle, Ernest L., 1952, Geology of the Hayden Creek Lead mine, southeast Missouri: AIME Transactions, v. 193, p. 477-483.

__________, 1982, Some major geological advances in Missouri Lead Belt: AIME, Southeast Missouri section meeting, Salem, Missouri, March, 1982.

__________, 1985, Breccias in Mississippi Valley-type deposits: Economic Geology, v. 80, p. 1736-1752.

__________, and Brown, J.S., 1954, Geologic problems in the Southeast Missouri Lead District: Geological Society of America Bulletin, v. 65, p. 201-221, 935-936.

__________, and Gerdemann, Paul E., in press, Recent exploration history in southeast Missouri, *in* Hollister, Victor F., ed., AIME.

Panno, Samuel V., Harbottle, G., Sayre, E.V., and Hood, W.C., 1983, Genetic implications of halide enrichment near a Mississippi Valley-type ore deposit: Economic Geology, v. 78, p. 150-156.

Parker, J.G., 1978, The occurrence and recovery of certain minor metals in the processing of lead and zinc: U.S. Bureau of Mines Open-File Report, 111 p.

Pelissonnier, Hubert, 1983, Metallogenic significance of J-lead, *in* Kisvarsanyi, G., Grant, S.K., Pratt, W.P., and Koenig, J.W., Eds., International Conference on Mississippi Valley Type Lead-Zinc Deposits, p. 216-225.

Pignolet, Susanne, and Hagni, Richard D., 1983, Cobalt-nickel mineralization associated with lead-zinc-copper mineralization in the Mississippi Valley-type deposits at Fredericktown, Missouri, *in* Kisvarsanyi, G., Grant, S.K., Pratt, W.P., and Koenig, J.W., eds., International Conference on Mississippi Valley Type Lead-Zinc Deposits, p. 187-194.

Pignolet-Brandom, Susanne, and Hagni, Richard D., 1985a, Mineralogy and mineral composition of cobalt and nickel and silver in the Southeast Missouri Lead district, *in* Park, W.C., Hausen, D.H., Hagni, R.D., eds., Applied Mineralogy: Proceedings of the Second International Congress on Applied Mineralogy in the Minerals Industry: AIME, New York, New York, p. 987-999.

__________, and __________, 1985b, Complex Pb-Zn-Cu-Ni-Co ores and concentrates from the Southeast Missouri Lead district: TMS-AIME and Canadian Institute of Mining and Metallurgy, International Complex Sulfides Symposium: Processing of ores, concentrates, and by-products, San Diego, California, p. 831-842.

__________, and __________, 1986a, Unusual occurrences of cobalt and nickel minerals in the Southeast Missouri Lead District: International Mineralogical Association, 14th General Meeting, Abstracts with Program, Stanford University, Stanford, California, p. 200-201.

__________, __________, Brandom, Robert T., Vierrether, Christopher B., Kremser, Daniel T., 1986b, Reflected light microscopy of pyrometallurgical products: International Mineralogical Association, 14th General Meeting, Abstracts with Program, Stanford University, Stanford, California, p. 200.

Posey, Harry H., Stein, Holly J., Fullager, Paul D., and Kish, Stephen A., 1983, Rb-Sr isotopic analyses of Upper Cambrian glauconites, southern Missouri; implications for movement of Mississippi Valley-type ore fluids in the Ozark Region, *in* Kisvarsanyi, G., Grant, S.K., Pratt, W.P., and Koenig, J.W., eds., International Conference on Mississippi Valley Type Lead-Zinc Deposits, p. 166-173.

Pratt, Walden P., Walker, Kim-Marie, Jenson, Susan K., Francica, Joseph R., Hastings, David A., and Trautwein, Charles M., 1983, Mineral-resource appraisal of the Rolla 1° x 2° quadrangle, Missouri: Manual vs. digital (computer-assisted) synthesis, *in* Kisvarsanyi, G., Grant, S.K., Pratt, W.P., and Koenig, J.W., eds., International Conference on Mississippi Valley Type Lead-Zinc Deposits, p. 584-595.

Randall, F.M., and Arterburn, R.A., 1970, Buick concentrator — a joint venture of AMAX Lead Company of Missouri and Homestake Lead Company of Missouri, *in* Rausch, D.O., and Mariacher, B.C., eds., AIME World Symposium on Mining and Metallurgy of Lead and Zinc, v. 1, p. 453-465.

Rickman, D.L., 1981, A thermochemical study of the ore deposits of the Milliken mine, New Lead Belt, Missouri: Ph.D. dissertation, University of Missouri-Rolla, 310 p.

Roedder, Edwin, 1977, Fluid inclusion studies of ore deposits in the Viburnum Trend, southeast Missouri: Economic Geology, v. 72, p. 474-479.

Rogers, Robert K., and Davis, James H., 1977, Geology of the Buick mine, Viburnum Trend, southeast Missouri: Economic Geology, v. 72, p. 372-380.

Rothbard, David R., 1983, Diagenetic history of the Lamotte Sandstone, southeast Missouri, *in* Kisvarsanyi, G., Grant, S.K., Pratt, W.P., and Koenig, J.W., eds., International Conference on Mississippi Valley Type Lead-Zinc Deposits, p. 385-395.

Rowan, Lanier, in press, A study of fluid inclusions within cathodoluminescent zones in gangue dolomites, Viburnum Trend Pb-Zn district, southeast Missouri, *in* Hagni, Richard D., ed., Process Mineralogy VI: AIME, New York, New York.

Ruiz, Joaquin, Kelly, William C., and Kaiser, Charles J., 1985, Strontium isotopic evidence for the origin of barites and sulfides from the Mississippi Valley-type ore deposits in southeast Missouri — a discussion: Economic Geology, v. 80, p. 773-778.

Russell, M.J., 1986, A model for the genesis of SEDEX deposits: Abstracts of the VII IAGOD Symposium, Lulea, Sweden, TERRA cognita, v. 6, no. 3, Strasbourg, France, p. 493.

Sangster, D.F., 1983, Mississippi Valley-type deposits: A geological melange, *in* Kisvarsanyi, G., Grant, S.K., Pratt, W.P., and Koenig, J.W., eds., International Conference on Mississippi Valley Type Lead-Zinc Deposits, p. 7-19.

Sawkins, F.J., 1969, Chemical brecciation, an unrecognized mechanism for breccia formation?: Economic Geology, v. 64, p. 613-617.

Schroer, Michael G., Volner, Scott L., and Watson, John L., in press, Flotation kinetics and ore microscopy of Viburnum lead ores, *in* Hagni, R.D., ed., Process mineralogy VI: including applications to precious metals and cathodoluminescence: AIME, New York, New York.

Sharp, J.M., 1978, Energy and momentum transport model of the Ouachita basin and its possible impact on formation of economic mineral deposits: Economic Geology, v. 73, p. 1057-1068.

Snyder, F.G., and Emery, J.A., 1956, Geology in development and mining, southeast Missouri Lead Belt: AIME Transactions, v. 208, p. 1216-1224.

______________, and Gerdemann, P.E., 1965, Explosive igneous activity along an Illinois-Missouri-Kansas axis: American Journal of Science, v. 263, p. 465-493.

_____________, and _____________, 1968, Geology of the Southeast Missouri Lead district, *in* Ridge, J.D., ed., Ore deposits of the United States, 1933-1967 (Graton-Sales Volume): AIME, New York, v. 1, p. 326-358.

_____________, and Odell, J.W., 1958, Sedimentary breccias in the Southeast Missouri Lead district: Geological Society of America Bulletin, v. 69, p. 899-926.

Spector, Allan, and Pichette, Raymond J., 1983, Applications of the aeromagnetic method to lead exploration in SE Missouri, *in* Kisvarsanyi, G., Grant, S.K., Pratt, W.P., and Koenig, J.W., eds., International Conference on Mississippi Valley Type Lead-Zinc Deposits, p. 596-603.

Stein, H.J., 1980, Evidence for intertidal-supratidal facies control of stratiform ore at the Magmont mine, Viburnum Trend, southeast Missouri, *in* Ridge, J.D., ed., Proceedings of the Fifth Quadrennial IAGOD Symposium, v. 1, E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, p. 767-784.

_____________, and Kish, S.A., 1985, The timing of ore formation in southeast Missouri: Rb-Sr glauconite dating at the Magmont mine, Viburnum Trend: Economic Geology, v. 80, p. 739-753.

Stormo, Scott, and Sverjensky, Dimitri A., 1983, Silicate hydrothermal alteration in a Mississippi Valley-type deposit, Viburnum Trend, southeast Missouri (abstract): 96th Annual Meeting, Geological Society of America, Indianapolis, Indiana, p. 699

Sverjensky, D.A., 1981, The origin of a Mississippi Valley-type deposit in the Viburnum Trend, southeast Missouri: Economic Geology, v. 76, p. 1848-1872.

_____________, 1984, Oil field brines as ore-forming solutions: Economic Geology, v. 79, p. 23-37.

_____________, Rye, D.M., and Doe, B.R., 1979, The lead and sulfur isotopic compositions of galena from a Mississippi Valley-type deposit in the New Lead Belt, southeast Missouri: Economic Geology, v. 74, p. 149-153.

Sweeney, Peter H., Harrison, Edwin D., and Bradley, Milton, 1977, Geology of the Magmont mine, Viburnum Trend, southeast Missouri: Economic Geology, v. 72, p. 365-371.

Taylor, C.M., and Radtke, A.S., 1969, Micromineralogy of silver-bearing sphalerite from Flat River, Missouri: Economic Geology, v. 64, p. 308-318.

Viets, John G., Mosier, Elwin L., and Erickson, M.S., 1983, Geochemical variations of major, minor, and trace elements in samples of the Bonneterre Formation from drill holes transecting the Viburnum Trend Pb-Zn district of southeast Missouri, *in* Kisvarsanyi, G., Grant, S.K., Pratt, W.P., and Koenig, J.W., eds., International Conference on Mississippi Valley Type Lead-Zinc Deposits, p. 174-186.

Voss, Robert L., and Hagni, Richard D., 1985, The application of cathodoluminescence microscopy to the study of sparry dolomite from the Viburnum Trend, southeast Missouri, *in* Hausen, Donald M., and Kopp, Otto C., eds., Mineralogy — applications to the minerals industry (Chapter 5): Proceedings of the Paul F. Kerr Memorial Symposium, AIME, New York, New York, p. 51-68.

Weakly, L.A., 1982, Ore moving logistics for room and pillar mines in the Viburnum Trend: Mining Engineering, v. 34, p. 403-409.

Wenner, D.B., and Taylor, H.P., 1972, O^{18}/O^{16} and D/H Studies of a Precambrian Granite-Rhyolite Terrane in S.E. Missouri (abstract): American Geophysical Union Transactions, v. 53, p. 534.

Wharton, Heyward, M., 1975, Introduction to the Southeast Missouri Lead district, *in* Paarlberg, N., ed., The 26th Annual Field Trip Guidebook: Association of Missouri Geologists, p. 3-7.

_____________, 1981, Letter to Paul A. Gerdemann on lead-zinc production totals for

Southeast Missouri Lead district: Missouri Department of Natural Resources, Division of Geology and Land Survey, 2 p.

____________, 1986, Total mine production and value from the Viburnum Trend mines from the start of mining in 1960: Missouri Department of Natural Resources, Division of Geology and Land Survey, 1 p.

Wicklein, Phillip C., 1983, Characteristics and geologic evaluation of carbonate formations hosting Mississippi Valley-type solution-collapse breccia zinc deposits, *in* Kisvarsanyi, G., Grant, S.K., Pratt, W.P., and Koenig, J.W., eds., International Conference on Mississippi Valley Type Lead-Zinc Deposits, p. 396-399.

Woolverton, D.G., 1975, Cu-Fe-S mineralization of the Sweetwater mine, Reynolds County, Missouri: M.S. thesis, University of Missouri, 71 p.

Wu, Y., and Beales, F., 1981, A reconnaissance study by paleomagnetic methods of the age of mineralization along the Viburnum Trend, southeast Missouri: Economic Geology, v. 76, p. 1879-1894.

SEDIMENTARY FACIES IN THE BONNETERRE FORMATION (CAMBRIAN), SOUTHEAST MISSOURI AND THEIR RELATIONSHIP TO ORE DISTRIBUTION

by

Paul E. Gerdemann

and

Jay M. Gregg

Geological Research Laboratory

St. Joe Minerals Corporation

P.O. Box 500

Viburnum, Missouri 65566

INTRODUCTION

Lead ore was discovered by the French explorer M. La Motte in 1720 near the present site of Fredericktown in Madison County, Missouri (fig. 1). Since then lead has been mined almost continuously in southeast Missouri; the mines have been an important factor in the settlement and economic development of the area (Snyder and Gerdemann, 1968). St. Joe Minerals Corporation has been mining in southeast Missouri since 1864 and is currently the largest domestic producer of lead.

After World War II it became clear that an understanding of the geology of the lead deposits would be necessary if further exploration was to be successful. Ohle and Brown (1954) outlined what they considered the major geologic problems of mineral exploration in southeast Missouri. Since then, numerous studies have added to our knowledge of the Mississippi Valley-type (MVT) lead-zinc districts of southeast Missouri (e.g. Snyder and Odel, 1958; Snyder and Gerdemann, 1968;

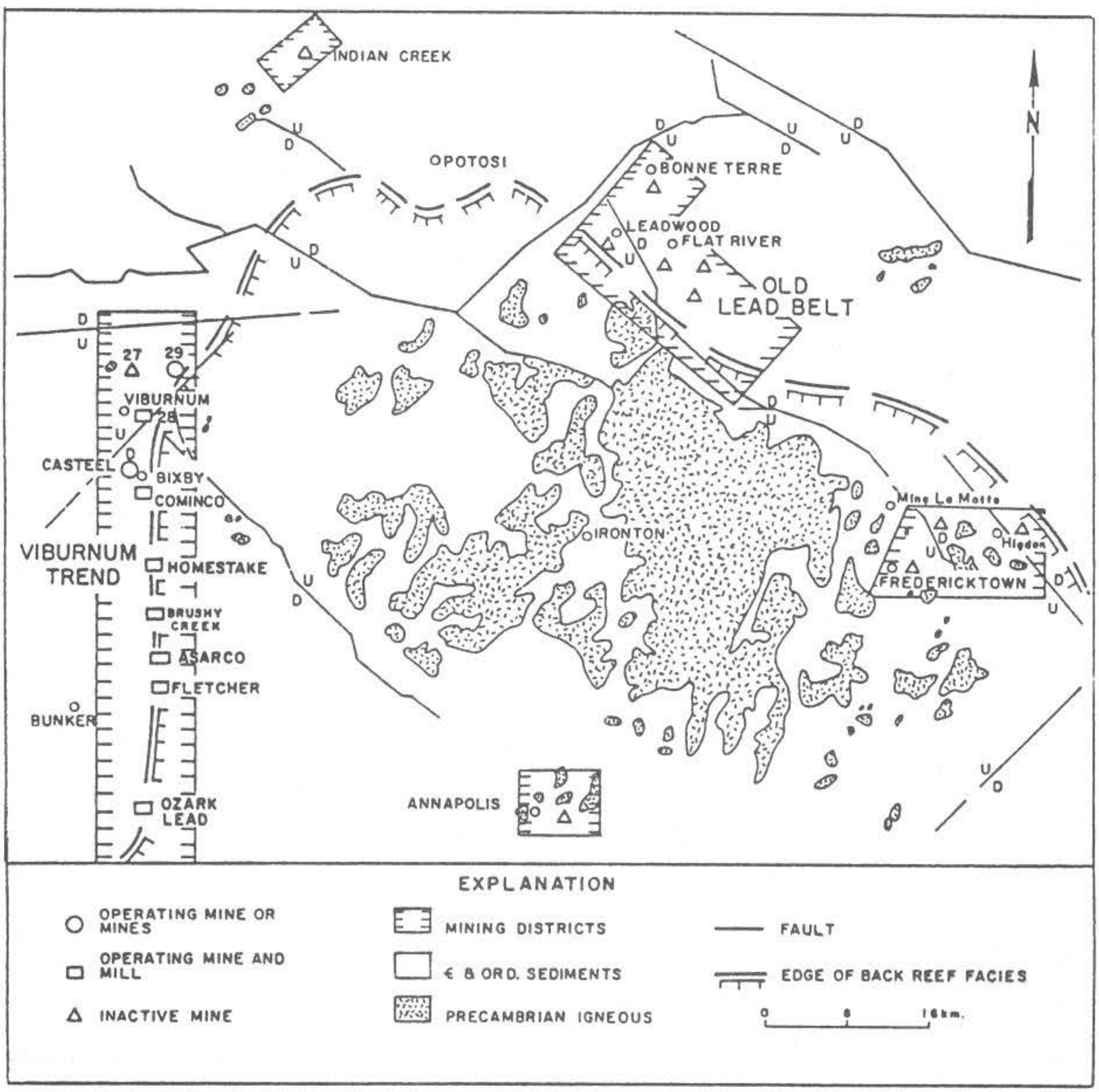


Figure 1 — Major geologic features and lead-zinc districts of southeast Missouri.

Gerdemann and Myers, 1972; and especially see Society of Economic Geologists, 1977).

Of the original problems outlined by Ohle and Brown (1954), the recognition of the relationship of facies to ore distribution has been critically important to exploration. This relationship, however, is not yet completely understood. Specifically, we do not know what geochemical characteristics lead to precipitation of ore minerals in some lithologies and not in others.

This paper gives a brief description of the facies encountered in the Bonneterre Formation and other mineralized units and some of the latest ideas concerning the origin of these lithologies and their relationship to mineralization.

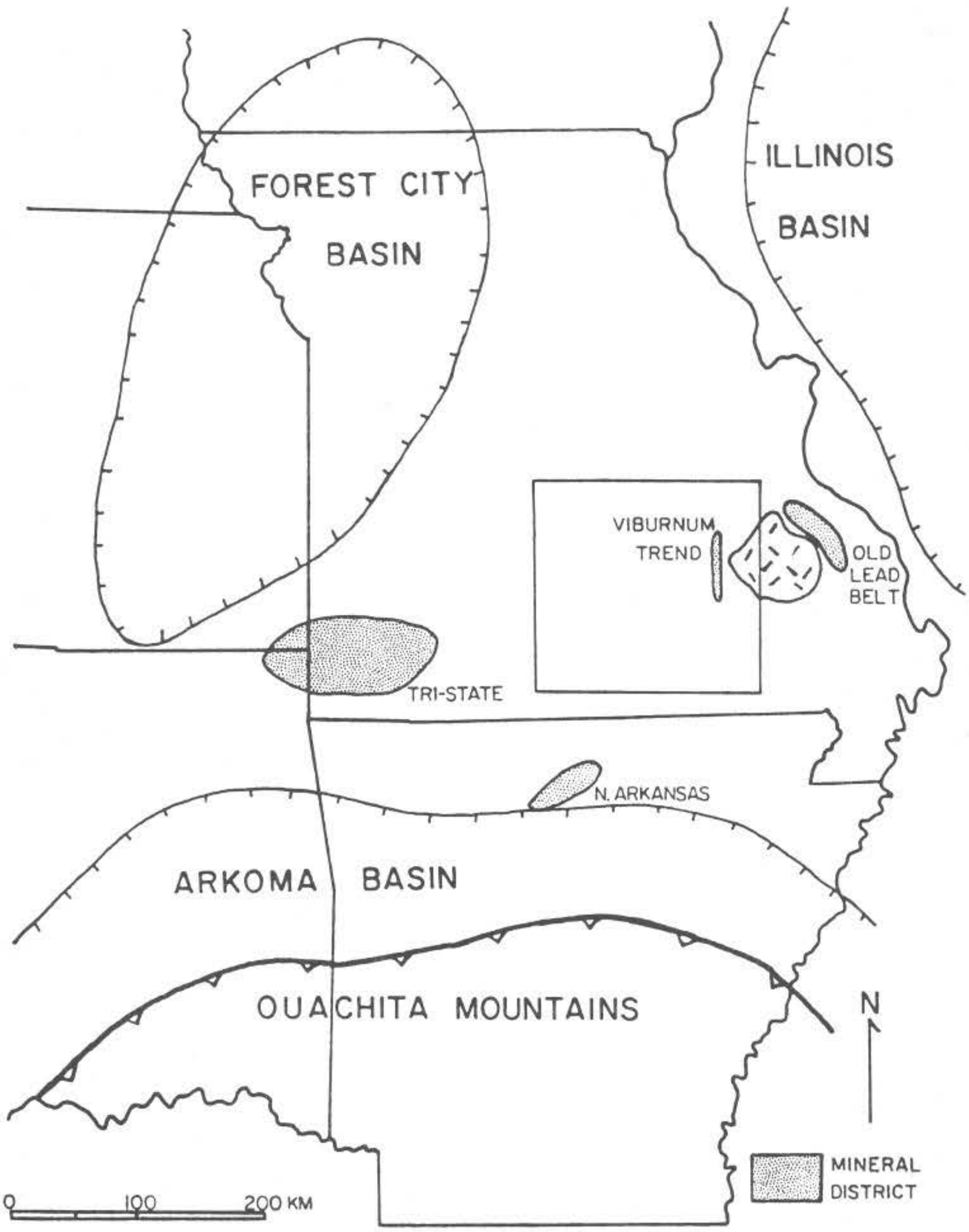


Figure 2 — Regional geological setting of southeast Missouri lead-zinc districts showing major sedimentary basins and other Mississippi Valley-type districts.

GEOLOGICAL SETTING

Southeastern Missouri is part of the stable cratonic interior region of North America. The principal geological feature of the area is the Ozark Uplift, which is bounded on the northeast by the Illinois basin, on the northwest by the Forest City basin, and on the south by the Arkoma basin and Ouachita Mountains. The regional tectonic setting and the distribution of major MVT districts (including those of southeastern Missouri) are shown in figure 2. Ore-forming fluids, which are judged to have been basinal brines, are believed to have moved northward through sandstone aquifers, out of the Arkoma basin (Leach et al., 1984; Gregg, 1985). At this time, however, other nearby basins cannot definitely be ruled out as a source of mineralizing fluids.

The Bonneterre Formation, which forms the lower part of an Upper Cambrian platform-carbonate sequence in southeast Missouri, hosts the MVT lead-zinc sulfide ore bodies of this area. The sediments were deposited in a shallow sea surrounding the St. Francois Mountains (fig. 3), which are composed mostly of silicic Precambrian volcanic and intrusive rocks, and were areas of high relief and islands during Late Cambrian time. The Bonneterre is conformably underlain by the Lamotte Sandstone, which unconformably rests on the Precambrian basement. The Lamotte consists primarily of quartz arenites, although it commonly is arkosic and/or conglomeratic near Precambrian highs. In addition, near these highs the Lamotte may locally "pinch out" and the Bonneterre may rest directly on the Precambrian. The Bonneterre is overlain by the interbedded limestone, dolomite, and shale of the Davis Formation. The sediments thicken southward and eastward and are locally displaced by normal faults that trend in a general northwesterly direction.

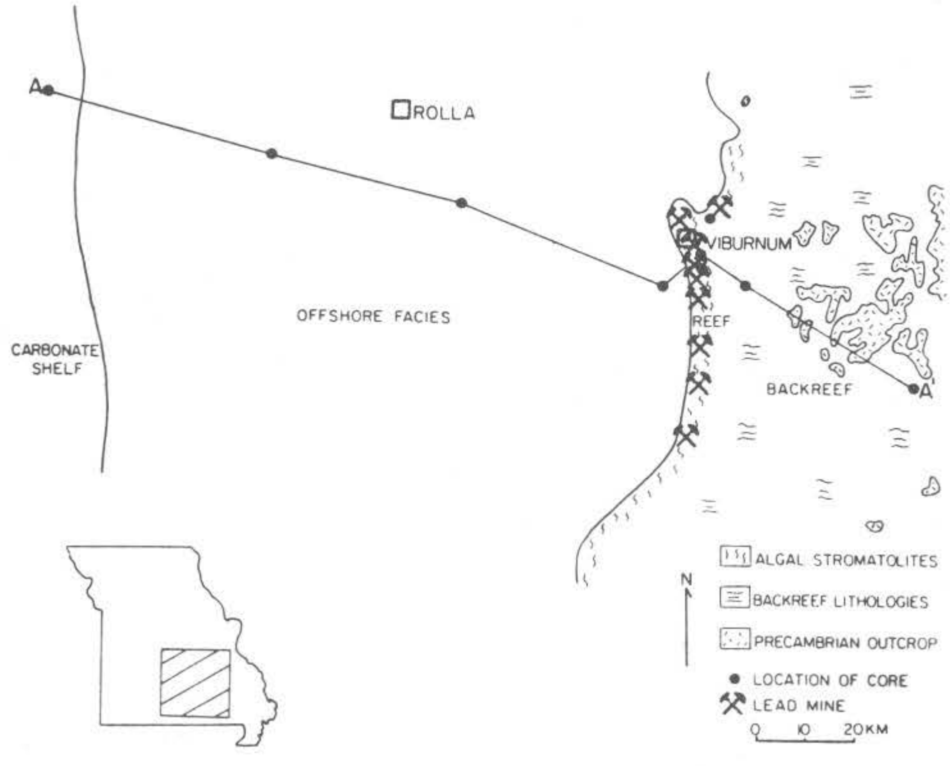


Figure 3 — Map showing line of section A-A' and distribution of major facies at approximately mid-Bonneterre time.

FACIES RELATIONSHIPS IN THE BONNETERRE

Facies relationships in the Bonneterre and nearby units are illustrated in figure 4. The Bonneterre Formation contains three basic facies: (1) an offshore shelf facies, (2) an algal stromatolite reef-grainstone bank complex that developed around the St. Francois Mountains, and (3) a back reef facies.

The offshore shelf facies is composed of silty mudstones and fossiliferous wackestones and packstones interbedded with dark green silty shales. The sequence is sandy at the base, where it conformably overlies the Lamotte Sandstone, and grades upward into the lithologically similar Davis Formation. The offshore facies probably represents moderately deep water conditions (below wave base but within the photic zone). Near the top of the offshore shelf sequence is a rather continuous oolitic bed that may represent a period of shallow-water conditions.

Deposition of the reef-grainstone bank complex began with glauconitic mudstones, packstones, and wackestones that were deposited in moderately deep- to shallow-water, low-energy environments. Occasionally the lower part of the reef complex contains oolitic grainstone bars that parallel the ancient shoreline. The oolitic beds represent a higher energy environment, probably above wave base. An algal "reef" or bioherm overlies the lower beds or occasionally rests directly on Precambrian igneous knobs where the lower beds are missing. The reef is composed of algal bioherms made up of digitate stromatolites and interdigitate oolitic, skeletal, and algal debris (fig. 5a). Interbedded with the algal bioherms are grainstone channels also composed of oolites, skeletal fragments, and algal clasts. The reef was probably deposited in the nearshore surf environment as indicated by the presence of interstromatolitic oolitic grainstones. The

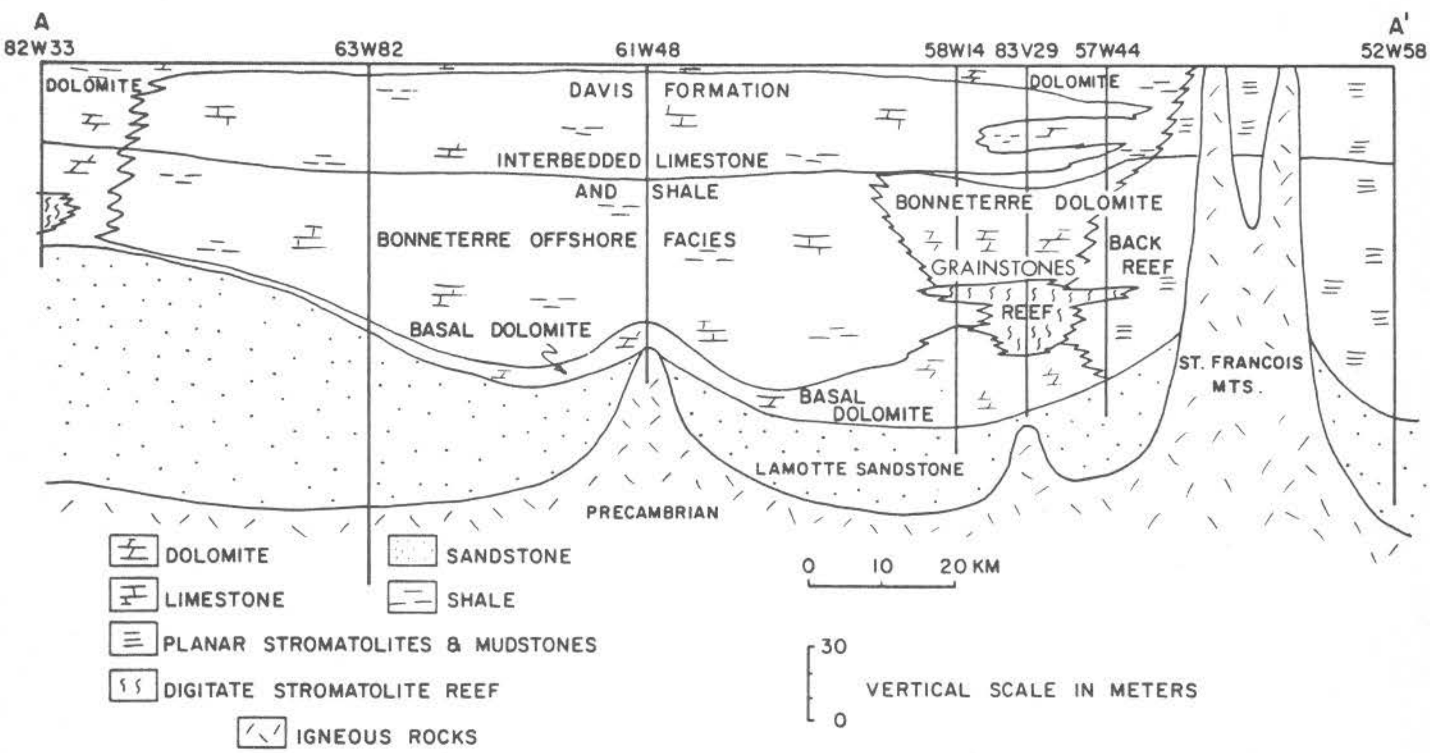


Figure 4 — Stratigraphic section A-A', through the Viburnum Trend lead-zinc district, showing facies relationships in the Lamotte Sandstone, and the Bonneterre and Davis Formations. Datum used is top of Davis Formation.

reef-grainstone bank carbonates are predominantly brown, but locally bleached beds are encountered (fig. 5b), which commonly have sharp upper contacts with brown rock and gradationally pass downward into the underlying brown carbonates. In some cases several bleached sequences may be encountered in a single drill core; they are interpreted as resulting from periodic subaerial exposure that caused oxidation of organic material in the rocks.

The upper reef-grainstone complex contains a thick sequence of oolitic and skeletal grainstones (fig. 5c) that were deposited as a series of shoals and offshore bars in a shallow-water, high-energy setting. These beds are followed by transgressive siltstones and mudstones conformably overlain by the interbedded carbonates and shales of the Davis Formation. On the basis of paleontology (Kurtz, 1986), an unconformity has been postulated to exist between the grainstone facies and the overlying transgressive beds.

The back reef, or "white rock," facies is largely composed of two distinct lithologic types: bleached lagoonal mudstones and planar algal stromatolites (fig. 5d). At some back reef locations, however, bleached digitate stromatolites, grainstones, and other lithologies are observed. The mudstones were deposited in protected shallow water interisland lagoons. The planar stromatolite beds were deposited in shallow water, as algal mats that were periodically subaerially exposed. The bleached appearance of the back reef rocks is probably due to oxidation during subaerial exposure.

DOLOMITIZATION

The algal reef-grainstone bank facies of the Bonneterre, including the underlying beds and overlying grainstones and transgressive beds, have been pervasively dolomitized (fig. 4). The back reef beds, with the exception of some of the lagoonal mudstones have also been dolomitized. Both evaporative reflux (Adams and Rhodes, 1960) and mixing zone dolomitization (Badiozamani, 1973; Folk and Land, 1975) mechanisms may be used to explain most of the dolomitization (fig. 6). The source of refluxing hypersaline brines may have been the back reef facies if evaporite conditions were widespread there. Although these conditions are known to exist in similar modern settings, such as the Persian Gulf, no direct evidence of evaporite conditions, such as gypsum or halite molds, exist in the Bonneterre. In addition, structures such as tepees and solution breccias, which are common in hypersaline conditions, are absent in the Bonneterre back reef. If one were to postulate a mixing zone dolomitization model (e.g. Badiozamani, 1973) for the reef facies the problem of dolomitization of the back reef remains. Possibly the planar stromatolites were dolomitized at near-seawater salinities by a mechanism similar to that producing dolomitized crusts in Holocene supratidal sediments at Ambergris Kay, Belize (Mazzullo et al., in press).

Understanding the origin of the Bonneterre dolomites is complicated by the epigenetic hydrothermal events associated with MVT mineralization. Many, if not most, of the early dolomites appear to have been texturally and geochemically altered, even where far removed from known ore bodies, making interpretation of early diagenetic events difficult (Gregg, unpublished data). The late mineralizing event may also have resulted in dolomitization of those beds that had been unaffected by an earlier dolomitization event.

The offshore facies of the Bonneterre Formation has not been dolomitized as much as the other facies. A regionally extensive basal dolomite bed, about 6 m thick, immediately overlies the Lamotte Sandstone. This dolomite probably resulted from the alteration of the lowermost limestone beds by mineralizing basinal brines moving through the underlying Lamotte aquifer (Gregg, 1985). Scattered ferroan dolomite and ankerite in the overlying limestone and shale beds were probably produced after burial during diagenesis of the shales (McHargue and Price, 1982; Gregg, 1986).

Figure 5a — Polished slab showing digitate stromatolite structures from the reef-grainstone bank facies in the Viburnum 27 mine; scale in inches.

Figure 5b — Contact between bleached algal stromatolite bed and overlying brown grainstone bed in the Fletcher mine.

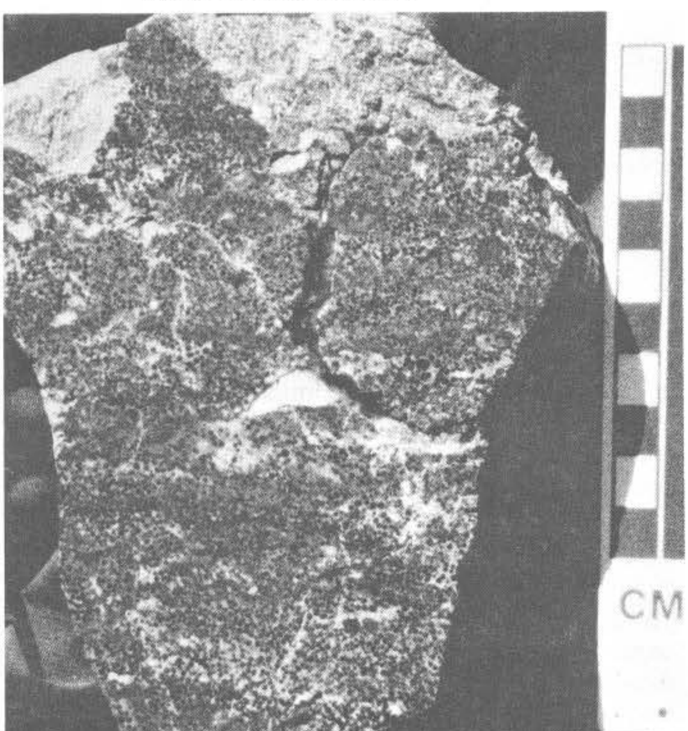


Figure 5c — Polished slab showing dolomitized oolitic grainstone from the reef-grainstone bank facies in the Casteel mine; scale in centimeters.

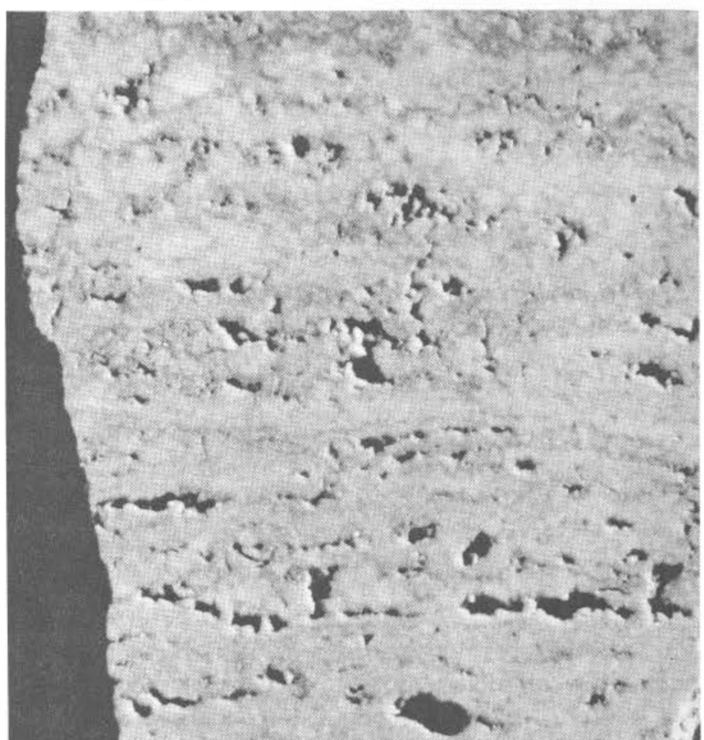


Figure 5d — Polished slab showing dolomitized planar stromatolites from the back reef facies of the Bonneterre; scale in inches.

RELATIONSHIP OF FACIES TO ORE MINERALIZATION

Mineralization is restricted to dolomitized facies of the Bonneterre Formation, the lower parts of the Davis Formation (usually associated with fractures), and to the upper portions of the Lamotte Sandstone, usually in "dirty" or arkosic facies near its pinch out onto Precambrian basement. Nearly all ore is in the Bonneterre Formation. It occurs from the base to the top of the formation and in all dolomitized lithologies. The preferred stratigraphic position varies with geographic location. The stromatolitic reef-grainstone bank facies is host for the vast majority of ore in the Viburnum Trend, the old Lead Belt, and Indian Creek mine areas.

Figure 7 is a detailed east-west section across the Viburnum Trend, located about midway between the Fletcher and Brushy Creek mines, showing the major facies. Figure 8 shows the location of the major facies along strike, as well as the distribution of mineralization. The relationship of mineralization to facies patterns illustrated here represents the predominant regional situation in southeast Missouri. There are significant variations of detail in different locations, but the major relationships persist regionally.

Small tonnages of ore-grade mineralization are in the back reef "white rock" facies. In the Annapolis, Missouri area, 29,000 tons of lead metal were produced between 1915 and 1931 (Wharton, 1975) from the "white rock" facies. Several additional small ore-grade concentrations of mineralization, as well as widespread trace mineralization, are in this general area. In addition, there are numerous other locations in southeast Missouri where scattered trace mineralization and even small ore-grade concentrations of mineralization are

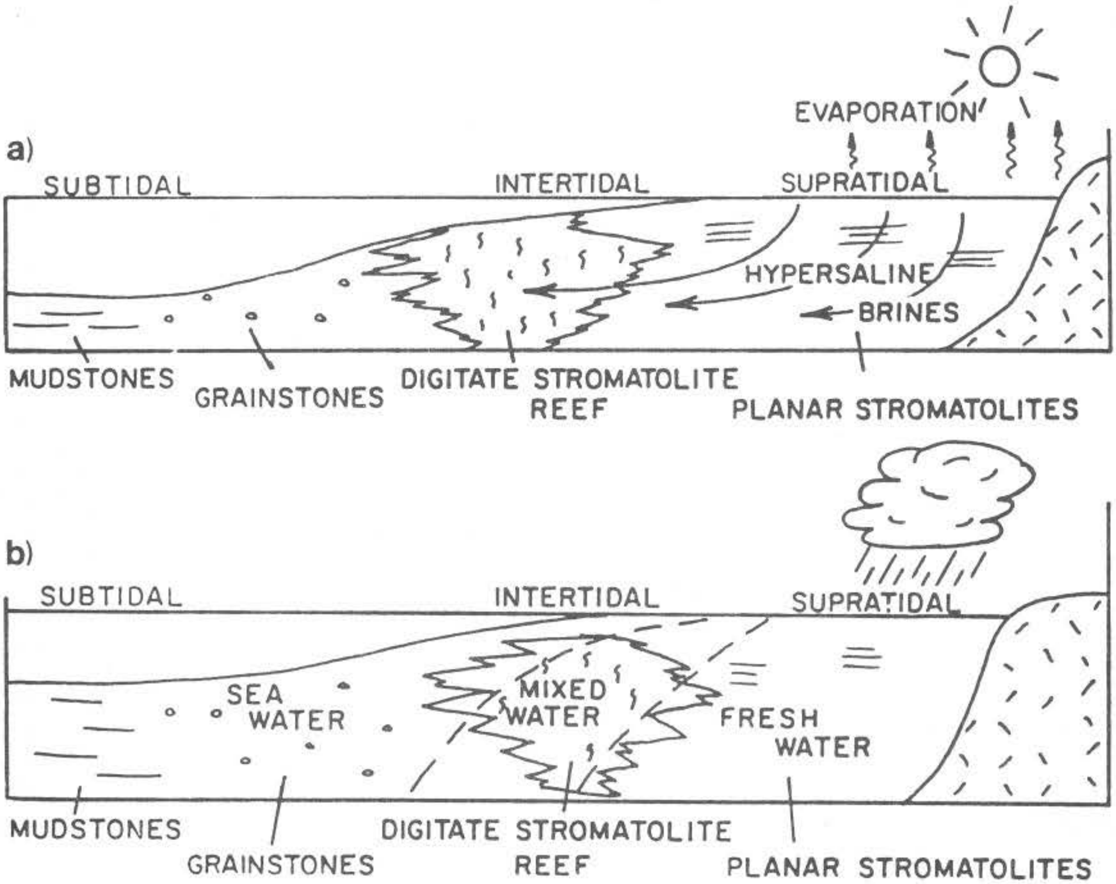


Figure 6 — Possible mechanisms for the dolomitization of the Bonneterre Formation: a) Evaporative reflux model and b) dorag or mixing zone model.

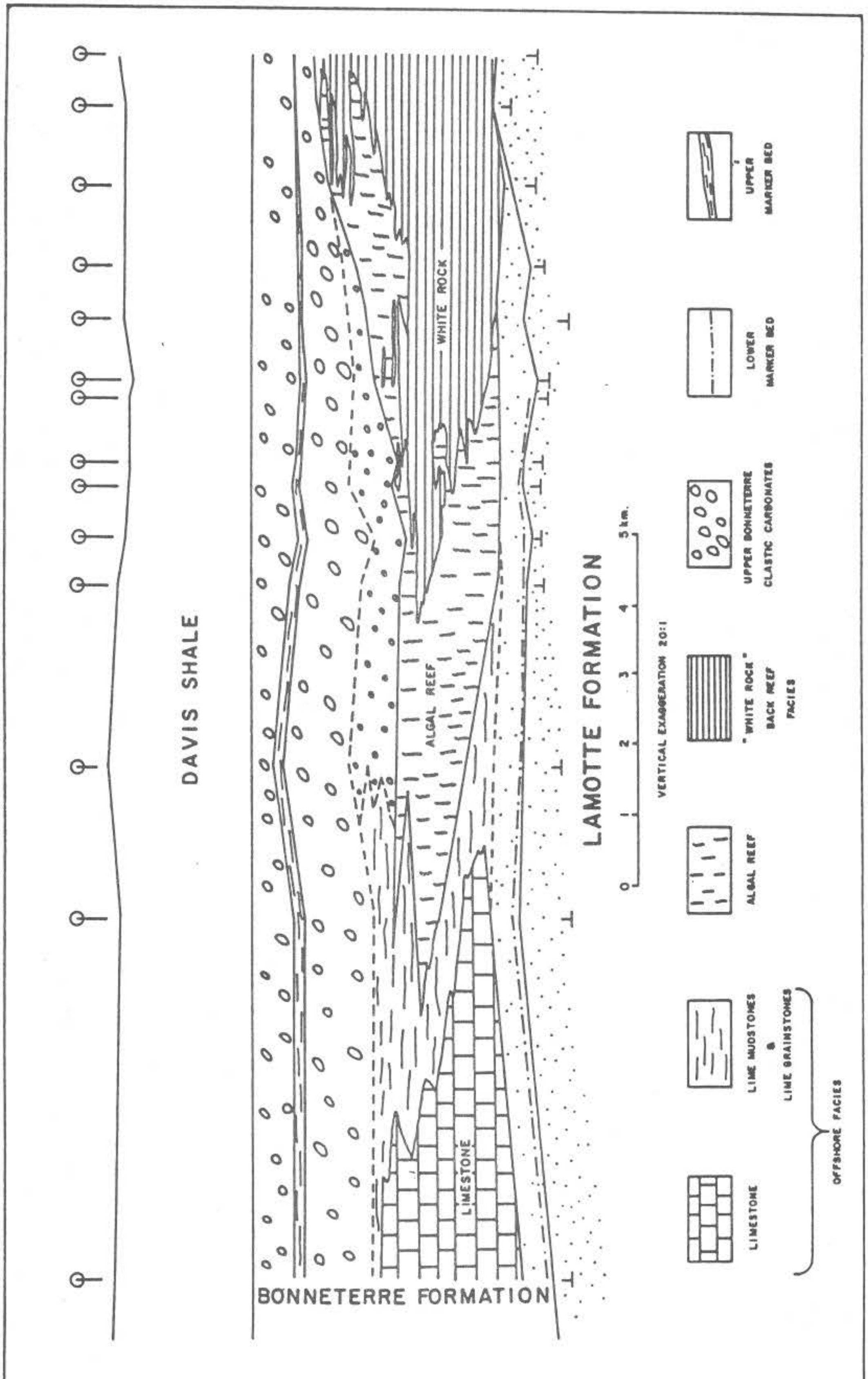


Figure 7 – Detailed section across the stromatolitic reef-grainstone bank facies of the Bonneterre Formation showing the relationships between the major lithologic types.

in the back reef facies, but none have been or promise to be significant ore producers.

In the main production areas, ore occurs in certain preferred stratigraphic positions. In the Mine Lamotte-Fredericktown area, ore was restricted to the lower beds of the Bonneterre and upper Lamotte Sandstone. In the Flat River-Leadwood-Bonneterre area, it was distributed throughout the entire Bonneterre Formation and upper Lamotte. In any particular mine or part of a mine, in this very large area (referred to collectively as the "old Lead Belt"), a particular stratigraphic position may have been the favored ore horizon. Overall, however, most ore was mined from beds below the reef. In the Viburnum Trend, ore is generally restricted to beds from mid-reef to the top of the Bonneterre. At the Indian Creek Mine most ore was mined from the reef-grainstone facies, particularly along the steeply dipping reef front where algal stromatolite bioherms intertongue with oolitic grainstones. At the northeastern end of the mine, ore was confined to the lower Bonneterre beds and the upper portion of the Lamotte Sandstone.

In most cases it is undetermined why a particular stratigraphic position was more favorable for mineralization. There is evidence that ore fluids traveled upward and laterally. Some beds with limited permeability acted as barriers to upward movement, and ore is present only beneath these units, except where they are fractured or brecciated. In such occurrences ore is distributed in the fractures and breccia and often spread out in overlying unbrecciated rocks.

The importance of the back reef, or "white rock," has been stressed by some authors (Davis, 1977). However, important examples of ore deposits, such as the Indian Creek Mine, many miles from the "white rock" area, greatly diminishes its importance to ore genesis. Indian Creek, however, is associated with a reef-grainstone bank.

The reason for the important association of ore and mineralization with the reef-grainstone bank is unknown. If ore fluids migrated through the Lamotte, the increased permeability of this facies, compared to the offshore facies, would permit much greater fluid movement. However, this fact does not explain why ore minerals were preferentially precipitated here rather than in other rocks of the Lamotte or Bonneterre. Because the relationship is so strong, it is suggested that chemical conditions in these rocks caused localization of mineralization. The nature of these conditions is, as yet, unknown.

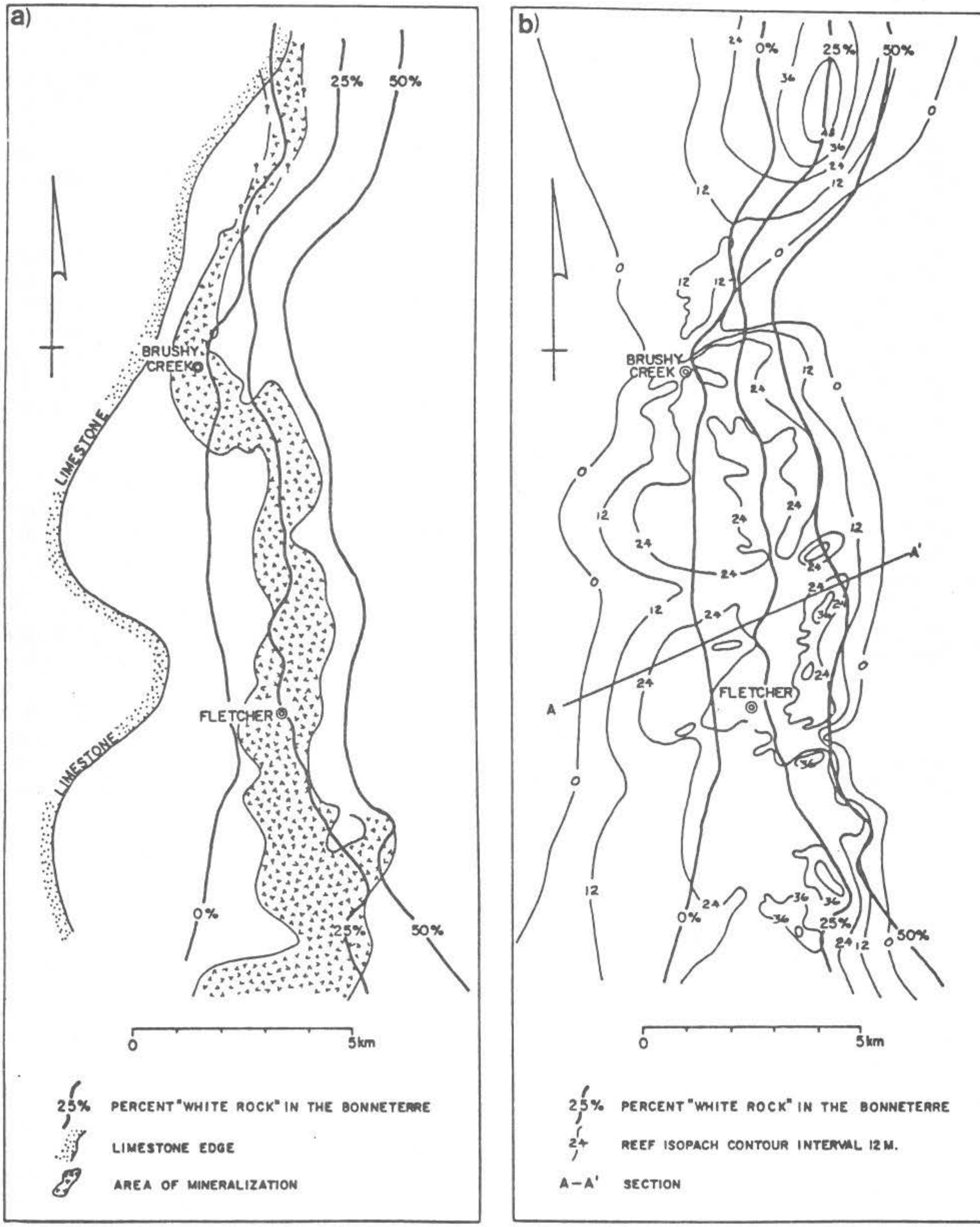


Figure 8 — a) Map showing position of mineralization, offshore facies (limestone), and back reef facies (expressed as % "white rock") within the Bonneterre Formation. b) Map showing "white rock" pinching out against stromatolitic reef within the Bonneterre Formation.

REFERENCES CITED

Adams, J.E., and Rhodes, M.L., 1960, Dolomitization by seepage refluction: American Association of Petroleum Geologists Bulletin, v. 44, p. 1912-1920.

Badiozamani, K, 1973, The dorag dolomitization model - application to the Middle Ordovician of Wisconsin: Journal of Sedimentary Petrology, v. 43, p. 948-965.

Davis, J. H., 1977, Genesis of the southeast Missouri lead deposits: Economic Geology, v. 72, p. 443-450.

Folk, R.L., and Land, L.S., 1975, Mg/Ca ratio and salinity: two controls over crystallization of dolomite: American Association of Petroleum Geologists Bulletin, v. 59, p. 60-68.

Gerdemann, P.E., and Myers, H.E., 1972, Relationships of carbonate facies patterns to ore distribution and to ore genesis in the southeast Missouri lead district: Economic Geology, v. 67, p. 426-433.

Gregg, J.M., 1985, Regional epigenetic dolomitization in the Bonneterre Dolomite (Cambrian), southeastern Missouri: Geology, v. 13, p. 503-506.

__________, 1986, Dolomitization by clay diagenesis in a transgressive facies of the Bonneterre Formation (Cambrian), southeast Missouri (abstract), *in* Gregg, J.M., and Hagni, R.D., eds., Symposium on the Bonneterre Formation (Cambrian), southeast Missouri: University of Missouri-Rolla, Department of Geology and Geophysics, p. 23.

Kurtz, V.E., 1986, Age and correlation of beds associated with the Bonneterre-Davis contact in southeast Missouri (abstract), *in* Gregg, J.M., and Hagni, R.D., eds., Symposium on the Bonneterre Formation (Cambrian), southeast Missouri: University of Missouri-Rolla, Department of Geology and Geophysics, p. 14.

Leach, David L., Viets, John G., and Rowan, Lanier, 1984, Appalachian-Ouachita orogeny and Mississippi Valley-Type lead-zinc deposits: Geological Society of America, 97th Annual Meeting Abstracts with Programs, Reno, Nevada, v. 16, no. 6, p. 572.

Mazzullo, S.J., Reid, A.M., and Gregg, J.M., 1986, Rapid and pervasive dolomitization of Holocene supratidal deposits, Amergis Kay, Belize: Geological Society of America Bulletin, (in press).

McHargue, T.R., and Price, R.C., 1982, Dolomite from clay in argillaceous or shale-associated marine carbonates: Journal of Sedimentary Petrology, v. 52, p. 873-886.

Ohle, E.L., and Brown, J.S., 1954, Geologic problems in the southeast Missouri lead district: Geological Society of America Bulletin, v. 65, p. 201-221, 935-936.

Society of Economic Geologists, 1977, An issue devoted to the Viburnum Trend, southeast Missouri: Economic Geology, v. 72, 524 p.

Snyder, F.G., and Gerdemann, P.E., 1968, Geology of the Southeast Missouri Lead District, *in* Ore deposits of the United States, 1933-1967 (Graton-Sales Volume), v. 1: New York, American Institute of Mining, Metallurgical, and Petroleum Engineers, p. 326-358.

__________, and Odel, J.W., 1958, Sedimentary breccias in the Southeast Missouri Lead District: Geological Society of America Bulletin, v. 69, p. 899-926.

Wharton, H.M., et al., 1975, Guidebook to the geology and ore deposits of selected mines in the Viburnum Trend, Missouri: Missouri Department of Natural Resources, Division of Research and Technical Information, Geological Survey, Report of Investigations 58, 60 p.

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

by

Paul E. Gerdemann

and

Jay M. Gregg

Geological Research Laboratory

St. Joe Minerals Corporation

P.O. Box 500

Viburnum, Missouri 65566

INTRODUCTION

This field trip was prepared by the senior author and others, using notes on extensive field studies conducted in the St. Francois Mountains region. These studies were part of exploration activities undertaken by St. Joe Minerals Corporation, during the 1950's, that eventually led to discovery of the Viburnum Trend lead-zinc district. The trip will serve to introduce geologists to many aspects of the sedimentology and economic geology of the St. Francois Mountains region. Although the trip is designed to occupy a full day, two days will allow a more leisurely pace, and several other points of geological interest, shown on the field trip map (fig. 1), may be visited (e.g., Silver Mines Forest Service Campground and Elephant Rocks State Park).

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 (MVT) sulfide mineralization.

ROAD LOG

Stop 1. — From Hwy 21-Hwy M intersection go 6.5 mi east on Hwy M. Outcrops on both sides of the road (fig. 1). Bonneterre dolomite, digitate algal stromatolite "reef" facies (fig. 2). This facies is not an "ecologic reef" in the sense of Dunham (1970) but is better termed a "bioherm" or "stratigraphic reef." Interpretation of the reef as a control on the distribution of mineralization in the "old Lead Belt" led to 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," individual mounds built of digitate stromatolites; they are described by Ohle and Brown (1954) from exposures in underground mines.

The rock at this outcrop is completely dolomitized. Galena was mined in the Bonneterre about 1 mi northwest of this roadcut, in the old Irondale Mine, on the bank of the Big River.

Stop 2. — From Hwy M-Hwy 8 intersection go 1 mi east on Hwy 8. Outcrops on both sides of the road. Upper part of the Bonneterre Dolomite contains interbedded oolitic grainstones (fig. 3), 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. Outcrops on both sides of the road. Interbedded dolomites and shales of the Davis Formation. Note the large concretion-like "boulders" (fig. 4), which are dolomitized algal bioherms. The Davis represents a transgressive offshore or "basinal" facies. The water was probably never deeper than the photosynthetic limit (about 40 m), as is shown 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, which can be found in the roadcut, indicate that these rocks were exposed to mineralizing fluids.

Stop 4. — From stop 3 go about 0.5 mi east and turn right off of Hwy 8 and go 0.1 mi to stop sign (first intersection). Turn right and go 0.7 mi and turn left at crest of the hill onto Mitchel Road. Go 1.5 mi and turn left at Davis Crossing Road. Go 2.9 mi and turn right (southwest) onto Hwy 32. Go 1.4 mi on Hwy 32 to intersection with County Road 32-B. The outcrop is on the right; it shows the conformable contact at the Lamotte-Bonneterre transition. 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) 1.9 mi on Hwy 32. The outcrop is on the right.

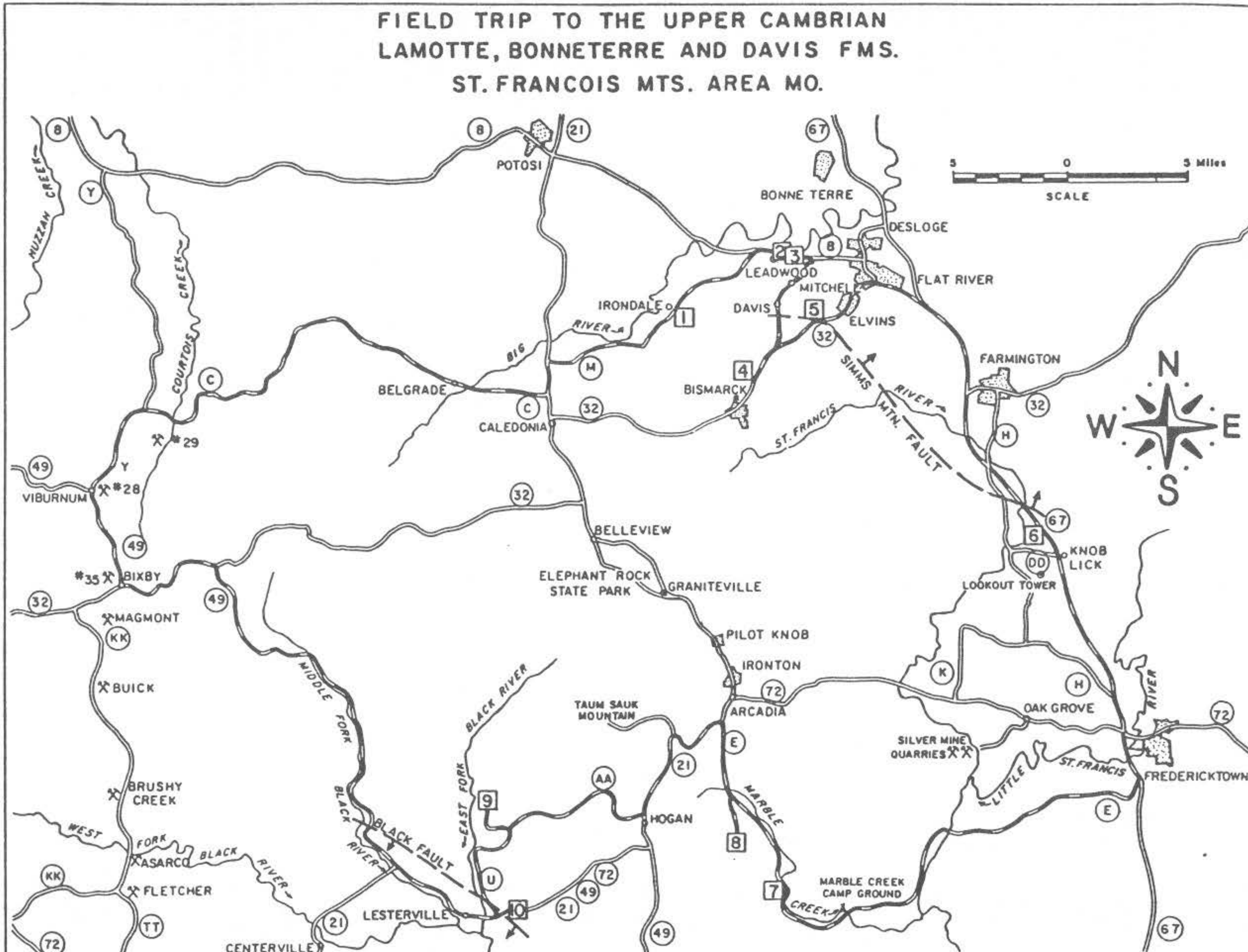


Figure 1 – Road map of the field trip area.

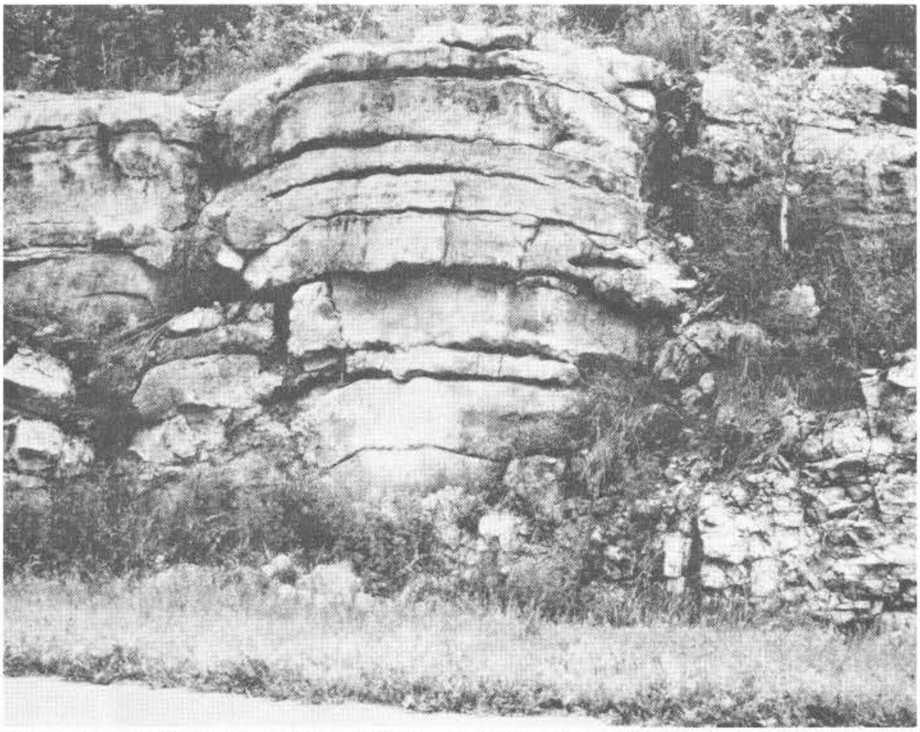


Figure 2 — Outcrop at stop 1 showing a "roll structure" in the algal reef facies of the Bonneterre Formation. This structure was formed from a build-up of digitate stromatolites. A grainstone channel made up of algal clasts can be observed on the lower left side of the structure. The outcrop is about 15 ft high.

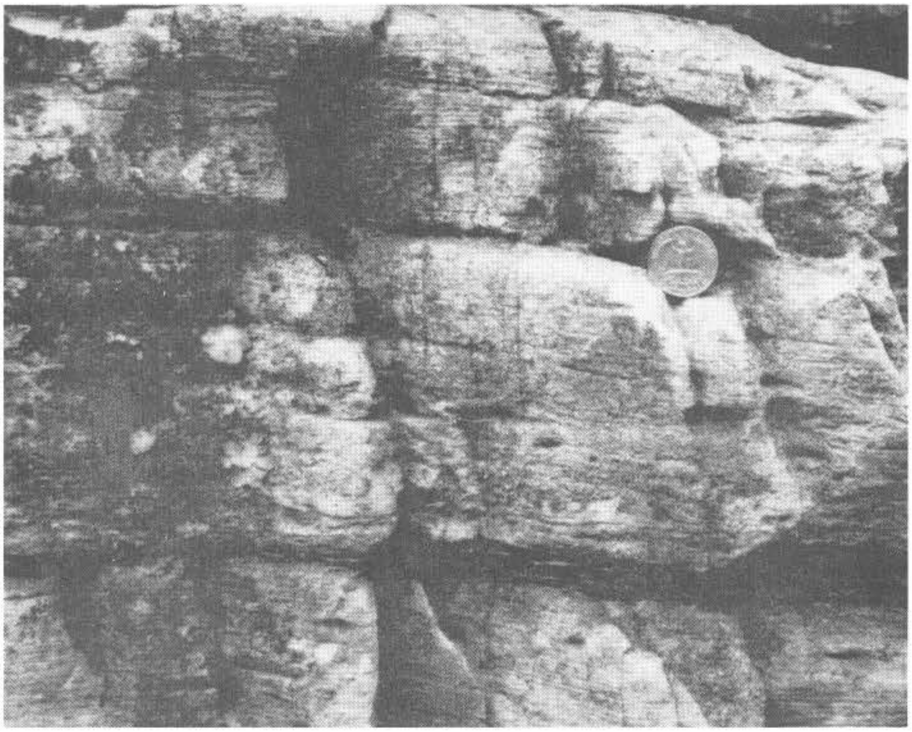


Figure 3 — Thinly bedded oolitic grainstones of the upper part of the reef-grainstone bank facies of the Bonneterre Formation.

Figure 4 — An outcrop of the Davis Formation at stop 3 showing a boulder-like algal bioherm (top left) and interbedded dolomite and shale. Dr. Frank Beales of the University of Toronto serves as the scale.

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 that transported the warm mineralizing brines from the basin to sites of sulfide ore deposition in southeastern Missouri (see Gregg, 1985). The outcrop is cut by several faults (fig. 5) of the Simms Mountain fault system. The main trace of the fault system is to the immediate northeast of the outcrop, where there is about 800 ft of throw, with the down-thrown side to the northeast. The Upper Cambrian Derby-Doerun Formation crops out on the northwest side of the road, just north-west of the Lamotte outcrop.

Stop 6. — Take Hwy 67 south to Farmington (see fig. 1). (Note: 4.7 mi south of the Hwy 67-Hwy W intersection the Simms Mountain fault cuts across the road). At 5.6 mi south of Hwy W intersection, the outcrop is on the right (west) side of Hwy 67. Thin-bedded Lamotte Sandstone overlies Precambrian igneous rocks (fig. 6).

Stop 7. — From Hwy 67-Hwy E intersection go 20.4 mi west on Hwy E to outcrop on the right. Bonneterre Dolomite back reef "white rock" facies. Dolomite with planar stromatolites, stacked hemispheroids, birdseye structure, etc. These features are consistent with the view that the back reef was a setting for evaporite

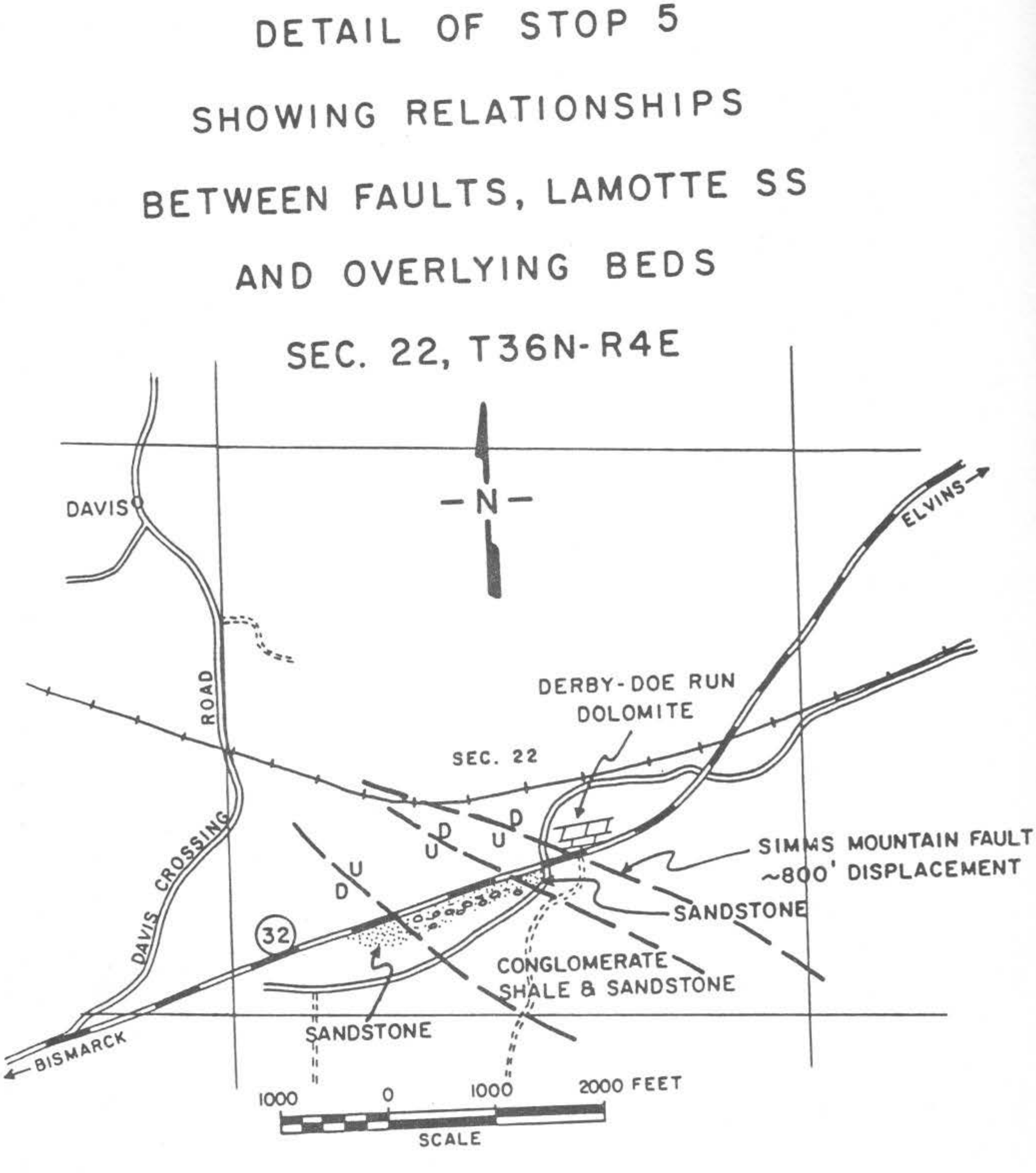


Figure 5 – Detail map of stop 5.

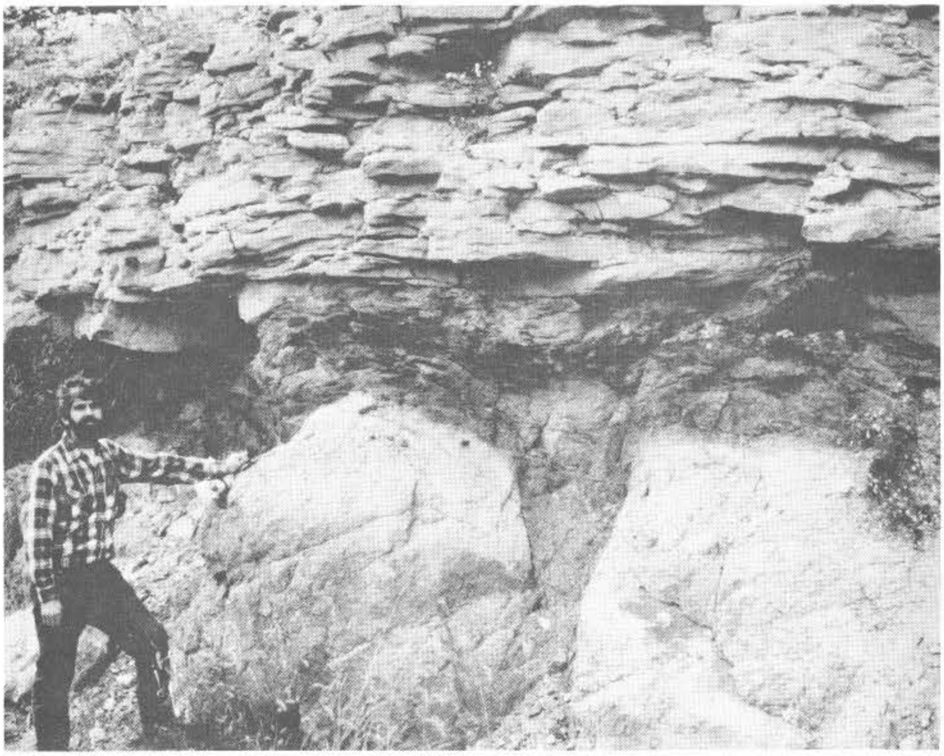


Figure 6 — Lamotte Sandstone overlaying a Precambrian granite at stop 6. A thin paleosol marks the ***unconformity*** *between the units. Dr. Joel Leventhal of the USGS is standing on the lower left.*

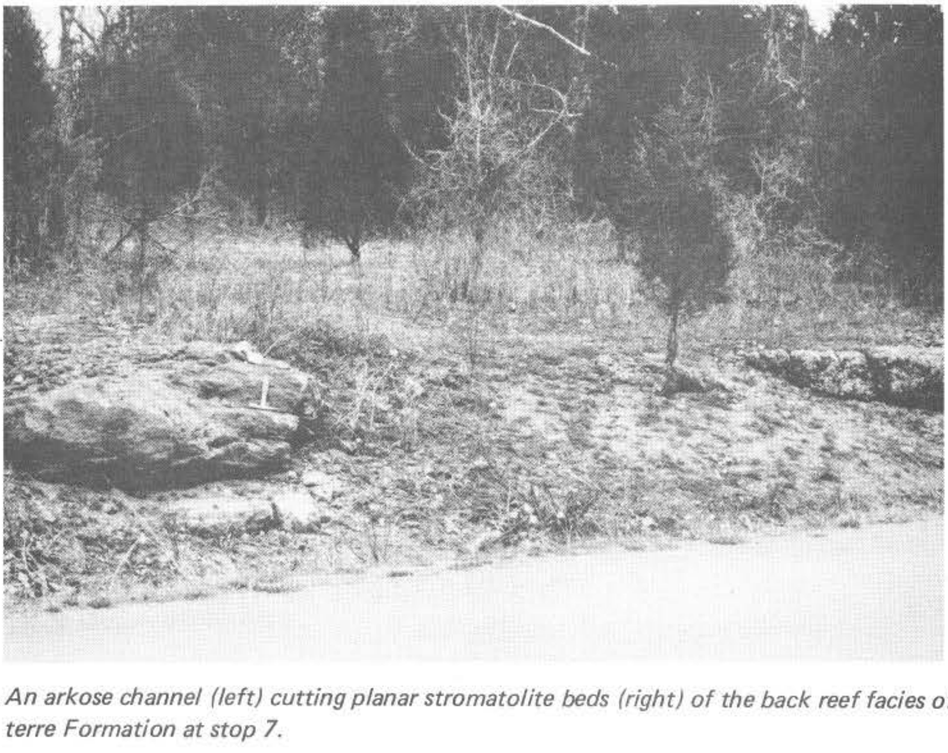


Figure 7 — An arkose channel (left) cutting planar stromatolite beds (right) of the back reef facies ***of the Bonneterre*** *Formation at stop 7.*

deposition. Evaporites are considered as a possible source of the sulfur in MVT ore bodies (Jackson and Beales, 1967). However, no direct evidence of evaporites, such as gypsum casts, tepee structures, or chicken-wire structures, have been reported in the Bonneterre "back reef." This view, therefore, remains controversial. Note the arkose channel that cuts the dolomite beds (fig. 7).

Stop 8. — On Hwy E, continue west 4.9 mi to county road on the left. Turn left (south) and go 1 mi to outcrop on the left. "Burrowed" mudstone of Howe (1968). This probably represents a "back reef" lagoonal facies. Pelleted micritic limestone and coarse crystalline dolomite form a "netted rock" (fig. 8) similar to the "net fabric" dolomite described by Zenger (1983) in the Lost Burro Formation (Cambrian), California. The dolomite at this location is believed to be epigenetic and probably was formed at about the time of lead and zinc mineralization. *The outcrop is on private property; therefore, please do not hammer on the rock!*

Stop 9. — Turn right at Hwy E-Hwy 20 intersection and go 6.8 mi to Hwy AA. At Hwy AA turn left (west) and go 10.5 mi to Taum Sauk power plant. Cambrian carbonate and shale units are draped over a Precambrian igneous knob (fig. 9). Excellent exposure showing the structural relationships between the sediments and the underlying igneous complex. The steep dip of the Cambrian units is the result of original sedimentary dip, possibly combined with differential compaction and pressure solution of the sediments (Bridge and Dake, 1929). Similar relationships between 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 onlapped Precambrian highs are believed to have formed "traps" where sulfide ores precipitated (see Grundmann, 1977).

Stop 10. — From the power plant go back 2.1 mi on Hwy AA to Hwy U intersection. Turn right (south) on Hwy U and go 6.6 mi to Hwy 21-49-72 intersection. Turn left (east) and go 0.5 mi to outcrop on the left. Lower Davis Formation "white rock" facies. Note planar stromatolites, rip-up clasts, and other shallow subtidal and intertidal features, which are similar to those in the underlying Bonneterre "white rock" and which contrast with the deeper water, Davis shale facies observed at stop 3.

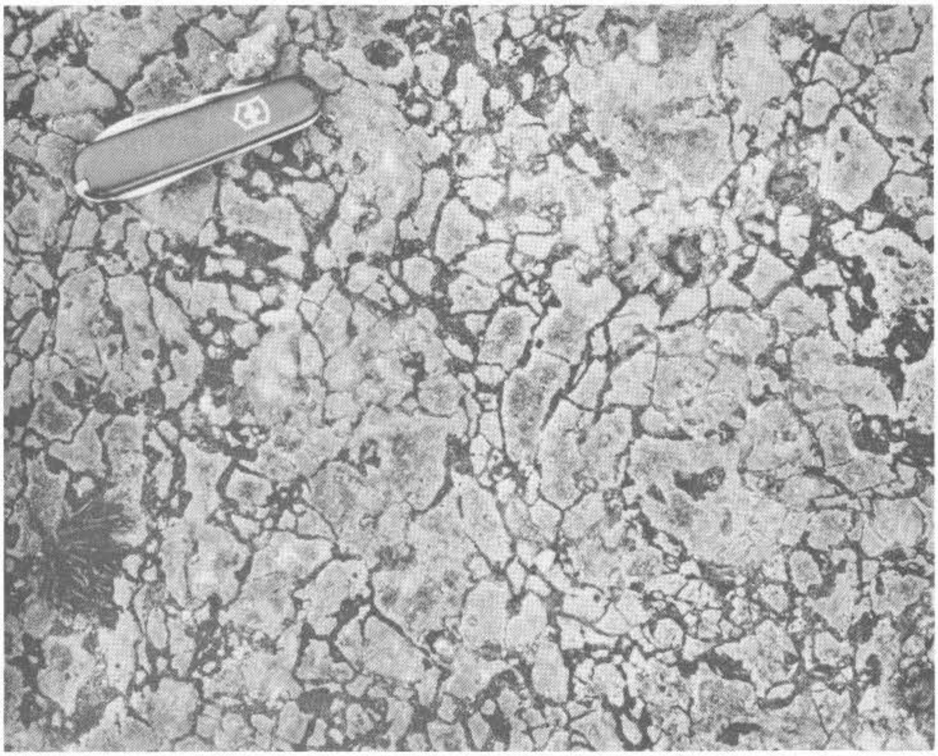


Figure 8 — Burrowed mudstone "netted rock" at stop 8. The light material is micritic limestone and the dark "netting" is coarsely crystalline dolomite.

Figure 9 — Upper Cambrian carbonate and shale sequence onlapping Precambrian igneous rocks at the Taum Sauk power plant (stop 9). The section shown is about 70 ft high.

REFERENCES CITED

Anderson, G.M., and Macqueen, R.W., 1982, Ore deposit models: Mississippi Valley-type lead-zinc deposits: Geoscience Canada, v. 9, p. 108-117.

Bridge, J., and Dake, C.L., 1929, Initial dips peripheral to resurrected hills: Missouri Bureau of Geology and Mines, 55th Biennial Report, Appendix I, p. 1-7.

Dunham, R.J., 1970, Stratigraphic reefs versus ecologic reefs: Bulletin of the American Association of Petroleum Geologists, v. 54, p. 1931-1932.

Gerdemann, P.E., and Myers, H.E., 1972, Relationships of carbonate facies patterns to ore distribution and to ore genesis in the southeast Missouri lead district: Economic Geology, v. 67, p. 426-433.

Gregg, J.M., 1985, Regional epigenetic dolomitization in the Bonneterre Dolomite (Cambrian), southeastern Missouri: Geology, v. 13, p. 503-506.

Grundmann, W.H., Jr., 1977, Geology of the Viburnum No. 27 Mine, Viburnum trend, southeast Missouri: Economic Geology, v. 72, p. 349-364.

Howe, W.B., 1968, Planar stromatolite and burrowed carbonate mud facies in Cambrian strata of the St. Francois Mountain area: Missouri Department of Natural Resources, Division of Research and Technical Information, Geological Survey, Report of Investigations 41, 113 p.

Jackson, S.A., and Beales, F.W., 1967, An aspect of sedimentary basin evolution: The concentration of Mississippi Valley-type ores during late stages of diagenesis: Bulletin of Canadian Petroleum Geology, v. 15, p. 383-433.

Kurtz, V.E., 1986, Age and correlation of beds associated with the Bonneterre-Davis contact in southeast Missouri (abstract), *in* Gregg, J.N., and Hagni, R.D., eds., Symposium on the Bonneterre Formation (Cambrian), southeast Missouri: University of Missouri-Rolla, Department of Geology and Geophysics, p. 14.

Ohle, E.L., and Brown, J.S., 1954, Geologic problems in the southeast Missouri lead district: Geological Society of America Bulletin, v. 65, p. 201-221, 935-936.

Thacker, J.L., and Anderson, K.H., 1977, The geologic setting of the southeast Missouri lead district — Regional geologic history, structure, and stratigraphy: Economic Geology, v. 72, p. 339-348.

Zenger, D.H., 1983, Burial dolomitization in the Lost Burro Formation (Devonian), east-central California, and the significance of late diagenetic dolomitization: Geology, v. 11, p. 519-522.

GEOLOGY OF THE ST. JOE MINERALS CORPORATION, NUMBER 28 MINE

by
James R. Pettus, Jr.
and
Robert G. Dunn, Jr.

St. Joe Minerals Corporation
P.O. Box 500
Viburnum, Missouri 65566

INTRODUCTION

St. Joe's Number 28 mine is in the Ozarks of southeast Missouri on the eastern edge of the small mining community of Viburnum, Missouri (fig. 1). Number 28 mine is a lead mine with significant zinc, copper, and silver values in Upper Cambrian carbonates of the Bonneterre Formation. The mine represents a classic Mississippi Valley-type ore deposit.

In 1955, St. Joe discovered lead ore about 3 mi northwest of the town of Viburnum. Intense prospecting during the following years outlined a large area of mineralization which has been exploited to date by four mines: the first, Number 27 mine was developed on a satellite ore body west of the main Viburnum Trend. It was adjacent to a granite knob outcrop. Ore reserves at Number 27 mine were depleted in 1978. The second mine to be developed was Number 28 mine, followed by Number 29 mine to the north. Casteel mine, shaft Number 35, which began production in 1984, is 5 mi south of Number 28 mine, just west of Bixby. These mines have all provided feed for a central flotation mill at Number 28 mine site. It has recently been expanded from an initial capacity of 7500 to 12,000 tons per day. The mill produces three products: galena concentrates, which are shipped to the St. Joe lead smelter at Herculaneum, Missouri, and sphalerite and chalcopyrite concentrates, which are shipped to various smelters.

GEOLOGIC SETTING

Surface outcrops in the vicinity of Number 28 mine are Upper Cambrian carbonates of the Eminence/Potosi Dolomites. A major unconformity is at the base of the Upper Cambrian. The underlying Precambrian rocks (granites and rhyolites approximately 1.4 billion years old) were deeply eroded, resulting in a rugged topography (figs. 2 and 3). The basal Upper Cambrian unit, the Lamotte Sandstone, and Cambrian conglomerates covered the surface with as much as 400 ft of clastics. A number of paleotopographic highs stood above the clastics, as peaks and islands ("knobs") in the Upper Cambrian sea. The lower knobs were buried during deposition of the Lamotte Sandstone and the Bonneterre Formation; the higher knobs were eventually covered by post-Bonneterre sediments. Facies variations that resulted from the different depositional environments in the vicinity of these knobs have been discussed in many papers (Gerdemann and Myers, 1972; Larsen, 1979; etc.) and are illustrated with terminology from the St. Joe Rock Classification System, for the Viburnum area in figures 4 and 5.

Figure 2 provides the regional geology of the Southeast Missouri Pb-Zn-Cu mining districts. Figure 3 shows the general geology of the Number 28 mine area, including mine workings, structural contours of the base of the Bonneterre, and the subcrop of the Lamotte Sandstone and the igneous rocks. Two large, northeast-southwest-trending Precambrian knobs are in the immediate mine area. The knob 3000 ft north of the shaft is 0.75 mi long, with a peak elevation of about 560 ft above sea level; it is composed of both granite and rhyolite. The other knob is 2000 ft southeast of the shaft, with a peak elevation of about 735 ft and a total length of 2 mi. Section A-A', figure 5, illustrates the main mining horizons in the mine. Approximately half the ore is in the reef facies and half is in the overlying calcarenites.

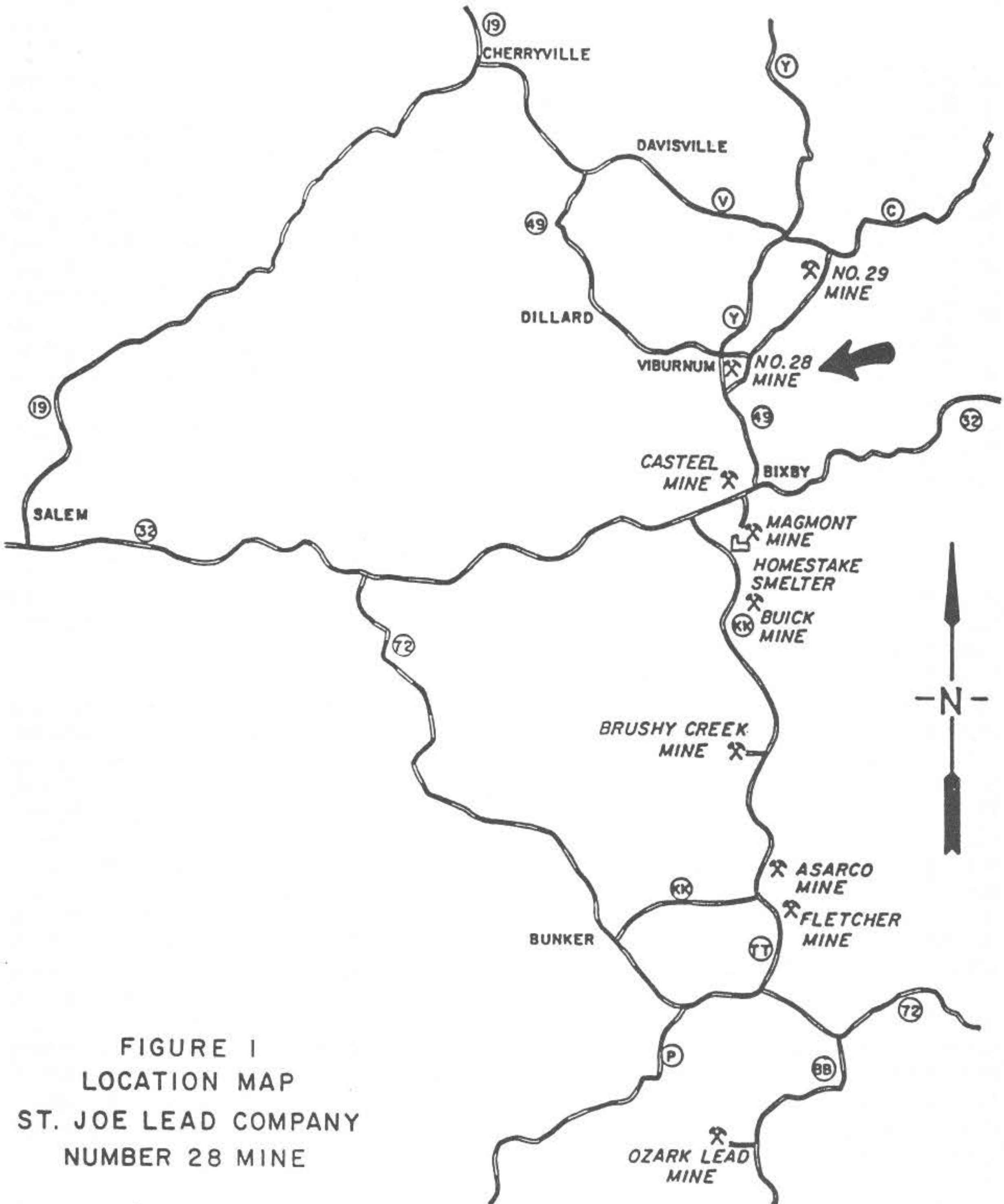


FIGURE 1
LOCATION MAP
ST. JOE LEAD COMPANY
NUMBER 28 MINE

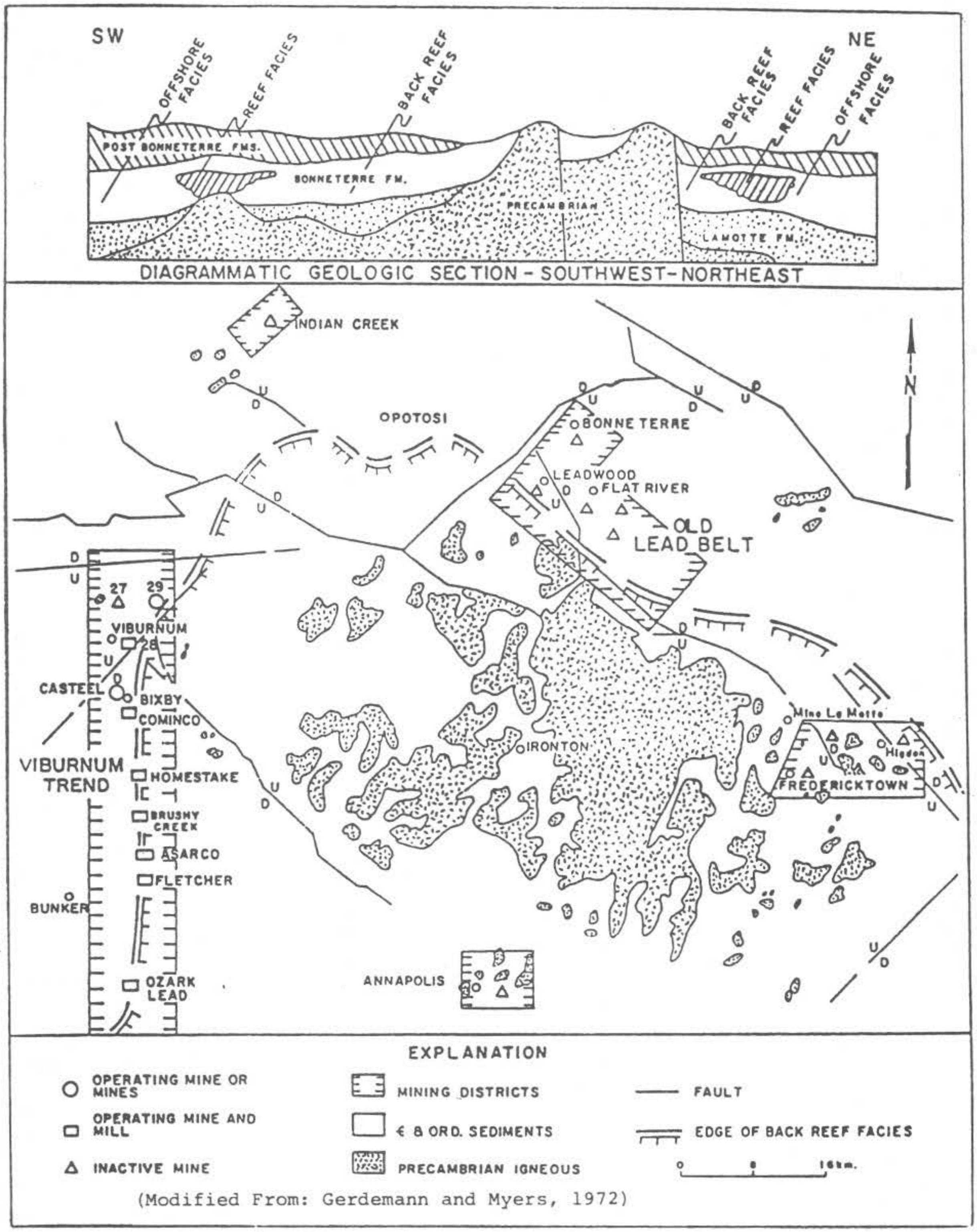


FIG. 2 — MAJOR GEOLOGIC FEATURES AND LEAD DISTRICTS OF SOUTHEAST MISSOURI

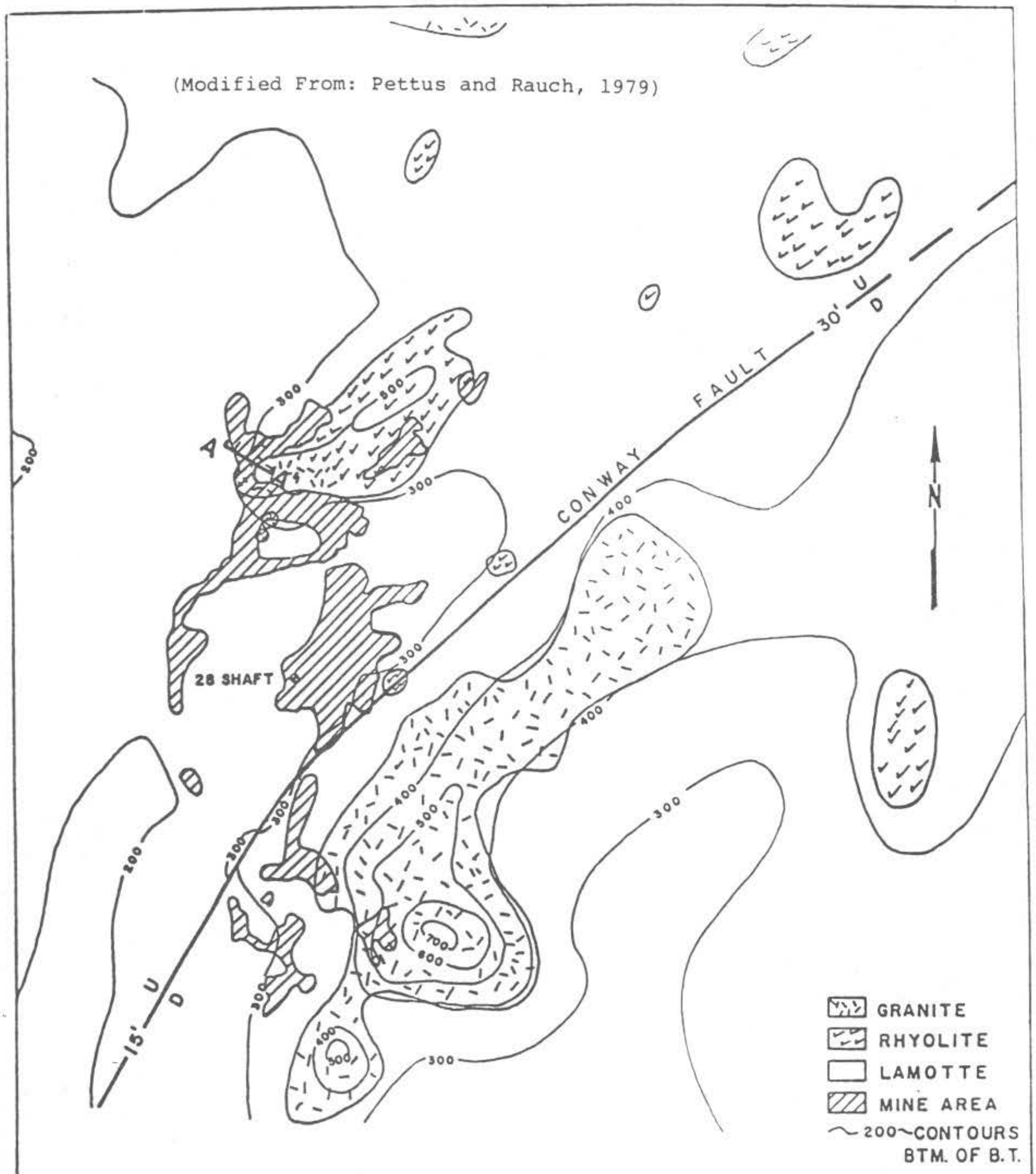


FIGURE 3
28 MINE VIBURNUM DIVISION
BASEMENT AND BOTTOM OF
BONNETERRE FORMATION

BONNETERRE FORMATION AVERAGE THICKNESS 300'

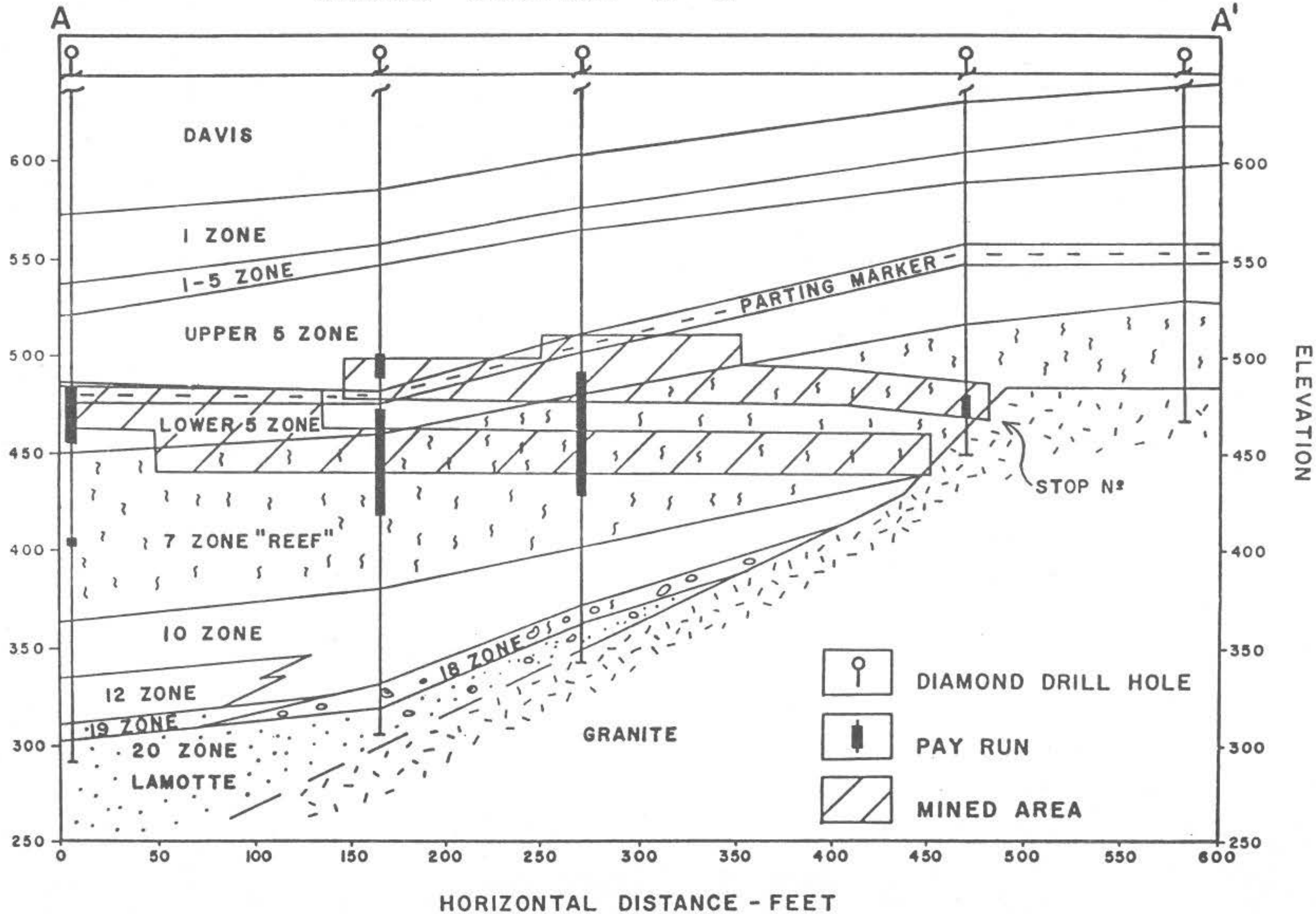
ORE	ZONE	LITHOLOGY
		DAVIS FORMATION
	1	DENSE TAN BANDED MUDSTONES
	1-5	POROUS BROWN CRYSTALLINE GRAINSTONE CONTAINING OOLITES AND ONCOLITES
	5	TAN CRYSTALLINE GRAINSTONE
	5	GRAY TAN OOLITIC GRAINSTONE
	7	BROWN DIGITATE ALGAL STROMATOLITE
	10	TAN OOLITIC GRAINSTONE
	10-12	TAN OOLITIC, TAN CRYSTALLINE, GRAY TAN MOTTLED GRAINSTONE
	19	SANDY TRANSITION GRAINSTONE
	20	LAMOTTE SANDSTONE
	21	PRECAMBRIAN

FIGURE 4. BONNETTE FORMATION SUBDIVISIONS IN VIBURNUM AREA (Adapted from Pettis and Rauch, 1979)

FIGURE 5

(Modified From: Pettus and Rauch, 1979)

CROSS SECTION A-A'



STRATIGRAPHIC ZONES AND ORE STRUCTURES

The algal stromatolites of the 7-zone reef are columnar (digitate) and are classified as separate, vertically stacked hemispheroids. Algal "fingers" average about an inch in diameter. Occasionally, head-shaped forms, 8-10 in. in diameter are seen in the mines. The algal stromatolites are reddish brown or tan and are generally darker at their edges. Algal detritus and other clastics accumulated between the algal columns. They are generally light colored with black silty shale partings and gray spots. The algal reef section is 60-100 ft thick in the mine. Surge channels (grooves) occur throughout the reef and are filled with clastic sediments (fig. 6). These channels generally trend northeast-southwest to east-west and the contact between the algal reef and the channel fill is often well mineralized. In addition to grainstone channel fills, there are also irregular lenticular bodies of inter-reef grainstones. Ore grades in the reef average about 3 percent lead.

Where the reef lies directly on the Precambrian basement, conglomerate occurs within the reef section. The conglomerate clasts usually consist of the same type of igneous rock as that in the adjacent knob. Clast size and quantity increase with increasing proximity to the knob. Usually associated with the conglomerate zones, mineralization occurs as disseminated galena around the clasts and in associated black silty shale bands. Many of the granite clasts are weathered, with their feldspar phenocrysts altered to white clay minerals. In some cases, sulfide mineralization fills cracks in the igneous clasts. Figure 7 shows granite conglomerate in the Bonneterre reef facies of stope 67V8 (southeastern part of the mine).

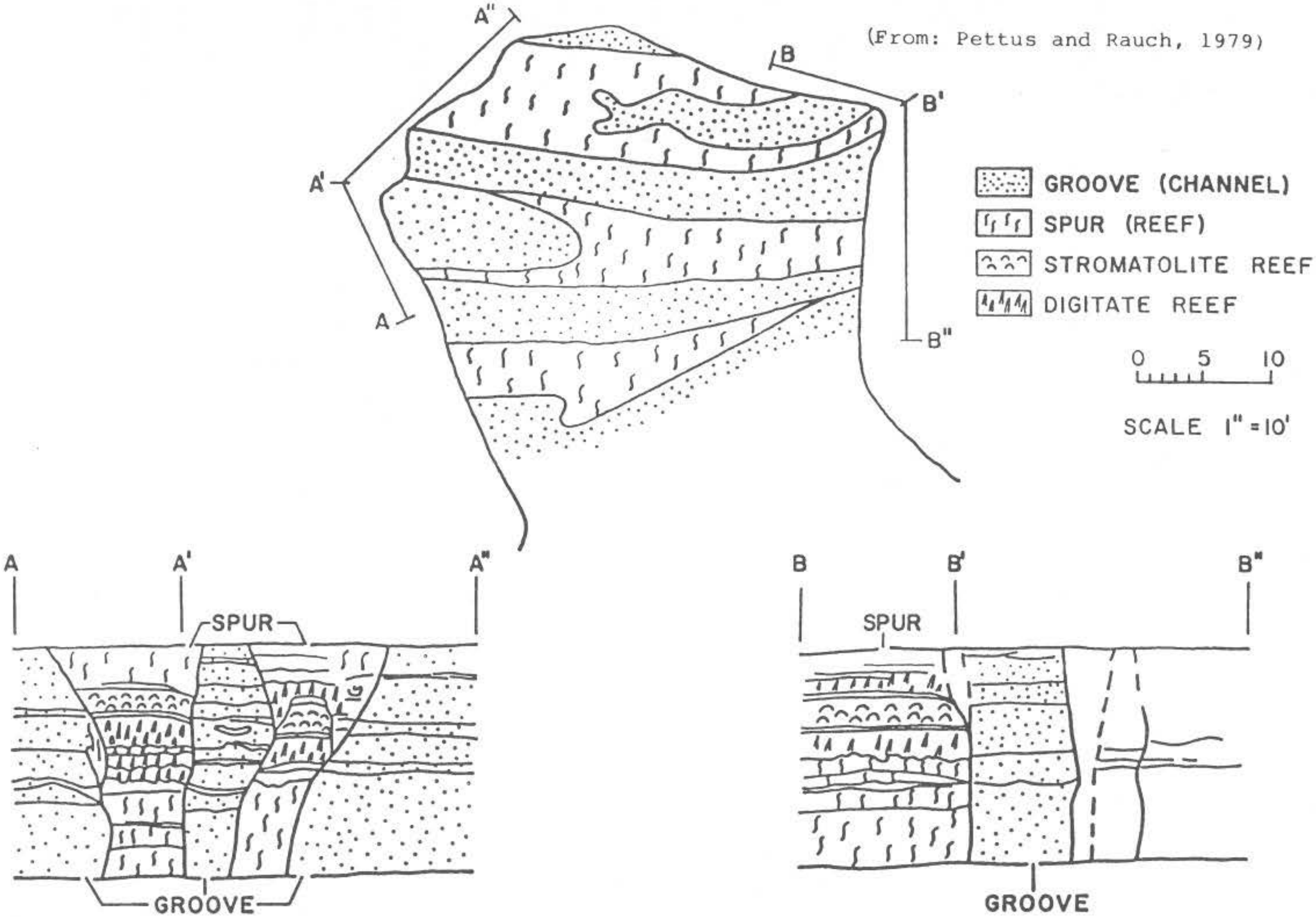
Clastic carbonate units (5 zone) occur above the 7-zone reef. The tan oolitic crystalline calcarenites of the lower 5 zone are 10-40 ft thick in the mine area. The parting marker is an interbedded series of gray silty calcarenites, 10-15 ft thick. The upper 5 zone is a brown-spotted, tan-brown oolitic crystalline calcarenite, about 40 ft thick in the mine area. Breccia zones in the lower and upper 5-zone beds are important ore-bearing structures (fig. 8); they generally contain the highest grade ore encountered at Number 28 mine. Breccia zones are usually long and narrow, with a general north-south trend. Observations have indicated that they bottom out at the top of the reef. The most persistent breccia zone, along the western side of Number 28 mine, has been traced for miles by drilling. In it ore occurs from the reef zone, upward through the 5 zone. Thickness of ore in this area can exceed 100 ft, and the width of the zone can exceed 300 ft. Photographs in figure 8 show typical examples of high-grade ore-matrix breccias. Breccias can contain up to 30 percent lead in places, but average about 5 percent.

FAULTING

A large, complex fault zone, the Conway fault (fig. 3), that strikes north-northeast to northeast across the southern third of the mine has caused difficult mining conditions, due to bad ground conditions and a large inflow of water to the mine. Some areas adjacent to the fault have produced abnormally rich ore that may be related to ground preparation and/or movement of ore fluids along the fault.

FIGURE 6

(From: Pettus and Rauch, 1979)



SPUR AND GROOVE STRUCTURES
IN ALGAL REEF

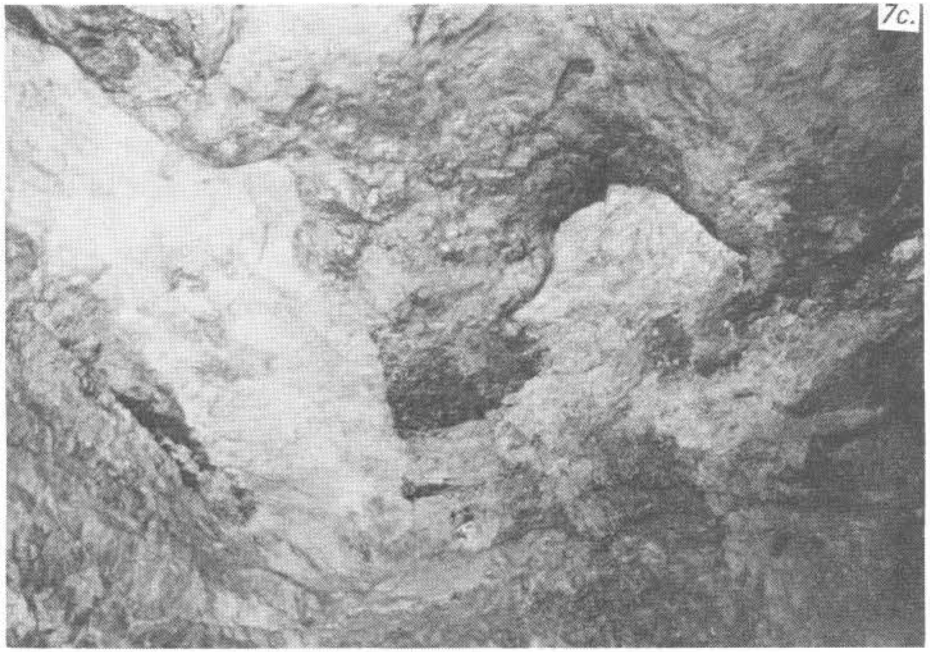


Figure 7a — Conglomerate occurs adjacent to a small bleached "hump" that possibly resulted from subareal exposure and erosion.

Figure 7b — Close-up of the area in the center of the left side of Figure 7a (garnite clasts occur in the reef facies).

Figure 7c — Looking up at the mine "back" which shows a plan view of the distribution of conglomerate. The white areas are bleached parallel "humps," linear in plan, with adjacent channel-like features filled with conglomerate.

Figure 8a — (stope 66V7) Slabs of brown dolomite enclosed in massive chalcopyrite with areas of disseminated galena. Note the rolled-up dolomite slab at the bottom center of the photograph.

Figure 8b — (stope 67V36) Local occurrence of strataform galena. This occurrence has the appearance of a stratified unit, possibly an internal sediment, and is overlain by massive iron sulfide which encloses a large slab of brown dolomite.

MINERALOGY

Ore mineralogy is simple. Lead occurs as galena, zinc as sphalerite, and copper as chalcopyrite. These ore minerals occur in an approximate ratio of 10:1:0.6, respectively, and all have minor amounts of silver. Accessory minerals include calcite, dolomite, quartz, pyrite, and marcasite. Sphalerite contains cadmium and most of the silver that occurs in the ore. Cobalt/nickel sulfides may be present, but cobalt and nickel concentrations do not reach economic levels at current metal prices.

ACKNOWLEDGMENTS

We thank the management of St. Joe Minerals Corporation for permission to publish this paper, and for cooperating in making necessary preparations for the mine tour.

We acknowledge the observations and discussions contributed over many years by past and present members of the St. Joe Southeast Missouri exploration, mine geology, and research geology staffs.

Thanks to Jay M. Gregg for his assistance with the photographs, Marcia Harris for typing, Butch Bowen for drafting, and to Mark Taylor for suggestions.

REFERENCES CITED

Gerdemann, P.E., and Myers, H.E., 1972, Relationships of carbonate facies patterns to ore distribution and to ore genesis in the southeast Missouri lead district: Economic Geology, v. 67, p. 426-433.

Larsen, K.G., 1979, Stratigraphic and facies nomenclature of the Viburnum Trend, southeast Missouri: Guidebook, 26th Annual Field Trip, Association of Missouri Geologists, 1979, p. 15-19.

Pettus, J., and Rauch, K., 1979, Geology of St. Joe Viburnum Mine No. 28: Guidebook, 26th Annual Field Trip, Association of Missouri Geologists, 1979.

MINE TOUR:
ST. JOE NUMBER 28 MINE

by

James R. Pettus, Jr.

and

Robert G. Dunn, Jr.

St. Joe Minerals Corporation

P.O. Box 500

Viburnum, Missouri 65566

MINE TOUR:
ST. JOE NUMBER 28 MINE

As a result of the dynamic nature of mining and particularly the current stage of mining at the Number 28 mine, access to particular occurrences and outcrops cannot be assured.

Figure 1 is a mine outline and map guide of the tour route. Figure 2 shows the general lithology of the Bonneterre Formation in the Viburnum area. Figure 3 (from the paper on the Number 28 mine) shows a detailed cross section from the north end of the mine. Figure 4 is a detailed plan view and two cross sections of groove and spur features in the 7-zone reef on the east side of the mine.

FIELD TRIP STOPS

(It may not be possible to visit all stops during the trip)

Stop 1. — The Conway fault zone is 200-300 ft wide with a downward displacement of 20 ft on the southeast side. (67V38 stope)

Stop 2. — Precambrian boulder beds on the flank of the large knob at the southeast end of the mine. (67V8 stope)

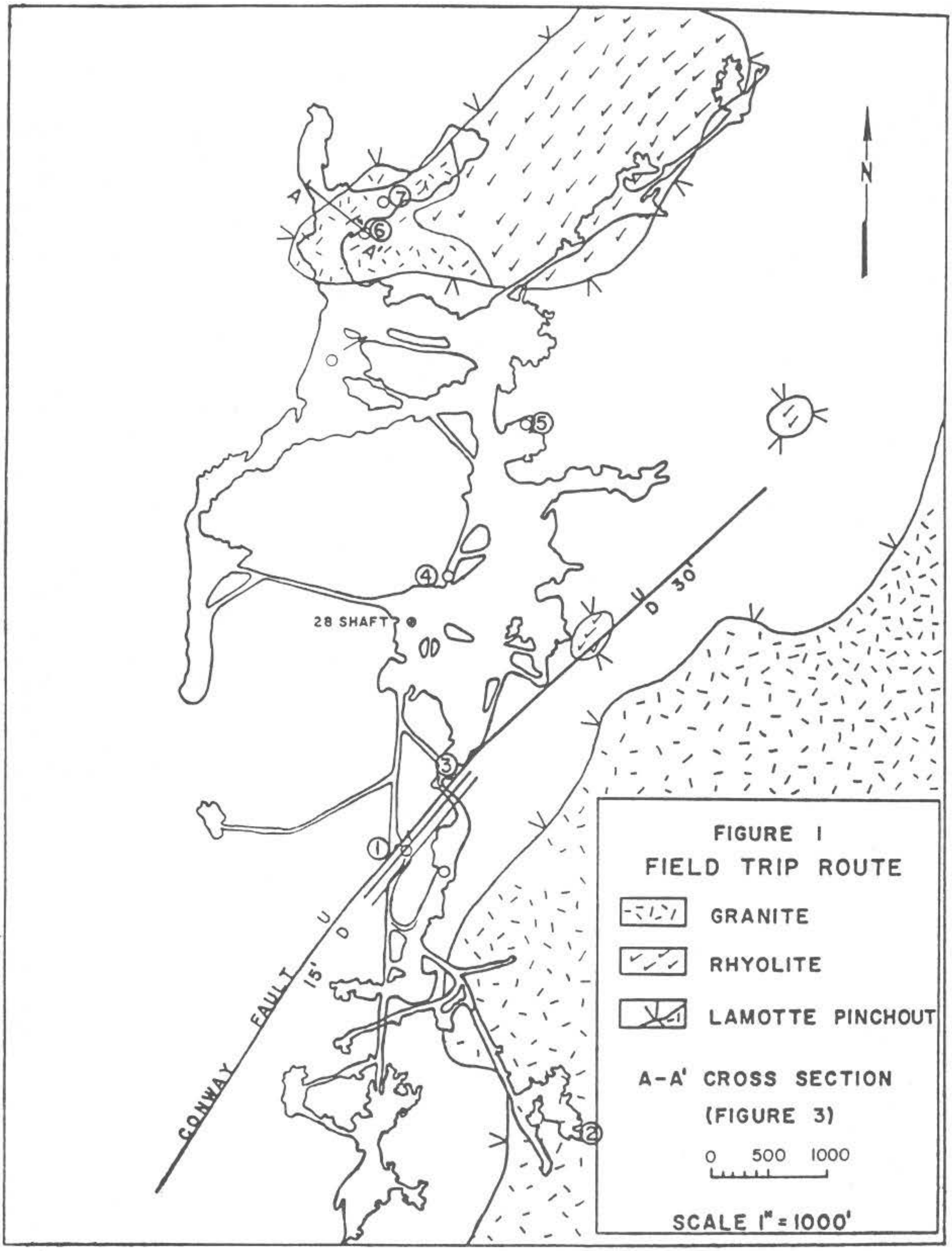
Stop 3. — This is a long, narrow north-south ore trend in the lower 5-zone oolitic calcarenite and the parting marker horizon. The ore is rich, but spotty, with much leaching and oxidation due to the nearby Conway fault zone.

Stop 4. — The best place in the mine to see groove and spur horizons in the back. This is a non-mineralized area.

Stop 5. — The 7-zone algal reef. There is good groove and spur development in this area. Illustrations in figure 4 are based on features observed at this location.

Stop 6. — Precambrian exposure. The 7-zone reef lies directly on the Precambrian, which dips into the floor to the west. This point is at the southeast end of Section A-A' in figure 3.

Stop 7. — Breccia ore. This is a high-grade lead and copper area.



(Modified From: Pettus and Rauch, 1979)

ORE	ZONE	LITHOLOGY
		DAVIS FORMATION
	1	DENSE TAN BANDED MUDSTONES
	1-5	POROUS BROWN CRYSTALLINE GRAINSTONE CONTAINING OOLITES AND ONCOLITES
	5	TAN CRYSTALLINE GRAINSTONE
	5	GRAY TAN OOLITIC GRAINSTONE
	7	BROWN DIGITATE ALGAL STROMATOLITE
	10	TAN OOLITIC GRAINSTONE
	10-12	TAN OOLITIC, TAN CRYSTALLINE, GRAY TAN MOTTLED GRAINSTONE
	19	SANDY TRANSITION GRAINSTONE
	20	LAMOTTE SANDSTONE
	21	PRECAMBRIAN

BONNETERRE FORMATION AVERAGE THICKNESS 300'

FIGURE 2. BONNETTE FORMATION SUBDIVISIONS IN VIBURNUM AREA (Adapted from Pettis and Rauch, 1979)

FIGURE 3

(Modified From: Pettus and Rauch, 1979)

CROSS SECTION A-A' -

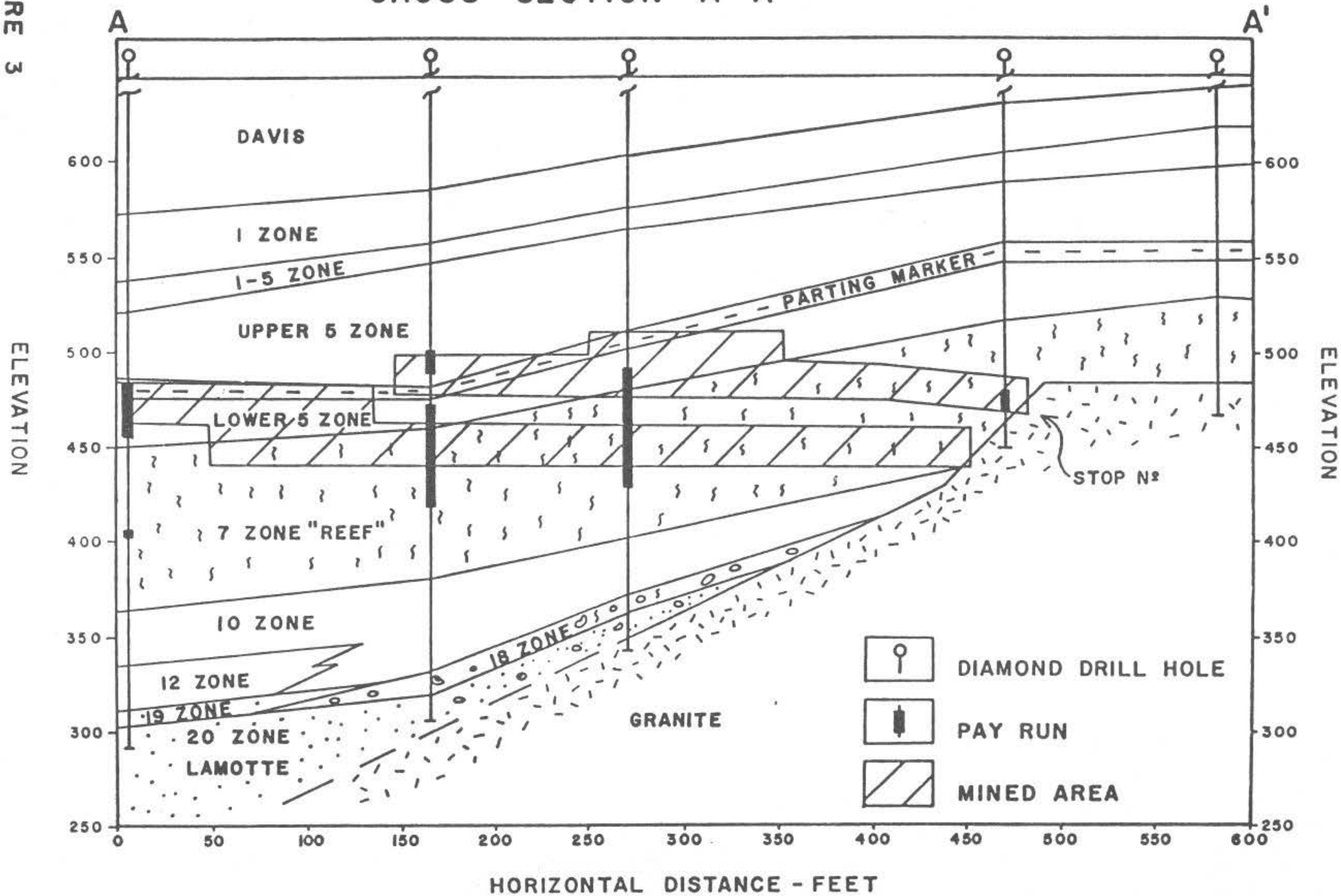
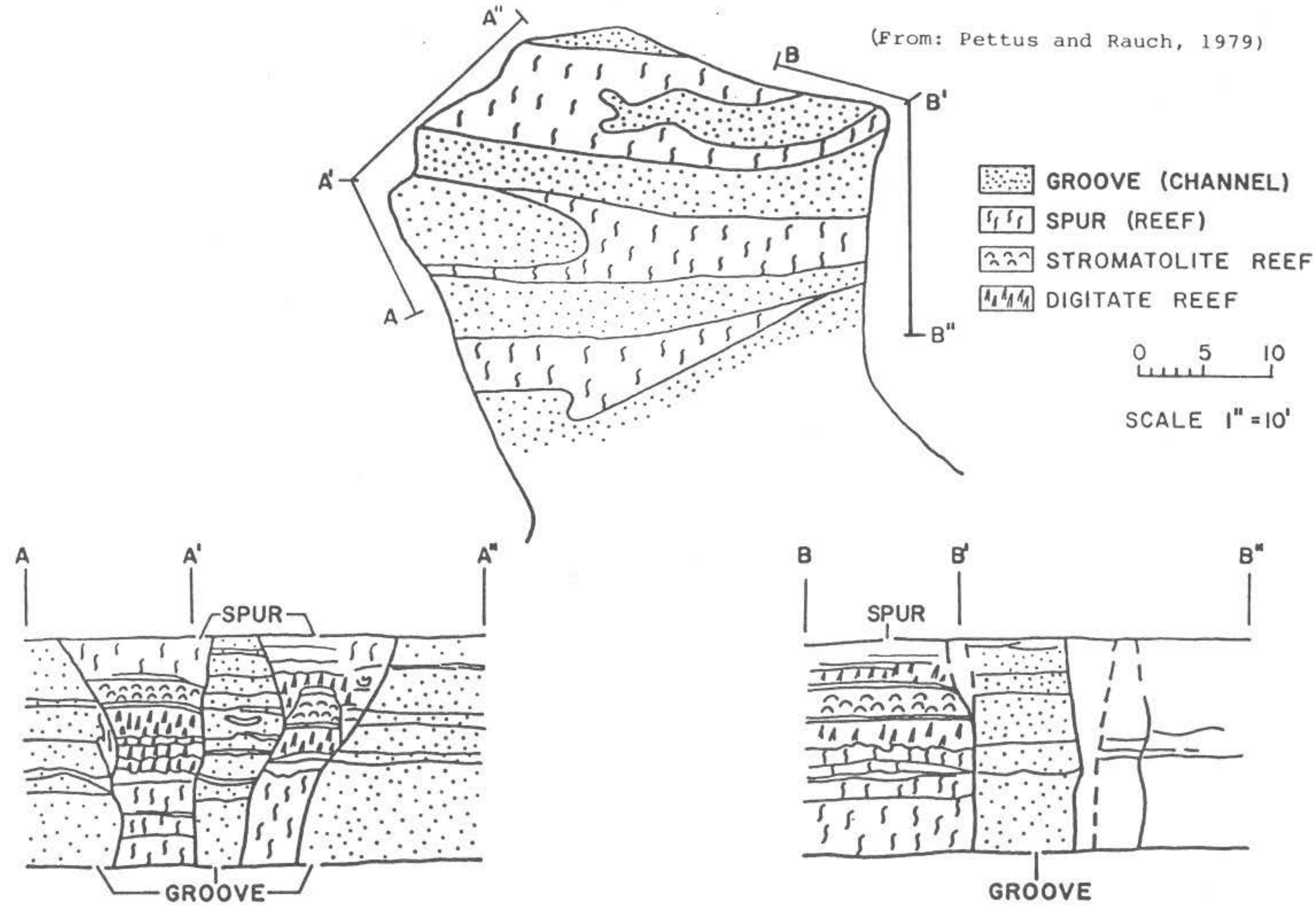


FIGURE 4



SPUR AND GROOVE STRUCTURES
IN ALGAL REEF

GEOLOGY OF THE MAGMONT MINE, VIBURNUM TREND, SOUTHEAST MISSOURI

by
Peter H. Sweeney, Edwin D. Harrison,
and Milton Bradley
Magmont Mine, Bixby, Missouri

Reprinted with permission of
The Society of Economic Geologists

Economic Geology
Vol. 72, 1977, pp. 365–371

Geology of the Magmont Mine, Viburnum Trend, Southeast Missouri

PETER H. SWEENEY, EDWIN D. HARRISON, AND MILTON BRADLEY

Abstract

The Magmont mine is about one and a half miles south of Bixby, Missouri, within the northern third of the Viburnum Trend. First intersected by surface drilling in September 1962, the Magmont orebody was outlined by about 200 drill holes. Production began in 1968 and continues at 1,000,000 tons of ore per year.

Economic mineralization occurs within the Bonneterre Formation, closely associated with solution-induced collapse breccias, gravity slumps, a favorable bed sequence called the "Silty Marker," and inter-reef calcarenites. The Davis shale overlies the Bonneterre Formation and has acted as an impervious barrier to solution flow. No structural irregularities within the Bonneterre Formation in the mine area can be attributed to underlying Precambrian knobs, which are apparently not present within this part of the "Buick embayment" (a local feature defined by a shallow, east-northeast-trending valley in the basement rocks).

A northeast-northwest joint system is present. One north-south, partially open fracture can be traced for 2,500 feet. Bounding, shale-filled subsidence faults mark the north-south trend of high breccia ore zones. Vertically, economic mineralization occurs between the base of the Davis shale and the base of the lower reef horizon of the Bonneterre Formation. Three north-south-trending, parallel ore zones comprise the Magmont orebody.

Laterally a roughly concentric mineral zoning is present. From outside to inside it is marcasite, marcasite-galena, and galena-chalcopyrite-sphalerite. Gangue minerals in addition to marcasite are dolomite, calcite, quartz, and minor dickite.

Lesser minerals are pyrite, siegenite, and bornite accompanied by minor amounts of other copper minerals.

Introduction

THE discovery of lead in the Viburnum Trend was made in 1955 by St. Joe Minerals Corporation in the Viburnum area. This 45-mile-long belt extends from north of Viburnum to Eminence and is located 50 miles west of the Old Lead Belt (Fig. 1). Cominco American Incorporated (as Montana Phosphate Products Company) and Dresser Industries (as Magnet Cove Barium) jointly began exploration in Missouri in 1960. From these original companies comes the name "Magmont". First drill intersection of the ore deposit at Magmont occurred in September 1962, and over 200 holes were drilled and 23 miles of core were taken to prove the orebody which lies about 1,200 feet below the surface (Fig. 2). Primarily galena, the deposit contains lesser values in zinc, copper, and silver.

The Magmont mine is in secs. 13, 14, and 23, T. 34 N., R. 2 W., in western Iron County, Missouri (Fig. 1). Production began in 1968 when the first ore from development work became available for milling. Capacity of the mine-mill complex is 1,000,000 tons per year and production continues at this rate.

Mining practice at the Magmont mine is the basic room-and-pillar, trackless method used in several mines in the Viburnum Trend. All ore is beneficiated in the Magmont mill where separate lead, zinc, and copper concentrates are produced. Lead concentrates are smelted on a toll basis at the AMAX-Homestake Buick lead smelter one-quarter mile southwest of the mine. Zinc concentrate goes to the AMAX electrolytic zinc plant at Sauget, Illinois, and copper concentrate is at present exported.

Structure

A basement structure, defined by a Precambrian high which extends westward from Bixby to Boss, Missouri, and the presence of several Precambrian knobs to the east and southeast of Bixby, roughly outlines the so-called Buick embayment. The Magmont mine is situated within the north-central part of this embayment (Fig. 1).

No Precambrian rocks are exposed in the Magmont mine, and none of the sedimentary features

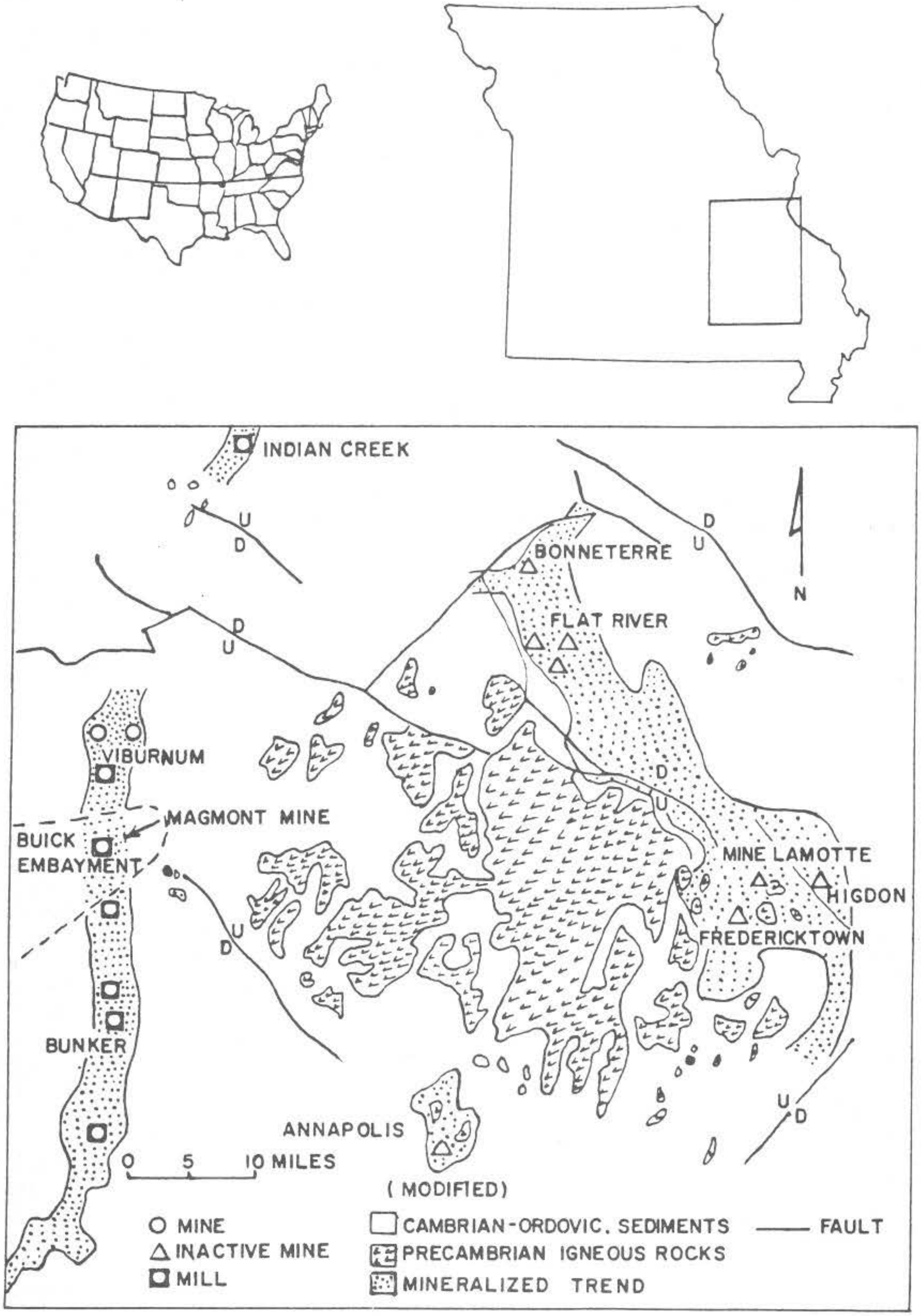


FIG. 1. Location map and position of Buick embayment relative to Viburnum Trend and the Magmont mine. Modified from Snyder and Gerdemann (1968).

exposed in the Bonneterre Formation can be directly attributed to Precambrian surface irregularities or supratenuous folding.

Incipient penecontemporaneous slumping occurs within the gray beds (Silty Marker unit) along the west edge of the mineralized trend where calcarenite sand bars formed local highs during sedimentation. Breccias induced by solution and subsequent collapse are apparent in all areas of extensive mineralization within and above the Silty Marker horizon (Figs. 2 and 3).

Within the Magmont mine, fracture patterns except for the high-ore area consist of a few distinct fractures which can be followed for some distance (Fig. 2). Innumerable smaller fractures which are more properly a joint system are oriented at about N 50°E and N 30°W. One throughgoing fracture striking N 10°W can be traced about 2,500 feet. It is open along much of its length and partially filled with calcite. No vertical displacement is apparent but slickensides suggest horizontal movement.

Low-angle diamond drilling directed at defining possible extensions of fractures into the Precambrian has been done. Numerous veinlets containing quartz and calcite and several shearlike intervals were intersected in the Precambrian. The attitude of both shears and veinlets is such that they are oriented near vertical and parallel to the north-south direction of the Viburnum Trend. Circumferential faulting (Snyder and Gerdemann, 1968) around the Precambrian Ozark Dome is an accepted fact. Lateral stresses occurring within this same period were undoubtedly as effective in producing fractures as were the vertical stresses and much more likely to produce the linear features observed in the Magmont mine. The absence of vertically offset beds, except within the brecciated areas, precludes any pronounced vertical movement on any of the throughgoing fractures in the mine area.

The bounding faults of the brecciated high-ore zone can be traced continuously for about 4,500 feet in the Magmont mine, and extend north and south into adjoining property (Fig. 2). This does not imply that these faults are continuous as individual fractures. They are an interlaced series of connected faults. All the high ore along this 4,500 feet is marked on both east and west sides by these distinctive, shale-filled subsidence fractures (Fig. 4). A few well-defined, northeast-trending, near-vertical fractures turn abruptly into the bounding faults. Others are traceable across the slumped areas, and apparently existed prior to the major vertical movement within the breccia piles. It appears that the pre-existing fracture system (Heyl and Mullens, 1972) has, to a certain extent, influenced the development of the slumped areas and has been responsible

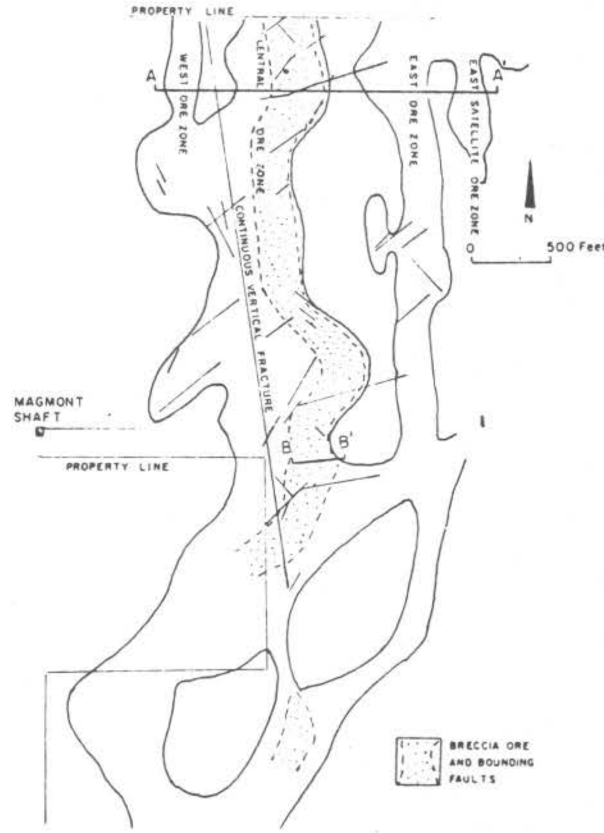


FIG. 2. Plan of northern part of the Magmont orebody showing ore trends and fracture pattern.

for the increased east-west widths of the breccia areas where northeast- and northwest-trending fractures are conspicuous (see Figures 2 and 3).

Stratigraphy

Figure 5 illustrates the stratigraphic sequence of the rock in the Magmont mine area. Figure 6 provides a short summary of the rock types of the Bonneterre Formation and the nomenclature used at the Magmont mine. Total thickness of the Bonneterre Formation averages about 285 feet in the Magmont mine area.

White rock, which results from bleaching and recrystallization of the back reef facies (Gerdemann and Myers, 1972) and which is so prominent along the east edge of the mineralized zone of the Viburnum Trend, is not so obviously developed in this unit of the Bonneterre Formation in the immediate area of the Magmont mine. This suggests that the solutions causing this alteration were not as effective at the greater lateral and vertical distances from basement rocks within the Buick embayment.

Ore Distribution

Mineralization within the mine area is almost totally restricted to the Bonneterre Formation with

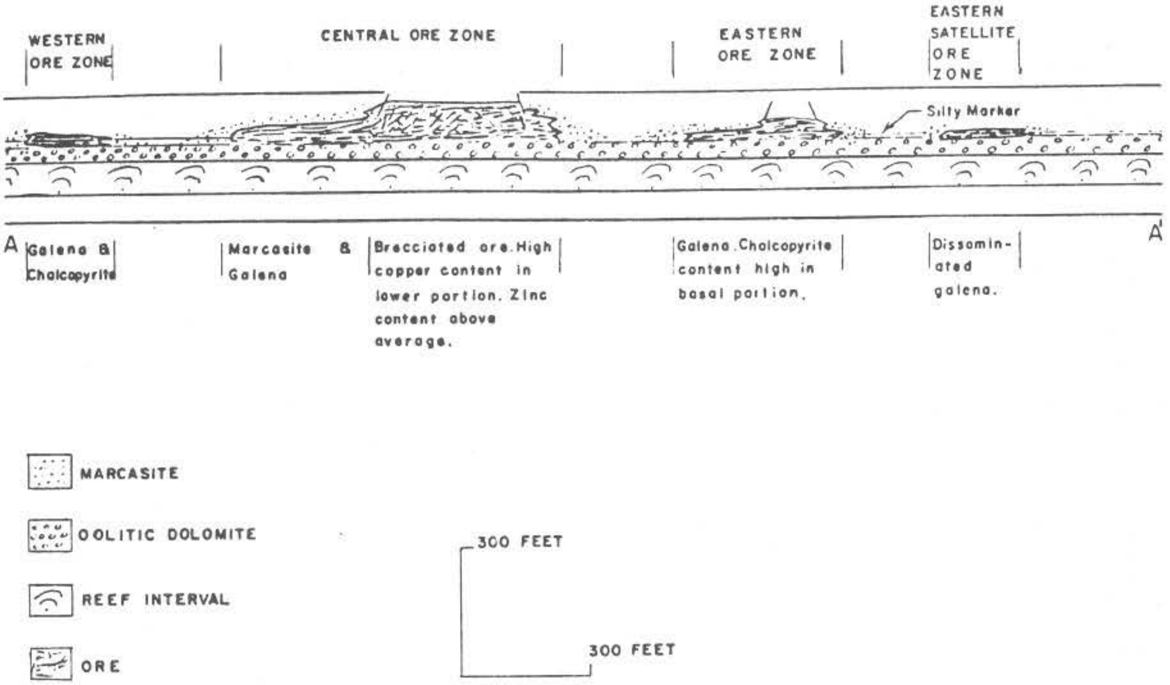


FIG. 3. Cross section A-A' through north part of the Magmont mine.

very minor mineralization in the Davis Formation and the Lamotte Sandstone.

Marcasite halos are adjacent to the ore trends on both east and west sides (Fig. 3). Galena, sphalerite, and chalcopyrite in that order are the most abundant ore minerals. Siegenite is most commonly associated with chalcopyrite. Bornite is present but not megascopically identifiable (Trancynger, 1975).

Gangue minerals in their order of prominence are marcasite, dolomite, calcite, quartz, and dickite. Silicification is conspicuous in the Magmont mine. Vugs within the main ore trends are characteristically lined with quartz druse.

Three ore zones, all aligned parallel to the north-south axis of the Viburnum Trend, occur within the Magmont mine (Figs. 2 and 3). East-west distance

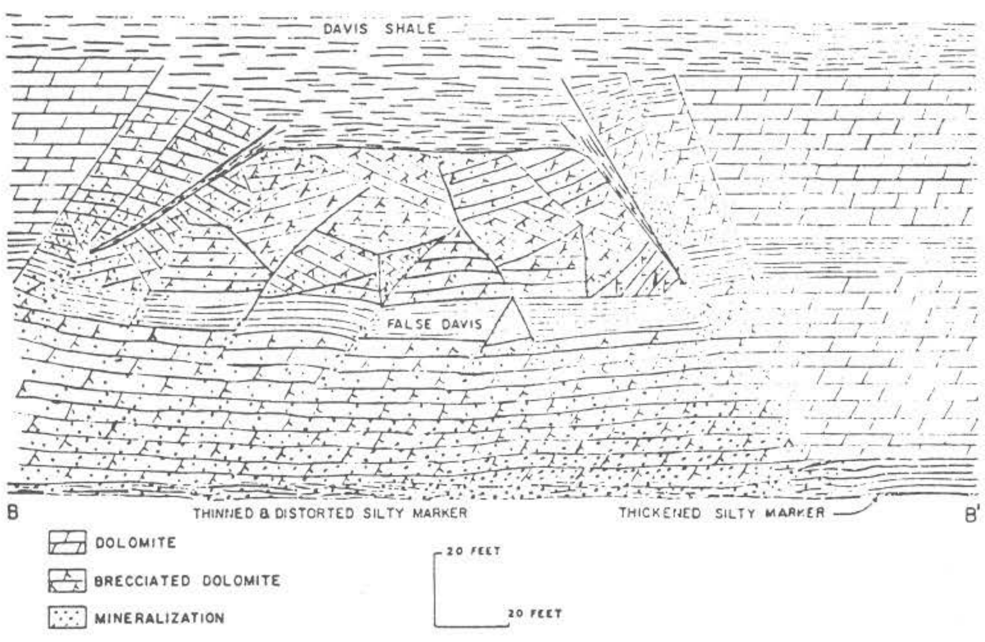


FIG. 4. Cross section B-B' showing breccia, associated subsidence fractures, and thinned Silty Marker.

across these three trends is about 2,000 feet. Vertically the ore is divided into A, B, C, and D horizons which are defined as follows:

A. From base of Davis Formation to base of slumped False Davis;

B. Base of slumped False Davis to base of Silty Marker;

C. Base of Silty Marker to base of Upper Reef;

D. Base of Upper Reef to base of Lower Reef. "B" is the main ore horizon, and the west, central, and east ore trends are well mineralized within this interval (Fig. 3).

Western ore zone

The western ore zone is characterized by incipient slumping along the west edge, which appears to be best explained as penecontemporaneous slumping of semiconsolidated material from a slightly raised area that was probably a calcarenite sand bar. These slumps show randomly oriented angular blocks of the gray, fine-grained units of the Silty Marker interbedded in the brown dolomites of the same unit. Above these slumped areas a small amount of brecciation has taken place and fracture filling has proceeded within the area of induced open space. Replacement of breccia fragments is commonly observed. Ore thickness within this area is commonly about 35 feet.

East of the slumped zone the Silty Marker shows irregular bedding with considerable variation in the thickness of the brown dolomites of this unit. Mineralization consists of massive galena bands with lesser amounts of sphalerite and some chalcopyrite. A marcasite area is present along the east side of this trend, which merges with the central ore along part of its length.

Central ore zone

The central ore zone contains the major tonnage of the Magmont mine. It is characterized by mineralization that extends vertically from the base of the Silty Marker up to and above the False Davis. The Silty Marker is well mineralized but shows marked thinning and distortion beneath the high-ore area. Brecciated and well-mineralized dolomites of the calcarenite units contain most of the ore above the Silty Marker. A conspicuous feature of the central ore is the brecciated central portion of this zone. False Davis shales are dropped vertically as much as 14 feet. Well-defined bounding faults of this slump structure are filled by overlying Davis Formation, as shown by the presence of fragments of the glauconitic dolomite which characterizes the base of this shale unit. This slump has the form of an inverted graben since the bounding faults dip outward from the graben block instead of inward (Fig. 4).

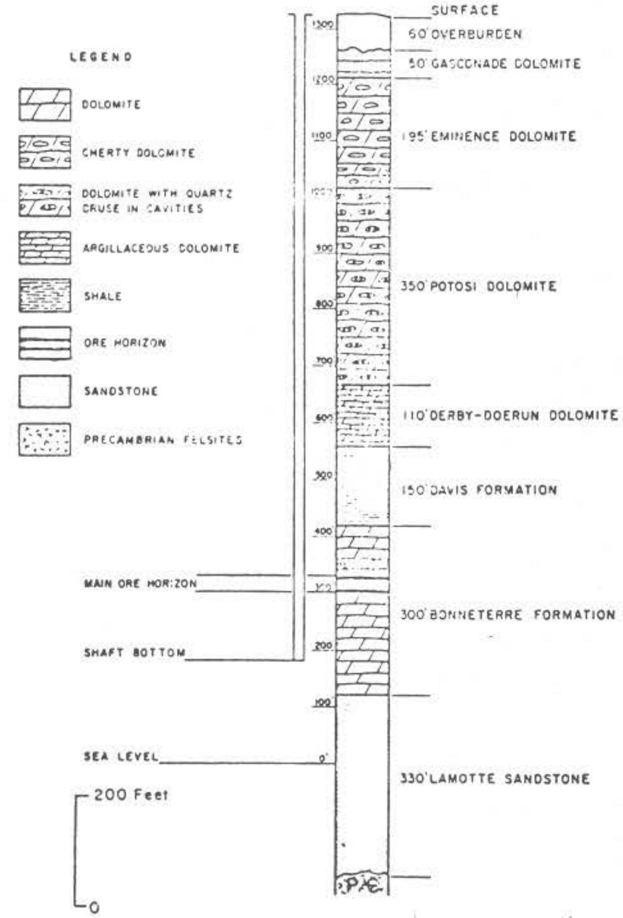


FIG. 5. Typical stratigraphic section, Magmont mine.

There is no apparent thinning or collapse of any rock units below the Silty Marker. The open space created to permit collapse of the overlying rocks has taken place within the 60 feet of strata between the base of the False Davis and the base of the Silty Marker. Angular breccia fragments indicate complete lithification before collapse of the breccia. The slumping extends to the Davis Formation in some areas of very intense brecciation, but mineralization stops abruptly at the base of this overlying, impermeable shale barrier.

Mineralization of the central ore zone consists of galena, sphalerite, chalcopyrite, and marcasite. Siegenite as minute intercrystalline growths is a minor constituent in the chalcopyrite. Drusy quartz makes up much of the cementing material in the interstitial space between breccia fragments and lines open cavities and vugs.

Eastern ore zone

This ore trend parallels the central ore zone but in the southeast part of the Magmont mine swings abruptly west and, at this date, appears to merge with the central ore zone.

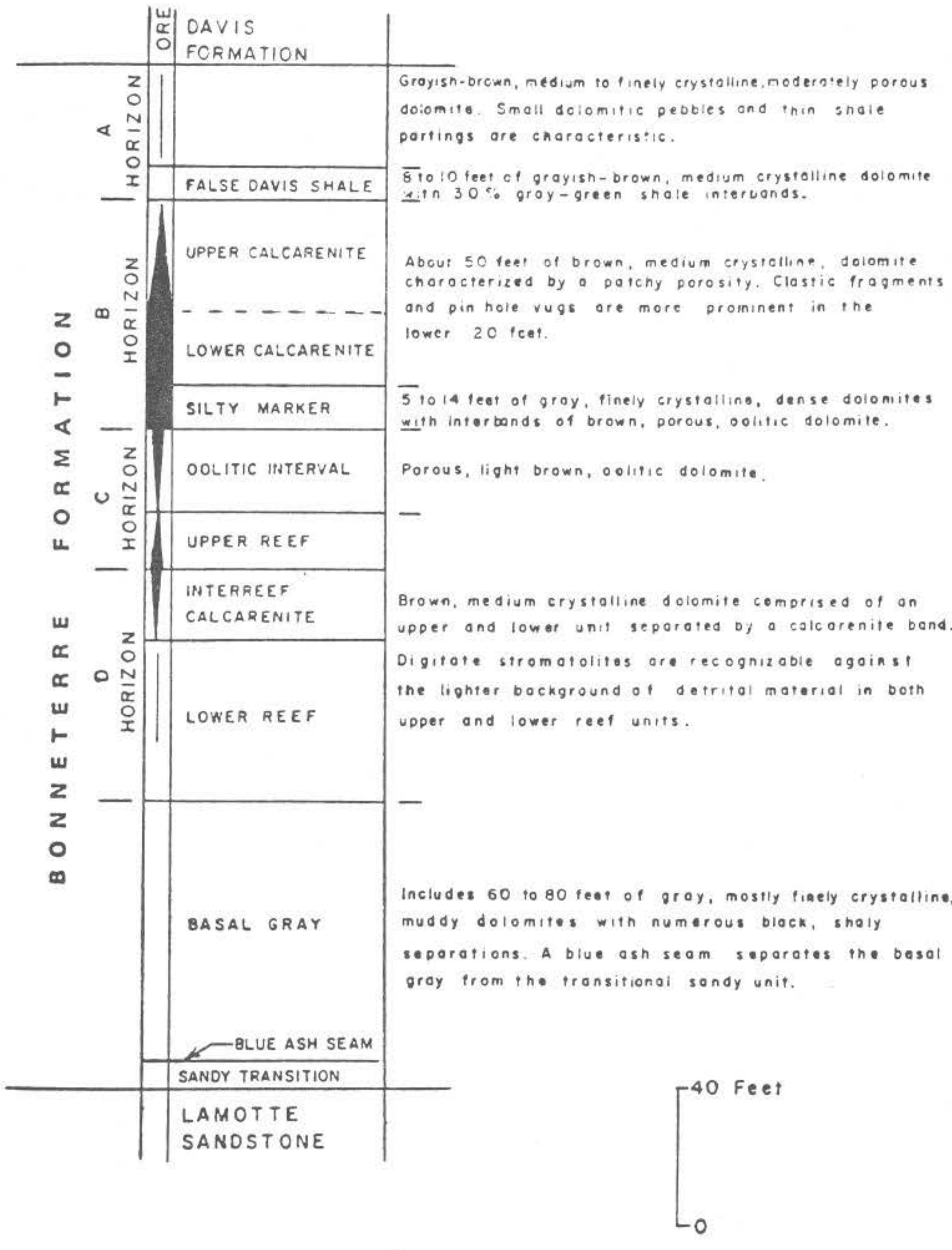


FIG. 6. Summary of rock types of Bonneterre Formation, relative amounts of ore in each unit, and nomenclature used at the Magmont mine.

The eastern ore zone averages about 200 feet in width in an east-west direction. Maximum vertical thickness is about 50 feet, and slumping is on a smaller scale but similar to that which occurs in the central ore zone. The Silty Marker unit which thins from west to east is about 4 feet thick here, and characteristically it is distorted within the mineralized area.

North-south-trending tongues of ore east of the eastern ore zone are characterized by extremely porous lower calcarenites which contain disseminated galena. The Silty Marker unit is difficult to recognize as the gray bands become progressively thinner to the east. Digitate stromatolites within the Upper Reef structure have been truncated and make direct contact with the lowest gray bed of the Silty Marker in some areas of the satellite ore zone.

Mineralization of "C" and "D" horizons

To date, ore on these horizons is known mostly by drilling. Initial efforts to mine "C"-horizon ore in the northern part of the mine were disappointing because of the low tenor and irregular distribution of mineralization. With further advance to the south "C"-horizon mineralization improves. Minable ore is predominantly in bands of detrital material which separate individual bioherms and fill scour channels within the Upper Reef horizon. Reef material, i.e., bioherms and the more massive structures containing digitate stromatolites, are characteristically only sparsely mineralized with galena occurring in vugs. Locally, the oolitic zone beneath the main ore trends contains substantial amounts of disseminated galena.

Summary

The fact that cave areas are usually associated with joint systems that have been imposed on carbonate rocks makes it easy to associate the karstlike structures which form the high-ore areas of the Viburnum Trend with fracture systems. The remarkable continuity and similar characteristics of these features which are aligned along the western edge of the St. Francois Mountains suggest that they have a common origin due to minor lateral north-south shifting adjacent to this ancient, stable, mountain mass. This offers the most uncomplicated explanation of the common characteristics of the breccia orebodies along the Viburnum Trend, whether they are in proximity to Precambrian highs or in the featureless sedimentary embayments. A hinge zone similar to that of Pine Point, Northwest Territories, Canada is not implied (Skall, 1975).

Localization of the major orebodies of the Magmont mine which are on the "B"-level horizon are closely associated with an obvious thinning of the Silty Marker beds. Although the bounding faults cannot be traced into the Silty Marker itself, the area of pronounced thinning and irregular bedding within this unit coincides approximately with the downward projection of these bounding faults. Brecciation of the rock units between the base of the Silty Marker and the overlying Davis Formation developed as a result of partial solution of the intervening rock units.

Mineralization of the strata overlying the Silty Marker is, in a general way, proportional to the brecciation of these rocks, which is proportional to the amount of collapse that has taken place. Collapse, in turn, is proportional to the amount of solution which has occurred.

Solutions must have followed the more permeable units of the Silty Marker and initiated the ground preparation for a large part of the Magmont orebody as well as providing the plumbing system for the ore-bearing solutions whether they were contemporaneous with or later than the ground preparation.

Magmont Mine
Bixby, Missouri 65439

September 9, 1976

REFERENCES

Gerdemann, P. E., and Myers, H. E., 1972, Relationships of carbonate facies patterns to ore distribution and to ore genesis in the Southeast Missouri lead district: Econ. Geol., v. 67, p. 426–433.

Heyl, A. V., and Mullens, T. E., 1972, Discussion, paleoaquifer symposium: Econ. Geol., v. 67, p. 532–533.

Heyl, A. V., Jr., Agnew, A. F., Lyons, E. J., and Behre, C. H., Jr., 1959, The geology of the Upper Mississippi Valley zinc-lead district (Ill.-Iowa-Wis.): U. S. Geol. Survey Prof. Paper 309, 310 p.

Skall, H., 1975, The paleoenvironment of the Pine Point lead-zinc district: Econ. Geol., v. 70, p. 22–47.

Snyder, F. S., and Gerdemann, P. E., 1968, Geology of the Southeast Missouri lead district *in* Ridge, J. D., ed., Ore deposits of the United States, 1933–67 (Graton-Sales Volume): New York, Am. Inst. Mining, Metall. Petroleum Engineers, v. 1, p. 326–358.

Trancynger, T., 1975, Sequence of deposition of the ore minerals at the Magmont Mine: Unpub. Master's thesis, Univ. of Missouri–Rolla.

GEOLOGY OF THE MAGMONT-WEST MINE (COMINCO AMERICAN INCORPORATED AND DRESSER INDUSTRIES) VIBURNUM TREND, SOUTHEAST MISSOURI

by

Milton F. Bradley

Chief Mine Geologist

Magmont Mine, Bixby, Missouri

INTRODUCTION

The Magmont-West area is in southeastern Missouri, approximately 90 mi southeast of St. Louis, along the western edge of the Viburnum Trend, or new Lead Belt.

During a Precambrian copper-iron exploration program begun in 1956 by American Zinc Company, lead-zinc mineralization was encountered in the Upper Cambrian Bonneterre Formation. Subsequent to 1973 evaluation, which showed that copper-iron mineralization in the West Dome area was uneconomical, emphasis was shifted to exploring for lead-zinc mineralization in the southeastern and south-central portion of the project area.

Drilling through 1977 resulted in discovery, in sections 15 and 16, of an estimated 2 to 3 million tons of lead-zinc-copper mineralization of a grade comparable to that currently being mined along the Viburnum Trend. Geologic studies indicate that specific shallow-water lithologies show a high positive relationship with ore-grade mineralization. Such lithologies in the northern portion of the mine area suggest that this area may warrant additional drilling.

LOCATION

The Magmont-West mine is in T. 34 S., R. 2 W., in Dent and Iron Counties, approximately 90 mi southwest of St. Louis. The mine area is on the western margin of the northern part of the new Lead Belt, or Viburnum Trend, mining district (fig. 1), where continuous mineralization extends from the St. Joe Minerals Number 28 mine on the north to the Ozark Lead Company's Sweetwater mine at the south, a distance of over 30 mi.

The mine property is bounded on the north, northeast, and east by land owned by St. Joe Minerals Corporation. The main Magmont properties (Cominco American-Dresser Industries and the Buick mine holdings (Homestake Mining Company) adjoin the mine to the east and south. Magmont-West is connected by a two-mile underground development drift from the Magmont workings to the east.

The largest town in the district, Viburnum, is 5 mi northeast of the center of the mine; two smaller towns, Boss and Bixby, are immediately west and east of the mine area.

HISTORY

In the mid-1950's, the American Zinc Company was attracted to the Boss-Bixby area by three prominent aeromagnetic anomalies, the areas of which were subsequently drilled as part of a regional Precambrian iron-ore exploration project. Although the principal effects were directed to the delineation of copper-iron mineralization, lead-zinc mineralization was found by chance in the overlying Cambrian Bonneterre Formation, during exploration of the areas of the anomalies.

In the period 1956-1973, some 52 of 151 holes were drilled specifically for lead-zinc mineralization, four of them intersecting significant mineralization (= 20 ft percent Pb + Zn + Cu) and an additional nine holes penetrated at least 1 ft of percent Pb, Zn, or Cu.

Several studies of the lead-zinc potential culminated in late 1975 with the decision of Getty Oil and partners to explore sections 9 and 16 in more detail for lead-zinc mineralization of the type known in the main Viburnum Trend east of the project area. Drilling in this second generation exploration project, designated the Viburnum Lead Project, proceeded from late 1975 to March 1978.

VIBURNUM TREND

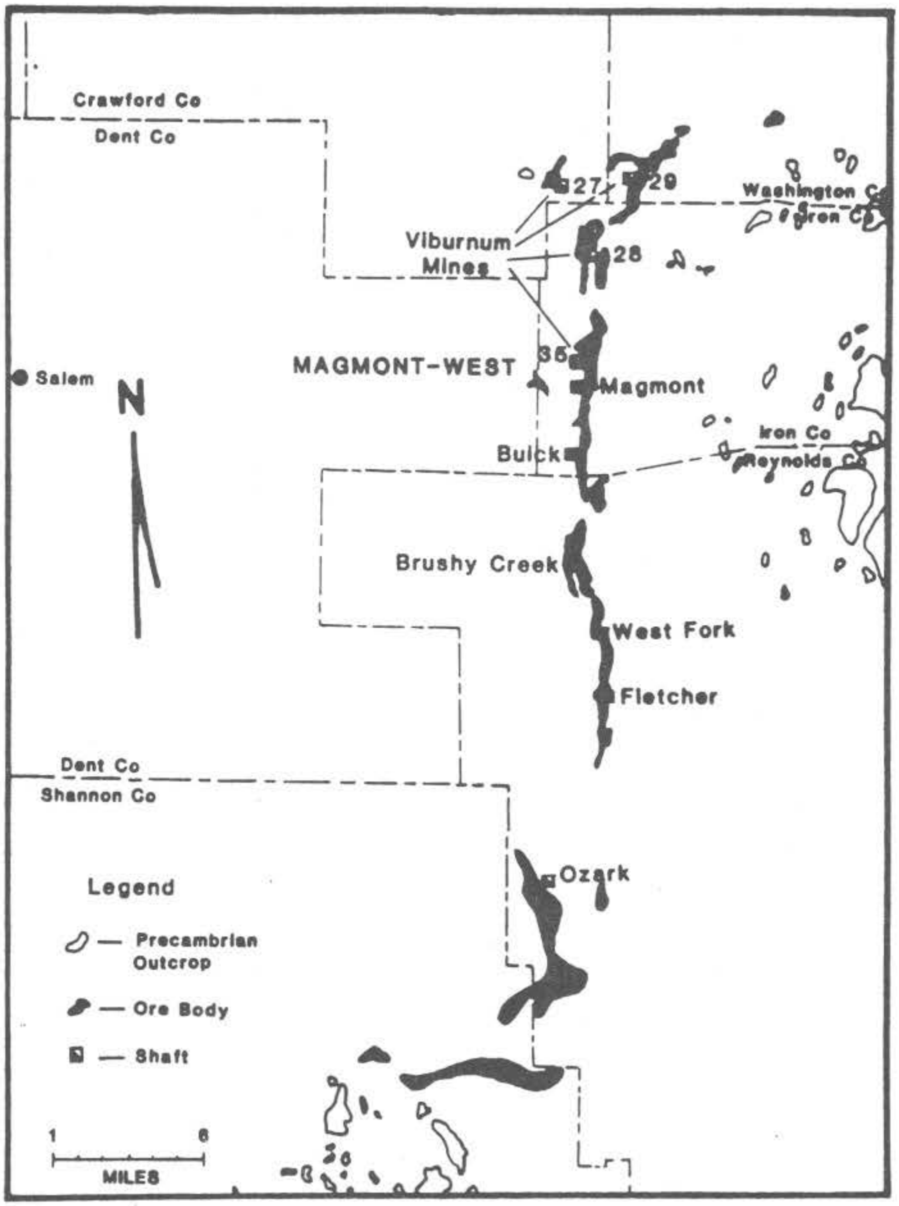


FIGURE 1

LOCATION MAP MAGMONT & MAGMONT-WEST

In 1979, Magmont mine (Cominco American-Dresser) purchased the approximately 7500 acres of government leases, prospecting permits, and private ground from Getty. In the next three years approximately 180 holes were drilled to explore the mine area further. In 1979 a development drift was started in the Magmont mine to intersect the Magmont-West ore body in sections 15 and 16, a distance of 10,500 ft to the west.

GEOLOGY

Regional Geology

The Southeast Missouri Lead district, in the central Mississippi Valley section of the stable U.S. Midcontinent region, contains several subdistricts around the periphery of the St. Francois Mountain igneous complex, which in surface exposures comprises maturely dissected Precambrian knobs.

Dipping gently away from the St. Francois Mountain complex are a series of Paleozoic sedimentary formations, the oldest of which is the Upper Cambrian Lamotte Sandstone. Conformably overlying the Lamotte Sandstone is the Bonneterre Formation, comprising dolomite and limestone, the unit that is host to most of the Viburnum Trend mineralization (figs. 2 and 2a).

Other Cambrian formations, in ascending order, are the Davis Formation, predominately a shale, and the Derby-Doerun, Potosi, and Eminence Dolomites.

The remainder of the stratigraphic section in the district, as shown in figure 3, also includes the Ordovician Gasconade Dolomite, Roubidoux Formation, and Jefferson City Dolomite.

Local Geology

Sedimentation began in the late Cambrian with deposition of the Lamotte Sandstone over an uneven Precambrian terrain. The Lamotte Sandstone covered the Precambrian surface, except where highs or knobs existed, i.e., Lamotte "pinchouts."

Deposition during Bonneterre time took place across a broad shelf or platform in three distinct facies: fore reef, reef, and back reef. West of the project area, the fore-reef facies was deposited as silty laminated carbonates. In that facies in the project area, fairly clean limestone predominates, but variable post-diagenetic alteration has changed much of it to dolomite.

The presence of digitate algal stromatolites defines the reef facies in the mine area, although other distinctive lithologies are also present. In the Magmont-West mine area the stromatolite reef(s) grew as fringing reefs around the three Precambrian knobs in the area (West dome, Central dome, North dome) and on broad platforms adjacent to parts of these positive areas (fig. 5). The principal platform reef south of the Central dome in sections 15 and 16 may represent a westward expansion of the main "barrier" reef development along the Viburnum Trend east of the mine area.

The back-reef facies, deposited as a primary (?) dolomite in a supratidal or lagoon environment, is not in the project area.

That portion of the Bonneterre Formation deposited above the stromatolitic reef facies represents deposition in the near-shore, shallow-water environment, in front of and behind the "barrier" reef. This environment resulted in a highly variable, but cyclic, sequence of carbonate sediments characterized by minor amounts of terrigenous chert material, particularly black shale.

On the Magmont-West Project the Bonneterre Formation is divided into 10 subunits as shown in figure 4.

A sequence of Cambrian and Ordovician formations overlies the Bonneterre Formation.

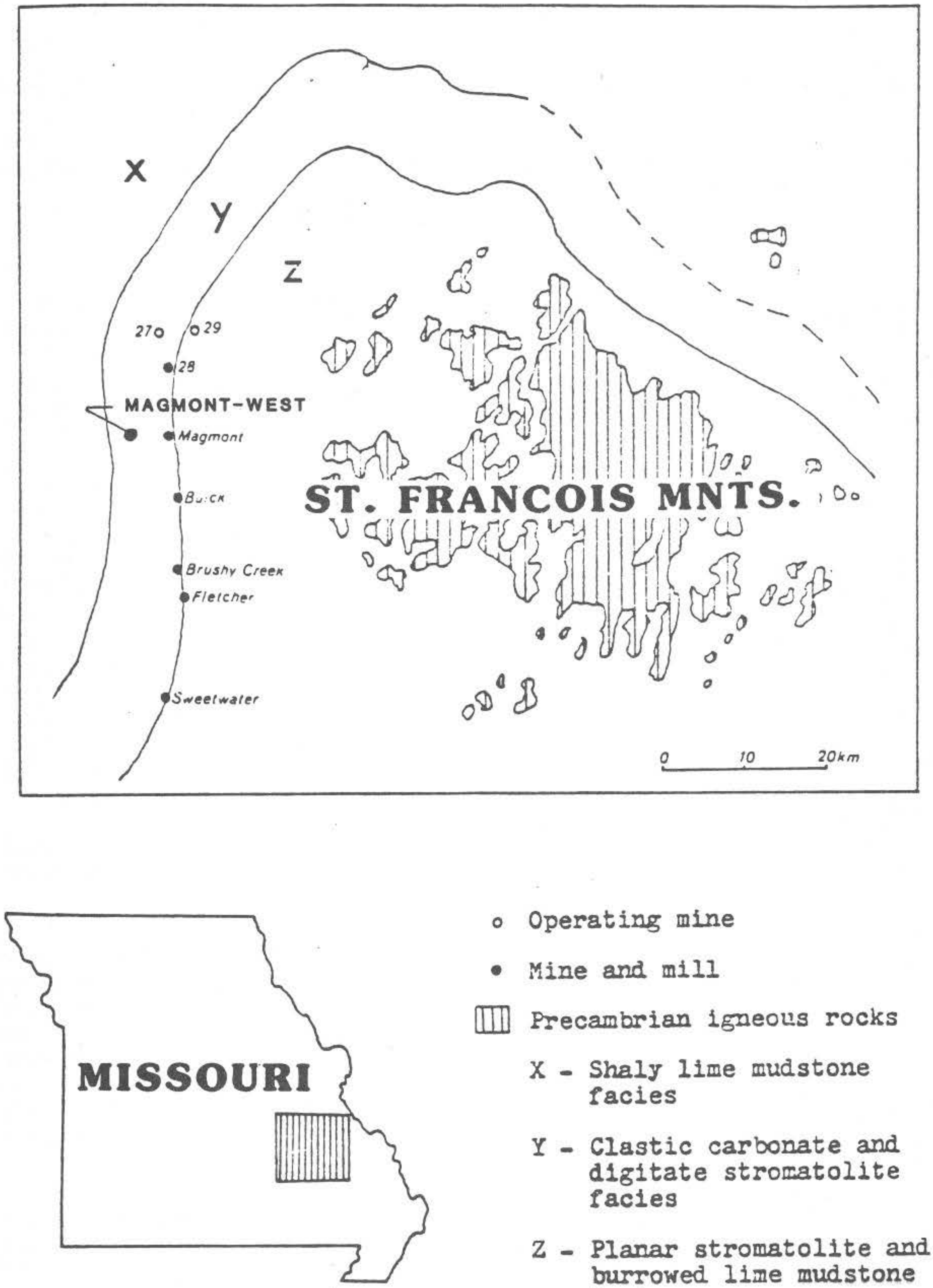


Figure 2 — Generalized pattern of facies of the Bonneterre Formation (modified after Kenneth Larsen, Ozark Lead Company)

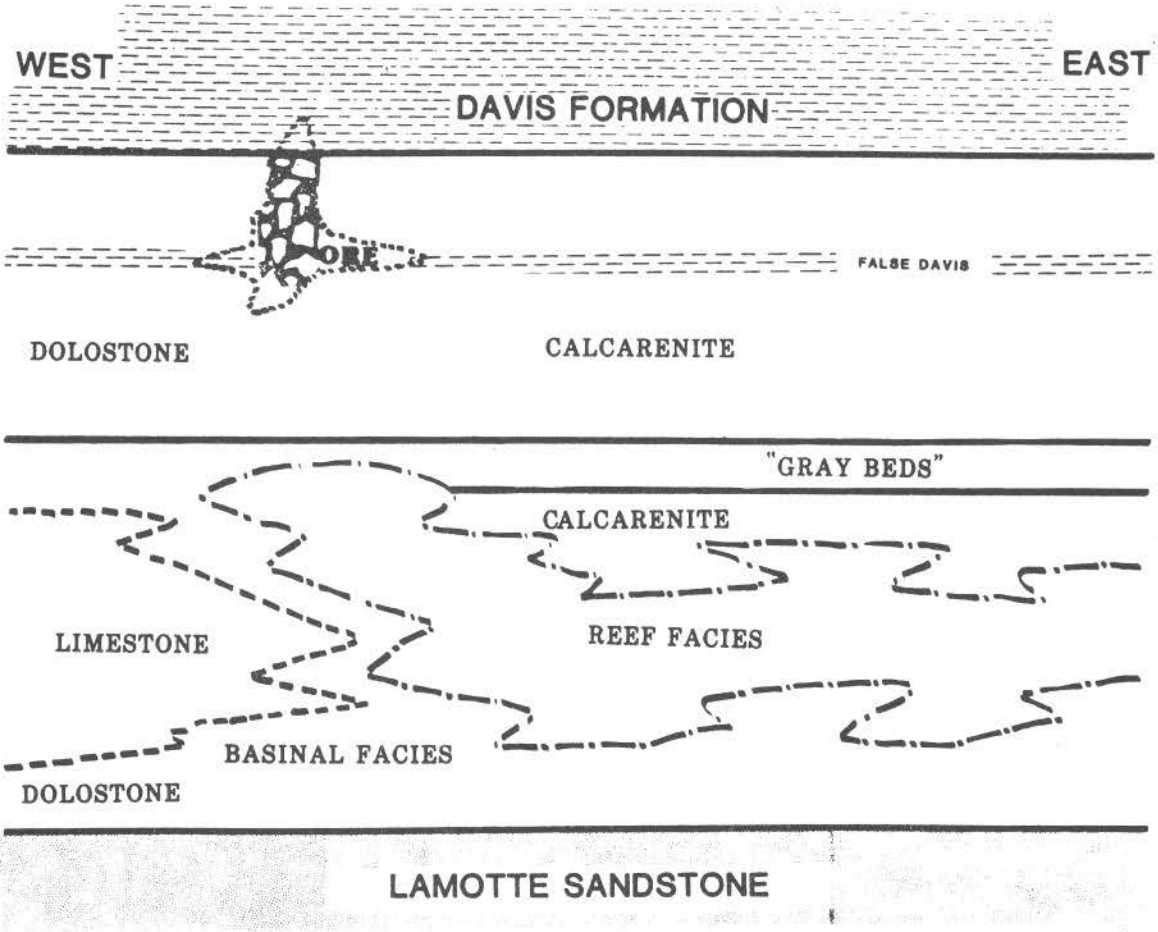


Figure 2a – Facies of the Bonneterre Formation, Bixby, Missouri

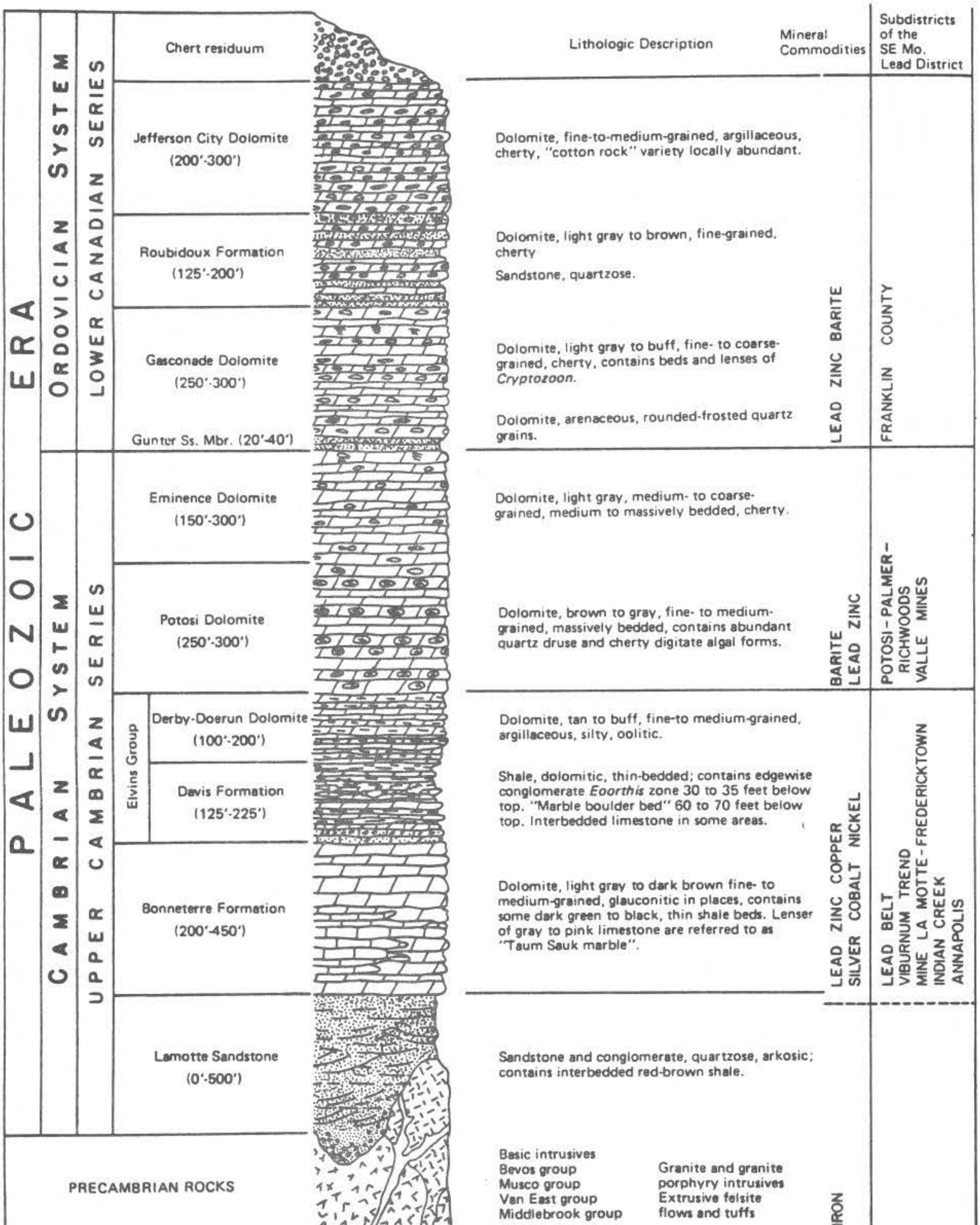
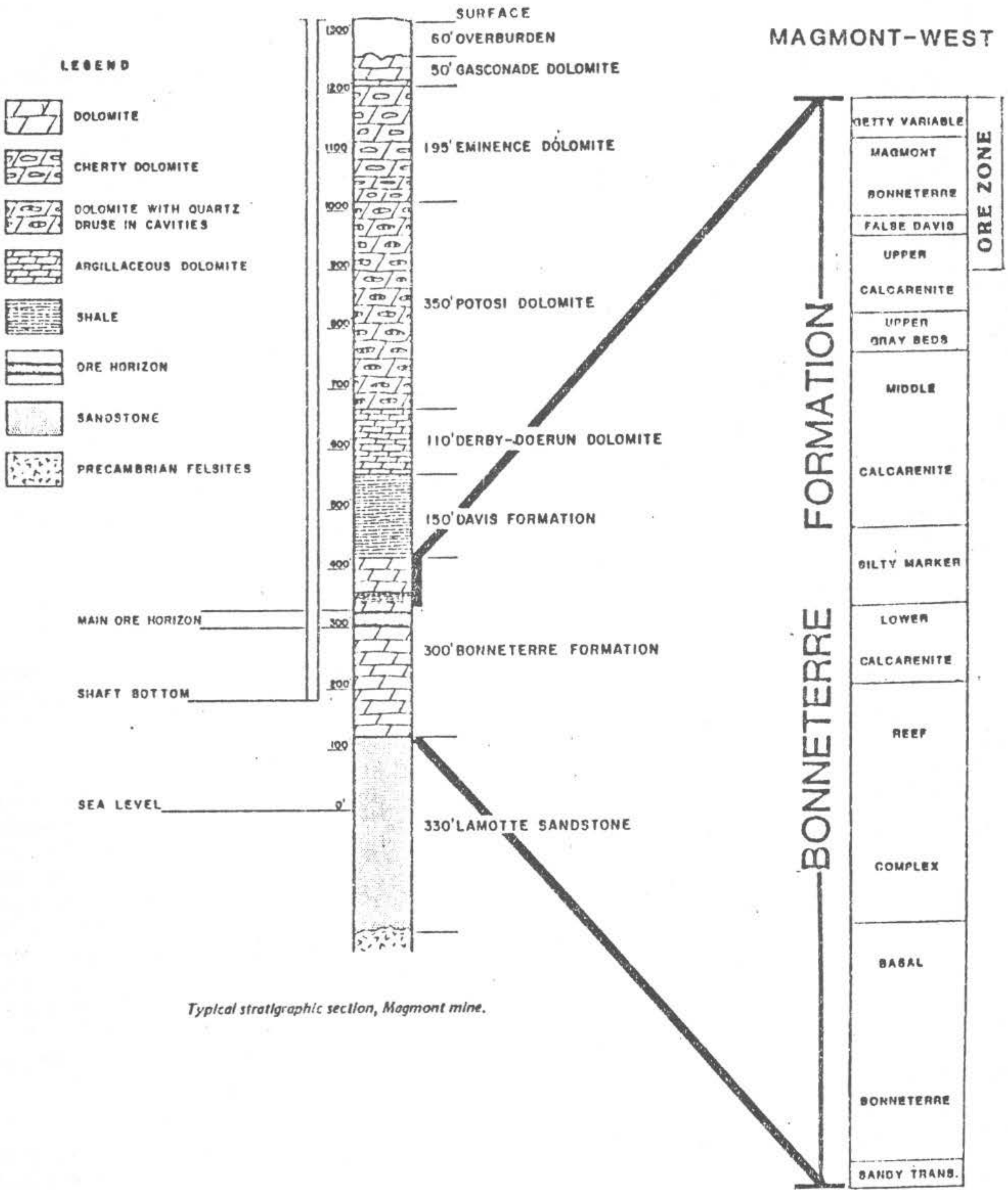


Figure 3 — Generalized stratigraphic column of the Viburnum Trend area (adapted from Hayes, 1961).

FIGURE 4

EXPANDED STRATIGRAPHIC SECTION



Typical stratigraphic section, Magmont mine.

STRUCTURE

Regional Structure

The dominant structural feature in southeastern Missouri is the Ozark dome; a positive feature through the Paleozoic, it is represented in part by the St. Francois Mountains igneous complex. Another smaller Precambrian area, the Eminence high is approximately 45 mi southwest of the St. Francois Mountains. The "Czar Knob," a small Precambrian high, is north of the town of Viburnum.

A second type of structural feature in southeastern Missouri is a roughly polygonal pattern of growth (?) faults around the periphery of the St. Francois Mountain complex.

Local Structure

The dominant structural features at the Magmont-West mine are three buried Precambrian highs, and two postulated regional zones. The Central dome, the largest of the three buried knobs occupies portions of sections 3, 4, 9, and 10 (fig. 5). The North dome is in section 4; the West dome, in sections 16 and 17, east of Boss and west of the principal area explored for lead and zinc.

Brecciation and gouge material encountered in lead-zinc drill holes in the northwestern corner of section 9 and in earlier holes in the southwestern corner of section 4 indicate the possible presence of a fault system. If present, it may be an extension of the northeast-southwest-trending Conway fault system, which extends southwestward from Viburnum into the area west of Bixby, as shown in figure 5.

A second, southerly trending fault may be in the eastern portions of sections 10 and 15. Evidence for such a fault includes a north-south-trending magnetic low, an offset of the Lamotte pinchout along the southern flank of the Central dome in the eastern part of section 10, and changes in the thickness and configuration of the Bonneterre subunits along the eastern side of section 15. Such a fault might also be a part of the Conway fault system.

MINERALIZATION

The ore minerals in the Viburnum Trend are galena, sphalerite, and chalcopyrite. A typical ore body in this district may average about 5.0 percent Pb, 1.0 percent Zn, and 0.25 percent Cu; ore grades several orders of magnitude above this are present.

The mineralization penetrated by American Zinc and Getty in the two mineralized areas in sections 15 and 16 averaged approximately 6.0 percent Pb, 2.0 percent Zn, and 0.25 percent Cu.

Mining in these areas by Magmont in the years 1982-1985 averaged approximately 5 percent Pb, 3 percent Zn, and minor copper.

Ore Controls

Various studies have attempted to relate mineralization to characteristics of the stratigraphy. So far, work indicates there seems to be no positive, highly correlative relationship between presence or absence of mineralization, and the thickness of any of the Bonneterre units.

It is abundantly clear that the False Davis subunit is one of the principal hosts to mineralization. Approximately half the mineralization in sections 15 and 16 is in the False Davis horizon. This is illustrated by figure 6, a metal-concentration diagram that shows the ft percent Pb + Zn + Cu penetrated in the upper four horizons of the Bonneterre Formation and in the lowermost Davis Formation. Figure 6 also shows that the False Davis and Upper Calcarenite contain 84 percent of the mineralization in sections 15 and 16.

About 12 percent of the discovered base-metal mineralization is in the Variable Zone and is

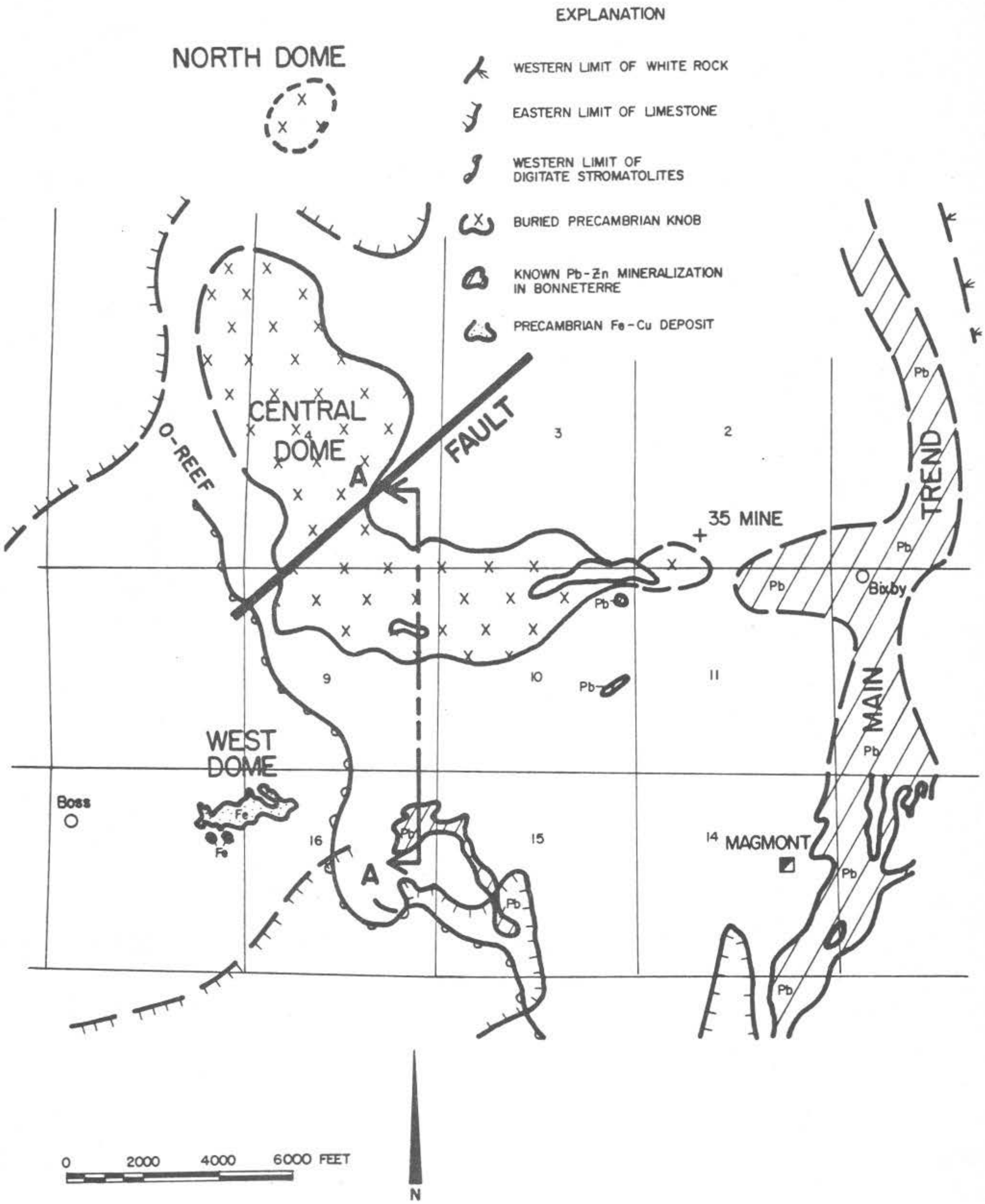


FIGURE 5. BOSS - BIXBY AREA

LINEAR BRECCIA

ORE ZONE CLASSIFICATION

The following classification is based on stratigraphic units, type of occurrence, and lateral distribution.

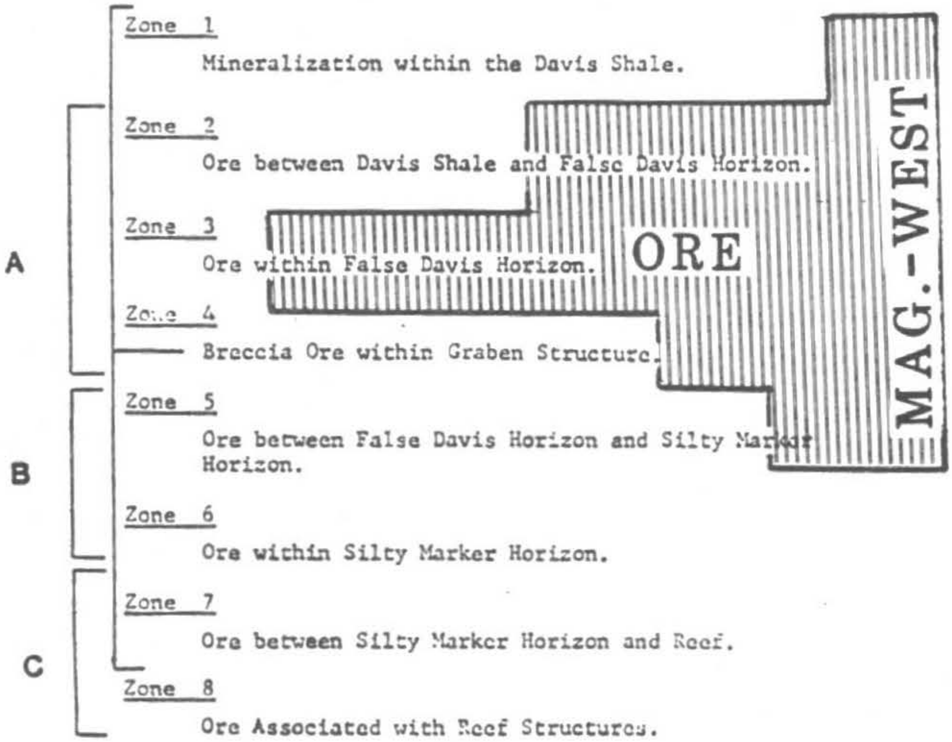


FIG. 6 METAL CONCENTRATION

divided about equally between highly brecciated replacement mineralization and very strong grain-for-grain (?) replacement mineralization. Mineralization, where present in the bottom few feet of the Davis Formation, generally represents the upper portion of the linear breccia bodies.

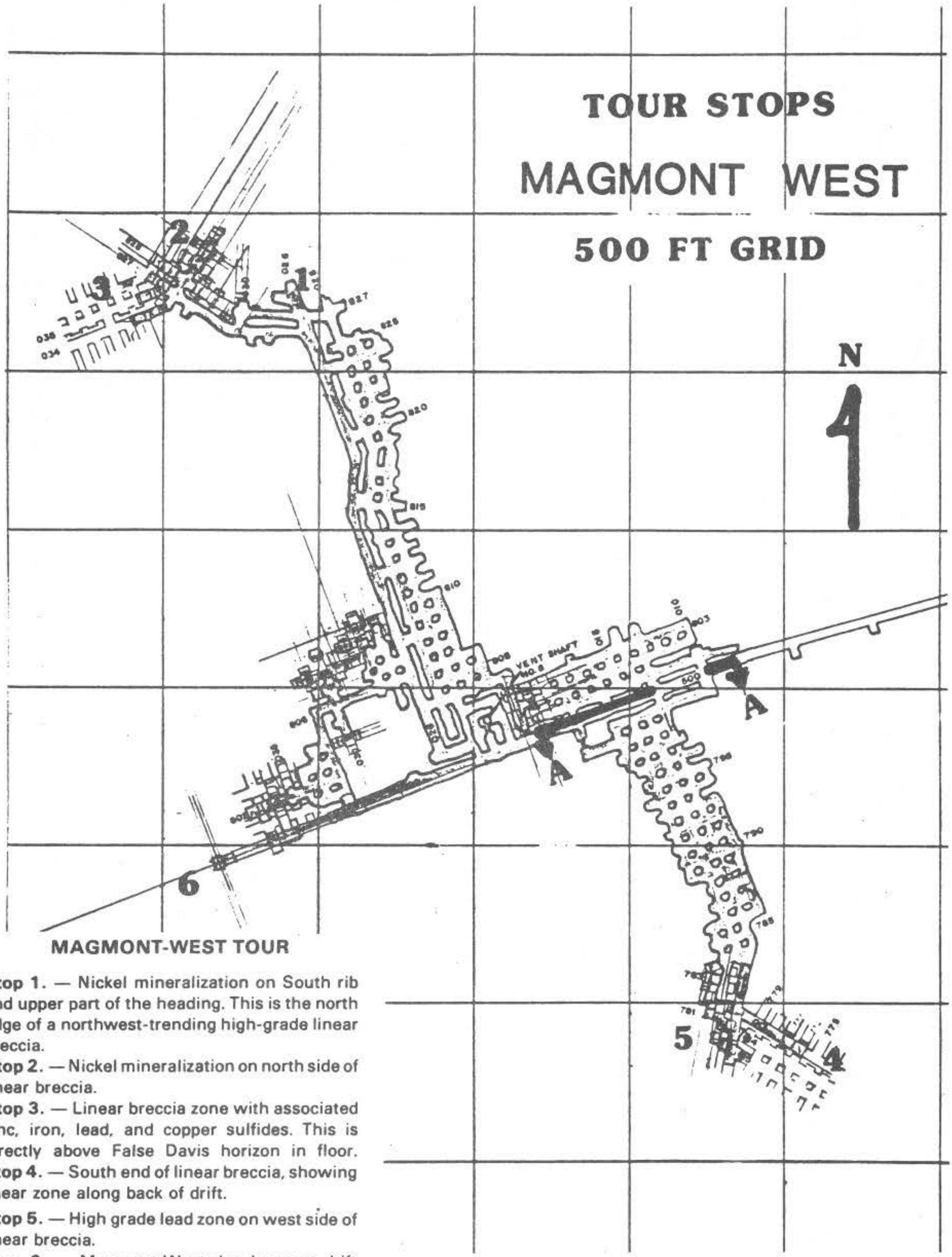
The majority of economically significant mineralization located so far in sections 15 and 16 is in the False Davis-Upper Calcarenite but extends upward to the lowermost part of the Davis Formation. Ore mineralization to date averages 5.0 percent Pb, 3.0 percent Zn, and 0.19 percent Cu.

ACKNOWLEDGMENTS

I thank the management of Cominco Metals for permission to publish this paper, and for its cooperation in making the necessary preparations for the mine tour.

My special thanks to the geologists of American Zinc and Getty Minerals, who did the previous work in the area and who considerably influenced shaping the ideas presented in this paper.

The work of Pete Sweeney, Ed Harrison, Rick Russell, Laura Nadelhoffer, and Bob Voss have greatly improved our understanding of the local ore controls and stratigraphy in the Magmont and Magmont-West ore bodies.



MAGMONT-WEST TOUR

Stop 1. — Nickel mineralization on South rib and upper part of the heading. This is the north edge of a northwest-trending high-grade linear breccia.

Stop 2. — Nickel mineralization on north side of linear breccia.

Stop 3. — Linear breccia zone with associated zinc, iron, lead, and copper sulfides. This is directly above False Davis horizon in floor.

Stop 4. — South end of linear breccia, showing shear zone along back of drift.

Stop 5. — High grade lead zone on west side of linear breccia.

Stop 6. — Magmont-West development drift showing units above and below False Davis horizon.

WASHINGTON COUNTY OR SOUTHEAST MISSOURI BARITE DISTRICT

by
Heyward M. Wharton

Missouri Department of Natural Resources
Division of Geology and Land Survey
P.O. Box 250
Rolla, Missouri 65401

INTRODUCTION

Residual barite and lead ores, formed by weathering and dissolution of Cambrian dolomites containing Mississippi Valley-type deposits, will be the focus of this excursion. Main stop in the barite district will be at the International Minerals & Chemical Corporation (IMCO) Services Apex mine and washer plant near Mineral Point in Washington County. IMCO Services is a Division of the Halliburton Company, a large oil field service and construction company. If time permits, the group will also inspect some barite mineralization in roadcuts along Highway 47, about 5 miles south of Richwoods. The Apex barite mine was initially operated by IMCO, from 1950 to 1964. IMCO Services announced plans for a new mine and plant at the site early in 1979. The new plant, largest ever built in the district, was designed to treat about 1.5 million tons of ore per year, yielding some 75,000 tons of barite concentrates, primarily for the drilling mud market. Actually it is two large plants built side by side and housed in one building. It included other innovations that will be described later. Production began in the spring of 1980, and barite concentrates were shipped by rail to the company's grinding plants in Louisiana and Texas. The drilling mud market collapsed during the severe recession in 1982, and the Apex operation has been shut down since then. In this visit, there will be a brief tour through the washer plant and an inspection of barite mineralization in nearby open-pit mine areas.

LOCATION

The southeastern barite district is an integral part of the Southeast Missouri Lead district since it was one of the major lead mining areas in the State before the Civil War. Barite is the dominant mineral in the residual barite-lead ores, but it was discarded as useless until a market developed for it around 1850. Barite is commonly referred to as "tiff" in this area, and the miners as "tiff diggers." The Palmer-Potosi-Richwoods barite-lead mining areas are shown in figure 1, in relation to the Lead Belt, Indian Creek, and Viburnum Trend lead mines. The barite district is north-northwest of the Precambrian exposures in the St. Francois Mountains, a structural high in the Ozark uplift, and it is about 50 mi south of St. Louis. The residual ores are derived from the two youngest formations in the Cambrian Series, the Potosi and Eminence Dolomites (fig. 2). The Bonneterre Formation, lower in the section, is host rock for all the large lead and lead-zinc deposits in the Southeast district. The Bonneterre mineralization also includes important amounts of copper, silver, cadmium, cobalt, and nickel.

NATIONAL IMPORTANCE OF THE DISTRICT

Missouri was either first or second in mine production of barite among the states from 1885 through 1982. During the initial 100 years, it was the leading state at one time or another in about 60 of those years. The State dropped to third place, after Nevada and Georgia, following the sharp decline in demand for drilling mud in the latter part of 1982. Missouri was both a world and national leader in total cumulative mine production through 1980, producing over 13 million tons of barite concentrates. See Brobst (1970), Haines & Miller (1978), and barite chapters in the Minerals Yearbooks in subsequent years. Nevada took over the lead in spectacular fashion in 1981, when its mines yielded a record 2,482,000 tons of barite concentrates in a single year. Nevada had become the foremost U.S. mine producer for the first time in 1969, and its leadership was firmly established by 1972. From then on, annual mine production increased rapidly, until by 1980 it reached around 85 percent of the national output. Barite's heavy weight, white color, and

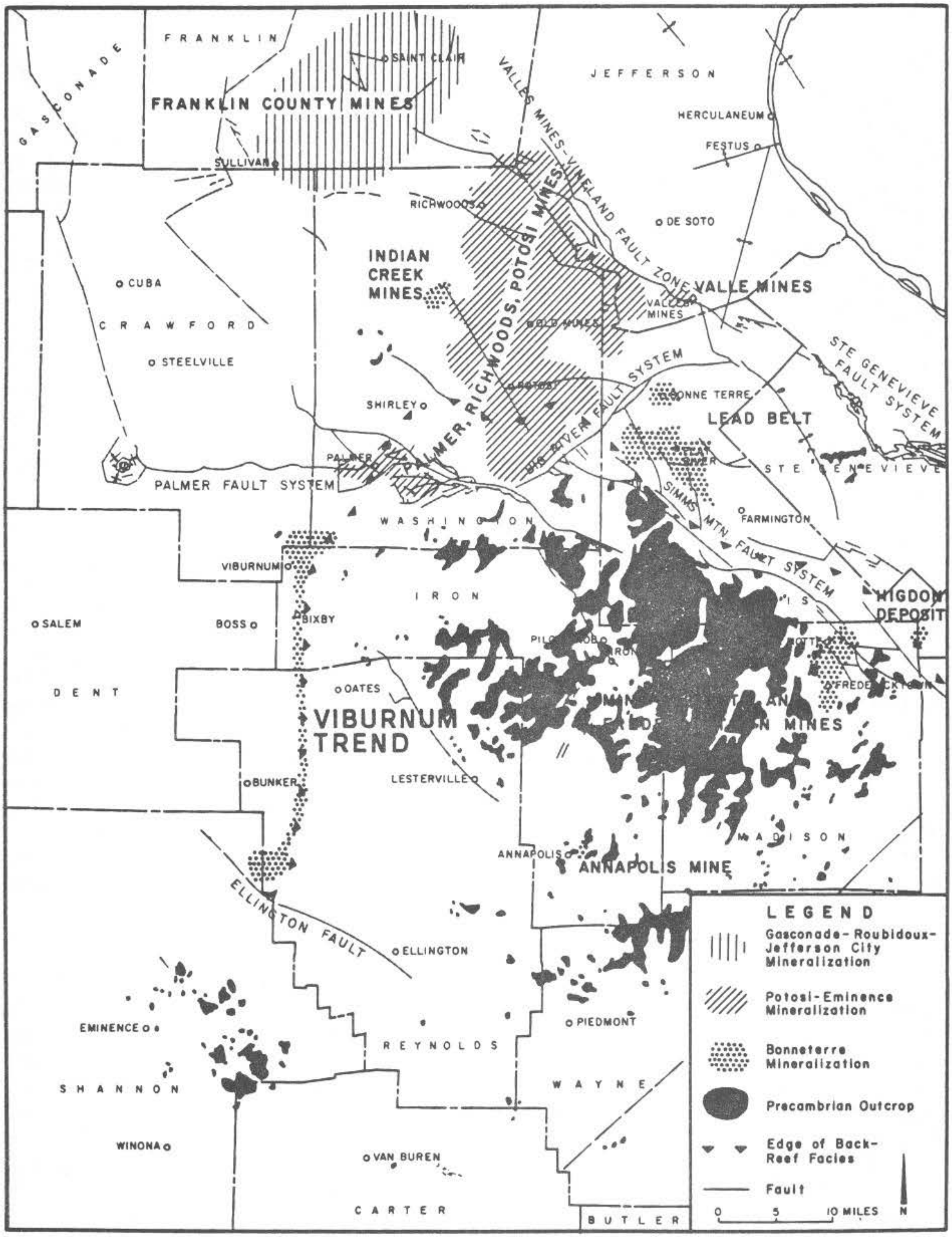
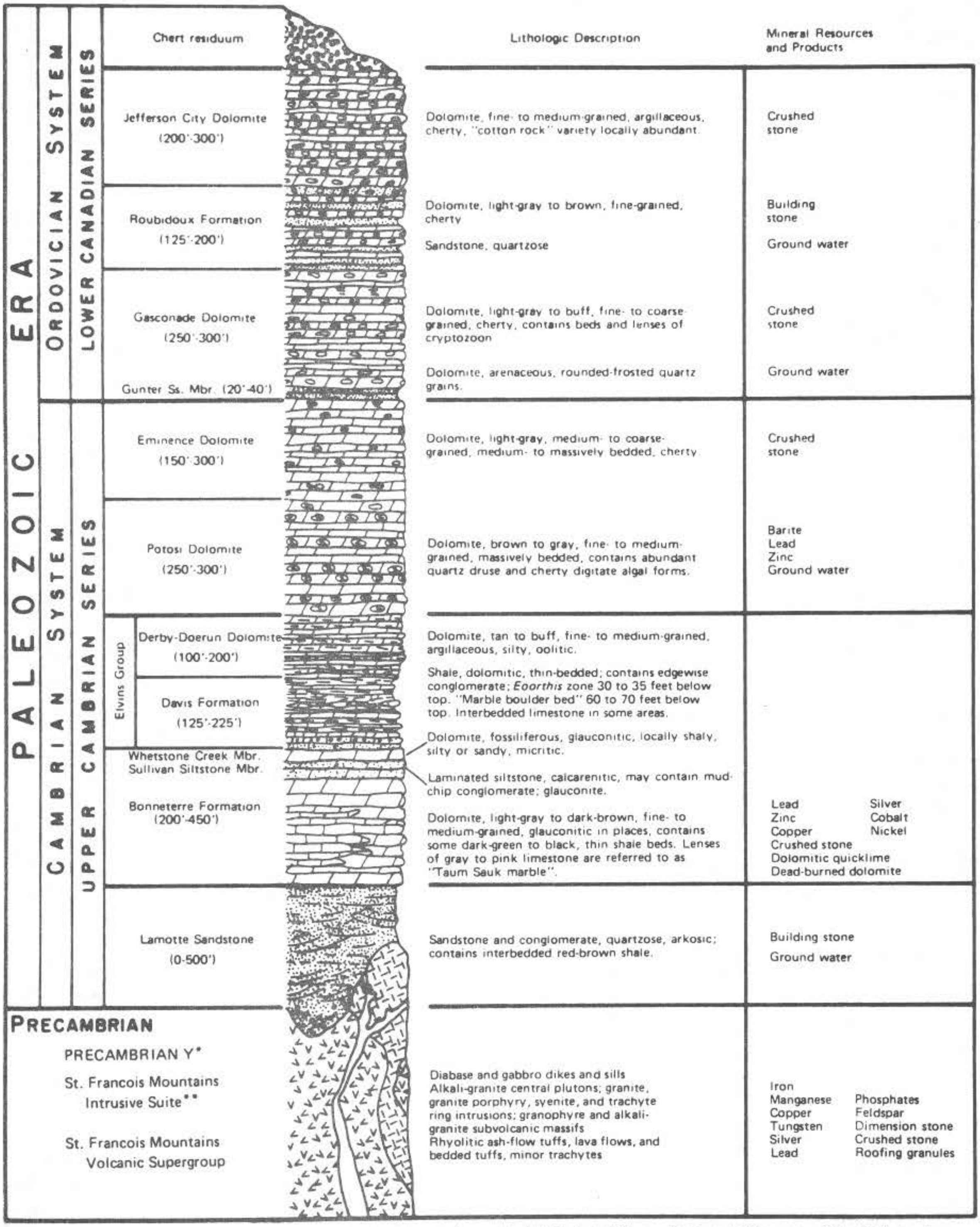


Figure 1 — Map of Southeast Missouri Lead district.



*James, H.L., 1972, Subdivision of Precambrian: an interim scheme to be used by U.S. Geological Survey Stratigraphic Commission Note 40, Amer. Assoc. Petroleum Geologists Bull., v. 56, n. 6, p. 1128-1133.
The subdivisions are purely temporal; the geochronologic boundaries of Precambrian Y are 800 m.y. and 1,600 m.y., B.P.

Figure 2 — Generalized stratigraphic column of the St. Francois Mountains

chemical inertness are mainly responsible for its usage. Currently, over 90 percent of the total U.S. output is used in drilling muds. Other uses are as fillers and extenders in paints, rubber, plastics, paper, and a host of other products. Barite is also used in glass manufacturing and for making barium chemicals.

GEOLOGY AND ORE DEPOSITS

Geologic investigations and mapping by Dake (1930), Muilenburg (1957), Wagner (1973), and others have established that the residual barite deposits in the district are derived mostly from the Upper Cambrian Potosi and Eminence Dolomites. The Potosi is over 200 ft thick in this area. It is a medium- and fine-grained brownish-gray dolomite that weathers to a dark-red residual clay. It contains abundant quartz druse, often formed on thin layers of chalcedony. The quartz druse and chalcedony are particularly well developed in the abundant zones of digitate algal stromatolites. The Eminence Dolomite, also over 200 ft thick in this area, is medium to coarse grained and tends to be lighter gray than the Potosi, more massively bedded, and cherty. Scarcity or lack of quartz druse and the development of a brownish residual clay help distinguish it from the Potosi.

Dake (1930) thought that minute particles of barite and silica were deposited simultaneously with the limey muds of the Potosi and Eminence Dolomites. Much later, when the rocks were subjected to weathering, he reasoned that the barite and silica were dissolved, concentrated, and reprecipitated in coarser masses in the residual clays. His main arguments were (1) lack of sizeable barite deposits in the bedrock of the district; (2) scarcity of faults and fractures needed for a conventional hydrothermal plumbing system; and (3) the thick, impermeable Davis Formation underlying the Potosi-Eminence formations in the district would be expected to act as a barrier to ascending hydrothermal solutions. Finally, he noted that barite veins are fairly common in the overlying Ordovician rocks, but significant residual deposits are lacking. This also suggests that the barite was *not* introduced by descending solutions. Dake's observations are valid in most respects. Today, however, there are much better bedrock exposures in the strip mines and roadcuts, many more drill logs, and consequently much improved geologic mapping. As a result, barite exposures in bedrock, faults, fractures, and jointing are all common enough in the district. Like the nearby Lead Belt, the barite district is largely bounded by major faults: Big River, Palmer, and Valles Mines-Vineland (fig. 1). More recent investigators, such as Wagner (1973), Leach (1980), Lange et al. (1983, 1985), and Kaiser, et al. (1986), tend to favor a basin brine source for the barite and lead. The larger faults probably served as channelways, and the solutions invaded porous and permeable horizons in the country rock where they were intersected by faults and fractures. The tendency of the barite to occur in preferred horizons can be seen today in the bedrock exposures. This suggests that solution activity by meteoric waters was probably important in opening up the ground for the mineralizing solutions from below.

Typical barite from the district is white, shiny, and often in coarsely crystalline, bladed aggregates. Fluid-inclusion data for sphalerite by Leach (1980) and Kaiser et al. (1986) suggest the mineralizing solutions were saline brines with temperatures ranging from about 70° to 110°C, and with 20 to 25 weight percent of salts. Wagner (1973) demonstrated mineral zoning in the linear "runs." A higher concentration of sulfides and coarser barite crystals occur in the center, grading outward to fine-grained barite. This was attributed in part to a mixing model, the warm saline solutions mixing with cold meteoric water in the host formations as the latter moved outward from the channelways. In the more recent study by Kaiser, Wagner, and Shanks (1986), sulfur and oxygen isotope data are given in support of the concept. They also speculate about a possible relationship between the barite mineralization and the lead-zinc mineralization in the Bonneterre Formation. They conclude: "Although there is no physical connection of the two types of mineralization, lead and sulfur isotope data suggest that they could be related." The paragenetic sequence in the barite district given in the Wagner report is as follows: chalcedony -> quartz druse -> marcasite -> pyrite -> galena -> sphalerite -> white barite -> chalcopyrite -> clear barite -> calcite.

MINING AND PROCESSING

The residual lead and barite ores in the district were mined and cleaned mostly by hand methods from the start of mining about 1725, until mechanical barite strip mines and washer-jig plants were introduced around 1924. The mineralized surficial clays, averaging about 10 ft deep, were mined by closely spaced clusters of shafts, 3 to 5 ft in diameter, that bottomed at the bedrock surface. In the strip mines, steam shovels eventually gave way to larger, more modern equipment: diesel shovels, front-end leaders, hydraulic and dragline excavators. Ore is hauled to the washer plants in large off-the-road dump trucks. Prospecting in the district is carried out using backhoes, and sometimes power augers, in a grid pattern.

At the washer plant, the barite ore is dumped into an ore chute, locally called a "dirt pan," and is washed into a large rotary breaker using high-pressure water. A flow sheet for the Apex washer is shown in figure 3. Material coarser than 3 in. is rejected in the breaker and the undersize flows into log washers. The log washer overflow is piped by gravity or pumped to the tailings pond, the underflow being fed into trommel screens where material coarser than about 1 in. is removed. The undersize, from -0.75 in. to -1 in. is fed into the jigs where the barite is recovered. It is believed that about 30 percent of the barite in the mill feed is lost during processing, with some 20 percent ending up in the tailings ponds. The ore potential of the tailings ponds was investigated by the Missouri Geological Survey some years ago (Wharton, 1972). We concluded that there are probably as much as 2 million tons of barite in an estimated 40 million tons of tailings in the 75 or so ponds known in the district.

IMCO's Apex washer, rated at 75,000 tpy, is the largest ever built in Missouri. It has some unique features in addition to its twin treatment units. A soaking pond and Sauerman scraper system was built, so that ore could be stockpiled and conditioned, and then fed to the washer at an optimum rate. The scraper system did not work properly, however, so the ore trucks then dumped directly into the dirt pans. Another innovation was the subsequent construction of a froth flotation plant designed to recover barite from washer discharges. The Apex washer had been shut down by the time the flotation plant was completed, but its operation checked out satisfactorily in a brief test. However, it remains to be seen if a secondary plant of this type would be economical in the district.

FUTURE PROSPECTS

Given the long mining history and the enormous output of barite from southeast Missouri, there has been serious concern for some time about the industry's survival. In fact, this led to the funding of the tailings pond study by the Missouri Legislature in 1969. Annual production of barite was cut in half in the 1970's, from over 200,000 tons to less than 100,000 tons. In the late 1970's, however, there was great demand and high prices for drilling mud barite, and two new companies were attracted to the area. As a result, mine production rebounded to nearly 200,000 tons in 1981. That did not last long, however, and by the second half of 1982, there was a crude oil glut, exploration faltered, and the rig count plummeted. Barite mine production was suspended in the district during all of 1983, and only three of the 12 formerly active mines resumed operations in 1984. Since then,

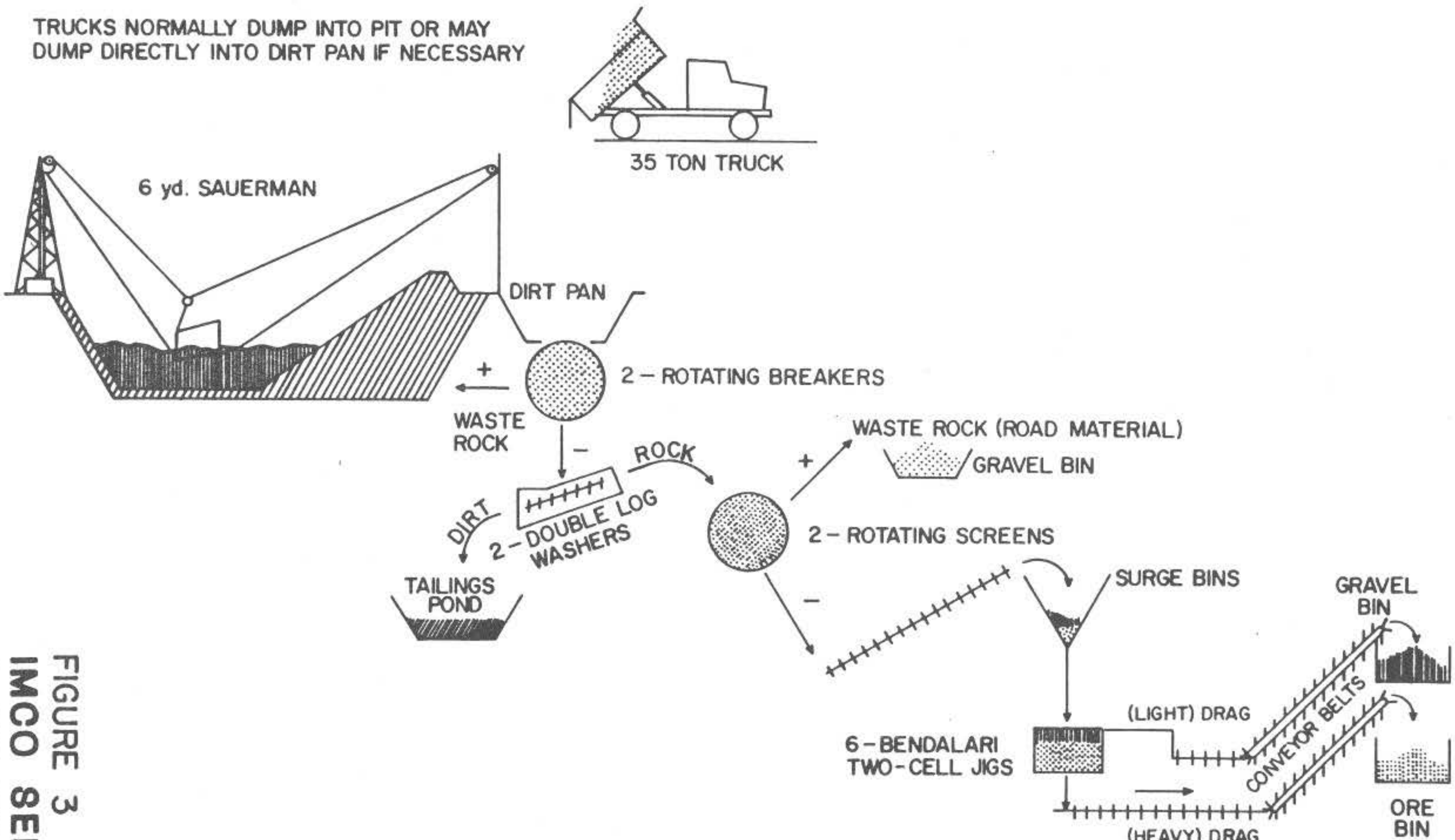


FIGURE 3
IMCO SERVICES
APEX WASHER

production has been sporadic and shipments directed mostly to the filler and chemical markets. Foreign imports and production from Nevada now supply nearly all the barite needed for drilling mud. Production costs and freight rates place Missouri at a disadvantage for that sizeable and important market, but the state is well situated to supply premium-grade barite to the filler and chemical markets. This means a modest-sized barite industry in the state, but, at the same time, a possibly extended life for the district. Unfortunately, this is at the expense of a large share of idle barite mine-mill production capacity in the state.

SELECTED REFERENCES

Brobst, Donald A., 1970, Barite: World production, reserves, and future prospects: U.S. Geological Survey Bulletin 1321, 46 p.

Dake, C.L., 1930, The geology of the Potosi and Edgehill quadrangles: Missouri Bureau of Geology and Mines, 2nd series, v. 23, 233 p.

Haines, Stanley K., and Miller, R.G., 1978, Barite - A statistical summary: U.S. Bureau of Mines Information Circular 8763, 25 p.

Kaiser, Charles J., Wagner, R.J., and Shanks, W.C., III, 1986, Geologic and geochemical controls of mineralization in the Southeast Missouri Barite district: Economic Geology v. 81 (in press).

Lange, S., Chaudhuri, S., and Clauer, N., 1983, Strontium isotope evidence of the origin of barites and sulfides from the Mississippi Valley-type ore deposits in southeast Missouri: Economic Geology v. 78, p. 1255-1261.

__________, 1985, Idem - A reply: Economic Geology v. 80, p. 775-776.

Leach, David L., 1980, Nature of mineralizing fluids in the barite deposits of central and southeast Missouri: Economic Geology v. 75, p. 1168-1180.

Muilenburg, Garrett A, 1957, Barite mining and production in Missouri: Missouri Geological Survey and Water Resources, Miscellaneous Publication 11, 13 p.

Ruiz, J., Kelly, W.C., and Kaiser, C.J., 1985, Strontium isotope evidence for the origin of barites and sulfides from the Mississippi Valley-type ore deposits in southeast Missouri: Economic Geology v. 80, p. 773-775.

Wagner, R. Joseph, 1973, Stratigraphic and structural controls and genesis of barite deposits in Washington County, Missouri: University of Michigan Ph.D. dissertation, 265 p.

Wharton, Heyward M., 1972, Barite ore potential of four tailings ponds, Washington County Barite district, Missouri: Missouri Geological Survey and Water Resources, Report of Investigations no. 53, 58 p.

GEOLOGY, ZONING, AND CONTROLS OF MINERALIZATION IN THE SOUTHEAST MISSOURI BARITE DISTRICT

by

R. Joseph Wagner
Reno, Nevada

The Southeast Missouri barite district, encompassing at least 200 mi^2, is about 75 mi southwest of St. Louis and is near the old and new Lead Belts. The low-grade deposits are residual, with the barite occurring as isolated lumps and gravel in a thick red clay regolith. The barite is insoluble residue derived from the weathering of the underlying Paleozoic dolostones, principally the Cambrian Potosi and overlying Eminence Dolomites.

The primary bedrock mineralization was deposited as "Mississippi Valley-type" open-space fillings in unconformity-related open-solution vugs. In addition to barite the primary mineralization comprises scattered galena, minor sphalerite and pyrite, and rare chalcopyrite. The mineralization was controlled by the intersection of flat-lying vuggy dolostone strata with steep faults or linear joint zones.

Most bedrock mineralization is confined to a stratigraphic interval 21 to 44 m thick, in which specific subunits controlled mineralization locally. Dissolution open vugs developed preferentially within selected dolostone lithologies, and thus the amount of barite in different lithologies generally is in proportion to the amount of open space each lithology affords. In the Potosi Dolomite most of the barite was deposited in solution vugs along algal structures or in laterally connected networks of fractures and small solution cavities along bedding planes betwen calcarenite units. The vugs are lined with drusy quartz that preceeded, and is genetically unrelated to the hypogene barite. Within the Eminence Dolomite, barite occurs as fracture fillings, in solution vugs along bedding planes, and in highly fractured thin-bedded stromatolitic units sandwiched between massive barren layers.

Individual barite deposits combine to form large linear runs (up to 5 mi long and over a mile wide). Each run displays a systemmatic mineralogical and barite textural zonation. Sulfides are most abundant in the central zone of a run, and consistently decrease in abundance and number of species towards the run's edge. Barite is also most abundant in the center of a run, decreases towards the periphery, and grades from a central zone of coarse-bladed crystals to a peripheral zone of fine-plumose crystals. The bedrock mercury content is anomalously low in the center and anomalously high beyond the edge of the ore runs, and suggests that the central zones of the runs represented heat centers.

Minor amounts of clear, euhedral barite crystals occur but are unrelated to the zoning patterns. Most of these crystals represent the product of solution and reprecipitation of the original barite by meteoric fluids.

Laboratory studies by Kaiser, Kelly, and Shanks (1983, and currently in press) have provided new information on the nature of the ore fluids, as well as the controls over mineral precipitation. Fluid inclusions in sphalerite indicate warm Na-Ca-Cl brines were present at least during early stages of mineralization. Salinity data for barite fluid inclusions are variable and may represent contamination (dilution?) by later fluids. Sulfur isotope studies show that the paragenetically early sulfides are isotopically lighter than later barite, and that barite becomes isotopically heavier from the center to the edge of a run. This spatial distribution indicates isotopically light sulfate, dominant near the central fault within a run and mixed with heavier sulfate, probably contained within the formation, waters of the host dolostones. Variations in oxygen isotopic composition also suggest mixing of two fluids and changes in temperature.

The distribution pattern of the barite and sulfides indicates outward are fluid flow from the central faults and joint zones. The precipitation of barite, and presumably the paragenetically earlier sulfides, was caused by Ba-Pb-Zn-H_2S-bearing warm, saline brines eminating from fault/joint zones and mixing with an oxidizing, sulfate-bearing and presumably cooler dilute fluid. The consistent changes in barite crystal size and habit implies deposition controlled by a barite supersaturation gradient that increased in time and space away from the center of the runs. Variations in temperature, salinity, sulfate concentration, Eh and/or pH created by the mixing of such fluids are all capable of contributing to the indicated barite supersaturation gradient.

The most probable time of hypogene mineralization is late Paleozoic. Relations of the deposits to overlying loess, and local and regional structural and physiographic considerations indicate that the mineralization was pre-upper Pleistocene, post-Pennsylvanian, and probably pre-Tertiary.

The relationship, if any, between the Washington County barite deposits and the Bonneterre Formation lead deposits of southeastern Missouri is unknown. If the two districts are genetically related, one possible explanation for the lack of barite in the Bonneterre might be the restriction (at the time of mineralization) of oxidized sulfate-bearing fluids to strata above the Davis Formation. Ascending fluids which breach the Davis cover along faults could then precipitate barite in the overlying formations.

REFERENCES CITED

Kaiser, Charles J., Kelly, William C., Wagner, R. Joseph, and Shanks, Wayne C., III, 1983, Zoning and controls of mineralization in the Southeast Missouri Barite district: Geological Society of America, 96th Annual Meeting Abstracts with Programs, Indianapolis, Indiana, v. 115, no. 6, p. 606.

Kaiser, Charles J., Kelly, William C., Shanks, Wayne C., III, and Wagner, R. Joseph, in press, Geologic and geochemical controls of mineralization in the Southeast Missouri Barite district: Economic Geology.

SEDIMENTARY HOSTED Pb-Zn-Ba MINERALIZATION OF THE OUACHITA MOUNTAINS, ARKANSAS
A Field Guide and Accompanying Descriptions

by
Timothy Master and
Charles G. Stone

TABLE I

CORRELATION OF PALEOZOIC ROCKS IN THE OZARK, ARKANSAS VALLEY, AND OUACHITA MOUNTAIN REGIONS, ARK.

AGE			OZARK – ARKANSAS VALLEY SECTION		MAP SYM.	OUACHITA MTN. SECTION		MAP SYM.
CARBONIFEROUS SYSTEM	PENNSYLVANIAN	DES MOINES	Boggy Fm.		IPby	Missing		
			Savanna Fm.		IPsv			
			Mc Alester Fm.		IPma			
			Hartshorne Sandstone		IPhs			
		ATOKA	Atoka Fm.		IPa	Atoka Fm.		IPa
		MORROW	Bloyd Shale	Kessler Ls. Mbr.	IPbh; IPbk	Johns Valley Shale		IPjv
				Woolsey Mbr	IPbw			
				Brentwood Ls. Mbr.	IPbb	Jackfork Fm.		IPj
			Hale Fm.	Prairie Grove Mbr.	IPhp			
				Cane Hill Mbr	IPhc			
	MISSISSIPPIAN	UPPER	Pitkin Limestone		Mpfb; Mp	Stanley Shale	Chickasaw Creek Mbr.	Ms
			Fayetteville Shale	Wedington SS Mbr.	Mf			
			Batesville Sandstone	Hindsville Ls. Mbr.	Mbh			
			Ruddell Shale		Mr		Hatton Tuff	
			Moorefield Fm		Mm	Ba	Hot Springs SS Mbr.	
		LOWER	Boone Fm.	Short Creek Oolite Mbr.	Mb	Ba Arkansas Novaculite	Upper Div.	MDa
				St. Joe Ls. Mbr.				
			Chattanooga Shale		MDcp			
DEVONIAN		UPPER		Sylamore SS			Middle Div.	
		MIDDLE	Clifty Limestone				Lower Div.	
		LOWER	Penters Chert					
SILURIAN		UPPER	Missing			Missouri Mountain Shale		SmOpc
			Lafferty Limestone		Slsb	Blaylock Sandstone		Smb
			St. Clair Limestone					
		LOWER	Brassfield Limestone					
ORDOVICIAN		UPPER	Cason Shale			Polk Creek Shale		Opc
			Fernvale Limestone		Of	Bigfork Chert		Obf
		MIDDLE	Kimmswick Limestone		Ocj			
			Plattin Limestone			Zn Womble Shale		Ow
			Joachim Dolomite					
			St. Peter Sandstone		Ose			
			Everton Fm.	Jasper Ls. Mbr.				
				Newton SS Mbr		Blakely Sandstone		Ob
				King River SS Mbr.				
		LOWER	Powell Dolomite		Op	Mazarn Shale		Om
			Cotter Dolomite		Ocjc			
			Jefferson City Dolomite			Crystal Mountain Sandstone		Ocm
			Roubidoux Fm.		Not exposed			
			Gasconade-VanBuren Fm	Gunter Mbr.		Collier Shale		Oc
CAMBRIAN		UPPER	Eminence Dolomite			Older rocks not exposed		
			Potosi Dolomite					
			Derby-Doerun-Davis Fm					
			Bonneterre Dolomite					
			Lamotte Sandstone					
PRE-C			Igneous Rocks					

STOP 1 — ARKANSAS NOVACULITE AT CADDO GAP

Legend has it that in 1541 Hernando DeSoto's party was attacked here by the Tula Indians, who rolled boulders down the steep slopes on them!

This classic sequence, beginning at the north end of the roadcut, comprises the following: olive tan to maroon shale and a thin chert sandstone conglomerate bed of the upper Missouri Mountain Shale; massive, dense, white to light-gray, highly jointed, and, at places, basally sandy novaculite and chert of the Lower Division of the Arkansas Novaculite; black shale, gray chert, and some gray novaculite of the Middle Division of the Arkansas Novaculite; thin-bedded to massive, cream to white, and, in part, tripolitic novaculite of the Upper Division of the Arkansas Novaculite; gray chert, greenish-black shale, quartzitic sandstone and a thin chert sandstone conglomerate bed of the Hot Springs Member of the basal Stanley Shale; and greenish-black shale, and graywacke of the lower Stanley Shale. Many other good exposures of the rocks occur along the highway, railroad, and Caddo River in the area. Based on conodont studies of this site, Hass (1951) placed the Mississippian-Devonian boundary some 27 ft below the top of the Middle Division. Structurally the rocks are rather severely deformed at this site. There are numerous steeply reclined kink folds. A tear fault that is present along the southern margin of the exposure probably affected the fold rotations. Jay Zimmerman and others have been studying in detail the geology of Caddo Gap and much of the surrounding region for a number of years. Figure 1 illustrates the exposed section of the structurally complex rocks.

To most investigators novaculite is a chemically pure microcrystalline variety of chert that typically breaks with a conchoidal or subconchoidal fracture. Lowe (1977, p. 136) shows that there are two distinct populations of detrital quartz grains in the massive white novaculite. One, consisting of fine-grained quartz distributed through the novaculite, probably represents cyclic introduction of aeolian detritus into the basin of deposition. The other comprises well-rounded to highly spherical medium to coarse grains in thin-bedded sandstone in the lower 70 ft of the Lower Division of the Arkansas Novaculite and uppermost Missouri Mountain Shale. Lowe postulates that this sand may indicate a shelf contribution from the north, by rapid sedimentation processes, such as turbidity currents. In the Middle Division of the Arkansas Novaculite, Lowe (1977, p. 138) describes thin alternating chert and shale beds, in which some chert beds contain coarser grains. Where they do, grading and current structures are common. He suggests that these appear to be fine turbidity current sequences and indicates the presence of C and D intervals of the Bouma sequence. Sholes (1977, p. 139) indicates that the novaculite beds are spiculitic and pelletal, whereas the chert is primarily Radiolaria bearing.

Keller et al., (1977, p. 834) in scanning electron microscope studies of the Arkansas Novaculite suggest that the term novaculite be restricted to the polygonal triple-point texture caused by low-rank thermal metamorphism. Recent SEM studies of many additional samples from various Paleozoic formations in the Ouachita Mountains, by Keller and Stone (1985) indicate the coarsest polygonal triple-point texture occurs near Little Rock, Arkansas, with another area of fairly coarse texture in the vicinity of Broken Bow, Oklahoma. At Caddo Gap polygonal triple-point texture is very fine to absent.

Tripoli used primarily for abrasive products has been mined from the Upper Division near Hot Springs, Arkansas to the east and in the Cossatot Mountains to the southwest. Novaculite is also extensively quarried, primarily near Hot Springs, for several types of the highest quality whetstone. Holbrook and Stone (1979) indicate that novaculite constitutes a tremendous resource of high-purity silica (99+ percent) in the central and southern Ouachita Mountains of Arkansas and Oklahoma. Manganese often occurs in the Lower Division of the Arkansas Novaculite in this area and farther west, and probably was derived from leaching of

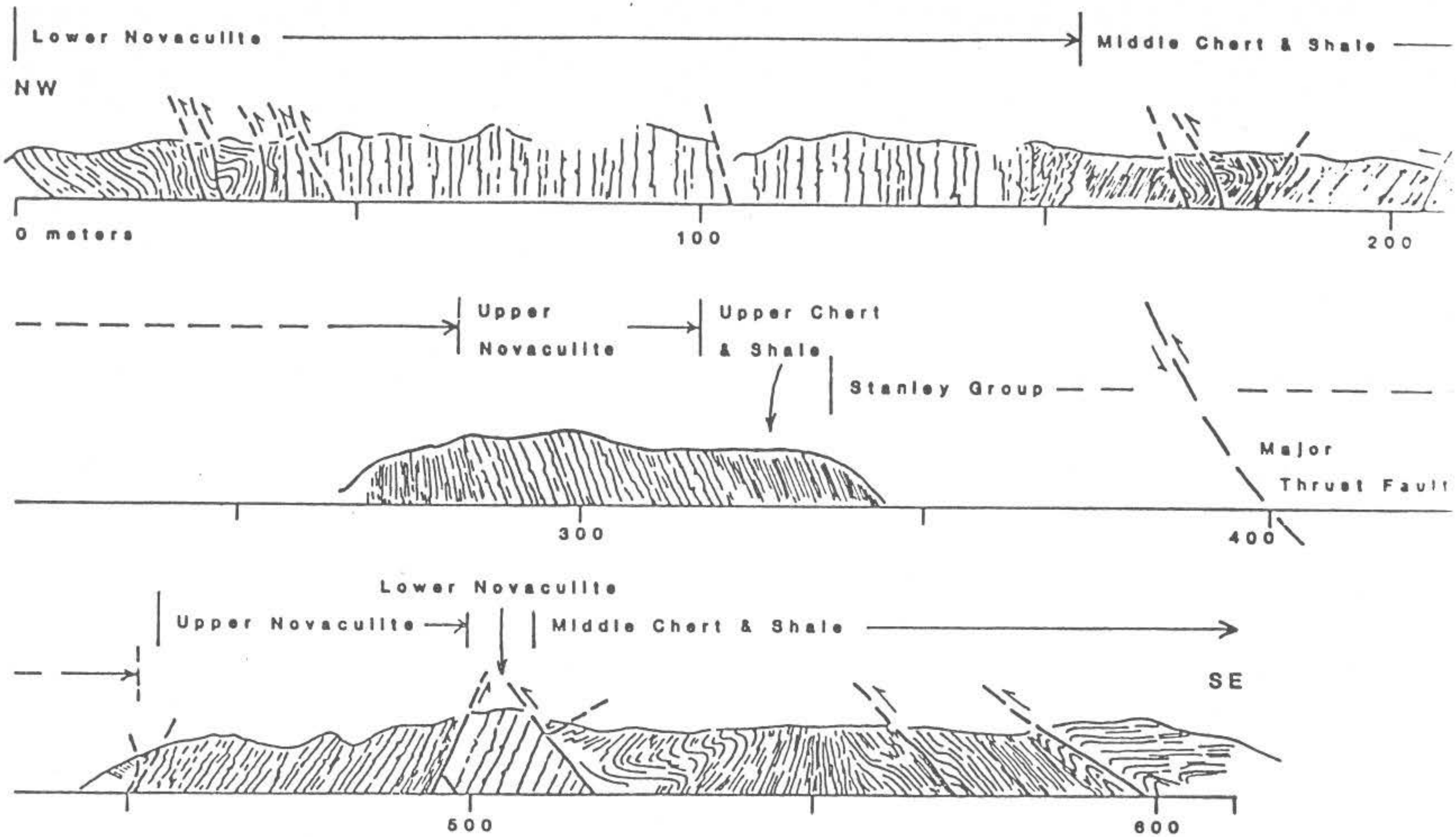


Figure 1 – Simplified cross section along Caddo Gap roadcut. Distances (in meters) are approximate owing to distortion in the photographic traverse from which this cross section was composed, and should be considered as only general guidelines. From Zimmerman (1984).

the novaculite. There has been some limited mining of small manganese veins and pockets in this area and westward into McCurtain County, Oklahoma. Investigations by Kidwell (1977) have disclosed a suite of rare iron phosphate minerals in some abandoned manganese mines in the Arkansas Novaculite, 10 to 35 mi west of here.

REFERENCES CITED

Hass, W.H., 1951, Age of Arkansas novaculite: American Association of Petroleum Geologists Bulletin, v. 35, no. 12, p. 2526-2541.

Holbrook, D.F., and Stone, C.G., 1978, Arkansas novaculite—e silica resource: Thirteenth Annual Forum on the Geology of Industrial Minerals, Oklahoma Geological Survey Circular 79, p. 51-58.

Keller, Walter D., Stone, Charles G., and Hoersch, Alice L., 1985, Textures of Paleozoic chert and novaculite in the Ouachita Mountains of Arkansas and Oklahoma and their geological significance: Geological Society of America Bulletin, v. 96, p. 1353-1363, 25 figs.

Keller, W.D., Viele, G.W., and Johnson, C.H., 1977, Texture of Arkansas novaculite indicates thermally induced metamorphism: Journal of Sedimentary Petrology, v. 47, p. 834-843.

Kidwell, A.L., 1977, Iron phosphate minerals of the Ouachita Mountains, Arkansas, *in* Stone, C.G., ed., v. 2, Symposium on the geology of the Ouachita Mountains: Arkansas Geological Commission Miscellaneous Publication, p. 50-62.

Lowe, D.R., 1977, The Arkansas novaculite: some aspects of its physical sedimentation, *in* Stone, Charles G., v. 1, Ouachita Symposium, Arkansas Geological Commission Miscellaneous Publication, p. 132-138.

Sholes, Mark A., 1977, Arkansas novaculite stratigraphy, *in* Stone, Charles G., ed., v. 1, Ouachita Symposium: Arkansas Geological Commission Miscellaneous Publication, p. 139-145.

Zimmerman, Jay, 1984, Geometry and origin of folds and faults in the Arkansas novaculite at Caddo Gap, *in* Stone, C.G., and Haley, B.R., eds., A guidebook to the Ouachita Mountains, Arkansas: Arkansas Geological Commission Guidebook 84-2, 131 p.

STOP 2 — BARITE IN THE WESTERN OUACHITA MOUNTAINS, ARKANSAS — THE DEMPSEY COGBURN AND OTHER BEDDED DEPOSITS

Barite or $BaSO_4$, a heavy nonmetallic mineral used primarily as a weighting agent in drilling for petroleum, has been identified at several localities on the south flank of the Ouachita Mountains (fig. 2). The largest, Chamberlain Creek, is near Magnet Cove on the east end of the Mazarn Barn (fig. 3). This property for a number of years was the largest producing barite mine in the world. On the west end of the Mazarn basin several barite occurrences have been identified west and north of Hopper, Arkansas, in the Fancy Hill district: the Fancy Hill (Henderson), McKnight, Dempsey Cogburn, and Gap Mountain deposits. Barite also occurs near Pigeon Roost Mountain northeast of Glenwood and near Hatfield and Dierks, Arkansas.

The properties near Hatfield, which are in the Middle Division of the Arkansas Novaculite, are small stratabound lenses of coarsely crystalline black to gray-green barite. There are similar occurrences at Boone Springs and Polk Creek Mountain northwest of Fancy Hill. The occurrences at Dierks are Cretaceous gravels and sands cemented by barite. All these latter barite

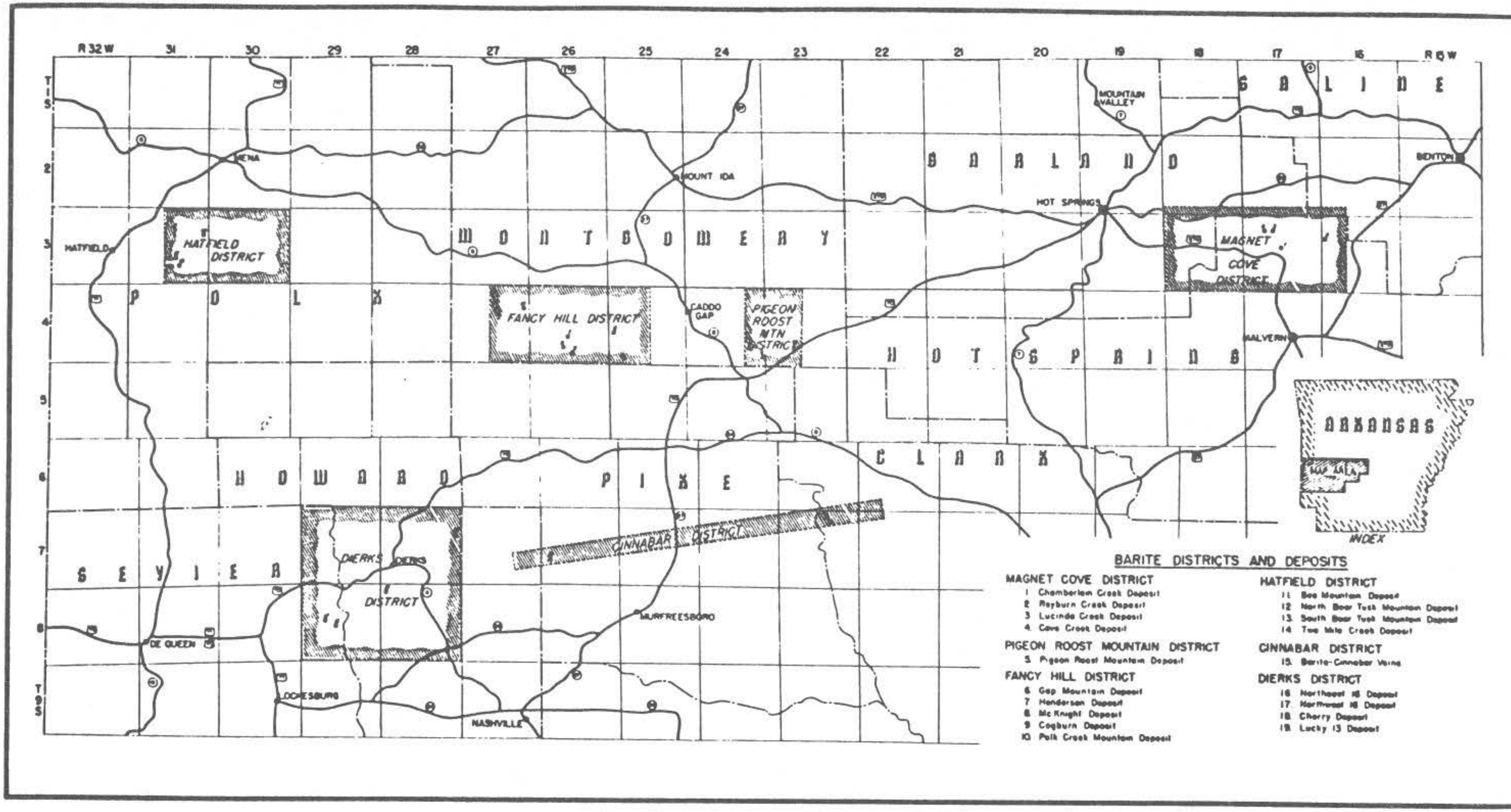


Figure 2 — Location map showing barite districts and larger known deposits in the Ouachita Mountains, Arkansas (from Scull, 1958).

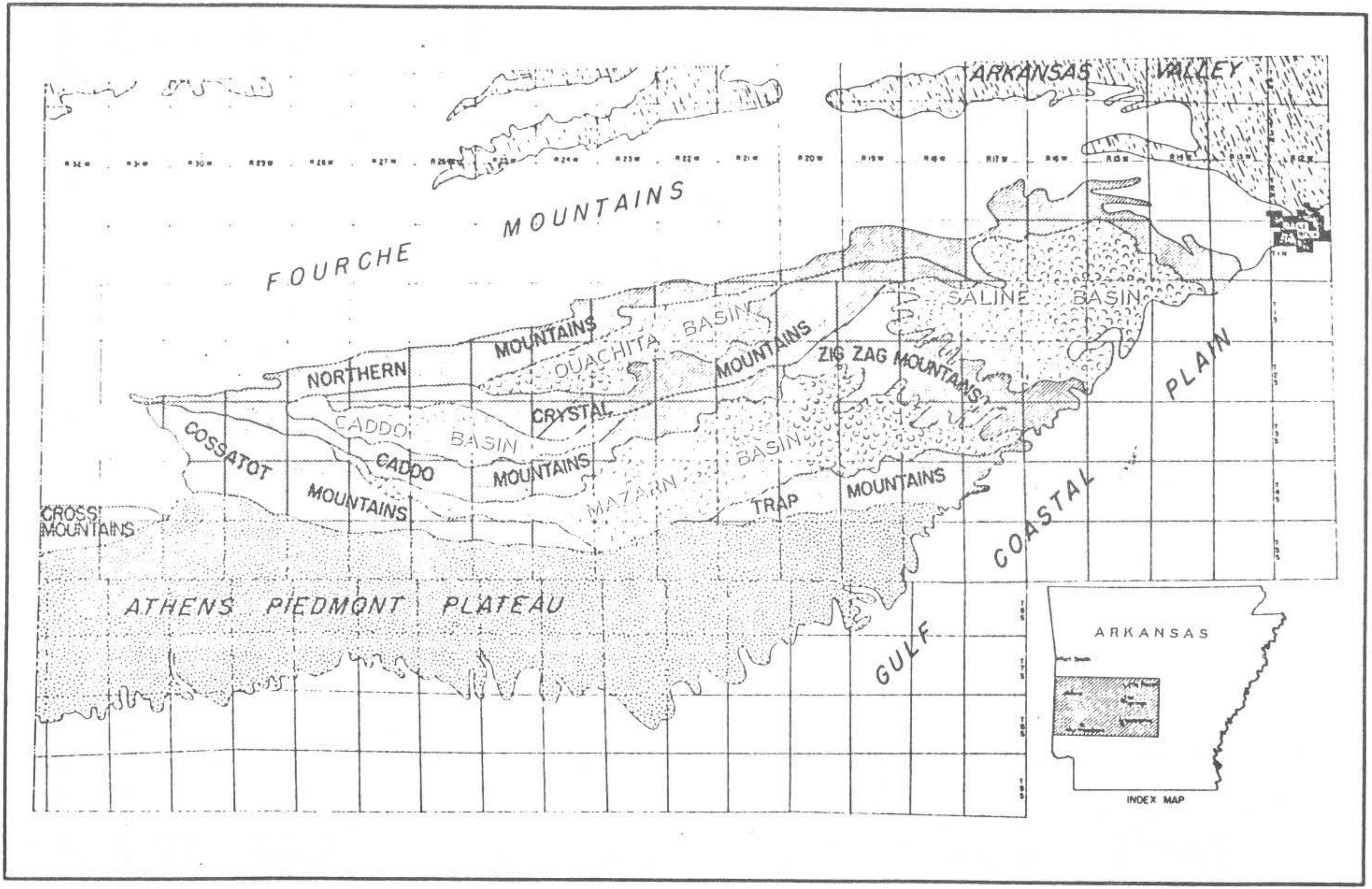


Figure 3 — Map showing physiographic provinces in the Ouachita Mountains, Arkansas (from Scull, 1958).

occurrences seem to have limited economic potential, so discussion in this paper concentrates on the bedded barites at Fancy Hill, McKnight, Dempsey Cogburn, and Gap Mountain.

Regional Stratigraphic Relationships

The commercial bedded barite deposits of the western Ouachita Mountains are restricted to the lower 100 ft of the Stanley Shale imme-

MESOZOIC

Upper Cretaceous

Woodbine Formation — tuffaceous sands and clays

Lower Cretaceous

Trinity Formation — Pike gravel member at base, overlain by loosely consolidated sandstones with Dierks and DeQueen limestone lentils; some gypsum and celestite beds; maximum thickness 600 ft

PALEOZOIC

Pennsylvanian

Jackfork Sandstone — thick massive sandstone units separated by thinner and less extensive shale units; maximum thickness 6000 ft

Mississippian

Stanley Formation — gray-green weathering dark-gray shale with thick siltstone and sandstone members; tuff beds locally near base; maximum thickness 6000 ft

Devonian-Mississippian

Arkansas Novaculite

Upper Division — tan to gray massive calcareous novaculite; locally quartzitic; maximum thickness 120 ft

Middle Division — thin-bedded dark-colored novaculite and shale; maximum thickness 450 ft

Lower Division — white to gray, dense, thick-bedded novaculite; maximum thickness 450 ft

Devonian

Missouri Mountain Shale — black, green and red fissile shale; maximum thickness 300 ft

Silurian

Blaylock Sandstone — tan to gray, fine- to medium-grained, thin- to medium-bedded quartzitic sandstone; intercalated gray to black graptolitic shale; maximum thickness 1500 ft

Ordovician

Polk Creek Shale — contorted and crumpled black graptolitic shale; maximum thickness 300 ft

Bigfork Chert — gray to black medium-bedded chert; thin black graptolitic shale partings; strongly crumpled; maximum thickness 800 ft

Figure 4 – Stratigraphic column for the Ouachita Mountains, Arkansas (after Scull, 1958).

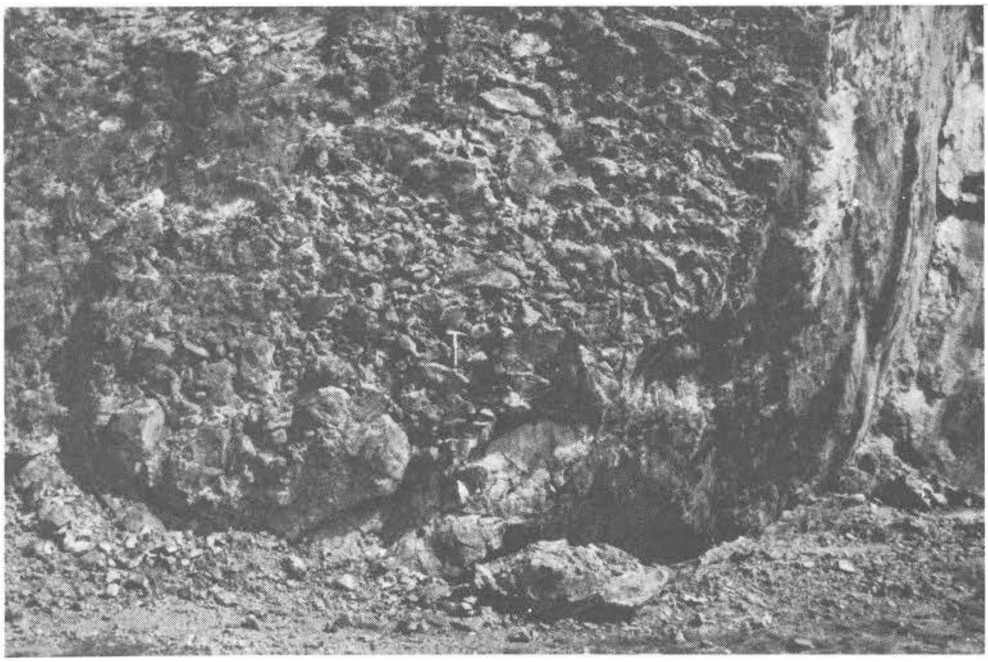


Figure 5 — Novaculite breccia at the top of the Upper Division of the Arkansas Novaculite at the Dempsey Cogburn mine. The face on the right is a cross fault showing novaculite below the breccia zone.

diately overlying the Arkansas Novaculite (fig. 4), which is on the order of 900 ft thick in this area and consists of three units. The Lower Division is between 250 and 400 ft thick. The Middle Division is 210 ft thick at Fancy Hill, 390 ft thick at Gap Mountain, and 364 ft thick at Caddo Gap. The Upper Division is 70 ft thick at Fancy Hill, 120 ft thick at Gap Mountain, and 118 ft thick at Caddo Gap. The upper surface of the Novaculite in this area is an 18-in.-thick rubbly broken zone, in places cemented by pyrite (fig. 5). This zone is very well displayed on the exposed Novaculite wall in the Dempsey Cogburn mine, and also at Chamberlain Creek. On a regional scale this stratigraphic horizon is represented by a chert-pebble conglomerate of greatly varying thickness. At Hot Springs the zone is the Hot Springs Sandstone Member, which is mapped in the basal Stanley Shale. In the western Ouachitas the zone is from 0 to 25 ft thick and consists of chert or novaculite clasts, usually 1 in. or less in size, in a siliceous matrix.

Above the Novaculite is the Stanley Shale, an approximately 6000-ft-thick (Scull, 1958) turbidite sequence of shale and sandstone that represents a radical change in depositional character from the Novaculite. Deposition changed from the very slow accumulation of mud to a rapid accumulation of turbidites, with perhaps a ten-fold increase in the rate of accumulation. The lower 100 ft of the Stanley, where the barite occurs, is primarily shale, but some lenses of dense gray sandstone are present, and they increase upward from the barite.

An interesting stratigraphic relationship in this area is the rapid thinning of the Blaylock Sandstone. Just south of the Dempsey Cogburn mine the Blaylock is about 600 ft thick; only 3 mi north it is absent.

Structure

The rocks are folded into a series of tight isoclinal folds that trend east-west. South of Fancy Hill the folds are broken along axial planes into a series of stacked thrust sheets that repeat the section several times. The sheet containing barite south of Fancy Hill appears to have been torn into several pieces. Seismic work has shown that the barite on Fancy Hill forms a synclinal trough in the Back Valley to the south (fig. 6).

The rapid thinning of the Blaylock from 600 ft to zero in 3 mi indicates that a growth fault was present through this area during Silurian time. Another indication of a possible deep structure are hot springs at Caddo Gap, 2 mi southwest of Caddo Gap, and 3.5 mi west of Fancy Hill. There are also two igneous dikes in the area, at Pigeon Roost Mountain and in Long Creek, near the last hot spring mentioned.

The presence of the barite, hot springs, dikes, and the thinning Blaylock all seem to point strongly toward a growth fault that was active during Silurian time and reactivated at the end of Novaculite time. Such reactivation caused brecciation of the upper surface of the Novaculite and provided the conduit for hydrothermal fluids that precipitated sulfides in the form of pyrite, and later, barite. The growth fault also provided the relief necessary to form the chert pebble conglomerates and the Hot Springs Sandstone, which probably accumulated as lobes at the base of canyons cutting across the escarpment (fig. 7). Since the growth fault was a zone of weakness, it probably broke as a thrust fault during compression, and therefore cannot now be identified.

Orebodies

For more than 9000 ft, the barite deposit at Fancy Hill follows a nearly straight line along the south side of Fancy Hill and dips 80 degrees to the south. A series of northeast-trending cross faults of generally small displacement offset the beds from 1 to 10 ft, but in a few places much larger displacements can be seen.

The footwall of the deposit is primarily shale, 2 to 50 ft thick. On the east end barite rests on sandstone. In places the shales are highly carbonaceous and pyritic. Above the barite 10 to 40 ft of shale are overlain by gray sandstones.

The barite zone averages 15 or 20 ft thick, but varies from 0 to 40 ft. Three types of barite are common in the ore: 1) massive, finely crystalline gray to black ore of generally high grade (60-80 percent $BaSO_4$), 2) masses of coalesced nodules that form a solid layer of barite (40-50 percent $BaSO_4$). and 3) scattered nodules in shale (0-40 percent $BaSO_4$). Some fractures across the barite contain crystals of barite up to 2 in. across.

Along strike, the barite pinches and swells to form several distinct ore lenses. Between the lenses, weak nodular zones can be seen in the shales. Down dip the continuity of the ore has been proven to depth of at least 600 ft. Westward there are two ore layers separated by interbedded shale and sandstone.

Origin

Based on structural and stratigraphic features, it appears the barite deposits are very much like those of the Selwyn Basin, in the Yukon Territory, Canada. In both areas the barite occurs in a sequence of rocks that initially represent a very quiescent depositional environment, followed by growth faulting and deposition of sulfides and barite. In the Ouachita Mountains growth faulting brecciated the upper surface of the Novaculite and provided the relief to form the chert-pebble conglomerate and the Hot Springs Sandstone. It also provided a conduit for the hydrothermal fluids from which the barite precipitated. The barite probably formed in small local depressions in the seafloor, which occasionally received influxes of mud and sand. Ore quality depended on the balance between barite and sediment influx. High-grade massive barite formed when sediment influx was near zero; as the rate of deposition increased, the quality decreased and a more nodular ore resulted. When shale completely overpowered the barite deposition, or barite influx decreased, more sparsely nodular material was formed.

Because the Canadian occurrences are also associated with lead-zinc-silver deposits, there has been some interest in examining this area for metals. Because the structural and stratigraphic settings are so similar, this basin appears to be a good prospect for further metal exploration based on the sedimentary exhalative model.

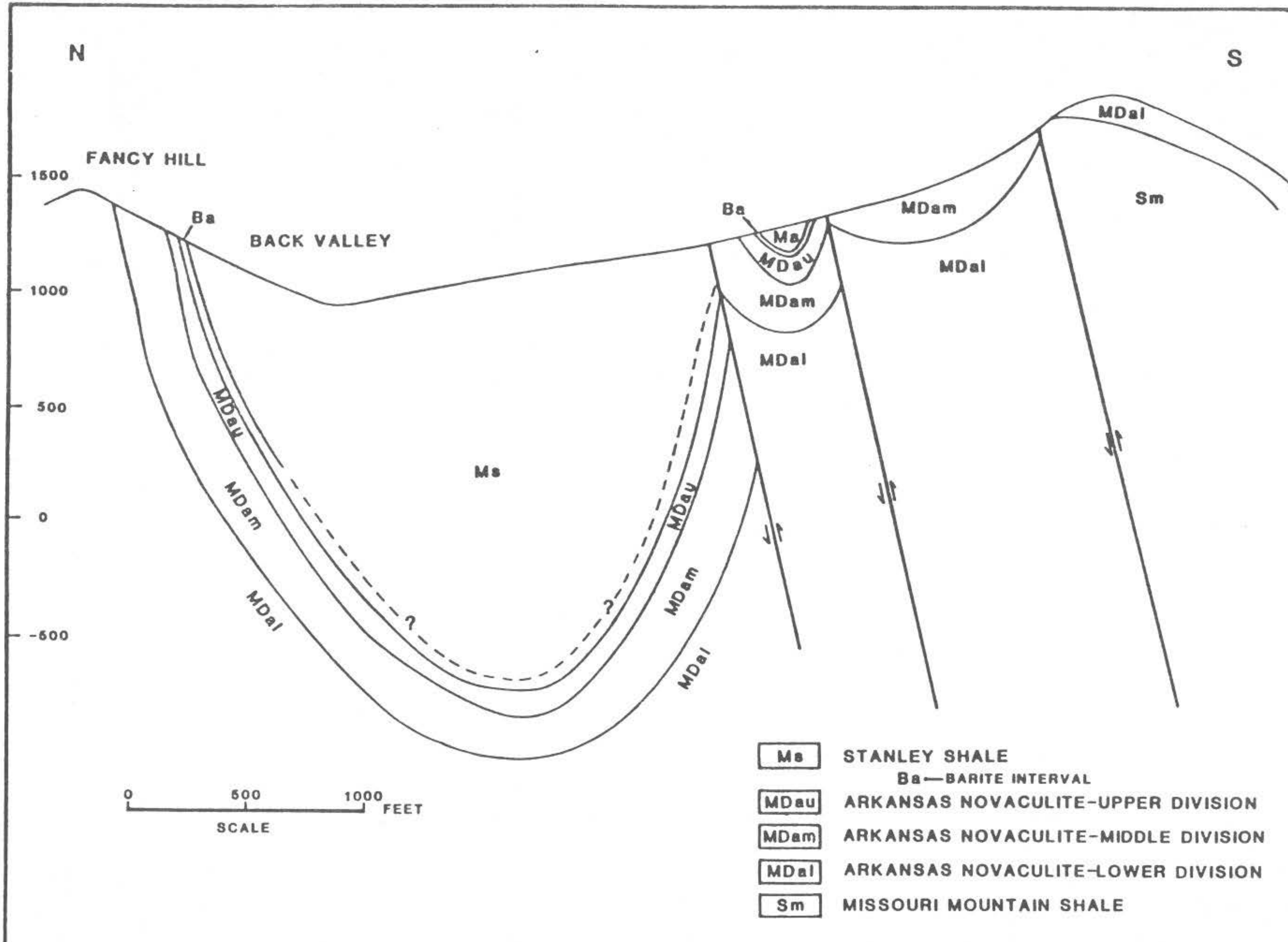


FIGURE 6: Section across Back Valley showing the generalized geology of the area (modified from E. F. Lawrence).

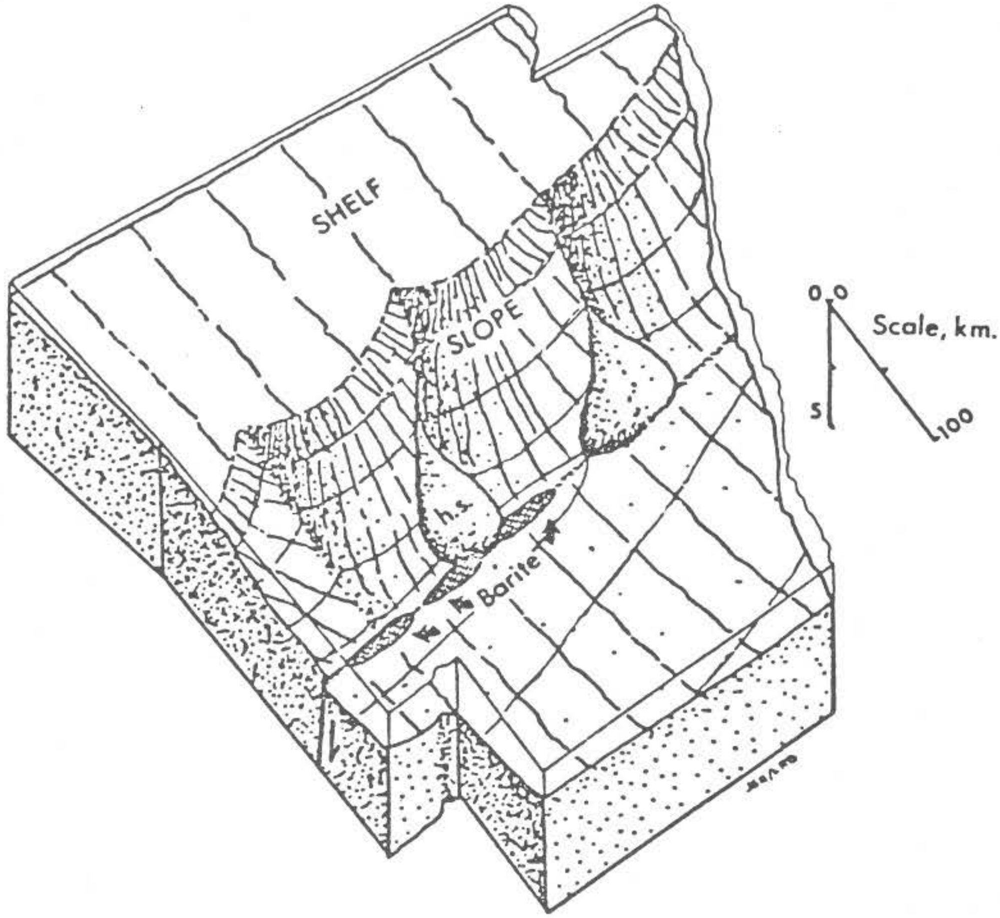


Figure 7 – Conceptual model showing the Hot Springs Sandstone Member (h.s.) and the growth fault along which hydrothermal fluids migrated to form pyrite and barite (modified from Hanor and Baria, 1977).

REFERENCES CITED

Hanor, J.S., and Barria, L.R., 1977, Control on the distribution of barite deposits in Arkansas, *in* Stone, C.G., ed., v. 2, Symposium on the geology of the Ouachita Mountains: Arkansas Geological Commission, p. 42-49.

Scull, B.J., 1958, Origin and occurrence of barite in Arkansas: Arkansas Geological Information Circular 18, 101 p.

STOP 3 — MISSOURI MOUNTAIN RED SLATE QUARRY, MOSQUITO PASS

The quarry at this location contains Missouri Mountain red slate interbedded with green slate. The color changes are apparently gradational and there are no observed lithologic changes across color boundaries. Whether this is a depositional feature or a later color zonation caused by reduction is currently unknown. A few thin silty and cherty beds occur in the shale and thin gossanous beds occur in both color types. One explanation for the iron content is an exhalative origin. The Missouri Mountain Formation in some other Ouachita Mountain locations is a gray-black shale.

STOP 4 — CALLAHAN MINING CORPORATION'S MACKS CREEK ZINC PROSPECT IN BIGFORK CHERT

This zinc prospect was discovered by regional stream sediment sampling at approximately 0.5-mi spacing and follow-up stream sampling on 100-ft spacing up drainages from anomalies. The properties were then grid-soil sampled on a 100 ft x 200 ft-spacing across the anomaly cutoff point. This drainage and the next drainge east contain up to 25,000 ppm zinc (2.5 percent) in the -80 mesh fraction. The stream is essentially an iron-manganese seep from the Bigfork Chert with a gray-black manganese zone near the origin and an iron zone down drainage. A manganese, iron ferricrete occurs in the dry creek bed above the headwaters. The property contains a weak east-west residual soil anomaly across the ridges and a few scattered lead anomalies in bedrock. A strong VLF-EM cross-over occurs across the anomaly near its up-drainage cutoff. The prospect is either a blind target in the upper Womble or the lower Bigfork. Drilling is planned initially to test shallow down-dip potential in the Bigfork and deeper penetration into the Womble.

STOP 5 — MELANGE IN UPPER WOMBLE SHALE AT MANFRED.

Downstream east of the low-water bridge is a chaotic exposure of upper Womble Shale. A complex assemblage of thin- to thick-bedded, dense limy siltstone, sandy limestone, chert- and shale-pebble conglomerate, and shale indicate multiple periods of folding and faulting. One period of folding and faulting appears to have been penecontemporaneous with deposition (sediment flow). A major fault separating Womble from Mazarn has been mapped just north of this stop. Notice the excellent cleavage, top and bottom indicators, quartz-calcite veins, slickenside zones, boudinage, and possible erratic materials. This occurrence is called the Manfred melange. Much of the upper Womble in this region resembles this exposure.

STOP 6 — CALLAHAN MINING CORPORATION'S MILL CREEK ZINC PROSPECT

This creek contains a good exposure showing soft-sediment deformation, including limestone fragments in chert. There is a gradational contact between the Womble Shale and the overlying Bigfork Chert. The anomalous zinc occurs in the Womble, the gradational zone, and into the lower Bigfork Chert.

STOP 7 — EXXON'S MILL CREEK AREA DRILLING (MC1) AND MELANGE IN CREEK EXPOSURE

This drill hole was located by geochemical techniques, using stream-sediment and rock-chip samples. The creek bed contains intricate soft-sediment deformation of limestone and carbonaceous shale with thin gossanous beds after iron carbonate or pyrite. It is interesting to note that nearby test holes (Callahan Mining Corporation's holes PC-1 through PC-3) have very little melange, an abundance of pebbly mudstone, and probable lower submarine fan turbidite with fragmental sphalerite. The Exxon core, on the other hand, contains abundant melange with laminated sphalerite and fewer transported fragments. The Exxon core is believed to be closer to the probable exhalation site, although brine pools may be somewhat removed from the source areas in the lower temperature, higher density exhalative type of brines.

STOP 8 — GEOMEX QUARTZ CRYSTAL MINE AND ORDOVICIAN DEBRIS FLOW DEPOSITS

We are most grateful to Mr. John Long, Superintendent, and other personnel of the Geomex Company for permitting us access to their quartz crystal mine and for invaluable assistance in examining these classic deposits.

Mining of quartz crystals in the Ouachita Mountains of Arkansas has been going on for many years; the first miners were probably Indians, who shaped them into arrowheads. Because of the clarity and perfect shape of many individual crystals and crystal clusters, the principal market over the years has been as specimens in individual and institutional mineral collections. During World War II about 5 tons of clear quartz crystals from Arkansas were used in the manufacture of radio oscillators to supplement Brazilian production. Currently, quartz crystals are used for manufacturing fusing quartz, which has many chemical, thermal, and electrical applications; for seed crystals (lasca) for growing synthetic quartz crystals; and, of course, for mineral specimens. It should be noted that the "Hot Springs Diamonds" for sale in the local rock shops and jewelry stores are cut from Arkansas quartz crystals.

Quartz veins are numerous and are found in a wide belt extending from Little Rock, Arkansas to Broken Bow, Oklahoma, in the central core area of the Ouachita Mountains. These veins, up to 60 ft wide, commonly contain traces of adularia, chlorite, calcite, and dickite. In a few places lead, zinc, copper, antimony, and mercury minerals are associated with the quartz veins. At relatively few localities however, do individual quartz crystals and crystal clusters attain the size and clarity requisite for mining.

In the Ouachita Mountains, quartz veins are closely associated with fault zones. It is believed that the quartz veins represent, in part, dewatering processes along the fault zones. The increase in pore fluids may well have contributed to overpressuring and related conditions and enhanced the overall faulting and folding process. The quartz veins with their associated minerals are presumed to be hydrothermal deposits of tectonic origin formed during the closing stages of the Late Pennsylvanian-Early Permian orogeny in the Ouachita Mountains.

The Geomex Mine is also known as the Coleman Mine, West Chance Area, Dierks No. 4 Mine and Blocher Lead (fig. 8). The quartz crystals are in veins in limy sandstone and conglomeratic sandstone beds of the Blakely Sandstone (Ordovician). Beds of conglomeratic sandstone exposed in the pit contain abundant weathered meta-arkose and granitic boulders, cobbles, and pebbles, and some clasts of limestone, chert, and shale. It is likely that these sediments were deposited in submarine fan channels and were derived from a granite-rich terrane to the north-northeast. It has been postualted by Stone and Haley (1977) and a number of others that these exotic boulders are probably Precambrian, but some believe that they represent early Cambrian accumulations. In this guidebook, the commentary following this description of the Geomex mine presents evidence that boulders from this pit and other sites are Middle Proterozoic. This area includes many thrust-faulted sequences with at least two major periods of folding, resulting in differing attitudes in fold hinge lines and axial planes. The mine itself is on the nose of a large, complexly deformed syncline.

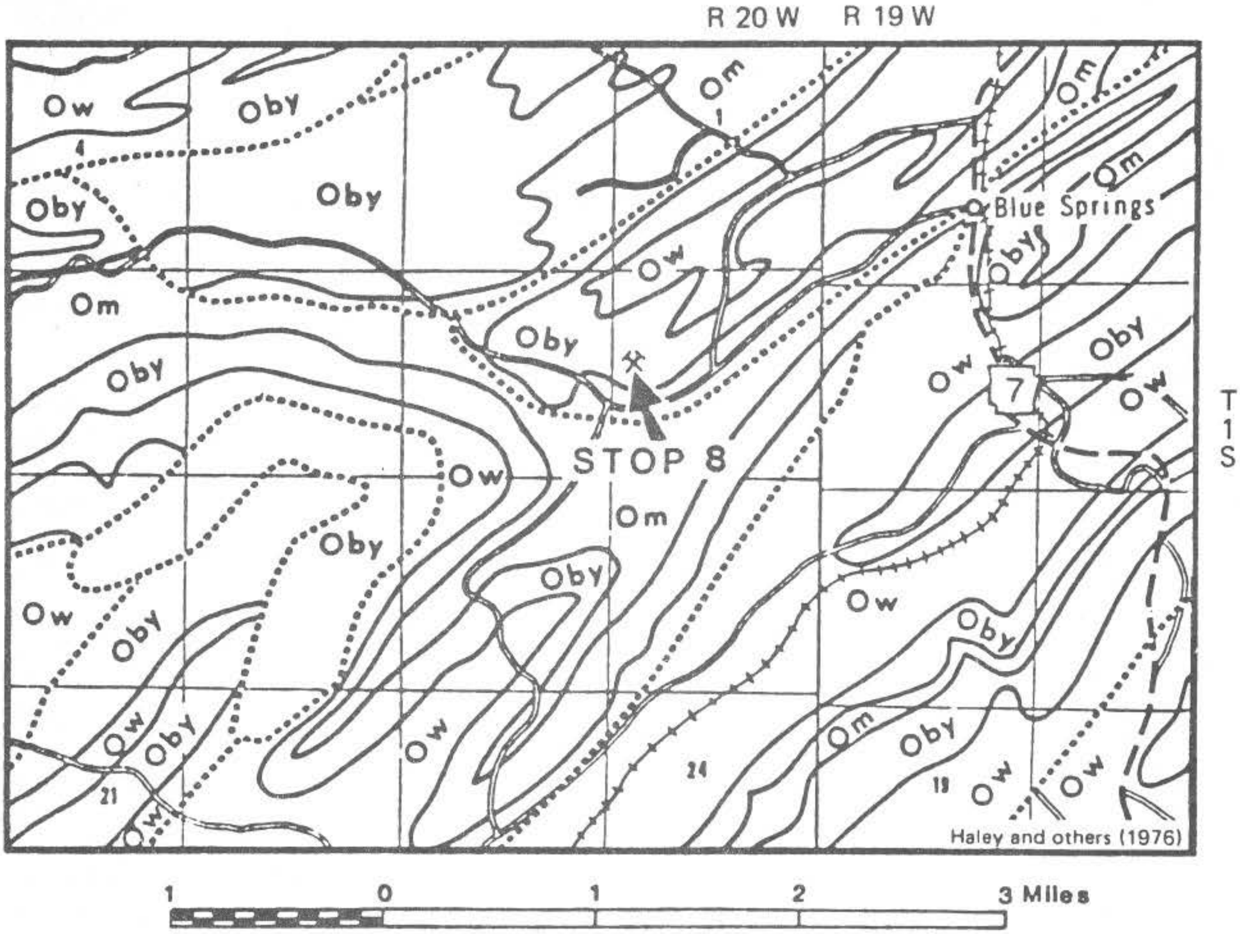


Figure 8 – Geologic map of the Blue Springs area, Arkansas showing location of the Geomex mine.

The quartz crystal veins are fracture fillings; the larger and more productive cavitites are at the intersection of two veins. Mining operations are relatively simple, consisting initially of removing overburden and loose rock with a bulldozer to expose the crystal-filled cavities, and then removing the quartz crystals with hand tools. Individual quartz crystals up to 5 ft long, weighing as much as 400 lbs, and clusters 15 ft long, weighing over 5 tons, have come from these mines.

REFERENCES CITED

Haley, B.R., et al., 1976, Geologic map of Arkansas: U.S. Geological Survey map, scale 1:500,000.

Stone, C.G., and Haley, B.R., 1977, The occurrence and origin of the granite-meta-arkose erratics in the Ordovician Blakely Sandstone, Arkansas, *in* Stone, C.G., ed., Symposium on the geology of the Ouachita Mountains, v. 1: Arkansas Geological Commission, p. 107-111.

Note: The commentary that follows provides recent data on the age of the exotic granitic boulders from the Geomex mine.

U-Pb ZIRCON AGES OF GRANITIC BOULDERS IN THE ORDOVICIAN BLAKELY SANDSTONE, ARKANSAS AND IMPLICATIONS FOR THEIR PROVENANCE*

The occurrence and origin of beds of granitic cobbles and boulders in the Ordovician Blakely Sandstone in Saline and Garland Counties, Arkansas, have been the subject of much discussion. Of particular importance in determining the provenance of the granite boulders and cobbles is their age. Paleozoic Rb-Sr whole-rock ages from these boulders are not interpreted as crystallization ages (Denison et al., 1977); therefore, three samples of granitic boulders and one sample of arkosic sandstone were collected from three localities for U-Pb zircon age determinations.

At the Uebergang uranium prospect in northern Saline County, Arkansas, many boulders and cobbles of granite and quartzite occur in the Blakely Sandstone, in addition to a few cobbles of gabbro and porphyritic andesite. One granite boulder yielded abundant euhedral, slightly discordant zircons that have an age of 1284±12 Ma.

Two granite boulders were collected from the Blakely Sandstone at Coleman's (now Geomex) quartz mine west of Blue Springs, Garland County, Arkansas. One boulder, about 1 m in diameter, is a coarse-grained granite that yielded abundant euhedral zircons varying from colorless to dark brown. Four fractions of clear and brown varieties are moderately discordant and lie on a chord that indicates an age of 1350±30 Ma. A boulder of medium-grained granite from the same outcrop yielded discordant zircons with an age of 1407±13 Ma. These figures indicate the boulders are Middle Proterozoic.

Detrital zircons separated from a sample of arkosic Blakely Sandstone from northern Saline County yielded several distinct populations of zircons that range from euhedral to rounded. Preliminary analysis of both euhedral and rounded fractions indicates a source age for the zircons between 1300-1350 Ma.

Analysis of zircons from the Blakely Sandstone yields ages that range from 1286-1407 Ma, possibly corresponding to a 1350-1400 Ma terrane of epizonal granities and rhyolites that extends from the Texas panhandle through eastern Oklahoma (Thomas et al., 1984). Although there are no known exposures of Precambrian rocks in Arkansas, the 1350- to 1400-Ma-old terrane has been extended into the subsurface of Arkansas based on aeromagnetic signatures (Thomas et al., 1984). The simplest interpretation of the age data derived from the Blakely Sandstone is that the granite boulders and arkose were derived from Precambrian basement to the north, perhaps along submarine fault scarps, as suggested by Stone and Haley (1977).

REFERENCES CITED

Denison, R.E., Burke, W.H., Otto, J.B., and Hetherington, E.A., 1977, Age of igneous and metamorphic activity affecting the Ouachita Foldbelt, *in* Stone, C.G., ed., Symposium on the Geology of the Ouachita Mountains: Arkansas Geological Commission, v. 1, p. 25-40.

Stone, C.G., and Haley, B.R., 1977, The occurrence and origin of the granite-meta-arkose erratics in the Ordovician Blakely Sandstone, Arkansas, *in* Stone, C.G., ed., Symposium on the Geology of the Ouachita Mountains: Arkansas Geological Commission, v. 1, p. 107-111.

Thomas, J.J., Shuster, R.D., and Bickford, M.E., 1984, A terrane of 1350-1400 m.y. old silicic volcanic and plutonic rocks in the buried Proterozoic of the midcontinent and in the Wet Mountains, Colorado: Geological Society of America Bulletin (in press).

STOP 9 — CHAMBERLAIN CREEK BEDDED BARITE DEPOSIT IN THE LOWER STANLEY SHALE

We thank Mr. Joe P. Hill, plant manager, and Mr. A.J. Higgins of N L Baroid Division of N L Industries, Inc. for permission to visit this abandoned mine and for information pertaining to their operations.

The Chamberlain Creek barite deposit is a stratiform deposit at the base of the Stanley Shale. The ore zone is conformable with the bedding and averages 60 ft thick. Structurally, the deposit is in an asymmetrical northward-verging syncline that plunges southwest toward the Magnet Cove intrusion (1 mi to the west) and is truncated at its eastern end by erosion, giving the orebody a spoon-like shape. The maximum length of the orebody is 3200 ft and its maximum width, 1800 ft. Some ore is nodular, but most has a dark-gray, dense appearance resembling limestone. The barite is intimately mixed with minor amounts of fine-grained quartz, pyrite, and shale. A typical analysis of high-grade ore is 85 percent barium sulfate, 11 percent silica, and 3 percent iron oxide and alumina. The average mill feed was about 60 percent barium sulfate. Inferred ore extends to the west in the Chamberlain Creek syncline to the contact of the Magnet Cove intrusion.

Currently very little of the barite interval is exposed, because the abandoned pit has gradually filled with highly acid water. There are, however, several good exposures of pre-barite strata on both flanks of the syncline. During this stop our primary interests are the meaning and importance of the black, often pyritic, shales, with discontinuous sandstone and minor chert masses of the Hot Springs Sandstone Member of the Stanley Shale, that occur below the barite zone. It is believed that these beds represent an interval of very slow deposition with a high organic content, interrupted by sporadic episodes of localized submarine slumping on the deep sea floor. These highly reduced strata probably aided in ponding the barium sulfates that were probably exhaled at places along the irregular faulted margin of the Ouachita trough in earliest Chesterian (Late Mississippian) time. Slickensides commonly filled with small quartz veinlets occur in most of the small faulted intervals that are mostly related to the late Paleozoic orogeny that formed the Ouachita Mountains. Some faults and small alkalic-lamprophyric dikes are a product of the nearby Magnet Cove intrusion of early Late Cretaceous age.

Magnet Cove Barium Corporation (Magcobar) began mining and processing (flotation) operations of ore from this deposit in 1939, and ceased in 1973. Magcobar's mill was in Malvern, Arkansas, about 7 mi south of the mine. Baroid Sales Division of National Lead Industries (N L Baroid) started their operations in 1941. Magcobar's headframe is on the north limb of the syncline, and although their mining operation began with stripping on the northern limb, they soon went to extensive underground operations. The office and mill of N L Baroid is on the southern limb of the syncline. Their operation began as a major open pit, converted to both open-pit and underground mining in 1961; in 1977 it went exclusively underground until operations ceased in 1980. N L Baroid's mill remained active until 1982, processing a blend of high-grade mill tailings, low-grade stockpile ore from this deposit, and similar ore from deposits in Montgomery County, in western Arkansas. Milling consisted of grinding to 200-mesh and concentrating by froth flotation. Final product grade was 98 percent barium sulfate. Nearly all barite produced from this deposit was marketed as a weighting agent for drilling fluids.

The origin of the barite in this and in similar barite deposits elsewhere in Arkansas has been the subject of much debate in the literature and on the outcorp. Scull (1958) classified the Arkansas barite occurrences as replacement deposits (most important volumetrically), cements, and fissure veins. He related all three types to hydrothermal fluids generated by Cretaceous alkalic intrusives. Zimmerman

(1964) examined barite ores in the Stanley Shale (Scull's replacement type), primarily at the Chamberlain Creek deposit, and postulated a sedimentary origin, and therefore a Mississippian age. Most recent studies have related the bedded ores to exhalative events during early Stanley deposition.

REFERENCES CITED

Scull, B.J., 1958, Origin and occurrence of barite in Arkansas: Arkansas Geological Survey Information Circular 18, 101 p.

Zimmerman, Richard A., 1964, The origin of bedded Arkansas barite deposits (with special reference to the genetic value of sedimentary features in the ore): Ph.D. Dissertation, University of Missouri—Rolla.

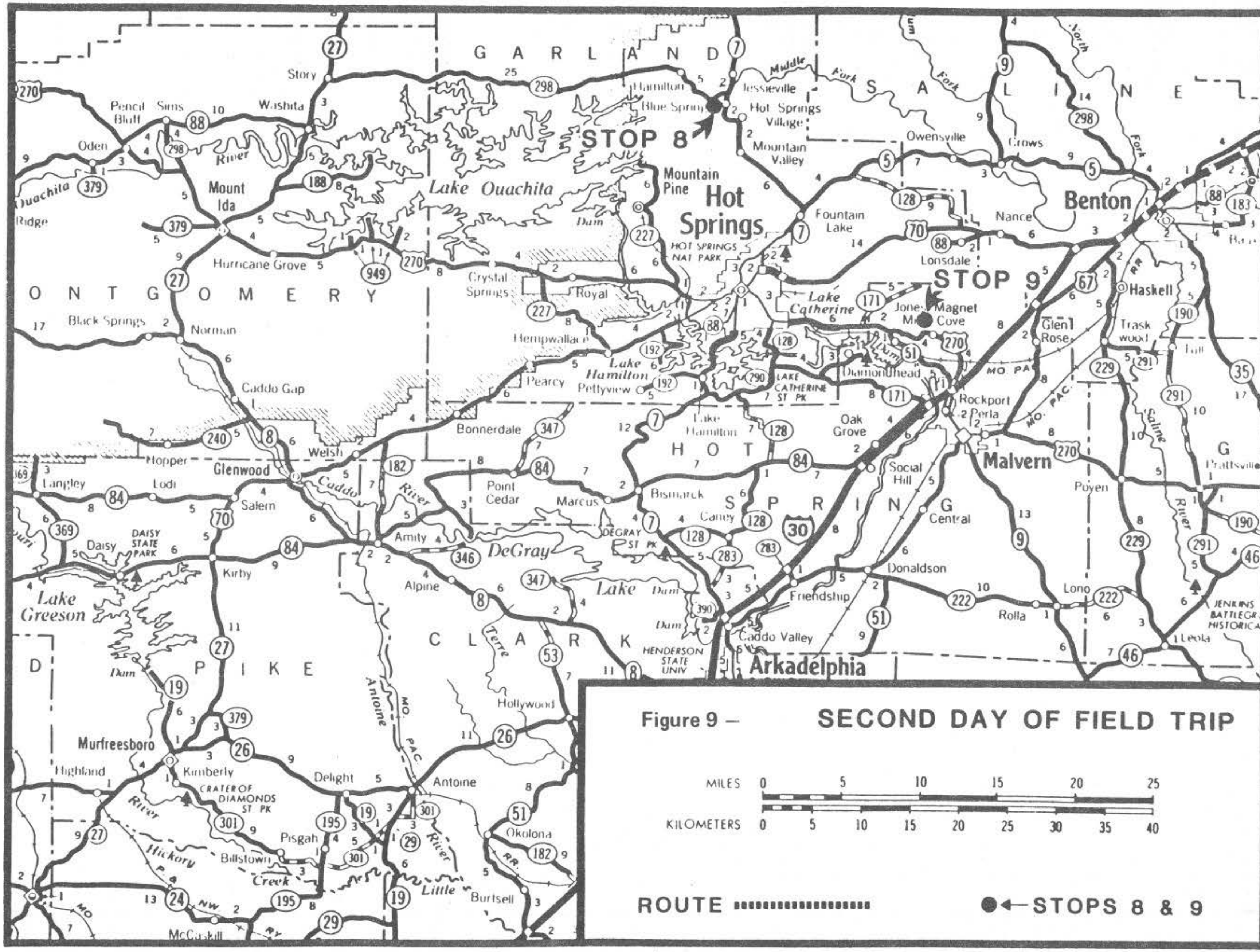


Figure 9 – SECOND DAY OF FIELD TRIP

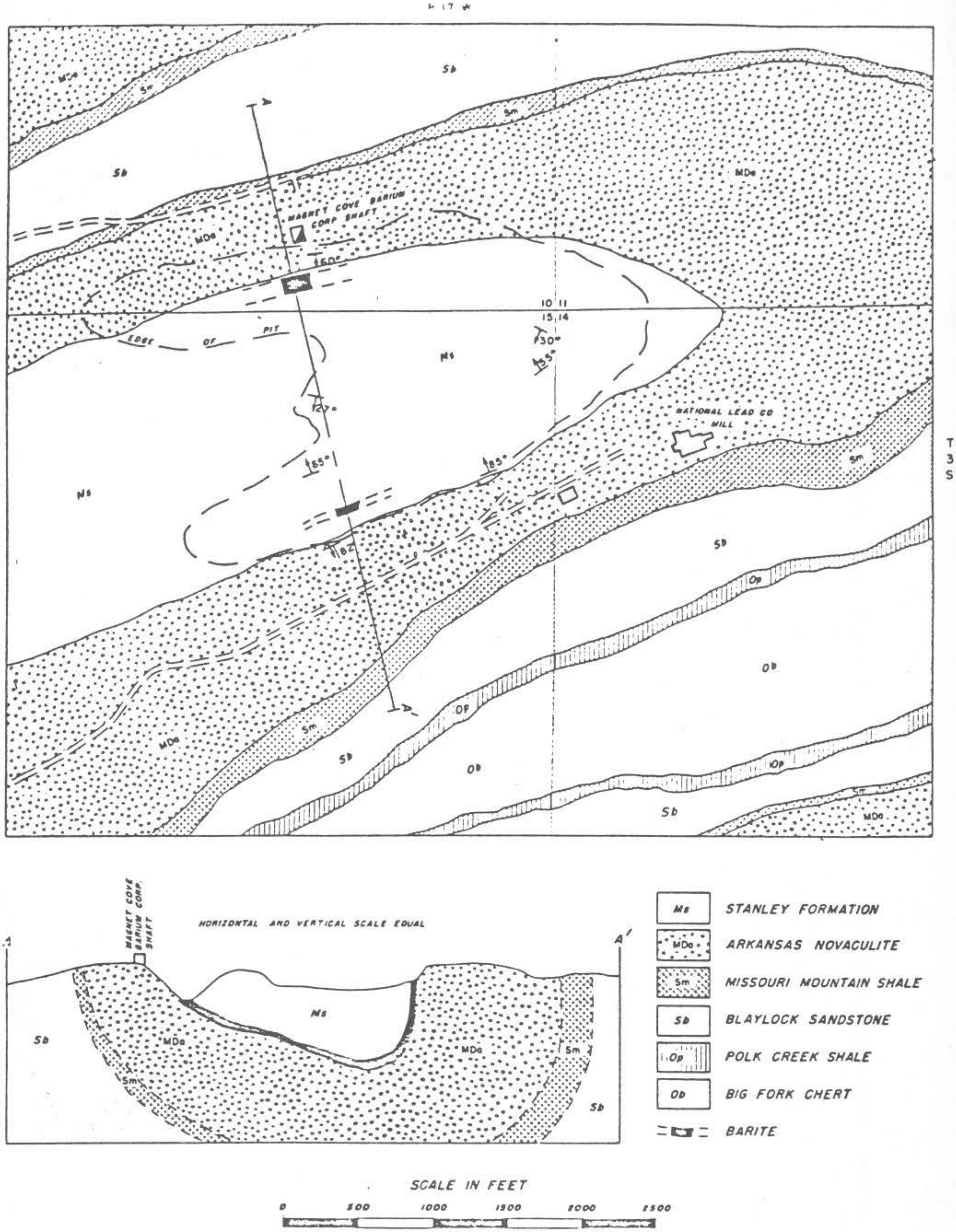


Figure 10 – Geologic map and cross section of the Chamberlain Creek barite deposit.

AFTER B J SCULL 1958

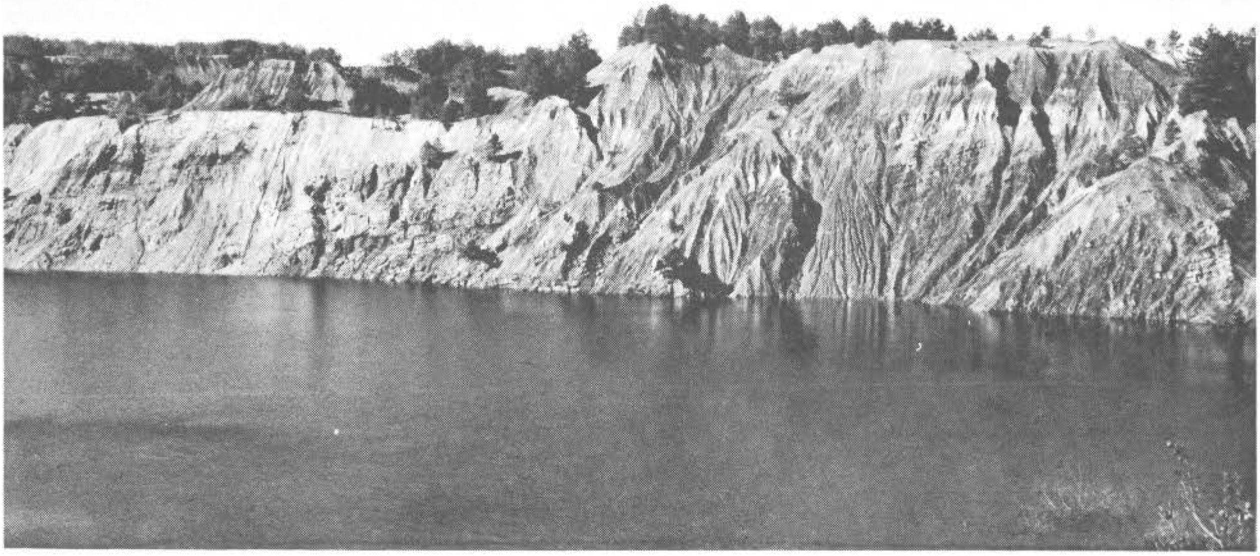


Figure 11 — Abandoned Chamberlain Creek barite pit near the center of the Chamberlain Creek syncline with lower Stanley shales and sandstones overlain by excavation materials. The thick interval of bedded barite formerly mined by open pit and underground methods is now below water level.

Figure 12 — Lenticular sandstone and some chert masses in black, often pyritic shales of the Hot Springs Sandstone Member of the basal Stanley Shale on the dip slope along north wall of the Chamberlain Creek barite deposit.

GEOLOGY AND MASSIVE SULFIDE POTENTIAL IN THE OUACHITA MOUNTAINS

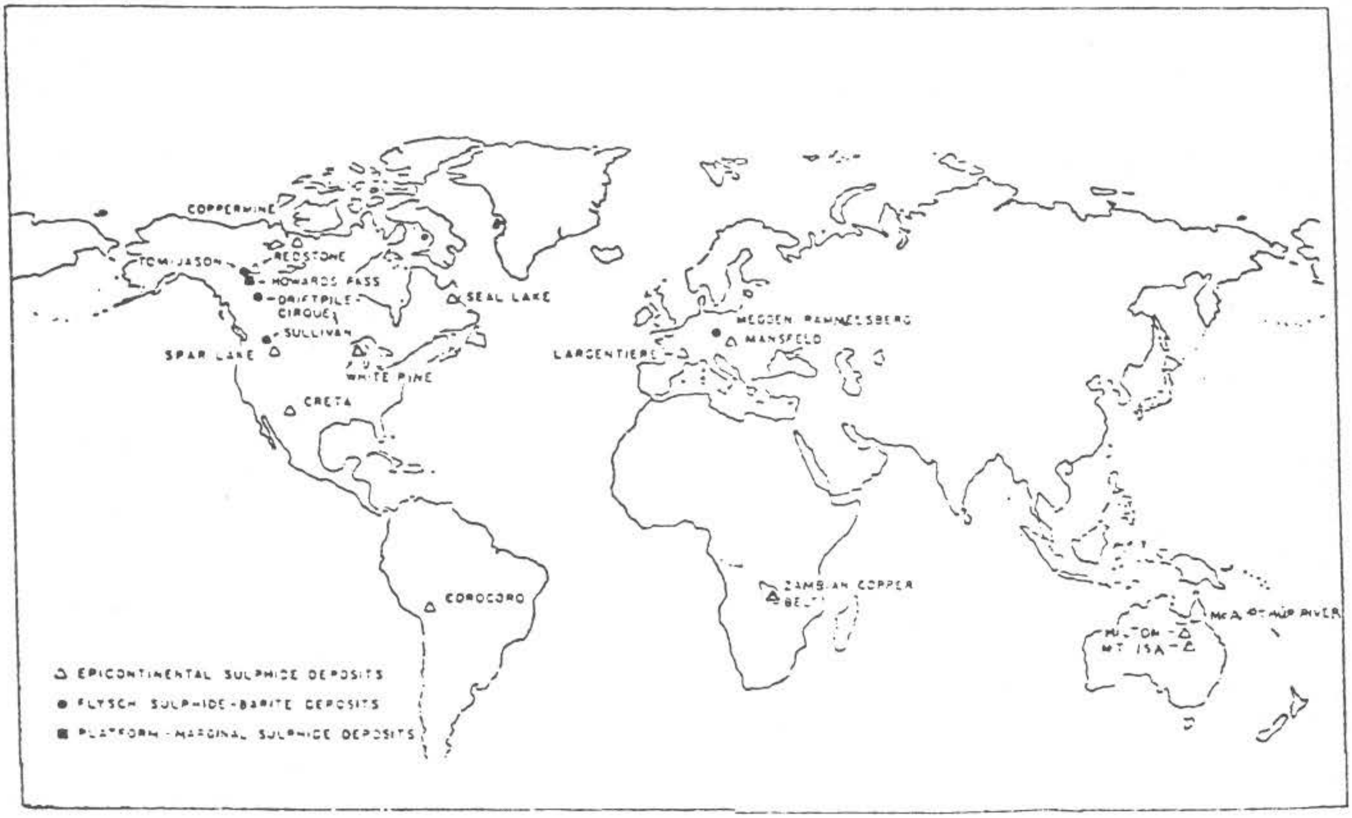
by
Timothy Master
Hot Springs, Arkansas

The geology of the Ouachita Mountains is favorable for clastic (shale)-hosted sedimentary exhalative (SEDEX) Zn-Pb-Ag platform-margin deposits comparable to the Howards Pass-type Deposit in the Selwyn Basin, Yukon Territory, Canada (fig. 1). SEDEX flysch-type barite deposits have been mined in Mississippian Stanley Shale in a region containing Zn and minor Pb anomalies in the mid-Upper Ordovician Womble-Big Fork Formations. The upper Womble Formation contains mid-lower submarine fan turbidites of the facies from northern sources ("Northern Facies") and grade upward into interbedded chert, micrite and thin carbonate fan-channel sandstones. The fan turbidites are interbedded with thick sedimentary melange and pebbly mudstone. Pebbles in the melange and mudstone contain primarily Womble fragments and also the underlying Blakely Sandstone. These interbedded high-energy units are believed to come from normal fault escarpments on the mid-lower fan facies of lower slope regime. Slump structure and debris flows characteristic of sub-basin type sedimentation are observed in the barite mines and in outcrop and core from the mid-Upper Ordovician Womble Formation. Fragments of stratiform sphalerite occur in the debris flows and pebbles within turbidite channels transported from a mineralized source area.

South of the projected basin axis, outcrops of Ordovician-Silurian basin-facies rocks from southern sources ("Southern Facies") are limited by thrust-plate cover of Devonian-Pennsylvanian rocks. Southern Facies rocks in the Upper Ordovician Big Fork Formation and Devonian-Mississippian Arkansas Novaculite Formation contain thick euxinic basin chert in contrast to the thin cherts and shales of the Northern Facies. An alkaline rhyodacite volcanic component becomes abundant in the Mississippian Stanley Shale, Devonian Arkansas Novaculite and Silurian Missouri Mountain Shale south of the axis. An ash component has also been described in the Ordovician Womble-Big Fork Formations. The Southern Facies contain northwest-directed paleocurrent directions in Ordovician-Mississippian rocks in contrast to the southwest-directed paleocurrent directions in the Northern Facies north of the axis. A thick wedge of Silurian Blaylock Formation turbidite sandstone and chert crops out south of the axis and pinches out at the axis. Potential for volcanogenic massive sulfide deposits of polymetallic type (fig. 2) may exist beneath thrust plates south of the axis; more distal SEDEX potential occurs near the projected basin axis.

In the Ouachita Mountains, carbonate-sand turbidite sequences containing sphalerite are similar in grain size and texture to fore-reef sand in a shallow water environment. However, Bouma sequences interbedded with pelagic shale and chert, lack of fossils, the abundance of rounded pyrite grains in fan channels, and the occurrence of sphalerite bands and dissemination in rounded and angular fragments within turbidite sequences, pebbly mudstone and melange indicate syngenetic sphalerite deposition in slope facies, followed by soft-sediment disruption and transport from a mineralized source.

Triassic-Cretaceous alkalic syenite-pyroxenite laccoliths(?), plugs, sills, and dikes and phonolite-trachyte flows and vents are aligned east-northeast along a projected reactivated basement structure that opened during the early Paleozoic and remained active through the Cretaceous. The recurrent subsidence along this "failed rift" explains the cyclic trough sedimentation in the Ordovician and Devonian-Mississippian rocks. The alignment of aeromagnetic anomalies and positive gravity contours reflect emplacement of northwest-trending alkalic plutons along Mesozoic basement structures that intersect the east-northeast trend at Hot Springs. These alkalic intrusive-volcanic trends are sites for anomalous precious metals, vanadium, and molybdenum. The thermal hot springs at Hot Springs possibly reflect recent hydrothermal activity at the intersection of these basement structures. Precious metals, Hg-Sb-Ba turquoise, and silicification-calcification and pyritization of chert-shale-limestone at various locations in the Ouachitas are indicators of geothermal convective-cell activity overlying and flanking intrusions and reactivated rift structures.



Major SEDEX Ore Deposits of the World.

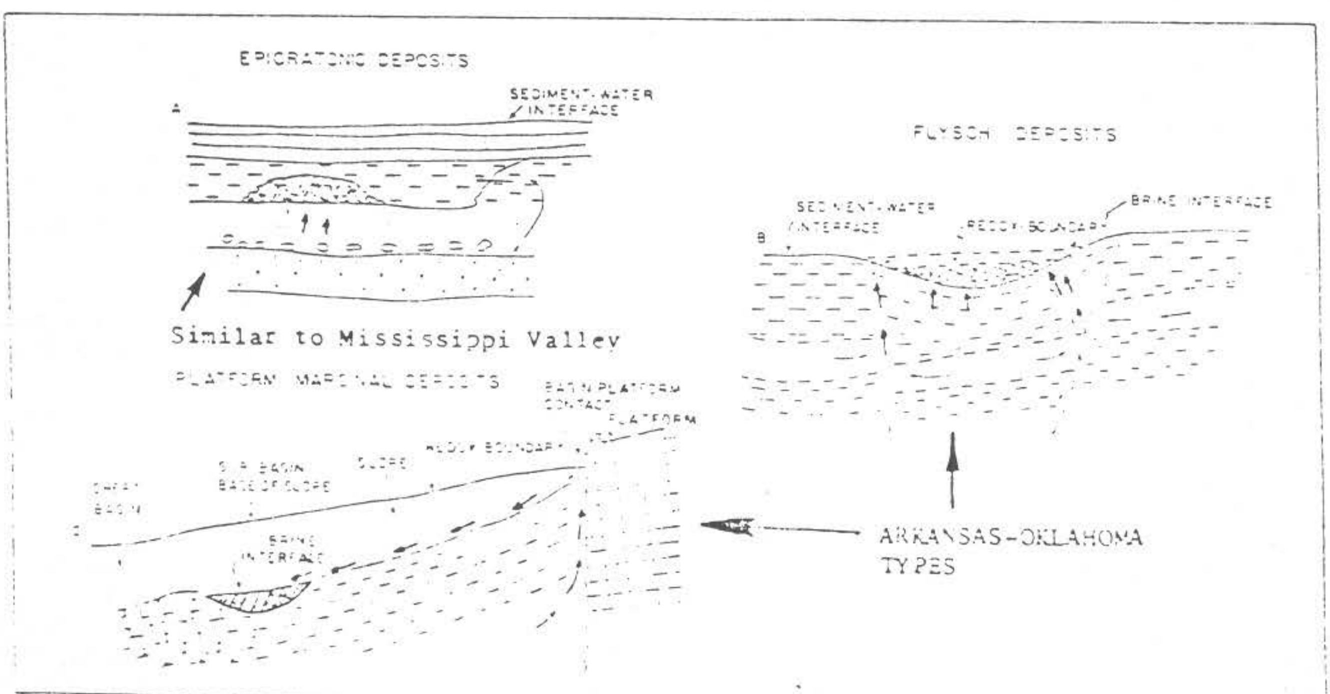


Fig.1; Major sedimentary exhalative deposits of the world and their environment of deposition. Adopted from Morganti, 1979.

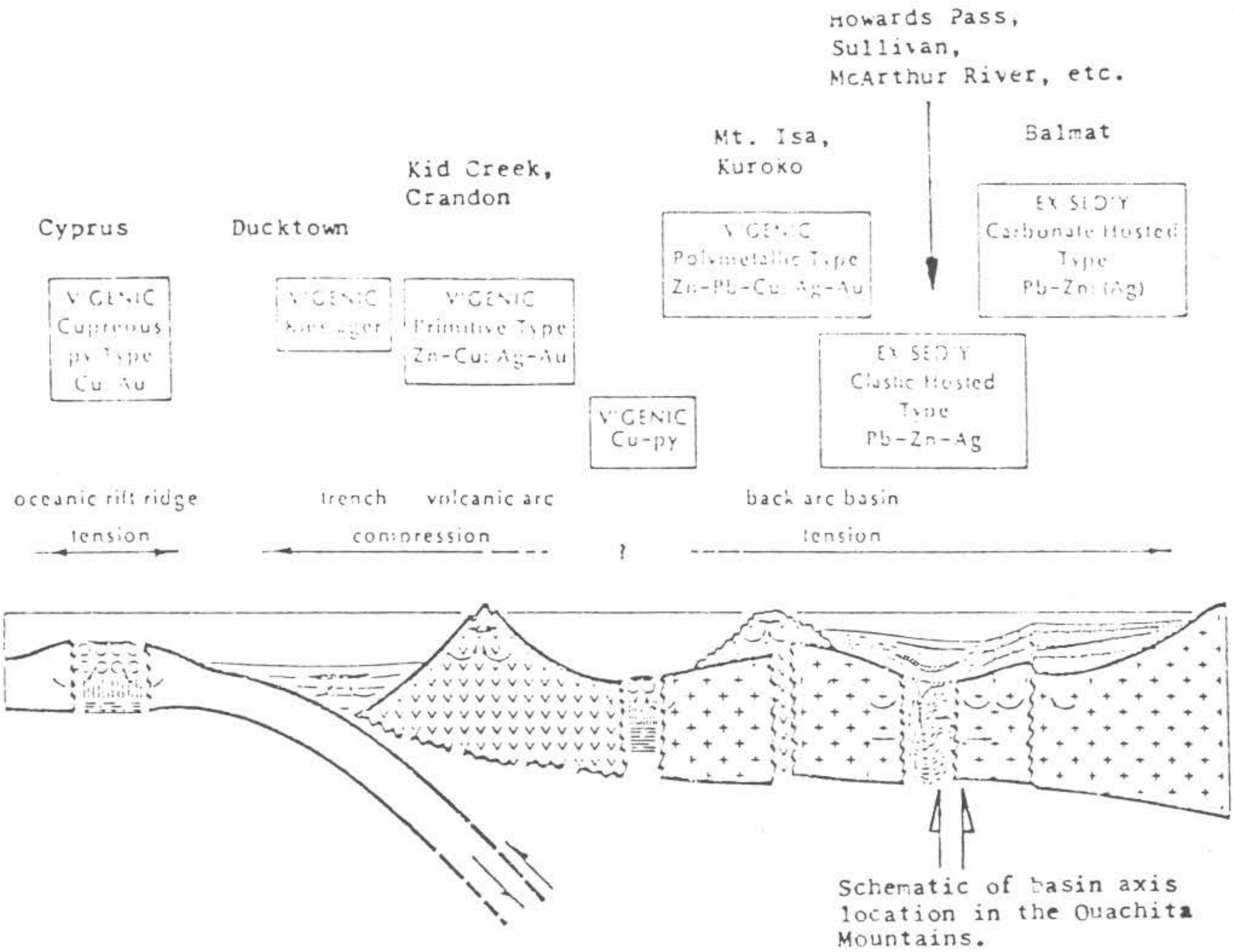


Fig.2; Diagramatic plate tectonic relationships and depositional enviornments of various massive base-metal sulfides. A basin axis trends from Mountain Fork in the Western Ouachitas to Hopper in the Central Ouachitas to Hot Springs in the Eastern Ouachitas, as indicated by Lowe,(1985). The subducted plate in the Ouachita Model is projected to dip south beneath the Central Ouachitas and is a late event of post Mississippian Stanley time, as indicated by Lillie et al, (1983). Evidence is lacking for most of the diagram to the left of the back arc basin.

Property investigation for massive sulfide Zn-Pb-Ag-Ba deposits in the Ouachita Mountains may follow a multiphase stream-seep-soil and rock sampling program and possibly IP, VLF to identify a trend and/or drill target, followed by identification of a mineralized stratigraphic horizon for testing in the direction of concealed mineralization.

REFERENCES CITED

Lillie, R.J., Douglas, N.K., de Voogd, B., Breuer, J.A., Oliver, J.E., Brown, L.D., Kaufman, J., and Viele, G.W., 1983, Crustal structure of Ouachita Mountains, Arkansas: A model based on integration of COCORP reflection profiles and regional geophysical data: American Association of Petroleum Geologists Bulletin, v. 67, p. 907-931.

Lowe, D.R., 1985, Ouachita trough: Part of a Cambrian failed rift system: Geology, v. 13, p. 790-793.

Morganti, J.M., 1979, Ore deposit models — 4. Sedimentary-type stratiform ore deposits: Some models and a new classification: Geoscience Canada, v. 8, no. 2, p. 65-75.