UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

METALLIC MINERAL-RESOURCE POTENTIAL OF THE ROLLA 1°x2° QUADRANGLE, MISSOURI, AS APPRAISED IN SEPTEMBER 1980

Walden P. Pratt, Editor

Prepared in cooperation with the
Missouri Department of Natural Resources,
Division of Geology and Land Survey

Open-File Report 81-518
1981

Tables

Page

Table 1. Resource potential for Mississippi Valley-type base-metal deposits in Bonneterre Formation and Lamotte Sandstone, September 1980.......... 15
2. Estimates of ore "deposits" in selected areas in the Rolla 1°x2° quadrangle, Missouri.......... 16
3. Estimated amounts and values of metals in potential ore "deposits" in selected areas of the Rolla 1°x2° quadrangle, Missouri.......... 19
4. Resource potential for Mississippi Valley-type base-metal and barite deposits in Cambrian and Ordovician formations overlying the Bonneterre Formation, September 1980.......... 22
5. Resource potential for Kiruna-type iron-apatite(-copper) deposits, September 1980.......... 29
6. Spectrographic analyses of hematite and magnetite from the Pilot Knob, Iron Mountain, and Pea Ridge iron deposits...... 31
7. Spectrographic analyses of rocks and minerals from Pilot Knob Mine, Iron County, Missouri.......... 32
8. Spectrographic analyses of ore and gangue minerals from Iron Mountain Mine, Iron County, Missouri.......... 33
9. Spectrographic analyses of rocks and minerals from Pea Ridge Iron Mine, Washington County, Missouri.......... 34
10. Whole-rock chemical analyses of samples from Avon, Dent Branch, and Bee Fork, Rolla 1°x2° quadrangle, Missouri...... 38
11. Spectrographic and chemical analyses of rocks from Dent Branch and Avon diatremes, Rolla 1°x2° quadrangle, Missouri.......... 39
12. Spectrographic analyses of lapilli tuffs from Bee Fork and carbonate breccia from the Crooked Creek cryptoexplosion structure, Rolla 1°x2° quadrangle, Missouri.......... 40
13. Descriptive models of pegmatitic and hydrothermal tin deposits.......... 43
14. Resource potential for platform-type pegmatitic and hydrothermal Sn-W-Zn-Pb-Ag deposits, September 1980.......... 44
15. Analyses of samples from Silver Mine area, Madison County, Missouri.......... 47
16. Chemical and spectrographic analyses of gabbroic rocks, Rolla 1°x2° quadrangle, Missouri.......... 53
17. Spectrographic and chemical analyses of Precambrian manganese ores and associated wall rocks, Rolla 1°x2° quadrangle, Missouri.......... 56
18. Spectrographic analyses of iron oxides and sulfides, Steelville district, Missouri.......... 60
19. Spectrographic and chemical analyses of limonitic iron ores, Wayne and Madison Counties, Missouri.......... 63
20. Spectrographic analyses of rock samples from the Cornwall Copper Mine area, Ste. Genevieve County, Missouri.......... 66
21. Spectrographic and chemical analyses of rocks from copper prospects in Shannon County, Missouri.......... 67

Page

Table 22. Spectrographic and chemical analyses of Precambrian quartz veins, Rolla 1°x2° quadrangle, Missouri.................... 69
23. Spectrographic and chemical analyses of selected Precambrian volcanic rocks, Rolla 1°x2° quadrangle, Missouri........... 71

ABSTRACT

Data on the mineralization, areal geology, structure, stratigraphy, sedimentary facies, petrology, trace-element geochemistry, and aeromagnetic and gravity patterns of the Rolla $1^{o}x2^{o}$ quadrangle have been integrated to provide a basis for a September 1980 appraisal of the metallic mineral-resource potential of the quadrangle. The appraisal method consisted of six steps:

(1) Compilation of geologic, lithofacies, geochemical, and geophysical maps of the quadrangle to identify the known and inferred geologic environments present.

(2) Determination of types of mineral deposits that could reasonably be expected to occur in the quadrangle on the basis of favorable geologic environments and known mineral occurrences.

(3) Development of conceptual, descriptive models of the various geologic parameters that characterize these mineral-deposit types.

(4) From each descriptive model, derivation of diagnostic and permissive "recognition criteria" for the occurrence or non-occurrence of that type of mineral deposit. Diagnostic criteria are those that are associated with all or nearly all known deposits and generally may be considered to be requisite to the presence of a deposit. Permissive criteria are those that are associated with enough known deposits that they may be considered to favor the presence of a deposit, although they are not required.

(5) Systematic examination of all available data for the presence or absence of the recognition criteria, or to show lack of information needed to determine their presence or absence.

(6) Evaluation of the areal distribution and relative importance of the recognition criteria to appraise the probability of occurrence of each mineral-deposit type throughout the quadrangle, and also indicate areas where data are insufficient for a knowledgeable appraisal.

On the basis of the geologic environments and known mineral occurrences in the Rolla quadrangle, we have considered recognition criteria for 17 different types of metallic mineral and related barite deposits. Three specific areas in the quadrangle have a very high potential for Mississippi Valley-type lead-zinc-silver-copper-nickel-cobalt deposits in the Bonneterre Formation and Lamotte Sandstone. We believe each of these areas contains at least one major deposit, with a subjective probability of 90 percent. Using appropriate typical known deposits as models, we estimate that the metals in the ground in these three postulated deposits (hypothetical resources) have a potential combined total value ranging from 2.2 billion dollars (based on conservative estimates of the size of each deposit) to 3.7 billion dollars (based on realistic estimates of size). In addition, four areas have a very high potential for small Mississippi Valley-type deposits in post-Bonneterre formations, three areas have a very high potential for large to moderate-sized deposits of Precambrian Kiruna-type iron ores, one area has a high potential for small residual barite deposits, at least one area has a high potential for tin-tungsten vein deposits, and much of the quadrangle may have a high general potential for Bokan Mountain-type uranium deposits at depths greater than 1,000 feet. Some potential exists, but cannot be evaluated as to how great, for fluorine-thorium rare-earth-bearing kimberlites, uranium in Paleozoic sandstones, and Stillwater-type iron-copper-nickel-cobalt deposits in layered mafic-ultramafic complexes. Some potential also exists for small deposits of

manganese in Precambrian and sedimentary rocks, and marcasite-pyrite-hematite, residual iron, and copper deposits in sedimentary rocks, but such deposits would not be commercial in the near future because of their small size and (or) unfavorable mineralogy. The quadrangle has low potential for coastal plain-type uranium deposits, base and precious metals in Precambrian quartz veins, and massive sulfide deposits.

INTRODUCTION

By Walden P. Pratt, U.S. Geological Survey

This report and the accompanying maps and tables present an appraisal as of September 1980 of the metallic mineral-resource potential of the Rolla 1°x2° quadrangle, Missouri. Barite is included in this appraisal as a related nonmetallic mineral.

This is the end product of a five-year cooperative project between the U.S. Geological Survey and the Missouri Division of Geology and Land Survey. Administered under the CUSMAP program (Conterminous United States Mineral Appraisal Program) of the U.S. Geological Survey, the project has integrated data from several areas of the geologic sciences—field geology, stratigraphy, petrology, geochemistry, and geophysics—to provide the basis for a unique multidisciplinary analysis of the area's resource potential. The Rolla quadrangle was selected for this study because it includes most of the southeast Missouri lead mining district and parts of the barite and iron-ore mining areas. The important base-metal ores of this major district occur in geologic formations that extend in the subsurface for hundreds of miles north and west through the midcontinental United States; hence the Rolla quadrangle should serve as a testing ground for appraisal methods that might later be used throughout the midcontinent region and in other regions where similar geologic environments suggest a potential for Mississippi Valley-type deposits.

Many maps and reports resulting from the Rolla 2° co-op project have already been published, and others are still in preparation. Many of the maps were used as source materials for the mineral-resource appraisals herein, and are listed under "References" at the end of this report.

The resource potential considered in this report includes undiscovered resources of conventional types, whether of economic, marginally economic, or subeconomic grade, that might be expected to occur in the geologic environments known or inferred to be present in the Rolla quadrangle. We do not consider nonconventional or low-grade ("common rock") materials (U.S. Bureau of Mines and U.S. Geological Survey, 1980).

Trace-element analyses of ore minerals and rocks from several (but not all) types of ore deposits were made during the course of this investigation, to determine the distribution and abundance of trace elements in the various mineral species and thereby to supplement previous observations on the characteristics and origin of the mineral deposits. These analyses have not been previously published elsewhere and are included at the appropriate places within this report.

The date September 1980 is an essential part of the title of this report. A mineral resource is defined as a natural concentration of elements in such form that a usable commodity can be extracted from it. Critical factors in the appraisal of a potential resource are its economic viability—whether or not it can be extracted at a profit—and the certainty of its existence. With changes in economic and legal conditions, development of new technologies of mining and mineral processing, improved understanding and theories of ore genesis, more detailed knowledge of the geology of the area, and development of new prospecting methods, an undeveloped or undiscovered mineral deposit may become a resource almost overnight. Thus any appraisal of resource potential is time-dependent, being based on economic and legal conditions, scientific and technologic knowledge, and data available, at a given time. There is no such thing as a "final" appraisal of the resource potential of any area. Therefore we emphasize that this report describes the resource potential of the Rolla quadrangle appraised as of September 1980.

Authors of individual sections of this report are indicated at the beginning of each section. Final editing was done by Pratt, who accepts responsibility for any errors and for numerous arbitrary decisions made in the interest of timely publication. Substantial contributions to the data base and preparation of the report, not reflected in the authorship, were made by Lindrith Cordell and Daniel H. Knepper, Jr., U.S. Geological Survey.

Methodology

The method used in this appraisal of resource potential owes much to a resource appraisal workshop that was convened in Golden, Colorado, in December 1979 (Shawe, 1981). As a part of that workshop, two groups of geoscientists from government, industry, and academia worked independently to design a methodology for appraising the resource potential of a $1^{o}x2^{o}$ quadrangle representative of the midcontinent geologic province. The area selected was the Poplar Bluff quadrangle, Missouri-Arkansas, which adjoins the Rolla quadrangle on the south. Inasmuch as that workshop included three of the authors of the present report as active participants, it is not surprising that the method used herein is similar to the workshop method in many respects, and we acknowledge here the indirect contributions of the other members of those two working groups to this report. The method consists of the following steps:

(1) Compilation of geologic, lithofacies, geochemical, and geophysical maps of the quadrangle to identify the known and inferred geologic environments present. In addition to compilation of existing data, this step required new reconnaissance mapping of approximately 65 percent of the quadrangle, aeromagnetic surveying of the west half of the quadrangle, integration of lithofacies data from logs of some 1,000 drill holes, and spectrographic and chemical analyses of about 11,000 insoluble-residue samples from 62 drill holes.
(2) Determination of types of mineral deposits that could be expected to occur in the quadrangle on the basis of (a) known worldwide associations of certain mineral-deposit types with geologic environments that are present in the quadrangle, and (b) known mineral deposits and occurrences that actually exist in the quadrangle.
(3) Development of conceptual, descriptive models of these mineral-deposit types.
(4) From each descriptive model, derivation of "recognition criteria" for the occurrence or non-occurrence of that type of mineral deposit.
(5) Systematic examination of the available data for existence of the recognition criteria.
(6) Evaluation of the areal distribution and relative importance of various recognition criteria to appraise the probability of occurrence of each

mineral-deposit type throughout the quadrangle, and also to indicate areas where data are insufficient for a knowledgeable appraisal.

Recognition Criteria

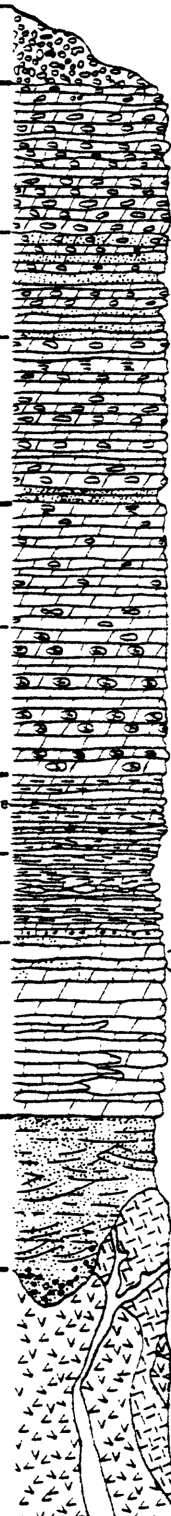
Recognition criteria--geologic parameters that affect the favorability for the presence of a mineral deposit--may be either diagnostic, permissive, or negative. (These terms are used in a descriptive sense, not in the genetic sense of Snyder, 1967.) Diagnostic criteria are those that are present in all, or nearly all, known deposits, and in most cases are considered to be required for the presence of a mineral deposit; conversely, the known absence of such criteria may either severely limit or definitively rule out the possibility of the presence of a deposit. Note, however, that the known absence of a geologic feature requires definite negative information, and negative information proving absence is not the same as the lack of positive information indicating that a feature is present. The existence of positive criteria is a favorable indication that a deposit may be present, although it does not guarantee that a deposit is present. For example, the descriptive model for the Mississippi Valley-type base-metal deposits in this area includes dolomite host rocks; thus the presence of dolomite is a diagnostic criterion, without which the existence of such deposits can be ruled out.

Permissive criteria are those that are present in enough known deposits that they may be considered to favor the presence of a deposit, although they are not required; their existence enhances the possibility for occurrence of mineral deposits, especially if diagnostic criteria are favorable, but their absence does not lessen the possibility. (In more practical terms, if two areas contained comparable favorable diagnostic criteria, the area with a larger number of permissive criteria would probably be considered more favorable for exploration.) Using the same example--Mississippi Valley-type base-metal deposits--the deposits tend to be, but are not always, associated with buried Precambrian knobs; thus the presence of a Precambrian knob favors the presence of a deposit, but the known absence of a knob does not diminish the possibility if favorable diagnostic criteria are present.

Negative criteria generally can be equated with the known absence of diagnostic criteria: thus exposed Precambrian bedrock is negative for Mississippi Valley-type deposits because it means that dolomite cannot be present. Because of this redundancy, negative criteria are not considered separately here.

Geology and mineral-deposit types of the Rolla quadrangle

The principal geologic formations of the Rolla quadrangle are sedimentary rocks, mostly dolomites, of Late Cambrian and Early Ordovician age, which overlie volcanic and granitic rocks of Precambrian Y age; figure 1 shows the names, thicknesses, and lithologies of the individual formations, as used by the Missouri Geological Survey, and figure 2A shows the approximate areas of outcrop of the Precambrian, Cambrian, and Ordovician and younger rocks. The Precambrian rocks are exposed mainly in the St. Francois Mountains in the eastern part of the quadrangle, where a complex of dominantly rhyolitic ash-flow tuffs is intruded by a composite batholith of biotite and amphibole-biotite granites; the buried Precambrian basement in the rest of the quadrangle is dominated by subvolcanic massifs of biotite granite, central



Era	System	Series	Formation	Lithologic Description	Mineral Resources and Products
PALEOZOIC ERA	ORDOVICIAN SYSTEM	LOWER CANADIAN SERIES	Chert residuum		
			Jefferson City Dolomite (200'-300')	Dolomite, fine- to medium-grained, argillaceous, cherty, "cotton rock" variety locally abundant.	Crushed stone
			Roubidoux Formation (125'-200')	Dolomite, light-gray to brown, fine-grained, cherty Sandstone, quartzose	Building stone Ground water
			Gasconade Dolomite (250'-300')	Dolomite, light-gray to buff, fine- to coarse-grained, cherty, contains beds and lenses of cryptozoon.	Crushed stone
			Gunter Ss. Mbr. (20'-40')	Dolomite, arenaceous, rounded-frosted quartz grains.	Ground water
	CAMBRIAN SYSTEM	UPPER CAMBRIAN SERIES	Eminence Dolomite (150'-300')	Dolomite, light-gray, medium- to coarse-grained, medium- to massively bedded, cherty.	Crushed stone **Barite** **Lead** **Zinc** **Ground water**
			Potosi Dolomite (250'-300')	Dolomite, brown to gray, fine- to medium-grained, massively bedded, contains abundant quartz druse and cherty digitate algal forms.	
			Elvins Group: Derby-Doerun Dolomite (100'-200')	Dolomite, tan to buff, fine- to medium-grained, argillaceous, silty, oolitic.	
			Elvins Group: Davis Formation (125'-225')	Shale, dolomitic, thin-bedded; contains edgewise conglomerate; *Eoorthis* zone 30 to 35 feet below top. "Marble boulder bed" 60 to 70 feet below top. Interbedded limestone in some areas.	
			Whetstone Creek Mbr.	Dolomite, fossiliferous, glauconitic, locally shaly, silty or sandy, micritic.	
			Sullivan Siltstone Mbr.	Laminated siltstone, calcarenitic, may contain mud-chip conglomerate; glauconite.	
			Bonneterre Formation (200'-450')	Dolomite, light-gray to dark-brown, fine- to medium-grained, glauconitic in places, contains some dark-green to black, thin shale beds. Lenses of gray to pink limestone are referred to as "Taum Sauk marble".	Lead, Zinc, Copper, Silver, Cobalt, Nickel Crushed stone Dolomitic quicklime Dead-burned dolomite
			Lamotte Sandstone (0-500')	Sandstone and conglomerate, quartzose, arkosic; contains interbedded red-brown shale.	Building stone Ground water
PRECAMBRIAN	PRECAMBRIAN Y*		St. Francois Mountains Intrusive Suite**	Diabase and gabbro dikes and sills. Granite, adamellite, syenite, diorite, and granite porphyry stocks, bosses, plutons, and sheet-like intrusive bodies.	Iron, Manganese, Copper, Tungsten, Silver, Lead Phosphates, Feldspar, Dimension stone, Crushed stone, Roofing granules
			St. Francois Mountains Volcanic Supergroup	Rhyolitic ash-flow tuffs, lava flows, and bedded tuffs.	

*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.

**The name St. Francois Mountains Intrusive Suite is used provisionally in this report, pending approval of the use of the term "intrusive suite" by the American Commission on Stratigraphic Nomenclature.

Fig. 1.--Generalized stratigraphic column, Rolla 1° X 2° quadrangle, Missouri. Formations younger than Jefferson City Dolomite occur only in extreme northeast and southeast corners of quadrangle and are not shown.

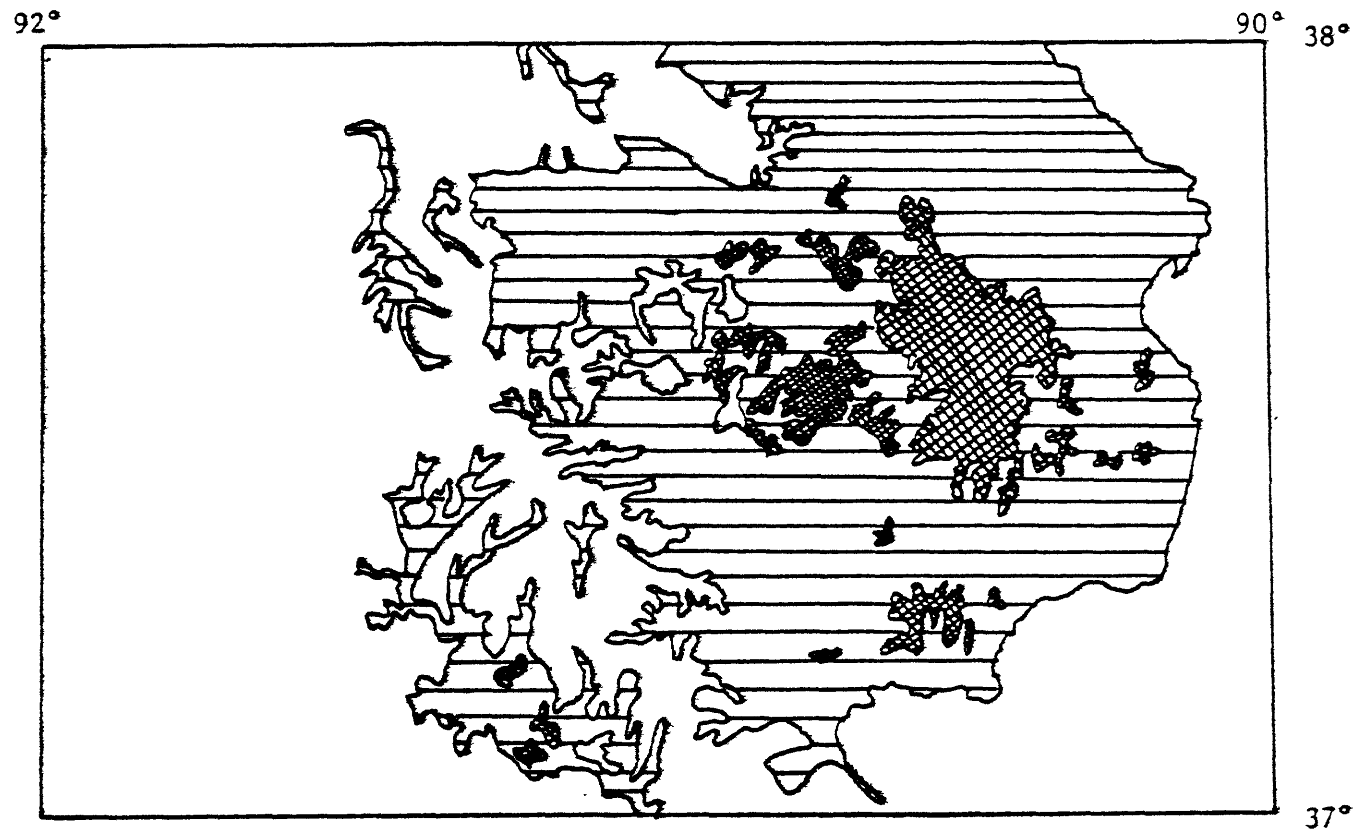
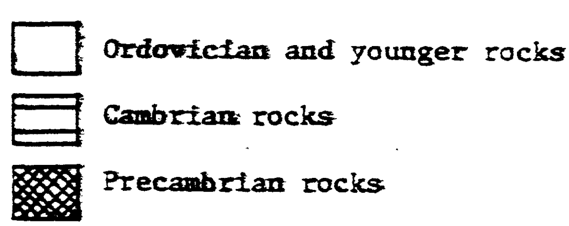


Fig. 2A.—Generalized geologic map, Rolla 1° X 2° quadrangle, Missouri.



plutons of two-mica microcline and albite granite (tin granite), and ring intrusions of amphibole-biotite granites (Kisvarsanyi, 1980a,b). The Cambrian and Ordovician rocks generally are flat-lying or dip gently away from the St. Francois Mountains; they are fairly well exposed around the flanks of these mountains but elsewhere in the quadrangle are mantled by thick residual cherty clays. Where the entire section of Upper Cambrian and Lower Ordovician rocks is preserved, mostly in the western part of the quadrangle, its total thickness is about 2,000 feet. It is overlain by younger sedimentary rocks in the extreme northeastern and southeastern parts of the quadrangle.

The principal metallic mineral deposits exploited in the quadrangle to date have been Mississippi Valley-type lead-zinc-silver-copper-nickel-cobalt ores in the Bonneterre Formation in the Mine La Motte-Fredericktown area, the Old Lead Belt, and the Viburnum Trend (fig. 2B), and Kiruna-type iron ores in Precambrian rhyolites in the St. Francois Mountains. Residual barite and lead deposits, derived largely from Mississippi Valley-type deposits in the Eminence and Potosi formations, have in some past times been of national significance. Several other types of mineral deposits or occurrences are known in the quadrangle, and certain geologic environments in the quadrangle suggest a potential for still others. Some known lithologies in the Precambrian basement complex, for example, are favorable environments for certain types of ore deposits, as has been discussed in general terms for the entire State of Missouri by Kisvarsanyi and Kisvarsanyi (1977). The remainder of this report is devoted to appraisals of the resource potential for the following 17 types of mineral deposits in the Rolla quadrangle, on the basis of known mineral deposits and occurrences in the quadrangle and known associations of deposit types with geologic environments present in the quadrangle:

1. Mississippi Valley-type base-metal deposits (lead-zinc-copper-nickel-cobalt) in the Bonneterre Formation and Lamotte Sandstone
2. Mississippi Valley-type base-metal and barite deposits in Cambrian and Ordovician rocks overlying the Bonneterre Formation
3. Barite deposits in residuum derived from vein and replacement deposits in Paleozoic rocks
4. Kiruna-type iron-apatite(-copper) deposits
5. Fluorine-thorium rare-earth-bearing kimberlite-carbonatite complexes
6. Vein deposits of tin-tungsten-copper-zinc-lead-silver in Precambrian rocks
7. Uranium and thorium in Precambrian rocks
8. Uranium in Paleozoic sedimentary rocks
9. Coastal plain-type uranium deposits
10. Iron-copper-nickel-cobalt(-platinum-chromium-titanium) deposits in layered mafic-ultramafic complexes
11. Manganese in Precambrian rocks
12. Marcasite-pyrite-hematite deposits of filled sinks
13. Residual brown iron ore deposits
14. Manganese deposits in sedimentary rocks and residuum
15. Copper deposits in sedimentary rocks
16. Base and precious metals in Precambrian veins
17. Massive sulfide deposits in Precambrian volcanic rocks

Finally, we recognize that there may always be "flukes." New variants of known types of mineral deposits, and indeed new types altogether, are still being discovered, and we do not presume that we can anticipate all such discoveries. But this would not justify the extreme conclusion that the entire area has a high potential for unknown types of deposits, or even the less extreme conclusion that, for example, all the Precambrian granites have a high potential for unusual types of gold-bearing quartz veins. Our objective in this investigation has been to consider all types of mineral deposits that could reasonably be expected to occur in the geologic environments that are known or inferred to exist in the area. On the basis of all the data available to us through September 1980, we believe that objective has been achieved.

Individual areal appraisals of the quadrangle for the various types of deposits are summarized in figure 16.

MISSISSIPPI VALLEY-TYPE BASE-METAL DEPOSITS IN THE BONNETERRE FORMATION AND LAMOTTE SANDSTONE

By

Walden P. Pratt, Ralph L. Erickson, Elwin L. Mosier, Sarah K. Odland, Marjorie S. Erickson, John G. Viets, Mary H. Miller, and Allen V. Heyl, U.S. Geological Survey, and Kenneth H. Anderson, James A. Martin, Ira R. Satterfield, Heyward M. Wharton, and Mark A. Middendorf, Missouri Geological Survey

Deposits of base-metal sulfides in carbonate host rocks, commonly referred to as "Mississippi Valley-type deposits," are economically the most important deposits known in the Rolla quadrangle, and have been the subject of intensive study by many geologists for many years. The Old Lead Belt (fig. 2B) produced some 8 million tons of lead during its long history (Weigel, 1965). The newer mines of the Viburnum Trend currently supply about 90 percent of the nation's lead as well as significant quantities of zinc (2nd rank in U.S. production), silver (5th rank), copper, and cadmium, and they contain notable resources of nickel and cobalt. The origin of these complex deposits is a subject of active controversy, which we do not address here. Our purpose, rather, is to present a descriptive (not genetic) model, summarizing what is now known about the essential features of these deposits and their relations to their host rocks. It is drawn mainly from Snyder (1968), Snyder and Gerdemann (1968), Gerdemann and Myers (1972), and Economic Geology (1977), supplemented by discussions with many geologists currently active in the area, and by our own ideas developed during our recent studies of the area.

Descriptive Model

Ore body

Size: Medium to large--n x 10 ft thick, n x 10^2 ft wide, n x 10^3 ft long.
Shape: Sinuous in plan, irregular multilevel stratiform in section.
Tonnage: Contains n x 10^7 tons of ore averaging about 6 percent lead, 1 percent zinc, and 0.3 percent copper, with smaller amounts of silver, cadmium, nickel, and cobalt.
Mineralogy: Dominantly galena > sphalerite, pyrite, and marcasite; minor chalcopyrite; very minor but collectively significant siegenite $[(CO_2Ni)_3S_4]$, polydymite (Ni_3S_4), bravoite $[(Fe,Ni)S_2]$, and vaesite (NiS_2); very minor arsenopyrite, bornite, covellite, djurleite ($Cu_{1.96}S$), and digenite; gangue minerals are dolomite, calcite, quartz, and dickite.
Depth: Known from near surface to 1,500 ft; could occur at any depth down to Precambrian basement.

Lithology of host rocks

1. Most deposits are in carbonate rocks:
   a. All carbonate-hosted deposits are in dolomite, none known in limestone.
   b. Deposits are near limestone-dolomite interface.

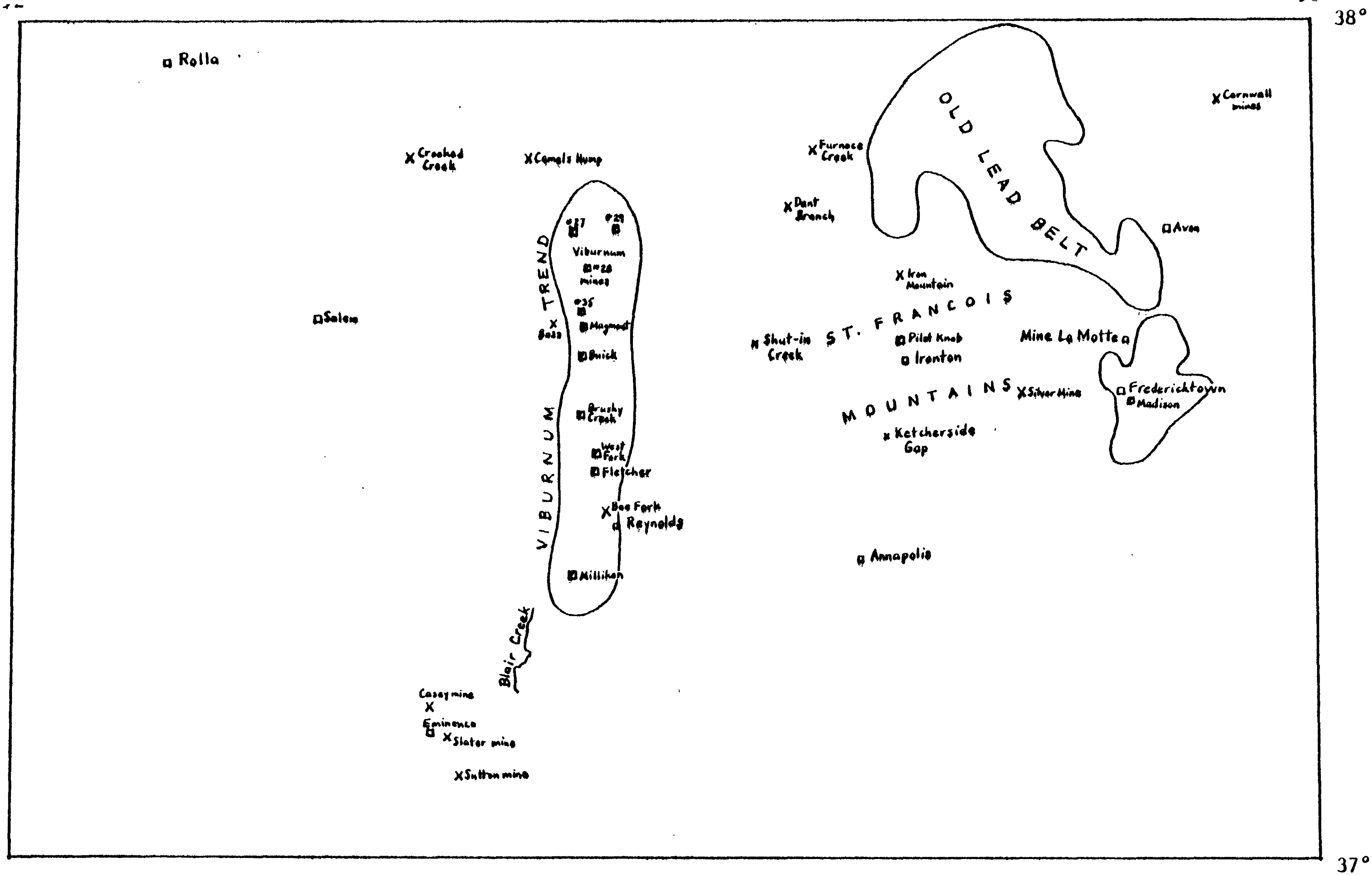


Fig. 2B.--Index map of Rolla 1° X 2° quadrangle showing localities mentioned in text

- ◩ Mine or deposit
- □ City or town
- x Other locality
- Outline of mining area

c. Deposits are in "brown rock" near "white rock" interface. ("Brown rock" is used here to mean finely crystalline brown dolomite containing iron oxides; "white rock" refers to coarsely recrystallized, white or very light gray, vuggy, illite-bearing dolomite.)
d. Deposits are near algal reefs; some within reefs.
e. Some of best ore is in solution-collapse breccias.
f. Most deposits in Bonneterre Formation occur where it is about 200-400 ft thick (Anderson, 1981).
g. Most deposits in Bonneterre Formation occur where its insoluble residue is >50 percent shale (Anderson, 1981).

2. Smaller deposits occur locally in Bonneterre-Lamotte sandy transition zone and in Lamotte Sandstone, nearly always in association with mineralization in the overlying Bonneterre Formation; other small deposits occur in dolomitic shale.
3. "Pinchout-type" deposits (no. 5 below) are not subject to the foregoing lithologic controls.

Controlling structures and other features

1. Deposits occur on the flanks of the Ozark uplift, in environments that were favorable for growth of reefs.
2. Faults, fractures, and joints were important controls because they facilitated fluid movement and hence development of solution-collapse breccias. Related fracturing has helped increase porosity and development of open spaces, favoring ore emplacement.
3. Major faults or steep flexures were also important because they may have influenced growth of reefs.
4. An impermeable (silty calcareous) shale facies of the Davis Formation is favorable because it served as a cap rock; coarse, recrystallized carbonate facies of the Davis is unfavorable.
5. "Pinchout-type" deposits are associated with pinchouts of the Lamotte Sandstone and lower Bonneterre Formation against Precambrian highs (knobs) in the subsurface, and may occur in a variety of rock types, including granite boulder beds (Snyder and Gerdemann, 1968, p. 335).
6. Deposits tend to be spatially related to small (10-15 mi in diameter), circular plutons of two-mica granite ("tin" granite) in the Precambrian basement (Kisvarsanyi, 1980b).

Geochemical and mineral indicators

Surface: None, except "halo" of anomalous metals and traces of visible galena if deposits are shallow.

Subsurface: Anomalously high amounts of base metals in insoluble residues of "barren" carbonate rocks outline the known mineralized trends. A combination of ≥100 AMF (anomalous metal feet) silver (Ag) and ≥300 AMF lead (Pb) is especially favorable (Erickson and others, 1978, 1979). (Anomalous metal feet is the ratio of reported metal content to a minimum anomalous content established by inspection of the data, multiplied by the thickness of the section, in feet, through which the anomalous content occurs. The minimum anomalous contents in these studies are 1 ppm (part per million) for Ag and 100 ppm for Pb. Thus a 10-foot sample containing 500 ppm Pb and 3 ppm Ag is reported as 50 AMF Pb and 30 AMF Ag. The AMF values are summed for each formation.)

Geophysical indicators

No direct indicators of mineralization known. Magnetic surveys have been used extensively as an indirect prospecting tool to delineate faults and especially to detect buried Precambrian knobs (Allingham, 1976).

Resource Appraisal

From the descriptive model above, we define 12 recognition criteria (see Introduction), 5 of which we consider diagnostic and 7 permissive. (NOTE: In this and other appraisal sections of this report, references following specific recognition criteria indicate only the sources of data used in map compilations for these appraisals. More general references are cited elsewhere.)

Diagnostic criteria and sources of data

1. In dolomite, near limestone-dolomite interface, defined as ls:dol = 1:16 (Kisvarsanyi, 1981; Thacker and Anderson, 1979a)
2. In "brown rock" near interface with "white rock" (Kisvarsanyi, 1981)
3. Near areas of faults and fractures in enclosing or underlying rocks (Pratt, 1981)
4. Near or within favorably situated digitate reef-complex facies (Kisvarsanyi, 1981)
5. Near areas of anomalously high amounts of base metals--at least 1,400 AMF--in insoluble residues of "barren" Bonneterre Formation (Erickson and others, 1978, 1979). In Annapolis area, defined by at least 500 AMF in Bonneterre Formation.

Permissive criteria and sources of data

1. Deposit or occurrence of base-metal minerals is known to be present in subject formation or in overlying formations (fig. 5)
2. Davis Formation is an impermeable shale facies, defined as having clastic:carbonate ratio $\geq$1:16 (Thacker and Anderson, 1979b)
3. Subsurface Precambrian knobs are known to be present (Kisvarsanyi, 1979)
4. Lamotte Sandstone thins or pinches out (Thacker and Anderson, 1979c)
5. Bonneterre Formation is 200-400 ft thick (Thacker and Anderson, 1979c)
6. Insoluble residue of Bonneterre Formation is >50 percent shale (Thacker and Anderson, 1979d)
7. Small, circular pluton of "tin" granite is present in basement (Kisvarsanyi, 1980b)

Using the sources indicated, we plotted the areal distribution of each of these criteria on three separate maps, one map for diagnostic and two maps for permissive criteria (figs. 3, 4, and 5, respectively). Areas of outcropping Precambrian rocks can be eliminated as having no potential because the Bonneterre and Lamotte formations are absent. The extreme northeast, southeast, and southwest parts of the quadrangle cannot be appraised at this time because the Cambrian rocks are deeply buried in these areas and no drill-hole data are available; a potential exists because the Bonneterre and Lamotte formations are assumed to be present, but whether the potential is high or low cannot be determined from available data. The remainder of the quadrangle was divided into 16 numbered areas (fig. 6) in which various combinations of diagnostic criteria are known or suspected to be present on the basis of available data. As a means of assigning an objective "score" to each of these areas in order to compare their relative favorability, we listed the areas in tabular form, along with columns for the various diagnostic and permissive criteria (table 1). For each area, the widespread presence of a criterion is assigned a value of 1, the known absence is given a value of -1, and a lack of sufficient information to determine the presence or absence of the criterion is indicated by 0; presence of the criterion in only part of the area is given a value of 1/2. The scores for each area are then summed, and the summed scores indicating relative favorability are shown in the final columns under diagnostic and permissive criteria. The two sums must be considered separately because by definition, the presence of permissive criteria enhances the favorability for mineral deposits only if diagnostic criteria are also present, whereas the absence of permissive criteria does not lessen the favorability if diagnostic criteria are present.

Our subjective interpretation of the resource potential indicated by these quasi-objective scores is as follows:

Large known deposits: areas 1, 2, 3
Very high potential: areas 4*, 6*, 9*
High potential: area 3
Low potential: areas 5, 7*, 8*, 10, 11, 12*, 13, 14, 15*, 16
Insufficient data: areas indicated on map

*Appraisal of these areas could change on the basis of additional data regarding presence or absence of certain criteria indicated by 0 in table 1.

The meaning of these evaluations can be better expressed qualitatively than quantitatively or statistically. Qualitatively, we believe the available data indicate that areas 4, 6, and 9 should have top priority as prospective areas for concealed base-metal deposits in the Bonneterre and Lamotte formations. That is to say, we believe the combination of recognition criteria is so compelling as to indicate a very high probability that at least one significant ore deposit comparable to the descriptive model occurs in each of these three areas.

A semiquantitative estimate of the number and size of these potential deposits should be useful as a basis for comparing the potential mineral-resource values of the areas with potential values for other types of land use. We present such an estimate herewith (table 2), based on the following reasoning:

1. Each area (4, 6, and 9 on fig. 6) is believed to contain at least one deposit, to which we assign a subjective probability of 90 percent to express our unanimous belief in the very high probability of occurrence (many of us would feel equally comfortable with a figure of 95 percent).
2. We believe there is also a probability that each area contains more than one deposit, and the 10 percent probability expresses our belief that the maximum number of deposits indicated is theoretically possible but realistically unlikely. This maximum number of possible deposits in each area is proportional to the size of the area, based on the assumption that the density of deposits in the prospective areas would be the same as in

Table 1.--Resource potential for Mississippi Valley-type base-metal deposits[1] in Bonneterre Formation and Lamotte Sandstone, September 1980

Map area no. (fig. 6)	Size of deposit (in short tons)	Recognition criteria: Diagnostic: In dolomite near ls.-dol. interface	Diagnostic: In "brown rock" near "white rock" interface	Diagnostic: Faults and fractures	Diagnostic: Algal reef rocks	Diagnostic: Anomalous base metals in insoluble residues	Diagnostic: SUM	Permissive: Mineral deposit or occurrence	Permissive: Davis Fm. is shaly (clastic: carbonate ≥ 1:16)	Permissive: Subsurface Precambrian knobs	Permissive: Lamotte Ss. thins or pinches out	Permissive: Bonneterre Fm. 200-400 ft thick	Permissive: Bonneterre residue >50% shale	Permissive: "Tin" granite pluton	Permissive: SUM	Estimated depth of burial (ft)	Subjective probability of occurrence (*see text p. 14-16)	Remarks
1	$325x10^6$	1	1	1	1	1	5	1	1	1	1/2	1	1	1	6 1/2	800-1200	Known deposits in Viburnum Trend	Fully explored-new deposits unlikely
2	$300x10^6$	1	1/2	1	1	1	4 1/2	1	1	1	1/2	1	1	1	6 1/2	0-400	Known deposits in Old Lead Belt	Do.
3	Large ($nx10^7$)	1	-1	1	0	1	2	1	0	1	1/2	1	1	1	5 1/2	500-800	High	Known deposit at Annapolis
4	do	1/2	0	1	0	1	2 1/2	1	1	1	1/2	1	1	1	6 1/2	600-1200	Very high*	
5	do	-1	N.A.	1/2	0	1	1/2	1	1	1/2	0	1	1	1	5 1/2	600-1200	Low	
6	do	1	0	1	0	1	3	0	1	1	1/2	1/2	1	1	5	1300-2200	Very high*	
7	do	1	0	1	0	-1	1	0	1	1	1	1/2	1	-1	3 1/2	1200-1500	Low*	
8	do	-1	N.A.	-1	0	0	-2	0	1	-1	-1	1	1	-1	0	1500-1700	Low*	
9	do	1	0	1	0	1	3	1/2	1/2	1	1	1/2	1	1/2	5	400-1500	Very high*	
10	do	1	-1	1/2	0	-1	- 1/2	0	1	1	1	1	1	1	6	400-1200	Low	
11	do	1	-1	1	0	-1	0	0	1	1	1	1/2	1	1	5 1/2	700-1200	Low	
12	do	1	0	1	0	0	2	1/2	1/2	-1	-1	1	1/2	1	1 1/2	0-400	Low*	
13	Moderate ($nx10^5$)	N.A.	N.A.	1/2	N.A.	1/2	1	0	0	1/2	N.A.	0	0	1	1 1/2	0-300	Low	In Lamotte Ss. outcrop area
14	Large	-1	N.A.	1	1/2	0	1/2	1/2	1	-1	-1	- 1/2	0	-1	-2 1/2	200-1500	Low	
15	do	-1	N.A.	0	0	1	0	0	1	1	1	1/2	1/2	-1	3	~1200	Low*	
16	do	-1	N.A.	1	0	-1	-1	1/2	1	1/2	-1	1	1/2	1/2	3	700-1600	Low	

[1]Mineral commodities include: lead, zinc, silver, copper, nickel, cobalt.

Table 2.--Estimates of ore "deposits" in selected areas in the Rolla $1^{o}x2^{o}$ quadrangle, Missouri

Area No. on fig. 6	Planimetric area on fig. 6 (sq mi)	Ratio to size of model area	Probabilities (in percent) and estimated number of "deposits"		Average model tonnage, in millions of short tons, and grade of each "deposit." All grades in percent except Ag.						
						Grade					
					Tonnage	Pb	Zn	Cu[1]	Ni[1]	Co[1]	Ag
1 (Viburnum Trend)	245.5	100%	100	12	20	5.9	1.1	0.3	0.02	0.015	0.25 oz/t
					("Average Viburnum Trend deposit")						
2 (Old Lead Belt-Mine La Motte)	397.8	100%	100	20	15	2.7	.16	.69	.29	.23	.031 oz/t
					(Mine La Motte deposit)						
4[2]	210.6	86% of area 1	90	1	16	2.46	.096	.11	.02	.015	.058 oz/t
			10	10	(Indian Creek deposit)						
6	168.6	69% of area 1	90	1	20	5.9	1.1	.3	.02	.015	.25 oz/t
			10	8	("Average Viburnum Trend deposit")						
9	344.5	87% of area 2	90	1	10	2.7	.16	.69	.29	.23	.031 oz/t
			10	17	(Mine La Motte deposit)						

[1]These estimates, which are based in part on grade of ores mined, are probably somewhat low because copper-, nickel-, and cobalt-rich portions of ore bodies commonly have been left unmined or only partly mined owing to subsequent beneficiation problems (Cornwall and Vhay, 1967; Kinkel, 1967).

[2]The estimated number of deposits in area 4 must be modified by the fact that this area is well known to have been intensely explored in the past, and no discoveries of large ore deposits have been announced. The 90 percent probability, however, expresses accurately our belief that there is a very high probability that at least one significant deposit occurs in this area.

the model areas. (The definition of what constitutes a single deposit must be arbitrary, because of the near-continuity of both mineralization and mine workings in the Viburnum Trend and especially in the Old Lead Belt. For the Viburnum Trend we use the present number of individually identified mines or deposits--twelve[7]. For the Old Lead Belt-Mine

---

[7] Viburnum Nos. 27, 28, 29, 35, Magmont, Buick, Brushy Creek, West Fork, Fletcher, Milliken, and two additional reported but unopened deposits, one west of Reynolds and the second along Blair Creek (Wharton, 1969, p. 66).

La Motte area, we arbitrarily divide the approximate tonnage of ore produced at Mine La Motte, 15 million tons, into the approximately 300 million tons of ore production plus reserves in the Old Lead Belt (Weigel, 1965), giving a purely theoretical number of 20 individual "deposits" in the Old Lead Belt.) The planimetric sizes of the various areas were measured on figure 6.

3. We assume that these deposits would be similar in most respects to the descriptive model, and the estimated size and grade of prospective deposits in each area would be most similar to the size and grade of known deposits nearby. Specifically:
   (a) The model for prospective deposits in area 4 is the Indian Creek deposit, which lies just north of the Rolla quadrangle but is considered a part of the Southeast Missouri district. The size of this deposit is estimated as 16 million tons of ore, on the basis of production of 13.5 million tons during 1954-1979 and an estimated 5 years of production remaining (production figures through 1979 supplied by St. Joe Minerals Corp.). Average grades for lead, zinc, copper, and silver calculated from figures supplied by St. Joe Minerals Corp.; grades for nickel and cobalt from "average Viburnum Trend deposit" (see below).
   (b) The model for prospective deposits in area 6 is an "average Viburnum Trend deposit" of 20 million tons of ore, as estimated by the Missouri Geological Survey; average metal grades are those cited by Clifford and Higley (1978, p. 2), except average grade for silver which was calculated by H. M. Wharton from production figures published annually by the U.S. Bureau of Mines.
   (c) The model for prospective deposits in area 9 is the Mine La Motte deposit, which had total production of approximately 15 million tons of ore (Paul Gerdemann, St. Joe Minerals Corp., written commun., 1975). The grade of 2.7 percent Pb was calculated from the tonnages of lead and ore actually produced during 1925-1959. Other metal grades from Mine La Motte are unavailable. The grades for copper, nickel, and cobalt represent an average ore from deposits near Fredericktown (Kiilsgaard and others, 1967, p. 51), and the grades for zinc and silver are calculated from metal ratios estimated by Snyder and Gerdemann (1968, p. 349) applied to the average grade of 2.7 percent Pb.
   (d) Cadmium has been reported as a byproduct of the Southeast Missouri ores (Guild, 1967), but is not included in these estimates because specific data on its content are not available.

Table 2, then, contains our semiquantitative estimate of the resource potential for base-metal deposits in the Bonneterre Formation and Lamotte Sandstone in the three areas we consider to have a very high potential. It should be obvious that these estimated tonnages and grades for undiscovered deposits must be used with considerable discretion; they in no way represent known reserves, but are only an attempt to assign realistic orders of magnitude to hypothetical resources (as defined by U.S. Bureau of Mines and U.S. Geological Survey, 1980), based on probable similarities to comparable known deposits. Although each model used here could probably be refined to some degree, we doubt that such refinements would affect the order of magnitude of any of the resulting estimates.

Finally, we believe this appraisal of resource potential will achieve its maximum usefulness only if we express it in terms in which it can be directly compared with potential values for other types of land use--i.e., dollars. Subject to all the foregoing assumptions and qualifications, we have calculated the approximate amounts and values of metals in the ground that might reasonably be expected to exist in these deposits (table 3). Tonnage and grade data are from table 2; unit prices are average spot prices as of September 30, 1980, as reported in the Wall Street Journal of October 1, 1980, p. 38, except for cobalt, which was taken from the London Mining Journal of October 3, 1980.

The total estimated value of more than 3 billion dollars, which includes the unrecoverable as well as the recoverable portion of the potential resource, is based on such a sequence of cumulative assumptions that it has little meaning except as to its order of magnitude. We do believe it is highly significant that we can reasonably assign to the minimum likely potential resources in these three areas a value measurable in the billions of dollars. Also of special significance is the order of magnitude for the total weight of cobalt, because it represents 2-3 years' domestic consumption of a critical material of which the United States currently imports about 90 percent of its needs. Indeed at the time of this writing, the Madison mine at Fredericktown is being dewatered in preparation for reopening to exploit its remaining cobalt-nickel reserves.

Table 3.--Estimated amounts and values of metals in potential ore "deposits" in selected areas of the Rolla $1^{o}x2^{o}$ quadrangle, Missouri

[Grades in percent, except silver, which is in oz/t]

Conservative estimates, based on minimum expected size of deposit									
	Area 4: 5,000,000 short tons ore		Area 6: 15,000,000 short tons ore		Area 9: 5,000,000 short tons ore				
Metal	Grade	Wt. metal	Grade	Wt. metal	Grade	Wt. metal	Total wt. metal	Unit price	Value, $ millions
Pb	2.46	123,000 s.t.	5.9	885,000 s.t.	2.7	135,000 s.t.	1,143,000 s.t.	$ .435/lb	$ 994.4
Zn	.096	4,800 s.t.	1.1	165,000 s.t.	.16	8,000 s.t.	177,800 s.t.	.3775/lb	134.2
Cu	.11	5,500 s.t.	.3	45,000 s.t.	.69	34,500 s.t.	85,000 s.t.	.96/lb	163.2
Ni	.02	2,000,000 lbs	.02	6,000,000 lbs	.29	29,000,000 lbs	37,000,000 lbs	3.50/lb	129.5
Co	.015	1,500,000 lbs	.015	4,500,000 lbs	.23	23,000,000 lbs	29,000,000 lbs	25.00/lb	725.0
Ag	.058	290,000 oz	.25	3,750,000 oz	.031	155,000 oz	4,195,000 oz	20.40/oz	85.6
								Total value	$2,231.9

Realistic estimates, based on inferred probable size of deposit									
	Area 4: 10,000,000 short tons ore		Area 6: 20,000,000 short tons ore		Area 9: 10,000,000 short tons ore				
Metal	Grade	Wt. metal	Grade	Wt. metal	Grade	Wt. metal	Total wt. metal	Unit price	Value, $ millions
Pb	2.46	246,000 s.t.	5.9	1,180,000 s.t.	2.7	270,000 s.t.	1,696,000 s.t.	$ .435/lb	$1,475.5
Zn	.096	9,600 s.t.	1.1	220,000 s.t.	.16	16,000 s.t.	245,600 s.t.	.3775/lb	185.4
Cu	.11	11,000 s.t.	.3	60,000 s.t.	.69	69,000 s.t.	140,000 s.t.	.96/lb	268.8
Ni	.02	4,000,000 lbs	.02	8,000,000 lbs	.29	58,000,000 lbs	70,000,000 lbs	3.50/lb	245.0
Co	.015	3,000,000 lbs	.015	6,000,000 lbs	.23	46,000,000 lbs	55,000,000 lbs	25.00/lb	1,375.0
Ag	.058	580,000 oz	.25	5,000,000 oz	.031	310,000 oz	5,890,000 oz	20.40/oz	120.2
								Total value	$3,669.9

MISSISSIPPI VALLEY-TYPE DEPOSITS IN CAMBRIAN AND ORDOVICIAN FORMATIONS OVERLYING THE BONNETERRE FORMATION

By Ralph L. Erickson, Elwin L. Mosier, Marjorie S. Erickson, Sarah K. Odland, and John G. Viets

This descriptive category of deposits includes the bedrock barite-lead-zinc deposits of the Washington County and Central Missouri districts, which are historically important, as well as barite-poor base-metal deposits of the Viburnum type that might occur in post-Bonneterre formations.

Descriptive Model

Reference: Snyder, 1968

Ore body

Size: Small--n ft thick, n x 10 ft wide and long.
Shape: Varies from circular in plan (in solution collapse structures) to narrow fissure vein systems in highly fractured rocks.
Tonnage: Estimated to be a few thousand tons of ore, grade unknown.
Mineralogy: Galena, sphalerite, and chalcopyrite; barite is a major ore mineral in some deposits. Anomalous amounts of cadmium, nickel, cobalt, silver, and germanium are commonly present in the sulfide minerals. Chief gangue minerals are calcite and quartz or jasperoid (hydrothermal silica).

Lithology of host rocks

1. Ores occur in dolomite; none are known in limestone.
2. In Cambrian rocks:
    a. Chiefly in the Potosi and Eminence Dolomites; most ore occurs within a 100-ft-thick zone that includes upper part of Potosi and lower part of Eminence.
    b. Small amounts of ore occur in Davis Formation where the formation overlies ore in Bonneterre Formation.
3. In Ordovician rocks, ores occur chiefly in Jefferson City Dolomite, but are known also in Gasconade and Roubidoux Formations.

Controlling structures and other features

1. Ground prepared by minor faults and fractures; ore does not occur on major faults.
2. Ground prepared by groundwater dissolution and subsidence.

Geochemical indicators

Surface: If deposits are shallow, anomalously high zinc, lead, and barium in stream sediments and soils, and anomalously high zinc in surface and groundwaters.
Subsurface: If deposits are deeply buried, anomalously high amounts of zinc, lead, and barium and lesser (but anomalous) amounts of copper, silver, cadmium, and molybdenum in insoluble residues of "barren" carbonate rocks.

Resource Appraisal

Diagnostic criteria and sources of data

1. In dolomite of post-Bonneterre formations (Thacker and Anderson, 1979e)
2. Near areas of faults and fractures in enclosing or underlying rocks (Pratt, 1981)
3. Near areas of anomalously high amounts of base metals in insoluble residues (Erickson and others, 1978)

Permissive criteria and sources of data

1. Deposit or occurrence known to be present (M. H. Miller, U.S. Geol. Survey, unpub. data)
2. Anomalous base metals in stream sediments (P. D. Proctor, U.S. Geol. Survey, unpub. data)

The resource appraisal was made in the same way as that for the base-metal deposits in the Bonneterre Formation and Lamotte Sandstone. Distribution of the recognition criteria is shown on figure 7 and resource potential on figure 8. The data for each map area are summarized in table 4. We conclude that areas 1, 2, 3, and 6 have a very high potential for small deposits of this type.

Table 4.--Resource potential for Mississippi Valley-type base-metal and barite deposits in Cambrian and Ordovician formations overlying the Bonneterre Formation as of September 1980

[Mineral commodities: lead, zinc, barite]

Map Area No. (fig. 8)	Size of deposit	Recognition criteria								Estimated depth of burial (ft)	Subjective probability of occurrence
		Diagnostic				Permissive					
		Faults and fractures	Anomalous base metals in insoluble residues	In dolomite	SUM	Mineral deposit or occurrence	Upper Potosi-Lower Eminence and (or) Jefferson City Dolomite present	Anomalous base metals in stream sediments	SUM		
1	Small	1	1/2	1	2 1/2	1	1	1	3	0-1100	Very high
2	do	1	1/2	1	2 1/2	1	1	-1	1	0-1000	Very high
3	do	1	1/2	1	2 1/2	1	1 1/2	-1	1 1/2	0-1300	Very high
4	do	0	1	1	2	0	1	-1	0	0-1200	High
5	do	1/2	-1	1	1/2	0	-2	1/2	-1 1/2	0-900	Low
6	do	1	1/2	1	2 1/2	0	1	-1	0	0-1300	Very high
7	do	0	- 1/2	1	1/2	0	1 1/2	-1	1/2	0-1300	Low
8	do	- 1/2	-1	1	- 1/2	0	1	-1	0	0-1400	Low
9	do	1	1/2	1/2	2	0	1 1/2	1	2 1/2	0-1400	High
10	do	1	-1	1	1	0	2	-1	1	0-1600	Low
11	do	1/2	- 1/2	1	1	0	1	-1	0	0-1300	Low
12	do	1	1/2	1	2 1/2	0	2	-1	1	0-1600	High

BARITE DEPOSITS IN RESIDUUM DERIVED FROM VEIN AND REPLACEMENT DEPOSITS IN PALEOZOIC ROCKS

By Heyward M. Wharton, Walden P. Pratt, and Sarah K. Odland

Descriptive Model

References: Brobst and Wagner, 1967; Muilenburg, 1954, 1957; Uhley and Scharon, 1954; Wagner, 1973; Wharton, 1972; Wharton and others, 1969, p. 1-8.

Ore body

Size: A few acres to more than 1,500 acres in area; up to 50 ft thick, average about 10 ft.
Mode of occurrence: Barite fragments, mostly 1/2-6 in. long, in clayey residuum.
Tonnage: n x 10^6 tons of ore.
Minimum grade (September 1980): 75-100 lbs barite per cu yd residuum.
Mineralogy: Barite, commonly accompanied by galena, marcasite, sphalerite. Marcasite may be completely altered to limonite. Gangue minerals are red clay (kaolinite and illite), quartz druse, chert, and dolomite.
Depth: Surface to top of bedrock, generally less than 200 ft.

Lithology of host rocks

1. Principal host is residuum derived from the upper half of the Potosi Dolomite or the lower two-thirds of the Eminence Dolomite. Minor production has also been reported in residuum developed from the Gasconade, Roubidoux, and Jefferson City formations, and in isolated cases, from the Bonneterre, Davis, and Derby-Doerun formations.
2. Some decomposed bedrock zones at the base of the residual ore occurrences have been sufficiently rich in barite and soft enough to mine profitably with conventional equipment. Bedrock barite resources are considered separately under "Mississippi Valley-type deposits in Cambrian and Ordovician formations overlying the Bonneterre Formation."

Structural controls

1. Principal controls are highly permeable zones related to fractures and voids in bedrock and porous algal reef (digitate stromatolite) structures.
2. The main producing areas are bounded by the major Palmer, Big River, and Vineland-Valles Mines fault systems (see fig. 9). Faulting within this block has probably increased the permeability of host rocks for penetration of the ore-forming fluids.

Geochemical indicators: Barite occurrences in insoluble residues of carbonate rocks from holes drilled for water wells and mineral tests; barite in panned concentrates of stream sediments.

Geophysical indicators: Positive gravity anomalies in very detailed surveys.

Resource Appraisal

Diagnostic criteria and sources of data

1. Outcrop area of Potosi Dolomite or lower part of Eminence Dolomite, or, of lesser importance, outcrop areas of Bonneterre, Davis, and Lower Ordovician (Canadian) formations (W. P. Pratt, U.S. Geol. Survey, unpub. data).
2. Proximity to major and minor faults within a major fault block (Pratt, 1981).
3. Anomalous Ba (≥100 ppm) in insoluble residues of uppermost 300 ft of drill holes (S. K. Odland, U.S. Geol. Survey, unpub. data).

Permissive criteria and sources of data

1. Barite deposit or occurrence at surface (Missouri Geological Survey, unpub. data).
2. Reported barite occurrence in drill-hole samples (Missouri Geological Survey, unpub. data).

The distribution of all recognition criteria is shown on figure 9, except for the outcrop areas of formations of secondary importance (Bonneterre, Davis, and Lower Ordovician formations), which would include nearly all of the area not shown as Potosi, lower Eminence, or pre-Bonneterre. Areas of outcropping Precambrian rocks and Lamotte Sandstone are eliminated as having no potential for residual barite deposits.

Potential Resource Area 1 contains remaining reserves of residual barite estimated at 2 million tons; an additional estimated 0.75 million tons is believed to be present in tailings ponds. The area probably has a high potential for additional undiscovered small deposits, but much of the area has already been thoroughly prospected.

Potential Resource Area 2 contains reported but unverified occurrences of barite in the Potosi-Eminence outcrop area and anomalous barium in insoluble residues of two drill holes. If the reported surface occurrences can be verified, the area should warrant further study by panning stream sediments to determine the extent of barite occurrences. The barite occurrences lie between the Black fault to the northeast and the Ellington fault to the southwest, which may define a structural block in the sense of diagnostic criterion #2. The extent of possible minor faulting within this area is unknown. Any major deposits of residual barite within this area probably would have been penetrated by one or more of the many holes that were drilled during exploration for deeper base-metal deposits. Therefore any potential that exists would likely be for smaller deposits only.

Potential Resource Areas 3 and 4 contain anomalous barium in insoluble residues of several drill holes in the Potosi-Eminence outcrop area. Like area 2, these areas are in potentially favorable structural settings but have been intensely explored by deep drilling, and therefore may have some potential for small deposits only.

The remainder of the Potosi-Eminence outcrop area and the remainder of the outcrop areas of the Bonneterre, Davis, and Lower Ordovician formations theoretically have a potential for residual barite deposits (Brobst, 1967). However, the absence of barite occurrences or anomalous barium in insoluble residues in structurally favorable areas, in view of the extensive drilling that has been done in many of these areas, leads us to conclude that the potential for large (significant) barite deposits outside area 1 is low. It is of interest to note that there are no major verified barite occurrences any appreciable distance south of the Palmer fault.

KIRUNA-TYPE IRON-APATITE-(COPPER) DEPOSITS

By Eva B. Kisvarsanyi, Missouri Geological Survey

Known deposits of this type include the Iron Mountain, Pilot Knob, Camels Hump, and Boss deposits in the Rolla quadrangle, and the Pea Ridge deposit located about 8 mi (12 km) north of the quadrangle in Washington County. Several of these magmatic-hydrothermal and contact metasomatic, nontitaniferous iron-ore deposits in the region have been important producers in the past, but at the time of this writing only the Pea Ridge and Pilot Knob mines are active, and the latter is about to be permanently shut down. The Iron Mountain deposit was depleted and the mine closed in 1966. The Camels Hump and Boss deposits have been extensively drilled but have not yet been exploited; the copper mineralization is the main interest in the Boss deposit. Total production from the various mines amounts to more than 42 million tons of ore and high-grade pellets; apatite is recovered for phosphate fertilizer manufacture.

Descriptive Model

References: Kisvarsanyi, 1966, 1976; Snyder, 1969; Wracher, 1976

Ore body

Size: Small (n x 10 ft thick, n x 10^2 ft wide, n x 10^2 ft long) to large (n x 10^3 ft thick, n x 10^3 ft wide, n x 10^3 ft long).
Shape: Tabular, cone sheet, dike, vein, irregular.
Tonnage: Up to n x 10^8 tons of ore in the larger deposits.
Grade: 30 percent to 60 percent Fe, ~1 percent Cu (in one deposit); a byproduct of mining is rare-earth-bearing phosphates (monazite), 2.5 percent P_2O_5 (in tailings).
Mineralogy: Dominantly magnetite and hematite, with chalcopyrite and bornite (in the Boss deposit); minor galena, sphalerite, molybdenite, chalcopyrite, bornite, chalcocite, pyrite. Gangue: Apatite, monazite, fluorite, barite, pyroxenes, actinolite, crocidolite, biotite, garnet, quartz, calcite, dolomite, sphene, tourmaline, (chlorite, epidote, sericite).
Depth: Near surface to 4,000 ft; could be at any depth in the buried basement rocks.
Mode of occurrence: Massive, fracture- and breccia-filling, disseminated, replacement, discordant or conformable, stratiform in bedded tuffs, residual in basal Paleozoic conglomerate.

Host rocks

Age: Precambrian, about 1.5 b.y. (St. Francois terrane)
Lithology: Intermediate to high-silica volcanic rocks (trachyandesite, trachyte, rhyolite); flows, ash-flow tuffs, bedded air-fall tuffs; syenite; granite (at one locality).
Wall-rock alteration: Generally little or none.
Associated dikes: Alkalic-intermediate, aplitic, and pegmatitic.

Controlling structures and other features

1. Most major deposits are within, or near margins of, inferred cauldron subsidence structures (Kisvarsanyi, 1980b).
2. Some deposits are located on major faults and fracture zones (Kisvarsanyi, 1979).
3. Volcanic and tectonic breccias and permeable tuffs are favorable hosts for open-space filling and disseminated deposits.
4. Ore tends to be associated with distinctive magnetite-trachytes (containing as much as 20 percent by volume of primary disseminated magnetite) and alkalic-intermediate dike rocks.
5. Most known deposits are associated with erosional highs on the Precambrian surface.
6. Post-ore faults and mafic intrusions may offset ore bodies.

Geochemical parameters

1. Ferride-element geochemistry of the deposits is characterized by vanadium and cobalt enrichments and by titanium, chromium, and nickel depletion.
2. High phosphorus, sulfur, fluorine, carbon dioxide, copper, and molybdenum is characteristic in some deposits.
3. Alkali-metal enrichments are characteristic in most deposits.

(See also Trace-element Geochemistry, below)

Geophysical indicators

1. High-amplitude positive magnetic anomalies are associated with the magnetite-dominant deposits.
2. Positive magnetic anomalies are also associated with magnetite-trachytes, and with mafic plutons several orders of magnitude larger than the iron deposits.
3. Buried deposits consisting dominantly of hematite may not be detected from magnetic maps.

Resource Appraisal

Diagnostic criteria and sources of data

1. Magnetite, hematite, and (or) chalcopyrite in seams, veins, or as disseminations (Crane, 1912; Kisvarsanyi, 1975)
2. Precambrian silicic volcanic rocks (Pratt and others, 1979; Kisvarsanyi, 1980b)

3-4. Magnetite-trachytes and (or) alkalic-intermediate rocks (Kisvarsanyi, 1980b)

5. High-amplitude positive magnetic anomaly (U.S. Geological Survey, 1978, 1979)
6. Within or near cauldron subsidence structure (Kisvarsanyi, 1980b)

Permissive criteria and sources of data

1. Recognition of characteristic gangue minerals in drill cores (Kisvarsanyi, 1975)
2. Near Precambrian high (Kisvarsanyi, 1979)
3. On or near Precambrian faults or fractures (Kisvarsanyi, 1979)

Using the sources indicated, we plotted these criteria on one map (fig. 10) as follows:

1. Locations of active and inactive mines and prospects
2. Locations of drill holes which penetrate mineralized rock or a diagnostic rock of the descriptive model (i.e., magnetite-trachyte)
3. Areal distribution of silicic volcanic rocks (surface and subsurface)
4. Areal distribution of trachytic rocks (surface and subsurface)
5. Major fault zones and inferred cauldron subsidence structures
6. Outlines of high-amplitude positive magnetic anomalies

Areas where two or more of the diagnostic criteria coincide have been arbitrarily blocked out as being favorable for the occurrence of deposits of the model type. They are numbered from 1 through 18 (fig. 11 and table 5). (Area No. 19 corresponds to the Avon magnetic anomaly discussed under the ore deposit model for layered intrusives.) The "scoring" within each area is as follows:

presence of a criterion:	+1
absence of a criterion:	-1
insufficient data:	0

As most of the criteria are present only within part (and often a very small part) of any given area, 1/2 values were not used. Our subjective interpretation of the resource potential indicated by the scores is as follows:

Large known deposits:	areas 1, 2, 3, 4
Very high potential for large to moderate-size deposits:	areas 5, 6, 7
High potential for moderate to small-size deposits:	areas 8, 9, 10, 14, 15, 16, 17*, 18*
Low potential for new discoveries of magnetite-dominant deposits:	areas 11, 12, 13

*In these areas, although the sum of diagnostic criteria amounts to only 1, neither the presence nor the absence of 6 criteria can be verified from the available data. We consider these areas more favorable than 11, 12, and 13 on the strength of favorable magnetic patterns and the recognitin of 4 diagnostic criteria in the adjacent area 5.

Table 5.--Resource potential for Kiruna-type iron-apatite-(copper) deposits--September 1980

[Mineral commodities: iron, phosphorus, rare earths, copper]

Map area no. (fig. 10)	Size of deposit	Recognition criteria: Diagnostic: Iron and copper minerals	Silicic volcanic rocks	Magnetite-trachytes	Other alkalic-intermediate dikes/stocks	Positive magnetic anomaly	Cauldron-subsidence structure	Sum	Recognition criteria: Permissive: Gangue minerals	Precambrian high	pC faults and fractures	Sum	Estimated depth of burial (ft)	Subjective probability of occurrence	Remarks
1	Large	+1	+1	+1	+1	+1	+1	6	+1	+1	+1	3	0-1500	Known deposits	Pilot Knob (surface and subsurface). Iron Mountain, several small surface deposits mined in the past.
2	Large	+1	+1	+1	+1	+1	+1	6	+1	+1	+1	3	0-2500	Known deposit	Pea Ridge is north of the area; Floyd Tower is outcrop. Probable deposits on the trachytic ring.
3	Large	+1	+1	+1	+1	+1	+1	6	+1	+1	+1	3	900-2000	Known deposit	Boss iron-copper deposit.
4	Large	+1	0	+1	0	+1	+1	4	+1	+1	+1	3	1200-1500	Known deposit	Camels Hump.
5	Large	+1	0	+1	+1	+1	0	4	+1	+1	0	2	1300+	Very high	Lake Spring anomaly.
6	Moderate	+1	+1	+1	0	+1	0	4	+1	+1	0	2	1200+	Very high	Missionary Ridge.
7	Moderate	+1	0	+1	0	+1	0	3	+1	+1	+1	3	800+	Very high	De Soto area.
8	Small	+1	+1	+1	0	+1	+1	5	0	+1	+1	2	0-1000	High	Crane Mountain-Blue School area, not explored; 5 million tons of low-grade ore in tuffs (Weixelman, 1958).
9	Small	+1	+1	+1	0	+1	0	4	0	+1	0	1	0-1000	High	Not fully explored.
10	Moderate	0	+1	+1	0	+1	+1	4	0	+1	+1	2	0-1000	High	Not fully explored.
11	Small	+1	+1	-1	-1	-1	+1	0	+1	-1	0	0	0-500	Known deposits	Several small surface deposits mined in the past.
12	Small	+1	+1	-1	-1	+1	-1	0	-1	+1	+1	1	0-500	Known deposits	Small surface deposits, residual boulder ore.
13	Small	+1	-1	-1	0	-1	-1	-3	-1	-1	+1	-1	0-500	Known deposit	Greasy Mine, the only Fe deposit in granite. It is near the Roselle lineament.
14	Moderate	+1	+1	0	0	-1	+1	2	0	+1	+1	2	0-1500	High	Major volcano-tectonic feature, not fully explored. Associated manganese mineralization; residual copper.
15	Small	0	+1	0	0	+1	+1	3	0	+1	+1	2	0-1000	High	Partial ring intrusion, insufficiently known.
16	Small	+1	+1	0	0	+1	+1	4	+1	+1	+1	3	0-1500	High	Not fully explored, favorable structural setting.
17	Moderate	0	0	0	0	+1	0	1	0	+1	0	1	1500+	High	Favorable magnetic patterns, not explored.
18	Moderate	0	0	0	0	+1	0	1	0	+1	0	1	1000+	High	Salem anomaly; favorable magnetic patterns associated with gravity anomaly.

Area No. 18 coincides with the Salem gravity anomaly discussed under the ore deposit model for layered intrusives. However, the combined magnetic pattern of areas Nos. 5, 17, and 18 is similar to that associated with volcanic terranes in the St. Francois Mountains. Area No. 18 therefore has a potential for both Kiruna-type deposits in shallow volcanic rocks of the St. Francois terrane, and for deep ore bodies of the layered model.

The potential for Kiruna-type deposits in the rest of the quadrangle is considered to be very low. Areas underlain by granite are the least favorable; those underlain by silicic volcanic rocks are somewhat more favorable. The latter may contain deposits consisting wholly of hematite.

Trace-Element Geochemistry

By Ralph L. Erickson and Elwin L. Mosier

The Pilot Knob, Iron Mountain, and Pea Ridge deposits were visited and sampled during the course of this study to determine the distribution and abundance of trace elements in the various mineral species. Spectrographic analyses (tables 6-9) show some characteristics that are common to all three deposits:

1. The ore minerals (hematite and magnetite) are relatively "clean," containing only small amounts of magnesium, titanium, manganese, cobalt, chromium, nickel, and vanadium (table 6). However, vanadium is unusually high (5,000 ppm) in a sample of specular hematite from Pilot Knob (table 7, no. 2).
2. Pyrite(?) identified megascopically from Pilot Knob and Pea Ridge is cobaltian, containing as much as 2,000 ppm Co (tables 7 and 9).
3. Calcite is manganiferous (2 to 5 percent Mn, table 8).
4. Apatite is characterized by high lanthanum and yttrium contents, as much as 5,000 ppm La and 2,000 ppm Y (table 8, no. 6; table 9, no. 10).
5. The high molybdenum content in pyrite from Pilot Knob and its presence in every sample analyzed from that mine are noteworthy and may have important implications as to the distribution and abundance of molybdenum in the Precambrian rocks of the St. Francois terrane.

Our impressions, derived from the mine visits and from the analytical data, are in agreement with current theories for the genesis of the deposits: they formed by ore-magma injections and intrusions of late-stage magmatic differentiates with pegmatitic and hydrothermal end phases. The ore bodies appear to have intrusive, stoping contacts with their foot- and hanging-walls; they contain partially assimilated fragments of the host rocks alined parallel to the contacts. Pegmatite-like stringers, pods, and miarolitic cavities are common within the ore bodies.

Table 6.--Spectrographic analyses of hematite and magnetite from the Pilot Knob, Iron Mountain, and Pea Ridge iron deposits

[Fe, Mg, Ca, and Ti reported in percent; all other elements reported in parts per million. G, greater than value shown; L, detected but below value shown; N, not detected at value shown. Ag(.05), As(200), B(10), Bi(10), Cd(20), Nb(20), Sb(100), Sn(10), Sr(100), W(50) not detected at value shown. E. L. Mosier, analyst]

	Sample locality no.							
	1	2	3	4	5	6	7	8
Fe	G(20)	G(20)	G(20)	G(20)	G(20)	G(20)	G(20)	G(20)
Mg	L(0.02)	0.07	0.1	L(0.02)	0.2	0.3	0.1	0.1
Ca	L(0.05)	0.05	0.1	L(0.05)	0.2	0.3	0.1	L(0.05)
Ti	0.15	0.3	0.2	0.002	0.07	0.15	0.2	0.05
Mn	30	200	300	50	70	200	150	200
Ba	700	100	50	N(20)	300	N(20)	N(20)	N(20)
Be	L(1)	N(1)	N(1)	N(1)	N(1)	3	N(1)	N(1)
Co	N(5)	20	50	N(5)	10	100	70	30
Cr	N(10)	N(10)	N(10)	N(10)	15	L(10)	N(10)	N(10)
Cu	L(5)	20	100	N(5)	N(5)	10	20	7
La	N(20)	N(20)	N(20)	N(20)	200	200	70	N(20)
Mo	15	N(5)	N(5)	150	20	N(5)	N(5)	50
Ni	N(5)	70	30	N(5)	50	50	70	30
Pb	N(10)	N(10)	N(10)	N(10)	N(10)	N(10)	N(10)	30
Sc	5	10	7	10	10	5	5	N(5)
V	15	200	300	5,000	300	300	300	150
Y	20	N(10)	20	N(10)	200	200	50	N(10)
Zn	N(200)	200	300	N(200)	N(200)	N(200)	N(200)	1,000
Zr	100	N(10)	N(10)	N(10)	N(10)	N(10)	N(10)	N(10)

Sample locality number	Description
1	Hematite, Pilot Knob.
2	Hematite, Iron Mountain.
3	Hematite, Iron Mountain.
4	Specular hematite, Pilot Knob.
5	Specular hematite, Pea Ridge.
6	Magnetite, Pea Ridge.
7	Magnetite, Pea Ridge.
8	Magnetite, Pilot Knob.

Table 7.--Spectrographic analyses of rocks and minerals from Pilot Knob Mine, Iron County, Missouri

[Fe, Mg, Ca, and Ti reported in percent; all other elements reported in parts per million. G, greater than value shown; L, detected but below value shown; N, not detected at value shown. B(10), Bi(10), Nb(20), W(50), Th(100) not detected at value shown. E. L. Mosier, analyst]

	Sample locality no.							
	1	2	3	4	5	6	7	8
Fe	G(20)	G(20)	G(20)	20	G(20)	20	10	15
Mg	L(0.02)	L(0.02)	0.1	1.5	0.02	L(0.02)	0.2	2
Ca	L(0.05)	L(0.05)	L(0.05)	1	0.2	0.5	1	2
Ti	0.15	0.002	0.05	G(1)	0.003	0.002	0.07	G(1)
Mn	30	50	200	5,000	100	50	500	2,000
Ag	N(0.5)	N(0.5)	N(0.5)	5	10	N(0.5)	200	N(0.5)
As	N(200)	N(200)	N(200)	N(200)	N(200)	700	1,500	N(200)
Ba	700	N(20)	N(20)	1,000	N(20)	N(20)	N(20)	500
Be	L(1)	N(1)	N(1)	1.5	N(1)	3	L(1)	N(1)
Co	N(5)	N(5)	30	1,500	2,000	500	150	50
Cr	N(10)	N(10)	N(10)	15	N(10)	N(10)	N(10)	N(10)
Cu	L(5)	N(5)	7	200	1,000	50	200	200
La	N(20)	N(20)	N(20)	200	N(20)	200	N(20)	N(20)
Mo	15	150	50	300	2,000	300	500	30
Ni	N(5)	N(5)	30	50	200	N(5)	200	30
Pb	N(10)	N(10)	30	30	1,000	20	G(20,000)	30
Sc	5	10	N(5)	20	N(5)	N(5)	N(5)	30
V	15	5,000	150	100	N(10)	N(10)	20	500
Y	20	N(10)	N(10)	70	N(10)	15	10	50
Zn	N(200)	N(200)	1,000	300	300	N(200)	G(10,000)	N(200)
Zr	100	N(10)	N(10)	200	20	20	10	100

Sample locality number	Description
1	Banded hematite from open cut near top of Pilot Knob.
2	Specular hematite, 710 level, Pilot Knob underground mine. Contains 30 ppm Sn.
3	Magnetite ore, lowest mine level, above contact with intrusive gabbro.
4	Yellow clayey gouge zone with pyrite in shear zone, 450 level. Contains 30 ppm Sn.
5	Pyrite from gouge zone, 450 level.
6	Pyrite and trace fluorite.
7	Base metal sulfide vein in gabbro, about 1 m below contact with magnetite ore. Contains 2,000 ppm Cd and 1,000 ppm Sb.
8	Gabbro.

Note: Calcite and actinolite (not reported in table) are manganiferous--2 to 5 percent Mn.

Table 8.--Spectrographic analyses of ore and gangue minerals from Iron Mountain Mine, Iron County, Missouri

[Fe, Mg, Ca, and Ti reported in percent; all other elements reported in parts per million. G, greater than value shown; L, detected but below value shown; N, not detected at value shown. Ag(.5), B(10), Bi(10), Cd(20), Mo(5), Nb(20), Sb(100), Sn(10), W(50), Th(100) not detected at value shown. E. L. Mosier, analyst]

	Sample locality no.					
	1	2	3	4	5	6
Fe	G(20)	G(20)	G(20)	0.2	L(0.05)	3
Mg	0.07	0.1	1	0.03	0.02	0.3
Ca	0.05	0.1	2	G(20)	G(20)	G(20)
Ti	0.3	0.2	0.1	L(0.002)	L(0.002)	0.002
Mn	200	300	G(5,000)	[1/] G(5,000)	200	1,000
As	N(200)	N(200)	N(200)	N(200)	N(200)	300
Ba	100	50	20	200	30	L(20)
Be	N(1)	N(1)	20	2	N(1)	1.5
Co	20	50	100	N(5)	N(5)	N(5)
Cr	N(10)	N(10)	L(10)	N(10)	N(10)	70
Cu	20	100	L(5)	L(5)	L(5)	L(5)
La	N(20)	N(20)	N(20)	N(20)	20	G(1,000)
Ni	70	30	70	N(5)	N(5)	7
Pb	N(10)	N(10)	N(10)	N(10)	N(10)	50
Sc	10	7	70	N(5)	N(5)	N(5)
Sr	N(100)	N(100)	N(100)	150	100	300
V	200	300	500	10	10	200
Y	N(10)	20	150	N(10)	100	1,500
Zn	200	200	500	N(200)	N(200)	N(200)
Zr	N(10)	N(10)	70	10	N(10)	20

[1/] Visually estimated to be 2-5 percent.

Sample locality number	Description
1	Hematite from vein in red-brown rhyolite porphyry; easternmost pit.
2	Hematite, middle pit.
3	Greenish-black amphibole with hematite intergrowth; westernmost pit.
4	Calcite; westernmost pit.
5	Fluorite; westernmost pit.
6	Apatite; westernmost pit.

Table 9.--Spectrographic analyses of rocks and minerals from Pea Ridge Iron Mine, Washington County, Missouri

[Fe, Mg, Ca, and Ti reported in percent; all other elements reported in parts per million. G, greater than value shown; L, detected but below value shown; N, not detected at value shown. Ag(.5), As(200), Bi(10), Cd(20), Nb(20), Sb(100), Sn(10), W(50), Zn(200) not detected at value shown. E. L. Mosier, analyst]

	Sample locality no.										
	1	2	3	4	5	6	7	8	9	10	11
Fe	G(20)	G(20)	G(20)	G(20)	G(20)	10	G(20)	G(20)	20	2	10
Mg	0.3	0.2	0.1	0.2	0.1	5	0.2	0.2	0.3	0.5	5
Ca	.3	.2	.1	.05	1	.1	.05	.1	1	20	1.5
Ti	.15	.07	.2	.3	.1	.3	.1	.05	.2	.005	.5
Mn	200	70	150	100	200	500	30	20	150	500	500
B	N(10)	N(10)	N(10)	N(10)	N(10)	L(10)	N(10)	L(10)	N(10)	10	15
Ba	N(20)	300	N(20)	N(20)	N(20)	1,000	20	N(20)	G(5,000)	30	200
Be	3	N(1)	N(1)	7	10	1.5	L(1)	5	N(1)	20	5
Co	100	10	70	100	70	100	2,000	G(2,000)	2,000	N(5)	70
Cr	L(10)	15	N(10)	10	N(10)	70	N(10)	N(10)	L(10)	N(10)	700
Cu	10	N(5)	20	150	15	150	70	10,000	20	L(5)	100
La	200	200	70	50	200	N(20)	N(20)	200	1,000	5,000	N(20)
Mo	N(5)	20	N(5)	N(5)	N(5)	N(5)	5	N(5)	N(5)	N(5)	N(5)
Ni	50	50	70	100	50	70	200	500	500	N(5)	150
Pb	N(10)	N(10)	N(10)	N(10)	N(10)	50	10	N(10)	150	30	N(10)
Sc	5	10	5	15	10	20	N(5)	N(5)	10	N(5)	30
Sr	N(100)	N(100)	N(100)	N(100)	N(100)	N(100)	N(100)	N(100)	N(100)	N(100)	150
V	300	300	300	200	200	70	10	30	70	50	300
Y	200	200	50	100	200	10	10	100	1,000	G(2,000)	30
Zr	N(10)	50	N(10)	70	50	50	30	50	20	N(10)	50
Th	N(100)	N(100)	N(100)	N(100)	N(100)	N(100)	N(100)	N(100)	300	200	N(100)

Sample locality number	Description
1	Massive magnetite ore; 2475 level.
2	Specular hematite; 2275 level.
3	Magnetite, 2320 level
4	Quartz-magnetite rock with a little disseminated pyrite; 2313 level
5	Skarn; gray-green tremolite(?), magnetite, apatite; hanging wall 2275 level.
6	Biotite, coarse greenish-black; 2275 level.
7	Pyrite from biotite-rich zone.
8	Pyrite(?) from magnetite-apatite rock; 2320 level.
9	Altered gouge zone with abundant pyrite(?); 2475 level.
10	Apatite crystal; 2320 level.
11	Chloritized greenish-black, dense dike rock; 2320 level.

FLUORINE-THORIUM RARE-EARTH-BEARING KIMBERLITIC CARBONATITE COMPLEXES

By Eva B. Kisvarsanyi, Walden P. Pratt, and Allen V. Heyl

Kimberlitic carbonatite diatremes and associated volcanic rocks occur at three localities in the Rolla quadrangle. Although economic mineralization is not known to be associated with them, their possible potential is important because of their similarity to the cryptovolcanic center at Hicks Dome, Ill., 90 mi (145 km) east of the Rolla quadrangle. At Hicks Dome, a cluster of mineralized explosion breccias in Devonian rocks contain thorium, niobium, beryllium, and rare-earth minerals, as well as fluorite, barite, and sphalerite, that are thought to be related to dikes of alkalic peridotite, lamprophyre, and kimberlite (Brown and others, 1954; Heyl and others, 1965, p. B10-B11; Heyl, 1972, p. 887). There may be a potential for similar mineralization associated with the diatremes in the Rolla quadrangle. The three diatreme areas (fig. 12) are:

Avon.--Within an area of about 75 sq mi near Avon, an estimated 100 or more kimberlitic diatremes and dikes of alkalic peridotite occur. (Kidwell (1947) originally reported 79 individual occurrences; about a dozen others have been found subsequently, and it seems very likely that detailed mapping will reveal still more.) These rocks are referred to as "kimberlitic" because thus far none of them have been found to contain any of the three minerals diagnostic of true kimberlites--chromian diopside, pyrope, and magnesian ilmenite (W. L. Mansker, oral commun., 1981). Associated with some of the intrusions are galena, sphalerite, barite, and fluorite (Heyl, 1972, p. 888-889). Mansker (1973) identified olivine, phlogopite, clinopyroxene, and chromian spinel in "brecciated lamprophyric kimberlite"; Rinehart (1974) recognized "eclogite-like" garnet-bearing peridotite fragments in carbonatite breccia. Trace amounts of thorium, niobium, chromium, yttrium, and rare-earth elements have been reported from some of the diatremes (Heyl, 1972; Rinehart, 1974). The age of the rocks is Devonian (Zartman and others, 1967).

Dent Branch-Furnace Creek.--Lapilli tuffs in the Bonneterre Formation contain clasts of alkalic-ultramafic composition at Dent Branch and Furnace Creek; at Dent Branch, crystalline calcite of possible carbonatitic origin is present (Snyder and Gerdemann, 1965; Wagner and Kisvarsanyi, 1969). The rocks are believed to be associated with nearby eruptive centers or explosion pipes similar to the Avon diatremes. Small amounts of millerite have been identified in the Dent Branch tuffs.

Bee Fork.--Lapilli tuffs around Bee Fork are similar in age and composition to those at Dent Branch, but are known only from drill holes. There may be several eruptive centers in this area, suggesting that another cluster of diatremes intersects the basement rocks.

The composition of samples from these three localities is given in tables 10-12. The spectrographic analyses (tables 11-12) show anomalous amounts of chromium, cobalt, nickel, vanadium, lanthanum, niobium, and yttrium characteristic of alkalic-ultramafic rocks. A sample of mafic breccia from Furnace Creek contains a trace-element suite similar to the Avon diatremes (A. V. Heyl, written commun., 1980).

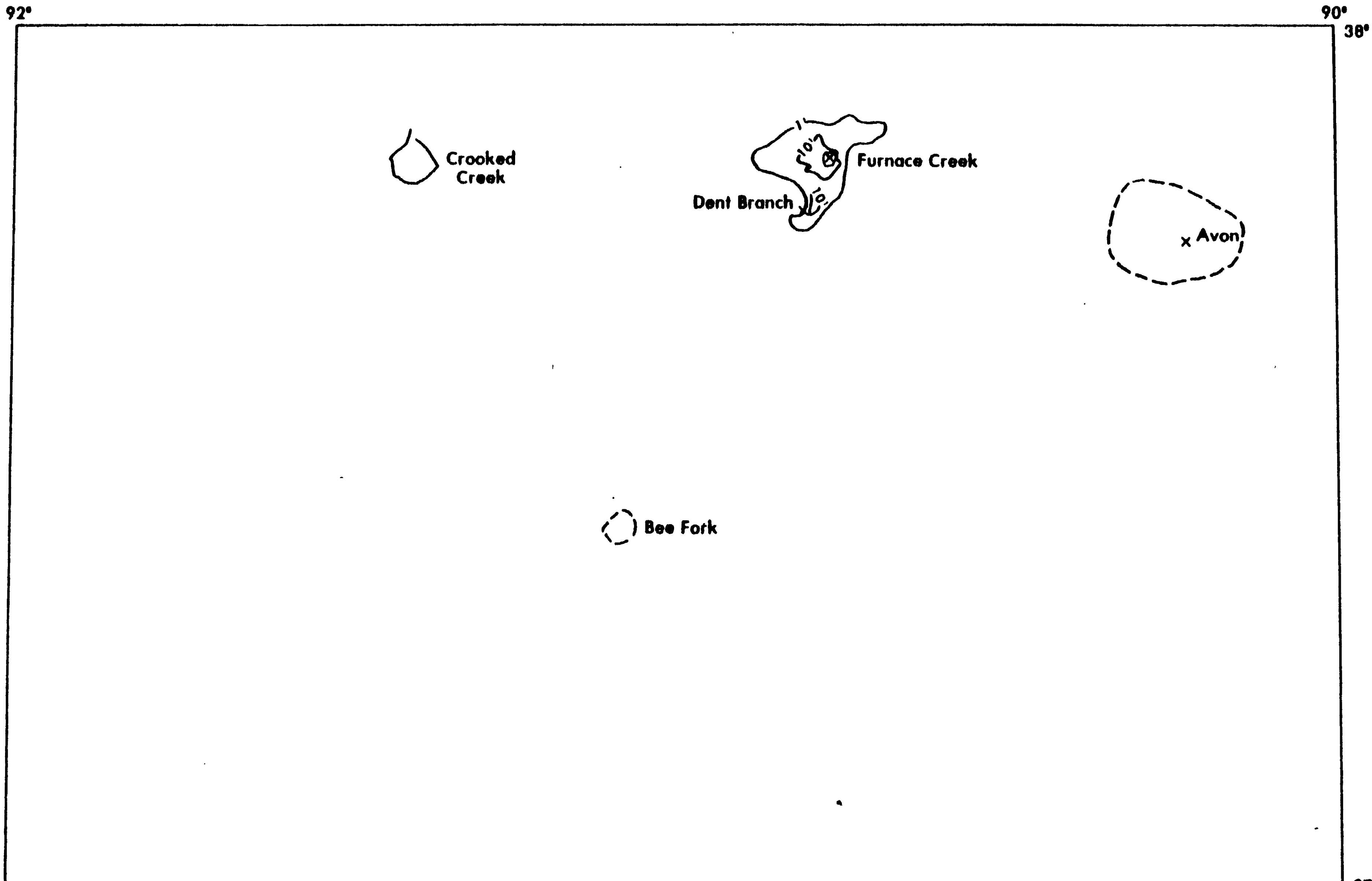


Figure 12. Three diatreme areas and the Crooked Creek cryptoexplosion structure, Rolla 1°x2° quadrangle, Missouri. Isopachs in Furnace Creek area show thickness of volcanic ejecta; innermost isopach is 100 ft.

The geologic setting and composition of the diatremes and lapilli tuffs are consistent with the interpretation that they represent the upper levels of alkalic-ultramafic plutonic complexes that occur at depths from several hundred to several thousand feet below the surface. Therefore, in each of these three localities there is a potential for diamondiferous kimberlites and for rare-earth minerals associated with carbonatites; at this time, however, the available data do not permit an appraisal as to whether this potential is high or low.

The Crooked Creek cryptoexplosion structure in the northwestern part of the quadrangle shows intense brecciation and is structurally similar to the kimberlitic carbonatite complexes. However, this structure is not known to contain any igneous rocks (Snyder and Gerdemann, 1965), and samples of what was described as intrusive carbonate breccia do not have the trace-element suite expected in carbonatites (samples CC-1 and CC-2, table 12). We do not consider the Crooked Creek structure to have potential for mineralization of this type.

Table 10.--Whole-rock chemical analyses of samples from Avon, Dent Branch, and Bee Fork, Rolla 1°x2° quadrangle, Missouri

[All elements reported in percent. Analyses by F. Brown, H. Smith, and Z. Hamlin]

	Sample locality no.			
	D-1	D-2	D-3	D-4
SiO_2	4.3	49.7	55.5	20.4
Al_2O_3	1.1	9.0	5.0	5.4
Fe_2O_3	.5	3.5	1.4	3.4
FeO	1.3	3.8	1.4	1.4
MgO	18.3	8.6	2.1	6.4
CaO	28.8	6.5	15.1	29.4
Na_2O	.20	.13	.01	.01
K_2O	.33	4.0	3.2	1.4
H_2O^+	.58	3.4	1.0	2.2
H_2O^-	.22	1.0	.38	.36
TiO_2	.08	2.8	1.0	1.7
P_2O_5	.01	.69	.24	.75
MnO	.16	.01	.02	.06
CO_2	42.7	6.6	12.5	25.7
F	.05	.21	.08	.30
SUM	98.6	99.9	98.9	98.9

Sample locality number	Description
D-1	Dent Branch carbonatite.
D-2	Bee Fork lapilli tuff.
D-3	Dent Branch lapilli tuff.
D-4	Avon diatreme.

Table 11.—Spectrographic and chemical analyses of rocks from Dent Branch and Avon diatremes, Rolla 1°x 2° quadrangle, Missouri

[Fe, Mg, Ca, and Ti reported in percent; all other elements reported in parts per million. G, greater than value shown; L, detected but below value shown; N, not detected at value shown. Spectrographic analyses by E. L. Mosier; atomic absorption analyses for Zn by J. G. Viets]

	Sample locality No.									
	DB-1	RO-39	-39A	-39B	-39C	RO-40	-40A	-41	42B	AV-1
Fe	10	3	3	G(20)	1	5	3	7	2	2
Mg	3	1	5	0.15	0.1	5	3	5	3	2
Ca	7	10	20	0.5	0.5	20	15	7	10	10
Ti	G(1)	1	0.02	0.007	0.002	0.7	0.7	1	0.2	1
Mn	1,000	700	2,000	100	100	1,000	1,000	1,500	1,000	500
Ag	N(0.5)	N(0.5)	N(0.5)	20	3	N(0.5)	N(0.5)	N(0.5)	N(0.5)	N(0.5)
Au	N(10)	N(10)	N(10)	N(10)	20	N(10)	N(10)	N(10)	N(10)	N(10)
B	15	15	N(10)	N(10)	N(10)	10	10	70	15	15
Ba	1,000	300	20	N(20)	N(20)	500	100	500	200	500
Be	10	3	1.5	N(1)	70	2	2	2	1.5	1
Bi	N(10)	N(10)	N(10)	N(10)	20	N(10)	N(10)	N(10)	N(10)	N(10)
Cd	N(20)	N(20)	N(20)	50	N(20)	N(20)	N(20)	N(20)	N(20)	N(20)
Co	100	30	100	300	G(2,000)	70	50	100	50	20
Cr	1,500	150	30	N(10)	N(10)	1,000	700	1,500	70	200
Cu	100	20	300	G(20,000)	3,000	30	30	20	20	30
La	70	50	N(20)	N(20)	N(20)	70	70	70	20	30
Mo	N(5)	N(5)	N(5)	30	10	N(5)	N(5)	N(5)	N(5)	N(5)
Nb	50	20	N(20)	N(20)	N(20)	30	30	30	N(20)	20
Ni	700	100	300	5,000	G(5,000)	200	150	500	100	150
Pb	30	30	N(10)	70	10	10	L(10)	L(10)	L(10)	15
Sc	20	7	5	N(5)	N(5)	15	15	10	7	5
Sn	N(10)	N(10)	N(10)	70	15	N(10)	N(10)	N(10)	N(10)	N(10)
Sr	700	300	100	N(100)	N(100)	500	100	300	N(100)	200
V	150	100	30	N(10)	N(10)	200	200	200	70	70
Y	30	20	15	N(10)	N(10)	20	15	15	20	20
Zn	N(200)	26	8	3,000	1,000	17	16	50	1	N(200)
Zr	200	100	N(10)	N(10)	20	100	100	70	100	100

	Sample locality No.	Description
Dent Branch	DB-1	Type 1 lapilli tuff.
	RO-39	Dark-gray lapilli tuff with rounded quartz grains; from outcrop along highway, Dent Branch.
	RO-39A	Coarsely crystalline white calcite knots (bombs?) in lapilli tuff, Dent Branch.
	RO-39B	Chalcopyrite from coarse crystalline calcite masses in lapilli tuff; bed of Dent Branch.
	RO-39C	Millerite needles in calcite as above.
Avon	RO-40	Serpentinized peridotite; intersection of State Highway ? and MM, Ste. Genevieve County.
	RO-40A	Breccia with calcite groundmass and apple green pyroxene(?).
	RO-41	Peridotite; Hellon Farm, sec. 2, T. 35 N., R. 7 E.
	RO-42B	Breccia, tan; composed of rounded quartz grains, Bonneterre dolomite fragments, rare igneous(?) fragments. Bucholz farm.
	AV-1	Diatreme, SW1/4 sec. 2, T. 35 N., R. 7 E., Ste. Genevieve County.

Table 12.—Spectrographic analyses of lapilli tuffs from Bee Fork and carbonate breccia from the Crooked Creek cryptoexplosion structure, Rolla 1°x2° quadrangle, Missouri

[Fe, Mg, Ca, and Ti reported in percent; all other elements reported in parts per million. G, greater than value shown; N, not detected at value shown. Ag = N(.5), Au = N(10), Bi = N(10), Cd = N(20), Mo = N(5), and Zn = N(200) not detected at value shown. Analyses by E. L. Mosier]

	Sample locality no.									
	BF-1	BF-2	BF-3	BF-4	BF-5	BF-6	BF-7	BF-8	CC-1	CC-2
Fe	3	2	2	5	5	5	7	7	0.7	0.5
Mg	3	3	3	5	5	3	3	5	2	2
Ca	10	10	10	3	5	5	7	7	G(20)	G(20)
Ti	.5	.5	.3	1	1	G(1)	1	G(1)	.02	.02
Mn	3000	2000	3000	500	700	500	1500	300	300	500
B	15	15	10	20	20	15	20	10	20	10
Ba	1000	50	20	500	3000	300	1500	700	30	20
Be	2	1	1	1.5	1.5	1.5	N(1)	2	N(1)	N(1)
Co	30	20	30	50	50	100	70	70	5	N(5)
Cr	500	700	500	700	1000	1500	700	500	N(10)	N(10)
Cu	50	50	70	20	30	70	50	100	5	5
La	50	N(20)	N(20)	70	70	50	150	150	N(20)	N(20)
Nb	20	20	20	20	50	50	50	70	N(20)	N(20)
Ni	200	70	50	500	500	700	150	300	N(5)	N(5)
Pb	N(10)	10	70	N(10)	N(10)	N(10)	15	20	50	30
Sc	5	7	5	7	10	10	10	10	N(5)	N(5)
Sn	N(10)	N(10)	N(10)	N(10)	N(10)	N(10)	N(10)	10	N(10)	N(10)
Sr	150	N(100)	N(100)	200	300	100	500	300	500	700
V	50	70	50	70	70	100	200	100	15	10
Y	15	30	20	20	20	20	30	70	15	10
Zr	70	100	70	100	150	200	200	200	30	30

Sample locality no.	Description
	All Bee Fork samples are from 3 drill holes in T. 31 N., R. 1 W. between Reynolds and Corridon, Mo. Samples BF-1, 2, 4, 5, 6, and 7 from one hole, BF-3 from a second hole, BF-8 from a third hole. Crooked Creek samples were taken from surface.
BF-1	Fine-grained lapilli tuff: <50 percent ultramafic lapilli cemented by coarse-grained calcite; from 1470 ft depth.
BF-2	Fine-grained tuffaceous sandstone: sand grains cemented by coarse-grained calcite containing <10 percent ultramafic material; from 1504 ft depth.
BF-3	Fine-grained tuffaceous sandstone: sand grains cemented by calcite containing <10 percent weathered or bleached tuffaceous material; from 1375 ft depth.
BF-4	Medium-grained sandy lapilli tuff: >50 percent ultramafic lapilli mixed with sand grains in tuffaceous matrix; from 1474 ft depth.
BF-5	Medium-grained sandy lapilli tuff: similar to BF-4; from 1411 ft depth.
BF-6	Medium-grained sandy lapilli tuff: >75 percent ultramafic material, both lapilli and ash, containing sand grains and minor calcite; also contains some igneous breccia clasts that were not sampled for the analysis; from 1405 ft depth
BF-7	Medium-grained lapilli tuff: <50 percent ultramafic lapilli cemented by coarse-grained calcite; contains angular breccia clasts of Precambrian silicic tuff; from 1401 ft depth.
BF-8	Medium-grained sandy lapilli tuff containing >50 percent ultramafic lapilli; includes igneous fragments and sand grains; from 1280 ft depth.
CC-1	Unusually hard, tightly cemented, fine-grained limestone breccia (intrusive breccia dike?), 2 ft wide, along eastern edge of Bonneterre fault block; contains a few small pyrite grains. NE1/4 SW1/4 NW1/4 sec. 17, T. 36 N., R. 4 W. From near contact.
CC-2	Same as CC-1, from center of dike.

VEIN DEPOSITS OF TIN-TUNGSTEN-COPPER-ZINC-LEAD-SILVER IN PRECAMBRIAN ROCKS

By Eva B. Kisvarsanyi, Walden P. Pratt, and Allen V. Heyl

Tin-tungsten vein deposits in the Silver Mine area (fig. 13) have been considered unique in the midcontinent region. The descriptive model below, therefore, is based on published and unpublished reports and data of the known deposits. However, in our appraisal of the resource potential we shall consider broader aspects of the geologic and tectonic environment of the region, examine descriptive models of similar deposits in other parts of the world, and try to establish salient features which are favorable to mineral deposits of this type.

Descriptive Model

References: Tolman, 1933; Hayes, 1947; Hobbs, 1967; Kiilsgaard, 1967; Lowell, 1975; Gustavson, 1977

Ore Body

Size: Small (n x 10^2 ft thick, n ft wide, n x 10 ft long) to medium (n x 10^2 ft thick, n x 10 ft wide, n x 10^3 ft long)
Shape: Lens-shaped, discontinuous quartz veins
Tonnage: 120 short tons tungsten concentrates; 3,000 oz silver; 50 tons lead ore
Grade: Average 3.4 percent tungsten oxide; 0.78 oz/t silver; 1.7 percent lead; 0.5 percent zinc
Mineralogy:
Ore minerals: wolframite, argentiferous galena, sphalerite, chalcopyrite, pyrite, arsenopyrite, covellite, hematite, cassiterite. One occurrence of stibnite has been reported (M. H. McCracken, Missouri Geological Survey, oral commun., 1980).
Gangue minerals: quartz, topaz, sericite, fluorite, zinnwaldite, chlorite, garnet
Secondary minerals: goethite, scheelite, stolzite, jarosite, francolite, fluorapatite, malachite, azurite, kaolinite, manganese wad
Depth: Veins have been followed from the surface down to a few hundred feet in depth

Host Rocks

Lithology: Precambrian granite (Silvermine Granite) and rhyolite
Wall-rock alteration: greisen
Age relationships from oldest to youngest: rhyolite, granite, intermediate dikes, quartz veins
Controlling structures and other features:

1. East and northeast-trending fractures and joints in granite
2. Intrusive contacts of granite with rhyolite
3. Precambrian faults
4. Brecciated volcanic rocks

Geochemical indicators: Tin, lead, and molybdenum anomalies in residual soils (pathfinder elements).

Geophysical indicators: None known.

Resource Appraisal

The basic premise in our appraisal of tin-tungsten-silver-lead resources in the Rolla quadrangle is that the Silver Mine deposits are not fortuitous but are characteristic of the Precambrian geologic and tectonic environment of the region. The deposits form an integral part of the St. Francois terrane which makes up the subsedimentary basement over most of the area (Kisvarsanyi, 1980a). The St. Francois terrane has a number of distinctive features, listed below, which in other parts of the world are diagnostic of platform-type tin-metallogenic provinces (Lugov, 1977; Olade, 1980).

1. High-level, anorogenic tectonic environment
2. Continental volcanic-plutonic terrane with granitic ring complexes
3. Late intrusions of granitoid plutons
4. Tension fractures and joints, some related to ring faults
5. Predominance of alkalic-silicic rocks: biotite (alkali feldspar) granite, hornblende granite, riebeckite granite, porphyry ring-dikes; includes some fayalite-bearing rocks
6. Tin granites with distinctive trace-element suite (enrichments in tin, lithium, niobium, thorium, and rare-earth elements)
7. Potassium exceeds sodium in most granitoids
8. Negative gravity anomalies

Platform-type granites in tin-metallogenic provinces may give rise to two types of primary tin mineralization: (1) pegmatitic tin-niobium-tantalum, and (2) hydrothermal tin-tungsten-zinc-lead. Generalized descriptive models of the two primary types of deposits are summarized in table 13; we believe that the models are pertinent to the Precambrian geology of the Rolla area and may prove to be helpful in exploration for this type of deposit. Both types of primary deposits may also be sources for placer deposits.

The obvious analogies of the models with the St. Francois terrane suggest the potential for tin-tungsten mineralization in the Rolla quadrangle; the central (tin granite) plutons are favorable as host rocks for the pegmatitic model, and the ring intrusions are favorable for the hydrothermal models. On the basis of the available data (Kisvarsanyi, 1980a, 1980b; U.S. Geological Survey, 1978, 1979) we have selected a number of features which we consider to be indicators of favorable geologic environments for tin-tungsten resources (fig. 13). The numbered areas correspond to inferred central plutons and ring intrusions in the buried Precambrian terrane. The numbers correspond to those in table 14. Where the indicator is known to be present, a value of 1 is given; where available information is not sufficient to determine whether the indicator is present or absent, a value of 0 is given. The sums of indicators for each area, therefore, should not be ranked against each other; each sum only shows how many of the indicators are known to be present.

Table 13.--Descriptive models of pegmatitic and hydrothermal tin deposits

	Model 1: Pegmatitic tin-niobium-tantalum deposits	Model 2: Hydrothermal tin-tungsten-zinc-lead-silver deposits (Silver Mine)
ORE BODIES		
Ore minerals	Cassiterite, columbite	Cassiterite, wolframite, sphalerite, argentiferous galena, arsenopyrite
Gangue minerals	Quartz, muscovite, albite	Quartz (up to 95 percent), muscovite (sericite), topaz, fluorite, feldspar
Grade	0.1-0.2 percent tin; 1-3 percent tantalum plus niobium	Average 0.8-1.5 percent tin and tungsten
Mode of occurrence	Disseminations in margins and roof zones of small granite plutons; rare-metal pegmatite association	As lodes and in fracture-controlled greisen veins with central quartz veins (cassiterite-quartz association)
Temperature of formation	High	300-600°C (hypo-xenothermal deposits such as the Silver Mine possible); telescoping
HOST ROCKS		
Lithology	Biotite granites, pegmatitic quartz-muscovite-albite granites	High-silica granites
Petrochemistry	$K_2O > Na_2O$; 71.0-75.0 percent SiO_2; 13.0-15.0 Al_2O_3; 2.0 percent ($FeO+Fe_2O_3$)	$K_2O > Na_2O$; 70.0-75.0 percent SiO_2; 12.0-16.0 percent Al_2O_3
Geochemistry	K/Rb<100; high F, B, P, (Be)	K/Rb 100-150; 0.8-1.2 percent F; 65-100 ppm (parts per million) Li; 3-17 ppm Be; 15-20 ppm B; 7-10 ppm Mo; 10-25 ppm Sn
Alteration	Intense albitization, greisenization	Greisenization, silicification
Depth of emplacement,	4-5 km	2-3 km
EXAMPLES	Nigerian younger granites, Brazilian and Australian shields Typically in outer zones of shields and platforms	Nigerian younger granites, Brazilian shield, central Asia In activated parts of median massifs and platforms

Table 14.--Resource potential for platform-type pegmatitic and hydrothermal tin-tungsten-zinc-lead-silver deposits--September 1980

[Mineral commodities: cassiterite, columbite, wolframite, galena, sphalerite]

Map area no. fig. 13	Indicators: Tin granite in outcrop or drill hole	Circular or oval magnetic low	Inferred ring intrusion	Pegmatites	Distinctive alteration	Pathfinder elements	Sum	Depth of burial (ft)	Remarks
1	0	0	1	0	1	1	3	0-500	Silver Mine ring intrusion; only known mineralization (cassiterite-quartz association model type) in area.
2	0	1	1	0	0	0	2	1500+	Cherryville ring intrusion and Steelville central pluton; inferred from drill hole and aeromagnetic data.
3	0	1	1	1	1	1	5	1000-1500	Trachytic ring intrusion surrounding inferred Pea Ridge central pluton.
4	1	1	0	0	0	0	2	1200+	Potosi central pluton.
5	0	1	0	1	0	0	2	2000?	Hawn Park pluton, inferred from Cordell (1979).
6	1	0	0	0	0	0	1	?	Dent Branch-Furnace Creek plutons; inferred from granite clasts in diatremes.
7	1	1	0	1	0	1	4	0-500	Graniteville pluton.
8	1	1	1	1	1	1	6	1500+	Buick pluton.
9	1	0	1	1	1	1	5	1000+	Bunker pluton.
10	1	1	1	0	0	0	3	1500+	Corridon pluton; inferred from granite clasts in Bee Fork diatremes.
11	1	1	1	0	0	0	3	1200-1500	Redford pluton.
12	0	1	1	0	0	1	3	1000+	Sabula pluton; Ketcherside Gap mineralization along its eastern perimeter.
13	0	0	1	0	1	1	3	0-1500	Redford-Annapolis ring intrusion.
14	0	0	1	0	1	1	3	400-1200	Marquand-Buckhorn ring intrusion.
15	0	0	1	0	1	1	3	1200-1500	Eminence ring intrusion around cauldron subsidence structure; volcanics preserved in center.
16	1	1	0	1	1	1	5	800-1500	Van Buren pluton.
17	1	1	1	0	1	1	5	0-1400	Piedmont pluton.
18	1	1	0	0	0	1	3	1800-2200	Greenville pluton.
19	0	1	0	0	0	0	1	Unknown	Magnetic anomaly suggestive of tin granite pluton, no other corroborating data.

Indicators of favorable geologic environments

1. Tin-granite pluton indicated by outcrop or drill hole.
2. Tin-granite pluton inferred from aeromagnetic map (circular or oval magnetic low).
3. Inferred ring intrusion.
4. Pegmatites.
5. Greisen-type alteration, quartz veins, albitization, etc.
6. Pathfinder elements.

Area 1 has the resource potential of most immediate interest, for two reasons. First, the known veins in the Silver Mine area were mined only for the tungsten and argentiferous galena in the veins; the potential for tin and tungsten in the greisens along their borders apparently has not been evaluated. Random samples of both greisen and sulfide-quartz vein material contain significant amounts of tin, and the vein material also contains notable tungsten, as would be expected (table 15). Second, recent geochemical surveys suggest some potential for tin-tungsten base-metal veins over an area of at least 4 sq mi northwest and southwest of the Einstein mine (Gustavson, 1977), and there may also be a potential for undiscovered veins under a thin cover of Lamotte Sandstone southeast and east of the Einstein mine (fig. 14).

Lowell and Kurz (1977) reported high gold contents in sulfides in the Silver Mine area, ranging from 0.17 weight percent gold in sphalerite to 0.79 percent in galena, determined by electron microprobe. To test the implication of that report for gold resource potential, we collected a sample of about 3 kg of vein quartz containing abundant pyrite, sphalerite, galena, and chalcopyrite. The entire sample was crushed and sieved, and a methylene-iodide concentrate of the +60 mesh fraction, consisting mostly of sulfides, was analyzed by atomic absorption for gold, and by standard semiquantitative spectrographic methods for 31 elements (table 15, sample no. 2). These analyses do not indicate significant gold content in the sulfides at this locality, and in fact Lowell states (oral commun., 1980) that he has been unable to reproduce the high gold analyses he reported in 1977.

Aside from area 1, areas 3, 8, 9, 16, and 17 appear to have the highest potential in the quadrangle for undiscovered tin-tungsten minerals because of the large number of indicators identified. Prospecting and exploration in these and the other numbered areas will be handicapped by the thick cover of sedimentary rocks. The potential for these types of deposits elsewhere in the quadrangle appears to be nil.

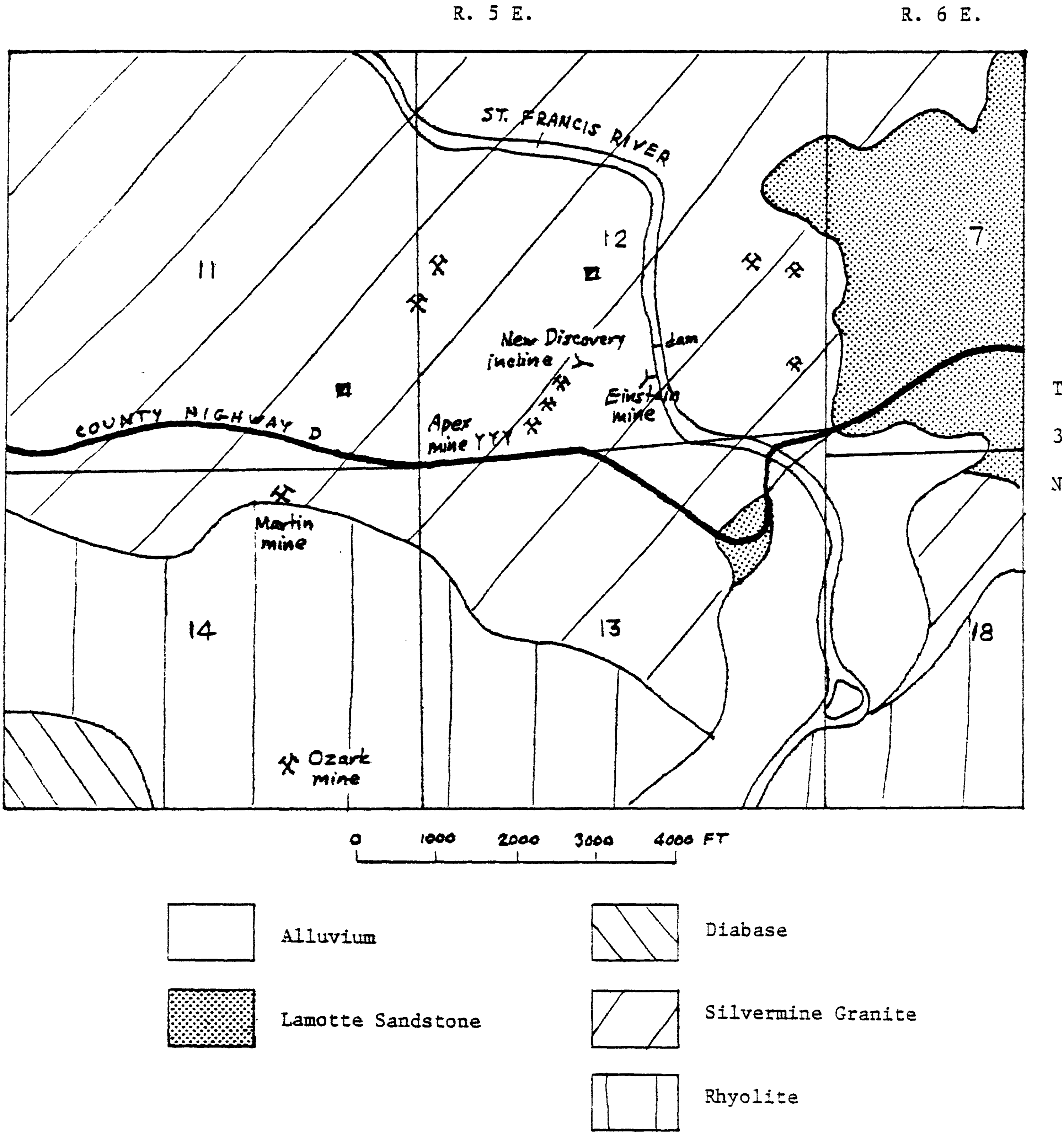


Fig. 14.—Generalized geologic map of Silver Mine area, Madison Co., Missouri. Geology modified from Hayes (1947) and Pomerene (1947).

Table 15.--Analyses of samples from Silver Mine area, Madison County, Missouri

[Fe, Mg, Ca, and Ti reported in percent; all other elements reported in parts per million. G, greater than value shown; L, detected but below value shown; N, not detected at value shown. Spectrograhic analyses by E. L. Mosier; atomic-absorption analyses for Au by J. G. Viets]

Sample No.-----	1	2	Sample No.-----	1	2
Fe	5	20	Cu	200	15,000
Mg	.5	.05	La	N(20)	N(20)
Ca	.5	.7	Mo	N(5)	N(5)
Ti	.1	.02	Nb	N(20)	N(20)
Mn	5,000	3,000	Ni	5	5
Ag	2	700	Pb	3,000	20,000
As	500	10,000	Sb	N(100)	N(100)
Au	N(10)	.05[1/]	Sc	L(5)	N(5)
B	20	N(10)	Sn	1,000	G(1,000)[2/]
Ba	200	100	Sr	150	100
Be	10	2	V	30	L(10)
Bi	50	500	W	500	G(1,000)[3/]
Cd	L(20)	500	Y	15	15
Co	N(5)	50	Zn	700	G(10,000)[4/]
Cr	N(10)	150	Zr	10	20
			Th	N(100)	N(100)

1/Au, average of five 10-gram replicates; individual analyses were 0.04, 0.06, 0.05, 0.05, 0.05 ppm.

2/Sn visually estimated at ~2,000 ppm.

3/W visually estimated at 5,000-10,000 ppm.

4/Zn visually estimated at 5-10 percent (50,000-100,000 ppm).

Sample no.	Description
1	Fluorite-rich greisen, from dump at New Discovery incline, 270 m N. 79° W. from Einstein mine shaft.
2	Sulfide concentrate (sphalerite, galena, chalcopyrite, and pyrite) from vein quartz on dump at New Discovery incline.

URANIUM AND THORIUM IN PRECAMBRIAN ROCKS

by Eva B. Kisvarsanyi

Uranium and thorium deposits are not known in the Rolla quadrangle. However, Malan (1972) and Nash (1977) have shown that the granites exposed in the St. Francois Mountains are among the most uraniferous igneous rocks in the United States. One of the plutons, the Graniteville granite, has an average of 16.9 ppm U (average of 10 samples), nearly three times the average of the other granitic rocks in the region. Other Graniteville-type tin-granite plutons are known or inferred in the buried Precambrian terrane (Kisvarsanyi, 1980a) and contain between 4 and 18 ppm U and between 12 and 43 ppm Th (single analyses of 8 core samples, Missouri Geological Survey, unpublished data). These radiogenic plutons are estimated to underlie as much as 15 percent of the quadrangle (fig. 13), and constitute a potential source from which large amounts of uranium and thorium might have been derived by late- or post-magmatic processes. Thus in contrast to the other appraisals in this report, we have here a known primary source of metals and must consider whether or not the Precambrian geologic environment was favorable for the transport and concentration of those metals into one or more deposits.

Rogers and others (1978) reviewed the factors controlling uranium deposits related to granitic magmas. Their classification of such deposits on the basis of tectonic occurrence defines two ideal end members, one of which (the Bokan Mountain type) has many features in common with the St. Francois igneous terrane. The principal features of the Bokan Mountain model are:

Types of ore deposits

1. Primary (orthomagmatic) disseminations and segregations in granite
2. Syngenetic mineral concentrations in aplites and pegmatites
3. Epigenetic (hydrothermal) deposits in veins and fractures with some replacement
4. Secondary (hydrothermal) deposits in pores of clastic sedimentary rocks

Host rocks

Lithology: Alkalic and/or peralkalic granites; associated syenites; may contain peraluminous granites and albite-riebeckite granites

Petrochemistry: Initial $^{87}Sr/^{86}Sr$ ratios generally less than 0.710 but may be higher; Th/U ratios generally greater than 1.0; derivation from mantle or lower crust suggested

Tectonic environment

Setting: Anorogenic or post-orogenic
Tectonic stage: Post-tectonic
Level of emplacement: Epizonal
Level of erosion: Shallow

Rogers and others (1978, p. 1549-1550) summarized their detailed review of granitic uranium deposits in the form of a set of criteria that they consider favorable for uranium occurrence:

General criteria for all types of deposits

1. Regions of similar geologic features with known uranium mineralization in several areas
2. Abundance of silicic and alkali-rich intrusive rocks
3. Presence of favorable structural traps and wall-rock lithology
4. Abundance of fluorite or other fluorine-bearing phases
5. Post-Archean age of magmatism

Specific criteria for Bokan Mountain-type deposits

1. Post-tectonic plutons
2. Sodic plutons, generally high-albite; possibly peralkalic
3. Abundance of favorable structures and wall-rock lithologies
4. Major pathfinder elements may be thorium, niobium, and fluorine

The St. Francois terrane meets all of the above criteria except that of known uranium mineralization and sodic plutons, and on this basis, the potential for Bokan Mountain-type uranium mineralization in the St. Francois terrane as a whole could be considered high. These criteria, however, are more pertinent to the identification of broad geologic terranes than to outlining small target areas for exploration. In the Rolla quadrangle the areas of exposed Precambrian rocks can be eliminated to the extent that they have been tested by the aerial radiometric surveys of the National Uranium Resource Evaluation (NURE) program (Texas Instruments, Inc., 1979a), which did not show significant anomalies other than somewhat higher background. Except for the margins of the Graniteville pluton, however, the radiogenic plutons are covered by 1,000 to 2,000 feet of sedimentary rocks, and uranium deposits at that depth cannot be detected by aerial or surface radiometric surveys.

We conclude that (1) the region may have a high general potential for granitic uranium deposits at considerable depths, but that (2) the potential of specific areas within the Rolla quadrangle cannot be appraised at this time, except that the areas of exposed Precambrian rocks can be eliminated, and (3) the pipe-and-vein geometry, and relatively small size, of the Bokan Mountain type of deposit would present such an elusive target for deep exploration that the economics of discovering and developing such a deposit would be prohibitive in the extreme.

URANIUM IN PALEOZOIC SEDIMENTARY ROCKS

by Walden P. Pratt

Nash (1977), in his study of uranium contents of outcropping Precambrian granites of the St. Francois Mountains, referred to in the previous section, suggested that these uraniferous igneous rocks might have served as sources of uranium for remobilization and concentration in Paleozoic sedimentary rocks onlapping the Precambrian--specifically, in basal sandstones, conglomerates, and arkoses of the Cambrian Lamotte Sandstone and (to a minor extent) other Cambrian units. Reconnaissance testing of this conceptual model, done by Odland and Millard (1979) through uranium and thorium analyses of 175 rock samples of lower Paleozoic sedimentary units from 28 drill holes, gave little indication that appreciable amounts of uranium have been mobilized from the granitic rocks and concentrated in the onlapping Cambrian clastic sediments. However, nodular masses of solid organic matter, containing 1 percent U as finely disseminated uraninite, have been reported from Mine La Motte in gray Lamotte Sandstone apparently associated with sandstone dikes (Arthur P. Pierce, oral commun., 1980). These occurrences were not extensive enough to be of economic interest in themselves, but they do clearly indicate some mobilization and redeposition of uranium.

Considering the small size of the potential mineralized targets, the sparsity of the sample locations used by Odland and Millard (only 17 holes penetrating the Lamotte Sandstone), and the fact that those samples came from holes that had been drilled for other reasons than to test channel sandstones in the Lamotte, we conclude that the potential for uranium deposits in the Lamotte Sandstone has not been adequately tested, and cannot be evaluated on the basis of available information.

COASTAL PLAIN-TYPE URANIUM DEPOSITS

by Ralph L. Erickson and Walden P. Pratt

A sandstone unit in the southeast corner of the Rolla quadrangle may have some potential for uranium deposits of the Texas Coastal Plain type, which occur in volcanic ash-rich sandstone aquifers of Tertiary age (Galloway, 1978; Reynolds and Goldhaber, 1978). Uranium in these deposits is thought to be derived by leaching of volcanic ash, transportation by groundwater, and fixation by reductants such as organic debris, sulfides, H_2S, or hydrocarbon gases. Faulting is thought to be important because faults may produce facies changes, form boundaries to fluid flow, or serve as conduits for movement of uranium-bearing groundwaters.

The only stratigraphic unit in the Rolla quadrangle that has lithologic similarity to the coastal plain model is the McNairy Formation of Late Cretaceous age, probably present (though very poorly exposed) in a small area in the extreme southeast corner of the quadrangle (T. 27 N., R. 9-10 E.). As exposed east of here in the Advance 7-1/2′ quadrangle, the formation is composed of sand, sandstone, clay, and lignite, in part interbedded (Amos and Blankenship, 1980). Lignite could act as the reductant to remove uranium contained in groundwater moving through the sandstone. Two possible sources for such uranium can be postulated. The most immediate source, and an integral part of the coastal plain model, would be volcanic ash in the McNairy Formation; but as described by Amos and Blankenship (1980), the formation does not include volcanic ash. An alternative source would be the uraniferous granites of the St. Francois Mountains; Tibbs and Unfer (1979) have examined this possibility and concluded that although such a source is feasible, the uranium potential in the McNairy Formation is lower near the margin of the Mississippi Embayment (oxidizing conditions) and higher toward the basin (reducing conditions), many miles southeast of the Rolla quadrangle. This is borne out by the NURE data releases for the Rolla and adjacent Poplar Bluff quadrangles (Texas Instruments, 1979a, b), which show no significant uranium anomalies in groundwater, stream water, or stream sediment in areas where the McNairy Formation is present at or near the surface. We conclude that the potential for coastal-plain sandstone uranium deposits in the Rolla quadrangle is low.

IRON-COPPER-NICKEL-COBALT (PLATINUM-CHROMIUM-TITANIUM) DEPOSITS IN PRECAMBRIAN LAYERED MAFIC-ULTRAMAFIC COMPLEXES

by Eva B. Kisvarsanyi and Ralph L. Erickson

These types of deposits are not known in the Rolla quadrangle, but discussion and speculation as to their occurrence is warranted by the fact that several differentiated, layered intrusions of gabbro-norite elsewhere in Missouri (Kisvarsanyi, 1974) cause magnetic anomalies similar in amplitude and areal extent to certain anomalies in the Rolla quadrangle. Disseminated pyrrhotite, magnetite, pentlandite, and chalcopyrite totaling as much as 15 percent by volume have been identified in some drill cores of these rocks from other parts of Missouri. The petrology of the intrusions is comparable to that of layered mafic-ultramafic complexes, such as the Stillwater, Sudbury, Skaergaard, Bushveld, etc., which contain some of the world's most important resources of chromium, platinum, nickel, and cobalt.

The potentially metal-bearing intrusions in Missouri are within the Precambrian basement, covered by 700 to 3,300 feet of sedimentary rocks. They have been penetrated by drilling to a maximum of 800 feet. Typically, they have a differentiated cap of diorite and quartz-diorite, grade through gabbro, norite, and troctolite with depth, and are cut by granite dikes. The concentration of metallic minerals increases with depth. Ultramafic rock was not penetrated in any of the drillholes.

The two magnetic anomalies in the Rolla quadrangle that might be related to mafic-ultramafic complexes are the Avon and Salem anomalies (fig. 10).

<u>The Avon anomaly</u> (no. 19 on fig. 11

A dumbbell-shaped, 3,265-gamma magnetic high was tested by a single core hole. At 674 feet depth, coarse-grained diorite was encountered and mafic rocks were penetrated to the bottom of the hole at 1,094 feet. The rock is cut by several granite dikes causing extensive hybridization. The section is similar to the dioritic cap of layered intrusions elsewhere in Missouri, and it grades into gabbro at about 950 feet depth. Chemical analyses of the gabbro from 976 and 1,074 feet depth are given in table 16.

<u>The Salem anomaly</u> (no. 18 on fig. 11)

A large gravity anomaly near Salem was modeled by Cordell (1979) and attributed to an intrabasement ultramafic pluton. The gravity anomaly is along an arcuate chain of prominent magnetic highs trending north-northeast from Licking to St. James. A test hole drilled in 1928 penetrated 876 feet of Precambrian rock from 1,750 to 2,626 feet depth. The quality of samples from this well is extremely poor. The section has been logged as "diorite with syenite and andesite dikes" on the basis of examination of cuttings by binocular microscope (Kisvarsanyi, 1975). The dominant minerals are plagioclase, amphibole, biotite, epidote, and chlorite. Short sections were interpreted as dikes because of distinct mineralogical changes, but of course, no actual intrusive contacts can be observed in cuttings. If Cordell's interpretation of the Salem gravity anomaly is correct, the top of the ultramafic body must be below the penetrated depth of Precambrian rock in this drillhole. Alternatively, the pluton may be a layered intrusive body with a dioritic cap, grading into more mafic compositions with depth.

Thus, there is some evidence for the existence of two layered mafic-ultramafic plutons in the Rolla quadrangle; however, the metallic resource potential of these plutons cannot be realistically appraised on the basis of the available data.

Although not an example of this type of deposit in the strict sense, a smaller differentiated mafic intrusive that does occur in the Rolla quadrangle is a mafic dike 400 ft thick, composed of olivine diabase and ophitic gabbro, which cuts and offsets the magnetite ore body in the subsurface at Pilot Knob (Wracher, 1976). The same intrusive is exposed on Shepherd Mountain about 1 mile west of Ironton, where it was studied in detail in outcrop and in drill core by Desborough (1967). He identified pyrrhotite, chalcopyrite, sphalerite, cubanite, pentlandite, and galena in these rocks but noted that the total quantity of primary sulfides in the rock probably nowhere exceeds 1.5 percent by volume. Sulfide content showed progressive enrichment from about 0.2 percent in olivine diabase to 0.4 percent in foliated gabbro to 1 percent in coarse gabbro. Pyrrhotite constituted more than half of the total primary sulfide. Desborough stated that although sulfides did develop in the Shepherd Mountain intrusive, their concentration is economically insignificant.

A chemical analysis of the gabbro from the Pilot knob mine is given in table 16.

MANGANESE IN PRECAMBRIAN ROCKS

by Eva B. Kisvarsanyi

Several small manganese prospects in Precambrian rhyolites and tuffs are known in the central and southern part of the quadrangle. The deposits are only of historical interest and most of them produced only a few tens of tons of ore in the late 1800's (Grawe, 1943). The largest of the deposits, Cuthbertson Mountain (fig. 10), is credited with a production of about 2,000 tons of ore. At present, none of the known prospects contain exploitable grade and tonnage of manganese.

Descriptive Model

References: Grawe, 1943
Dorr, 1967

Ore body

Size: small--n x 10 ft thick, n x 10 inches wide, n x 10^2 ft long
Shape: vein (in rhyolites); stratiform, tabular, nodular masses (in tuffs)

Table 16.--Chemical and spectrographic analyses of gabbroic rocks, Rolla 1°x 2° quadrangle, Missouri

[Ag(0.5), As(200), Au(10), B(10), Be(1), Bi(10), Cd(20), Cr(10), La(20), Nb(20), Sb(100), Sn(10), W(50), Zn(200) not detected at value shown; NA, not analyzed. Chemical analyses for SG samples, N. Skinner and D. Kobilis; and for PK-1, Z. Hamlin. Spectrographic analyses by E. L. Mosier--sample PK-1 only]

Chemical analyses (in percent)			
	Field No.		
	SG-1-976	SG-1-1074	PK-1
SiO_2	49.1	48.3	45.2
Al_2O_3	15.4	15.2	13.6
Fe_2O_3	5.8	5.8	4.3
FeO	7.9	7.4	13.1
MgO	5.7	5.9	5.1
CaO	7.3	7.8	7.4
Na_2O	3.0	2.9	3.8
K_2O	0.91	0.88	0.99
H_2O+	0.98	1.2	0.77
H_2O-	0.15	0.17	0.15
TiO_2	1.7	1.7	3.3
P_2O_5	0.47	0.42	0.68
MnO	0.15	0.16	0.26
CO_2	0.06	0.67	0.03
Total	98.6	98.5	98.7
Spectrographic analyses (in parts per million)			
Ba	NA	NA	500
Co	NA	NA	50
Cu	NA	NA	200
Mo	NA	NA	30
Ni	NA	NA	30
Pb	NA	NA	30
Sc	NA	NA	30
Sr	NA	NA	300
V	NA	NA	500
Y	NA	NA	50
Zr	NA	NA	100

Description

SG-1-976	Gabbro from drill hole in the Avon anomaly, NW 1/4 SE 1/4 sec. 15, T. 35. N., R. 7 E., 976 ft depth.
SG-1-1074	Same, 1,074 ft depth.
PK-1	Gabbro from Pilot Knob mine.

Tonnage: n x 10^3 short tons of Mn ore
Grade: average 37 percent Mn, 0.12 percent Co in vein ore, some Fe; maximum 50 percent Mn in nodules, some Fe
Mineralogy: braunite, pyrolusite, psilomelane, wad (manganese and iron oxide mixture)
Gangue minerals: alunite, barite, calcite, feldspar, fluorite, hematite, kaolinite, quartz, sericite, tremolite
Depth: near surface, but could be at any depth in the buried Precambrian volcanic rocks
Mode of occurrence: veins in rhyolite porphyry, breccia and fracture fillings; replacements in bedded air-fall tuffs

<u>Host rocks</u>

Age: Precambrian, 1.5 b.y.
Lithology:

1. Rhyolite porphyry flows and ash-flow tuffs
2. Bedded air-fall tuffs, apparently chiefly of rhyolitic composition; locally contains manganiferous limestone beds. Residual manganese oxide boulders may occur on flanks of rhyolite knobs
3. Alteration is moderate along the veins, extensive in the tuffs

<u>Controlling structures and other features</u>

1. Precambrian fracture and fault zones (vein ores)
2. Local Precambrian depositional basins, volcanic crater lakes? (tuffaceous ores; hot springs)
3. Spatial (geographic) association of deposits in Precambrian rocks with manganese deposits in the overlying sedimentary rocks
4. On structural highs

<u>Geochemical indicators</u>: titanium, barium, arsenic, lead, copper, molybdenum, antimony, zinc, cobalt, (nickel) anomalies

<u>Geophysical indicators</u>: magnetic highs may reflect rhyolite knobs and/or associated iron mineralization

Resource Appraisal

The small size of the deposits and the difficulties encountered in obtaining acceptable grade in the past discourage consideration of this kind of deposit as an important resource potential. However, as manganese is a strategic commodity, even small deposits may become important in the future.

Theoretically, buried deposits could be associated with fractured volcanic highlands and tuffaceous beds. The Precambrian-Paleozoic unconformity appears to be a favorable geologic horizon for residual deposits.

Trace-element Geochemistry

by Ralph L. Erickson, Elwin L. Mosier, and John G. Viets

Two of the better known occurrences of manganese in Precambrian rhyolites in the quadrangle were visited and samples collected for analysis. The first of these, Thorny Mountain (fig. 10), is representative of vein-type deposits; the second, Cuthbertson Mountain (fig. 10), is a replacement-type deposit.

The Thorny Mountain prospect consists of black manganese oxide in stringers, veinlets, pods, and breccia-filling in dense unaltered maroon rhyolite porphyry. The veinlets are thin and discontinuous and much of the manganese occurs as fracture coatings. The richest manganese mineralization occurs as the cement of a fault breccia zone that strikes N. 22° E. almost at right angles to the strike of banding in the rhyolite. Two vertical shafts have been dug on this zone. The Cuthbertson Mountain deposits consist of brown to black soft wad ore disseminated in altered bedded tuffs.

Analyses of the manganese oxide from these two localities (table 17) show a common and interesting suite of metals--barium, arsenic, zinc, lead, antimony, copper--that suggests to us that these manganese deposits are hydrothermal and not supergene in origin. Arsenic, antimony, mercury, tungsten, barium, and beryllium commonly are precipitated from manganese- and iron-rich hot spring systems in the Western United States, and this suite is also common to Carlin-type gold ores in Nevada. Both the sampled deposits contain arsenic, antimony, and beryllium; tungsten is enriched at Thorny Mountain and mercury was detected at Cuthbertson Mountain. However, the absence of gold above the detection limit of 0.05 ppm weakens the analogy with Carlin-type gold ores. We believe the trace elements indicate that the metals were deposited from hot spring waters of Precambrian age moving up fault zones, fractures, and joints in the rhyolite. Deposits of this type have not been found in overlying Cambrian sedimentary rocks.

MARCASITE-PYRITE HEMATITE DEPOSITS OF FILLED SINKS

by Mary H. Miller

Throughout central Missouri, roofless solution cavities in Carbonate strata are filled with marcasite, pyrite, hematite, clay, coal, galena, barite, and pieces of sandstone and dolomite rock (Bretz, 1950, p. 790; Hayes, 1957). Many of these "filled-sink" deposits have been mined for hematitic iron ore, and a few have been mined for other commodities, notably marcasite and pyrite for sulfuric acid. During the late 1800's and early 1900's, nearly one-third of Missouri's iron ore production came from these deposits in the Steelville district in Crawford, Dent, and Phelps Counties; two mines in the Rolla quadrangle, the Meramec and the Cherry Valley, each produced more than 200,000 tons of hematitic iron ore (fig. 15). From about 1911 to 1949, more than 250,000 tons of pyrite was mined in Missouri; a major portion of this ore came from solution-collapse structures in Phelps and Crawford counties, including about 135,000 long tons of pyrite ore from the Moselle No. 10 mine

Table 17.—Spectrographic and chemical analyses of Precambrian manganese ores and associated wall rocks, Rolla 1°x 2° quadrangle, Missouri

[G, greater than value shown; L, detected but below value shown; N, not detected at value shown; NA, not analyzed. Ag(0.5), Bi(10), Cd(20), Nb(10), Sc(5), Sn(10) not detected at value shown. Spectrographic analyses by E. L. Mosier; atomic absorption analyses for Au, Hg, In, Tl, and W by J. G. Viets, and for Zn by E. Tapia. Fe, Mg, Ca, Ti in percent; all other elements in parts per million]

	Cuthbertson Mountain deposit			Thorny Mountain deposit	
	Sample locality No.				
	RO-66	-66A	-66B	52	52A
Fe	1.5	2	3	1.5	0.2
Mg	0.2	0.5	0.7	0.1	0.3
Ca	0.07	0.15	L(0.05)	L(0.05)	0.7
Ti	0.05	0.2	0.3	0.15	0.03
Mn	G(5,000)	1,000	300	300	G(5,000)
As	1,000	N(200)	N(200)	N(200)	200
B	10	N(10)	150	10	500
Ba	G(5,000)	2,000	700	2,000	5,000
Be	50	2	5	1.5	20
Co	20	N(5)	5	N(5)	N(5)
Cr	15	N(10)	20	N(10)	20
Cu	100	L(5)	L(5)	10	150
Ge	10	N(10)	N(10)	N(10)	15
La	70	50	20	100	50
Mo	15	N(5)	N(5)	N(5)	20
Ni	20	N(5)	5	N(5)	N(5)
Pb	500	30	20	30	2,000
Sb	200	N(100)	N(100)	N(100)	1,000
Sr	150	N(100)	N(100)	N(100)	L(100)
V	50	20	100	L(10)	N(10)
W	2	1	2	7	500
Y	70	50	30	50	30
Zn	700	[1]180	[1]10	[1]L(5)	300
Zr	20	200	200	300	20
Au	N(.05)	N(0.05)	N(0.05)	N(0.05)	N(0.05)
Hg	0.64	NA	NA	NA	0.04
In	0.1	NA	NA	NA	0.1
Tl	0.2	NA	NA	NA	0.4

[1]Atomic abosrption analysis.

	Sample locality	Description
Cuthbertson Mountain	RO-66	Black manganese oxide impregnating ash-flow tuff.
	RO-66A	Black dense rhyolite ash-flow tuff with stubby pink feldspar phenocrysts.
	RO-66B	Gray, platy-weathering air-fall tuff.
Thorny Mountain	RO-52	Maroon rhyolite porphyry.
	RO-52A	Black manganese oxide from breccia zone.

in Phelps County (Grawe, 1945). Total production of iron ore from the Steelville district amounted to 4-million long tons from some 125 deposits.

Descriptive Model

References: Grawe, 1945
Bretz, 1950
Hayes, 1957

Ore body

Size: n x 10^2 ft diameter, n x 10 to n x 10^2 ft deep
Shape: Circular, steep-sided, bowl-shaped
Tonnage: n x 10^5 tons pyrite ore in larger deposits
Grade: 40-60 percent Fe (shipping ore)
Mineralogy: Hematite, limonite, marcasite, pyrite; minor chalcopyrite, asbolite (earthy cobalt oxide), cuprite, malachite; gangue is quartz, chert, calcite, and dolomite.

Host rocks

Sinks are developed preferentially in a zone of coarse crystalline, chert-free dolomite, 50-60 ft thick, in the upper Gasconade Dolomite, above the contact with cherty dolomite of the lower Gasconade. The sink structures extend up into the overlying Roubidoux Formation.

Associated structures and other features

1. Sink may be outlined by a ring of sandstone boulders ("rim rock") derived from rim of "bowl" formed by sandstone bed (Roubidoux) that originally slumped into sink.
2. Fluctuations of groundwater table control development of sinks and oxidation of iron sulfides to iron oxides.

Geochemical indicators

Not investigated.

Geophysical indicators

Ground magnetic surveys show anomalies over concentrations of specular hematite (Hayes, 1957, p. 24).

Electrical resistivity surveys can detect and determine the depth of a deposit (where pyrite and marcasite are being oxidized), but not size and quality.

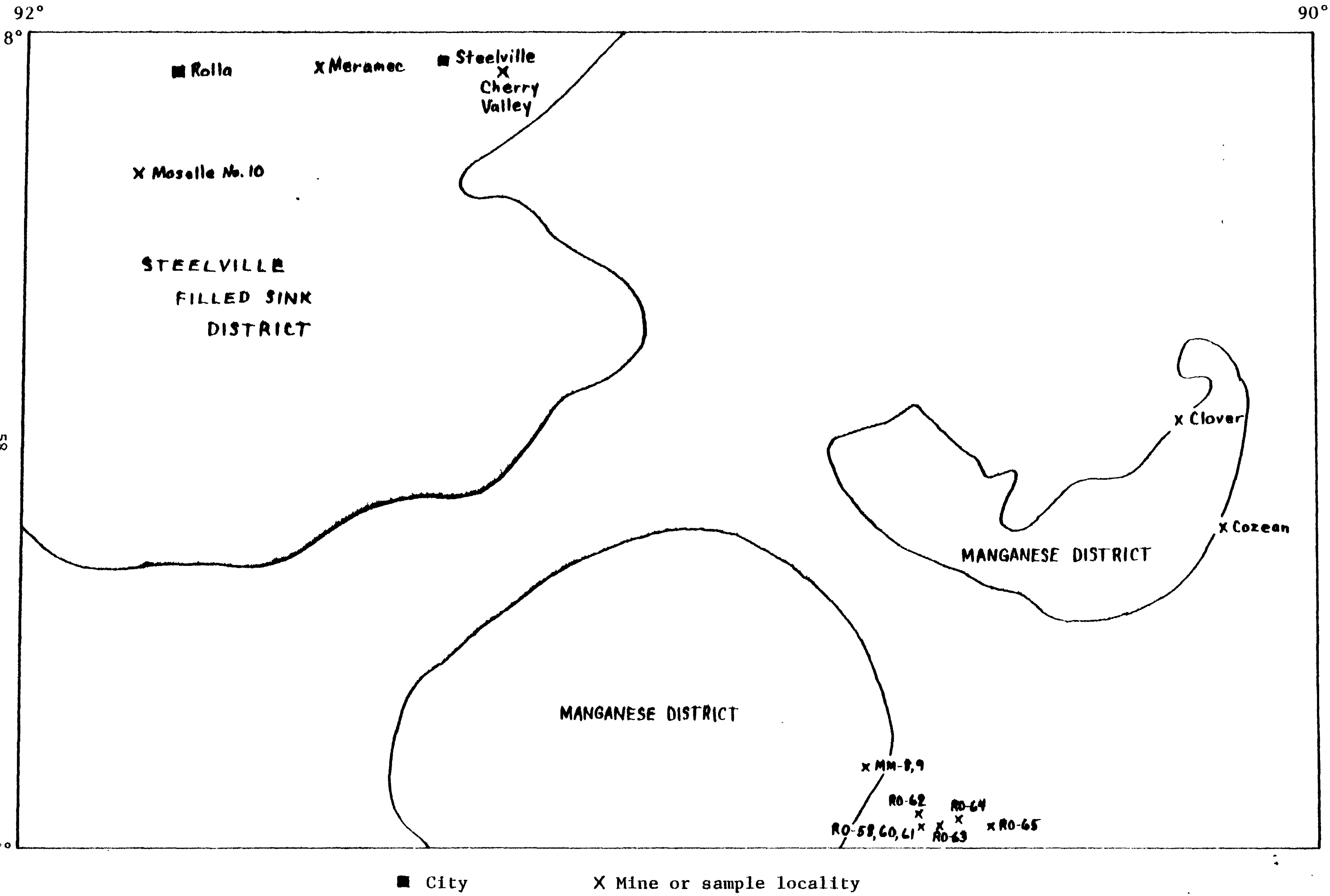


Fig. 15.--Locations of iron ore and manganese deposits in sedimentary rocks, Rolla 1° X 2° quadrangle, Missouri.

Resource Appraisal

Diagnostic Criteria:

1. Solution-collapse structure--oval or circular in plan; a few are crescent-shaped or irregular.
2. Steeply dipping "rim rock" beds (45^{o}-90^{o}) outline solution-collapse structure.
3. Proximity to St. Francois Mountains had a role in karst development and sink-filling with clay and metallic minerals.

Permissive Criteria:

1. Outcrop area of Gasconade Dolomite or lower part of Roubidoux Formation; base of upper Gasconade is most important horizon.
2. Outcrop areas of other Canadian dolomites (Jefferson City and Cotter Dolomites).
3. Former overlap of Pennsylvanian rocks (sources of iron, according to Grawe, 1945).

The northwestern quarter of the Rolla quadrangle fulfills the diagnostic criteria and most of the permissive criteria; this area has a high potential for additional marcasite-pyrite-hematite deposits. However, the physical properties of the iron minerals in these deposits are unsuitable to present standards for iron ores, and even if new deposits were discovered, commercial development would be unlikely (Hayes and Guild, 1967, p. 84-86; Wharton and others, 1969, p. 51-53). Other portions of the quadrangle appear to have little or no potential for deposits of this type.

Trace-element Geochemistry

Pyrite-marcasite ores for the most part contain less than detectable amounts of trace metals; some hematite ores contain trace amounts of vanadium, molybdenum, lead, and chromium (table 18).

RESIDUAL BROWN IRON ORE DEPOSITS

by Mary H. Miller

During the 19th century and early 20th century many small near-surface brown iron (limonitic) deposits in Missouri produced about 400,000 tons of ore. Although exact production figures are not available, deposits of this type in Missouri have yielded more than 2-million tons.

Descriptive Model

References: Crane, 1912
U.S. Bureau of Mines, 1943
Hayes, 1957
Meidav and others, 1958

Table 18.--Spectrographic analyses of iron oxides and sulfides, Steelville district, Missouri

[G, greater than value shown; L, detected but below value shown; N, not detected at value shown. Analyses by E. L. Mosier. Fe, Mg, Ti in percent; all other elements in parts per million]

	Sample locality No.					
	1	2	3	4	5	7
Fe------	50	20	G(50)	50	50	50
Mg------	L(0.05)	L	L	L	L	L
Ti------	0.005	0.005	0.005	L	0.007	0.007
Mn------	30	20	L(20)	L	30	30
As------	N(500)	N	N	N	N	N
Ba------	N(50)	N	N	N	N	N
Be-----	N(2)	N	N	N	N	N
Co-----	N(10)	N	N	N	20	15
Cr-----	N(20)	N	100	70	N	70
Cu-----	L(10)	10	L	L	30	70
Mo-----	N(10)	N	70	70	100	100
Ni-----	N(10)	N	30	50	70	50
Pb-----	N(20)	70	100	N	30	100
Sc-----	N(10)	N	N	N	N	N
V------	N(20)	N	100	150	N	200
Zn-----	N(500)	N	N	N	N	N
Zr-----	N(20)	N	N	N	N	N

Sample locality No.	Description
1	Moselle No. 10 mine, Phelps Co.: pyrite/marcasite
2	Do.
3	Moselle No. 10 mine, Phelps Co.: hematite
4	Do.
5	Cherry Valley No. 1 mine, Crawford Co.: hematite
7	Cherry Valley No. 1 mine, Crawford Co.: specular hematite

Ore body

Size: n x 10 - n x 10^2 ft diameter, n - n x 10 ft thick
Shape: Irregular, roughly lenticular; flat-lying to gently inclined
Depth: 0 - n x 10 ft below surface
Tonnage: n x 10^5 tons ore
Grade: 45-55 percent Fe (shipping ore)
Mineralogy: Limonite; minor hematite, pyrite, and marcasite; gangue is chert and quartz.

Host rocks

Residuum, principally from Gasconade, Roubidoux, and Jefferson City formations; some deposits in residuum from Cambrian formations.

Controlling structures and other features: None known.

Geochemical indicators: On ground surface, limonite fragments with characteristic metal content.

Geophysical indicators: Resistivity is lower where limonite occurs near surface.

Resource Appraisal

Diagnostic Criteria:

1. In residuum derived chiefly from the Gasconade, Roubidoux, Jefferson City, or Cambrian formations.
2. Limonite fragments on surface.

Permissive Criteria:

1. Known occurrence

The resource outlook for these deposits must take into account that (1) individual deposits tend to be small, (2) iron content is usually medium or low-grade, and chemical composition variable, and (3) beneficiation to 50 percent or more Fe, with properties acceptable for blast-furnace use, is difficult and often impossible using conventional gravity equipment.

Areas of high potential for brown iron ore deposits are those where thick residuum (n x 10 ft thick) derived from preferred formations is present; the east-central and southeastern portions of the Rolla quadrangle are favorable areas. The western half of the quadrangle has a lower potential for these deposits, but some may be present at the unconformity between the Gasconade and Eminence formations. Ores have been produced from these deposits as recently as 1957, and small production may occur in the future depending on existence of a local market.

Trace-element Geochemistry

by Ralph L. Erickson and Elwin L. Mosier

Many small surface prospects opened on shows of dark-brown to black limonitic iron oxide in what appear to be filled sinks are present in Wayne County near the southern border of the quadrangle. Most are ponded with water, and geologic relationships are obscured, but they all appear to be solution-collapse structures filled with chert and clay residuum and various forms of iron oxide. The oxides occur as cement between chert fragments in residuum, and as ropy, porous masses that resemble pahoehoe lava. The largest prospect visited had been selectively mined over a roughly circular area of about 300-m diameter.

Limonitic materials from 9 of these prospects in Wayne County, and from a similar one (Cozean mine) in Madison County, were analyzed spectrographically and chemically to determine the trace metal suite that occurs with these deposits (table 19). They are characterized by low base- and precious-metal content, and the manganese content is low in most samples. Arsenic and nickel are the most abundant trace metals; both show a wide value range and the high values correlate well with each other. Molybdenum is almost consistently present, in amounts ranging from 10 to 200 ppm. Arsenic, beryllium, cobalt, copper, and nickel all appear to be somewhat higher in these limonitic ores than in the marcasite-pyrite-hematite ores (see table 18).

MANGANESE DEPOSITS IN SEDIMENTARY ROCKS AND RESIDUUM

by Mary H. Miller

Small deposits of manganese oxides occur in sedimentary rocks and residuum in the Rolla $1^{o} \times 2^{o}$ quadrangle, but apparently the only production from such deposits was during World War I when 80 to 100 tons of manganese ore was shipped from the Clover Mine in the NW 1/4 sec. 30, T. 33 N., R. 8 E., Madison County (fig. 15). Although several other prospects occur in the area, none is known to have shipped any ore.

Descriptive Model

Reference: Grawe, 1943

Ore body

Size: Very small, n - n x 10 cu ft
Shape: Irregular, probably lenticular, flat-lying
Depth: n ft below surface
Tonnage: n - n x 10 tons ore
Grade: 15-35 percent Mn (shipping ore)
Mineralogy: Manganite, psilomelane, pyrolusite, wad; gangue minerals are kaolinite or halloysite, limonite, goethite, and quartz (chert, sand, druse).

Host rocks

1. Residuum, principally from Gasconade, Eminence, or Potosi formations; some deposits in Jefferson City or Roubidoux formations.

Table 19.—Spectrographic and chemical analyses of limonitic iron ores, Wayne and Madison County, Missouri

[G, greater than value shown; L, detected but below value shown; N, not detected at value shown. Ag(0.5), Au(0.05), B(10), Bi(10), Cd(20), La(20), Nb(20), Sb(100), Sn(10), Sr(100), W(50), Y(10), Zr(10) not detected at value shown. NA, not analyzed. Spectrographic analyses by E. L. Mosier; atomic absorption analyses for Hg and Zn by E. Tapia and J. D. Sharkey. Fe, Mg, Ti in percent; all other elements in parts per million]

Sample locality No.	MM-8	MM-9	RO-58	-60	-61	-62	-63	-64	-65	COZ
Fe	30	30	20	G(20)	G(20)	G(20)	G(20)	G(20)	G(20)	G(20)
Mg	0.05	0.15	0.02	0.03	0.1	0.05	0.07	0.05	0.02	0.05
Ti	0.03	0.007	0.02	L(0.002)	0.01	0.002	L(0.002)	0.003	0.003	0.015
Mn	20	150	G(5,000)	500	300	100	70	100	70	200
As	700	N(500)	N(200)	3,000	1,000	300	200	N(200)	5,000	1,500
Ba	N(50)	N(50)	300	30	20	N(20)	N(20)	N(20)	20	L(20)
Be	3	7	1.5	2	10	2	1	7	1	7
Co	50	70	30	50	30	7	7	15	70	20
Cr	100	50	20	50	50	30	50	50	70	50
Cu	20	30	20	50	70	10	50	50	7	100
Hg	NA	NA	0.06	0.08	0.14	0.16	0.16	0.08	0.12	NA
Mo	30	15	N(5)	20	15	10	70	50	30	200
Ni	100	100	5	1,000	200	70	20	30	500	70
Pb	70	N(20)	15	50	20	30	100	70	30	500
V	150	150	20	30	70	20	30	20	15	100
Zn	N(500)	N(500)	10	15	40	700	500	500	N(5)	700
Sc	15	L(10)	N(5)	N(5)	N(5)	N(5)	N(5)	N(5)	N(5)	N(5)

Sample locality No. (see fig. 15)	Description
MM-8	Hematite and limonite, thought to be from one of old mines in $SE^1/_4$sec. 14, T. 28 N., R. 3 E.; collected at old ore washer at Leeper.
MM-9	Limonite pipe ore, same locality as sample MM-8.
RO-58	Black Fe and Mn(?) oxides cementing chert breccia; pit in residuum, NE corner, sec. 10, T. 27 N., R. 4 E.
RO-60	Dark-brownish-black Fe oxides; pit, $SW^1/_4NE^1/_4SE^1/_4$sec. 10, T. 27 N., R. 4 E.
RO-61	Dark-brown ropy concretionary Fe oxide; pit in residuum, 100 m SE of RO-60.
RO-62	Limonite in form of ropy lava; pit in $NE^1/_4NW^1/_4$sec. 3, T. 27 N., R. 4 E.
RO-63	Limonite ore; large pit at E center $NW^1/_4$sec. 12, T. 27 N., R. 4 E.
RO-64	Limonite; pit in $NE^1/_4SE^1/_4$sec. 6, T. 27 N., R. 5 E.
RO-65	Limonite; pit in $SE^1/_4NW^1/_4NE^1/_4$sec. 10, T. 27 N., R. 5 E.
COZ	Massive limonite; Cozean mine, in residuum from Gasconade Dolomite, $NE^1/_4SW^1/_4$sec. 2, T. 31 N., R. 8 E., approximately 3 mi SE of Marquand.

2. Chert breccias
3. Manganiferous sandstones

Controlling structures and other features

Related to present erosion surface. Some deposits appear to be related to unconformities.

Geochemical indicators: Not investigated

Geophysical indicators: None known

Resource Appraisal

Diagnostic criteria:

1. Residuum derived from the Gasconade, Eminence, Potosi, Jefferson City, or Roubidoux formations; or the outcrop area of any of these formations.

Permissive criteria:

1. Known occurrence
2. Gasconade-Eminence unconformity or the Devonian-Silurian unconformity (Perry County)
3. Occurrence of limonitic deposits

The areas of highest potential appear to be the southeastern quarter of the quadrangle and the southern part of the northeastern quarter. However, the high silica and/or alumina and iron in these deposits, and their small size and erratic grade, make them unsuitable for production on a commercial scale (Dorr, 1967, p. 89). The western half of the quadrangle apparently has low potential for deposits of this type.

COPPER DEPOSITS IN SEDIMENTARY ROCKS

by Walden P. Pratt, Ralph L. Erickson, and Elwin L. Mosier

References: Bridge, 1930, p. 169-182
Kinkel, 1967, p. 63-66
Weller and St. Clair, 1928, p. 331-336

Copper deposits occur in sedimentary rocks in the Rolla quadrangle in two distinctly different types of geologic setting.

(1) In the Cornwall mines area in Ste. Genevieve County (fig. 2b), chalcopyrite ore altered to bornite, chalcocite, malachite, azurite, and cuprite occurred "as a replacement and impregnation of soft, porous chert beds, as a cement in sedimentary breccia, in small chimneys at vertical fissures, and irregularly filling erosion depressions in the dolomite" (Weller and St. Clair, 1928, p. 332). The mineralization formed irregularly bedded deposits along unconformities within and at the base of the Powell Formation of Ordovician age. Sporadic mining operations from 1863 to 1916 produced ores reported to have contained as much as 25 percent copper (in carefully cobbed

ore) and commonly 16 percent copper (probably in sorted ore); total production figures are not available but probably amount to a few thousand tons of copper.

(2) In the Eminence area, ores composed of chalcopyrite, chalcocite, cuprite, and malachite occurred chiefly as a replacement of the calcareous matrix in a basal conglomerate of the Eminence Dolomite of Cambrian age at and near its contact with the underlying Precambrian rhyolite porphyry. At one locality, ore occurred several hundred ft above the Precambrian, along bedding planes beneath impervious beds in the Gasconade Dolomite of Ordovician age. Mining was carried on from 1838 to 1840 and on a smaller scale at various times up to 1927; total production probably was on the order of several hundred tons of copper.

Samples of ore minerals from both areas were analyzed to determine whether or not other metals of economic significance are associated with the copper ores. Results of the analyses are given in tables 20 and 21. Significant points are: (1) All samples contain only trace amounts of metals other than copper. (2) Gossan samples from the Cornwall area (table 20, samples 4 and 5) are somewhat enriched in silver, arsenic, lead, and zinc as compared to chalcopyrite and breccia ore (samples 1-3). (3) The fault gouge sample from the Cornwall area (sample 6) is particularly intriguing because its trace-element suite has a basic igneous rock signature--titanium, barium, beryllium, chromium, lanthanum, scandium, strontium, vanadium, yttrium, and zirconium. These elements are mostly below detection limits in all the other samples, but are present in sample 6 in amounts commensurate with some basic igneous component in the fault zone, analogous to diatremes elsewhere in Missouri. (4) The sample from the Slater Mine in the Eminence area (table 21, sample RO-50) contains significant amounts of bismuth (200 ppm) and molybdenum (200 ppm), which suggests that this deposit was formed at higher temperatures than the other and may be closer to a primary metal source.

There probably is some potential for the existence of similar concentrations of copper minerals in the same respective geologic formations down dip from the near-surface occurrences that were easily discovered and exploited. However, the results of exploratory drilling to test this potential have thus far been negative in both areas. The difficulty and expense of discovering, mining, and beneficiating such deposits, and their minuscule size relative to present-day commercial copper deposits, mean that any such deposits that may exist would have very little importance as resources for the foreseeable future.

BASE AND PRECIOUS METALS IN PRECAMBRIAN VEINS

by Walden P. Pratt and Ralph L. Erickson

Quartz veins are fairly common in the Precambrian terrane of the St. Francois Mountains, and a few such veins contain base-metal sulfides. Examples are a 6-cm vein containing minor galena and chalcopyrite, which cuts alkali rhyolite in Shut-in Creek east of Bell Mountain (fig. 2b), and a thin vein containing sparse sphalerite and galena that cuts a gabbro sill underneath the magnetite ore body in the Pilot Knob mine. Pyrite-sphalerite-calcite veinlets in the Precambrian basement at the Fletcher mine in the Viburnum Trend (Roedder, 1977, p. 477) are included in this category although

Table 20.—Spectrographic analyses of rock samples from the Cornwall Copper Mine area, Ste. Genevieve County, Missouri

[G, greater than value shown; L, detected but below value shown; N, not detected at value shown. Bi(10), Cd(20), Nb(10), Sn(10), W(50) not detected at value shown. E. L. Mosier, analyst]

	Sample locality No.					
	1	2	3	4	5	6
Fe	20	20	10	20	15	5
Mg	L(0.02)	0.1	1	0.03	0.7	1
Ca	L(0.05)	0.1	2	L(0.05)	10	0.2
Ti	0.005	0.01	0.01	0.015	0.01	0.5
Mn	N(10)	30	70	N(10)	100	200
Ag	2	5	3	30	15	N(0.5)
As	N(200)	N(200)	N(200)	1,000	200	N(200)
B	N(10)	N(10)	15	10	L(10)	20
Ba	N(20)	N(20)	N(20)	N(20)	N(20)	200
Be	N(1)	N(1)	N(1)	N(1)	N(1)	5
Co	N(5)	N(5)	5	N(5)	50	20
Cr	N(10)	10	10	10	20	150
Cu	G(20,000)	G(20,000)	G(20,000)	20,000	G(20,000)	2,000
La	N(20)	N(20)	N(20)	N(20)	N(20)	70
Mo	N(5)	N(5)	N(5)	20	15	N(5)
Ni	N(5)	N(5)	5	N(5)	70	50
Pb	30	100	50	150	200	100
Sb	N(100)	150	N(100)	100	150	N(100)
Sc	N(5)	N(5)	N(5)	N(5)	N(5)	20
Sr	N(100)	N(100)	N(100)	N(100)	N(100)	300
V	N(10)	N(10)	10	N(10)	20	200
Y	N(10)	N(10)	N(10)	N(10)	N(10)	50
Zn	N(200)	N(200)	200	N(200)	7,000	500
Zr	N(10)	N(10)	N(10)	N(10)	N(10)	100

Sample locality No.	Description
1	Chalcopyrite—Grifore dump.
2	Chalcopyrite—Grifore dump.
3	Breccia ore; fine-grained, pale-yellow-gray limestone fragments and quartz grains cemented with blue and green secondary copper minerals, chalcopyrite, and possible cuprite. Grifore dump.
4	Orange-brown earthy gossan with traces of original chalcopyrite. Grifore dump.
5	Yellow-brown gossany breccia with quartz and secondary copper minerals. Chicago drift area.
6	Clay gouge from fault zone—Chicago drift area.

Table 21.--Spectrographic and chemical analyses of rocks from copper prospects in Shannon County, Missouri

[G, greater than value shown; L, detected but below value shown; N, not detected at value shown. Cd(20), La(20), Nb(20), Sb(100), Sc(5), Sn(10), Sr(100), W(50) not detected at value shown. Spectrographic analyses by E. L. Mosier; atomic absorption analyses for Au by J. G. Viets; for Hg by E. Tapia; and for Zn by J. D. Sharkey. Fe, Mg, Ca, Ti in percent; all other elements in parts per million]

	Sample locality No.		
	RO-47	-49A	-50
Fe--------	1	7	0.5
Mg--------	0.2	1	0.05
Ca--------	0.5	2	0.07
Ti--------	0.007	0.01	0.005
Mn--------	15	200	500
Ag--------	5	5	10
As--------	N(200)	500	N(200)
Au--------	N(0.05)	N(0.05)	N(0.05)
B---------	15	N(10)	N(10)
Ba--------	30	70	200
Be--------	1	1.5	N
Bi--------	N(10)	N(10)	200
Co--------	30	20	50
Cr--------	15	10	L(10)
Cu--------	G(20,000)	G(20,000)	G(20,000)
Ge--------	10	7	N(5)
Hg--------	0.16	0.34	1.20
Mo--------	N(5)	20	200
Ni--------	70	15	30
Pb--------	100	100	500
V---------	50	20	10
Y---------	N(10)	20	30
Zn--------	10	110	140
Zr--------	10	30	20

Sample locality No.	Description
RO-47	Malachite in clay and chert residuum, Casey Mine, SW 1/4 sec. 14, T. 29 N., R. 4 W.
RO-49A	Copper concentrate from old, abandoned table concentrator, Sutton Mine, NE 1/4 sec. 18, T. 28 N., R. 3 W.
RO-50	Green copper minerals from Slater Mine, NE 1/4 sec. 36, T. 29 N., R. 4 W.

they do not contain quartz. The age of several of the veins has been identified as Precambrian (1400-1500 m.y.) on the basis of lead isotope compositions (B. R. Doe, U.S. Geological Survey, written commun., 1980).

The trace-element content of these veins is variable. A sulfide-rich fraction of the vein at the Pilot Knob mine (table 7, sample 7) contains major zinc, lead, and cadmium, and anomalously high amounts of several other metals--200 ppm Ag, 1500 As, 150 Co, 500 Mo, 200 Ni, and 1000 Sb--indicating that the vein mineralogy is more complex than is readily apparent in hand specimen. The trace-element suite of the Shut-in Creek vein (table 22, sample RO-38A) contains the expected base metals (lead, zinc, copper, and cadmium) and a little silver, but is otherwise essentially barren. A sample of a sulfide-free quartz vein in alkali rhyolite southeast of Ironton (table 22, sample G16) is similarly low in trace elements, and lower in most elements than the typical volcanic rocks of the region (see Pratt and others, 1980).

The exposed Precambrian rocks are in general notably free of hydrothermal alteration and have been thoroughly prospected. Although the existence of base and precious metal-bearing quartz veins in the subsurface Precambrian terrane is geologically possible, the available evidence suggests that the probability is low. Moreover, if such deposits did exist, they would present very small targets for deep exploration under the thick sedimentary cover of most of the Rolla 1^ox 2^o quadrangle. We therefore conclude that the economic potential for such deposits is nil.

MASSIVE SULFIDE DEPOSITS IN PRECAMBRIAN VOLCANIC ROCKS

by Walden P. Pratt

Major stratabound ore bodies of copper, lead, and zinc sulfides, commonly known as massive sulfide deposits, occur in volcanic and volcaniclastic rocks in many parts of the world, and this report would be incomplete without addressing the potential for such deposits in the widespread volcanic field of the St. Francois Mountains.

The important massive sulfide deposits of the world range widely in age, structural form, and metamorphic history, but all are associated with submarine volcanic or volcaniclastic rocks (Anderson, 1969; Tatsumi and Watanabe, 1971; Sangster, 1972; Cox and others, 1973). The volcanic rocks range from basaltic pillow lavas to silicic lavas and pyroclastic rocks; where the mineralized rocks are silicic lavas, they generally represent the upper parts of thick volcanic complexes whose voluminous lower and middle parts consist largely of basaltic and andesitic flows and breccias. The volcanic rocks of the St. Francois Mountains do not fulfill the essential criteria of this model; they were nearly all deposited subaerially, and they are predominantly rhyolitic (Pratt and others, 1979). Subsurface Precambrian rocks in the Rolla quadrangle include minor flows, dikes, and ring intrusions of trachyte, trachyandesite, and trachybasalt, but there is no evidence that the extensive rhyolites are parts of thick complexes of rhyolite-andesite-basalt (Kisvarsanyi, 1980a).

Some minor occurrences of sulfides in the St. Francois Mountains' volcanic rocks are known. (1) Amygdaloidal andesite about 13 mi south-southeast of Ironton was reported by Weixelman (1959, p. 15) to contain chalcopyrite, chalcocite, and galena, but spectrographic and chemical analyses

Table 22.--Spectrographic and chemical analyses of Precambrian quartz veins, Rolla 1° x 2° quadrangle, Missouri

[Fe, Mg, Ca, and Ti reported in percent; all other elements reported in parts per million. G, greater than value shown; L, detected but below value shown; N, not detected at value shown. Spectrographic analyses by E. L. Mosier; colorimetric analyses for As and W, and atomic-absorption analyses for Ag, Bi, Cd, Cu, Pb, Sn, and Zn by S. M. Kneipple; atomic-absorption analysis for Sb by J. Sharkey]

	Sample No. G16	Sample No. RO-38A		Sample No. G16	Sample No. RO-38A
Fe------	0.3	0.1	Cu-----	[1]L(5)	1,000
Mg------	0.03	L(.02)	La-----	70	N(20)
Ca------	0.07	0.15	Mo-----	N(5)	N(5)
Ti------	0.02	0.002	Nb-----	N(20)	N(20)
Mn------	70	30	Ni-----	N(5)	N(5)
Ag------	[1]0.15	15	Pb-----	[1]L(5)	[3]G(20,000)
As------	[2]10	N(200)	Sb-----	[1]N(1)	N(100)
Au------	N(10)	N(10)	Sc-----	N(5)	N(5)
B-------	30	10	Sn-----	[1]N(1)	N(10)
Ba------	70	20	Sr-----	N(100)	N(100)
Be------	150	N(1)	V------	N(10)	N(10)
Bi------	[1]L(0.5)	N(10)	W------	[2]N(1)	N(50)
Cd------	[1]L(0.05)	100	Y------	700	N(10)
Co------	N(5)	N(5)	Zn-----	[1]L(5)	1,500
Cr------	N(10)	N(10)	Zr-----	30	N(10)

[1]Atomic-absorption analysis.
[2]Colorimetric analysis.
[3]Pb visually estimated at ~30,000 ppm.

Sample No.	Description
G16	Quartz vein in alkali rhyolite, 12 mi south-southeast of Ironton, NW 1/4 SW 1/4 SE 1/4 sec. 26, T. 32 N., R. 4 E., Des Arc NE quadrangle.
RO-38A	Galena- and chalcopyrite-bearing quartz vein in alkali rhyolite, prospect adit on Shut-in Creek east of Bell Mtn., SW 1/4 NE 1/4 SE 1/4 sec. 30, T. 34 N., R. 2 E., Johnson Shut-ins quadrangle.

of a sample of this rock containing galena as the only visible sulfide show barely anomalous lead and no unusual contents of other base metals (table 23, sample No. G39). The trace-element contents of andesites from several other localities in the St. Francois Mountains are similarly unremarkable (table 23, sample Nos. C109, D21, G41, and G84). (2) Drilling at Ketcherside Gap some years ago reportedly penetrated "massive sulfides" in volcanic rocks at an unknown depth (P. R. Dingess, Asarco Inc., oral commun., 1980). Samples of this mineralized rock are not available. Prospect pits at the surface at this locality show secondary green copper minerals impregnating and staining intensely altered laminated air-fall tuff, but analyses of this rock show nothing unusual (table 23, sample No. RO-71A). Alkali rhyolite from 1/2 mi west of this locality likewise contains no unusual trace elements (table 23, sample No. C80), and two other alkali rhyolites from about 1 mi northwest and 1.5 mi north-northwest of Ketcherside Gap have trace-element suites similar to sample C80 (table 23, sample Nos. C79 and C81). In fact a large suite of volcanic rocks selected as representative of all the exposed volcanic rocks in the region contains no anomalous amounts of base or precious metals, or of common pathfinder elements such as arsenic and antimony (Pratt and others, 1980).

We conclude that the potential for conventional massive sulfide deposits in volcanic rocks in the Rolla $1^{\circ} \times 2^{\circ}$ quadrangle is virtually nil. The origins of the minor sulfide occurrences in volcanic rocks are not known, but their geochemical associations are unremarkable. If they represent some manifestation of ore deposits of an unknown type, the resource potential for such deposits cannot be appraised on the basis of present knowledge.

Table 23.—Spectrographic and chemical analyses of selected Precambrian volcanic rocks, Rolla 1°x 2° quadrangle, Missouri

[N, not detected at value shown; NA, not analyzed. Spectrographic analyses by E. L. Mosier (RO-71A) and D. F. Siems; other analyses by S. M. Kneipple, J. D. Sharkey, and J. G. Viets. Fe, Mg, Ca, Ti reported in percent, all other elements reported in parts per million]

	Sample No.								
	G39	C109	D21	G41	G84	RO-71A	C80	C79	C81
Fe	7	10	5	10	10	3	2	2	2
Mg	1.5	1	2	5	1	2	0.02	0.03	0.05
Ca	2	1.5	2	3	2	3	0.10	N(0.05)	0.10
Ti	0.5	1	0.5	1	1	0.05	0.10	0.15	0.10
Mn	3,000	700	1,000	2,000	1,500	2,000	300	500	1,000
Ag	[1]0.20	N(0.5)	N(0.5)	[1]0.20	N(0.5)	2	[1]3	[1]0.60	[1]0.25
As	[2]10	N(200)	N(200)	[2]10	N(200)	N(200)	[2]30	[2]60	[2]10
Au	N(10)	N(10)	N(10)	N(10)	N(10)	[1]N(0.05)	N(10)	N(10)	N(10)
B	15	20	30	20	30	N(10)	15	100	20
Ba	1,000	1,000	1,000	1,000	1,000	1,000	300	200	300
Be	3	1	1	1	2	5	2	2	2
Bi	[1]<0.5	N(10)	N(10)	<0.5	N(10)	N(10)	[1]<0.5	[1]<0.5	[1]<0.5
Cd	[1]0.45	N(20)	N(20)	[1]0.05	N(20)	N(20)	[1]<0.05	[1]<0.05	[1]<0.05
Co	20	20	30	70	20	20	N(5)	N(5)	N(5)
Cr	10	20	100	N(10)	15	20	<10	10	<10
Cu	[1]<5	N(5)	50	[1]<5	70	20,000	[1]<5	[1]25	[1]<5
Hg	[3]0.10	NA	NA	[3]0.30	NA	[3]0.14	[3]0.14	[3]0.12	[3]0.06
La	100	<20	50	20	100	N(20)	70	70	70
Mo	N(5)	N(5)	N(5)	N(5)	N(5)	10	N(5)	N(5)	N(5)
Nb	<20	<20	N(20)	N(20)	<20	N(20)	<20	<20	<20
Ni	5	15	50	5	5	20	5	5	5
Pb	[1]200	<10	10	[1]<5	50	20	[1]<5	[1]<5	[1]<5
Sb	[1]N(1)	N(100)	N(100)	[1]N(1)	N(100)	N(100)	[1]N(1)	[1]N(1)	[1]N(1)
Sc	20	50	20	30	30	N(5)	7	7	7
Sn	[1]N(2)	N(10)	N(10)	[1]N(2)	N(10)	N(10)	[1]N(2)	[1]N(2)	[1]N(2)
Sr	300	<100	300	500	500	N(100)	100	<100	<100
V	100	200	200	500	150	30	<10	10	10
W	[2]<1	N(50)	N(50)	[2]N(1)	N(50)	N(50)	[2]1	[2]3	[2]2
Y	100	70	30	50	100	30	70	70	50
Zn	[1]200	N(200)	N(200)	[1]80	N(200)	[1]250	[1]5	[1]<5	[1]5
Zr	200	300	150	100	200	70	300	500	200

[1]Analyzed by atomic absorption spectrometry.
[2]Analyzed by colorimetric method.
[3]Analyzed by mercury analizer.

Sample No.	Description
G39	Amygdaloidal andesite with visible galena, NE1/4 SW1/4 sec. 29, T. 32 N., R. 5 E.
C109	Amygdaloidal andesite, NW1/4 NW1/4 sec. 24, T. 38 N., R. 1 W.
D21	Andesite with minor pyrite, S1/2 NE1/4 sec. 17, T. 33 N., R. 8 E.
G41	Dark-purple andesite, SE1/4 NE1/4 sec. 29, T. 32 N., R. 5 E.
G84	Andesite, ctr. SE1/4 sec. 11, T. 32 N., R. 1 E.
RO-71A	Copper-stained altered tuff in prospect pit, Ketcherside Gap, NE1/4 sec. 36, T. 33 N., R. 3 E.
C80	Alkali rhyolite, ctr. of N edge sec. 36, T. 33 N., R. 3 E.
C79	Alkali rhyolite, NE1/4 NE1/4 SW1/4 sec. 24, T. 33 N., R. 3 E.
C81	Alkali rhyolite, SW1/4 NW1/4 SW1/4 sec. 25, T. 33 N., R. 3 E.

REFERENCES

Allingham, J. W., 1976, Interpretation of aeromagnetic anomalies in southeastern Missouri: U.S. Geological Survey Open-File Report 76-868, 319 p., 1 pl., scale 1:250,000.

Amos, D. H., and Blankenship, D. B., 1980, Geologic map of the Advance quadrangle, Missouri: U.S. Geological Survey Miscellaneous Field Studies Map MF-1197, scale 1:24,000.

Anderson, C. A., 1969, Massive sulfide deposits and volcanism: Economic Geology, v. 64, no. 2, p. 129-146.

Anderson, K. H., 1981, Isopach and selected lithofacies map of the Cambrian Bonneterre Formation, Rolla 1^{o}x 2^{o} quadrangle, Missouri: U.S. Geological Survey Miscellaneous Field Studies Map MF-1002-I, scale 1:250,000.

Bretz, J. H., 1950, Origin of the filled sink structures and circle deposits of Missouri: Geological Society of America Bulletin, v. 61, p. 789-834.

Bridge, Josiah, 1930, Geology of the Eminence and Cardareva quadrangles: Missouri Bureau of Geology and Mines, 2d ser., v. 24, 228 p.

Brobst, D. A., and Wagner, R. J., 1967, Barite, in Mineral and water resources of Missouri: Missouri Division of Geological Survey and Water Resources, 2d series, v. 43, p. 99-106.

Brown, J. S., Emery, J. A., and Meyer, P. A., Jr., 1954, Explosion pipe in test well on Hicks Dome, Hardin County, Illinois: Economic Geology, v. 49, no. 8, p. 891-902.

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.

Cordell, Lindrith, 1979, Gravity and aeromagnetic anomalies over basement structure in the Rolla quadrangle and the southeast Missouri lead district: Economic Geology, v. 74, p. 1383-1394.

Cornwall, H. R., and Vhay, J. S., 1967, Cobalt and Nickel, in Mineral and water resources of Missouri: Missouri Division of Geological Survey and Water Resources, 2d ser., v. 43, p. 68-70.

Cox, D. P., Schmidt, R. G., Vine, J. D., Kirkemo, Harold, Tourtelot, E. B., and Fleischer, Michael, 1973, Copper, in Brobst, D. A. and Pratt, W. P., eds., United States Mineral Resources: U.S. Geological Survey Professional Paper 820, p. 163-190.

Crane, G. W., 1912, The iron ores of Missouri: Missouri Bureau of Mines and Geology [Report], 2d series, v. 10, 434 p.

Desborough, G. A., 1967, Closed system differentiation of sulfides in olivine diabase, Missouri: Economic Geology, v. 62, no. 5, p. 595-613.

Dorr, J. V. N., 1967, Manganese, in Mineral and water resources of Missouri: Missouri Division of Geological Survey and Water Resources [Report], 2d series, v. 43, p. 88-91.

Economic Geology, 1977, An issue devoted to the Viburnum Trend, southeast Missouri: Economic Geology, v. 72, no. 3.

Erickson, R. L., Mosier, E. L., and Viets, J. G., 1978, Generalized geologic and summary geochemical maps of the Rolla 1^{o}x 2^{o} quadrangle, Missouri: U.S. Geological Survey Miscellaneous Field Studies Map MF-1004A, scale 1:250,000.

Erickson, R. L., Mosier, E. L., Viets, J. G., and King, S. C., 1979, Generalized geologic and geochemical maps of the Cambrian Bonneterre Formation, Rolla 1^{o}x 2^{o} quadrangle, Missouri: U.S. Geological Survey Miscellaneous Field Studies Map MF-1004B, scale 1:250,000.

Galloway, W. E., 1978, Uranium mineralization in a Coastal Plain fluvial aquifer system--Catahoula Formation, Texas: Economic Geology, v. 73, p. 1655-1676.

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

Grawe, O. R., 1943, Manganese deposits of Missouri: Missouri Division of Geological Survey and Water Resources 62d Biennial Report, appendix 6, 77 p.

_____1945, Pyrite deposits of Missouri: Missouri Geological Survey and Water Resources, 2d series, v. 30, 482 p.

Guild, P. W., 1967, Minor metals associated with zinc-lead ores, in Mineral and water resources of Missouri: Missouri Division of Geological Survey and Water Resources [Report], 2d series, v. 43, p. 73-74.

Gustavson, J. B., 1977, Geochemical prospecting for porphyry systems in the St. Francois Mountains, Missouri: American Institute of Mining, Metallurgical, and Petroleum Engineers Preprint, 36 p.

Hayes, W. C., Jr., 1947, Geology of the Ozark-Martin mine area, Madison County, Missouri: Rolla, University of Missouri School of Mines and Metallurgy, Master's thesis.

_____1957, Exploration and development of the sedimentary iron ores of Missouri: Missouri Division of Geological Survey and Water Resources Information Circular no. 14, 33 p.

Hayes, W. C., and Guild, P. W., 1967, Iron, in Mineral and water resources of Missouri: Missouri Division of Geological Survey and Water Resources [Report], 2d ser., v. 43, p. 74-88.

Heyl, A. V., 1972, The 38th parallel lineament and its relationship to ore deposits: Economic Geology, v. 67, p. 879-894.

Heyl, A. V., Brock, M. R., Jolly, J. L., and Wells, C. E., 1965, Regional structure of the Southeast Missouri and Illinois-Kentucky mineral districts: U.S. Geological Survey Bulletin 1202-B, 20 p.

Hobbs, S. W., 1967, Tungsten, in Mineral and Water Resources of Missouri: Missouri Division of Geological Survey and Water Resources [Report], 2d series, v. 43, p. 91-93.

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

Kiilsgaard, T. H., 1967, Silver, in Mineral and Water Resources of Missouri: Missouri Division of Geological Survey and Water Resources [Report], 2d series, v. 43, p. 70-72.

Kiilsgaard, T. H., Hayes, W. C., and Heyl, A. F., 1967, Metallic Minerals Resources Lead and Zinc, in Mineral and water resources of Missouri: Missouri Division of Geological Survey and Water Resources [Report], 2d series, v. 43, p. 41-63.

Kinkel, A. R., Jr., 1967, Copper, in Mineral and water resources of Missouri: Missouri Division of Geological Survey and Water Resources [Report], 2d series, v. 43, p. 63-68.

Kisvarsanyi, E. B., 1974, Operation Basement--Buried Precambrian rocks of Missouri--their petrography and structure: American Association of Petroleum Geologists Bulletin, v. 58, p. 674-684.

_____1975, Data on Precambrian in drillholes of Missouri including rock type and surface configuration: Missouri Geological Survey Report of Investigations no. 56, 19 p.

Kisvarsanyi, E. B., 1979, Structure contour map of buried Precambrian basement-rock surface, Rolla 1^{o}x 2^{o} quadrangle and adjacent areas, Missouri: U.S. Geological Survey Miscellaneous Field Studies Map MF-1001B, scale 1:250,000.
_____1980a, Granitic ring complexes and Precambrian hot-spot activity in the St. Francois terrane Midcontinent region, United States: Geology, v. 8, p. 43-47.
_____1980b, Subsurface geology of the Precambrian St. Francois terrane, southeastern Missouri: Missouri Division of Geology and Land Survey Open-File Map OFM-80-1-GI (Contribution to Precambrian Geology No. 8), scale 1:125,000.
Kisvarsanyi, Geza, 1966, Geochemical and petrological study of the Precambrian iron metallogenetic province of southeast Missouri: Rolla, University of Missouri Ph. D. Dissertation, 198 p.
_____1976, Precambrian metallogenesis in the St. Francois mountains igneous province, southeast Missouri in Studies in Precambrian geology of Missouri: Missouri Division of Geology and Land Survey, Report of Investigations no. 61, p. 164-173.
_____1981, Interpretive map showing regional depositional facies of the Cambrian Bonneterre Formation, Rolla 1^{o}x 2^{o} quadrangle, Missouri: U.S. Geological Survey Miscellaneous Field Studies Map MF-1002J, scale 1:250,000.
Kisvarsanyi, Geza, and Kisvarsanyi, E. B., 1977, Mineral-resource potential of the basement complex in Missouri: Missouri Academy of Science Transactions, v. 10 and 11, p. 16-43.
Lowell, G. R., 1975, Precambrian geology and ore deposits of the Silver Mine area, southeast Missouri--A review in G. R. Lowell, ed., A fieldguide to the Precambrian geology of the St. Francois Mountains, Missouri: Cape Girardeau, Southeast Missouri State University, p. 81-88.
Lowell, G. R., and Kurz, S. L., 1977, Minor element compositions of sulfides from a topaz greisen [Abstract]: Society of Economic Geologists, 57th Annual Meeting, Vancouver, B.C., v. 2, p. 33.
Lugov, S. F., 1977, Tin mineralization during evolution of the crust: Soviet Geology, no. 10, p. 46-58.
McIlroy, Paul, Coffman, J. S., Rice, W. L., and Hibpshman, M. H., 1974, Availability of U.S. primary lead resources: U.S. Bureau of Mines Information Circular 8646, 47 p.
Malan, R. C., 1972, Distributions of thorium and uranium in Precambrian rocks of Missouri: U.S. Atomic Energy Commission, RD-12, p. 45-52.
Mansker, W. L., 1973, Petrology of a southeastern Missouri ultramafic pipe: Columbia, Missouri, University of Missouri Masters thesis.
Meidav, Tsvi, Hayes, W. C., Heim, G. E., 1958, Resistivity surveys of Missouri limonite deposits: Missouri Division of Geological Survey and Water Resources, Report of Investigations No. 24, 27 p.
Muilenburg, G. A., 1954, Barite mining in Missouri, in Kansas Geological Society Guidebook, 17th Field Conference: Missouri Geological Survey and Water Resources, Report of Investigations No. 17, p. 45-50.
_____1957, Barite mining and production in Missouri: Missouri Geological Survey and Water Resources, Miscellaneous publication 11, 13 p.
Nash, J. T., 1977, Uranium in Precambrian granitic rocks of the St. Francois Mountains, southeastern Missouri, with comments on uranium resource potential: U.S. Geological Survey Open-File Report 77-787, 30 p.

Odland, S. K., and Millard, H. T., Jr., 1979, Uranium and thorium content of some sedimentary and igneous rocks from the Rolla 1°x 2° quadrangle, Missouri: U.S. Geological Survey Open-File Report 79-1080, 14 p.
Ohle, E. L., 1952, Geology of the Hayden Creek lead mine, southeast Missouri: American Institute of Mining and Metallurgical Engineers, Technical Publication 32271, p. 477-483.
Olade, M. A., 1980, Geochemical characteristics of tin-bearing and tin-barren granites, northern Nigeria: Economic Geology, v. 75, no. 1, p. 71-82.
Pomerene, J. B., 1947, Geology of the Einstein-Apex tungsten mine area: Rolla, University of Missouri School of Mines and Metallurgy M.S. thesis, 39 p.
Pratt, W. P., 1981, Composite map of structures in the Rolla 1°x 2° quadrangle, Missouri: U.S. Geological Survey Miscellaneous Field Studies Map MF-1000A, scale 1:250,000 (in press).
Pratt, W. P., Odland, S. K., Hubert, A. E., Siems, D. F., and Viets, J. G., 1980, Spectrographic and chemical analyses of exposed Precambrian rocks, Rolla 1°x 2° quadrangle, Missouri: U.S. Geological Survey Open-File Report 80-25, 26 p.
Pratt, W. P., Anderson, R. E., Berry, A. W., Jr., Bickford, M. E., Kisvarsanyi, E. B., and Sides, J. R., 1979, Geologic map of exposed Precambrian rocks, Rolla 1°x 2° quadrangle, Missouri: U.S. Geological Survey Miscellaneous Investigations Series Map I-1161, scale 1:125,000.
Reynolds, R. L., and Goldhaber, M. B., 1978, Alteration of iron-titanium oxide minerals, pt. 1 of Origin of a south Texas roll-type uranium deposit: Economic Geology, v. 73, no. 8, p. 1677-1689.
Rinehart, J. G., 1974, Geology of some carbonatites of the Ste. Genevieve county area, southeastern Missouri: Lincoln, University of Nebraska Master's thesis.
Roedder, Edwin, 1977, Fluid inclusion studies of ore deposits in the Viburnum Trend, Southeast Missouri: Economic Geology, v. 72, p. 474-479.
Rogers, J. J. W., Ragland, P. C., Nishimori, R. K., Greenberg, J. K., and Hauck, S. A., 1978, Varieties of granitic uranium deposits and favorable exploration areas in the eastern United States: Economic Geology, v. 73, p. 1539-1555.
Sangster, D. F., 1972, Precambrian volcanogenic massive sulphide deposits in Canada--A Review: Geological Survey of Canada, Paper 72-22, 44 p.
Shawe, D. R., compiler, 1981, U.S. Geological Survey Workshop on nonfuel mineral-resource appraisal of wilderness and CUSMAP areas: U.S. Geological Survey Circular 845 (in press).
Snyder, F. G., 1967, Criteria for origin of stratiform ore bodies with application to southeast Missouri, in Genesis of stratiform lead-zinc-barite-fluorite deposits (Mississippi Valley type deposits)--A synposium, New York, 1966: Economic Geology Monograph 3, p. 1-12.
Snyder, F. G., 1968, Geology and Mineral Deposits, Midcontinent United States, 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. 257-286.
Snyder, F. G., 1969, Precambrian iron deposits in Missouri, in Magmatic ore deposits, a symposium: Economic Geology Monograph 4, p. 231-238.
Snyder, F. G., and P. E. Gerdemann, 1965, Explosive igneous activity along an Illinois-Missouri-Kansas axis: American Journal of Science, v. 263, p. 465-493.

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.

Tatsumi, T., Watanabe, T., 1971, Geological environment of formation of the Kuroko-type deposits: Society of Mining Geology of Japan, Special Issue 3, p. 216-220.

Texas Instruments, Inc., 1979a, Aerial radiometric and magnetic reconnaissance survey of portions of Arkansas, Illinois, Indiana, Kentucky, Missouri, and Tennessee, Final Report, v. 1 and v. 2D, Rolla quadrangle: U.S. Department of Energy, Open-File Report No. GJBX-43(80).

Texas Instruments, Inc., 1979b, Aerial radiometric and magnetic reconnaissance survey of portions of Arkansas, Illinois, Indiana, Kentucky, Missouri, and Tennessee, Final Report, v. 1 and v. 2C, Poplar Bluff quadrangle; U.S. Department of Energy, Open-File Report No. GJBX-42(80).

Thacker, J. L., and Anderson, K. H., 1979a, Preliminary carbonate lithofacies maps of the Cambrian Bonneterre Formation, Rolla 1^{o}x 2^{o} quadrangle, Missouri: U.S. Geological Survey Miscellaneous Field Studies Map MF-1002C, scale 1:250,000.

------1979b, Preliminary carbonate lithofacies maps of the Cambrian Davis Formation, Rolla 1^{o}x 2^{o} quadrangle, Missouri: U.S. Geological Survey Miscellaneous Field Studies Map MF-1002E, scale 1:250,000.

------1979c, Preliminary isopach maps of the Cambrian Lamotte Sandstone and Cambrian Bonneterre Formation, Rolla 1^{o}x 2^{o} quadrangle, Missouri: U.S. Geological Survey Miscellaneous Field Studies Map MF-1002A (2 sheets), scale 1:250,000.

------1979d, Preliminary maps of sand/shale ratio in the Cambrian Bonneterre Formation, Rolla 1^{o}x 2^{o} quadrangle, Missouri: U.S. Geological Survey Miscellaneous Field Studies Map MF-1002B, scale 1:250,000.

------1979e, Preliminary isopach and sand/shale ratio maps of the Cambrian Davis Formation, Rolla 1^{o}x 2^{o} quadrangle, Missouri: U.S. Geological Survey Miscellaneous Field Studies Map MF-1002D, scale 1:250,000.

Tibbs, N. H., and Unfer, Louis, Jr., 1979, Uranium potential in southeast Missouri: University of Missouri-Rolla, Sixth Annual UMR-DNR Conference and Exposition on Energy, Rolla, October 16-18, 1979, Proceedings, p. 1-6.

Tolman, Carl, 1933, The geology of the Silver Mine area, Madison County, Missouri: Missouri Geological Survey, 57th Biennial Report of the State Geologist, Appendix 1, 39 p.

Uhley, R. P., and Scharon, LeRoy, 1954, Gravity surveys for residual deposits in Missouri: Mining Engineering, v. 6, no. 1, p. 52-56.

U.S. Bureau of Mines, 1943, Limonite Deposits of Southeastern Missouri: War Minerals Report 136, p. 1-16.

U.S. Bureau of Mines and the U.S. Geological Survey, 1980, Principles of a resource/reserve classification for minerals: Geological Survey Circular 831, p. 1-5.

U.S. Geological Survey, 1978, Aeromagnetic form-line contour map of the east part of the Rolla 1^{o}x 2^{o} quadrangle, Missouri: U.S. Geological Survey Open-File Report 78-330, scale 1:250,000.

U.S. Geological Survey, 1979, Aeromagnetic map of the Rolla, Missouri, area: U.S. Geological Survey Open-File Report 79-966, scale 1:250,000.

Wagner, R. E., and Kisvarsanyi, E. B., 1969, Lapilli tuffs and associated pyroclastic sediments in Upper Cambrian strata along Dent Branch, Washington county, Missouri: Missouri Geological Survey and Water Resources Report of Investigations 43, 80 p.

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

Weigel, W. W., 1965, The inside story of Missouri's exploration boom-- Part 1: Engineering and Mining Journal, v. 166, no. 11, p. 77-172.

Weixelman, W. D., 1959, Geology of the northeast portion of Des Arc Quadrangle Iron and Madison Counties, Missouri: Rolla, University of Missouri, M.S. thesis, 71 p.

Weller, Stuart, and St. Clair, Stuart, 1928, Geology of Ste. Genevieve County, Missouri: Missouri Bureau of Geology and Mines, 2d series, v. 22, 352 p.

Wharton, H. M., 1972, Barite ore potential of four tailings ponds, Washington County Barite district, Missouri: Missouri Geological Survey Report of Investigations 53, 58 p.

Wharton, H. M., Martin, J. A., Rueff, A. W., Robertson, C. E., Wells, J. S., Kisvarsanyi, E. B., 1969, Missouri Minerals--Resources, Production, and Forecasts: Missouri Geological Survey and Water Resources Special Publication 1, 303 p.

Wracher, D. A., 1976, Geology of the Pilot Knob Magnetite Deposit, Southeast Missouri: in Studies in Precambrian Geology of Missouri: Missouri Division of Geology and Land Survey, Report of Investigations no. 61, p. 155-161.

Zartman, R. E., Brock, M. R., Heyl, A. V., and Thomas, H. H., 1967, K-Ar and Rb-Sr ages of some alkalic intrusive rocks from central and eastern United States: American Journal of Science, v. 265, p. 848-870.