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U.S. Geological Survey– Missouri Geological Survey Symposium Mineral-Resource Potential of the Midcontinent

Program and Abstracts

St. Louis, Missouri, April 11–12, 1989

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Edited by WALDEN P. PRATT and MARTIN B. GOLDHABER

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PREFACE

For the past several years the U.S. Geological Survey (USGS), in cooperation with 16 State geological surveys, has been conducting a series of research projects related to mineral-resource potential in the U.S. Midcontinent region. This work began in 1975 under the Conterminous U.S. Mineral Assessment Program (CUSMAP), as a transect of $1° \times 2°$ quadrangle projects across southern Missouri and adjacent areas—the Rolla, Springfield, Harrison, Joplin, and Paducah quadrangles (see figure). Public meetings were held in 1981 and 1985, respectively, to present results from the Rolla and Springfield CUSMAP projects. More recently, as part of the Midcontinent Strategic and Critical Minerals Project, map and data compilations at 1:1,000,000 scale and related topical studies have been undertaken for a much larger area, from lat 36° to 46° N. and from long 88° to 100° W.; still more recently, Precambrian basement compilations have extended even farther north and west (see figure). Progress reports on several of the topical studies have been presented at various national or regional meetings; a few such papers were given at the Fifth USGS McKelvey Forum in Reno, Nevada, January 24–26, 1989.

In an effort to reach a larger number of those who might be interested in this research, we held a symposium, patterned after our McKelvey Forums, at St. Louis, Missouri, April 11–12, 1989. The purpose of the meeting was to present summaries or progress reports on regional compilations and topical research done during the first five years of the Midcontinent project, in addition to more detailed reports on the geology, stratigraphy, sedimentology, geochemistry, geophysics, and mineral-resource potential of the Harrison and Joplin $1° \times 2°$ quadrangles. This circular contains the program and abstracts from that meeting, arranged in alphabetical order of first author. We welcome discussions from our colleagues in industry and academia.

All the recent research under these programs in the Midcontinent region has been done in cooperation with the State geological surveys, and it is no exaggeration to say that without their wholehearted participation, on both organizational and personal levels, this symposium would not have taken place. On behalf of our USGS colleagues it is a pleasure to acknowledge the contributions of these organizations:

Arkansas Geological Commission
Illinois State Geological Survey
Indiana Geological Survey
Iowa Geological Survey Bureau
Kansas Geological Survey
Kentucky Geological Survey
Minnesota Geological Survey
Missouri Division of Geology and Land Survey
Montana Bureau of Mines and Geology
Nebraska Conservation and Survey Division
North Dakota Geological Survey
Oklahoma Geological Survey
South Dakota Geological Survey
Tennessee Division of Geology
Wisconsin Geological and Natural History Survey
Geological Survey of Wyoming

We owe special thanks to Ira Satterfield of the Missouri Division of Geology and Land Survey for his enthusiastic handling of the logistical details of this meeting.

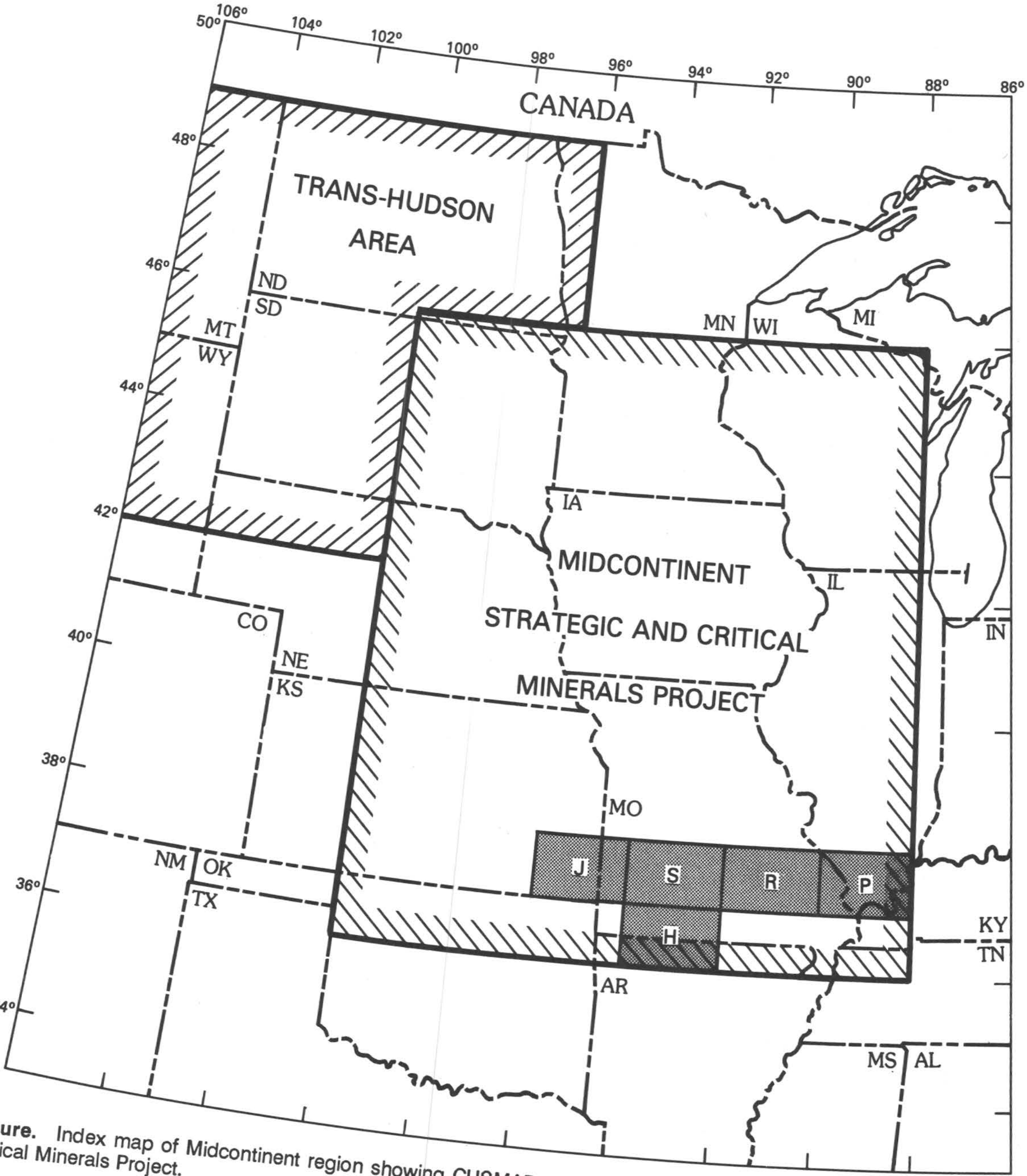

Figure. Index map of Midcontinent region showing CUSMAP quadrangles and area of Midcontinent Strategic and Critical Minerals Project.

PROGRAM

MONDAY, APRIL 10, 1989

7:00–9:00 p.m.	Registration and poster setup

TUESDAY, APRIL 11, 1989

MIDCONTINENT STRATEGIC AND CRITICAL MINERALS PROJECT

8:15 a.m.	Welcome and opening remarks *Walden P. Pratt*, U.S. Geological Survey, and *Frank Girardeau*, representing the Executive Director of St. Louis County
8:30 a.m.	An introduction to the research programs of the U.S. Geological Survey *Michael P. Foose*, Office of Mineral Resources, U.S. Geological Survey
8:50 a.m.	Evolution of the Midcontinent CUSMAP projects and the Strategic and Critical Minerals Project *Walden P. Pratt*
9:00 a.m.	Strategic and critical minerals: What are they and who needs them? *Subhash B. Bhagwat and J. James Eidel*
9:30 a.m.	Tectonic history of the Illinois Basin—An overview *Dennis R. Kolata, W. John Nelson, and J. James Eidel*
10:00 a.m.	Coffee and poster break
10:30 a.m.	Correlation of hydrothermal dolomite generations across the Mississippi Valley-type mineralizing system of the Ozark region *Timothy S. Hayes, James R. Palmer, and E. Lanier Rowan*
11:00 a.m.	Tectonic and stratigraphic control of subsurface geochemical patterns in the Ozark region *R.L. Erickson, Barbara Chazin, M.S. Erickson, E.L. Mosier, and Helen Whitney*
11:30 a.m.	Sulfur sources for southeast Missouri MVT ores—Implications for ore genesis *Martin Goldhaber and Elwin Mosier*
12:00 noon	LUNCHEON ADDRESS—The importance of mineral deposits in the Midcontinent, past and future *Ernest L. Ohle*
1:30 p.m.	Implications from fluid inclusions for the hydrology and sulfide precipitation mechanisms of the Viburnum Trend lead-zinc district, southeast Missouri *E. Lanier Rowan and David L. Leach*
2:00 p.m.	Regional permissivity of selected carbonate units for Mississippi Valley-type deposits in the northern Midcontinent *Walden P. Pratt*, for the Midcontinent Project Team
2:30 p.m.	Manganese potential of the Cretaceous rocks flanking the Sioux Ridge, Minnesota and South Dakota *Dale R. Setterholm, Richard H. Hammond, and William F. Cannon*
3:00 p.m.	Coffee and poster break
3:30 p.m.	Proterozoic anorogenic granite-rhyolite terranes in the Midcontinental United States—Possible hosts for Cu-, Au-, Ag-, U-, and rare-earth-element-bearing iron oxide deposits similar to the Olympic Dam orebody *P.K. Sims, K. J. Schulz, and Eva B. Kisvarsanyi*

4:00 p.m.	Methodology for analysis of the Proterozoic metallogenic province of southeast Missouri: A blueprint for State and Federal cooperation (a.k.a. the "Olympic Dam Project") *Eva B. Kisvarsanyi and Charles E. Robertson*
4:30 p.m.	Geologic mapping and evaluation of the Pea Ridge iron ore mine (Washington County, Missouri) for rare-earth element and precious metal potential *Laurence M. Nuelle, Mark Alan Marikos, and Cheryl M. Seeger*

TUESDAY EVENING, APRIL 11, 1989

7:00–10:00 p.m. POSTER SESSION

(This list does not include titles of poster papers that were also presented orally.)

MIDCONTINENT PROJECT

Folio of Midcontinent maps and cross sections *Walden P. Pratt* for the Midcontinent Project Team

Geology, bedrock topography, and potential mineral resources of the Trans-Hudson orogen, U.S.A. *P.K. Sims, Zell E. Peterman, and T.G. Hildenbrand*

Geologic mapping project of the Pea Ridge iron ore deposit, Washington County, Missouri *Laurence M. Nuelle, Cheryl M. Seeger, and Mark A. Marikos*

Preliminary report on the Texaco deep Precambrian drill hole in the Midcontinent Rift System *Pieter Berendsen, K. David Newell, W. Lynn Watney, John Doveton, and Don W. Steeples*

Regional Upper Cambrian lithofacies framework of southern Missouri *James R. Palmer*

Fluid inclusion gas geochemistry as a monitor of ore depositional processes in Mississippi Valley-type deposits in the Ozark region *A.H. Hofstra, D.L. Leach, G. P. Landis, J.G. Viets, E.L. Rowan, and G.S. Plumlee*

Genetic implications of regional and temporal trends in ore-fluid geochemistry of Mississippi Valley-type deposits of the Ozark region *John G. Viets and David L. Leach*

Geochemical anomalies and sulfur isotope systematics of Upper Cambrian clastic rocks in the Midcontinent—Relation to ore fluid movement *Elwin L. Mosier, Martin B. Goldhaber, and Jack Masters*

Regions of feldspar precipitation and dissolution in the Lamotte Sandstone, Missouri—Implications for MVT ore genesis *Sharon F. Diehl, Martin B. Goldhaber, and Elwin L. Mosier*

Drilling information on the morphology of Missouri sinkhole deposits of flint clay *H.A. Tourtelot, M.B. Goldhaber, and I.R. Satterfield*

Reactions involving organic matter and thiosulfate in precipitating sulfides, disulfides, fluorite, and barite, and in producing the carbonate paragenesis in Mississippi Valley-type ores *Charles S. Spirakis and Allen V. Heyl*

Ore microscopy of the Paoli silver-copper deposit, Oklahoma *Craig A. Thomas, Richard D. Hagni, and Pieter Berendsen*

Missouri's core library partnership *Sarah Hearne Steelman and Ira R. Satterfield*

HARRISON, JOPLIN, AND PADUCAH CUSMAP PROJECTS

Cross sections of Lower Ordovician carbonate depositional lithofacies and Mississippi Valley-type zinc and iron sulfide mineralization in the Caulfield district, Harrison 1°×2° quadrangle, Missouri *Timothy S. Hayes, James R. Palmer, and Gary Krizanich*

Influence of Precambrian topography on long-term solution letdown of overlying carbonate sequences in the Harrison quadrangle *Ernest E. Glick*

The relationship of remote-sensing anomalies to the real world—Examples from the Midcontinent and the CUSMAP study areas *Frank W. Wilson and James R. McCauley*

Geology and mineral-resource potential of the Precambrian basement in the Harrison and Joplin quadrangles *Eva B. Kisvarsanyi*

Subsurface geochemistry of the Harrison and Joplin 1°×2° quadrangles *R.L. Erickson, Barbara Chazin, M.S. Erickson, E.L. Mosier, Helen Whitney, Pieter Berendsen, and Mary E. Daily*

Ore distribution in the Missouri and Kansas portions of the Tri-State district of Missouri, Kansas and Oklahoma *Laurence M. Nuelle and Michael C. McFarland*

Heavy-oil resource potential of the Joplin quadrangle *Bruce W. Netzler*

Calculation of coal resources of the Bronaugh 7½′ quadrangle, southwestern Missouri, using the National Coal Resources Data System *Joy Lorraine Bostic, Laurence M. Nuelle, David C. Smith, M. Devereux Carter, Noreen Rega, and Kathleen K. Krohn*

Use of GSLITH to display downhole geochemical data *Mark Alan Marikos*

Industrial mineral resources of the Joplin quadrangle *David A. Grisafe and A.W. Rueff*

Present status of the Paducah CUSMAP project *Bruce R. Johnson, J. James Eidel, James W. Baxter, W. John Nelson, and E. Donald McKay III*

WEDNESDAY, APRIL 12, 1989

HARRISON AND JOPLIN CUSMAP PROJECTS

8:30 a.m.	Geologic and structural overview of the Harrison quadrangle *Mark A. Middendorf and John David McFarland III*
8:50 a.m.	Geology of the Joplin quadrangle *James R. McCauley, David C. Smith, and Charles E. Robertson*
9:10 a.m.	Subsurface structural geology of the Joplin quadrangle *Kevin P. Blair and Pieter Berendsen*
9:30 a.m.	Application of Cambrian lithofacies mapping in the Springfield, Harrison, and Joplin CUSMAP assessments for Mississippi Valley-type deposits *James R. Palmer, Timothy S. Hayes, Cheryl M. Seeger, Gary Krizanich, Melanie Werdon, and John W. Whitfield*
9:50 a.m.	Coffee and poster break
10:20 a.m.	Geophysical studies in central Midcontinent CUSMAP quadrangles *Lindrith Cordell and Anne E. McCafferty*
10:40 a.m.	Metallic mines and prospects of the Harrison and Joplin quadrangles *Michael C. McFarland, George W. Colton, and James R. McCauley*

11:00 a.m.	Coal resources of the Joplin quadrangle *Lawrence L. Brady, Laurence M. Nuelle, David C. Smith, Joy Lorraine Bostic, and Daniel B. Haug*
11:20 a.m.	Late Mississippian high-angle reverse faulting in the southwestern Harrison quadrangle—Implications for underground gas storage *Ernest E. Glick*
11:40 a.m.	Assessment of potential for undiscovered Mississippi Valley-type deposits in the Harrison and Joplin quadrangles by *W.P. Pratt and others, J.A. Martin and others, W.V. Bush and others, and P. Berendsen and others*
12:00 noon	END OF SYMPOSIUM

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Edited by Walden P. Pratt *and* Martin B. Goldhaber

Affiliations of authors are abbreviated as follows; addresses and telephone numbers are listed at the end of the abstracts.

USGS	U.S. Geological Survey
AGC	Arkansas Geological Commission
ISGS	Illinois State Geological Survey
KGS	Kansas Geological Survey
MGS	Missouri Geological Survey
MNGS	Minnesota Geological Survey
SDGS	South Dakota Geological Survey
UMR	University of Missouri-Rolla

Preliminary Report on the Texaco Deep Precambrian Drill Hole in the Midcontinent Rift System

Pieter Berendsen, K. David Newell, W. Lynn Watney, John Doveton, and Don W. Steeples, KGS

The Texaco No. 1 Poersch well, located in sec. 31, T. 5 S., R. 5 E., in Washington County, Kansas, was drilled to a depth of 11,300 ft. The well is the second deepest penetration to date in the Midcontinent rift system and the deepest well in Kansas. The well was sited near the northern edge of a pronounced aeromagnetic and gravity anomaly on top of a Proterozoic anticlinal structure that was originally detected on a nearby east-west COCORP seismic profile a few miles north of the Poersch well. A few miles north of the well, Precambrian sedimentary rocks of the Rice Formation occur in distinct fault-bounded basins that are aligned with the faulted Abilene anticline. This anticline is recognized in surface rocks of Permian age and resulted from reactivation of older basement structures. To the south, wells penetrating Precambrian rocks generally encounter mafic volcanic and intrusive rocks. A prominent northwest-trending fault system passes within a short distance of the well. This extensive fault system can be traced to the southeast where it appears to coincide with the Bolivar-Mansfield tectonic zone in western Missouri. Eight Cretaceous kimberlite bodies are at the intersection of this fault system and the Abilene anticline.

The top of the Precambrian basement in the Poersch well is encountered at 2,846 ft. The basement rocks can be divided into two distinct successions of almost equal thickness. The upper part down to a depth of 7,429 ft is characterized by a preponderance of mafic volcanic rocks and minor mafic and silicic intrusive rocks that make up 90 percent of the section. Oxidized siltstone and arkose account for the remainder. Below 7,429 ft arkose and subarkose and oxidized siltstone and shale make up 90 percent of the section. Mafic intrusive and extrusive rocks make up the remaining 10 percent.

Manuscript approved for publication October 16, 1989.

The abrupt change from a sedimentary-dominated to a volcanic-dominated sequence indicates a pronounced change in the tectonic regime from a period of relative quiescence to a period of intense volcanic and intrusive activity. The sedimentary rocks encountered in the Poersch well are similar to those one might expect to be deposited during a natural evolutionary cycle in a continental half-graben or graben system with interior drainage and through-going axial drainage. No organic-rich sediments were found in the Poersch well. A single porous zone occurs between 11,055 and 11,077 ft.

Gabbro tops the Proterozoic sequence, and an unknown amount of rock was removed before the overlying Ordovician Simpson Group was deposited. Correlation of the rocks encountered in the Poersch well with Precambrian rocks in the Great Lakes region, where the stratigraphy is better understood, is still not clear. The succession of volcanic rocks (Portage Lake Volcanics) in the Great Lakes region that is overlain by a sedimentary sequence (Copper Harbor Conglomerate-Nonesuch Shale-Freda Sandstone-Bayfield Group) is not recognized in the Poersch well. Tectonostratigraphic development in the southern part of the rift may be markedly different from that in the northern part, thereby giving rise to a succession of rocks that cannot be directly correlated with rocks farther north.

Strategic and Critical Minerals—What Are They and Who Needs Them?

Subhash B. Bhagwat and J. James Eidel, ISGS

Concern about adequate supplies of minerals and materials in the United States dates back over a hundred years. In the 1880's the U.S. Navy replaced its wooden ships with metal ships and found out that the required materials were not available in adequate quantity. In 1886, the U.S. Senate held hearings on materials shortfall, but no action was taken. Similar experiences during World War I and renewed concerns in the 1930's finally led to government action in 1938 when the first stockpiles program was established. Because of their original association with military concerns, the terms "strategic" and "critical" were always associated with national defense. This paper traces historical concerns about minerals and materials availability and spells out the problems involved in defining the terms strategic and critical—words whose meanings have evolved over the decades since World War II. Technological and economic changes that have brought the world closer through trade underlie the changes in definition. Securing supplies of essential minerals and materials is no longer limited to owning deposits or stockpiling supplies but involves diplomacy as well as international monetary relations. Human rights issues are intimately intertwined with securing an adequate supply of materials. Constantly changing geopolitical situations necessitate that strategic and critical minerals constantly be redefined. The terms strategic and critical must be defined in the context of the uses of minerals or materials. This paper outlines the areas of the U.S. economy that require strategic and critical minerals and materials and considers how the use of strategic and critical minerals may change in the future. Understanding the dynamism of strategic and critical mineral demand will be useful in shaping future exploration strategies.

Subsurface Structural Geology of the Joplin Quadrangle

Kevin P. Blair and Pieter Berendsen, KGS

Formation tops from approximately 3,250 wells in the Joplin quadrangle were used to draw structure contour maps on the tops of carbonate rocks of Mississippian age and rocks of the Arbuckle Group of Early Ordovician and Cambrian age. Preliminary maps for each county in the Kansas part of the quadrangle were drawn to a scale of 1:100,000 with a contour interval of 20 ft, then synthesized along with the Missouri data into a 1:250,000-scale compilation using a 50-ft contour interval.

The subsurface structural geology of the quadrangle is dominated by a number of through-going, northwest-trending fold-fault systems of variable width (Fall River, Chesapeake, and Bolivar-Mansfield tectonic zones). Discontinuous patterns of horsts and grabens along strike suggest wrench motion along these trends. Northeast-trending faults and folds, subordinate to the primary northwest-trending structures, occur throughout the quadrangle. Individual domal culminations and small downwarped depressions occur in patterns suggestive of the interference of two trends of folding.

Our mapping indicates that economically important structures commonly occur at intersections between these two structural trends. The Fredonia anticline is a major horstlike structure situated at the junction of the Fall River tectonic zone (FRITZ) and a prominent, unnamed northeast-trending fold-fault system. Mineralization near Oswego in eastern Labette County, Kansas, appears to be located at the intersection of a zone of northeast-trending folds and the FRITZ. Similarly, the Picher field, in the Tri-State district, occurs at the junction of the FRITZ and the major northeast-trending Miami trough. Minor structures also occur along the length of the Chesapeake tectonic zone. The prominent Bolivar-Mansfield tectonic zone may be traced through the quadrangle west into Kansas and east into the Springfield quadrangle. Mineralization associated with the Big Jumbo and Prescott areas in Kansas occurs in this zone.

Many of these major tectonic zones can be recognized on geophysical maps of the Precambrian basement. On the basis of structural analysis elsewhere, we believe that many structures mapped in the Paleozoic carbonate rocks in the Joplin quadrangle are reactivated basement structures.

Calculation of Coal Resources of the Bronaugh 7–1/2′ Quadrangle, Southwestern Missouri, Using the National Coal Resources Data System

Joy Lorraine Bostic, Laurence M. Nuelle, and David C. Smith, MGS, and
M. Devereux Carter, Noreen Rega, and Kathleen K. Krohn, USGS

Coal resources of the Bronaugh 7–1/2′ quadrangle, Vernon County, Missouri, were calculated by using the National Coal Resources Data System (NCRDS). The NCRDS is a computerized data base developed and maintained by the U.S. Geological Survey, Branch of Coal Geology, Reston, Virginia, specifically for calculating coal resource tonnages by manipulating coal stratigraphic data and digitized line data through a series of interactive data base managers and graphics software programs.

Coal stratigraphic data were collected in the field, correlated, and encoded for entry in the NCRDS by geologists at the Missouri Department of Natural Resources. Stratigraphic point locations, coal croplines, and mined-out areas were digitized and formatted for entry in the NCRDS. This information was uploaded to the PRIME minicomputer in Reston, Virginia, by geologists and staff of the Branch of Coal Geology.

Seven coal seams of the Cherokee Group, Desmoinesian Series, underlie the Bronaugh quadrangle (from oldest to youngest): Weir-Pittsburg, Tebo, Mineral, Fleming, Croweburg, Wheeler, and Mulky. In recent years all coal production in the area has been from the Croweburg and Mineral seams. The Mineral seam is 15–20 in. thick and is separated from the overlying Croweburg by 15 ft of interbedded shale and sandstone. The Croweburg coal seam is 12–15 in. thick. Maximum overburden thickness in the area is 60 ft. Remaining identified coal resources of the Croweburg and Mineral seams are estimated to be 2.6 million tons and 5.9 million tons, respectively. Owing to the variable thickness and lack of data points, coal resources of the other five coal seams were not calculated.

Coal Resources of the Joplin Quadrangle

Lawrence L. Brady, KGS, Laurence M. Nuelle, David C. Smith, and Joy Lorraine Bostic, MGS, and Daniel B. Haug, KGS

Coal beds are widespread in the Joplin quadrangle except in the southeastern part of the quadrangle where rocks older than Pennsylvanian age are exposed. All coal beds are of Pennsylvanian age; most of the coal resources are in the Cherokee Group. A calculated 3,170 million tons (2,880 million metric tons) of coal resources are present at depths less than 100 ft (30 m) and having a bed thickness of 14 in. (35 cm) or more. The Mineral, Weir-Pittsburg, Rowe, Bevier, and Croweburg coal beds contain the largest amounts of strippable resources. Thirteen additional coal beds also have strippable resources in the quadrangle.

Deep coal resources, those deeper than 100 ft (30 m) and generally lying west of the outcrop belt of the Cherokee Group, represent more than 21 billion tons (19 billion metric tons) of coal resources. Twenty-nine different coal beds were recognized that are thicker than 14 in. (35 cm). The coal beds having the largest resources include the Bevier, Riverton, Mineral, Weir-Pittsburg, and the Croweburg coals. Deep coal resources that exceed 42 in. (105 cm) in thickness total approximately 800 million tons (725 million metric tons).

Mining of coal by seven mines in the quadrangle amounted to 1.032 million tons (0.936 million metric tons) in 1988, with coal strip mined from the Rowe, Drywood, Weir-Pittsburg, Mineral, Croweburg, and Bevier coal beds. The coal is mainly used for power generation, but large tonnages are also used for cement manufacture. Most of the coal is high-volatile A or B bituminous (HvAb or HvBb) in rank. Generally, the coals are considered to be medium to high sulfur, but a low- to medium-sulfur (0.82–2.43 percent S), unnamed coal bed is present in Missouri.

Geophysical Studies in Central Midcontinent CUSMAP Quadrangles

Lindrith Cordell and Anne E. McCafferty, USGS

First-order gravity and aeromagnetic trends in the central Midcontinent region are generally east-northeast and align with age and facies boundaries in the Proterozoic basement, to the extent that the geology of the basement is known from scanty drilling. Second-order geophysical features trend northwest and are attributed to basement structure, probably because these trends occasionally can be correlated with surface structures and intersect the east-northeast regional geologic strike. The northwest structural grain of the Precambrian basement is of interest to studies of the habitat of mineral deposits to the extent that this grain facilitated generally northward movement of ore-bearing solutions out of the Arkoma basin. A swath of CUSMAP quadrangles along the 37th parallel, from southeastern Kansas to southern Illinois, provides a chance to study the geology of basement rocks, using the geophysical data, in some detail.

Basement rocks consist primarily of widespread unmetamorphosed felsic flow and plutonic rocks, and local inliers of prevolcanic metamorphic rocks. Plutons are easy to distinguish from flows by using gray-scale-imaged aeromagnetic data in the Rolla quadrangle, where the mapping of these can be integrated with good geologic exposure. Calderas and ring dikes are more problematical. Geophysical data provide evidence against the existence of the Taum Sauk caldera but suggest other possible calderas and ring dikes not identified in geologic mapping. Very large positive anomalies near Salem in the Rolla quadrangle, originally attributed to ultramafic rocks, are being reevaluated now in the light of possible Olympic Dam affinity. Northwesterly geophysical and, by inference, structural trends are the features of predominant interest in the Springfield quadrangle, particularly those trends associated with gravity and magnetic lows defining the "Central Missouri tectonic zone." Some tectonic zones inferred from regional geophysical studies are not evident in the detailed interpretation of geophysical data. Beginning with the Springfield quadrangle and in subsequent CUSMAP quadrangles to the south and west, recognition in the geophysical data of the boundary between "Spavinaw" and "St. Francois" nonmetamorphic volcanic-plutonic terranes becomes increasingly difficult.

Also of much interest, and also poorly constrained by conflicting data, is the location of the inliers of prevolcanic metamorphic terrane. Only in the Joplin quadrangle at the western end of the CUSMAP transect can a magnetic texture clearly referable to the prevolcanic metamorphic terrane be discerned. Here susceptibility "terrace" mapping, a new technique, and image aeromagnetic data enable us to delineate a larger tract of the metamorphic terrane than was expected on the basis of drill-hole data.

Preliminary analysis of regional aeromagnetic data for depth to magnetic source suggests large basement paleotopographic relief in the area of the Harrison quadrangle. This surface, subsequently buried by transgressive detrital strata, could influence regional patterns of fluid migration. In light of this, a more rigorous analysis for depth to magnetic source is now in progress on the newly acquired detailed aeromagnetic data from the eastern part of the Harrison quadrangle.

Regions of Feldspar Precipitation and Dissolution in the Lamotte Sandstone, Missouri—Implications for MVT Ore Genesis

Sharon F. Diehl, Martin B. Goldhaber, and
Elwin L. Mosier, USGS

The Upper Cambrian Lamotte Sandstone is considered to be a major aquifer for warm basinal brines that formed the Mississippi Valley-type (MVT) mineral deposits in Missouri. Petrographic studies of authigenic potassium feldspar in the Lamotte constrain the geochemistry of the ore fluids. This mineral phase is important because (1) it has been dated as late Paleozoic in age, which broadly coincides with the inferred time of ore genesis, (2) previous petrographic studies constrain the relative timing of dissolution of authigenic feldspar with deposition of the ore, and (3) MVT ore fluids are typically anomalously rich in K^+.

Petrographic studies of samples from central and southeastern Missouri show that trends in the precipitation and dissolution of potassium feldspar overgrowths are related to sample location and sample depth (fig. 1). Northwest and southwest of the St. Francois Mountains, authigenic potassium feldspar is volumetrically important, making up as much as 18 percent of the cement in feldspar-rich layers. The overgrowths occur in porous arkosic arenites in which a later clay phase coated grains and inhibited quartz overgrowths. The potassium feldspar overgrowths are adularialike in habit, inclusion free, and rarely twinned, and they completely surround detrital feldspar cores, indicating precipitation in a loosely packed porous environment. Authigenic potassium feldspar in samples from lower in the Lamotte section have undergone partial to total dissolution; however, higher in the Lamotte section, near the transition zone, potassium feldspar overgrowths are unaffected by acidic, dissolving solutions. More complete dissolution of potassium feldspar overgrowths occurs within a northwest-trending corridor encompassing the St. Francois Mountains (fig. 1).

Two episodes of potassium feldspar precipitation are indicated by partially dissolved early overgrowths surrounded by later well-formed rhombic overgrowths; however, only one generation of authigenic potassium feldspar is evident to the southeast of the St. Francois

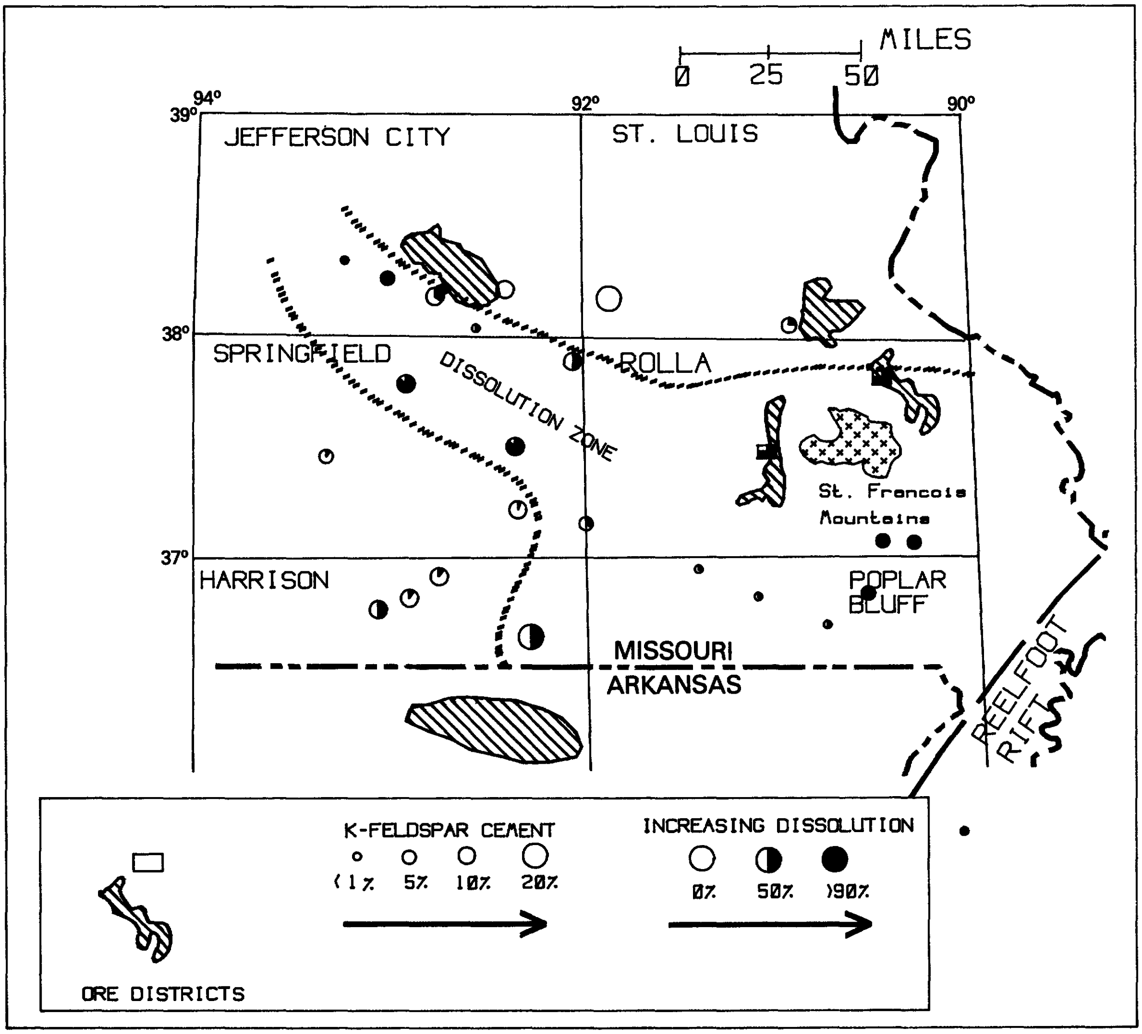

Figure 1. Distribution map of potassium feldspar overgrowths in the Lamotte Sandstone, southeastern Missouri, showing abundance of potassium feldspar cement and amount of dissolution of potassium feldspar cement. Ore districts from Rothbard (1983).

Mountains and within the Reelfoot rift. Authigenic albite cement is common only in samples from the rift, in which it commonly replaces potassium feldspar overgrowths and their detrital cores.

Published petrographic studies of Lamotte-hosted mineralization in southeast Missouri demonstrate that the first episode of authigenic potassium feldspar formation predated mineralization and that dissolution of the overgrowths accompanied ore formation (Rothbard, 1983). Our data show that this ore-stage dissolution event was regionally extensive and was most intense along a northwest-trending corridor that includes the lead belts and the St. Francois Mountains. Fluid inclusion data from southeast Missouri show that K^+ concentrations were very high during ore deposition. Potassium feldspar should be stable in a high K^+ environment; however, our data suggest that the ore fluid was acidic in order to both dissolve potassium feldspar overgrowths and carry metals and H_2S in solution. The broad dissolution zone in the southeast part of the state suggests that this acid fluid originated in the Reelfoot rift.

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Tectonic and Stratigraphic Control of Subsurface Geochemical Patterns in the Ozark Region

R.L. Erickson, Barbara Chazin, M.S. Erickson, E.L. Mosier, and Helen Whitney, USGS

Subsurface geochemical studies in four contiguous 1°×2° quadrangles in parts of Missouri, Arkansas, and Kansas and along a north-south transect of drill holes in western Illinois reveal surprisingly consistent regional patterns of distribution and abundance of metals that have important implications for the genesis of Mississippi Valley-type (MVT) deposits. Insoluble residues of "barren" carbonate rocks of Cambrian age throughout this broad area commonly are lead rich and contain an extensive suite of other metals (Zn, Cu, Ni, Co, Mo, Ag, As). This lead-rich metal suite is characteristic of Cambrian-hosted ore deposits in the Southeast Missouri lead district. Residues of carbonate strata of Ordovician, Mississippian, and Pennsylvanian age tend to be zinc rich with respect to lead, and anomalous concentrations of other metals (Cu, Ni, Co, Mo, Ag, and As) are rare.

The widespread occurrence of ore-related metals in insoluble residues of Paleozoic carbonate rocks attests to the passage of metal-bearing fluids through vast areas of the Ozark region. Leach and Rowan (1986) provided compelling evidence that MVT deposits in the Ozark region formed from a single hydrologic system related to fluid migration northward out of the Arkoma basin in response to Ouachita tectonism. Our geochemical data generally support their model, but recently acquired data from drill holes along the west margin of the Mississippi embayment and the Illinois basin suggest that fluids migrating from the Illinois basin and (or) the New Madrid rift zone may have played a significant role in the genesis of the Southeast Missouri lead district. All of our data, however, suggest that Cambrian strata were the major regional aquifers in the Ozark region for transport of an extensive suite of metals, regardless of which sedimentary basin is favored as a metal/brine source. Further, the geochemical data suggest an explanation for the differences in ore composition (that is, zinc rich versus lead rich) between vertically stacked host rocks and between MVT mineral districts in the Ozark region. If we accept the premise that Cambrian strata were the major regional aquifers for fluids, then mineral districts hosted by post-Cambrian rocks could form where geologic structures intersect and tap the Cambrian aquifers. Fluids released up these structures would selectively deposit metal sulfides according to their relative solubility in the presence of reduced sulfur (Ag < Cu < Pb < Co < Ni < Zn). Zinc, the most mobile metal in the suite, should travel farther and thus become enriched upward relative to the other metals as the fluid is selectively depleted in the less mobile metals. This process could result in formation of structurally controlled, zinc-rich districts in post-Cambrian carbonate strata (Mississippian-hosted Tri-State and Ordovician-hosted Northern Arkansas zinc districts). Fluids remaining in the Cambrian aquifers would retain their full complement of metals and continue to migrate in Cambrian strata in search of a "depository" for their metal burden. The Cambrian-hosted Southeast Missouri lead district with its extensive suite of other metals may be such a depository. The implications of the subsurface geochemical patterns are that Cambrian aquifers provided the plumbing system for all Ozark MVT districts and that the Illinois basin and New Madrid rift zone, as well as the Arkoma basin, may have served as metal/brine sources in the Ozark region.

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Subsurface Geochemistry of the Harrison and Joplin 1°×2° Quadrangles

R.L. Erickson, Barbara Chazin, M.S. Erickson, E. L. Mosier, and Helen Whitney, USGS, and Pieter Berendsen and Mary E. Daily, KGS

Subsurface geochemical studies in the Harrison quadrangle reveal three principal areas of high metal concentrations in insoluble residues of Paleozoic carbonate rocks. The northeast anomalous area is part of a geochemical trend that extends from the southern border of Missouri northwestward across the adjacent Springfield quadrangle. The trend is hosted in dolomites of the post-Bonneterre Cambrian of J.R. Palmer (Missouri Geological Survey, written commun., 1989) and appears to follow a northwest structural grain bounded on the northeast by the Bolivar-Mansfield tectonic zone. The south-central anomalous trend is hosted in both Cambrian and Ordovician dolomites on the east flank of a Precambrian high and along the projection of the Chesapeake tectonic zone. The west-central anomalous area has no apparent relationship to known tectonic zones or buried Precambrian ridges and is considered to be less significant than the other two trends.

Paired geochemical maps compiled for Cambrian and Ordovician strata show that Pb, Ag, Cu, As, and Ni are most abundant in insoluble residues of Cambrian rocks and that zinc is most abundant in Ordovician rocks—a consistent pattern throughout the Ozark region.

Subsurface geochemical studies in the Joplin quadrangle indicate that the abundance of ore-related elements in insoluble residue samples of Paleozoic carbonate rocks is much less than the abundances obtained in the adjacent Springfield and Harrison quadrangles. The geochemical maps show broad low-level anomaly patterns approximately parallel with the regional strike of the sedimentary units in the quadrangle. The patterns show no clear association, however, with known structural or geophysical trends. The summary geochemical map, compiled on a generalized geologic, structure, and aeromagnetic base, shows two broad geochemically anomalous areas. The western area is caused chiefly by anomalous amounts of zinc in Pennsylvanian strata and by anomalous amounts of Cu, Pb, Zn, Ag, Ni, As, and Mo in Cambrian-Ordovician strata. The southeast anomalous area reflects the Tri-State zinc-lead district and is caused by anomalous amounts of zinc in Mississippian strata and by a zinc-lead-rich base-metal suite in Cambrian-Ordovician strata.

Surprisingly, all drill holes in the northeast quadrant of the Joplin quadrangle show anomalous amounts of zinc in Mississippian strata. Most Mississippian zinc deposits and occurrences are structurally controlled and commonly do not exhibit large lateral halos. This broad consistent pattern suggests that significant potential for discovery of concealed zinc deposits beneath relatively thin Pennsylvanian cover exists in the area—particularly in areas of faulting or brecciation.

Influence of Precambrian Topography on Long-Term Solution Letdown of Overlying Carbonate Sequences in the Harrison Quadrangle

Ernest E. Glick, USGS

Maps showing structure contours on the top or bottom of the Boone Formation (Mississippian) in the Harrison 1°×2° quadrangle (Purdue and Miser, 1916; McKnight, 1935; E.E. Glick, work in preparation) indicate the presence of apparently randomly scattered domes and basins that generally cannot be convincingly attributed to any known tectonic event. These features range in size from about a square mile to more than 10 mi^2. Dip of the Boone generally is less than 2°, but persistence of dip results in several hundreds of feet of structural relief. Some of these structures are faulted on at least one side.

My working hypothesis, inherited from earlier workers—especially E.L. Ohle, formerly of Hanna Mining Co.—suggests that each Boone high probably is underlain by a Precambrian basement high. This proposed cause-and-effect relationship relies on the assumption that structural relief can result from differential deposition, compaction, or solution. Boone structural anomalies, however, could not have been caused by differential deposition and compaction that was completed in pre-Boone time. Thus, letdown by means of differential solution is favored.

Two fundamentally different processes must be considered in looking for the cause of this carbonate solution: (1) hot brine invaded the area during the time of mineralization (shown by fluid inclusions in crystals), and (2) the original marine salt, as well as the brine of mineralizing solutions, has been flushed out during the past 250 million years.

J.R. Palmer (Missouri Geological Survey, oral commun., 1989) has observed that essentially all of the dissolution noted in rock core from this area predates the lead-zinc mineralization. Block faulting during Late Mississippian time (Glick, this volume) and extension faulting during Middle Pennsylvanian time also predate mineralization. Some basins and domes may have begun to form by differential solution during mineralization, and the process may have continued slowly during the following 250 million years of erosion. At least shallow solution is still in progress.

If the basins and domes are indeed indicative of Precambrian topography, this concept offers access to a key factor in mineral deposition. One hole drilled on the side of a Boone high 12 mi southeast of Harrison reveals Lower Ordovician rocks on Precambrian basement in an area where several hundred feet of Cambrian rocks would be expected.

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Late Mississippian High-Angle Reverse Faulting in the Southwestern Harrison Quadrangle—Implications for Underground Gas Storage

Ernest E. Glick, USGS

Purdue and Miser (1916) described thinning of the Fayetteville Shale (Chesterian) across three antiformal structures in the southwestern quarter of the Harrison 1°×2° quadrangle. Contours drawn on top of the underlying Boone Formation (Mississippian) clearly reflect more structural closure than do contours drawn on horizons within the overlying Pennsylvanian sequence.

One of these structures, the Carrollton dome, was selected as a potential gas-storage site by the Arkansas Western Gas Company. In the early 1960's gas injection was begun into the Gunter Sandstone Member of the Gasconade Formation, which is at the base of the Ordovician sequence—here at a depth greater than 2,000 ft. The initial bubble of gas escaped the injection area, and J.M. Clark, a geologist with the company, began an appraisal of the site to determine whether gas could be stored there. He found (personal commun., 1966) that the structure is complicated by a mostly concealed pre-Morrowan fault. One fortuitously located drill hole cut duplicate sections of the Boone Formation (one on each side of the fault) that indicate high-angle reverse displacement. The eastern block, containing the prospective gas reservoir, overrides the western one.

As shown by Purdue and Miser, this area was tectonically active during Chesterian deposition, active in the sense that selected areas were arched and uplifted several hundred feet, producing structures without a common trend. This suggests simultaneous regional marine deposition and local block faulting at depth that broke near-surface layers locally but generally only flexed them. No blocks overlain by anomalously thick Fayetteville sequences have been specifically noted, but the data are inconclusive.

Even though the structures and reservoir rocks of this area appear appropriate for gas storage, an apparently connected fresh-water column from the surface to the basement—well below sea level—suggests an intercommunicative hydraulic system. Artesian flow here and there, however, indicates that some aquifers are confined, even in sequences without shale beds.

Other local structures also offer promise for gas storage, perhaps in deeper reservoirs that are likely to have a Cambrian shale cap or in closed structures capped by younger shales. If the Carrollton dome gas bubble can be located, it will define a storage reservoir in an unexpectedly complex structure that has no convincing shale cap. As yet, the experiment is inconclusive.

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Sulfur Sources for Southeast Missouri MVT Ores—Implications for Ore Genesis

Martin Goldhaber and Elwin Mosier, USGS

The site(s) and mechanism(s) of sulfide generation are among the key remaining questions in the origin of Mississippi Valley-type (MVT) lead-zinc deposits. To address these questions for the lead belts of southeast Missouri, possible local and distant H_2S sources were evaluated using data from sulfur isotope studies of acid-insoluble residues of Cambrian through Mississippian carbonate rocks (more than 350 samples) and heavy mineral concentrates from basal clastic units. These new results were compared to existing sulfur isotope data for Viburnum Trend sulfides, hosted by the Upper Cambrian Bonneterre Formation, which indicate that main-stage galena-sphalerite-FeS_2 has a very heavy $\delta^{34}S$ range of +10 to +27 permil, and late-stage sulfides are lighter (-5 to +10 permil). Thus, at least two H_2S sources are required, heavy and light.

In order to identify possible locally derived H_2S sources, a 16-km core fence transecting the Viburnum Trend from fore-reef limestone on the west to back-reef dolomite on the east was studied. No heavy sulfur isotope anomaly in FeS_2 matching that of main-stage Viburnum Trend ore was found in the back-reef (whiterock) facies, a result that precludes reduction of sulfate in potential back-reef evaporites as an H_2S source.

However, a stratigraphically controlled and regionally extensive heavy sulfur isotope anomaly was identified. Regional sampling reveals a marked stratigraphic trend in $\delta^{34}S$ of epigenetic FeS_2. The broadest range and heaviest $\delta^{34}S$ values (-10 to +40 permil, mean +8 permil) are in portions of the Bonneterre Formation and the underlying basal clastic rocks (Lamotte/Reagan/Mount Simon Sandstones, $\delta^{34}S$ values as high as +33 permil). Within the Bonneterre, the isotopically heavy sulfur matching that of main stage ores (>10 permil) is largely confined to the Whetstone Creek (WC) and Sullivan Siltstone (SS) Members that comprise the upper part of the formation. These two members may have constituted an aquifer within the Bonneterre in contrast to much of the underlying basinal shale and micrite facies of the Bonneterre and overlying shaly Davis Formation, which were aquitards. In marked contrast, iron sulfide samples from units stratigraphically above the Bonneterre contain sulfur that is predominantly lighter isotopically than main-stage Viburnum Trend ores.

A plot of sulfur isotope data from basal clastic rocks of Missouri, Illinois, Arkansas, and Oklahoma shows that the heavy isotope anomaly (>10 permil) forms a large ring around the St. Francois Mountains, but only lighter sulfur (<10 permil) occurs in samples collected 25–50 km or less from the ore districts. In contrast, anomalously heavy sulfur from the overlying Bonneterre spatially overlaps the Viburnum Trend. Thus, although both the Bonneterre and the Lamotte carried heavy sulfur, the Bonneterre was the proximal source for this component in the Trend, whereas the Lamotte evidently carried a lighter sulfur component to the Trend.

An attempt was made to evaluate the southern Illinois Basin as a source of isotopically heavy sulfur because both Upper Cambrian and Middle Ordovician rocks in this part of the basin contain anhydrite whose isotopic composition was measured to be +27 to +34 permil. These evaporites are impregnated with bitumen at some depths. Isotopic analyses of coexisting sulfides show only light values in the evaporite-bearing section ($\delta^{34}S$ = -0.5 to -10.9); however, deeper burial and elevated temperature may have favored thermochemical reduction of evaporite sulfur farther south in the Reelfoot rift, where evaporites are presumed to exist in Lower Cambrian rocks.

Mixing of at least two H_2S- (and metal-?) bearing brines having distinct $\delta^{34}S$ values and flow paths (Bonneterre for heavy H_2S and Lamotte or post-Bonneterre units for lighter H_2S) gave rise to the lead belt mineralization. This mixing mechanism explains the wide range in $\delta^{34}S$ of these ores and is also consistent with constraints from lead isotope data, ore textures, and ore mineralogy.

Industrial Mineral Resources of the Joplin Quadrangle

David A. Grisafe, KGS, and A.W. Rueff, MGS

The known industrial mineral resources of the Joplin quadrangle are crushed stone, clay and shale, construction sand and gravel, asphaltic sandstone, and dimension stone. The production value of these resources during 1987, the latest year of complete data as supplied by the U.S. Bureau of Mines, was almost $25,600,000. If finished products such as cement and ceramic products are included, the value is many times that amount.

Crushed stone is the most important of the industrial minerals in the quadrangle, and resources are large, of high quality, and generally well distributed. Limestone is the basis of a highly developed cement industry in the western part of the quadrangle and is used extensively throughout the quadrangle for the production of aggregate and aglime. Chert from mine-mill tailings of the now depleted zinc mines and from a bedrock quarry is used for railroad ballast, aggregate, roofing granules, and abrasives. Clay and shale resources are large and are used in the manufacture of cement, brick, sewer pipe, tile, pottery, and animal feed supplements. Alluvial deposits of sand and gravel are locally important as aggregate but have no significance outside the quadrangle. There is no present production of asphaltic sandstone and dimension stone, although there are large resources and a record of major past production. Hypothetical resources of industrial sand are available, but there has been no production.

Cross Sections of Lower Ordovician Carbonate Depositional Lithofacies and Mississippi Valley-Type Zinc and Iron Sulfide Mineralization in the Caulfield District, Harrison 1°×2° quadrangle, Missouri

Timothy S. Hayes, USGS, James R. Palmer, MGS, and Gary Krizanich, USGS

Logs of eight cores from the Caulfield zinc district have been compiled into two short cross sections. This detailed logging has: (1) generated a model for Lower Ordovician cyclic peritidal carbonate sedimentation, (2) provided detailed correlation of the district's host rocks, (3) demonstrated that there was no lithofacies control on economically important Caulfield district mineralization, (4) confirmed that the Alice mine ores are hosted by a pipe-shaped zone of solution-collapse crackle breccia, (5) provided evidence that the host breccia pipe is connected to a subsurface stratal dissolution collapse breccia and that both breccias probably formed by pre-ore surficial karstification, and (6) correlated hydrothermal dolomite generations, demonstrating that the Caulfield district mineralization was part of a regionwide Mississippi Valley-type (MVT) hydrothermal system in the Ozark region.

If the Alice mine is typical of Caulfield district orebodies, the economic potential of the district is limited to orebodies of 500,000 tons or less; however, because of its simple structural control and paragenesis, the Alice mine is an excellent place for further scientific study. Additional work should be able to test between major hypotheses on metals and sulfur sources. Currently the data appear to favor that both metals and sulfide sulfur were carried by a single solution that rose up the Alice mine breccia pipe, as proposed for other

MVT's in a study by Sverjensky (1984). A two-solution model (Beales and Jackson, 1966; Anderson and Garven, 1987) appears possible only if the rising metals-bearing solution in the breccia pipe met a sulfur-bearing solution recharging laterally along the stratabound breccia.

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Correlation of Hydrothermal Dolomite Generations Across the Mississippi Valley-Type Mineralizing System of the Ozark Region

Timothy S. Hayes, USGS, James R. Palmer, MGS, and E. Lanier Rowan, USGS

Hydrothermal dolomite generations, correlatable between Mississippi Valley-type (MVT) districts and throughout barren sections elsewhere across the Ozarks, provide important constraints on theories of Ozark region MVT ore genesis. MVT sulfide mineralization in the Ozark region is accompanied by a series of fracture- and vug-crusting or limestone-replacing, coarse, hydrothermal saddle dolomites, which at many places have the color sequence (1) gray to tan, (2) white, (3) limpid, and (4) pink. These color zones generally correlate (by potassium ferricyanide staining) with zone I—tan and white, zones II and III—limpid, and zone IV—pink, of the cathodoluminescent microstratigraphy of Voss and Hagni (1985) and Rowan (1986). Interlayering of the paragenetically late dolomite crusts and ore sulfides in orebodies of the Southeast Missouri, Northern Arkansas, and Tri-State districts allows correlation of sulfide stages between districts and demonstrates that a single, interconnected mineralizing system existed across the region at all stages. The dolomite crusts also occur remote from ore, across the region and throughout the stratigraphy, interlayered with trace-metals-anomalous pyrite, marcasite, and pyrobitumens reported by Erickson and others (this volume). The abundance of the hydrothermal dolomite is directly proportional to the trace-metals content of the insoluble residues. Hydrothermal dolomite is relatively scarce within and above shaly aquitards but is much more abundant above shale-free depositional paleohighs. The regionally ubiquitous hydrothermal dolomites, combined with differences in detail within the paragenetic sequence—near versus remote from ore—indicate that chemical reactions unique to the orebodies occurred at a time when the connected secondary porosity of the entire carbonate section over the whole region was being saturated by ore solutions.

Ozark region MVT host breccias include fault breccias, paleokarst breccias, sedimentary breccias, compactional breccias, and probably other types. Recognition of hydrothermal dolomite allows pre-ore to be distinguished from ore-stage events and indicates that minerals deposited by the ore fluids and those deposited when local meteoric recharge cooled and diluted the ore fluids are the latest minerals in all rocks of the region. Hydrothermal dolomite correlation demonstrates that the ore stage of every MVT deposit of the Ozarks occurred since Early Pennsylvanian time and probably since 310 million years ago (Missourian Series of Upper Pennsylvanian).

MVT ore deposits of the Ozark region formed where ore solutions could, or had to, escape upward, probably under artesian pressure. The same clear relation to fluid movement upward is not everywhere true of the regional insoluble residue metals and hydrothermal dolomite anomalies. Both major districts of the Ozark region are adjacent to and upsection from the pinchout of one or more shaly units. Other Ozark region MVT ores are found where aquitards were structurally breached by faulting or paleokarst collapse, and the ore fluids could climb section.

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Fluid Inclusion Gas Geochemistry as a Monitor of Ore Depositional Processes in Mississippi Valley-Type Deposits in the Ozark Region

A.H. Hofstra, D.L. Leach, G.P. Landis, J.G. Viets, E.L. Rowan, and G.S. Plumlee, USGS

A quadrupole mass spectrometer was used to obtain quantitative analyses of the gases present in fluid inclusions in hydrothermal dolomite, quartz, sphalerite, and galena from Mississippi Valley-type (MVT) occurrences in the Ozark region. The gas compositions of fluid inclusions in these minerals are used to characterize the physical and chemical parameters of the ore fluids and provide insights into the geochemical processes leading to ore deposition.

The gases contained in fluid inclusions were released for analysis by thermal decrepitation and analyzed by two different methods. In the bulk analysis method, 5- to 10-g samples are heated from 100 to 350 °C; all the gas released from the many thousands of fluid inclusions in the sample is collected in the vacuum inlet system and analyzed by the mass spectrometer. In the TRASH method (Time Resolved Analysis of Spectral Happenings), 10- to 100-mg samples are placed under vacuum (10^{-8} torr) in a furnace that is ramped from 100 to 400 °C. The quadrupole mass spectrometer, operating in multiple ion monitoring mode, serves to profile the release of gas from the sample as a function of temperature. The sudden release of gas from the decrepitation of an individual fluid inclusion in the sample produces a sharp spike on the gas-release profile. The composition of the gas released during each fluid inclusion decrepitation event can be determined from the net intensity change between the spike maximum and the immediately preceding baseline. The gas composition of individual inclusions having diameters greater than about 10 microns can be determined.

Bulk analyses of these samples yield anomalously high CO_2 contents of as much as 10 mole percent and small amounts (generally <1 mole percent) of other gases including H_2S, SO_2, N_2, Ar, CH_4, and other short-chain hydrocarbons. The TRASH data show two populations of inclusions in the samples: gas-dominant CO_2-rich inclusions and water-dominant inclusions having the same minor gas speciation as the bulk analyses. CO_2-rich fluid inclusions containing variable amounts of H_2O may record heterogeneous trapping of a two-phase fluid. The results of TRASH analyses of water-dominant fluid inclusions are shown in figures 2a and 2b. The ternary diagram in figure 2a shows that regionally there are only very small variations in the gas composition of the hydrothermal fluids. Inclusions in sphalerite, galena, and quartz (fig. 2b) generally contain from 0.5 to 2 mole percent gases other than water, whereas inclusions in dolomite contain as much as 7 mole percent gases. In all minerals, CO_2 is the major gas, and amounts (typically <0.3 mole percent) of H_2S, SO_2, N_2, Ar, CH_4, and short-chain hydrocarbons are smaller. Figures 2a and 2c show that fluid inclusions in sphalerite and galena contain more H_2S (~0.25 mole percent) than fluid inclusions in quartz and dolomite (~0.025 mole percent). Figure 2b shows that fluid inclusions in dolomite contain more CO_2 (~2 mole percent) than fluid inclusions in quartz, sphalerite, and galena (~0.62 mole percent). Some of this difference is undoubtedly due to thermal decomposition of the host minerals during TRASH analysis (sulfides decompose to yield H_2S and carbonates CO_2); however, the amount of gas released by thermal decomposition of galena, sphalerite, and dolomite was found to be negligible below about 250 °C. Many of the fluid inclusions analyzed decrepitate at temperatures below 250 °C. These inclusions also exhibit the same compositional differences described above; at least part of the difference in gas composition between sulfides and dolomite probably is due to real differences in the composition of the hydrothermal fluids during periods of sulfide deposition relative to periods of dolomite deposition. Figure 2c shows that the relative amounts of H_2S and CH_4 contained in inclusions in sulfides vary systematically from district to district, again suggesting that the relative differences in gas composition reflect real differences in the gas composition of the hydrothermal fluids.

The TRASH data show that the anomalously high CO_2 contents as measured by the bulk method are due to the sum of the contributions from both H_2O-rich and CO_2-rich inclusions. The two populations of inclusions have been found in samples of regional hydrothermal dolomite and in samples of ore. The data suggest that CO_2 effervescence was a widespread phenomenon in the ore zones during sulfide mineralization and along fluid migration pathways during deposition of regional hydrothermal dolomite. The fluids were saturated with respect to CO_2. The gas data can be used, together with temperature and salinity estimates from microthermometry, to estimate the pressure or depth of burial during mineralization. The CO_2 contents of as much as 10 mole percent, as determined by the bulk analysis method, are an order of magnitude greater than the amount that would be soluble in a saline (~20 eq. wt. percent NaCl) aqueous fluid under the pressure-temperature conditions of ore deposition (<150 °C, <200 bars). The CO_2 contents of water-dominant fluid inclusions in quartz and sulfides, as determined by the TRASH method, have a mode of about 0.62 mole percent that corresponds to a pressure of about 135 bars at 150 °C. This is a reasonable pressure for these systems given that

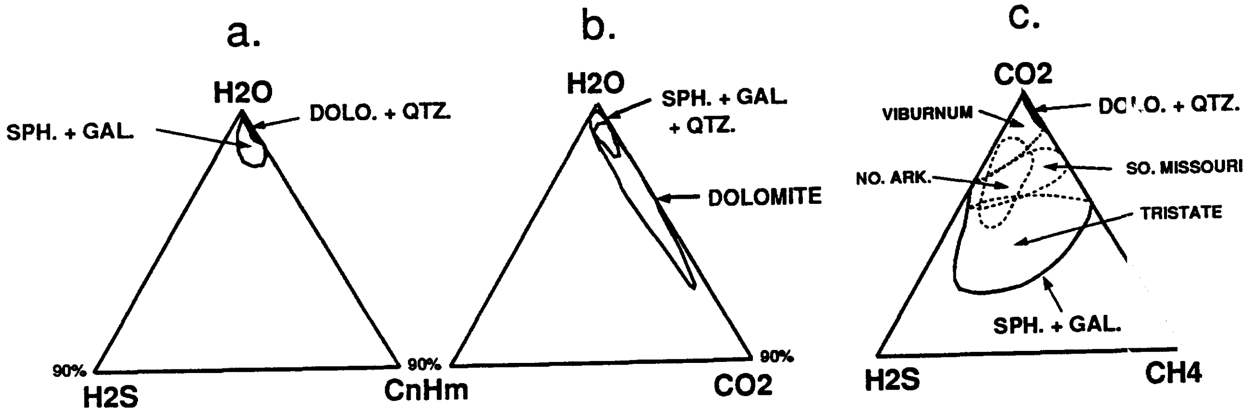

Figure 2. Ternary plots of gas compositions of fluid inclusions from Mississippi Valley-type occurrences in the Ozark region. a, Water-rich apex of the H_2O-H_2S-C_nH_m diagram ($H_2O > 90$ percent) showing the gas composition of water-dominant fluid inclusions in ore and gangue minerals from MVT deposits in the Ozark region. b, Water-rich apex of the H_2O-C_nH_m-CO_2 diagram ($H_2O > 90$ percent) showing the gas composition of water-dominant fluid inclusions. CO_2-rich fluid inclusions plot below the water-rich region shown. c, CO_2-CH_4-H_2S plot of both water-dominant and gas-dominant fluid inclusions. The gas compositions of inclusions in sphalerite and galena from each district define distinct fields on the diagram.

stratigraphic reconstructions indicate burial depths of 1–2 km. The presence of small amounts of other gases such as CH_4 in the solution would raise the pressure somewhat. The gas data can also be used to calculate the pH of the ore fluids if we assume dolomite saturation and use analyses of the electrolytes in the inclusions to fix the Ca/Mg ratio (~3.2) and ionic strength (~4.0). The speciation calculations yield an acid pH of about 4.5.

CO_2 effervescence in the ore fluids results from two processes and has important implications for deposition of both ore and gangue minerals. First, thermodynamic reaction path modeling shows that CO_2 effervescence under isothermal conditions will result in the deposition of large amounts of dolomite. The calculations also show that sphalerite will be deposited during the first increments of CO_2 effervescence due to an increase in pH. We propose that much of the regional hydrothermal dolomite in the Ozark region was deposited during continuous, slow effervescence of a CO_2-saturated brine as it migrated slowly through carbonate aquifers to shallower crustal levels and to lower pressures. This depositional mechanism is consistent with the observation of cathodoluminescent stratigraphy in hydrothermal dolomite that can be correlated across much of the Ozark region. Sphalerite deposition is predicted at sites where this fluid is focused sharply upward to lower pressure environments and may account for sphalerite-rich deposits in the Northern Arkansas and Tri-State districts. Second, CO_2 effervescence in the ore zones of some districts is a consequence of carbonate dissolution caused by sulfide deposition. Large amounts of acid can be produced by sulfide deposition, particularly where a metal-rich brine mixes with a local source of H_2S or with another brine rich in H_2S. For example, in the Viburnum Trend, hydrothermal breccias and etched and disrupted growth bands in dolomite, as seen using cathodoluminescence, provide direct evidence of carbonate dissolution in many ore zones. Gas data showing high H_2S and CH_4 values in sulfides and relatively lower values in quartz and dolomite provide further evidence in support of mixing during periods of sulfide deposition. In summary, the data are consistent with ore deposition by CO_2 effervescence at some locations and by mixing at others. Current research should further constrain the ore fluid composition in each district and provide the basis for more detailed modeling of the processes and factors that localized MVT mineralization in the Ozark region.

Present Status of the Paducah CUSMAP Project

Bruce R. Johnson, USGS, and J. James Eidel, James W. Baxter, W. John Nelson, and E. Donald McKay III, ISGS

A cooperative evaluation of the mineral potential of the Paducah 1° × 2° quadrangle (Missouri-Illinois-Kentucky-Indiana) is being carried out by the USGS and the geological surveys of the four States under the Conterminous U.S. Mineral Assessment Program (CUSMAP). The preparation of intermediate map products, on which the assessments will be based, is underway.

Data from an intensely studied area consisting of four 7½′ quadrangles centered on Hicks Dome in southeastern Illinois were used in a pilot study of the feasibility of assembling and manipulating the diverse CUSMAP data sets and maps in a Geographic Information System (GIS) environment. Well data including stratigraphic tops, bedrock and surficial geologic maps, structure contour maps, hypsography, planimetric data, and gravity and magnetic surface data were integrated using ARC/INFO and ISM software. The pilot study defined the manner in which data will need to be handled for a fully computer-integrated effort for the Paducah project. Following completion of digitizing for the entire Paducah quadrangle, models of mineral occurrences will be produced using GIS to assist in resource assessments.

Bedrock geology has been compiled on mylar for the four 30′ × 60′ series maps that cover the Paducah 2° sheet at a scale of 1:100,000—West Frankfort (NE), Paducah (SE), Carbondale (NW), and Cape Girardeau (SW). Compilation is complete except for the addition of the geology from three 7½′ Missouri quadrangles now being mapped. Digitizing of the West Frankfort and Paducah sheets is scheduled to begin in late April or early May 1989 and should be finished for the four sheets by middle to late September 1989. Surficial map products, digitized at a scale of 1:250,000, consist of (1) a stack unit map showing the stratigraphic superposition and range of thickness of geologic units to a depth of 50 ft and (2) a surficial geologic map derived from the stack map. The Illinois portion of these products will be completed by late spring or early summer and ready for final compilation by the Missouri Geological Survey. The USGS has contracted with Wilds Wm. Olive to address surficial data in Kentucky. Maps showing areas containing potential sources of nonmetallic, nonfuel minerals, limestone, tripoli, and certain clays will be derived from the bedrock map, and similar maps will be derived for sand and gravel from the stack unit map.

Subsurface maps and cross sections will be used in the evaluation of both nonfuel- and energy-related mineral potential. Midcontinent Strategic and Critical Minerals Project products and recent Illinois State Geological Survey subsurface maps and cross sections prepared in conjunction with Illinois Basin studies for the Geological Society of America (Decade of North American Geology, volume D–2) and American Association of Petroleum Geologists (Interior Cratonic Sag Basins volume of the Petroleum Basin Series) are providing much basic data for evaluation of subsurface geology in terms of mineral potential.

Potential field data have been compiled and derivative maps prepared by USGS. The applicability to the Paducah project of an existing USGS depth-to-basement map has been discussed. Interpretation of acquired seismic data and access to proprietary seismic profiles have provided a new understanding of the configuration of the New Madrid rift system.

Activities related to assessing the potential for Mississippi Valley-type lead, zinc, and fluorspar deposits continue. The locations of metallic and nonmetallic mines and prospects and minor surface occurrences of known mineralization in outcrops, quarries, and drill holes have been compiled and, with tabular data, entered into the computer program GSMODS as part of the Midcontinent project. The output from GSMODS has been reviewed and corrected and additional data on occurrences provided. Insoluble residues, prepared from cuttings and core samples representing major carbonate units of all ages and from 45 borings in Illinois, have been analyzed for 31 different elements by the USGS; metal content in terms of anomalous metal feet has been calculated for 4,558 samples representing approximately 73,000 total ft of drilling. Samples from an additional 29 Ordovician and deeper holes and from 13 that penetrate Devonian rocks have been obtained for acidization and analysis—approximately 2,850 additional samples representing approximately 57,000 total ft.

Energy-resource mapping is underway, and resource, industry, structure, and coal-quality maps and coal-facies cross sections are scheduled for digitizing and completion by October 1989.

A list of 38 potential topical studies and ongoing research projects pertinent to the Paducah CUSMAP project was compiled and circulated.

Geology and Mineral-Resource Potential of the Precambrian Basement in the Harrison and Joplin Quadrangles

Eva B. Kisvarsanyi, MGS

The four-State region of Kansas, Missouri, Oklahoma, and Arkansas that includes the Harrison and Joplin quadrangles (fig. 3) is underlain by the Middle Proterozoic (1.35–1.40 Ga) Spavinaw granite-rhyolite terrane (Sims and others, 1987), similar to the epizonal St. Francois granite-rhyolite terrane, which is well known from outcrops and drill cores in southeast Missouri (Kisvarsanyi, 1981). The Precambrian basement is covered by Phanerozoic sedimentary rocks ranging in thickness from 330 to 1,000 m. It has no historic record of mineral production, and its unidentified resources must necessarily be appraised from sparse drill-hole information, geophysical maps, and analogies with similar terranes. The identification of the Spavinaw terrane in the two quadrangles is based on basement-rock samples from 22 drill holes. Fine- to medium-grained, red, granophyric alkali-feldspar granite and rapakivi

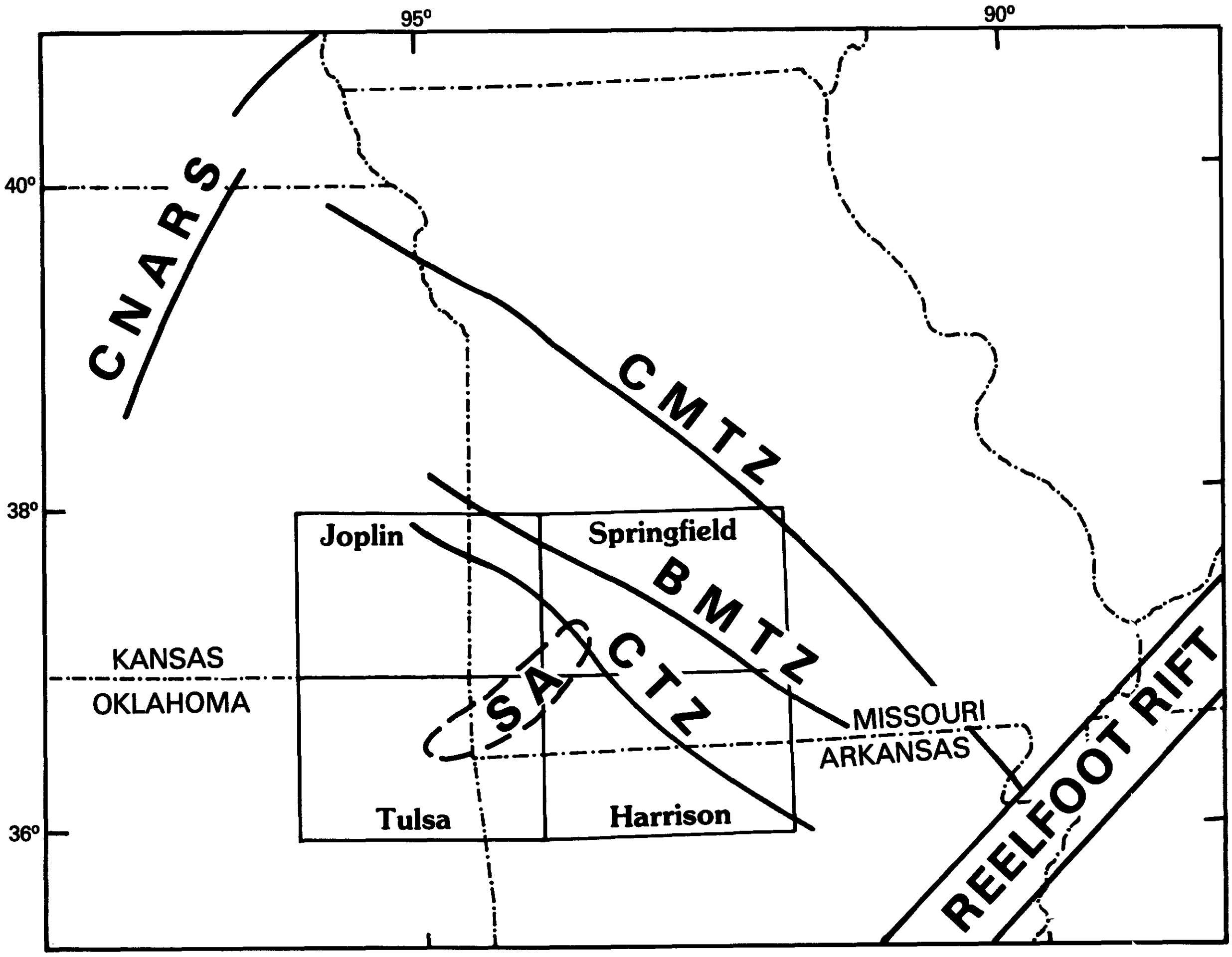

Figure 3. Index map of northern Midcontinent area showing location of Joplin, Tulsa, Springfield, and Harrison quadrangles, Central North American rift system (CNARS), Reelfoot rift, and major tectonic zones and structures that cross the area. CMTZ, Central Missouri tectonic zone; BMTZ, Bolivar-Mansfield tectonic zone; CTZ, Chesapeake tectonic zone; SA, Spavinaw arch.

granite, typical of Middle Proterozoic anorogenic terranes of the region, occurs in samples from nine drill holes; volcanic rock, mostly rhyolite and some trachyte and trachyandesite, occurs in ten; and clastic sedimentary(?) rock occurs in three.

Two major Precambrian tectonic zones, the Bolivar-Mansfield (BMTZ) and the Chesapeake (CTZ) (Kisvarsanyi, 1984), strike northwesterly across the area (fig. 3). They coincide with known structures in overlying Paleozoic rocks and were reactivated in Paleozoic time. The Precambrian rocks are generally downfaulted between the two tectonic zones and form a complex graben in which pre-Upper Cambrian clastic sequences locally accumulated. The broad pre-sediment Spavinaw arch extends northeast from central Oklahoma into southwestern Missouri and is underlain by granite and associated volcanic rocks of the Spavinaw terrane. By analogy with the St. Francois terrane, it is assumed that the area of the arch has rugged relief and somewhat similar geology to that of southeast Missouri, where several calderas, cauldron subsidence structures, and granite ring complexes have been mapped.

Petrographic, geochemical, and tectonic analogies suggest that the Spavinaw and St. Francois terranes could have similar metallogenesis and that the same types of mineral deposits could be expected in both. The most important of the possible mineralization types is a class of Proterozoic iron oxide-rich deposits that commonly occurs with rare-earth elements and other metals (Cu, U, Au, Ag) and is referred to as "Olympic Dam-type."

Worldwide, these deposits typically occur in anorogenic granite-rhyolite terranes, are associated with magnetic and gravity anomalies, and can be targets for exploration in buried terranes. In the St. Francois terrane, more than two dozen magnetite and hematite deposits are known, some with associated rare-earth element and copper-gold mineralization. Several areas are judged favorable for hosting Olympic Dam-type deposits in the Harrison and Joplin quadrangles.

1. An area of volcanic rock in the south-central part of the Joplin quadrangle, represented by four core holes, is characterized by altered trachyte and trachyandesite. The alteration is propylitic; hematite, epidote, and chlorite form massive replacements, and calcite and chalcedony occur as veins and fill lithophysae. This type of alteration is typically associated with magnetite and hematite deposits in the St. Francois terrane.

2. A sequence of red clastic rocks within the graben defined by the BMTZ and the CTZ near the Kansas-Missouri State line is as thick as 300 m and is underlain by syenite. It appears to be a local accumulation of clasts derived from nearby granite and rhyolite terranes. Samples from the clastic sequence consist of very fine drill cuttings, and the fabric of the rock cannot be positively identified. The rock has a low metamorphic grade; granite and rhyolite clasts are unaffected, but the clay-size matrix is partly sericitized. This sequence may represent rapid deposition of clastic sediments in the graben; alternatively, it may be a heterolithic volcanic breccia. Drill holes immediately south of the clastic sequence bottom in rhyolite. Large-scale brecciation could be associated with volcanic eruptions and caldera formation and could provide favorable sites for mineralization.

3. Magnetic and gravity anomalies outline 10 areas that may be favorable for mineralization in the Harrison quadrangle, but drill-hole data are insufficient to judge their potential.

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Methodology for Analysis of the Proterozoic Metallogenic Province of Southeast Missouri: A Blueprint for State and Federal Cooperation (a.k.a. the "Olympic Dam Project")

Eva B. Kisvarsanyi and
Charles E. Robertson, MGS

Southeast Missouri has 6 major (20–200 million tons of ore) and 24 minor magnetite-apatite-hematite deposits that define a Proterozoic metallogenic district 125 km long and 50 km wide, elongated north-northwest. The deposits are hosted by silicic volcanic rocks of the anorogenic St. Francois granite-rhyolite terrane, which is partly exposed in the St. Francois Mountains. Iron mining from shallow surface deposits commenced in 1815 and continued until 1966; since 1964 mining activity has shifted to deposits covered by 400–500 m of Paleozoic strata. The petrotectonic setting of the southeast Missouri deposits is strikingly similar to that of the giant Olympic Dam Cu-Au-Ag-U-rare-earth element deposit, the largest among a number of lesser deposits on the Stuart shelf in South Australia. Both the St. Francois and Stuart shelf deposits belong to a special class of Proterozoic iron oxide-rich deposits that share a number of common features and may result from similar ore-forming processes.

Among Proterozoic anorogenic terranes generally considered favorable for hosting Olympic Dam-type deposits in the U.S. Midcontinent (Sims and others, this volume), the St. Francois terrane in southeast Missouri is by far the most accessible. In addition to its extensive outcrops in the St. Francois Mountains, more than 650 drill cores amounting to a cumulative total of 40,000 m are available for study. Furthermore, the Pea Ridge underground mine provides access to one of the major deposits in the northwestern part of the district. As a major component of its Midcontinent Strategic and Critical Minerals Project, the USGS, in cooperation with the Missouri Geological Survey (MGS), has undertaken a 5-year multidisciplinary study to develop a descriptive model for Olympic Dam-type deposits and identify areas in the region favorable for hosting such deposits. The project is an extension of the regional geologic and metallogenic synthesis of the northern Midcontinent (Sims and others, 1987) by the USGS and a logical continuation of the Operation Basement program by the MGS.

The principal responsibilities of the MGS include but are not limited to (1) compiling a digital data base for drill holes to the Precambrian basement and updating the existing basement map, (2) detailed mapping of accessible Pea Ridge mine workings, in cooperation with the Pea Ridge Iron Ore Company, and sampling for systematic petrographic, ore microscopic, and geochemical analysis (Nuelle and others, this volume), (3) detailed logging and sampling of core from major undeveloped deposits, including 30,000 m of exploration core from the Boss copper-iron ore body, and (4) mapping accessible workings and sampling available core from inactive mines in the St. Francois Mountains. The USGS will be primarily responsible for (1) regional geophysical synthesis, (2) regional geochemical synthesis, and (3) studies of ore depositional processes. Both agencies will collaborate on specific site studies, such as the Pea Ridge mine mapping project, on various topical studies on ore mineralogy and paragenesis, wall-rock alteration, and lineament and structural analysis, and on developing a descriptive model. Status reports will be released as open-file maps and reports; formal reports will be published subsequently by either of the two agencies or in professional journals, as deemed appropriate.

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Tectonic History of the Illinois Basin—An Overview

Dennis R. Kolata, W. John Nelson, and J. James Eidel, ISGS

The Illinois Basin began as a failed rift that developed during the breakup of a supercontinent approximately 600 Ma. A rift basin, in the southernmost part of the present Illinois Basin, subsided rapidly and was filled with about 3,000 m of latest Precambrian(?) through Middle Cambrian sediments. By Late Cambrian time, the rift-bounding faults became inactive; a broad, relatively slowly subsiding embayment, extending well beyond the rift and open southward to the Iapetus Ocean, persisted through most of the Paléozoic Era.

Widespread deformation swept through the proto-Illinois Basin beginning in Late Mississippian time and continuing to the end of the Paleozoic. Uplift of basement fault blocks resulted in formation of many major folds and faults. The timing of deformation and the location of these structures in the forelands of the Ouachita and Alleghanian orogenic belts suggest that much of the deformation resulted from continental collision between North America and Gondwana. The associated compressional stress reactivated the ancient rift-bounding faults and upthrusted the northern edge of a crustal block within the rift approximately 1,000 m. Concurrently, dikes (radiometrically dated as Early Permian), sills, and explosion breccias formed in or adjacent to the reactivated rift. Hicks Dome and Tolu arch apparently formed at this time.

Subsequent extensional stress, probably coincident with breakup of Pangea, caused the crustal block within the rift to sink back to near its original position. In addition, high-angle northeast- to east-trending normal faults formed in the Fluorspar area fault complex (FAFC). Mineralization in the FAFC postdates initial movements on the host faults, which displace and hence postdate the Early Permian dikes. Petroleum in fluorite fluid inclusions and as seeps and coatings in fluorspar mines indicates that hydrocarbons migrated through the FAFC during and after mineralization.

Structural closure of the southern end of the Illinois Basin was caused by uplift of the Pascola arch resulting from reactivation of the rift sometime between Late Pennsylvanian and Late Cretaceous time. Uplift of the arch very likely had an effect on thermal gradients, fluid flow, and formation of geologic structures within and adjacent to the rift. The time of uplift, however, is not clearly understood.

Use of GSLITH to Display Downhole Geochemical Data

Mark Alan Marikos, MGS

GSLITH, a software program developed by the USGS (Selner and Taylor, 1987) to display stratigraphic cross sections and slice maps, can be applied to display downhole geochemical analytical data, allowing rapid plotting and easy visualization of spatial trends. Raw data for each sampled interval are stored in a data base that includes the well identifier, top and bottom depths, analytical results for each element, and a code indicating the stratigraphic unit into which the interval falls. A second data base contains header and coordinate data for each well. The data bases are extracted, recalculated, and resorted to create derivative data bases exported as GSLITH-format ASCII data files for input to the GSLITH program.

In cross-section mode, each sampled interval is displayed as a GSLITH "unit" and plotted in a color that represents the class or rank of the analytical result for the specified element, elemental ratio, elemental sum, or other derived value. Values are scaled in a "cool to warm" color sequence for easy visualization of trends within and between wells. Sorting of input data by well identifier and class minimizes the time spent by the plotter changing pens. By appropriate manipulation of the input data sets, particular stratigraphic units may be shown, as well as plots of the entire depth penetrated.

Slice-map mode allows display of various derivative dot maps. These maps may represent anomalous metal feet (AMF) values or other derived functions of the analytical values for particular horizons or the entire well. Appropriate preprocessing of the input data determines the data displayed and its scope. Automated preprocessing allows rapid evaluation of variations in metal suites, cutoff values, and color scaling.

The cost of color printing limits the utility of GSLITH maps and sections for direct publication. The program could be used to generate color separates for multicolor printing by plotting only those intervals (sections) or dots (slice maps) that represent one class on each plot. Modification of the program to drive color ink-jet or electrostatic plotters would greatly speed plotting time and make it practical to generate copies quickly. The required rasterization would allow a useful modification of the program to plot three-dimensional orthographic stick diagrams of the wells. The rasterized file would be written from back to front, as viewed, thus overwriting hidden features with features in front of them before plotting.

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Geology of the Joplin Quadrangle

James R. McCauley, KGS, and
David C. Smith and Charles E. Robertson, MGS

The Joplin quadrangle straddles the State line between the southeast corner of Kansas and southwest Missouri. West-to-northwest dips in the bedrock reflect the location of the quadrangle on the Prairie-Plains homocline of the northwest flank of the Ozark dome, the dominant structural feature of the area.

The oldest rocks exposed in the quadrangle are Canadian (Lower Ordovician) dolomites of the Jefferson City and Cotter Formations, which are exposed in the northeastern corner. These are overlain unconformably by limestone and shale of Mississippian (Kinderhookian) age. Osagean limestone of the Burlington and Keokuk Limestones overlie Kinderhookian strata and crop out in isolated patches in the southeastern corner of the quadrangle. Meramecian limestone belonging predominantly to the Warsaw Formation overlies the Osagean limestone and crops out in a wide band trending northeasterly from the southeastern corner of Kansas. Chesterian rocks are limited to scattered exposures in the Joplin area. Pennsylvanian shale and sandstone of the Atokan and Desmoinesian Cherokee Group and minor limestone and economically important coal beds form a broad outcrop belt from the south-central part to the northeastern corner of the quadrangle.

Northwest of a line from Oswego to Fort Scott, Kansas, are alternating limestone and shale and some channel sandstone of the Desmoinesian Marmaton Group; Missourian Pleasanton, Kansas City, and Lansing Groups; and Virgilian Douglas and Shawnee Groups of Pennsylvanian age. These rocks form a series of subparallel northeast-trending outcrop bands that are progressively younger to the northwest and culminate with the Deer Creek Limestone, the youngest Paleozoic formation in the quadrangle. These outcrops are characterized by gently dipping, east-facing cuestas formed on the erosionally resistant limestone.

Two major northwest-trending fault zones cross the quadrangle. The Bolivar-Mansfield fault system crosses the extreme northeastern corner, and the Chesapeake diagonally bisects the Missouri portion. Many minor structures occur in the quadrangle as well, including the Dederick-Eldorado Springs dome in the northeast. The Rose and Silver City domes in the northwest are laccoliths, the latter having outcrops of Cretaceous lamproite, the youngest bedrock and the only igneous rock exposed in the quadrangle.

Metallic Mines and Prospects of the Harrison and Joplin Quadrangles

Michael C. McFarland, MGS, George W. Colton, AGC, and James R. McCauley, KGS

An important element in the appraisal of the mineral-resource potential of the Harrison and Joplin quadrangles was the determination of the number and types of known metallic mineral deposits, including their location, character, and significance. This information was compiled from records on file at the individual State surveys. Commodities and ore minerals, modes of occurrence, host-rock lithologies, ore controls, periods of mining activity, and production statistics were summarized for each known or reported mine, prospect, and occurrence. The information was then entered into GS-MODS (Mineral Occurrence Database System), a computerized system developed within the U.S. Geological Survey (USGS), Branch of Central Mineral Resources, expressly for the purpose of organizing, analyzing, and displaying mineral occurrence data. Output included individual site record forms, county summary listings, and map displays at 1:250,000 scale. Map displays were made by merging GS-MODS data with the plot capabilities of GS-MAP and GS-DRAW, which are USGS-developed software used to generate maps and illustrations. From these record and map sets, a realistic basis was established for determining the type and size of possible undiscovered metallic mineral deposits that might be present in the study areas.

The Harrison quadrangle includes parts of southwestern Missouri and northwestern Arkansas (lat 36°–37° N., long 92°–94° W.). A total of 983 mines, prospects, and occurrences were researched: 642 in Missouri and 341 in Arkansas. Zinc, lead, and copper sites make up 85 percent of the deposits, sphalerite, galena, and chalcopyrite being the most significant ore minerals. Iron sites are 15 percent of the total, pyrite, marcasite, limonite, and hematite being the ore minerals. Major mining areas include the Aurora zinc-lead district (Missouri), the Northern Arkansas zinc-lead district (Arkansas), and the West Plains brown iron district (Missouri). Mineral deposit types identified in the quadrangle include (1) Mississippi Valley-type (MVT) zinc-lead deposits in cherty Mississippian limestone and cherty Ordovician dolostone and (2) residual brown iron ore deposits in Ordovician residuum.

The Joplin quadrangle includes parts of southwestern Missouri and southeastern Kansas (lat 37°–38° N., long 94°–96° W.). A total of 2,850 mines, prospects, and occurrences were inventoried: 2,067 in Missouri and 783 in Kansas. Zinc and lead sites make up 99 percent of the deposits; the dominant ore minerals are sphalerite, hemimorphite, smithsonite, galena, and cerussite. A very few sites are of iron, limonite and hematite being the ore minerals. The world-class Tri-State zinc-lead district (Oklahoma, Kansas, and Missouri) is in the southeastern corner of the quadrangle. Mineral deposit types identified in the quadrangle include (1) MVT zinc-lead deposits in cherty Mississippian limestone and (2) residual brown iron ore deposits in Pennsylvanian and Mississippian residuums.

Geologic and Structural Overview of the Harrison Quadrangle

Mark A. Middendorf, MGS, and
John David McFarland III, AGC

The rocks exposed in the Harrison quadrangle are exclusively sedimentary. They range in age from Early Ordovician to Early Pennsylvanian and are represented principally by dolostone and limestone, although sandstone, and to a lesser degree shale, are also present.

The Lower Ordovician Canadian Series—Gasconade Dolomite, Roubidoux Formation, Jefferson City Dolomite, Cotter Dolomite, and Powell Dolomite—comprises the bedrock of approximately 45 percent of the quadrangle. The lithologies of these formations identify a series of shallowing-upward sequences from intertidal to subtidal and supratidal environments on a regional carbonate shelf. Post-Cotter Ordovician units thin and pinch out to the north near the Missouri-Arkansas State line and to the west, owing to modern erosional truncation and stratigraphic diminishment. In the lower Middle Ordovician (Whiterockian and lower Mohawkian) of Arkansas, sandstone is the dominant lithology of the Everton Formation and St. Peter Sandstone. Above the St. Peter Sandstone, the Joachim Dolomite, Plattin Limestone, and Kimmswick Limestone are shallow carbonate platform deposits. The Upper Ordovician Cincinnatian Series is represented in Arkansas by the Fernvale Formation and Cason Shale; the Cason spans the Ordovician-Silurian boundary.

The Silurian of Arkansas is areally limited, represented by the Cason Shale (in part) and the St. Clair Limestone. In both states the Devonian is of limited mappable exposure, comprising the Fortune Formation or Clifty Limestone of the Middle Series and the Chattanooga Shale of the Upper Series.

Mississippian rocks predominantly are variably cherty limestone, very finely to coarsely crystalline and fossiliferous (abundant crinoid debris and brachiopods); sandstone and shale are subordinate. The general depositional setting for these rocks is shelf margin to platform and shallow basin. The division of the Mississippian System is shown in figure 4.

Sandstone and interbedded thin shale and limestone compose the Pennsylvanian units and are found as channel to shallow marine deposits. In Arkansas the Bloyd and Hale Formations of the Morrowan Series are overlain by the Atoka Formation of the Atokan Series. In Missouri the Pennsylvanian units are assigned to the Cherokee Group of the Desmoinesian Series.

The Harrison quadrangle is in a stable cratonic region on the southwest flank of the Ozark uplift and

System	Series		Formation: Missouri	Formation: Arkansas	
Mississippian	Upper	Chesterian	Fayetteville Formation Batesville Formation Hindsville Formation	Pitkin Limestone Fayetteville Formation Batesville Formation	
Mississippian	Upper	Meramecian	Warsaw Formation	Moorefield Formation	
Mississippian	Lower	Osagean	Keokuk Limestone Burlington Limestone Elsey Formation Reeds Spring Formation Pierson Limestone		Boone Formation
Mississippian	Lower	Kinderhookian	Northview Formation Compton Limestone Bachelor Formation	St. Joe Limestone Member	Boone Formation

Figure 4. Mississippian stratigraphy of the Harrison quadrangle.

contains a moderate number of mapped faults. High-angle normal faults and long, narrow grabens are dominant. A northwest trend in the eastern three-quarters of the northern half of the quadrangle changes to east-west and northeast in the western part. Faults have been detected along the trend of the Bolivar-Mansfield fault zone into this quadrangle from the Springfield quadrangle to the north, although they are not continuous and appear to split into two subparallel trends. Structures in Canadian post-Roubidoux units are difficult to discern because of the large thickness and lack of good marker beds. In the southern half of the quadrangle, two major faults and at least one minor fault are discernible; major structural trends are northeast and east-west, and a minor west-northwest trend is apparent.

Geochemical Anomalies and Sulfur Isotope Systematics of Upper Cambrian Clastic Rocks in the Midcontinent—Relation to Ore Fluid Movement

Elwin L. Mosier and Martin B. Goldhaber, USGS, and Jack Masters, ISGS

Basal Cambrian formations in the Midcontinent consist of the Upper Cambrian Mount Simon Sandstone in Illinois and the equivalent time-transgressive Lamotte and Reagan Sandstones in Missouri and Arkansas. These formations lie directly on the Precambrian basement and are conformably overlain by Upper Cambrian carbonate rocks. The basal sandstones are regarded as a likely aquifer through which metal-bearing basinal brines migrated. To evaluate this possibility, sandstone samples were collected from more than 130 drill holes in Illinois, Missouri, Arkansas, and Kansas. Heavy-mineral concentrates obtained from the samples were analyzed for mineralogy, chemical composition (33 elements by induction coupled plasma-atomic emission spectroscopy), and sulfur isotope composition. Detrital heavy minerals generally make up less than 0.5 percent of the sample and include zircon, tourmaline, garnet, glauconite, rutile, apatite, hematite, epidote, monazite, sphene, spinel, biotite, and ilmenite. Hydrothermally introduced heavy minerals include pyrite, marcasite, chalcopyrite, bornite, arsenopyrite, and galena.

Chemical analyses of the heavy-mineral concentrates of the sandstones show a widespread epigenetic suite of metals (Ag, As, Co, Cr, Cu, Mo, Ni, Pb, and Zn) that confirms the basal sandstones served as an aquifer for the migration of metal-rich fluids. Anomalous concentrations of metal are not randomly distributed, however, but rather tend to group in several specific areas. For example, copper values of less than 0.15 percent, and elevated lead concentrations cluster in the vicinity of the St. Francois Mountains and southwest of this area in Oregon, Shannon, and Carter Counties, Missouri. Sulfur isotope measurements made on approximately 60 sulfide-bearing samples span a wide range of values, from -21 to +33 permil. A significant grouping of the data lies between +10 and +25 permil. This range is the same as that found in the main-stage mineralization of the Southeast Missouri lead district, a similarity that suggests sandstones could have been a conduit for H_2S as well as metals.

Early diagenetic hematite cement is a prominent feature of the sandstone in the area north of the Missouri River and east of the St. Francois Mountains adjoining the Illinois Basin. The regional distribution of barium is closely related to the presence of this hematitic cement, and the distribution of both hematite and barium is antipathetic to the distribution of the epigenetic suite of metals. The hematite-bearing sandstone originally may have been present over much of the Ozark region. Warm basinal brines passing through the hematite-barium-rich sandstone would have leached the iron and barium. Thus, areas of bleached basal sandstone (low iron) may reflect pathways of fluid migration (and a major barium source) in the basal sandstone. Conversely, hematitic barium-rich zones would represent areas where hydrothermal flow was minimal. These observations, together with the regional chemical and isotopic studies, may be useful in identifying areas favorable for ore deposition.

Heavy-Oil Resource Potential of the Joplin Quadrangle

Bruce W. Netzler, MGS

Previous heavy-oil studies in Missouri have focused on the area of the Joplin quadrangle because heavy-oil-bearing sandstones are present there and pinch out westward into Kansas. Heavy oil occurs in sandstones of the Pennsylvanian Cherokee Group, which crops out in the southeasternmost part of the quadrangle and is 100–120 ft below the surface in the northwestern part of the quadrangle. The Cherokee contains four potential reservoir intervals: (1) lower part of the Warner Formation, (2) upper part of the Warner Formation, (3) lower part of the Bluejacket Formation, and (4) upper part of the Bluejacket Formation. The lower part of the Bluejacket and the upper part of the Warner contain most of the potential heavy-oil reserves. The gravity of this oil ranges from 25 to 8 °API, and in the lower ranges the oil is very viscous to almost solid.

Previous realistic estimates of reserves range from 1.4 to 8.3 billion barrels of oil in place (J.S. Wells, Missouri Geological Survey, unpublished map, 1974; Wells and Heath, 1979). The economic cutoff for production of heavy oil in Missouri is about $20 per barrel. Using this amount and a proven recovery rate of as much as 50 percent of oil in place with existing methods, this resource is worth $14–85 billion using existing estimates.

A total of 715,000 barrels of oil has been produced in the Missouri portion of the Joplin quadrangle from the beginning of production records in late 1966 through 1988. From 1983 to 1985, more than half of Missouri's total oil production came from heavy-oil deposits in this area.

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Geologic Mapping and Evaluation of the Pea Ridge Iron Ore Mine (Washington County, Missouri) for Rare-Earth Element and Precious Metal Potential

Laurence M. Nuelle, Mark Alan Marikos, and Cheryl M. Seeger, MGS

As part of a cooperative effort by the U.S. Geological Survey and the Missouri Department of Natural Resources, Geological Survey Program, the Pea Ridge iron ore deposit is being evaluated as a possible variant of the Olympic Dam-type deposit (Kisvarsanyi and Robertson, this volume). The Pea Ridge Iron Ore Company granted access to the mine for geological mapping and topical studies to determine ore genesis and to evaluate the deposit for potential mineral commodities not presently recovered.

The Pea Ridge iron ore deposit, long interpreted as a magmatic intrusion of magnetite into Middle Proterozoic intrusive porphyritic rocks, has been considered a deposit that comprises several distinct mineralogical zones (Emery, 1968). Later work by J.R. Husman (unpublished company reports) refined the mineralogy, texture, and distribution of the zones and documented rare-earth elements and gold. Husman also identified the host rock to be volcanic, rather than plutonic.

Our work to date has refined the mineralogical zones and added a previously undescribed zone. The zonation described is that of orebody scale or assemblage zoning. Our zonal terminology is subject to revision as the investigation proceeds.

To date we have defined six mineralogical assemblages; each zone is characterized by distinct and generally abrupt changes in mineralogy. (1) The amphibole zone (Emery's quartz-amphibole zone) contains mostly amphibole and varying amounts of quartz. (2) The magnetite zone (the same as Emery's magnetite zone) contains more than 60 percent iron ore, most of which is magnetite, and varying amounts of apatite. (3) The hematite zone (Emery's specular hematite and quartz-hematite zones) represents hydrothermally altered portions of the magnetite zone. (4) The brecciated wall-rock magnetite zone (Emery's porphyry-breccia zone) is wall-rock breccia having little clast abrasion or rotation. Magnetite, some of which was subsequently altered to hematite, filled fractures and replaced much of the host rock through metasomatism. (5) The breccia pipe zone, previously undescribed, comprises at least four breccia bodies containing varying amounts of potassium feldspar, barite, and rock-flour matrix. Breccia pipes are rare-earth element mineralized to such an extent that the Pea Ridge deposit can be considered an iron–rare-earth element deposit. (6) The silicified zone (in part correlating to Emery's quartz-amphibole and quartz-hematite zones) represents wall-rock areas or other assemblage zones that were silicified during a relatively late stage event. Quartz veins pene-contemporaneous with silicification contain minerals such as monazite, rutile, and xenotime. Erratic gold contents have been reported from the breccia pipe and silicified zones.

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Ore Distribution in the Missouri and Kansas Portions of the Tri-State District of Missouri, Kansas, and Oklahoma

Laurence M. Nuelle and
Michael C. McFarland, MGS

As part of the Joplin CUSMAP mineral assessment, the Missouri and Kansas portions of the Tri-State district were evaluated for potential ore deposits. The assessment consisted of outlining favorable blocks of ground defined by a set of criteria (Pratt and others, this volume), plotting mines and prospects (McFarland, this volume), and reviewing ore distribution (this report).

Tri-State district orebodies are in Mississippian rocks, mostly the Keokuk Limestone (Osagean) and Warsaw Formation (Meramecian); minor deposits are in the Osagean Reeds Spring Formation and in Chesterian rocks. Beds were assigned letter designations during district exploitation; the lettered beds alphabetically increase in age downward through the stratigraphic succession. Important productive beds were the E, G, H, K (Warsaw Formation), and M and N (Keokuk Limestone), all consisting of cherty limestone or alternating beds of chert and limestone (Brockie and others, 1968).

Orebodies have three basic geometries. (1) Circle deposits, associated with paleosinkholes, fill curved fracture patterns around the structure's margin and have a circular appearance in plan view and a truncated cone appearance in cross section. (2) Run deposits occupy narrow shear zones and have a long linear appearance; a minority of runs occupy sinuous fracture zones that resemble the shape of a meandering channel. (3) Sheet-ground deposits are extensive, flat-lying orebodies having grades that generally do not exceed much more than 3 percent combined lead and zinc, about half the grade of other deposits. Sheet-ground mines are irregularly shaped areas mined by the room-and-pillar method.

Most orebodies are zoned; a central dolomitic core is surrounded by the main ore run, which in turn is surrounded by jasperoid, and finally by unaltered limestone. Sphalerite and galena, the only ore minerals recovered, are present in a ratio of about 5:1. The association of mineralization to jasperoid and dolomite is well documented (for Missouri deposits) by six maps compiled by Thiel in 1922. The maps, large and cumbersome, were digitized into a computer file using GSMAP (a U.S. Geological Survey computer drafting program) so that they can be plotted on scales more useful for field work. They will be available from the Missouri Division of Geology and Land Survey as an open-file report.

Ideas about ore genesis have not changed greatly since the turn of the century. Much current thought is that ore-bearing fluids were transported by aquifers in Cambrian and Ordovician rocks, and overlying shales acted as aquitards; peripheral pinchout of the various shales causes the district to be in a "shale window." The lack of aquitards in the "window" coupled with extensive fracturing allowed ore-bearing fluids to rise and deposit ore minerals upon a decrease in pressure. Much of this was described as early as 1894. The importance of the shale pinchouts was known as early as 1907. The ore deposits are thought to be post-Pennsylvanian because some ore occurs in fractured Pennsylvanian shales that covered the entire district during ore deposition.

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Geologic Mapping Project of the Pea Ridge Iron Ore Deposit, Washington County, Missouri

Laurence M. Nuelle, Cheryl M. Seeger, and Mark Alan Marikos, MGS

Under the auspices of the U.S. Geological Survey's Midcontinent Strategic and Critical Minerals Project, the U.S. Geological Survey and the Missouri Department of Natural Resources, Geological Survey Program, are evaluating Midcontinent Middle Proterozoic iron ore deposits as possible variants of the Olympic Dam deposit (Kisvarsanyi and Robertson, this volume). The first phase involves geologic mapping of the Pea Ridge deposit, the only active Midcontinent iron ore mine producing from a geologic setting similar to that of the Stuart shelf of South Australia.

A geologic mapping program was designed to document systematically the geologic and mineralogical features. The mapping method is one developed mostly by the Anaconda Company for mapping porphyry copper deposits. The map scale of 1 in. = 20 ft reveals many features important to the understanding of the deposit, which would be missed using a larger scale. Geologic features along drift ribs are projected to a horizontal map plane about 5 ft above the floor. Twenty-one color-coded pencils are used to represent mineralogical and structural features, thereby minimizing note writing and allowing the map to be easily scanned. Rock features such as composition, structure, texture, and vein fillings are plotted on the rock side of the field map; alteration features are plotted on the air side (fig. 5).

The extent of mined-out areas precludes mapping of the entire deposit. Instead, we map traverses that cross several geologic boundaries to document ore emplacement and other geologic events. Three levels will be extensively mapped to determine vertical variations in the deposit. Smaller areas on other levels containing significant exposures will be mapped to better elucidate important geologic relationships.

Because of differences in map scales between company base maps and our maps and the number of color- coded pencils used, map reproduction is difficult. This difficulty, however, is greatly reduced with the use of personal computers. Company mine maps are digitized and stored in data files by using GSDRAW (a U.S. Geological Survey computer drafting program). When a traverse is selected, the desired portion of the mine map is reproduced at the required scale. This map then becomes the base map for the underground traverse. When underground traverses are complete, the information and other traverses of the same mine level are transferred to a posting sheet, which is a plan-view geologic map.

The same computer program is used to digitize posting sheets. A variety of symbols and colors allows the plan-view geologic maps to be reproduced upon demand. Owing to hardware and software limitations, some designations on the computerized maps are different from those of the original posting sheets. For example, a fluorite-bearing quartz vein, shown as yellow and purple on the posting sheet, is a yellow line on the computer-plotted map, with an "F" adjacent to the yellow line indicating fluorite. All maps will be available to the public as open-file reports through the Missouri Division of Geology and Land Survey.

The Importance of Mineral Deposits in the Midcontinent, Past and Future

Ernest L. Ohle, University of Arizona

The Midcontinent area was the location of the first great mineral deposits discovered in the United States. As migration spread westward from the eastern seaboard along the Ohio-Mississippi-Missouri River system, localities where lead minerals outcropped soon attracted attention and became population centers. Some developed into major districts by the end of the 19th century—the Upper Mississippi Valley (discovered in 1682), Southeast Missouri (1720), and the Tri-State (Missouri-Kansas-Oklahoma, 1880).

Although lead for bullets was of great importance in pioneer life, demand for other metals, such as copper and zinc, awaited more sophisticated needs caused by the Industrial Revolution. The Michigan native copper district was developed just as the inventions of the telegraph, telephone, and electric light created a need for large amounts of the red metal, whereas zinc for galvanizing, paints, rubber, and die casting was needed somewhat later. The Midcontinent was sufficiently endowed to satisfy these needs before deposits in most western areas were discovered.

Remarkable characteristics of some of the Midcontinent mineral districts are their great size and considerable longevity. Although the known exploitable reserves of the Upper Mississippi Valley and Tri-State districts have been exhausted after dominating the zinc-lead industry for many decades, the great Southeast Missouri district still rules lead production statistics

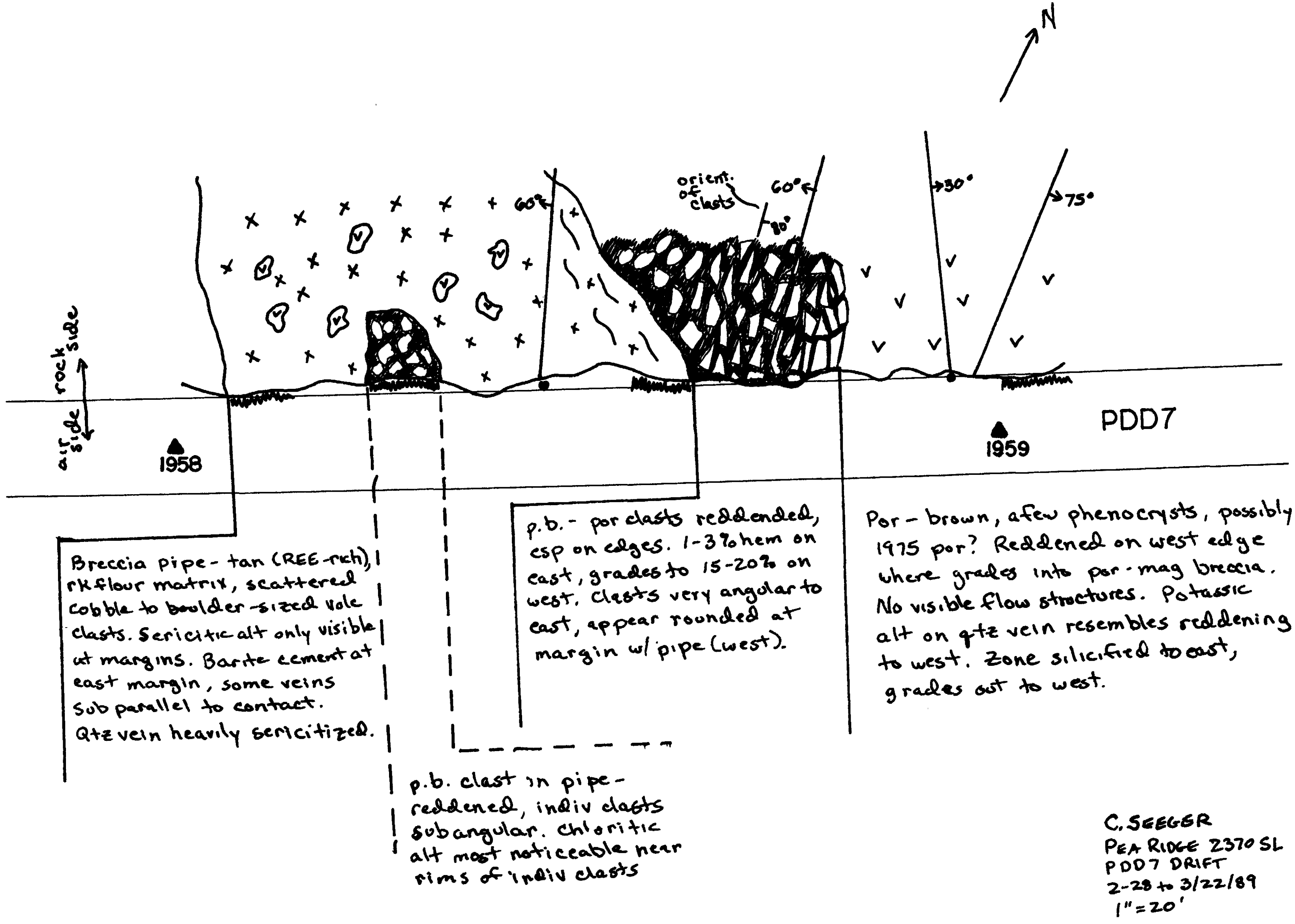

Figure 5. Hypothetical example of an underground traverse map. The rock and mineral features would be plotted in color rather than in black and white as shown here. Minimal field notes accompany the map. Rock features are plotted on the rock side of the drift and alteration features are plotted on the air side.

and probably will for a few more decades. The great Michigan native copper mines are inactive today, but from 1865 until after World War I, so-called Lake copper was the quality standard of the industry. Smaller but still significant production continues from the shale-hosted White Pine mine.

The Lake Superior banded iron-ore deposits first became important on the Marquette Range in 1852. Production here was followed by ore discoveries on the Menominee and Penokee-Gogebic Ranges and, in 1890, by the recognition of the great Mesabi. Development of these enormous deposits has changed the character and location of the iron and steel business ever since. Not until similar ore became available from overseas was there a serious challenge to Lake Superior domination. Slackening of Lake Superior production has been a matter of economics, not ore exhaustion. So-called natural ores are still available but of less interest to furnace operators because they cannot match the physical and chemical consistency of concentrates and pellets.

Important industrial mineral deposits also have been productive in the Midcontinent, particularly those of fluorspar in southern Illinois and Kentucky and barite in Missouri.

The mineral production history of the Midcontinent has been long and glorious, and the output there still is very significant. But as known reserves are depleted, new discoveries will need to be made in concealed locations. Fortunately, geologic studies over the past 50 years have given us much-improved understanding of the geologic relationships surrounding the orebodies and offer hope that duplications of the favorable settings can be found. In addition, newly recognized and newly understood ore types have been found in recent years to be represented in the Precambrian of the Midcontinent, and these largely concealed rocks may be expected to attain economic importance in the decades ahead. The purpose of this conference is to point out some of the significant features that lead to optimism that such discoveries will be made.

Regional Upper Cambrian Lithofacies Framework of Southern Missouri

James R. Palmer, MGS

Upper Cambrian rocks in southern Missouri have significant potential for hosting Mississippi Valley-type (MVT) ore deposits. Preliminary regional lithofacies analysis of proven and potential Cambrian MVT host rocks has resulted in a clearer understanding of stratigraphic relationships and problems.

Upper Cambrian rocks are at least 4,700 ft thick near the Reelfoot graben in southeast Missouri and thin gradually toward western Missouri, where they are 700 ft thick. The nature of pre-upper Lamotte Sandstone rocks near and in the Reelfoot graben in Missouri remains largely unknown.

Above the fluvial, alluvial, and marine sandstone of the Upper Cambrian Lamotte Sandstone, the Upper Cambrian sequence comprises a series of transgressive-regressive cycles within a regional carbonate shelf. The regional shelf margin is at the Reelfoot graben (fig. 6). North and northwestward from the graben, facies transitions between intrashelf basinal shales and platform carbonate rocks are characteristic of homoclinal ramps. Some local facies variations indicate, however, that ramps were, at places, distally steepened and that fringing banks existed at places along some ramps.

There are two basic types of Cambrian transgressive-regressive sequences. Type I sequences within the intrashelf basinal areas consist of shallowing-upward cycles 60–200 ft thick composed of (1) basinal shale and lime mudstone, wackestone, and packstone, grading upward to (2) carbonate mudstone, wackestone, packstone, and grainstone of the ramp and shoal, and locally topped by (3) platform-peritidal cycles dominated by bedded cryptalgal boundstone. The middle to upper parts of these cycles are mostly dolostone. In contrast, platform core areas have type II brown to "whiterock" dolostone cycles 20–300 ft thick or more. These have (1) abrupt transgressive bases of packstone or grainstone, (2) ramp or subtidal-platform mudstone and wackestone, (3) either a packstone-grainstone shoal or a fringing bank of cyclically bedded cryptalgal boundstone, and (4) emergent-platform cryptalgal laminated to coarsely crystalline and locally brecciated "whiterock" dolostone. In CUSMAP assessments only intrashelf basin shale and ramp shaly limestone have been consistently assigned a low potential for MVT deposits. All other facies, in some geographic and stratigraphic setting, have been rated potentially favorable for MVT deposits.

Because most Cambrian formations were named where the Davis Formation is present and is composed mostly of intrashelf basinal shale and limestone, formation names outside of that intrashelf basin setting, where the sequences are type I, have little application in the platform core areas, where sequences are type II. Paleohydrologic studies and MVT assessments and exploration models are dependent upon an accurate representation of that regional stratigraphic and sedimentational framework. The first step in understanding the framework is recognition of the relationships between lithofacies and formational type section terms already in use.

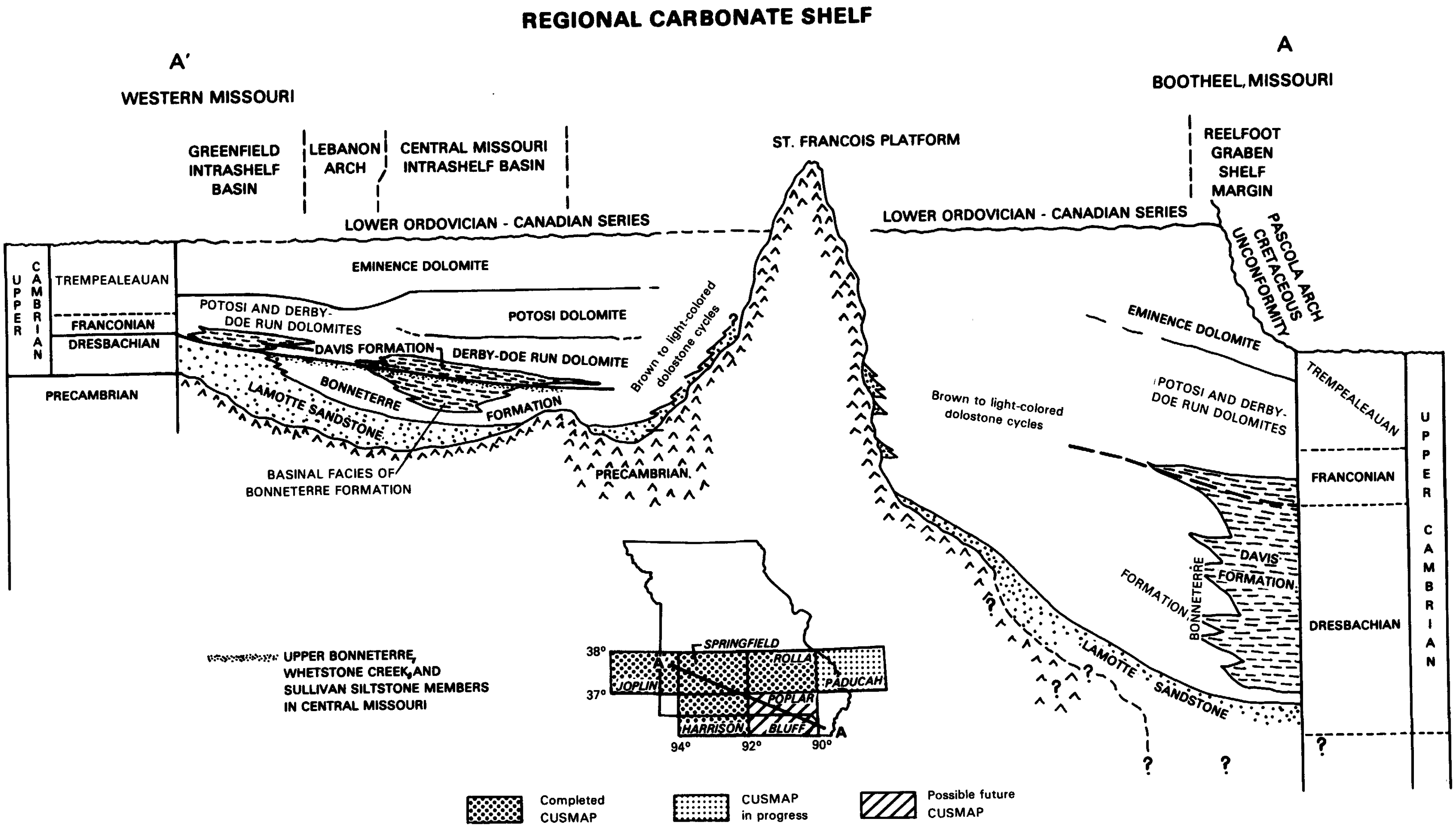

Figure 6. Generalized Upper Cambrian stratigraphy of southern Missouri. This generalized stratigraphic section shows locally dramatic relief on the Precambrian surface in southern Missouri, though it is shown highly exaggerated here. The Cambrian sequence thins gradually westward, and the number of recognizable transgressive-regressive cycles also decreases. At the regional shelf margin there are nine transgressive-regressive cycles in the Bonneterre Formation through Eminence Dolomite, whereas there are only three transgressive-regressive cycles in equivalent western Missouri Upper Cambrian rocks. Type sections for the Bonneterre and Davis Formations and Derby-Doerun (as used by the Missouri Geological Survey) and Potosi Dolomites are all within the Central Missouri intrashelf basin.

Application of Cambrian Lithofacies Mapping in the Springfield, Harrison, and Joplin CUSMAP Assessments for Mississippi Valley-Type Deposits

James R. Palmer, MGS, Timothy S. Hayes, USGS, Cheryl M. Seeger, MGS, Gary Krizanich, Melanie Werdon, USGS, and John W. Whitfield, MGS

Upper Cambrian sedimentary rocks of the western Ozark region were deposited by seas that onlapped the southeast-sloping Precambrian craton in at least two major transgressive-regressive stages. A simplified complete carbonate shelf transgressive-regressive sequence, from the base upward, is:

1. A lag of variably shaly pelletal glauconitic and skeletal wackestone and packstone;
2. Intrashelf basinal shale and interbedded carbonate rocks, whose shaliest interval marks maximum transgression;
3. Deep-ramp, thinly interbedded quartz siltstone and carbonate mudstone, grainstone, and thrombolite boundstone;
4. Ramp-shoal oolitic, skeletal, or pelloidal grainstone and packstone;
5. Thrombolite to digitate, microbial cryptalgal boundstone;
6. Platform shallowing-upward cycles of thrombolite upward to cryptalgal boundstone; and
7. Emergent-platform, cryptalgal-laminated and coarsely crystalline, locally brecciated "whiterock" dolostone marking the top of the transgressive-regressive cycle.

During Cambrian deposition, local lithofacies varied dramatically, controlled in part by topography. Geometrically variable carbonate platforms first formed around several highland areas on the Precambrian erosional surface. Basal Cambrian sandstones are thin or absent across some highland areas. Ramp and platform carbonate rocks prograded across shallow basins where interbedded shale and carbonate rocks had been deposited earlier. Transgressions superposed shaly basinal facies over carbonate rocks of the ramp and platform. The lithologic variation in these onlap and offlap Cambrian sequences determined in part migration pathways for later subsurface solutions.

Basinal shales and deep-ramp shaly limestones acted as aquitards to the migration of dolomitizing and later mineralizing fluids. Certain tight dolostones may also have impeded movement of mineralizing solutions. Basinal and deep-ramp shaly rocks are the only rocks remaining undolomitized over most of the region.

Mississippi Valley-type (MVT) deposits in the Ozarks are adjacent to and up section from regional aquitard pinchouts or where aquitards were structurally breached; these locations suggest that MVT ore precipitated where brines escaped confinement and migrated upward. Regionally, most MVT-stage mineralization is found within areas of secondary or enhanced porosity or as replacement bodies in non-shaly carbonates. In our judgement there are no particularly favorable lithofacies or arrangements of lithofacies. Excluding basinal shales and deep-ramp limestones, every facies has somewhere been host to important Southeast Missouri district MVT mineralization. Only the aquitards are unfavorable because they lacked vertical permeability at ore stage. All rocks that had MVT-stage porosity and permeability are favorable, particularly where they are adjacent to and up section from aquitard pinchouts. Important potential for undiscovered MVT deposits exists in all three quadrangles marginal to and above the pinchouts of Bonneterre and Davis Formation aquitards.

Folio of Midcontinent Maps and Cross Sections

Walden P. Pratt, USGS, for the Midcontinent Project Team

One of the first tasks undertaken in the Midcontinent Strategic and Critical Minerals Project was to compile an inventory of selected aspects of subsurface geology of the core area of the project—the area defined by lat 36°–46° N., long 88°–100° W. The U.S. Geological Survey (USGS) contracted with the various State geological surveys for input, which in most cases consisted of 1:1,000,000-scale interpretive lithofacies or other maps compiled by geologists in each State from drill-hole logs available in the respective State files. The USGS then combined the State maps for each product onto a common 1:1,000,000-scale base for use in studies of resource potential and for eventual publication. The current status of these products, which constitute the folio of the northern Midcontinent, is as follows:

Availability of data for selected deep drill holes (Mugel)—Published, USGS MF–1835–A.

Water table and salinity, Cambrian-Ordovician and Mississippian aquifers (Jorgensen and others)—Published, MF–1835–B.

Radiometric dates of basement rocks (Marvin)—Published, MF–1835–C.

Isopachs and clastic/limestone/dolomite ratios, Sauk sequence (Pratt)—Published, MF–1835–D.

Phanerozoic structures (Anderson)— Published, MF–1835–E.

Precambrian basement terranes and structure (Sims)—Released, USGS Open-File Report 85–0604; in press, MF–1853–A.

Alkaline igneous rocks, carbonatites, and peridotites (Hills and others)—In press, MF–1835–F.

Lithologic cross sections along even latitudes and longitudes (Mugel)—In revision, MF map.

Isopachs and limestone/dolomite ratios, carbonate rocks of the Bonneterre Formation, Upper Ordovician carbonate rocks, and Mississippian carbonate rocks (Pratt)—In preparation, MF map.

Extent of selected shales in thicknesses greater than 5 ft (Pratt)—In preparation, MF map.

Regional Permissivity of Selected Carbonate Units for Mississippi Valley-Type Deposits in the Northern Midcontinent

Walden P. Pratt, USGS, for the Midcontinent Project Team

A popular general model for formation of Mississippi Valley-type (MVT) deposits in platform carbonate rocks of the Midcontinent invokes upward movement of metal-bearing brines from an underlying aquifer to a site in the carbonate section where the metals are precipitated as sulfides. Implicit in this model are (1) windows through any regional shale underlying the host unit and, for many workers, (2) a shale caprock overlying the host unit. Additional factors considered important by many include the presence of faults and proximity to a regional-scale limestone-dolomite transition.

Using this model, the Midcontinent Strategic and Critical Minerals Project team has compiled a set of 10 1:1,000,000-scale maps of the project area (lat 36°–46° N., long 88°–100° W.). Three maps show the thickness and limestone/dolomite ratios of three proven host-rock carbonate packages: the Upper Cambrian package (Bonneterre Formation-Eau Claire Formation and equivalents), the middle Upper Ordovician (Cincinnatian) package (Galena Dolomite-Viola Limestone-Kimmswick Limestone), and the Lower Mississippian (Kinderhookian-Osagean) package (Choteau-Burlington-Keokuk Limestones) (fig. 7). The other maps show the extent of 5 ft or greater thicknesses of the principal shale units: (1) the Upper Cambrian Davis Formation and equivalents, the Middle Ordovician (2) Glenwood Shale and equivalents and (3) Decorah Shale, (4) the Upper Ordovician Maquoketa Shale and equivalents, (5) the Devonian Chattanooga-Maple Mill-New Albany Shales, (6) the Mississippian Warsaw Shale, and (7) the Pennsylvanian Cherokee Group.

Various combinations of these maps can be used to identify areas that should be lithologically permissive for MVT deposits. For example, for the Bonneterre-Eau Claire host, the underlying Lamotte-Mount Simon Sandstones provide the aquifer, and a cap of overlying shales of the Davis might provide a trap; thus, areas where the shale of the Davis caps the limestone-dolomite transition in the Bonneterre-Eau Claire would be permissive—the more so at any coincidence with major fault zones. As another example, if the Galena package is considered the potential host, two permissivity models are possible: one with the Lamotte-Mount Simon as the aquifer, requiring coinciding windows in the shales of the Davis, Glenwood, and Decorah; the other with the Middle Ordovician St. Peter Sandstone as an aquifer, requiring windows only in the Glenwood and Decorah. Favorability in both models would be enhanced by fault zones and Maquoketa caprock shales.

Several permutations of the various aquifers, host carbonate rocks, and shales are possible, and several examples are shown. The Galena-host model using the Lamotte-Mount Simon aquifer confirms permissivity of the Upper Mississippi Valley district and identifies other permissive areas in northwest and north-central Missouri and in Shawnee and Coffey Counties, Kansas. The Galena-host model using the St. Peter aquifer suggests additional permissive areas in south-central and eastern Iowa. A Mississippian-host model confirms the Tri-State district (Kansas-Missouri-Oklahoma) and suggests additional permissive areas in north-central Missouri and possibly southwestern Illinois.

These and other examples indicate that the regional maps should be useful preliminary prospecting tools for identifying large-area potential targets; in all cases they should be supplemented by more detailed analysis of available drill-hole logs and samples.

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Assessment of Potential for Undiscovered Mississippi Valley-Type Deposits in the Harrison and Joplin quadrangles

W.P. Pratt and others, USGS, J.A. Martin and others, MGS, W.V. Bush and others, AGC, and P. Berendsen and others, KGS

The assessments of the Harrison and Joplin quadrangles are the most recent stages in an evolution of

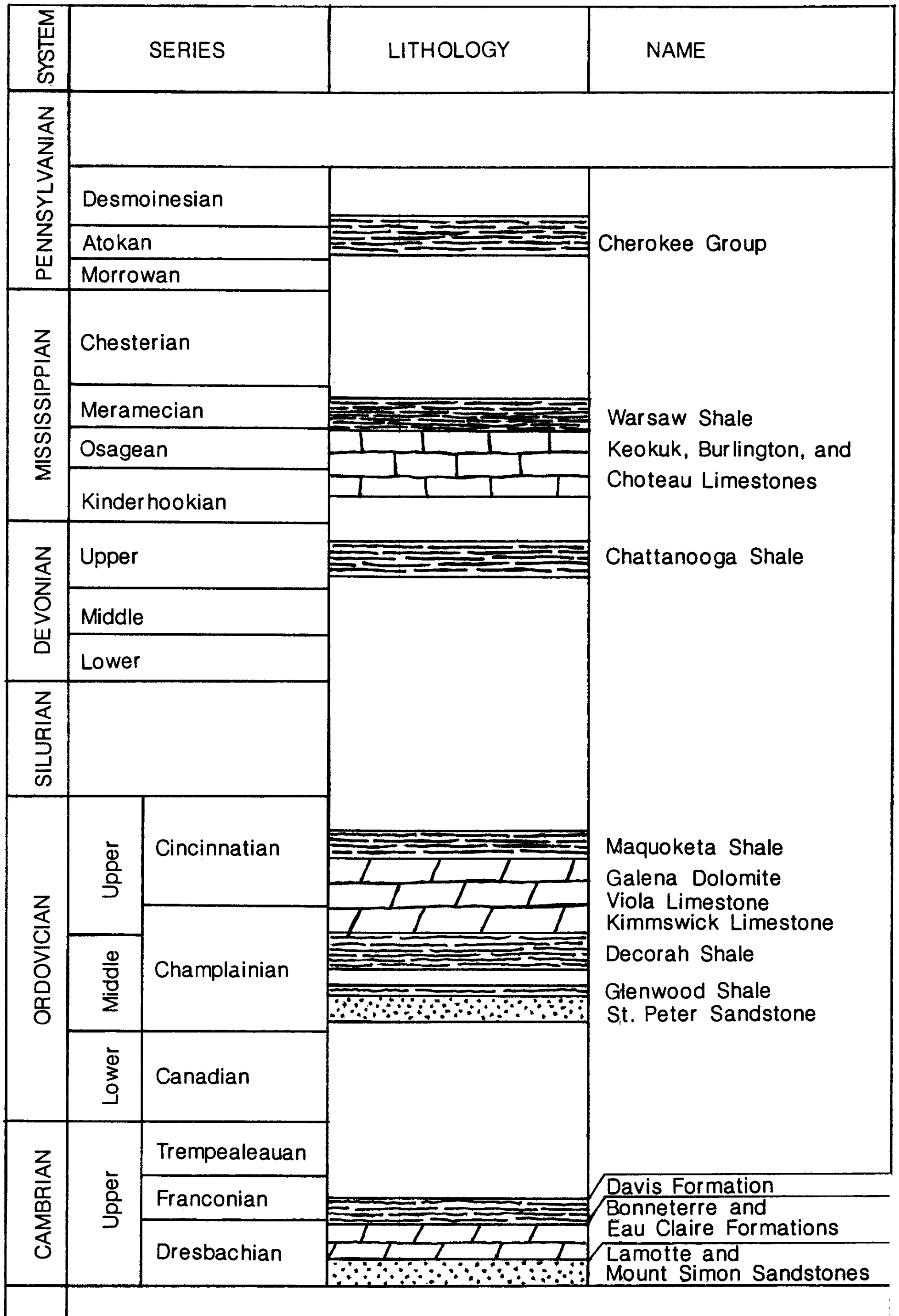

Figure 7. Relation of selected carbonate units, shales, and sandstone aquifers in the northern Midcontinent region. Modified from Adler (1987).

assessment methods that began with the Rolla CUSMAP assessment in 1980. This evolution results mostly from additional studies and understanding of depositional lithofacies of the carbonate rocks and the relation of facies to mineralization.

In the Rolla assessment, the principal host rock considered was the Upper Cambrian Bonneterre Formation, and the assessment model for Mississippi Valley-type (MVT) deposits included three facies-related diagnostic criteria: proximity to the limestone-dolomite interface, "brown rock" dolomite host rock, and proximity to digitate stromatolite boundstone (reef) facies. The two other factors included in the assessment model were geochemical anomalies in insoluble residues of apparently barren carbonates, and favorable structure (faults and fractures); these latter two factors have been retained through all the subsequent CUSMAP assessments.

In the Springfield CUSMAP assessment (1985), the principal prospective host was the "post-Bonneterre Cambrian" sequence of Palmer (1985). In the Springfield quadrangle that sequence contains the geochemical anomalies and that sequence was shown to be transected by facies boundaries similar to Rolla's Bonneterre host rocks. The model was more generalized in that favorable facies were defined only as dolomitized shallow-water carbonate rocks.

The Harrison CUSMAP assessment (1987), again considered both the Bonneterre Formation and the post-Bonneterre Cambrian. This time the limestone-dolomite interface was one favorable criterion, but the favorable carbonate facies was defined as a "zone of abrupt changes in depositional lithofacies adjacent to ramp facies." Knobs on the basement surface, in most cases inferred from aeromagnetic data, were also considered favorable because the underlying Lamotte Sandstone, evidently a principal aquifer for mineralizing fluids, may pinch out against the knobs, localizing an orebody like those of the Old Lead Belt. Using these criteria, the team identified a northwest-trending area in Douglas and Ozark Counties, Missouri, as having high potential (with a moderate degree of certainty) for undiscovered MVT deposits and an area in eastern Boone and western Marion Counties, Arkansas, as having high potential with a low degree of certainty. (The level of potential is based on the amount and kinds of evidence suggesting a favorable geologic environment for mineralization; the degree of certainty reflects the availability of data.)

The Joplin CUSMAP assessment, done early in 1989, incorporated a major change in philosophy of the model: continuing studies of carbonate facies indicate that the critical lithologic factor is not the favorability of a particular carbonate facies, but only the unfavorability of shaly ramp and basinal facies aquitards—all other lithofacies are favorable, particularly where they are adjacent to and upsection from a shale pinchout. This reaffirms with new support the old concept of "windows" in underlying shale units. Applying these criteria to the Joplin quadrangle, the CUSMAP assessment team identified two areas, one in the east-central part of the quadrangle and one in the southwest, considered to have moderate potential for undiscovered MVT deposits in Cambrian-Ordovician rocks. In Mississippian rocks, the assessment criteria correctly indicate a high potential for the area of the Tri-State district and confirm a high potential rating for an area of known mineralization north of Oswego, Kansas. Of greater interest, the criteria also indicate, with a moderate level of certainty, an area of high potential in the northeastern part of the quadrangle and additional areas of high potential northwest and north of Oswego.

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Implications From Fluid Inclusions for the Hydrology and Sulfide Precipitation Mechanisms of the Viburnum Trend Lead-Zinc District, Southeast Missouri

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Measurements on fluid inclusions in hydrothermal gangue dolomite place constraints on the thermal-hydrologic processes that formed the Viburnum Trend Mississippi Valley-type (MVT) lead-zinc district. The fluid inclusion measurements can be placed in a paragenetic context based on a well-defined cathodoluminescent growth zonation that facilitates correlation with other dolomites outside the Viburnum Trend. Cathodoluminescent zonation distinguishes dolomite growth zones as older or younger than main stages of mineralization (octahedral galena). Measurements were made on Bonneterre Formation–hosted hydrothermal dolomite cements in mine samples as well as on drill-core samples from as much as 10 km outside of the district.

Homogenization temperatures and salinities in samples from mines are not systematically different from those in samples from outside of the district. Modes of homogenization temperature distributions differ by not more than 20 °C, so that a temperature gradient, if present, should not have exceeded approximately 20 °C within the study area. These observations are interpreted to indicate that the Viburnum Trend was not thermally anomalous with respect to surrounding country rock and that fluid flow occurred on a broad scale, not only through the Lamotte Sandstone but through the overlying Cambrian carbonate rocks as well.

The absence of a significant, recognizable decrease in temperature either vertically within the section or east-west across the district, coupled with the minor amount of silica in the district, argues against cooling as a primary cause of sulfide precipitation. Fluids whose primary aquifer was the Lamotte Sandstone, dominantly a quartz-arenite, should have been in equilibrium with quartz. Quartz in the Viburnum Trend occurs as a minor, drusy, vug-lining phase, but the district lacks the intense silicification found in other MVT districts such as the Tri-State. Quartz solubility is strongly temperature dependent, and a decrease of 10 °C or more should have precipitated as many moles of silica as galena (assuming a galena solubility between 1 and 10 ppm); clearly, this is not the case.

Hydrothermal vug-lining and pore-filling dolomites hosting warm (approximately 105–125 °C), saline fluid inclusions are ubiquitous in the porous, dolomitic facies of Bonneterre Formation. On the basis of stratigraphic reconstructions, however, it is unlikely that the Bonneterre was buried deeper than 1 km. The distribution of warm inclusions beyond the Viburnum Trend district implies that fluid migration was on a regional scale. Fluid inclusion temperatures inconsistent with typical geothermal gradients (25–35 °C/km) may be explained by long-distance migration of warm, basin-derived brines in a gravity-flow hydrologic system. The flow rates and advective heat transport characteristics of a gravity-flow system are capable of maintaining elevated temperatures at shallow stratigraphic depths.

Ice final-melting temperatures (Tm) in fluid inclusions range from -15 to -27 °C with a distribution mode at approximately -21 °C. Using these Tm values and the cation ratios of J.G. Viets and D.L. Leach (U.S. Geological Survey, written commun., 1989), absolute concentrations for the individual cations were calculated using the thermochemical model of Spencer and others (in press). High but variable salinities (3.4–5.2 total salt molality) in virtually all primary inclusions from the dolomites are evidence for the presence of more than one distinct fluid during mineralization.

In a one-solution mineralization model, dilution is a possible sulfide precipitation mechanism. The difference in lead solubility (for an equal quantity of reduced sulfur) in the extremes of the salt concentration range, 3.4 versus 5.2 molal, reaches 1 ppm only for pH values below approximately 4.5. Accepting 1 ppm as a minimum metal concentration for a viable ore-forming fluid, it seems unlikely that dilution could have been a major cause of sulfide precipitation. Fluid inclusions in very late stage calcite document the incursion of lower salinity fluid (0.5–2.5 molal NaCl equivalent), probably during collapse of the mineralizing hydrologic system.

Given the limitations that the fluid inclusion data place on cooling or dilution, pH change, coupled with addition of reduced sulfur, appears, thus far, to be the most plausible sulfide precipitation mechanism.

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Manganese Potential of the Cretaceous Rocks Flanking the Sioux Ridge, Minnesota and South Dakota

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Cretaceous strata in southwestern Minnesota and eastern South Dakota have lithologic, geochemical, and depositional attributes of strata that host economic deposits of manganese at many localities around the world, as described in recently proposed depositional models for sedimentary manganese (Cannon and Force, 1983; Frakes and Bolton, 1984; Force and Cannon, 1988).

The models propose that a dilute ore-forming solution can be developed in anoxic parts of stratified seas where iron is removed as pyrite and where manganese is concentrated to values as much as 500 times those common in normal seawater. Manganese ore can form where this manganese-rich solution is transported to an oxygenated environment, such as along the margins of a depositional basin, and precipitated as oxide or carbonate minerals in regions where clastic sedimentation is supressed. Physical processes near shore may further concentrate the manganese-rich material.

The Cretaceous rocks surrounding the Sioux Ridge in southeastern South Dakota and southwestern Minnesota were first proposed to be favorable for sedimentary manganese deposits by Cannon and Force

(1983) on the basis of their geochemical and depositional model and the general characteristics of the region. Our current study has refined that assessment by improving delineation of the distribution and lithology of Cretaceous strata, especially in Minnesota (Setterholm and others, 1987), and by determining the concentration and distribution of manganese and iron in the Cretaceous strata, both laterally and stratigraphically (Setterholm and others, 1987; Hammond, 1988).

In southwestern Minnesota and in adjoining parts of South Dakota, Upper Cretaceous strata were deposited along the eastern side of the Western Interior Seaway on a gently sloping surface flanked by the Sioux Ridge, and they have correlative deeper water and, in part, anoxic facies to the west. The Sioux Ridge was a quartzite highland that at times formed either a peninsula or a group of islands. Rocks of the Dakota Formation, Graneros Shale, Greenhorn Formation, Carlile Shale, Niobrara Formation, and Pierre Shale define a shelf facies that passes into nearshore facies, such as the Split Rock Creek Formation along the Sioux Ridge paleocoast, and a regionally consistent lithostratigraphic succession of shallow marine and coastal sediments in Minnesota. Although decidedly more clastic, the Minnesota rocks correlate well with parts of the established Upper Cretaceous shelf sequence in South Dakota.

Two key components of the manganese depositional models have been documented in the study area. First, high manganese anomalies, although subeconomic, have been observed at several places in rocks deposited in an open-shelf environment. In particular, two drill holes north of the Sioux Ridge encountered a zone 40–60 m thick in the Pierre Shale in which manganese content is highly anomalous, ranging from 1 to 5 percent, and manganese:iron ratios are also very elevated, with values approaching 1. These, and other thinner zones elsewhere in the stratigraphic section, indicate that a geochemical fractionation of iron and manganese periodically occurred within a large region of the basin and strongly manganese enriched rocks were deposited. Second, strata reflecting cyclic oxic-anoxic conditions have been observed in both nearshore and shelf facies. The presence of these strata implies that flow paths existed between anoxic parts of the basin, where manganese-rich solutions were formed, and nearshore sites favorable for ore deposition.

The only parts of the study area that are definitively unfavorable for manganese deposits, in addition to Precambrian outcrop areas, are those areas where suitable Cretaceous strata are not likely to be present, such as areas containing only coarse clastic Cretaceous strata. All areas containing at least part of the marine section, including the Greenhorn Formation, Carlile Shale, Niobrara Formation, and Pierre Shale (or the equivalent Split Rock Creek Formation), are considered favorable. Because we have demonstrated that all essential criteria of earlier models are satisfied in the area and that very substantial regional manganese anomalies exist, we consider the area to be favorable for sedimentary manganese deposits with a higher level of certainty than existed previously.

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Geology, Bedrock Topography, and Potential Mineral Resources of the Trans-Hudson Orogen, U.S.A.

P.K. Sims, Zell E. Peterman, and T.G. Hildenbrand, USGS

Geological, geophysical, and well-log data were analyzed to map the subsurface geology and basement topography of the Early Proterozoic Trans-Hudson orogen (THO) and adjacent tectonostratigraphic terranes (fig. 8). The map was compiled as part of a cooperative Federal-State project with the geological surveys of Nebraska, North Dakota, South Dakota, Minnesota, Montana, and Wyoming. The purpose of the map is to improve our knowledge of the geologic framework of the Precambrian basement in the north-central United States and to evaluate the mineral resource potential of the buried rocks of the Trans-Hudson orogen.

The THO is a deformed, generally north-trending orogenic belt of Early Proterozoic (1,840–1,910 Ma) age that extends from outcrop areas in Manitoba and Saskatchewan in the Canadian Shield southward beneath

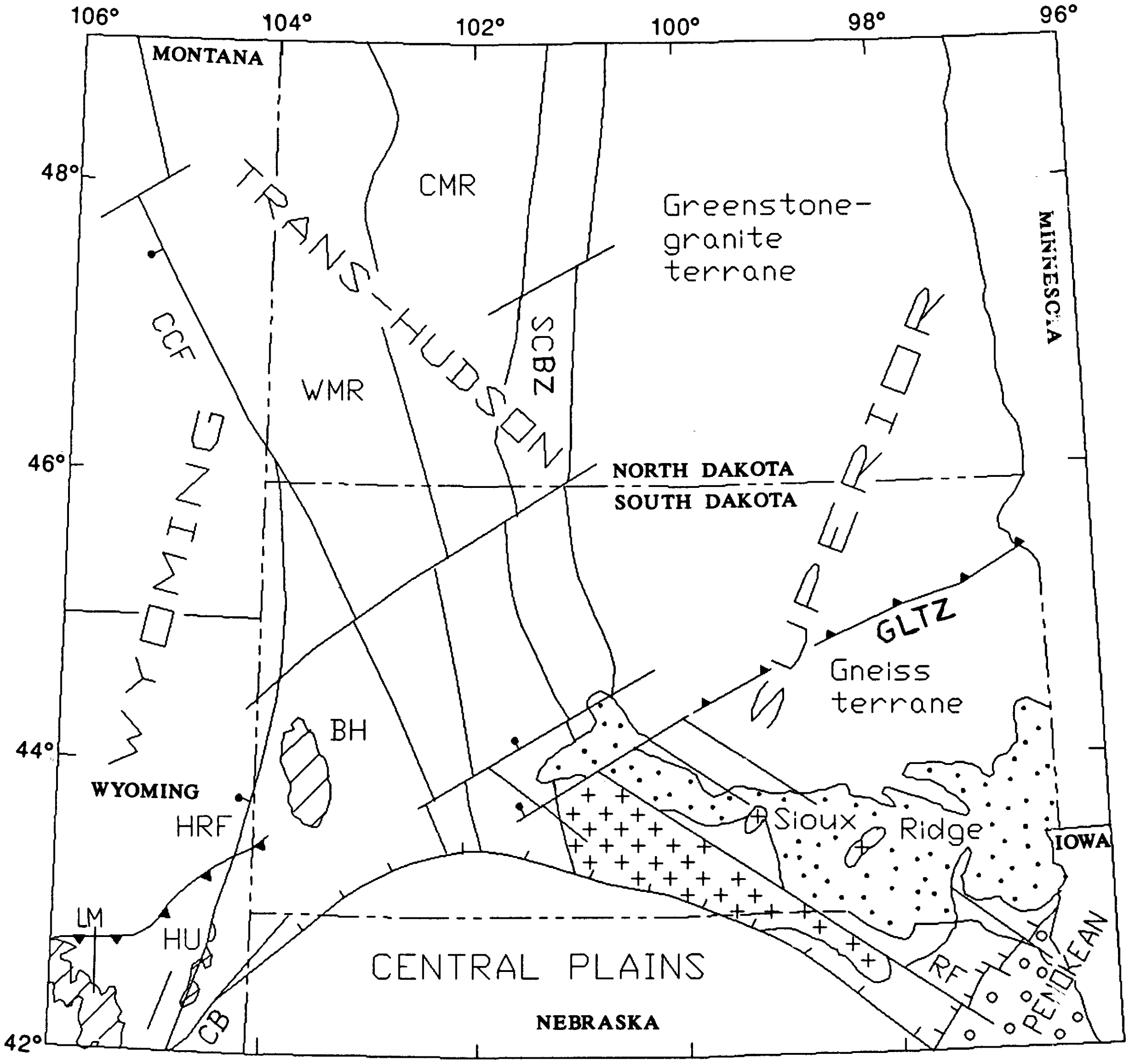

Figure 8. Tectonic map of Precambrian basement, northern Great Plains, United States. Archean Superior and Wyoming cratons are separated by Early Proterozoic Trans-Hudson orogen. Superior craton is flanked on the southeast by the Early Proterozoic Penokean orogen. The Early Proterozoic Central Plains orogen truncates both cratons and older Proterozoic orogens on the south. BH, Black Hills; CB, Cheyenne belt; CCF, Cedar Creek fault; CMR, Central magnetic region; GLTZ, Great Lakes tectonic zone; HRF, Hartville-Rawhide fault; HU, Hartville uplift; LM, Laramie Mountains; RF, Reservation fault; SCBZ, Superior-Churchill boundary zone; WMR, Western magnetic region. +, Early Proterozoic granite; dots, Sioux Quartzite; open circles, volcanic rocks of Wisconsin magmatic terranes.

Phanerozoic strata into the subsurface of the northern Great Plains. It consists mainly of Early Proterozoic arc-related rocks (Green and others, 1985; Lewry and others, 1985) but includes Archean rocks. The orogen separates two major Archean cratons, the Superior on the east and the Wyoming on the west, and represents a major constructional phase in the assembly of the North American craton. It terminates southward against the younger (1,630–1,800 Ma) Early Proterozoic Central Plains orogen in southern South Dakota.

Units delineated in the THO on the map are modified from the magnetic units of Green and others (1985), inasmuch as well-log data alone are not adequate to delineate major rock units. The orogen is divided into four major units, from east to west: (1) Superior-Churchill boundary zone (SCBZ), (2) Central magnetic region (CMR), (3) Western magnetic region (WMR), and (4) Black Hills domain (BHD). The SCBZ is a 35-mile-wide linear zone of low magnetization that abruptly truncates the east-northeast magnetic fabric of the Archean Superior province; it is correlated with the Thompson nickel belt exposed in Manitoba. The CMR is characterized by high-amplitude, medium-wavelength magnetic anomalies on a moderately low regional background. Well-log data are consistent with its being composed primarily of arc-related rocks, as suggested by Green and others (1985). The WMR is characterized by low magnetic relief and long-wavelength anomalies and also is inferred to be composed mainly of arc-related rocks. Basalt is possibly a major component in southwestern North Dakota and adjacent areas; granulite-facies rocks occur in northwestern North Dakota and northeastern Montana. The Laramide Black Hills uplift characterizes a wedge-shaped, probably fault-bounded domain (BHD) in western South Dakota that consists of Early Proterozoic metasedimentary and metavolcanic rocks (1,885, 1,970, and 2,150–2,550 Ma) that overlie reworked Archean basement rocks. The western boundary of the THO in the United States is marked by two major faults, the Cedar Creek (CCF) and Hartville-Rawhide (HRF) faults, which are expressed by large-scale, steep gravity and magnetic gradients. The HRF possibly merges with the much younger (~1,700 Ma) Cheyenne belt (CB) southwest of the Hartville uplift.

Aside from the Black Hills uplift, mineral resources in the THO must be sought in the subsurface. Stratabound gold deposits of Homestake type could exist beneath a shallow cover of Phanerozoic rocks around the northern margin of the Black Hills uplift. Nickel and copper deposits similar to those in the Thompson nickel belt could exist in the ultramafic-mafic intrusive rocks in the SCBZ. The most favorable targets are pyroxenitic bodies in the SCBZ in Stanley and Jones Counties, near Pierre, South Dakota, which lie at depths of less than 3,000 ft. In western North Dakota, the basement surface beneath the Phanerozoic Williston basin is at depths between -5,000 and -14,000 ft, depths prohibitive for exploration under present conditions.

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Proterozoic Anorogenic Granite-Rhyolite Terranes in the Midcontinental United States—Possible Hosts for Cu-, Au-, Ag-, U-, and Rare-Earth Element-Bearing Iron Oxide Deposits Similar to the Olympic Dam Orebody

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The Olympic Dam orebody is the largest and most valuable of several iron oxide-rich deposits on the Stuart shelf in South Australia. Its copper content ranks with that of Chuquicamata, Chile, and its uranium content constitutes about 10 percent of the world's estimated uranium resources. It contains about 1.2×10^6 kg Au, 7×10^6 kg Ag, and about 0.15 percent rare-earth elements. By any standard, it is one of the world's largest orebodies.

Several workers have suggested that the Olympic Dam orebody is a variant of a class of iron oxide-rich deposits that includes the deposits of Kiruna, Sweden, and southeastern Missouri. These deposits are characterized by large tonnages of iron ore (magnetite and (or) hematite), nearly ubiquitous apatite, local carbonate minerals, and anomalous abundances of Ba, Fl, U, Th, and rare-earth elements. Contents of metals other than iron are extremely variable. The deposits occur in a continental setting, have a close spatial and temporal association with anorogenic (A-type) granite and rhyolite, and at the orebody scale are enclosed in brecciated wall rock. Their ages cluster at about 1.4–1.7 Ga.

Because of the extensive Proterozoic anorogenic terranes in the midcontinental United States and the several known iron oxide orebodies in southeastern Missouri, the 1.48-Ga St. Francois terrane, in particular, and other terranes of both older and younger ages merit consideration as possible exploration targets for mineral deposits similar to the Olympic Dam deposit. The anorogenic terranes are the (1) 1.83-Ga granite-rhyolite suite in central Wisconsin, (2) 1.76-Ga granite-rhyolite terrane in southern Wisconsin, (3) 1.48-Ga St. Francois terrane in southeastern Missouri, and (4) 1.35- to 1.40-Ga Spavinaw terrane in southern Missouri, southern Kansas, and northern Oklahoma. Mesozonal anorogenic granite bodies (1.35–1.50 Ga), which are possible deeper seated intrusions related to the high-level granite and rhyolite, are widely scattered within a northeast-trending belt that traverses the Midcontinent region. The dominant rock types in all the bodies are potassium-rich, alkali-feldspar granite and associated ash-flow tuffs. These rocks contain anomalous amounts of the same lithophilic minor elements present in the iron orebodies.

The anorogenic rocks have been interpreted as partial melts of older (1.7–1.9 Ga) calc-alkaline crustal rocks that experienced one or more episodes of partial melting during earlier orogenic activity. The anorogenic rocks are believed to have formed in an extensional environment and could have had associated, evolved, oxidized iron-rich hydrothermal systems capable of generating metal deposits similar to that at Olympic Dam.

Alteration patterns and magnetic anomalies can be guides to mineral deposits. In the St. Francois Mountains, propylitic alteration of the country rocks is apparently spatially associated with iron orebodies. The alteration of primary biotite and hornblende to hematite and magnetite could be related to hydrothermal activity associated with the ore-forming process. Circular negative magnetic anomalies distinctly define the high-level, late-stage granitic plutons, many of which enclose the known iron oxide deposits. These anomalies could be excellent targets for exploration in areas covered by Phanerozoic strata.

Reactions Involving Organic Matter and Thiosulfate in Precipitating Sulfides, Disulfides, Fluorite, and Barite and in Producing the Carbonate Paragenesis in Mississippi Valley-type Ores

Charles S. Spirakis and Allen V. Heyl, USGS

Constraints on the genesis of Mississippi Valley-type (MVT) deposits include precipitation of a variety of minerals, oscillations between precipitation and dissolution of both ore and gangue minerals, paragenetic sequence, and restriction of ore formation to less than 210 °C. All of these constraints and others may be explained by reactions between a hot (80–210 °C), thiosulfate ($S_2O_3^=$)- and metal-bearing solution and organic matter at the sites of mineralization.

Surdam and Crossey (1985) concluded that the in situ heating of organic matter initially dissolves carbonate minerals as a consequence of production of organic acids. With additional heating (~120 °C), organic acids begin to break down to CO_2 and CH_4. The addition of CO_2 in the presence of organic acid pH buffers (provided by organic acids that have yet to degrade) precipitates carbonate minerals. At still higher temperatures (~140 °C), organic acids quickly degrade, so the pH buffer is lost. Without a buffer the continual addition of CO_2 lowers the pH and carbonate minerals dissolve. Application of these ideas to the genesis of MVT deposits may account for the observed carbonate paragenesis of dissolution, precipitation, and renewed dissolution (Spirakis and Heyl, 1988). Addition of CO_2 also may break the MgF^+ complex by forming $MgHCO_3^+$ and trigger the precipitation of fluorite (Spirakis and Heyl, 1988).

The problem of transporting metals (Pb, Zn, Ba) and sulfur in the same solution may be resolved by carrying sulfur in a form, such as thiosulfate, that cannot (as long as it remains thiosulfate) precipitate either sulfide or sulfate minerals. One process that might precipitate sulfide and disulfide minerals in MVT's is reduction of thiosulfate by organic matter—a process which, in contrast to sulfate reduction, is rapid at temperatures of MVT ore genesis (Pryor, 1962). Another reaction that may precipitate sulfides is:

$$9S_2O_3^= + 2Pb^{++} + 6H^+ \leftrightarrow 3H_2O + 2PbS + 4S_4O_6^=.$$

In this case, pH changes might cause the oscillations between precipitation and dissolution of sulfides that are typical of MVT ores. Certain types of bacteria, which have been isolated from oil field brines and which in the presence of organic matter are capable of metabolizing thiosulfate (Semple and others, 1987), can exist at the less than 80 °C temperatures of the late-barite stage. Their metabolism produces both sulfide and sulfate, which may trigger precipitation of both oxidized and reduced sulfur minerals in the late-barite stage. The breakdown of thiosulfate at temperatures much above 210 °C may account for the restricted temperature range of MVT ores.

Organic matter is the factor common to all of these proposed reactions, and it is suggested that concentrations of organic matter in the host rock cause certain sites to become the focus of mineralization.

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Missouri's Core Library Partnership

Sarah Hearne Steelman and
Ira R. Satterfield, MGS

In 1988 the Missouri General Assembly authorized the Missouri Department of Natural Resources, Division of Geology and Land Survey, to raise money that could be used toward the purchase and renovation of a building in which to store core samples. The General Assembly also appropriated approximately $18,000 from general revenue to be expended for that purpose. The core library fund drive represents a partnership between the private sector and both Federal and State governments. Charts and other illustrations show which groups in the private and public sectors contributed to the drive. The presentation also describes the value of Missouri core to those entities interested in developing and protecting Missouri's resources.

The core library can be compared to a public library containing books, where ideas and thoughts are researched and developed.

Ore Microscopy of the Paoli Silver-Copper Deposit, Oklahoma

Craig A. Thomas and Richard D. Hagni,
UMR, and Pieter Berendsen, KGS

The Paoli silver-copper deposit is in Garvin County, south-central Oklahoma, about 35 mi southeast of Norman. Several deposits in the Paoli area were mined for silver and copper to a limited extent at the turn of the century. Subsequent intensive exploratory drilling during the early 1970's led to the partial delineation of the unmined Paoli deposit (Shockey and others, 1974). Because of its near-economic character, high silver content, well-defined distribution, known general geologic controls, and availability of extensive drill core, the Paoli deposit was selected for a collaborative study to provide new information on the character of the red-bed copper deposits of the Midcontinent region.

The Paoli deposit has been interpreted (Shockey and others, 1974) as a solution or roll-front type of deposit. The silver and copper minerals occur within paleochannels in the Permian Wellington Formation. The paleochannels are characterized by greenish-gray, friable, well-sorted, fine- to medium-grained, subrounded sandstone, whereas the rest of the Wellington Formation is carbon-rich red claystone and siltstone. The silver-copper solution fronts appear to be controlled by oxidation-reduction interfaces that are marked by red-gray color changes in the host sandstone. Some of the solution fronts have been traced by drilling for distances of as much as 2 mi.

Surficial nodules of malachite and hematite locally mark the oxidation-reduction front. Barite occurs as a cement in some sandstones in the Paoli area. Barite also forms small, local nodules at Paoli and large nodules elsewhere in Garvin County in Permian sandstones.

Examination of polished thin sections made from samples selected from drill core shows that unoxidized ore contains gray and bluish-gray copper sulfide minerals having the optical properties of chalcocite and digenite. Although the chalcocite grains vary in size from 5 μm to about 2 mm, the most common grain size is about 40–60 μm. The outer portions of some chalcocite grains are a deep blue, similar to digenite. The smaller grains typically are bluish gray throughout, and scanning electron microscope-energy dispersive spectroscopy analysis suggests that their compositions are uniform.

Several manners of chalcocite occurrence have been determined in preliminary ore microscopic study of the polished thin sections. Chalcocite most commonly replaces carbonate cement around clastic quartz grains but locally replaces clastic grains of feldspar. Some chalcocite grains, those larger than 140 μm, are almost spherical. Smaller grains, those less than 140 μm, are cubic or almost hexagonal and may be pyrite replacements.

Silver occurs as native silver and may form cruciform crystals as large as 3.5 mm across.

Pyrite was observed in polished thin sections to occur as small cubic crystals 20–40 μm across. Other pyrite grains are almost spherical in shape. Pyrite also occurs as partly replaced cores in surficial hematite nodules.

Identified gangue minerals include clastic grains of quartz, feldspar, rutile, ilminite, anatase, and zircon, together with dolomite, calcite and local chlorite cements. Initial study of uncovered thin sections by cathololuminescence (CL) microscopy shows the presence of yellowish-orange, zoned dolomite and yellow zircon. The dolomite cements exhibit five growth zones: (1) a large core of non-CL ferroan dolomite, followed by (2) a narrow, dark-orange-red CL band, (3) a narrow, bright-yellow CL band, (4) a narrow, medium-bright-orange CL band, and (5) a broad, dark-orange-red CL outer band.

Additional ore microscopic, scanning electron microscopic, electron microprobe analysis, and cathodoluminescence microscopic studies of the Paoli ores are in progress.

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Drilling Information on the Morphology of Missouri Sinkhole Deposits of Flint Clay

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We are exploring the hypothesis that the origin of sinkhole deposits of flint clay in Missouri is related to the regional hydrothermal event generally accepted to be the cause of Missouri lead-zinc deposits. Core holes were drilled in 1987 to obtain information on the form of the sinkholes and on the non-clay sediments within the sinkholes.

The Wacker clay deposit, about 5 mi north of Owensville, Missouri, has been explored by drilling by the A. P. Green Refractories Co. The company kindly furnished results of this drilling and granted permission for the U.S. Geological Survey and the Missouri Division of Geology and Land Survey to drill three core holes at the Wacker site in 1987.

Company drilling suggests that a pipelike body of clay lies on sandstone. The clay-sandstone contact is very steep along the north side of the deposit and somewhat gentle on the south side except for a steep portion near the deepest part. The nature of the sandstone used by the company to mark the bottom of the deposit is uncertain. Some of the sandstone used to identify the bottom of the deposit on the south side may in fact be tongues of sandy clay that extend into the deposit from the sandstone wall. Even with this uncertainty, the clay forms a reasonably pipelike body.

The first new core hole, located in the apparent thickest part of the clay deposit, intersected a sandstone at a depth of about 110 ft. The sandstone, 120 ft thick, is variably iron stained, silica cemented, and leached, and the bedding is much disturbed. Beneath the sandstone, about 30 ft of hard, silica-cemented breccia containing pieces of limestone and chert was drilled. The material was so hard as to prevent further drilling. The material appears similar to breccias in many karst settings.

A second core hole was drilled outside of the sinkhole area as revealed by company drilling. The upper 93 ft of the core consisted of red, iron-rich, sandy clay, some sandstone, and scattered chert pieces. The name "residuum" gives a clue as to its character but may not explain its origin. Unaltered dolomite was encountered below the residuum and was successfully cored from 140 ft to the total depth of 155 ft (altitude 785 ft). The top of the sandstone in the first hole was at an altitude of about 810 ft. The clay deposit and at least part of the sandstone is thus shown to be set into a general matrix of unaltered country rock.

The third core hole, about 50 ft outside the apparent rim of the sinkhole, penetrated almost 50 ft of altered bedrock. The material consisted of red and green shale and chert nodules and rock fragments identical to the dipping rocks that can be seen behind the sandstone wall at many older clay pits where the sandstone wall has slumped or was removed in connection with a haul way. Dips are about 30°.

Through the kindness of the Dillon Clay Co., a hole was drilled at the Spurgeon pit, about 20 mi south of the Wacker pit and about 6 mi north of Cuba. The hole showed a section similar to that in the Wacker deep hole. Sandy, iron-rich clay 155 ft thick overlies about 70 ft of very light colored sandstone that has been much leached. A chert breccia similar to that at the Wacker pit underlies the sandstone, but only 17 ft was drilled. Drilling at other pits in this immediate vicinity had shown as much as 125 ft of similar sandstone without reaching breccia.

Small amounts of secondary marcasite occur in the upper 15 ft of the sandstone in the Spurgeon pit. This marcasite has a sulfur isotopic composition of $\delta^{34} = +16$ to -16, a range consistent with sulfur isotopic compositions of the pyrite of the Moselle and Cherry Valley pyrite mines in the pyrite belt to the south. Paleomagnetic data from surface outcrops of iron-rich clay from other pits in the vicinity of the Spurgeon pit suggest a late Paleozoic age for emplacement of the hematite.

Drilling has confirmed that some sinkhole deposits of refractory clays consist of two parts: an upper, almost pipelike mass of clay underlain by a pipelike mass of sandstone and a silica-cemented chert breccia that underlies the sandstone. The sinkhole is set into unaltered carbonate rocks of the Jefferson City Dolomite of Ordovician age. These data do not contradict the hypothesis of relationship of sinkhole deposits to a regional hydrothermal event, but much more needs to be learned.

Genetic Implications of Regional and Temporal Trends in Ore-Fluid Geochemistry of Mississippi Valley-Type Deposits of the Ozark Region

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The geochemistry of fluids extracted from aqueous fluid inclusions in epigenetic gangue and ore minerals from throughout the stratigraphic section of the Ozark region records the passage of huge volumes of highly saline fluids. The limited range in composition of these fluids suggests that they are the result of the same hydrothermal event and may have a common origin. The extracted fluids share many similarities regionally, but significant temporal differences in inclusion-fluid chemistry, as well as differences in isotopic composition and metal character of the resulting deposits, define two geochemically distinct types of ore-forming fluids. The fluids have two end-member compositions that we refer to as (1) Tri-State or TS-type, which we believe to have migrated mostly through carbonate aquifers, and (2) Viburnum Trend main-stage or VTM-type, which appears to be associated with basal sandstone aquifer flow.

VTM-type fluids are enriched in potassium and are associated only with deposits close (less than 100 m) to the basal Lamotte Sandstone. The main-stage octahedral galena ore of the Viburnum Trend and much of the Old Lead Belt ore is thought to be derived from this type of ore fluid. Galena deposited by VTM-type fluids contains less-radiogenic lead than galena deposited by TS-type fluids. Sulfides deposited by VTM-type fluids also contain isotopically heavier sulfur and significant amounts of copper, cobalt, nickel, and silver. Sphalerite deposited by VTM-type fluids is uniquely enriched in silver and depleted in gallium.

TS-type fluids have low potassium content as compared to VTM-type fluids and are characteristic of deposits where ore-forming fluids migrated through significant volumes of carbonate rock. These fluids are thought to have formed the ore deposits of the Northern Arkansas, Tri-State, and Central Missouri districts and the cubic galena-stage minerals of the Viburnum Trend, as well as the many trace occurrences of sphalerite found throughout the Ozark region. Galena deposited by TS-type fluids has very radiogenic lead, and sulfides have isotopically lighter sulfur than sulfides deposited by VTM-type fluids. A systematic south-to-north increase in potassium in these fluids suggests that the fluids were from a southerly source.

A possible explanation for the origin of these two types of ore-forming fluids is that a single parent brine evolved into two distinct chemistries owing to reactions with geochemically distinct aquifers during migration. Although the fluids have evolved through reactions with their host aquifers during migration, their similarities and the regionally continuous nature of fluid-conducting aquifers suggest a common origin for the fluids in the Arkoma basin. Predictable temporal changes in flow paths as a result of foreland basin evolution and deformation would have produced early basal-sandstone flow followed by regional carbonate-aquifer flow during the Ouachita orogeny.

The Arkoma basin extends southeasterly beneath the Mississippi embayment to a poorly understood juncture with the Black Warrior foreland basin. It is problematic whether the VTM-type fluids that formed much of the ore of the Southeast Missouri district were derived from the Arkoma or the Black Warrior basin because these basins share a parallel evolution associated with the Ouachita orogeny in the Carboniferous. In either case, VTM-type fluid flow was probably funneled through sedimentary rocks within the Reelfoot rift into the Southeast Missouri district. Regardless from which basin these fluids were derived, fluids migrating through the sediment fill of the rift were probably confined mainly to the basal sandstone by less permeable shaly limestones.

The Relationship of Remote-Sensing Anomalies to the Real World—Examples from the Midcontinent and the CUSMAP Study Areas

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We elaborate upon an old hypothesis which states that once the early-formed crust of the Earth attained sufficient buoyancy, thickness, and strength to react in a brittle fashion, it was broken into semirectangular sub-blocks by tensional stresses, perhaps associated with changes in rotational velocity of the globe or development of its equatorial oblateness. The roughly orthogonal fractures bounding these crustal blocks were spaced approximately equally by the dissipation of stresses between adjacent megafractures, depending on the thickness and strength of the local crust. We further propose that once the primordial crust was cracked, the fractures became the loci of stress release for whatever combinations of horizontal or vertical forces were subsequently applied to the bases and margins of the buoyant crustal slabs throughout geologic time. On the old continental shields or cratons, this system of mega-shears was reactivated many times, resulting in repeated differential horizontal and vertical displacement of adjacent sub-blocks, causing fracturing, fluid migration, abrupt sedimentological changes, and development of structural features along them, as well as development of consequent or conjugate structures in the margins of adjacent blocks. Thus the system of shears may be thought of as swaths of extremely long term geo-energy potential and exchange and, as such, the most likely locations for tectonic activity and migration, trapping, and deposition of economic minerals and hydrocarbons. Because these through-crustal fractures (including the outlines of meteorite or bolide impact craters) continue to be active, they propagate upward through succeeding layers and are reflected by surface flexures, faults and joints, stream patterns, outcrop anomalies, and even imaged tonal changes perhaps related to disseminated mineralization or released diffused gases that affect the regolith and vegetation. These comprise the various lineaments, curvilinears, and other features noted on topographic maps, air photos, and space imagery from which remote-sensing maps are derived.

Specific examples from the Midcontinent are the Chesapeake, Bolivar-Mansfield, and other northwest-trending structural zones in Missouri, which are traced into Kansas as major stream lineaments. The description and patterns of mapped faults associated with these zones in Missouri, and the interpretation of stream patterns in Kansas strongly suggest that the principal displacements were horizontal, episodic, and with reversed sense of movement at various times depending on the direction of applied principal horizontal compressive stress and the orientation of the resisting or passive block. We postulate that the stresses originated at the eastern margins of the craton during continent-continent collisions beginning during Grenvillian or earlier times and continued with other major episodes during Taconian, Acadian, Appalachian, Ouachitan-Wichitan, and later times. The stresses are assumed to have been transmitted via Precambrian rocks and the stacks of Cambrian-Ordovician through Mississippian carbonate rocks overlying the basement. Some of the displacement occurred as bed-parallel slippage on inter-bedded shales or less competent zones and is difficult to detect. Vertical displacement was relatively less important, consisting of differential block tilting, scissoring, pull-aparts, and pop-ups along the traces of the wrench zones. Major northeast-trending fracture zones are also present in the Midcontinent area but are generally not named. The Midcontinent rift and associated features, Nemaha Ridge, Chanute-Kansas City trend in Kansas, and the Webb City-Osceola and Lampe-Mansfield trends in Missouri are examples. The northeast-trending features seem to be important traps for hydrocarbon accumulation in basal Pennsylvanian sandstones in Kansas and may have influenced mineral deposition in older beds in Missouri.

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Circulars present administrative information or important scientific information of wide popular interest in a format designed for distribution at no cost to the public. Information is usually of short-term interest.

Water-Resources Investigations Reports are papers of an interpretive nature made available to the public outside the formal USGS publications series. Copies are reproduced on request unlike formal USGS publications, and they are also available for public inspection at depositories indicated in USGS catalogs.

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Maps

Geologic Quadrangle Maps are multicolor geologic maps on topographic bases in 7 1/2- or 15-minute quadrangle formats (scales mainly 1:24,000 or 1:62,500) showing bedrock, surficial, or engineering geology. Maps generally include brief texts; some maps include structure and columnar sections only.

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Miscellaneous Investigations Series Maps are on planimetric or topographic bases of regular and irregular areas at various scales; they present a wide variety of format and subject matter. The series also includes 7 1/2-minute quadrangle photogeologic maps on planimetric bases which show geology as interpreted from aerial photographs. Series also includes maps of Mars and the Moon.

Coal Investigations Maps are geologic maps on topographic or planimetric bases at various scales showing bedrock or surficial geology, stratigraphy, and structural relations in certain coal-resource areas.

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