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America's heartland—An exploration frontier for new mineral-deposit types

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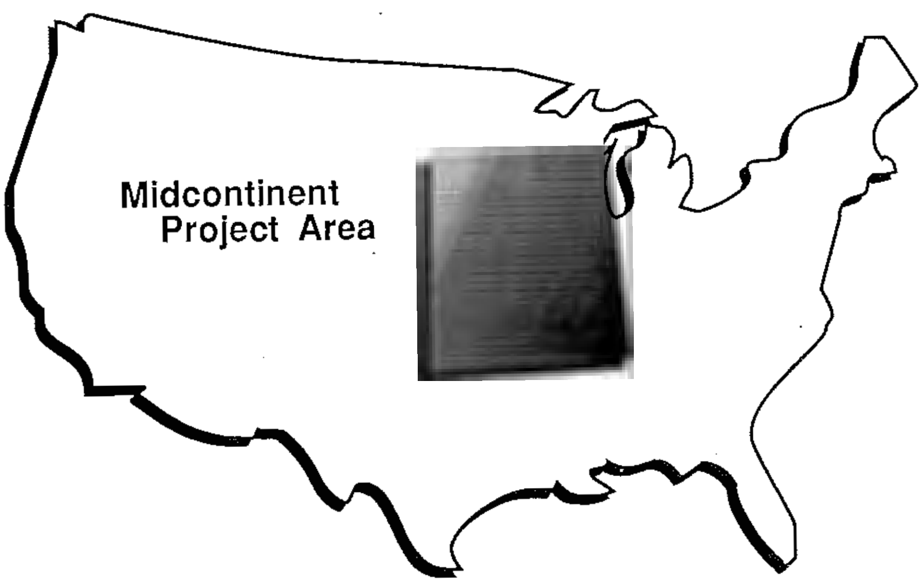
The Midcontinent region of the United States has long been known for its important mineral resources. Development of the lead-zinc deposits of the Upper Mississippi Valley district in southwestern Wisconsin, the fluorite-zinc deposits of southern Illinois, the iron-ore deposits in the St. Francois Mountains of Missouri, and the famous Mississippi Valley-type (MVT) lead-zinc-copper-silver (+cobalt-nickel) deposits of southeast Missouri played an important role in the economic development of the entire region. There is substantial evidence, however, that major undiscovered



deposits of manganese, cobalt, platinum-group elements, nickel, diamonds, and other important commodities may exist at mineable depths beneath the sedimentary cover rocks of the region.

The USGS is coordinating a major cooperative effort involving scientists from the USGS and 16 State geological surveys to define the varied mineral-resource potential of a 433,000-square-mile area, extending from 36° to 46° N. latitude to 88° to 100° W. longitude (the equivalent of 60 1° x 2° quadrangles). The objectives of this Midcontinent project are (1) in a first phase, to inventory geologic data, publishing it as a folio of 1:1,000,000-scale maps and cross sections that give a three-dimensional image of major geologic and hydrologic terranes and known mineral deposits in the region; (2) in a second phase, to investigate the origin and extent of specific mineralizing systems through multidisciplinary topical studies; and (3) in both phases, to evaluate the potential for major new deposit types in the region. We are currently in the latter stages of the second phase of the project.

The first-phase regional investigations have demonstrated that many of the mineral deposits, particularly the MVT deposits, formed in response to huge, long-lived mineralizing systems of subcontinental scale. New regional compilations of mineral-resource occurrences and host-rock characteristics provide a framework for delineating favorable areas for the occurrence of additional undiscovered deposits and substantially enhance exploration models needed for successful discovery of new MVT deposits in the Midcontinent as well as other similar geologic environments worldwide.

The second-phase topical investigations are focused on four types of mineral deposits that

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America's heartland

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have received much less study in the past than MVT deposits:

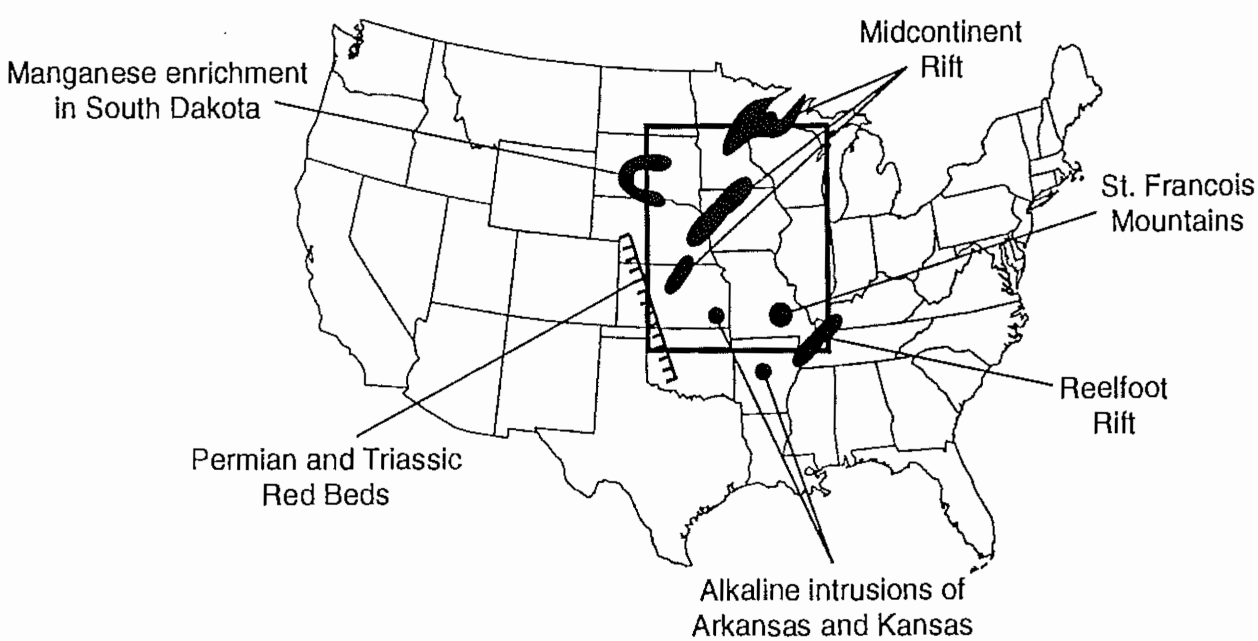
- iron, copper, rare-earth element, and gold deposits (Olympic Dam-type);
- sediment-hosted manganese deposits;
- mineral deposits related to alkaline igneous intrusions; and
- sediment-hosted red-bed copper-silver-cobalt deposits.

Brief descriptions of each of these deposit types and the nature of current work by USGS and State geological survey collaborators are provided below.

A recent project workshop concluded that sedimentary-exhalative, zinc-lead-copper-silver-barite deposits similar to the Red Dog and Ruby Creek deposits in Alaska and the Navan and Tynagh deposits in Ireland may be present in some rocks and structures of the Reelfoot rift underlying the Mississippi embayment. Although rock cuttings and drill core are available from wells in Arkansas, Tennessee, Kentucky, Missouri, and Illinois that penetrate the rift, no systematic evaluation has been undertaken yet by scientists from either the USGS or State geological surveys. Research on these natural resources would provide stimulus and leadership for future mineral exploration and economic development for the region.

Olympic Dam-type deposits

The Olympic Dam deposit of south Australia contains over $100 billion (1992 prices) of iron, copper, uranium, rare-earth element, and gold ore. This deposit occurs in a geologic environment that is intriguingly like the St. Francois Mountains of Missouri, where known deposits have similar ages, host rocks, structural setting, and ore minerals. Clearly, discovery of a deposit similar to



Location of geologic terranes permissive for undiscovered mineral deposits in the Midcontinent of the United States.

Olympic Dam in the Midcontinent would have profound economic consequences for the region. Currently, scientists of the USGS and the Missouri Geological Survey are studying the characteristics and genesis of the Pea Ridge, Boss-Bixby, and nearby iron, copper, rare-earth element, and gold deposits in the St. Francois Mountains in order to identify new targets buried beneath cover rocks and conduct a quantitative assessment for Olympic Dam-type deposits in the Midcontinent region.

Sediment-hosted manganese deposits

The world's known manganese resources are dominated by a few very large deposits that were formed in shallow marine environments. A genetic model developed recently by USGS scientists indicates that vigorous mixing of oxygen-depleted water from deep basins with oxygen-rich surface water is required. These conditions may have been met in Cretaceous time (ca. 75 million years ago) in parts of what are now South Dakota and southeast Minnesota.

Currently, scientists of the South Dakota Geological Survey are evaluating the manganese potential of Cretaceous sedimentary rocks near Chamberlain, South Dakota, that were deposited around emergent islands of Precambrian Sioux Quartzite. When detailed mapping, stratigraphic studies, and shallow drilling are completed, the South Dakota scientists will have delineated manganese-enriched parts of the Cretaceous sequence, identified higher grade zones, and tested the validity of the genetic model.

Mineral deposits related to alkaline igneous intrusions

Alkaline igneous rocks occur widely in the Midcontinent region as roughly circular intrusions or clusters of intrusions that are associated with rift environments. The chemical composition of the intrusions varies widely, and different intrusions may have potential for a broad range of potentially valuable elements or commodities, including titanium, vanadium, niobium, rare-earth elements, copper, molybdenum, diamonds, vermiculite, bauxite, or kaolinite. Current USGS activity focuses on the vanadium and titanium resources of the Magnet Cove and Potash Sulfur Springs alkaline igneous complexes in Arkansas. Scientists of the Kansas Geological Survey currently are investigating rocks of the Rose and Silver City domes in southeast Kansas. Several other alkaline rock provinces in Illinois, Kentucky, Missouri, and Tennessee are known, but have had little past research on their chemistry or mineral-resource potential, and are not being studied at the present.

Sediment-hosted red-bed copper-silver-cobalt deposits

A likely environment for metal-bearing red-bed deposits occurs in the rift-fill sedimentary rocks of the Midcontinent rift, which are exposed in Michigan, Minnesota, and Wisconsin, and extend southeastward in the subsurface into Iowa, Nebraska, and Kansas. Rocks similar to the Nonesuch Shale, which hosts the large White Pine copper-silver deposit in Michigan's Upper Peninsula, may extend in the subsurface throughout the rift. Sparse drill core and seismic data currently are being evaluated by scientists in the USGS and the Kansas, Nebraska, and Iowa Geological Surveys in a collaborative effort to evaluate the mineralizing systems of the Midcontinent rift.

A regional study of the mineral-resource potential of Permian and Triassic red-bed sedimentary rocks of Oklahoma, Kansas, Nebraska, and Texas is being undertaken by scientists at the Oklahoma, Kansas, and Nebraska Geological Surveys. These deposits are generally small, but have extremely rich ores. Initial compilations of known mineral occurrences along with the distribution of evaporite deposits have been completed. Spatial overlap between the two data sets implies a probable genetic link between formation of evaporite and copper deposits, a connection that is being modeled currently by scientists of the Oklahoma Geological Survey. ❑

Warren C. Day
Walden P. Pratt

"The chemical composition of the intrusions varies widely, and different intrusions may have potential for a broad range of potentially valuable elements or commodities..."

The USGS Midcontinent Project—Mineral-deposit model studies in a historic and vital mining region

Mississippi Valley-type (MVT) deposits

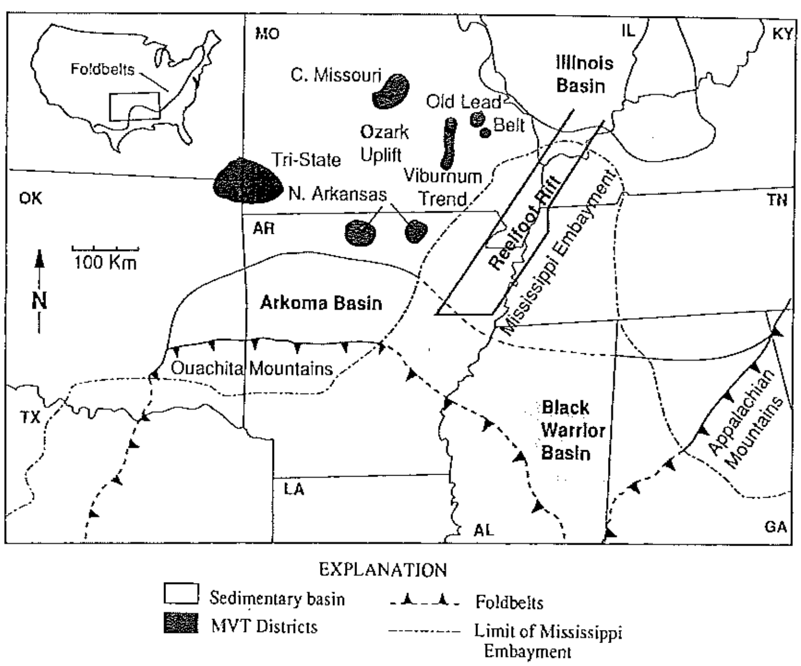
Scenic, oak covered rolling hills, secluded hollows, limestone caves and magnificent springs have made the Ozark region famous. Less well known is the importance of the region as the world's leading producer of lead and zinc, metals of vital importance to a healthy industrial economy. The Tri-State District, Viburnum Trend, and Old Lead Belt of southeast Missouri represent the largest economic accumulations of lead and zinc yet discovered in the earth's crust. Deposits of lesser importance also occur in the Central Missouri and Northern Arkansas districts, and trace and minor occurrences of sphalerite are common throughout most of the Ozark region.

Associated with faults, fractures, collapse structures, and algal reefs in relatively flat lying shallow marine carbonate rocks of Cambrian through Pennsylvanian age (550 to 280 million years ago), these deposits presented an enigma to early investigators because unlike other deposits types, these deposits have no relation to an intrusive heat source. Their unique nature led early investigators to conclude these deposits were formed by cool descending ground water and because of their abundance in the Midcontinent region, they were classified as the Mississippi Valley-type (MVT).

In the mid-1930's, however, studies of ore fluids preserved as fluid inclusions in ore minerals revealed that the temperature when these fluids were trapped was between 90° and 130°C and that the fluids were very saline, containing over 20 percent dissolved salts by weight—five times saltier than seawater. This discovery discounted the ground water theory and suggested an ore-fluid source similar to brines found in deep sedimentary basins.

Research by scientists at the USGS, State geological surveys, universities, and the Geological Survey of Canada, have contributed to a genetic model for this important metallogenic province. These studies show that the Ozark metallogenic province was the product of an enormous hydrothermal system that affected more than 350,000 cubic kilometers of rock.

The Model: Plate convergence along the southern margin of the North American craton set the stage for the formation of the largest Mississippi Valley-type lead-zinc metallogenic province in the world. Plate convergence in the Late Paleozoic (ca. 330-260 million years ago) created a series of depositional basins (foredeeps) along the southern margin of North America. The largest and deepest of three foredeeps was the Arkoma Basin of Arkansas and Oklahoma, which has a poorly understood connection with the Black Warrier foredeep to the east in Alabama and Georgia. By Late Pennsylvanian to Permian time (ca. 290-260 million years ago), final plate suturing and uplift of the southern tectonic flank of the Arkoma and Black Warrior basins during uplift of the Ouachita mountains established an enormous hydrothermal system in the Ozark region. Effects of this system include the formation of MVT lead-zinc districts with widespread trace sulfides and sparry dolomite, extensive but subtle hydrothermal alteration, reset paleomagnetic and radiometric dates, and regional thermal anomalies.



Location of the Ozark Mississippi Valley-type districts relative to adjacent sedimentary basins and the Reelfoot rift.

The model that best explains the regional hydrothermal system is topographically driven fluid flow. Meteoric water, recharged in the uplifted orogenic flank of the foredeep, migrates through deep portions of the foredeep basin, thereby acquiring heat and dissolved components, and is discharged through broad areas on the craton.

Although fluid flow was extensive throughout the stratigraphic section, certain regional aquifers were the principal pathway for the main ore districts. Rock-water interactions in lithologically different aquifers led to deposits with different metal and isotopic compositions. Migration of the ore fluids through carbonate rocks, primarily the post-Bonneterre Cambrian-Ordovician regional aquifer, produced the zinc-dominant sulfide deposits in the Northern Arkansas, Tri-State, Central Missouri, and Southeast Missouri barite districts. In the Southeast Missouri lead districts, two chemically and isotopically distinct fluids were present during ore deposition. The main-stage (octahedral galena-stage) ores were produced by a potassium-rich brine containing less radiogenic lead that migrated through the basal sandstone aquifer; this brine had a significant migration pathway through thick arkosic Cambrian sandstones in the Reelfoot rift complex. A second fluid containing more radiogenic lead, chemically and isotopically similar to the regional brine that formed other Ozark MVT districts, produced the late cubic galena-stage ores.

Paleohydrological features that focused fluid flow up the stratigraphic section localized the Ozark MVT ore districts. Important paleohydrological controls included shale depositional edges, limestone to dolostone transitions, sedimentary facies associated with carbonate reefs, faults, and highs in basement topography. These features created opportunity for fluid mixing, cooling, and fluid-rock reactions to precipitate ore.

Reaction-path modeling of quantitative fluid-inclusion compositions shows that no one depositional process can reproduce all the hydrothermal mineral assemblages observed throughout the Ozark region. Rather, specific districts require their own distinctive depositional mechanism(s) that reflect host-rock composition, structural setting, and hydrology. The regional occurrences of sparry dolomite with trace sulfides were formed by isothermal or near isothermal effervescence of CO_2 in response to decrease in confining pressure during fluid migration to shallower depths. The Central Missouri and Southeast Missouri barite districts are best explained by the mixing of two dolomite saturated brines with different H_2S and metal contents. Northern Arkansas and Tri-State districts can largely be explained by the reaction of a dolomite-saturated brine with cool limestone. The lead-dominant replacement ores in the Southeast Missouri lead districts require the mixing of a dolomite saturated, lead-rich, and H_2S-poor brine with a cooler, more dilute, and H_2S-rich brine. Reaction-path calculations also show that cooling, CO_2 effervescence, and thermochemical sulfate reduction could not have played a dominant role in ore deposition.

Although much progress has been made toward understanding this important resource, considerable work remains. Ongoing research at the USGS focuses on characterizing specific fluid-migration pathways, particularly from the Reelfoot rift. Preliminary results show very hot (temperatures greater than 250°C) MVT ore fluids traveled deep in the rift complex. Identification of specific fluid-flow paths may narrow the search for undiscovered resources. In addition, USGS research is transfering these concepts to other North American MVT districts to improve our understanding as well as to lead to a predictive metallogenic model. This technology transfer is currently underway by the USGS involving developing economies such as those of Poland and other Eastern European countries.

"Ongoing research at the USGS focuses on characterizing specific fluid-migration pathways, particularly from the Reelfoot rift."

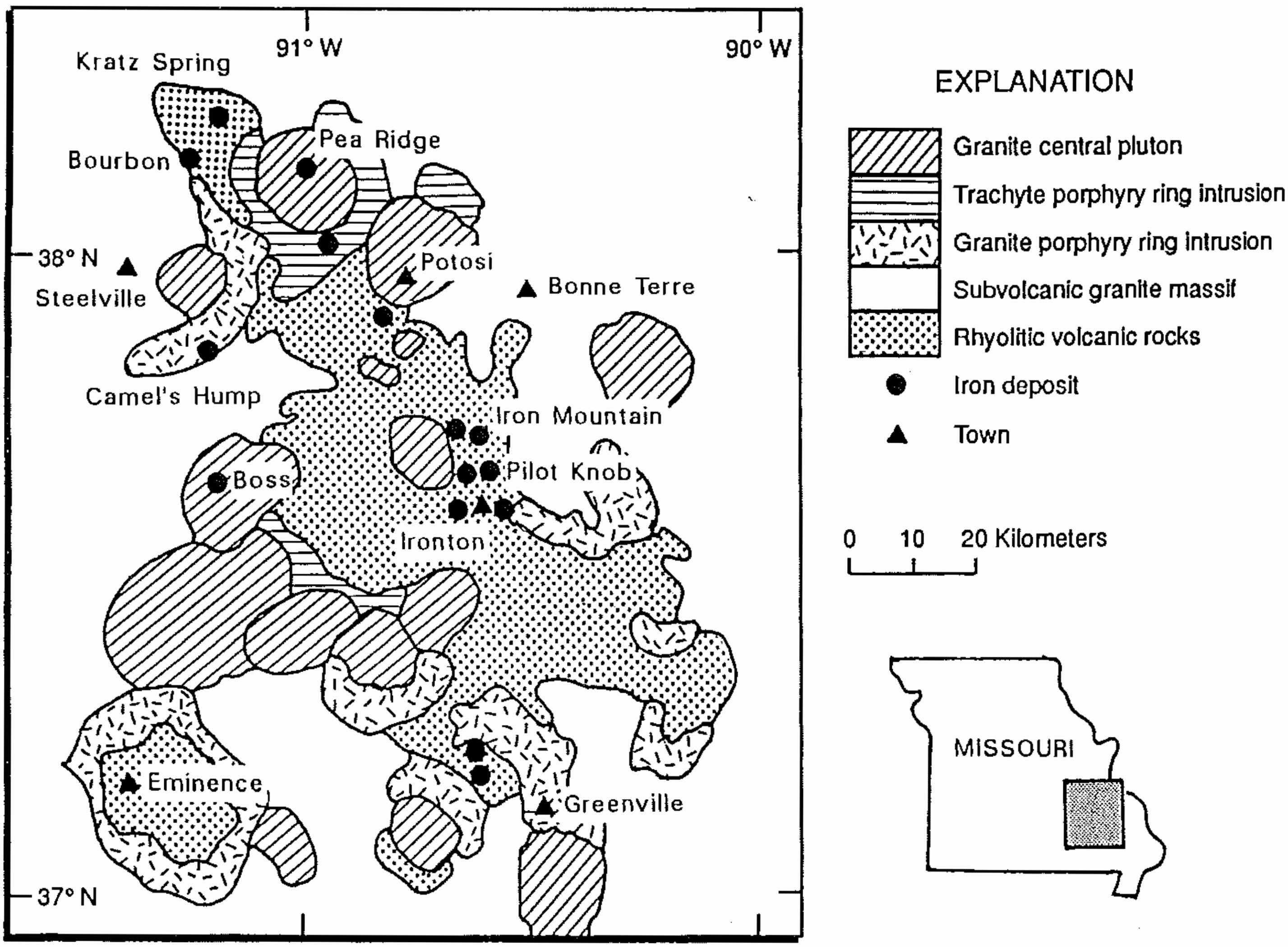
Current USGS and State geological survey compilations provide a basis for delineating permissive areas for MVT deposits in the Midcontinent region. A generalized exploration model for MVT deposits includes the following criteria: (1) presence of, or proximity to the limestone-dolostone "interface" (defined as a 1:1 ratio); (2) presence of a window or edge in an underlying shale unit to focus upward migration of metal-bearing brines into the potential host rocks; and (3) presence of an overlying shale caprock to confine migration to the host rocks. ❑

John Viets, Dave Leach, Al Hofstra, and Geoff Plumlee

Olympic Dam-type deposits in the Midcontinent—Possible concealed elephants?

Middle Proterozoic granite-rhyolite terranes approximately 1.5 billion years old in the Midcontinent are intriguingly similar to rocks in southern Australia that host the gigantic Olympic Dam deposit. The Australian deposit is one of the world's largest ore deposits. Although Olympic Dam is primarily an iron-oxide deposit, it contains an estimated 32 million tonnes of copper, 1.2 million tonnes of uranium oxide, 1.2 million kg of gold, and significant concentrations of rare-earth elements (REE). Inasmuch as the Olympic Dam deposit contains more than $100 billion worth of metals at today's prices, the potential economic consequences of the geological similarities in the Midcontinent region merit close evaluation. Currently, scientists of the USGS, Missouri Geological Survey, and private industry are investigating the detailed geologic setting, controls of mineralization, and the mineral-resource values of the Middle Proterozoic St. Francois terrane of southwestern Missouri.

Rhyolite ash-flow tuffs, lava flows, and coeval granite plutons of the St. Francois terrane host 32 known iron oxide mines and prospects. These deposits occur as intrusive, vein, and replacement bodies, with the iron oxides magnetite and hematite as the pre-



Geologic map of the St. Francois terrane, southeast Missouri, showing some of the known iron deposits (modified from Kisvarsanyi, 1980).

dominant ore minerals. The deposits contain economically important amounts of titanium, phosphorous, uranium, rare-earth element, base- and precious-metals (particularly copper), barium, and fluorine. One deposit in particular, Pea Ridge, offers the best three-dimensional view of this type of mineral deposit in the Midcontinent.

The Pea Ridge deposit

Until 1963, Middle Proterozoic hematite deposits were the major source of iron ore in Missouri. Since the Pea Ridge mine opened in 1964, all iron ore production has been from subsurface magnetite deposits.

The host rocks in the Pea Ridge deposit consist of rhyolitic ash-flow tuffs that are interpreted to be the filling of a collapsed volcano, or caldera, now preserved as a large "roof pendant" on top of a circular 20-km-wide central granite pluton.

The tabular Pea Ridge iron orebody discordantly cuts its host rhyolitic rocks. Replacement and open-space fill textures characterize the deposit. Rare-earth element-bearing breccia pipes cut rocks of the footwall and the eastern margin of the deposit. A uranium-lead date of 1.46 billion years on xenotime from a quartz vein (W.R. Van Schmus, University of Kansas, written commun., 1988) confirms that the age of the Pea Ridge deposit to be contemporaneous with the regional igneous activity.

Magnetite is the main ore mineral. Hematite, apatite, quartz, phlogopite, chlorite after phlogopite, pyrite, chalcopyrite, monazite, calcite, fluorite, barite, xenotime, calcium sulfate (anhydrite), and potassium feldspar account for about 12 to 35 modal percent in the massive magnetite ore zone. Gangue minerals present in other zones of the deposit include sericite, tourmaline, rutile, zircon, topaz, epidote, and allanite.

Four rare-earth element-bearing breccia pipes have been delineated along the footwall and eastern edge of the magnetite orebody. Rare-earth elements are vital "high-tech" minerals used in television tubes, ceramics, and super conductors. Monazite is the predominant rare-earth element-bearing mineral in the breccia pipes. Lesser amounts of other cerium-, yttrium-, and lathanium-bearing minerals have also been observed.

Precious metals are distributed erratically in the breccia pipes. Gold concentrations locally exceed 1 part per million. Trace precious metal-bearing minerals include tellurides and electrum.

Fluid-inclusion and stable-isotope studies indicate that the Pea Ridge deposit formed from highly saline, high-temperature hydrothermal fluids derived from cooling magmas. Temperatures varied from greater than 530° to about 400°C during deposition of and alteration associated with the magnetite ore. The rare-earth element-bearing breccia pipes were rapidly and explosively emplaced at a temperature of about 300°C. ❑

Gary B. Sidder
Warren C. Day

"One deposit in particular, Pea Ridge, offers the best three-dimensional view of this type of mineral deposit in the Midcontinent."

We'd Like to Keep in Touch!

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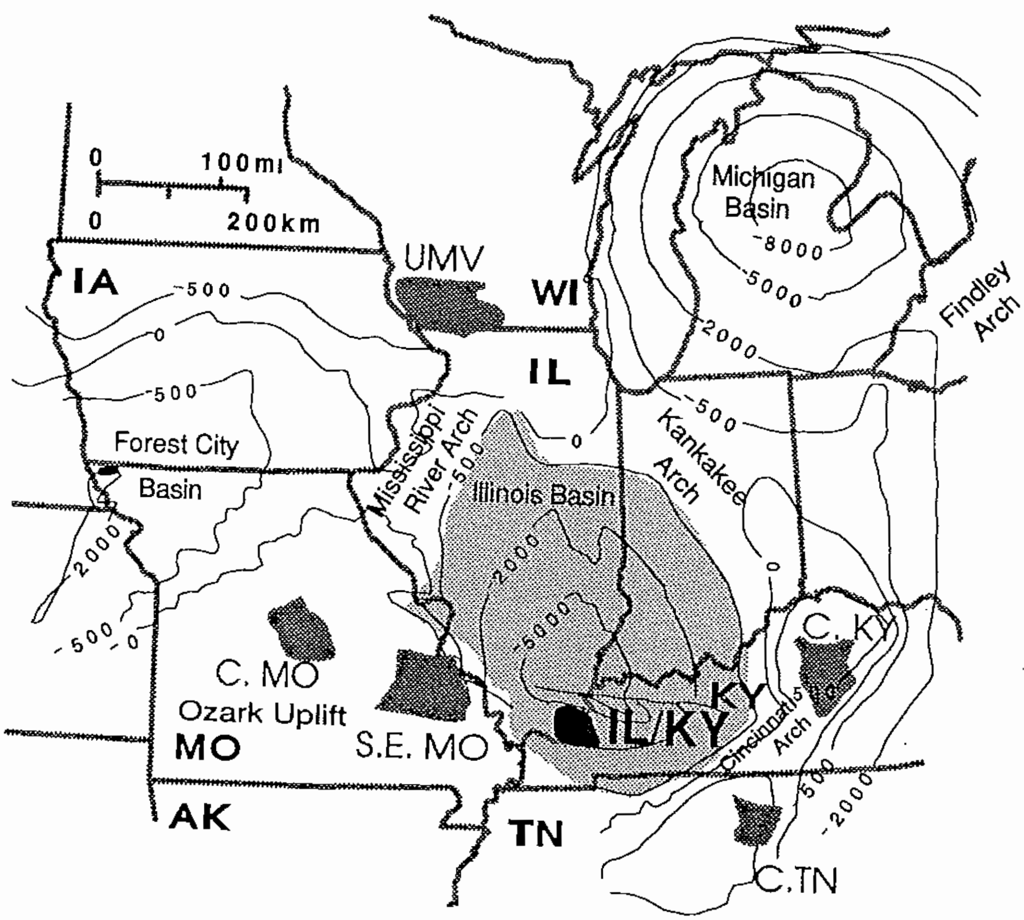
The Illinois Basin—A flow path for ore-forming solutions?

The Illinois Basin is spatially associated with at least six major Mississippi Valley-type (MVT) ore districts that may have formed as a result of regional paleohydrologic activity in the Basin. These ore districts include the Viburnum Trend and Old Lead Belt of southeast Missouri, Missouri barite district, the Upper Mississippi Valley district to the north, the Central Tennessee and Central Kentucky districts to the east, and the Illinois-Kentucky fluorspar district within the southern Illinois Basin itself. The Viburnum Trend and Old Lead Belt are among the largest accumulations of mineable galena yet discovered in the earth's crust.

Don White of the USGS first proposed (in 1958) that MVT ore-forming fluids were connate brines (i.e., "oil field brines"). This realization led to an ore-genesis model that suggested MVT ore formation was a natural consequence of sedimentation and basin evolution in which ore fluids were set in motion by compaction of basin-fill materials.

Evidence is accumulating that compaction alone causes fluids to flow much too slowly to produce mineralization. Brine migration of the scale and rate required to form large MVT districts evidently requires a gravity driven (artesian) flow system brought about by waters recharging in the highlands formed during major mountain-building events.



Vicinity map of the southern Midcontinent of the United States. The Illinois Basin (light grey) is bounded on the northwest by the Mississippi River Arch, on the northeast by the Kankakee Arch, on the west by the Ozark Uplift, and on the east and southeast by the Cincinnati Arch. Several Mississippi Valley-type ore districts (dark grey) occur around the periphery of this basin including the Upper Mississippi Valley district (UMV), the Central Missouri district (C. MO), the Southeast Missouri districts (S.E. MO), the Central Kentucky district (C. KY) and the Central Tennessee district (C. TN). Only the Illinois-Kentucky Fluorspar district (IL/KY) in black occurs within the basin itself. Contours show depth (in feet) to the top of the Trenton limestone (or equivalents).

New investigations that constrain the "paleohydrologic" history of the region have come from a wide range of disciplines. The most detailed study is in the Illinois-Kentucky fluorspar district.

This district has some unique characteristics compared to others in the region. It is the only Midcontinent MVT district with fluorite as the major economic commodity, and it is also the only one with a clear spatial relationship to igneous rocks. The district includes Hicks Dome, a crypto-volcanic explosion feature and probable alkalic intrusive center, as well as a number of lamprophyre dikes and numerous intrusive breccia plugs dated as Permian (ca. 270 million years old). The mineralization postdated igneous activity. Nevertheless, this spatial link to igneous rocks is uncharacteristic of MVT ores as a class. Study of seismic reflection, geochemical and fluid-inclusion data indicates that MVT mineralization here was in fact related to a very large basinal brine-flow system that interacted with igneous volatiles from the later stages of the Hicks Dome magmatism.

A high-quality seismic reflection profile, giving a cross-section view of Hicks Dome, shows that the entire section of Paleozoic rocks (ca. 550-250 million years old) and the top of Precambrian basement are domed. The data also indicate an upward tapering cone of highly disrupted sedimentary rocks above the basement contact. These features indicate both intrusion of a large magma body at depth, and also explosive release of igneous volatiles at Hicks Dome.

To evaluate the possible thermal influence of the igneous activity on the fluorspar district (FSD), fluid-inclusion studies were made on fluorite samples from 16 mines encompassing the entire district (2,560 km^2). The temperatures of fluorite formation decline distinctly from the center of Hicks Dome (175°C), to the flanks of the dome (150°C), to the Cave-in-Rock subdistrict (130-150°C), to more distant outliers on the southern margin of the district (100-120°C).

Detailed study of suites of ore samples from throughout the district revealed that the sequence of formation of hydrothermal minerals is correlatable, deposit to deposit and throughout the country rocks between deposits, over the entire extent of the district. The thermal zoning, coupled with the paragenetic study, is consistent with the conclusion that mineralizing fluids were subject to heat from igneous processes.

Chemical reaction-path modeling constrained by fluid-inclusion data indicates that cooling, reaction with host limestone, or isothermal boiling, involving only a fluorite-saturated MVT "connate" brine, could not duplicate the observed ore and gangue mineral paragenesis. On the other hand, calculations modeling addition to such an MVT brine of HF and CO_2 at 300°C (approximating a CO_2 and HF-bearing gas phase expelled from a crystallizing alkalic magma) predicts extensive fluorite precipitation and development of acidic (pH 2.5 or lower), F-rich, Ca-poor fluids. Cooling of the fluids to $\leq$150°C leads to further fluorite precipitation, mimicking relationships seen in vein ores of the district. Modeling of the subsequent reaction of acidic 150°C fluids with limestone nicely reproduces the relationships observed in bedded ores. Thus the modeling supports other lines of evidence showing igneous processes have an important role in FSD mineralization.

Yet it is probable that Hicks Dome was a rather local thermal and chemical influence on a vastly larger hydrothermal system. Hydrothermal carbonate, sulfide, and fluoride minerals can be correlated paragenetically and geochemically from west of the FSD to the central Tennessee district and to the central Kentucky district. This implies the operation of a hydrothermal system affecting perhaps 35,000 cubic miles of rock and probably requires artesian-driven flow.

Epigenetic fluorite enrichment can be traced from the southern Illinois Basin northward as far as the Iowa-Missouri border, confirming the major brine flow northward toward the northern portion of the basin.

Ores from at least the Illinois-Kentucky fluorspar district, the Upper Mississippi Valley, the Central Tennessee, and the Central Kentucky districts may have formed in a large hydrothermal flow system migrating through this Basin. ❑

Martin B. Goldhaber

" Epigenetic fluorite enrichment can be traced from the southern Illinois Basin northward as far as the Iowa-Missouri border, confirming the major brine flow northward toward the northern portion of the basin."