Mineral Resources of the Illinois Basin in the Context of Basin Evolution

St. Louis, Missouri, January 22-23, 1992

Program and Abstracts

Edited by **Martin B. Goldhaber** and **J. James Eidel**

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This report is preliminary and has not been edited or reviewed for conformity with U.S. Geological Survey, Illinois State Geological Survey, Kentucky Geological Survey, Missouri Division of Geology and Land Survey, and Indiana Geological Survey standards.

PREFACE

The mineral resources of the U.S. midcontinent were instrumental to the development of the U.S. economy. Mineral resources are an important and essential component of the current economy and will continue to play a vital role in the future. Mineral resources provide essential raw materials for the goods consumed by industry and the public. To assess the availability of mineral resources and contribute to the ability to locate and define mineral resources, the U.S. Geological Survey (USGS) has undertaken two programs in cooperation with the State Geological Surveys in the midcontinent region.

In 1975, under the Conterminous U.S. Mineral Assessment Program (CUSMAP) work began on the Rolla 1° X 2° Quadrangle at a scale of 1:250,000 and was continued in the adjacent Springfield, Harrison, Joplin, and Paducah quadrangles across southern Missouri, Kansas, Illinois, Arkansas, and Oklahoma. Public meetings were held in 1981 to present results from the Rolla CUSMAP and in 1985 for the Springfield CUSMAP.

In 1984, the Midcontinent Strategic and Critical Minerals Project (SCMP) was initiated by the USGS and the State Geological Surveys of 16 states to map and compile data at 1:1,000,000 scale and conduct related topical studies for the area from latitude 36° to 46° N. and from longitude 88° to 100° W. Precambrian basement compilations for the SCMP were extended even farther north and west.

In an effort to reach a larger number of those who might be interested in midcontinent mineral resource data and research, a symposium, patterned after the USGS McKelvey Forums was held at St. Louis, Missouri, April 1989. The purpose of the meeting was to present summaries or progress reports on the regional compilations and topical research done during the first five years of the SCMP midcontinent project and more detailed reports on the geology, stratigraphy, sedimentology, geochemistry, geophysics, and mineral-resource potential of the Harrison and Joplin 1° X 2° quadrangles. The first results and status of the Paducah CUSMAP were presented at this meeting. Progress reports on the CUSMAP and SCMP projects were presented and continue to be presented at various national and regional meetings.

Plans to undertake the assessment of the mineral resource potential of the Paducah Quadrangle were approved in 1985 and work by the USGS, the Illinois State Geological Survey (ISGS), the Kentucky Geological Survey, the Missouri Division of Geology and Land Survey, and the Indiana Geological Survey began in 1987. In 1986, a joint USGS/ISGS pilot study extended the insoluble residue analysis methods developed for the Rolla Quadrangle to a traverse of core and rotary drill holes along western Illinois and across the Paducah Quadrangle. Results from this traverse indicate that the mineralization documented on the east side of the Ozark Uplift on the Rolla Quadrangle extended into the Illinois Basin.

The Illinois State Geological Survey, the Indiana Geological Survey, and the Kentucky Geological Survey formed the Illinois Basin Consortium (IBC) in 1989 to foster cooperative research projects on basin-wide geologic and mineral resource-related problems. The USGS Evolution of Sedimentary Basins Program has undertaken a number of research projects on the Illinois Basin that complement the IBC program.

Results from the Paducah CUSMAP resource evaluation and topical studies and the IBC and USGS Evolution of Sedimentary Basin studies are presented in this open file abstract volume. This volume contains the program and abstracts from the January 1992 St. Louis Paducah-IBC meeting. The abstracts are arranged in alphabetical order by the first author's name.

This symposium on the Paducah CUSMAP and IBC efforts presents the results of cooperative research programs that utilized the talent, equipment, and other resources of the federal and state geological surveys. Without this federal-state cooperation, this assessment could not have taken place. This open file volume records the contributions of these organizations:

U.S. Geological Survey
Illinois State Geological Survey
Kentucky Geological Survey
Missouri Division of Geology and Land Survey
Indiana Geological Survey

The USGS and State Geological Surveys welcome discussions from our colleagues in industry and academia.

Marty Goldhaber
Jim Eidel

Schedule of Events—Wednesday, January 22

7:00-8:15 Registration and Poster setup

8:15 **Martin B. Goldhaber and J. James Eidel**; Welcome and opening remarks

8:20 **Harry A. Tourtelot**; Welcome from the USGS

8:30 **Norman C. Hester and Jennie L. Ridgley**; Welcome from the Illinois Basin Consortium

8:40 **J.J. Eidel and M.B. Goldhaber**; The Paducah CUSMAP—A broad spectrum of resources in a rift-related interior cratonic basin

Geologic Background Session
M.B. Goldhaber and J.J. Eidel
Session chairs

9:00 **D.R. Kolata and W.J. Nelson**; Evolution of the Illinois Basin

9:30 **T.G. Hildenbrand, R.P. Kucks, and P.C. Heigold**; Geologic and structural evolution of the southern Illinois basin based on potential field studies

10:00 Coffee break

10:30 **W.J. Nelson**; Sructural geology of the Paducah quadrangle

11:00 **T.S. Hayes, E.J. LaRock, J. Gaines, C.M. Seeger, Z. Lasemi, and W.W. Olive**; Mapping lithologic criteria for mineral deposit potential using a subsurface lithologic database with ARC/INFO

11:30 **M.B. Goldhaber, H.A. Folger, C.D. Taylor, E.L. Mosier, C.A. Gent, K.C. Hackley, and J.M. Masters**; Paducah Cusmap subsurface geochemical studies

12:00 Lunch

Luncheon ($16):

David L. Leach, Speaker
The plate tectonics of brine migration and the formation of Mississippi Valley-type metallogenic provinces

Industrial minerals and coal
Martin Noger and Jim Baxter
Session chairs

1:30 **R.C. Berg, M.R. Greenpool, J. Whitfield, W.W. Olive, and J.A. Rupp**; Surficial deposits of the Paducah 1° x 2° quadrangle

2:00 **C.G. Treworgy, M.H. Bargh, R.J. Jacobson, and G.K. Coats**; Assessment of the coal resources of the Paducah quadrangle

2:30 **B.R. Johnson, R.R. Pool, G.N. Green, and B.J. Stiff**; Digital mineral deposit models and geographic information systems as resource assessment tools

3:00 Coffee Break

3:30 **G.R. Dever, Jr. and W.W. Olive**; Industrial mineral resources in the Kentucky part of the Paducah 1° x 2° quadrangle

3:45 **J.W. Baxter, L.R. Smith, B.J. Stiff, G. Dever, Jr., W.A. Anderson, A. Rueff, and M. McFarland**; Assessment of limestone and dolomite resources of the Paducah 1° x 2° quadrangle

4:05 **J.M. Masters, A. Rueff, W.W. Olive, J.W. Baxter, W. Anderson, M. McFarland, and B.J. Stiff**; Assessment of the construction sand and gravel and industrial sand resources of the Paducah 1° x 2° quadrangle

4:25 **R.E. Hughes, W.W. Olive, A. Rueff, J.W. Baxter, W. Anderson, M. McFarland, and B.J. Stiff**; Assessment of the clay and shale resources of the Paducah quadrangle

4:45 **J.J. Eidel, R.B. Berg, J.M. Masters, A. Rueff, and B.J. Stiff**; Tripoli (Microcrystalline silica) resources of the Paducah quadrangle

7:00 - 10:00
Poster Session and Cash Bar

B.W. Arnold and J.M. Bahr
Fracture flow modeling related to MVT mineralization in the Upper Mississippi Valley District, southwest Wisconsin

J.B. Droste and L.C. Furer
Chronostratigraphy of the early Pennsylvanian rocks in the subsurface of Indiana

H.A. Folger and M.B. Goldhaber
A geochemical cross section of the Paducah 1° x 2° quadrangle

L.C. Furer
Basement tectonics in the Eastern Illinois Basin and their effect on early Paleozoic sedimentation

N.R. Hasenmueller, W.S. Boberg, J. Comer, Z. Smidchens, W.T. Frankie, D.K. Lumm, T. Hamilton-Smith, and J.D. Walker
Study of gas production potential of New Albany Shale [Group] in the Illinois Basin

J.C. Hohman
Upper Ordovician sequence stratigraphy of the southern Illinois Basin

D.W. Houseknecht and G. Wood
Petrology of Pennsylvanian sandstones in southern Illinois and Missouri—Provenance implications of vertical and lateral variations in composition

Hue-Hwa Hwang
Origin of shallow saline groundwater in the central and southern Illinois Basin

H.D. Jones, S.E. Kesler, P.G. Spry, C.K. Richardson, J.R. Kyle, W.H. Anderson, and F.C. Furman
Determination of the limits of Mid-Continental brine flow by sulfur isotopes from Mississippi Valley-type deposits

M.K. Lee, K.W. Larson, and C.M. Bethke
Modeling fluid flow and brine diagenesis in the Illinois Basin

W. Li
Origin of Middle Ordovician dolomites in the Illinois Basin

D.L. Macke
Sedimentary cycles in the Mississippian St. Louis limestone, southwest Indiana

M.A. Middendorf
Surface geologic mapping in Missouri—Look at it this way

E.L. Mosler and M.B. Goldhaber
Geochemical studies of the dilute HCL soluable fraction of subsurface samples from the Paducah 1° x 2° quadrangle

D.F. Oltz, J.E. Crockett, R. Mast, R.H. Howard, J.A. Rupp, and M.C. Noger
Oil and gas potential in the Paducah quadrangle

Paducah Cusmap Team
Paducah quadrangle resource assessments:
- Vein fluorspar resources
- Bedded fluorspar resources
- Ordovician fluorspar resources
- Limestone and aggregate resources
- Clay resources
- Sand and gravel resources
- Coal resources
- Tripoli resources

J.K. Pitman, M.B. Goldhaber, and T.H. Shaw
Regional diagenetic patterns in the St. Peter Sandstone, Illinois Basin—Evidence for multiple episodes of fluid movement during the late Paleozoic

G.S. Plumlee and M.B. Goldhaber
The possible role of magmatic gases in the genesis of Illinois/Kentucky fluorspar deposits—Implications from chemical reaction path modeling

C.J. Potter, P.C. Heigold, C.D. Taylor, and M.B. Goldhaber
A seismic reflection profile across Hicks dome

Poster Session—Continued

R.L. Reynolds, M.B. Goldhaber, and L.W. Snee
Paleomagnetic study of the Grants breccia and the Downeys Bluff sill—Implications for the influence of Permian igneous activity on Mississippi-Valley type mineralization in southern Illinois

J.E. Repetski
Lower Ordovician stratigraphy and facies in and adjacent to the Reelfoot Basin, southern midcontinent, U.S.A.

J.L. Ridgley
Sedimentary cycles in the Mississippian St. Louis limestone southwest Indiana

M.L. Sargent, J.D. Treworgy, S.T. Whitaker, and M.C. Noger
Three structural cross sections through selected deep wells within and adjacent to the Paducah 1° x 2° quadrangle, southern Illinois, southeastern Missouri, and western Kentucky

T.H. Shaw
Early-Middle Ordovician evolution of the Illinois Basin—Paleontologic and sedimentologic constraints

E.C. Spiker, R.B. Finkelman, A.L. Bates, J.R. Hatch, and R.D. Harvey
Sulfur geochemistry of a sphalerite-bearing Illinois Basin coal

C.S. Spirakis and A.V. Heyl
Shortcomings of some proposed precipitation mechanisms for Mississippi Valley-type deposits

J.D. Treworgy, and S.T. Whitaker
The Illinois Basin in cross section

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Schedule of Events—Thursday, January 23

Base Metals
Jim Martin and Tim Hayes
Session chairs

8:30 **C.M. Bethke, M.K. Lee, and K.W. Larson**; Paleohydrology of the Illinois Basin, oil migration, ore genesis, and sedimentary diagenesis

9:00 **T.S. Hayes and W.H. Anderson**; Regionwide correlation of the hydrothermal paragenesis of the Illinois/Kentucky fluorspar district

9:20 **J.W. Baxter, W. Anderson, T.S. Hayes, and R.R. Pool**; Vein and bedded fluorspar mineralization in the Paducah sheet

9:45 **W.H. Anderson**; Present and potential mineral resources in the Paducah 2° quadrangle and rift-related mineralization in central Kentucky

10:00 Coffee Break

10:30 **M.B. Goldhaber, T.S. Hayes, J.J. Eidel, E.J. Larock, and M.L. Sargent**; Assessment of Mississippi Valley-type mineralization—Examples from the Dutchtown Formation

11:00 **J.R. Palmer**; Cambrian and Ordovician stratigraphy and the potential for Mississippi Valley-type and Mount Isa-Type base metals, western Paducah 1° x 2° area

11:30 **C.M. Seeger and E.B. Kisvarsanyi**; Potential for magmatic-hydrothermal Fe-REE-Cu-(Au?) deposits in the Proterozoic basement of the Paducah 1° x 2° quadrangle

12:00 Lunch

Topical Studies
Jennie L. Ridgley and Norman C. Hester
Session chairs

1:30 **L.M. Walter, A. Stueber, T.J. Huston, A. Martini, V. Granath, and R.E. Blake**; Origin, evolution, and migration of Illinois Basin brines

2:00 **N.S. Fishman**; Diagenetic studies of the Mt. Simon sandstone—Implications for paleohydrology

2:15 **C.J. Potter, P.C. Helgold, C.D. Taylor, and M.B. Goldhaber**; Interpretation of a regional seismic reflection line, southern Illinois Basin—Cambrian rifting, Illinois/Kentucky fluorspar district faulting, and Hicks dome

2:30 **D.W. Houseknecht**; Diagenesis of the St. Peter sandstone along a traverse from the Ozark dome into deepest Illinois Basin

2:50 **T. Shaw**; Early-Middle Ordovician evolution of the Illinois Basin; paleontologic and sedimentologic contraints

3:10 Coffee Break

3:40 **R.C. Burruss, C. Richardson, J.N. Grossman, F.E. Lichte, and M.B. Goldhaber**; Regional and microscale zonation of rare-earth elements in fluorite of the Illinois/Kentucky fluorspar district

4:10 **C.D. Taylor, E.L. Rowan, M.B. Goldhaber, and T.S. Hayes**; A relationship between Hicks Dome and temperature zonation in fluorite from the Illinois/Kentucky fluorspar district—A fluid inclusion study

4:25 **L.W. Snee and T.S. Hayes**; $^{39}Ar/^{40}Ar$ geochronology of intrusive rocks and Mississippi-Valley-type mineralization and alteration from the Illinois/Kentucky fluorspar district

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Note: Affiliations of authors are abbreviated as follows:

USGS	—	U.S. Geological Survey
ISGS	—	Illinois State Geological Survey
MGS	—	Missouri Division of Geology and Land Survey
KGS	—	Kentucky State Geological Survey
IGS	—	Indiana State Geological Survey

Present and Potential Mineral Resources in the Paducah 2-Degree Quadrangle and Rift-Related Mineralization in Central Kentucky

Warren H. Anderson (KGS)

Advances in the study of ore genesis in the Kentucky-Illinois Fluorspar District will create new opportunities for the mining industry in the Kentucky portion of the New Madrid Rift System. The CUSMAP project identified more than 400 mineral occurrences in western Kentucky. Most of these occurred along the major northeast-trending fault systems in the district. Most of the major fluorspar production to date (30 percent) has come the Tabb Fault System in the southeastern portion of the district. New data about the Hutson Mine make the potential for reopening this mine more likely. The Coefield aeromagnetic ring anomaly indicates that this alkalic intrusive is probably a southern extension of the Hicks Dome intrusive. Mineralization should consist of carbonitites, REE, and iron/magnetite.

Chemical analysis of insoluble residues of well samples in the Jimmy Bell No. 1 showed anomalous values for Cu, Pb, and Co. Other slightly anomalous values were for Mo, Zn, Ag, and Ni. These anomalies occurred at a depth of 13,000 feet, which would place them in the first major carbonate sequence (Knox Group) above the Mt. Simon sands in this portion of the basin. Elsewhere, the Eau Claire shales occur in the interval between the basal sands and the first carbonate unit. This region could be a shale window for major mineralization in the deep subsurface. This preliminary information confirms the idea of mineralization occurring in the first carbonate above a shale window.

Rift-related mineralization in Proterozoic rocks may exist in the deep subsurface along the Grenville Front in parts of central Kentucky and Ohio. The provincial boundary between the Grenville and Central Terranes could be an excellent area for syn- and epigenetic mineralization. Precise timing and location of tectonic events related to the Grenville Front would play an important role in mineralization. The occurrence of polymetamorphic events in the Grenville, post-Grenvillian igneous events, granulite facies metamorphism, and the presence of the metamorphic mineral cummingtonite could indicate a significant grade of metamorphism during and after Grenville events for metal remobilization. The presence of iron and other undescribed opaque minerals, rift-related mylonites, and suture zones provide much of the structural mechanics necessary for precipitation of base and precious metals in the eastern Midcontinent region. Numerous metasediments, quartzites, and thick carbonate sequences, including marble, provide effective hosts for these minerals.

Fracture Flow Modeling Related to MVT Mineralization in the Upper Mississippi Valley District, Southwest Wisconsin

Bill W. Arnold and Jean M. Bahr (University of Wisconsin-Madison)

Fracturing in carbonate host rocks of the Middle Ordovician Sinnipee Group is the primary factor controlling ore localization in the Upper Mississippi Valley zinc-lead district. Because of the low matrix permeability of these rocks, fractures are the dominant path for fluid flow. Dissolution along fractures prior to or during mineralization widened fractures and increased fracture permeability, creating a positive feedback mechanism of increased fluid flow and dissolution in zones of high initial fracture permeability. Focusing of fluid flow is an important process in ground preparation and ore deposition in carbonate-hosted MVT mineralization. Numerical simulations of flow in two-dimensional stochastic discrete fracture networks, using fracture pattern data obtained from mapping of fractures in a quarry floor, were used to characterize the fluid flow within the carbonate strata. Fractures mapped at the quarry were divided into two sets, both of which correspond to orientations of mineralized fractures elsewhere in the district. Each fracture set is described by normal distribution of strike, constant dip, lognormally distributed fracture trace length, and fracture density. Fracture aperture was not measured, but is assumed to be a lognormally distributed parameter. The fracture trace length distribution could not be determined directly because of fracture trace truncation at quarry walls. The actual fracture trace length distribution was estimated by matching measured, nontruncated fracture length distribution characteristics to simulated values using a trial and error technique of Monte Carlo simulations.

Multiple realizations of the fracture pattern using the same statistical parameters are used in fluid flow simulations with given boundary conditions to determine permeability characteristics of the medium. Preliminary results indicate that for hydraulic gradients oriented within 60° of the principle direction of anisotropy, bulk permeability of the medium is lognormally distributed for this fracture pattern. With the hydraulic gradient approximately parallel to the dominant fracture set, fracture permeability varies over about two orders of magnitude in 100 realizations of 100 m by 100 m domains with a statistically homogeneous fracture pattern. Plots of mean permeability for simulations on a permeability ellipse indicate that the average fractured medium behaves as an equivalent porous medium in terms of horizontal anisotropy. The effect of scale on the flow properties of the fracture pattern was investigated by varying the size of the domain. The standard deviation, as a measure of variability of equivalent permeability, decreases to an approximately constant value at scales greater than about 150-200 m as shown on the figure below.

Data on dimensions of zinc ore bodies in the district indicate a bimodal distribution of ore body sizes. The larger ore bodies are related to discrete structural features such as synclines, through which fluid flow focusing can be explained as a result of structural controls. The ore bodies smaller than 250 m are generally elliptical and more randomly located. Fluid flow focusing at these scales may be related to increased variability of fracture permeability inferred from these simulation results. In a heterogeneous medium fluid flow focusing increases with increasing permeability contrast. Increased variability of fracture permeability for domains smaller than 200 m by 200 m suggests that this may be a controlling scale for the fluid focusing which led to the formation of smaller zinc ore bodies.

Vein and Bedded Fluorspor Mineralization in the Paducah Sheet

J. W. Baxter (ISGS), W. Anderson (KGS), T. S. Hayes (USGS) and R. R. Pool (ISGS)

The Illinois-Kentucky Fluorspar Mining District lies within a complexly faulted portion of the Shawnee Hills section of the Interior Low Plateaus Physiographic Province. The deposits are essentially of two types:

- fissure-filling veins in rocks of Mississippian age along faults with typical vertical displacements of 30-150 m (100 to 500 ft)
- flat-lying, strata-bound, replacement or "bedded" deposits at favorable horizons in limestone of late Valmeyeran (middle Mississippian) to early Chesterian (late Mississippian) age commonly located adjacent to major graben-bounding faults along fractures or minor faults of little displacement.

The fluorspar district is located near the southern end of the Illinois Basin at the intersection of the Reelfoot Rift and its east-trending extension into Kentucky, the Rough Creek Graben. The district sits astride the Tolu Arch-Hicks Dome.

In the vein-type mineralization, the principal minerals are fluorite and calcite with lesser amounts of sphalerite, galena, and barite. Some vein-type mines in Kentucky produced only zinc and a few only barite. Veins 1-3 m (3-10 ft) wide are the most common; some veins as much as 14 m (45 ft) wide have been found. Ore shoots commonly range from 60-120 m (200-400 ft) in strike-length and achieve greater lengths in the most productive mines. Mineralization commonly extends vertically 30 to 60 m (100-200 ft), but some workings are known to have extended nearly 250 m (800ft) vertically. The widest and most extensive vein deposits have been found where the faults are bounded by competent Ste. Genevieve and/or St. Louis Limestones; however, some commercial-size veins have been found where the wallrocks are made up of younger Chesterian strata.

The bedding-replacement type mineralization is located on either side of a major northeast-trending structural element, the Rock Creek Graben, and follows a group of northeast-trending fractures and minor faults. Some northwest- trending cross-structures also are mineralized. The bedding-replacement deposits in Illinois and Kentucky are commonly 15-60 m (50-200 ft) wide and 1.5-6 m (5-20 ft) thick; lengths range from 60 m (200 ft) to 3 km (2 mi). The ore ranges from 20 to 35 percent CaF_2 and commonly contains about 4 percent zinc as sphalerite and, locally, silver-bearing galena. Minor copper ore values, occurring as chalcopyrite, have been recovered from the metallic concentrates. Barite, practically absent in some bedded ore bodies, is abundant around the outer margins of others.

Replacement-type deposits are restricted to certain favorable stratigraphic levels. The three favored ore horizons are, in ascending order: (1) sub-Rosiclare ore, below the Spar Mountain Sandstone Member of the Ste. Genevieve Limestone or at the level of the Spar Mountain where that sandstone is missing; (2) Rosiclare ore, in the upper part of the Joppa Member of the Ste. Genevieve, and (3) Bethel ore, in the upper part of the Downeys Bluff Limestone. Less extensive deposits have been found in the Karnak Member of the Ste. Genevieve, in the upper part of the Levias Member of the Renault, and in a zone of transition between the Ste. Genevieve and the underlying St. Louis Limestone. All favored horizons are limestones. The two uppermost are overlain by sandstones that are shaly at the base and could have acted as aquitards; each favored interval may have been exposed to erosion or reworking during a depositional hiatus marking a minor marine regression.

Diagnostic criteria used in assessing the potential for vein and bedded fluorspar in the Paducah Quadrangle are: (1) spatial relationship to regional tectonic features (above or adjacent to rift); (2) location of mapped faults (vein model) or graben structures and graben-bounding faults (bedded model); (3) fault displacement (vein model) or displacement of graben bounding faults (bedded model); (4) SLAR- and LANDSAT-interpreted faults and grabens; (5) orientation of mapped and interpreted faults and grabens; (6) domal structures and noses; (7) locations of mines, prospects and other mineral occurrences; (8) subsurface occurrences; (9) insoluble residue geochemistry (anomalous F, metals, barium); (10) well water fluorine geochemistry, and (11) presence or absence of favorable host rocks.

Some of the listed criteria require additional explanation. Vein deposits are found mainly along north- and northeast-trending faults of moderate displacement, i.e. 16 to 150 m (50 to 500 ft). Known bedded deposits occur outside and adjacent to major grabens, and generally parallel a single graben-bounding fault or relatively narrow graben-bounding fault zone with relatively large displacement, i.e. >150 m (500 ft). Bedded ore bodies also follow the predominant northeast-southwest orientation of faults.

The geochemical database utilized in the assessment is a compilation of more than 15,000 emission spectrographic determinations, made on HCl-insoluble portions of carbonate rock samples from 124 drill holes, and fluorine-in-water analyses from the Paducah Quadrangle National Uranium Resource Evaluation (NURE). Weighted values that approximate the relative importance of each criterion in the process of mineralization and appropriate buffer zones for point-source data and certain areal defined data were assigned. The weighted criteria were analyzed using the Geographical Information System (GIS). Weights assigned to individual criteria were summed, but subjected to maximums, as were the total values for individual polygons depicted on the final assessment map. The maximum value for polygons on the vein fluorspar assessment map is 31; on the bedded fluorspar 30. The range of values was subdivided into high, moderate, and low mineral potential.

Areas showing highest potential for vein-type deposits are essentially restricted to the present known extent of the Illinois-Kentucky Fluorspar District. Moderate potential is shown in the vicinity of the McCormick Anticline in northwestern Pope County, Illinois, along the Ste. Genevieve-Rattlesnake Ferry Fault Zone in Missouri, and in connection with northeast-trending faults in Missouri. Limited areas in these regions achieve moderately high potential.

High potential for bedded fluorspar deposits is also primarily restricted to the fluorspar district but moderate potential is shown for a relatively large adjacent area west of the district that includes the McCormick Anticline. Targets with moderate ranking exist along and near the Ste. Genevieve-Rattlesnake Ferry Fault Zone in Missouri and Illinois and associated with a few northeast-trending faults in Missouri.

Assessment of Limestone and Dolomite Resources of the Paducah 1°x 2° Quadrangle

J. W. Baxter, L. R. Smith, and B. J. Stiff (ISGS), G. Dever, Jr. and W. Anderson (KGS), A. Rueff and M. McFarland, (MGS)

Large quantities of limestone and dolomite suitable for construction, agricultural, and industrial uses are present in rocks of Mississippian, Devonian, Silurian and Ordovician age in the Paducah Quadrangle. Raw materials currently produced from the Paducah CUSMAP region that were assessed include: (1) high-purity limestone, (2) high-specification aggregate, and (3) lower specification aggregate and commercial limestone and dolomite. There has been production of rough building stone, dimension stone, and commercial "marble" (polished stone) in the past and the potential for these commodities also has been assessed. Present production of crushed stone in the quadrangle is largely for aggregate and cement production. Cement is considered to be a manufactured product and is not discussed in this report.

For the appraisal, the mapped geologic units were grouped into use categories based on the known or potential suitability of the unit for specific commercial applications. The use category for each unit was determined by past and present performance records of material from that unit, published laboratory tests, and similarity to other rock units with a history of extraction and use in or near the Paducah Quadrangle. Three separate categories of carbonate rock resources are considered.

(1) High purity limestone. High-purity limestones are those that, at some places, contain a quarriable/mineable section of limestone with a minimum $CaCO_3$ content of 95 percent. This criterion is met in at least seven formations with a history of production in or near the Paducah Quadrangle.

In addition there are other formations that may contain a section of limestone containing a minimum of 95 percent CaCO.

(2) Aggregate resources . The Paducah Quadrangle contains resources for the production of concrete or bituminous aggregate material. Quality testing for material to be used in highway construction is generally carried out on a stock pile by stock pile basis and specifications may vary from state to state. High-specification aggregate in this assessment is a category used to designate stone that generally meets local quality specifications for use in portland cement concrete.

Some formations are not thought to be prospective for high-specification aggregate but are considered to be potential resources in terms of the probability that they contain stone capable of meeting less stringent requirements for lower specification aggregate and for other commercial uses.

(3) Carbonate building stone. The Paducah Quadrangle contains limestone resources suitable for use as building stone although there is no present production and apparently no well-developed market. Available resources are placed in this category because of past production or their similarity to units outside the quadrangle having a history of use. Rough-shaped blocks quarried from units of this category have been used in building construction, for flagging or as rubble. The Harrodsburg Member of the Ullin Limestone in Union County, Illinois, has been quarried for building stone, utilized as raw material for cut stone and dimension stone, and has been polished and marketed commercially as "marble". Other formations have been demonstrated to take a polish and may also have a place under this category of use.

Three separate models were constructed to assess the potential for limestone and dolomite products: high-purity limestone, aggregate, and building stone. Diagnostic criteria used for the Geographical Information System (GIS) assessment of potential for the production of carbonate rock products in the Paducah Quadrangle include (1) presence of favorable bedrock formations, (2) history of use and production and (3) occurrences (location of active and inactive quarries) and (4) thickness of unconsolidated overburden (0-20, 20-50, and greater than 50 feet).

Potential for high-purity limestone exists in some specific areas, particularly those underlain by the Kimmswick Limestone, Harrodsburg Member of the Ullin Limestone, and the Ste. Genevieve Limestone. Highest potential for the Kimmswick is along the Mississippi River, near Cape Girardeau, Missouri and Thebes, Illinois; for the Harrodsburg, in portions of the outcrop belt in Union and Alexander Counties; for the Ste. Genevieve, in Hardin County, Illinois and the adjacent portion of Kentucky.

Greatest potential for production of construction aggregate in Missouri, especially for the high-specification category, occurs within the outcrop belts of the Plattin, Pecatonica and Joachim Formations that extend south of the Ste. Genevieve Fault Zone. In Illinois, primary targets will most likely be restricted to the Ste. Genevieve and Kinkaid Limestones. In Kentucky, the principle sources will continue to be the Ste. Genevieve, Warsaw, Kinkaid, and Salem Limestones and, for uses where a high-silica content is desirable or not detrimental, the Fort Payne Formation.

There are, at present, no viable markets for production of roughly shaped carbonate building stone nor production of dimension or polished stone. However, extensive areas in Missouri underlain by Ordovician Dolomites, and areas in Illinois underlain by Mississippian bedrock, can provide roughly shaped materials for local use or for restoration of historic structures. Greatest potential for production of dimension stone and polishable limestone (commercial marble) lies within the Harrodsburg Member of the Ullin Limestone in Union and Pulaski County in Illinois. Limestone in fault blocks mapped as Warsaw in the southeast corner of the quadrangle is lithologically similar to the Harrodsburg, but may have fractures and other discontinuities detrimental to use. Portions of the Salem Limestone in southeast Illinois that are nearly black in color, and parts of the Silurian in southwest Illinois display shades of red, have been previously evaluated and have potential as sources of chips for use in terrazzo floors. The latter has been utilized commerciallyfor this purpose on a small scale.

Surficial Deposits of the Paducah 1°X 2° Quadrangle

**Richard C. Berg and Mary R. Greenpool (ISGS),
William Whitfield (MGS), Wilds Olive (USGS), and John Rupp (IGS)**

Surficial material maps provide information on the distribution of near-surface resources such as sand and gravel and some clay resources and on the extent and amount of overburden that must be removed prior to mining of mineral resources in bedrock.

The surficial deposits depicted on the Paducah 1°x 2° Quadrangle were mapped in a three-dimensional stack-unit format. A stack-unit map shows the distribution of surficial geologic materials in their order of occurrence to a specific depth.

The Paducah Quadrangle includes portions of Illinois, Missouri, Kentucky and Indiana. Original mapping for the Illinois portion of the map was that from the Stack-unit map of Illinois at a scale of 1:250,000 (C 542 "Stack-Unit Mappingof Geologic Material in Illinois to a Depth of 15 Meters," Richard C. Berg and John P. Kemlpton. 1988). Surficial deposits information for the Missouri, Kentucky, and Indiana portion of the maps was derived from respective state maps. Remapping of portions of the study area followed field checking.

This map is one of the first to portray detailed three-dimensional, near-surface lithostratigraphy using an array of colors with line and dot patterns. General color groups were assigned to represent dominant surficial deposit types. Alluvium deposits are colored yellow, lacustrine deposits are purple, diamicton is red or pink, Pennsylvanian bedrock is green, etc. Color shades within major color groups were based upon stack-unit sequences regardless of thickness or continuity of any unit(s) within a given sequence. Map areas showing loess overlying diamicton overlying Pennsylvanian bedrock would all be colored the same shade of pink regardless of the thickness or degree of continuity of any of the three materials within the stacked sequence. Line and dot patterns were chosen to differentiate between stack-unit sequences of the same color shade. The assignment of line and dot patterns was based on continuity and thickness of materials within the stack-unit. Thick loess overlying diamicton and Pennsylvanian bedrock has an overlay pattern different from thin loess overlying diamicton and Pennsylvanian bedrock.

A total of 132 sequences of materials are differentiated from among the 14 glacial and semi-lithified materials and 12 bedrock materials that were mapped on the Paducah Quadrangle. The continuity of major color groups illustrates regional geologic provinces. Within these provinces, individual map areas are differentiated. Each color shade group combined with a line or dot pattern represents a unique sequence of geologic materials.

Regional and Microscale Zonation of Rare Earth Elements in Fluorite of the Illinois-Kentucky Fluorspar District

R. C. Burruss (USGS), C. K. Richardson (University of Iowa-Ames), J. N. Grossman (USGS), F. E. Lichte (USGS), and M. B. Goldhaber (USGS)

Variations of rare earth element (REE) distributions in fluorite from the Illinois-Kentucky fluorspar district (FSD) are important tracers of mineralization and fluid flow processes because the paragenesis of fluorite mineralization can be correlated district-wide. Chondrite normalized REE distribution patterns were measured on specific stages of fluorite deposition for samples throughout the district by instrumental neutron activation (INAA). Additional measurements were made at specific localities by laser ablation, inductively coupled plasma mass spectrometry (LA-ICP-MS) and by laser excited photoluminescence spectroscopy (PLS).

Purple fluorite at Rose Mine has a distinct light REE (LREE) depleted and heavy REE (HREE) enriched pattern whereas blue fluorite at this mine and all stages of fluorite at other localities from throughout the district are depleted in both LREE and HREE, with a maximum in the pattern at Eu. Fluorite from the Rose Mine, adjacent to Hicks Dome, contains the highest total REE in the district with values 10-20 times lower in fluorite from outlying mines. Zoned fluorite crystals from individual mines have highest total REE in early growth zones (Y2 and P2 in the terminology of Richardson and Pinckney, 1984, Econ. Geol.) with later stages of the paragenesis showing either continuously decreasing or fluctuating total REE content. The regional and local zoning patterns indicate a decrease in total REE available for partitioning into fluorite both in space away from Hicks Dome and in time from early to late stages of fluorite deposition.

Microscale variations in REE in single fluorite crystals were investigated by LA-ICP-MS and by PLS. LA-ICP-MS measures all REE in 0.25 mm spots. PLS is a new technique that measures ions in 3 micrometer spots and is presently only calibrated for Er^{3+} and Eu^{2+} ions. Chondrite-normalized patterns for Rose Mine purple and blue fluorites are the same for both LA-ICP-MS and INAA and all three techniques give the same chondrite-normalized Eu/Er ratio within experimental limits. Eu/Er measured by PLS in traverses (measured at 250 micrometer intervals perpendicular to growth direction) across the latest fluorite zones (P6 through P7 in Richardson and Pinckney terminology) in Hill Mine fluorite give averages consistent with samples cut from these zones and analyzed by INAA. The detailed traverses show distinctly lower Eu/Er in the clear zone that separates the P6 and P7 zones. This clear fluorite zone contains primary petroleum fluid inclusions. It is possible that this variation is due to changes in the oxidation-reduction state of the aqueous fluid through introduction of hydrocarbons, although changes in fluid flow paths to include petroleum source beds and reservoirs with different REE compositions are also possible.

The regional and microscale observations of REE zonation in the FSD fluorite allow several conclusions. Regionally high REE centered on Hicks Dome is consistent with Hicks Dome as a major source of mineralizing fluids. Depletion in LREE in all samples indicates that the fluorite and REE were not directly derived from alkalic igneous sources which always show significant (approx. 100X chondrite) enrichment in LREE in associated fluorites. The unusual LREE and HREE depletion in most of the FSD fluorites requires extensive fractionation of any initial REE distribution in the original hydrothermal fluid prior to fluorite mineralization. Finally, our initial observations of microscale zonation suggest that further study of REE zonation will reveal details of the "paleohydrology" of fluorite mineralization and aid the assessment of undiscovered fluorite resources in this region.

Industrial Mineral Resources in the Kentucky Part of the Paducah 1° x 2° Quadrangle

Garland R. Dever, Jr. (KGS) and Wilds W. Olive (USGS)

Industrial mineral resources in the Kentucky part of the Paducah 1° x 2° quadrangle include limestone, sand, gravel, sandstone, and clay. Deposits of impure tripoli may be a potential resource.

Large quantities of limestone suitable for construction, agriculture, and industrial uses are present in rocks of Mississippian age. Faulting controls resource distribution in much of the area. Currently, three open-pit quarries and one underground mine produce stone from the Fort Payne Formation and the Warsaw, Ste. Genevieve, and Kinkaid Limestones. Two of the quarries, which are among the largest in the Nation, ship 75 to 98 percent of their stone by barge, mainly to markets in the southern United States.

Fort Payne siliceous limestone is quarried for railroad ballast and skid-resistant aggregate, with lesser quantities used as aggregate in concrete and asphaltic concrete. Construction aggregate, riprap, and agricultural limestone are produced from the Warsaw. High-calcium bioclastic limestone in the formation was used for sulfur dioxide (SO_2) emission control in a wet-scrubbing system at a coal-fired power plant and in a 20-MW atmospheric fluidized-bed combustion (AFBC) pilot plant.

Construction aggregate, agricultural stone, riprap, and industrial stone are produced from the Ste. Genevieve. High-calcium oolitic limestone in the formation is selectively quarried for rock dust, water treatment, and asphalt-shingle filler. It also has been used by chemical and metallurgical industries, and for SO_2 emission control in an AFBC pilot plant. The Kinkaid Limestone, which crops out along the border of the Western Kentucky Coal Field, is mined for construction aggregate and agricultural stone.

Sand is being dredged from the Ohio River near Paducah and is used for ready-mixed concrete, asphaltic concrete, mortar mix, and golf course greens. Gravels of Cretaceous to Holocene age, mainly composed of chert, have been used as road metal on secondary roads and in the base course of paved highways.

High-silica sandstones of Mississippian and Pennsylvanian age formerly were quarried for glass and ferrosilicon manufacture. Small quantities of dimension stone for local use have been obtained from several Mississippian sandstones. Clay deposits of Cretaceous to Pleistocene age are suitable for ceramic, absorbent, and other industrial uses, but none are being produced at the present time.

Chronostratigraphy of the Early Pennsylvanian Rocks in the Subsurface of Indiana

John B. Droste and Lloyd C. Furer (IGS)

The Raccoon Creek Group contains the oldest rocks of the Pennsylvanian System in Indiana and consists in descending order of the Staunton, Brazil, and Mansfield Formations. These formations have been subdivided using a geophysical log signature format method which has been verified by sample studies. Fine-grained marker beds consisting of limestones, shales, and coals in the Staunton and Brazil Formations can be recognized with confidence as approximate time markers. Marker beds are less prevalent in the underlying Mansfield Formation, which is dominated in most places by sandstone that has complex facies relationships. The Mansfield Formation ranges in thickness from zero at its present eroded limit to more than 800 feet in pre-Pennsylvanian paleovalleys. The Mansfield has been subdivided by the format method into three informal chronostratigraphic subsurface units: the upper, middle, and lower divisions. The top of the lower Mansfield is approximately at the position of the French Lick Coal Member. The thickness of the lower Mansfield is controlled significantly by pre-Pennsylvanian topography. The unit is partially exposed in very few places along the present outcrop belt. The Blue Creek Coal Member generally represents the top of the middle Mansfield. The middle Mansfield ranges in thickness from 150 to 250 feet and is commonly present in the outcrop belt. The top of the upper Mansfield is at the base of the

Tripoli (Microcrystalline Silica) Resources of the Paducah Quadrangle

J. James Eidel, R. B. Berg, and J. M. Masters (ISGS), A. Rueff (MGS), and B. Stiff (University of Illinois)

Tripoli or microcrystalline silica has been mined for 80 years in Illinois. More than 2.2 million tons were produced between 1913 and 1989. There are currently two active surface mines and one underground mine in Illinois. Microcrystalline silica products from Illinois are used as fillers or extenders, as abrasives and in the manufacture of cement. In Missouri, over 5 million tons were produced as railroad ballast and road metal between 1903 and 1924. Much smaller tonnages were produced through the 1950's, primarily for road metal with small amounts consumed in ceramics and silica brick. There are no active mines in Missouri.

Tripoli occurs in two districts in southern Illinois, the Elco District in Alexander and southern Union County and in the smaller Wolf Lake District in northern Union County. Tripoli occurs in Perry and Cape Girardeau Counties, Missouri. Limestone and dolomite of the Clear Creek Chert formation of the Tamms Group (Lower Devonian) has been leached and extensive silicification has formed in dense to friable microcrystalline silica. Lamar (1953) described the deposits and documented replacement of carbonate facies by silica. Weller and Ekblaw (1940) called upon deep weathering to explain the removal of carbonate, but Berg and Masters (in press) have documented fluid inclusion homogenization temperatures around 200_ C from silica overgrowths of quartz crystals. Berg and Masters also noted that the deposits are spatially related to positive magnetic anomalies and concluded that the silicification and removal of the carbonate may be related to heated groundwater.

The tripoli or microcrystalline silica ore deposit model is comprised of three diagnostic criteria: (1) occurrence of tripoli or microcrystalline silica, (2) favorable host rock, i.e. the Tamms Group Clear Creek Chert, and (3) post-Precambrian magnetic anomalies representing igneous (alkalic?) plutons.

The occurrence of tripoli or microcrystalline silica is a direct indicator of tripoli mineralization and was accorded the highest weight. Favorable host rocks were given less weight and the indirect spatial relationship of positive magnetic anomalies the least weight. Tripoli occurrences were buffered with a one mile radius. A Geographical Information System (GIS) was used to analyze the weighted and buffered data.

The resultant model defines discrete areas in which to conduct further exploration for tripoli. The three diagnostic criteria result in seven combinations, ranked in order of increasing exploration potential, with tripoli occurrence plus favorable host rock plus positive magnetic anomaly being the highest and positive magnetic anomalies alone being the lowest. The model, which utilizes only three diagnostic criteria, provides a simple example for demonstrating the utility of the GIS system in analyzing more complex hydrothermal ore deposit models.

Future exploration for tripoli should focus on prospecting for tripoli both within these districts and in areas of prospective host rock that overlie positive magnetic anomalies. Special attention should be paid to massive chert beds such as those at the top of the Clear Creek Chert; such beds may be in part siliceous sinter and near-surface silica replacement and, thus, represent previously unrecognized hydrothermal activity.

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The Paducah CUSMAP - Abroad Spectrum of Resources in a Rift-Related Interior Cratonic Basin

J. J. Eidel (ISGS) and M. B. Goldhaber (USGS)

Like all the Conterminous U.S. Mineral Assessment Programs (CUSMAP) before it, the Paducah Quadrangle (37-38 degrees north latitude and 88-90 degrees east longitude) was chosen for study because of the significant mineral resources that it had produced and the potential for future discovery and production that it holds. The Paducah Quadrangle and immediate environs comprise one of the most abundantly endowed fuel and non-fuel mineralized areas in the world (fig. 1).

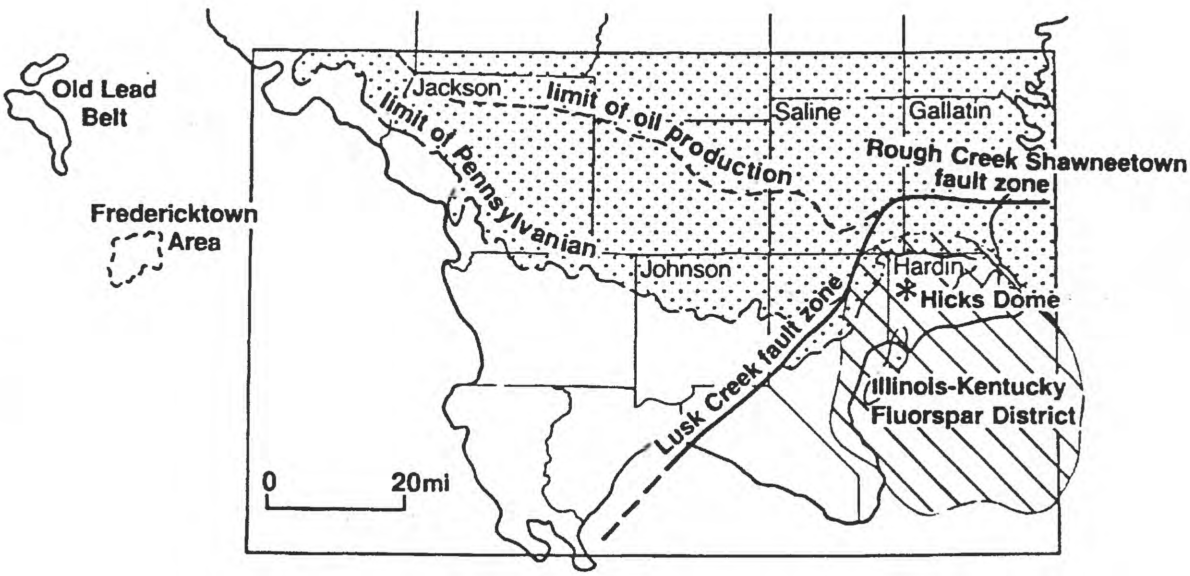

Figure 1.

The Illinois-Kentucky Fluorspar district encompasses the southeastern portion of the quadrangle; the district has produced more than 12 million tons of fluorspar and several million tons of other metals. The Old Lead belt in Missouri, 22 miles west of the Paducah Quadrangle has produced approximately 285 million tons of lead. The cobalt-lead-zinc ore bodies of the Fredericktown area in Missouri lie within 12 miles of the western edge of the Paducah Quadrangle and ore grade intercepts have been drilled just outside the quadrangle. The Paducah Quadrangle contains the southern extension of the Illinois Basin coal measures; approximately 2.3 billion tons of high- and medium-sulfur coal have been produced from the quadrangle. The southern extension of the Illinois Basin oil fields reaches into the northern portion of the Paducah Quadrangle; more than 600 million barrels of oil have been produced. Industrial mineral production has been from widespread sand and gravel and stone quarries, clay pits, and tripoli or microcrystalline silica mines. Historic records are incomplete, but it is certain that cumulative production of industrial minerals from the Paducah Quadrangle exceeds hundreds of million tons. More than 2.2 million tons of tripoli were produced between 1913 and 1989.

The quadrangle encompasses three distinct structural provinces: the southern portion of the Illinois Basin, in part overlying the northern portion of the Reelfoot rift and the adjoining western portion of the Rough Creek graben; the northern extremity of the Mississippi Embayment; and the easternmost portion of the Ozark Uplift.

Heyl et al., 1965, compiled the structure and mineral occurrences of the Paducah Quadrangle and called attention to the widespread nature of the mineralization. The U.S. Geological Survey and the Missouri Geological Survey conducted the Rolla CUSMAP study immediately west of the Paducah Quadrangle during the years 1976 to 1980. The Rolla 1° X 2° CUSMAP Quadrangle pioneered mid-continent mineral resource assessment at a scale of 1:250,000. Rolla and the subsequent Springfield, Harrison and Joplin Quadrangles provided detailed stratigraphic and geochemical insight to ore control and the origin of Mississippi Valley-type lead-zinc-copper-silver mineralization. For example, Erickson and co-workers developed a semiquantitative emission spectrographic method for analyzing acid insoluble residues from apparently unmineralized core in and adjacent to known ore bodies for the Rolla Quadrangle that was subsequently used for each mid-continent CUSMAP. They demonstrated that a halo of anomalous base metal values that encircled the St. Francois Mountains contained all known base metal ore bodies. Erickson et al., 1987, conducted a similar acid insoluble residue study for a series of drill holes extending along a traverse of the west edge of the Illinois Basin and eastward through the Paducah Quadrangle. The anomalous metals values from this study indicated that the halo of mineralization about the St. Francois Mountains extended into the Illinois Basin. Eidel et al., 1988, Erickson, et al., 1989, and Eidel and Baxter, 1989, suggested that deep circulating brines in the Illinois Basin and the underlying Reelfoot Rift and Rough Creek Graben were responsible for fluorine and base metal mineralization east of the Ozarks. Goldhaber et al., 1990, provided lead isotope data that support a deep-seated origin for lead from the Illinois-Kentucky Fluorspar District and for lead in the Cambrian sediments of the Paducah Quadrangle.

The bedrock geology of the Paducah Quadrangle was compiled from 69 1:24,000 quadrangles, 6 1:62,500 quadrangles, and 10 other maps at various scales. Published 7.5 minute geologic quadrangle maps cover all the Kentucky portion of the Paducah Quadrangle and much of the Fluorspar Mining District in Illinois. In recent years, 15 more 7.5 minute quadrangles covering the southern margin of the Pennsylvanian rocks in Illinois have been mapped and have been, or soon will be, published. In Missouri, 29 7.5 minute quadrangles have been completed in recent years. Mapping at this scale is continuing in both states. Potential field data (magnetic and gravity) were compiled and interpreted. Lithostrati-graphic data from 290 drill holes, representing more than 500,000 total feet of drilling, were converted into digital computer files. Using the Interactive Surface Modeling Software by Dynamic Graphics, isopach and isolitic maps of numerous stratigraphic horizons were prepared to determine aquitard and aquifer edges. Geochemical data for the Paducah Quadrangle include semi-quantitative emission spectrographic determinations of anomalous metal values performed on more than 15,000 samples of insoluble residues from cuttings and core from 124 drill holes.

Nineteen ore deposit models have been and are being compiled and interpreted using the Illinois Geographic Information System (GIS). The Paducah CUSMAP will be the first CUSMAP assessment that has been successfully completed using a GIS system.

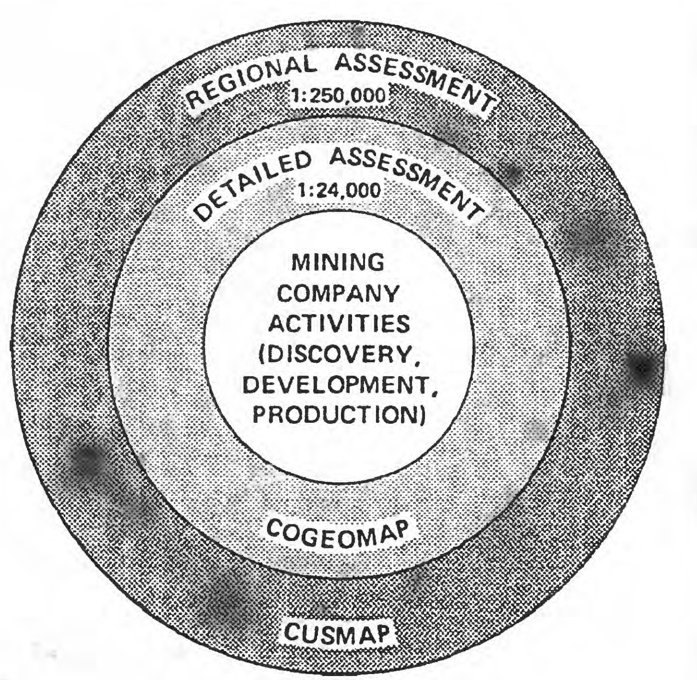

Figure 2.

Diagnostic criteria for the existence of an ore deposit were established for each ore deposit type and weighted with respect to the significance of the criteria. Many ore deposit types that are not yet known to exist in the Paducah Quadrangle were considered by comparing the Illinois Basin and underlying rift system with similar environments on other continents. The forthcoming USGS Bulletin and Open File reports, both by the USGS and the State geological surveys, will provide numerous new data on hypothesized and as yet undiscovered metallic and non-metallic ore deposit types and fuel resources on the Paducah quadrangle. New interpretations of the data by industry users are anticipated.

The purpose of the CUSMAP program is to provide the basic information required to facilitate exploration and evaluation of the mineral resources that form the foundation of our economy (fig. 2). The economy of the region encompassed by the Paducah Quadrangle is currently depressed. Unemployment in the region is significantly higher than in the more industrialized areas of Illinois, Kentucky and Missouri. It is the hope of the U.S.G.S., the Illinois State Geological Survey, the Kentucky Geological Survey, and the Missouri Department of Lands and Geology that CUSMAP data will encourage additional large scale mapping, provide a basis for expanding our knowledge of the resources of the region, and facilitate successful exploration programs. The extent to which the CUSMAP data encourages exploration and evaluation of the mineral resources of the region will be a measure of the success of the program.

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Diagenetic studies of the Mt. Simon Sandstone—Implications for paleohydrology

Neil S. Fishman (USGS)

Preliminary studies of core samples of the Cambrian Mt. Simon Sandstone, Illinois and Indiana, indicate that the sandstone has undergone a complex diagenetic alteration history, which includes precipitation and dissolution of authigenic minerals, dissolution of unstable detrital grains, and compaction. Unraveling the nature and timing of alterations in the Mt. Simon, a thick (up to 2500 ft), widespread unit throughout the Illinois Basin, is crucial to understanding the sources and areal extent of movement of fluids through the basin.

Petrographic observations reveal that numerous authigenic minerals have precipitated in pores of the Mt. Simon. Among these authigenic cements, quartz, as overgrowths on detrital grains, is the most abundant and comprises up to about 20% of the volume of the sandstone. The quartz overgrowths are commonly euhedral but some are also intergrown and appear as interpenetrating overgrowths. Potassium feldspar (K-feldspar) also occurs as an authigenic phase. The K-feldspar is present as both large, euhedral overgrowths on detrital feldspars (both plagioclase and potassium feldspar) and as small rhombs in pores. Authigenic clays in the Mt. Simon appear morphologically and compositionally as illite, as indicated by SEM-EDS analyses. The illitic clays display both "flame-like" (scalloped with curled edges) and "ribbon-like" (fibrous) textures. The two morphologically distinct clays differ compositionally, with the illite ribbons containing iron in addition to potassium, aluminum, and silicon. Additional authigenic minerals observed include iron oxides and minor amounts of carbonates (composition unknown) and pyrite. Other alterations observed in the Mt. Simon include grain compaction, moldic porosity, and partial dissolution of authigenic cements such as carbonate, quartz and K-feldspar.

Paragenetic relations are difficult to establish because of the variability in the presence and/or absence of phases between different cores across the study area as well as variability with depth in an individual core. Some minerals, such as pyrite and iron oxides, appear, where they are present, to have precipitated early in the alteration history of the Mt. Simon; however, there is at least another, later generation of pyrite. Minus-cement porosities (total of porosity + authigenic quartz + authigenic K-feldspar) of up to 26% in the Mt. Simon, as well as textural features (long and concave-convex grain contacts), together suggest that there the sandstone underwent compaction prior to precipitation of the quartz and K-feldspar. Carbonate minerals appear to post-date quartz and K-feldspar overgrowths and the illite coats other authigenic minerals and as such precipitated later in the paragenetic sequence of alterations.

It is interesting to note that detrital feldspar contents in the Mt. Simon can vary markedly between adjacent laminations. This variability appears to control, in places, the presence and abundance of authigenic K-feldspar. It appears that , at least in some parts of the Mt. Simon, a detrital feldspar was required as a nucleation site for authigenic K-feldspar. However, locally, small rhombs of authigenic K-feldspar also precipitated in the absence of a detrital feldspar grain. Paragenetic relations between K-feldspar overgrowths and the small K-feldspar rhombs are uncertain.

Continued efforts will focus on regional and local mapping of the distribution, if any, of diagenetic alterations in the Mt. Simon. Through this work, hypotheses concerning the timing and paleohydrology in the Mt. Simon will be tested.

A Geochemical Cross-Section of the Paducah 1° X 2° Quadrangle

H.A. Folger and M.B. Goldhaber (USGS)

Geochemical logs of the concentrations of five elements, fluorine, barium, strontium, lead, and zinc versus depth were constructed from chemical analysis of acid insoluble residues of rock cuttings from seven drill holes. These holes comprise an east-west transect across the Paducah CUSMAP study area. The geochemical logs were correlated stratigraphically using a structural cross section by Sargent et al. (this volume). Elevated concentrations of each of the five elements were found in four stratigraphic packages. The first package occurs in the Mississippian (St. Genevieve, St. Louis, Salem and Warsaw Formations) which host mineralization of the Illinois-Kentucky fluorspar district. The second is found in the stratigraphic units above the St. Peter Sandstone, Dutchtown, Joachim, Platteville. Rocks of this age host mineralization of the upper Mississippi Valley district at the north end of the Illinois basin. The third occurs in units below the St. Peter Sandstone and includes the Shakopee, Cotter, and Powell Formations of the Upper Knox group. These units host ores in the Central Kentucky and Central Tennessee districts. The fourth occurs in the Cambrian Franconia and Eau Claire Formations equivalent to Bonneterre which host S.E. Missouri lead-zinc districts ores.

Fluorine concentrations which are anomalous when compared to regional background values (ie. >0.1 wt %) are observed in all four stratigraphic packages (fig. 1) and in each case the anomalous values are continuous across the transect. Fluorine concentrations show a slight tendency to increase from east to west toward the Ozark Dome in all horizons below the Mississippian. Barium is present in anomalous levels (>1000 ppm) in the Cambrian Eau Claire Fm on the eastern edge of the transect but decreases as the Ozark Dome is approached. Consistently high barium values also occur above the St. Peter Sandstone with concentrations somewhat lower on the eastern edge of the transect and increasing towards the Ozark dome. Strontium enrichment (values >1000 ppm) is striking in units which straddle the St. Peter Sandstone (the Dutchtown above and the Everton-Shakopee below). These enriched zones occur throughout the transect area. The occurrence of strontium anomalies in the Cambrian section faintly mirrors the behavior of barium with enrichment decreasing toward the Ozark Dome. Lead is enriched in three distinct areas. First, high lead values (>100 ppm) were measured in Cambrian units with an increase up the eastern flank of the Ozark Dome. Second, anomalous concentrations occur in upper and middle Knox Group, just below the Everton unconformity. Values increase toward the west. And third, there is an area of lead enrichment in Devonian limestones below the New Albany shale near the crest of the Tolu Arch. Zinc enrichment (>200 ppm) is minor and generally follows lead.

Clearly, certain strata are favorable to metal enrichment in ore related elements. Two interrelated factors may contribute to this enrichment. These are the presence of favorable host beds in proximity to widespread aquifer horizons. Favorable host beds include limestone units which in the region are known to be reactive toward MVT ore fluids. The widespread distribution of elevated fluorine concentrations is noteworthy. If we assume a source area for fluorine in the area of the Illinois-Kentucky fluorspar district, then the data imply fluorine dispersal for distances of at least 150 km from the source area. We interpret the prominent strontium maxima as indicative of recrystallization of limestone (high in Sr) to dolomite (low in Sr) and the trapping of released Sr as $SrSO_4$ by sulfate-bearing brines. The consistent presence of anomalous concentrations of ore related elements throughout specific stratigraphic packages indicates the extensive regional movement of enriched brines through the Illinois basin along key aquifers. The proximity of the St. Peter Sandstone to overlying Upper and Middle Ordovician units and underlying Everton and Upper Knox units and the proximity of the Mt. Simon Sandstone to the Cambrian stratigraphic package, supports the theory that these sandstones acted as aquifers for transport of the metals and fluorine. Other potential aquifers include the upper Knox unconformity and the sands within the Eau Claire/ Franconia formations.

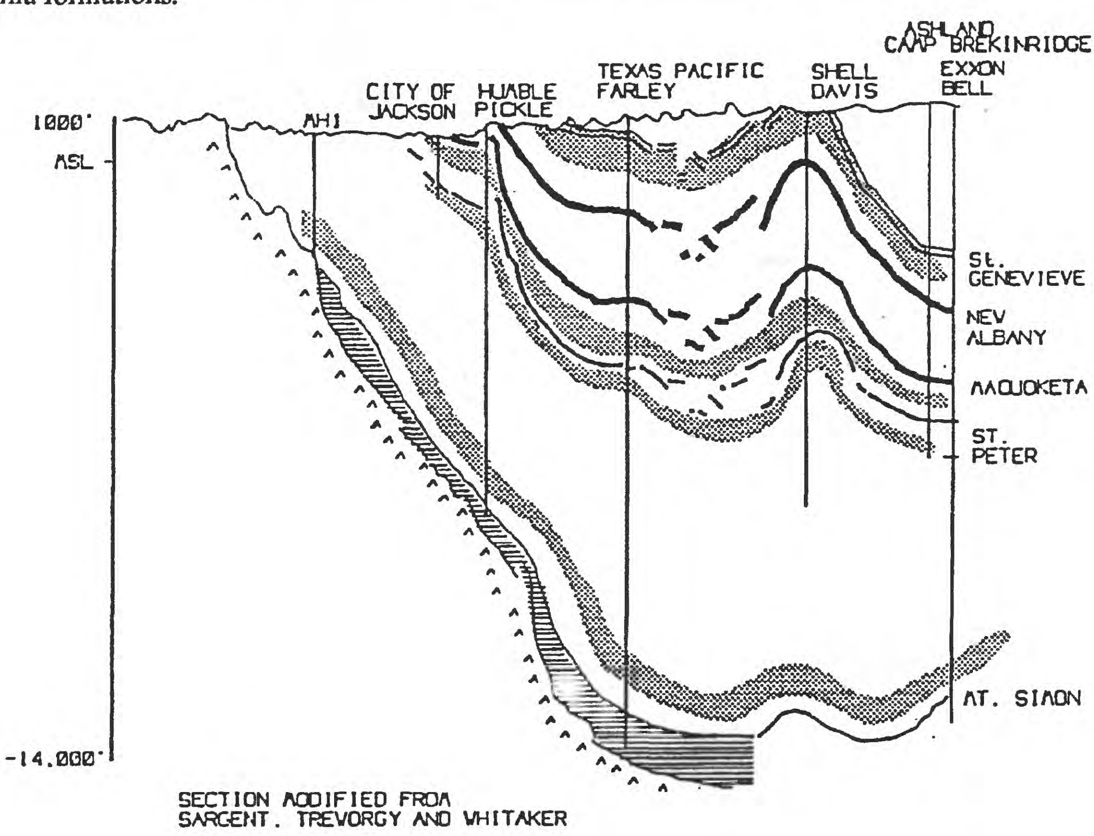

Figure 1. Cross-section showing the four stratigraphic packages (stippled).

Basement Tectonics in the Eastern Illinois Basin and Their Effect on Early Paleozoic Sedimentation

Lloyd C. Furer (IGS)

A unifying regional tectonic working model is proposed as an alternative explanation for several anomalous geologic features that have been observed for many years in the Illinois Basin. Studies are in progress on all deep wells in Indiana to delineate more accurately structural deformation that may have affected the initiation and distribution of some Silurian reefs within the Terre Haute Bank. An estimate of the general location of concealed early Paleozoic faults in Indiana is based on several lines of evidence, including detailed subsurface field studies, reinterpretation of published structure maps, anomalous bedding dips in outcrops, historical earthquake distribution, anomalous thermal events, published gravity/magnetic studies, and limited seismic data.

One model that explains the Silurian data is as follows: In southern Indiana, the northeast-trending basement faults parallel faults of the Wabash Valley Fault System. Movement on these faults has occurred during Paleozoic periods of compression or extension as these faults became reactivated. This fault movement has had subtle effects on the thickness and/or facies distribution of certain lower Paleozoic intervals, including the Cambrian Mount Simon Sandstone, Cambrian Eau Claire Formation, Cambro-Ordovician Knox Supergroup, Ordovician Trenton Limestone, and Ordovician Maquoketa Group. In most cases the faulting occurred in conjunction with the formation of a regional unconformity.

Proterozoic (1.2-1.0 Ga) faulting was a key mechanism in forming the very thick (18,000 ft.; 5487 m) recently recognized Precambrian Basin of Indiana, Ohio, and Kentucky. The basin was formed by plate-margin rifting along a series of very steep northeast-trending faults in the older Precambrian granitic basement. These faults are intersected by a set of northwest-trending basement faults. The location of some individual reefs within the basin-rimming Terre Haute Bank may have been controlled by positive structural features formed by the intersection of this NE and NW conjugate fault system.

Paducah CUSMAP Subsurface Geochemical Studies

Martin B. Goldhaber, Helen A. Folger, Cliff D. Taylor, Elwin L. Mosier, and Carol Gent (USGS), Keith Hackley and Jack Masters (ISGS)

Geochemical investigations have been conducted during the course of the Paducah CUSMAP program on approximately 15,000 samples from 124 drill holes in and adjacent to the 1° X 2° quadrangle and on samples selected to address topical research issues. Acid insoluble residues of Paleozoic carbonate rocks from drill holes were analyzed by semi-quantitative emission spectroscopy for the elements Pb, Zn, Cu, Co, Ni, Mo, As, Ag, Ba, Sr, Be, La, Y, Nb, and Th. Fluorine in the insoluble residues was determined quantitatively by a Na_2CO_3/ZnO fusion-ion selective electrode analytical technique. Measured values were compared to statistically determined anomalous concentrations (Table 1), and the anomalous values summed using the concept of "anomalous metal feet" (AMF) as defined by Erickson et al. (1981). Selected samples were analyzed for stable sulfur isotopes on sulfide and sulfate minerals. The subsurface geochemical studies have identified specific geographic areas and strata strongly enriched in ore-related metallic and non-metallic elements. The topical studies have identified specific processes of hydrothermal ore formation including source(s) of sulfide sulfur.

Deeply buried Upper Cambrian strata (Bonneterre/Eau Claire through Eminence Formations) of the southern Illinois basin are highly enriched in Pb relative to regional background values and, to a lesser extent, in Zn and Ag. Rocks of the same age where more shallowly buried in the vicinity of the Ozark Uplift (in the western portion of the quadrangle), have even more striking Pb, Zn, and Ag anomalies and, in addition, contain high concentrations of Cu, Co, and Mo. Highly anomalous concentrations of F and Ba were not found in the AMF data for Upper Cambrian rocks sampled for this project, although specific narrow stratigraphic horizons contained elevated values (see e.g. Folger and Goldhaber; this volume). Insoluble residues from Lower Ordovician (plus undiferentiated Knox Group) strata in the southwestern area of the quadrangle contain anomalous amounts of Pb, Zn and F.

Table 1
Anomalous Levels of Elements
Used for Paducah CUSMAP Studies
In PPM unless otherwise specified

Ag	1	Mo	10
As	200	Nb	30
Ba	1000	Ni	70
Be	3	Pb	100
Co	30	Sr	1000
Cu	100	Th	100
F	.1 wt %	Y	30
La	70		

Results from the analysis of insoluble residues obtained from Middle and Upper Ordovician strata comprising the interval between the St. Peter Sandstone and Maquoketa Shale indicate two geographic areas that contain high concentrations of Ba, Sr, F, Pb, and Zn. One of these areas is located along and southwest of the St. Genevieve Fault system, and the second is found above the northwestern portion of the Reelfoot Rift (and northern portion of the Rough Creek Graben). A third less intense area of enrichment lies along and to the north of the Cottage Grove Fault system.

Mississippian rocks, as expected, contain high concentrations of F, Pb, Zn, Cu, Ba, and Sr in the Illinois-Kentucky fluorspar district. Anomalous F, Ba and Sr concentrations extend to the east of the fluorspar district in Upper Mississippian rocks and F, Ba, Sr and Cu, to the southwest and to the northeast of the district in Lower Mississippian rocks.

The suite of elements Nb, Y, Be and Th is known from previous work to be present in mineralization associated with the Hicks dome "cryptovolcano". The same suite of elements is in fact dramatically enriched in Middle and Upper Ordovician rocks from one well in the immediate vicinity of Hicks dome, and more widely dispersed in overlying Devonian and Mississippian rocks. This dispersal extends for a distance of 15-20 Km radially away from Hicks dome, and for much greater distances in a broad pattern to the northeast of the dome along the Wabash Valley zone of faults. There is no evidence of a second center for introduction of the "Hicks dome" element suite.

Based on previous CUSMAP studies in carbonate platform areas of the southern mid-continent, widespread enrichment of metallic and other ore-related elements in the acid insoluble residues obtained from carbonate rocks are known to reflect the passage of hydrothermal solutions (Erickson et al. 1981). Based on the large data set for the Paducah quadrangle, migration of hydrothermal solutions was also widespread in the southern Illinois basin. The presence of prominent Pb, Zn, and Ag anomalies in deep basinal sediments implies that hydrothermal solutions circulated to these levels within the Illinois basin but precipitation of trace mineralization was evidently more intense as the solutions rose towards the flanks of the Ozark dome. The data for Middle and Upper Ordovician rocks suggests the importance of major fault systems as influences on hydrothermal flow processes and also implicates the Reelfoot rift as an area of possible hydrothermal fluid upflow. Element dispersal from the area of the Illinois-Kentucky fluorspar district was widespread. This dispersal is traced by the northeasterly enrichment in the elements Nb, Be, La and Th from a "point source" at Hicks dome, and by a similar distribution of F, Ba, Sr and Cu in Lower Mississippian age rocks away from the Fluorspar district.

We have attempted to assess the southern Illinois basin as a flow path for H_2S-bearing fluids by comparing sulfur isotope values measured on epigenetic sulfides (pyrite/marcasite) in drill-holes remote from known mineralization, to published $\delta^{34}S$ values from ore districts. The $\delta^{34}S$ values increase (become heavier) with stratigraphic age, approaching values for evaporate minerals in deeply buried Cambro-Ordovician rocks. We interpret this trend to indicate an increasing proportion of sulfide sulfur was derived from thermochemical (non-bacterial) sulfate reduction which produces isotopically heavy sulfur. The Mississippian hosted Illinois-Kentucky fluorspar district contains isotopically heavier sulfur than unmineralized rocks at the same stratigraphic interval but remote from the district. We interpret this to indicate that a local source of H_2S from thermochemical sulfate reduction forming within the district.

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Assessment of Mississippi Valley–Type Mineralization Examples from the Middle Ordovician Dutchtown Formation

M.B. Goldhaber (USGS), T.S. Hayes (USGS), J.J. Eidel (ISGS), E.J. LaRock (USGS), and M.L. Sargent (ISGS)

Genetic models for Mississippi Valley Type (MVT) ores have been highly refined by recent regional and ore district studies. These advances have been progressively incorporated into CUSMAP mineral assessments in the southern midcontinent (compare Pratt, 1981 and Martin and Pratt, 1991). In the Paducah CUSMAP study, the assessment for MVT mineralization was done digitally using a geographic information systems (GIS) approach (Johnson et al this volume). We utilized a generalized model for genesis of MVT deposits. As an illustration of this process, we present here an application to the Middle Ordovician Dutchtown Formation.

The underlying conceptional model for MVT deposits is based on the notion that ore-forming hydrothermal fluids travel through aquifer units (sandstones or porous dolomitic units) under considerable excess hydrostatic head driven by regional gravity flow systems (Bethke this volume; Hayes and Anderson, this volume). While migrating laterally in these aquifers, the fluids may deposit trace amounts of Pb, Zn, Cu, Co, Ni, As, Mo, Ba, and F (Goldhaber et al. this volume). The ore fluids have a tendency to rise along faults or when no longer confined by impermeable layers (aquitards). Both shales and limestones when sufficiently thick (≥10 feet) constitute aquitards. The rising fluids engender mineralization when they encounter favorable limestone host beds.

Based on this conceptional model, a set of 7 diagnostic criteria were established and given numerical weights. Highest weight was given to the presence of favorable limestone host rocks. As discussed by LaRock et al. (this volume) the Dutchtown contains a sequence of interlayered limestone and dolostone. This sequence was separated into three vertical slices (fig. 1) which were assessed seperately. The upper slice (fig. 2) contains a prominent limestone-dolomite interface (i.e. the 0 limestone isolith) which extends across the northern and west-central Paducah quadrangle.

The presence of an underlying aquifer, the St. Peter sandstone (fig. 1) was considered a favorable factor. Aquifer pinchouts were accorded relatively high favorability because at such locations, hydrothermal fluids would be forced upwards into potential ore host beds. Likewise, edges of aquitard units underlying the upper Dutchtown including limestone beds in the middle and lower Dutchtown were considered favorable. Faults were included as favorable because they might also allow ore fluids to rise locally into contact with favorable host beds.

Geochemical data were incorporated into the model in the form of the summed and contoured "anomalous metal feet" (AMF, see Erickson et al., 1981) of the elements Pb, Zn, Cu, Co, Ni, Ag, As, and Mo; contoured AMF values for F and contoured AMF values for Ba. Highest weight was assigned to data from the Middle and Upper Ordovician, as enrichment of ore-related elements in strata of this age might indicate migration of ore fluids in the target portion of the section. Lower Ordovician and Silurian data received lesser weight. Since domal structures can act to focus fluid flow to specific areas, they were deemed favorable. Trace mineralization both at the surface and in drill holes likewise was taken as an indicator of passage of ore-fluids and added to the model.

After assigning appropriate buffer zones for point and certain areal data the various weighted criteria were analyzed by the GIS approach. Areas showing high potential for mineralization in the upper Dutchtown occur in the Illinois-Kentucky fluorspar district. Moderate potential exists in southern Perry County and northern Cape

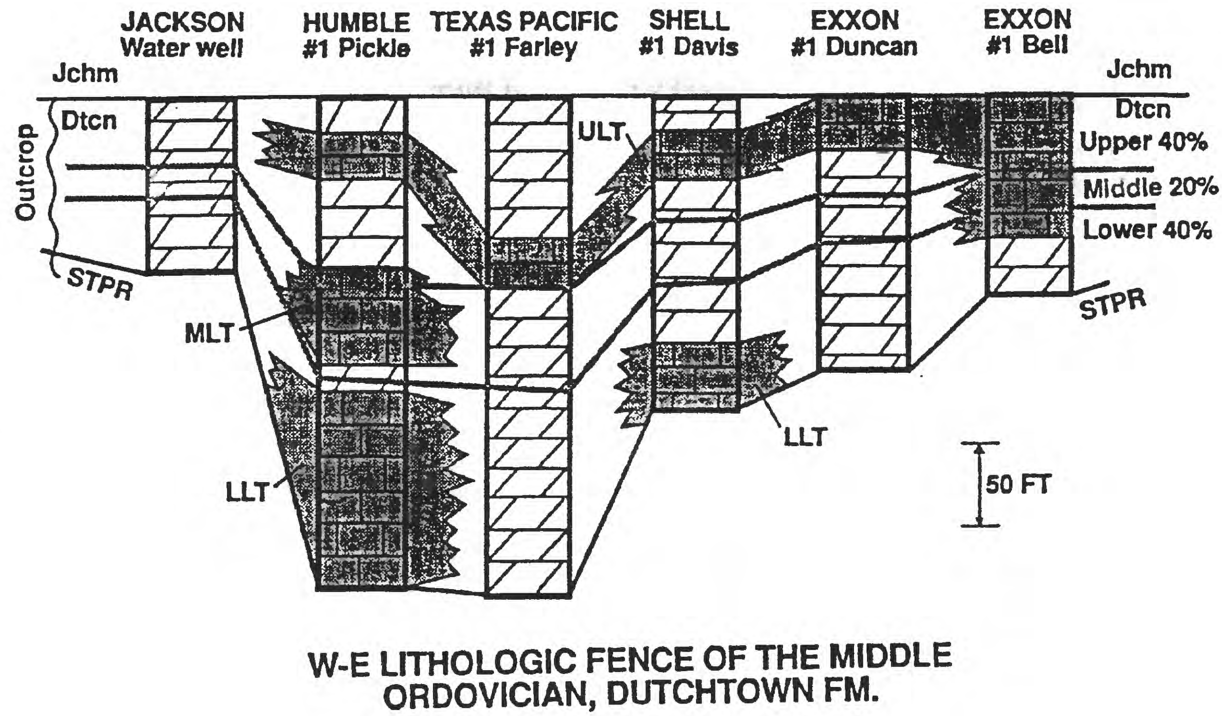

Figure 1. West (left) to east (right) cross section of the Dutchtown (Dtcn) Formation with a datum of the base of the Joachim (Jchm) fomration. STPR is the St. Peter sandstone. Shaded areas show the areas of limestone in the Dutchtown. The light lines show the division of the Dutchtown into the upper (ULT), middle (MLT), and lower (LLT) slices.

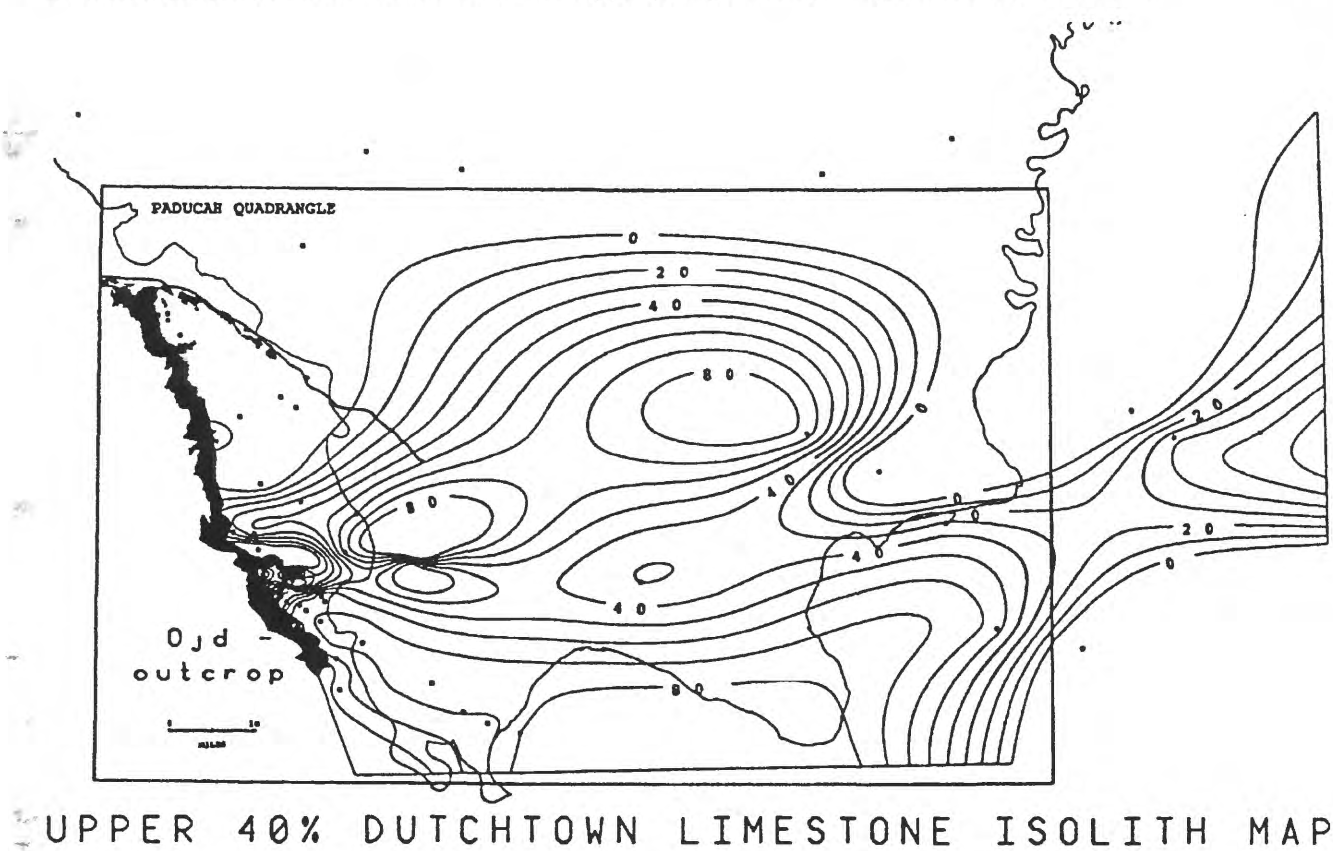

Figure 2. Plan view map showing the contoured thickness of the upper Dutchtown limestone isolith showing the presence of a limestone-dolomite interface (0 limestone thickness) in the east central, northern, and west central portion of the Paducah quadrangle. The pattern labeled Ojd is the outcrop of the Ordovician Joachim and Dutchtown outcrop area.

Girardeau County Missouri. When model runs for the middle and lower Dutchtown are added, the previously mentioned areas continue to be favorable, but additional areas in southern Cape Girardeau County, Missouri, southern Jackson County and northern Williamson County, Illinois, and northern Ballard County, Kentucky, are estimated to have moderate or better potential for Dutchtown hosted MVT mineralization.

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The Illinois Basin Consortium

D.C. Haney (KGS), N.C. Hester (IGS), and M.W. Leighton (ISGS)

The Illinois Basin, covering an area of some 110,000 square miles in parts of Illinois, Indiana, and Kentucky, contains about 120,000 cubic miles of Paleozoic sedimentary rocks that are the source of a wealth of energy, and industrial-metallic mineral resources. To critically assess the resources and adequately define the geologic hazards in this large area, detailed geologic information is required on a basin-wide scale. Recent advances in basin analysis methods together with the advent of computers and the development of extensive computer databases have opened a new era in our understanding of how basins form and evolve. Society requires these data to locate and develop the resources it consumes and to solve the environmental problems that resource consumption can cause.

The acquisition and analysis of data at this scale is a challenge. The ability of any single agency to provide and interpret the data at a time when state and federal budgets are declining is limited. Therefore, the pooling of facilities, equipment and expertise through interagency and industry cooperation has emerged as the most practical means for conducting cost-effective geological research.

In response to the need for more detailed and sophisticated information in a changing financial climate (funding structure), the state geological surveys of Illinois, Indiana, and Kentucky formed the Illinois Basin Consortium (IBC) in 1989. The consortium was organized to advance the geologic understanding of the Illinois Basin through cooperative, integrated basin-wide studies.

The mission of the IBC program is to develop and carry out focused studies that will:

1. establish the geologic framework of the Illinois Basin by completing a series of cross sections to basement that transect state boundaries,
2. formulate geologic models and concepts for basin-forming, basin-filling, and basin-modifying processes,
3. assess the potential for groundwater, coal, oil, natural gas, and industrial minerals resources, and
4. assess basin-wide geologic hazards related to earthquake risks and other environmental concerns.

The member surveys of the IBC have the resources needed to carry out most of the required research. These resources include highly trained earth scientists with a wealth of local experience, support staffs, extensive sample collections, databases and database management systems, computers and software to analyze basic data, well-equipped laboratories, and field equipment, including drilling rigs and seismic and other geophysical instruments.

In order to accomplish the goals and objectives of the IBC, certain data and special expertise are needed from other organizations. The U.S. Geological Survey's program on Evolution of Sedimentary Basins, with its present emphasis on the Illinois Basin, provides an important addition to the goals of this program. Several universities are also involved in specific projects that supplement the overall effort.

The IBC, working in conjunction with the federal government, other state agencies, industry, and academia, is beginning to provide answers to critical questions regarding the basin-wide geology, resources, and hazards of the Illinois Basin. The IBC program plan serves as a guide to the organization and coordination of the IBC effort.

Study of Gas Production Potential of New Albany Shale (Group) in the Illinois Basin

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The New Albany Shale (Devonian and Mississippian) is recognized as both a source rock and a gas-producing reservoir in the Illinois Basin. The first gas discovery was made in 1885, and was followed by the development of several small fields in Harrison County, Indiana, and Meade County, Kentucky. Recently, exploration for and production of New Albany gas has been encouraged by the IRIS Section 29 tax credit. To identify technology gaps that have restricted the development of gas production from the shale gas resource in the basin, the Illinois Basin Consortium (IBC), composed of the Illinois, Indiana, and Kentucky Geological Surveys, is conducting a cooperative research project with the Gas Research Institute (GRI).

An earlier study of the geological and geochemical aspects of the New Albany was conducted during 1976-78 as part of the Eastern Gas Shales Project (EGSP), sponsored by the Department of Energy (DOE). The current IBC/GRI study is designed to update and reinterpret EGSP data and incorporate new data obtained since 1978. During the project, emphasis is being placed on interpreting relationships between gas production and basement structures by constructing cross sections and maps showing thickness, structure, basement features, and thermal maturity. The results of the project will be published in a comprehensive final report in 1992. The information will provide a sound geological basis for ongoing shale-gas research, exploration, and development in the basin.

Regionwide correlation of the hydrothermal paragenesis of the Illinois-Kentucky fluorspar district

Timothy S. Hayes (USGS) and Warren H. Anderson (KGS)

The paragenetic sequence of hydrothermal minerals, found occluding secondary porosity or replacing earlier minerals, is correlatable, deposit to deposit and throughout the country rocks between deposits, over the entire extent of the Illinois-Kentucky fluorspar district and far beyond the district's known boundaries. That sequence is correlatable throughout the entire testable stratigraphic section, and, though there are pronounced differences in relative phase proportions both vertically and laterally, no locations are yet known where the sequence is violated. The regionwide correlatability is interpreted to indicate that each individual deposit and remote occurrence was part of a gigantic-scale interconnected hydrothermal system that probably included both the Central Tennessee zinc district and the Central Kentucky district (fig. 1). Regionwide paragenetic correlation also characterizes Mississippi Valley-type (MVT) districts of the Ozark Region (Hayes et al., 1990) and the Upper Mississippi Valley (Heyl and West, 1982). The Illinois-Kentucky-Central Tennessee MVT paragenetic sequence does not, preliminarily, appear to correlate with the sequence found in MVT's of the bordering Ozark Region.

The value of regionally correlatable mineral sequences is twofold. First, regionwide correlation demonstrates the probable presence of the hydrothermal system in the rocks between known districts thereby predicting new areas favorable for exploration. Second, correlated samples quickly lead to greater understanding of deposit genesis. Individual minerals in the sequence are probably "snapshots" in relative time that may show varying precipitation conditions in space, as has already been shown for fluorites in this system (Richardson and Pinckney,

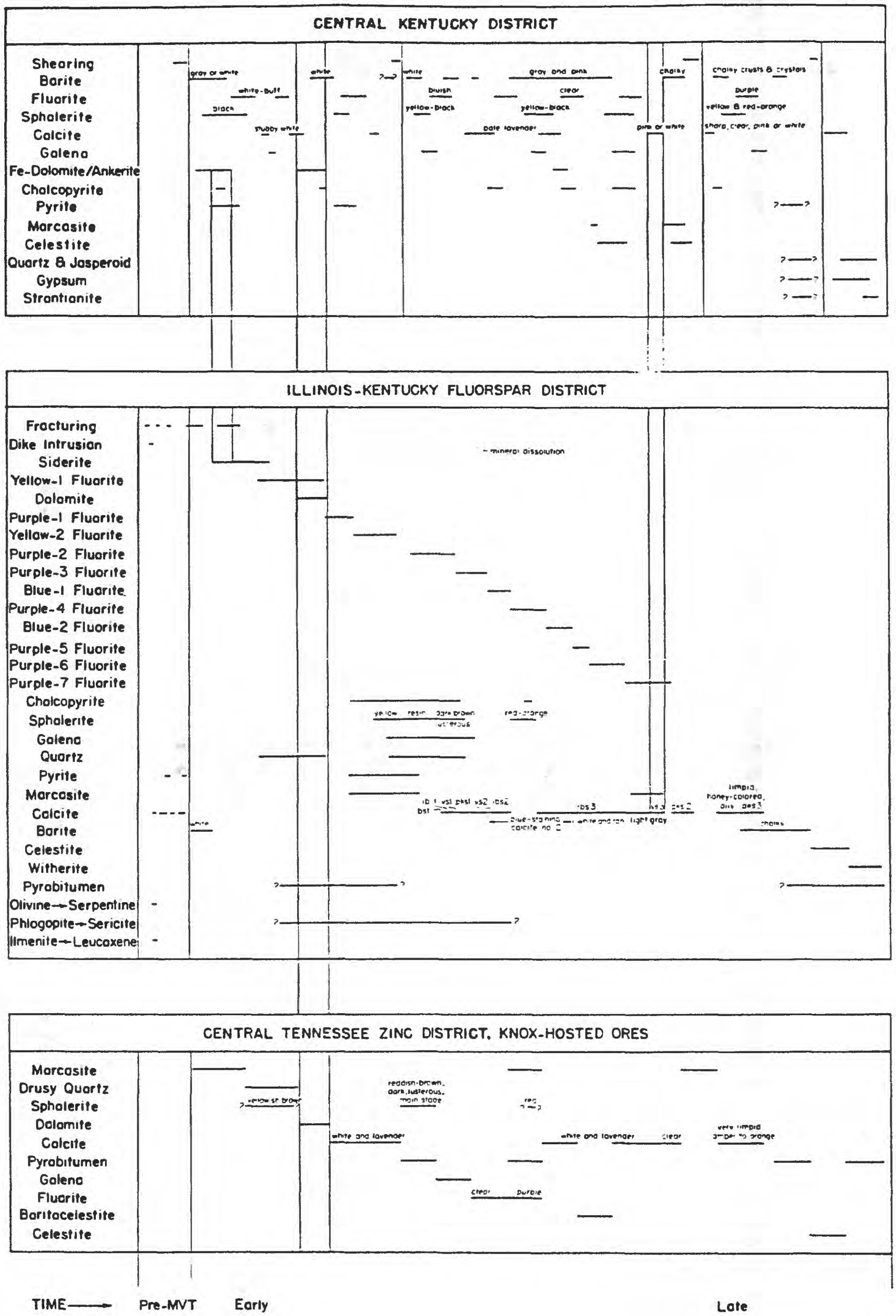

Figure 1. Preliminarily correlated paragenetic diagrams of the Central Kentucky mineral district, the Illinois-Kentucky fluorspar district, and the Central Tennessee zinc district. Correlations in relative time are indicated by vertical bars connecting a mineral stage, district-to-district, and, with less certainty, by vertical alignment of mineral stages. Read abbreviations for the Illinois-Kentucky fluorspar district calcite stages as follows: bs1—blue-staining calcite number 1; lbs1—light-blue-staining calcite number 1; vs1—violet-staining calcite number 1; pks1—pink-staining calcite number 1; etcetera. The diagram for Central Kentucky district is modified from Jolly and Heyl (1964). The diagram for Illinois-Kentucky fluorspar district is partially modified from Richardson and Pinckney (1984) and from Spry et al. (1990). The diagram for Central Tennessee is modified from Gaylord and Briskey (1983).

1984; Rowan et al., in press). Conceptually more valuable, though, are pairs of different minerals, one, an ore mineral from within an orebody, and the other, a paragenetically correlatable non-ore mineral from outside of ore. Detailed geochemical studies of such pairs should indicate reasons for ore deposition versus mere trace mineralization within the regionwide system.

There are several features of the Illinois-Kentucky fluorspar district paragenesis that distinguish it from the Ozark system and make its study worthwile. The Illinois-Kentucky system oscillated between calcite and sulfide/fluorite precipitation, whereas the Ozark system oscillated between dolomite and sulfides (Hayes et al., 1990). Conspicuous iron-rich calcites may distinguish this paragenesis from all others. Fluids that precipitated fluorite or sphalerite ores at some places but only iron-rich calcite at others also altered the phlogopite of the district's mafic igneous rocks to sericite. The MVT mineralization is therefore at least slightly younger than the Early Permian igneous rocks, and isotopic dating of the alteration sericite may absolutely date the MVT system. Outside of ore shoots on veins, and apparently both above and below both vein ore shoots and bedding replacement deposits, the principal hydrothermal minerals of this MVT system were iron-rich calcite and celestian barite. It may have once been that the district had a "bottom" below which only non-econcomic amounts of fluorite and sphalerite were precipitated. Such a "bottom" might have been the bottom of a boiling interval, or it may have been the level below which an upper level aquifer's waters could not penetrate in ore deposition by mixing. Below the ore, main-stage sphalerite appears to have been "displaced" in paragenetic position by pyrite and marcasite, and early yellow fluorite appears to have been "displaced" by quartz. Within ore, the fluorite appears to "displace" paragenetically equivalent calcite from elsewhere outside of ore.

Hydrothermal carbonate minerals of both the Central Tennessee zinc district and the Central Kentucky district appear to correlate with the carbonate sequence of the Illinois-Kentucky fluorspar district (Fig. 1). These districts have early siderite or ankerite; have a single, pre-sphalerite stage of saddle dolomite; and have long, repetitive sequences of calcite precipitation with interspersed fluorites, barites, and sphalerites and with cyclic changes in calcite iron content. All three districts have sphalerites with elevated mercury contents (Jolly and Heyl, 1968), and the regional paragenetic correlation indicates that all of the mercury-anomalous sphalerites may be from a single stage. With the preliminary correlation of the 3 districts' parageneses, it is also preliminarily concluded that all three are part of a single system that may have affected over 35,000 cubic miles of rocks. From its scale, location, and timing, the system was almost certainly an artesian-driven system with a Southern Appalachian recharge. Regionwide correlation is not, however, a denial that a variety of local conditions may have controlled ore deposition within the larger regional hydrothermal system. District to district there may have been quite different causes of ore deposition.

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Mapping Lithologic Criteria for Mineral Deposit Potential Using A Subsurface Lithologic Database Interactive with ARC/INFO

Timothy S. Hayes and Edward J. LaRock (USGS), John Gaines and Cheryl M. Seeger (MGS), Zakaria Lasemi (ISGS), and Wilds W. Olive (KGS)

The Paducah CUSMAP subsurface lithologic database was created to provide data for the mapping of subsurface lithologic criteria used in mineral deposit assessments for sedimentary rock-hosted ores. It was designed especially to aid assessment for Mississippi Valley-type deposits (MVT's). Recent progress in understanding MVT ore depositional processes allowed the Paducah assessment team to summarize sedimentary criteria for MVT's in terms of (1) reactive host rocks—limestones adjacent to any paleoaquifer, (2) paleoaquifers—any porous sandstones or dolostones, and (3) paleoaquitards—shales, poorly permeable limestones, and the crystalline basement. Reactive host rocks are evaluated by mapping lateral limestone-dolostone interfaces in the form of limestone isolith maps within a stratigraphic interval. Paleoaquifers used in MVT fluid migrations are evaluated with isolith maps of sandstones and dolostones within a stratigraphic interval. Paleoaquitards, whose lateral pinchouts allow MVT fluids to escape upwards, are evaluated with shale or limestone isolith maps within a stratigraphic interval.

Whereas, earlier CUSMAP studies mapped sedimentary criteria in a maximum thickness of about 3500 feet (1070 m) of cumulative sedimentary section representing 6 depositional epochs, the Paducah CUSMAP team faced a cumulative section thickness between 14,000 and 19,000 feet (4300-5800 m) representing 14 depositional epochs. Thus, the subsurface lithologic database was created to partially automate the process of mapping lithologies. The existing libraries of drill records available through the state geological surveys of Illinois, Kentucky, and Missouri were used to create products in digital form compatible with other ARC/INFO digital products in a Geographic Information Systems (GIS) assessment of mineral potential.

The Paducah subsurface lithologic database added to the design of an existing stratigraphic database used by the Illinois State Geological Survey. Files were added providing abbreviated alphameric descriptions of major (>33 to 100% by volume), lesser (20 to 49%), and minor (1 to 33%) lithologies for each depth interval in a drillhole. Lithologic files were tied to both drillhole location files and stratigraphic files through a drillhole number and through drilled depths. Each state provided partial coverage of its lithologic drillhole records in digital form beginning with the stratigraphically deepest penetrations and providing additional holes from a 25-mile buffer zone beyond the quadrangle boundaries. Eventually, lithologic logs of 414 drillholes were encoded totalling over 600,000 feet (183,000 m) of lithologic coverage, at least 4-times the footage covered in any previous Midcontinent CUSMAP study.

Sedimentary criteria maps for mineral resource potential evaluations are in progress with around 25 map products completed at this writing. An early test case using only Missouri drillholes to produce a limestone isolith map of the lower half of the Bonneterre Formation of Cambrian age is representative of the application of product maps (Fig. 1). A three-mile buffer zone on both sides of the computer-generated zero-foot isolith of lower Bonneterre limestone includes all (100%) of the known Bonneterre-hosted lead-zinc ore of the Old Lead Belt, yet the buffer zone covers only about one-third of the mapped area. Similar limestone-dolostone maps for the Dutchtown, Joachim, and Kimmswick Formations of Middle Ordovician age reinforce geochemical anomalies

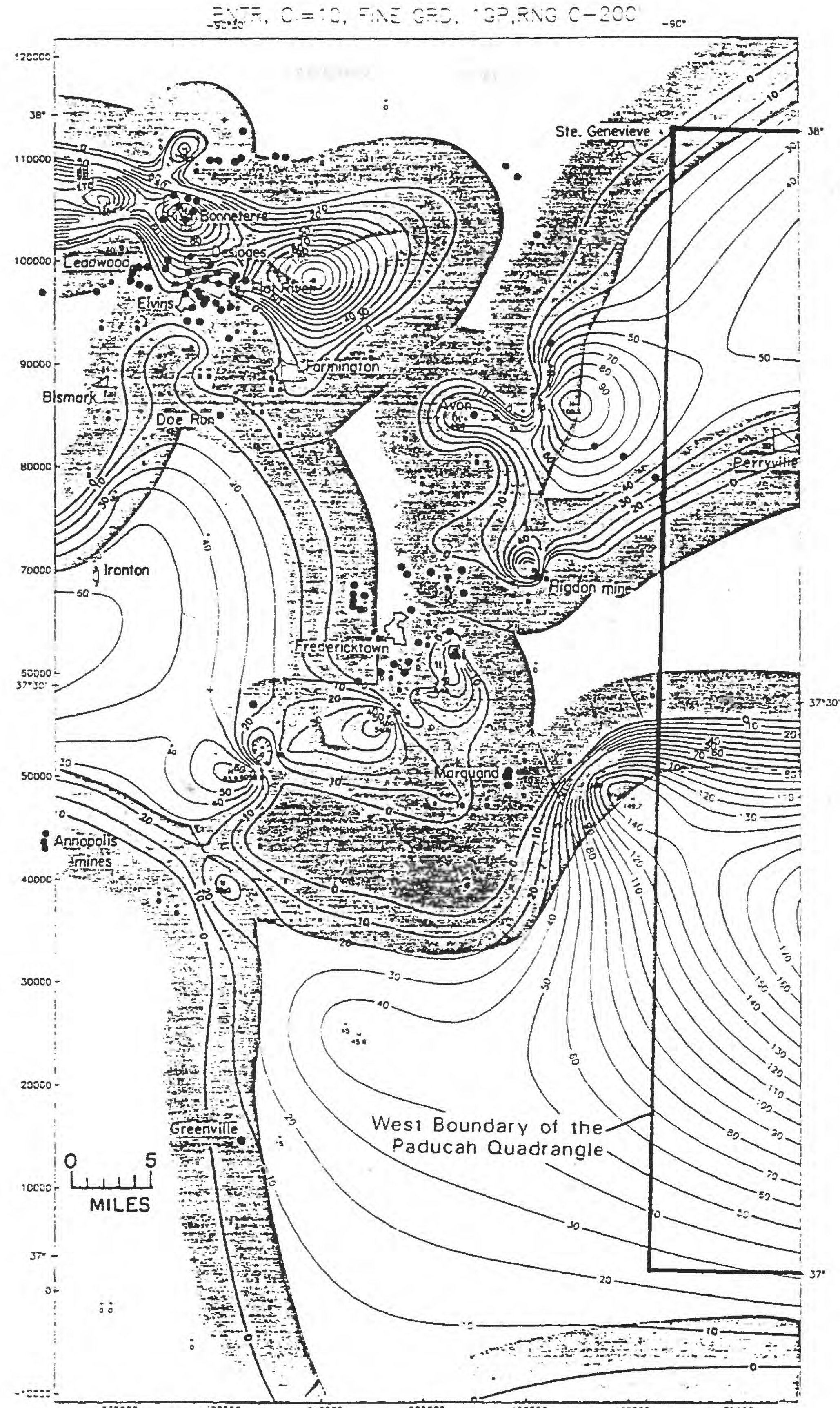
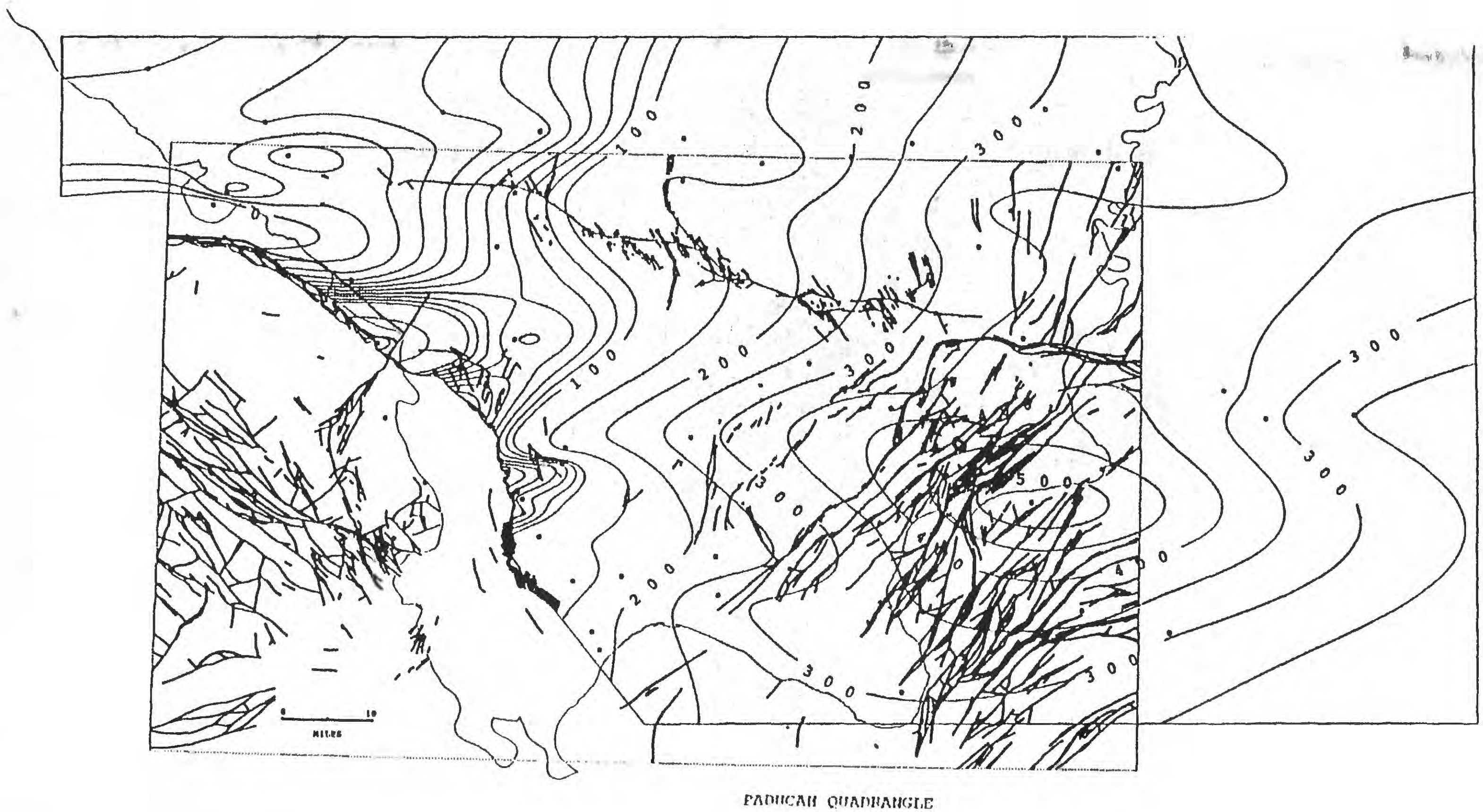


Figure 1. Isolith contour map of limestone thickness, in feet, within the lower half of the Bonneterre Formation of Cambrian age, generated from the Paducah subsurface lithologic database, compared with mine shaft and prospect locations of Mississippi Valley-type Pb-(Cu-Zn-Ag-Co-Ni-barite) deposits (black dots) from Miller (1982). Shaded area is a three-mile buffer zone on both sides of zero-foot contours, that buffer zone enclosing all Bonneterre-hosted lead ores of this test case area.



MIDDLE DEVONIAN-Through-LOWER MISSISSIPPIAN CONTINUOUS SHALE ISOLITH

Figure 2. Isolith contour map of vertically continuous "New Albany" shale thickness, in feet, from the Middle Devonian through Early Mississippian (Kinderhookian) stratigraphic interval, and mapped faults, Paducah 1 X 2-degree Quadrangle. Black dots are drillhole locations, the data points used in contour map generation. Areas of parallelism of contours with the Ste. Genevieve-Rattlesnake Ferry Fault system on the western part of the quadrangle probably indicate synsedimentational faulting. Note the change in contour directions along the southeastward projection of the Ste. Genevieve-Rattlesnake Ferry Fault zone. Discrete contour closures within the map area, taken together with knowledge of New Albany formational subdivision, probably indicate depositional sub-basins. The sub-basins are further evidence of sysedimentary tectonism in the Late Devonian-Early Mississippian.

and known mineral occurrences in suggesting high MVT potential in the western part of the quadrangle in those intervals. Limestone remnants stratigraphically equivalent to the Central and Eastern Tennessee districts' Mascot and Kingsport Formation host rocks of Early Ordovician age are present in the Paducah Quadrangle, trending from the southeastern part to the center.

Database products have also provided some unanticipated looks into the sedimentary tectonics of the southern Illinois Basin. An aquitard isolith map of cumulative continuous shale in the Middle Devonian through Lower Mississippian rock interval, centered on the New Albany Shale Group, clearly shows deposition controlled by the Ste. Genevieve-Rattlesnake Ferry Fault system and likely shows several discrete sub-basins of "New Albany" shale deposition (fig. 2). An isopach map of the Dutchtown Formation gives a clear picture of the margins of the Illinois Basin in Middle Ordovician time and suggests that extensional tectonism accompanied subsidence at the time of the Appalachian region's Taconian orogeny. With the suggestion of active tectonism at this previously unsuspected time, as well as in the Mid-to-Late Cambrian and the Late Devonian, we conclude that sedimentation and extensional tectonism were sporadic, recurrent, interrelated, and tied to events in the Appalachian-Ouachita belt in the early history of the southern Illinois basin.

Production of additional digital maps using the subsurface lithologic database is continuing with many additional stratigraphic intervals remaining to be addressed. Meanwhile, we anticipate that the lithologic database can provide maps of interest for the Illinois Basin-Evolution of Sedimentary Basins project, if areal coverage is extended beyond the Paducah Quadrangle.

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Geologic and structural evolution of the southern Illinois Basin based on potential-field studies

T.G. Hildenbrand and R.P. Kucks (USGS), and P.C. Heigold (ISGS)

Analysis of potential-field data in the southern Illinois Basin area provides a geologic picture of the subsurface that indicates a long and complex tectonic and magmatic history. During middle Proterozoic time (about 1.6 Ga), basement consisted of gneissic rocks with structures expressed as northwest-trending magnetic and gravity anomalies. Some of these structures may have been zones of weakness along which later structures developed, such as a proposed shear zone represented as the south central magnetic lineament (SCML). The SCML is a prominent, linear magnetic feature that trends northwest from eastern Tennessee into Missouri. In the southern Illinois Basin area, the SCML is clearly defined as a 40-km-wide band of magnetic highs that, on the basis of modeling, may reflect large plutons emplaced along the shear zone. Because Keweenawan (1.1 Ga) igneous bodies encountered in drill-holes in eastern Tennessee and Kentucky may be structurally related to this shear zone, emplacement of the intrusions may span an interval from 1.6 to 1.1 Ga.

During early Paleozoic time (about 570 Ma), the breakup of the North American supercontinent resulted in the formation of several aulacogens, which included the Reelfoot rift and Rough Creek graben that trend into the Illinois Basin area. Our preferred interpretation of the relation between these two rifts is that the Reelfoot rift simply bends eastward to merge with the Rough Creek graben. This interpreted bend in the rift may be related to a preferred strain direction or to an obstacle, such as competent, homogeneous batholithic rocks of the nearby St. Francois Mountains. Volcanic activity in the St. Francois Mountains included the emplacement of Precambrian tin-granite plutons. Oval magnetic and gravity lows on the west edge of the Paducah quadrangle probably delineate such plutons.

At the juncture of the rifts, northwest- and northeast-trending faults may have provided channelways for magma. Prominent gravity highs parallel these faults and form the Paducah gravity lineament (PGL). Because these anomalies have sharp corners at intersections of the faults, the associated large intrusions may have been emplaced in a block-faulted region. Strike-slip motion along the northwest-trending faults is indicated by deflections in the southeastern margin of the Reelfoot rift. We propose that northwest-trending faults related to the old (1.6 b.y) gneissic basement were reactivated and intruded by magma. Although the age(s) of the mafic intrusions along the PGL has yet to be determined, the rocks may be Cambrian, Devonian, late Paleozoic, and (or) Cretaceous. These mafic intrusions form a 100-km-wide zone near the axis of the Reelfoot graben and trend northwest for 180 km into eastern Missouri where the zone narrows to 30 km.

The postrifting phase included the accumulation of thick sections of sediment, as evidenced by the deepening of magnetic basement (>6 km) in the Rough Creek graben. Moreover, postrifting igneous events may have emplaced magnetic intrusions along northwest-trending faults in southwestern Illinois and along or near the north-northeast-trending Wabash Valley fault system. Magnetic basement is considerably shallower than Precambrian basement in these two areas.

Other evidence for postrifting intrusion is the subtle, local, shallow-source magnetic highs, enhanced by a high-pass filter. These magnetic highs probably delineate late Paleozoic ultramafic dikes at shallow depths (<1 km). Of particular importance is the observation that positive anomalies coincide with the mineral districts near Omaha Dome, Coefield, and Hicks Dome. For Hicks Dome, these positive anomalies probably reflect mica-periodotite dikes on the flanks of this dome (formed by alkalic to carbonate magmatism). Perhaps some of the other shallow-source positive anomalies delineate shallow intrusions with associated mineralization.

Upper Ordovician Sequence Stratigraphy of the southern Illinois Basin

John Hohman (Indiana University)

Geophysical signatures of wireline well logs, which have been calibrated with geological information from well cuttings and outcrops, were used to delineate two depositional sequences within the Upper Ordovician section in the southern part of the Illinois Basin. These depositional sequences were identified and correlated by tracing a hierarchy of chronostratigraphically significant horizons in the rock record that range from essentially time synchronous marine flooding surfaces to diachronous unconformities. In either case, the horizons are chronostratigraphically significant in that they separate older strata below from younger strata above and thereby partition the section into genetically related subdivisions that place the strata in their proper spatial and temporal positions.

The marine flooding surfaces in the Ordovician section are recognized in the rock record by evidence of a relative increase in water depth during deposition as expressed for example by changes in the lithofacies upward from sandstones and carbonate grainstones to shale. Unconformities, however, are recognized by discontinuities in stratal patterns that can be expressed by either truncation of strata associated with a relative decrease in water depth or onlap of strata associated with a relative increase in water depth. The sequences by definition are bounded by unconformities and internally subdivided by marine flooding surfaces. Within the Upper Ordovician, the Galena Group sequence and Maquoketa Group sequence are recognized. The Galena Group sequence includes the uppermost Champlainian Kimmswick Limestone and Decorah Shale along with their equivalent units. The Maquoketa Group sequence includes the Cincinnattian Cape Limestone, Scales Shale, Thebes Sandstone and Orchard Creek Shale along with their equivalent units.

The depositional sequences and their correlations are illustrated in a grid of cross sections. The most striking feature seen in the cross sections is the lack of lateral continuity of genetically related rock units. This is demonstrated primarily by the eastward pinch out of the Galena Group sequence, the onlap at the base of the Maquoketa Group sequence onto the pre-Galena section and the Galena itself in a east to west direction, and truncation at the top of the Maquoketa Group sequence by pre-Silurian erosion. As a consequence, the Galena Group sequence observed in southeast Missouri and western Illinois outcrops is not encountered in the subsurface to the east in the Illinois Basin because it has thinned to the point of being undistinguishable as a unit. In addition, the part of the Maquoketa Group sequence observed in these same outcrops is irregularly preserved in the subsurface due to local pre-Silurian erosion. Generally, in large areas of the subsurface a stratigraphically lower section of the Maquoketa often comprises the majority of the sequence.

Petrology of Pennsylvanian Sandstones in Southern Illinois and Missouri: Provenance Implications of Vertical and Lateral Variations in Composition

David W. Houseknecht and Gary Wood (University of Missouri)

Pennsylvanian sediment dispersal patterns in the Midcontinent have been well understood since the landmark work performed in the Illinois Basin and adjacent areas during the 1950's. Among the contributions of that research effort was documentation of a stratigraphic gradation in sandstone composition, from "orthoquartzites" at the base of the Pennsylvanian (Morrowan) to "subgraywackes" at the top (Missourian). The upward decrease in quartz content was complemented mostly by an increase in "detrital matrix," along with a modest increase in mica and lithic fragments.

In an attempt to evaluate the composition of sand distributed across the Midcontinent during the Pennsylvanian, we have performed petrographic analyses on 50 sandstone samples from a single core that spans most of the Pennsylvanian System in Williamson County, Illinois (the same core sampled by Potter and Glass, 1958), 57 sandstone samples from 10 relatively shallow cores in north-central and western Missouri, and 14 outcrop samples from Pennsylvanian "channel" sands in north-central and western Missouri.

Framework grain compositions display significant vertical and lateral variations within this sample set. Samples from the southern Illinois core display an abrupt decrease in quartz and increase in metamorphic lithic fragments together with a slight increase in feldspar from the Morrowan to the Desmoinesian (mean Morrowan = $Q_{100}F_0L_0$; mean middle Desmoinesian = $Q_{80}F_3L_{17}$), followed by a small increase in quartz and feldspar together with a decrease in metamorphic lithic fragments upward into the Missourian (mean = $Q_{84}F_7L_{10}$). Although the upward decrease in quartz content has been known since the 1950's, the volumetric importance of metamorphic lithic fragments has not been documented. We suspect that this results from the difficulty in recognizing pelitic metamorphic lithic fragments, many of which have been plastically deformed into "pseudomatrix" during compaction.

The influx of low grade metamorphic detritus into the Illinois Basin indicates derivation of sediment from an uplifted orogenic belt, and the Atokan through Desmoinesian timing suggests the Appalachians as a likely candidate. We propose that sediment derived from the central (or northern) Appalachians may have crossed the Findlay arch and entered the Illinois Basin from the east or northeast. Alternatively, the pelitic metamorphic detritus may have been derived from the Lake Superior region, although an explanation for an abrupt influx of sediment from that source area is lacking.

Westward into Missouri, lateral variations are apparent in Desmoinesian and Missourian sandstones. Although generally similar in framework grain composition to the Illinois samples, Missouri samples consistently contain less quartz and more feldspar and metamorphic lithic fragments. At this time, we do not have an adequate explanation for this lateral variation in composition.

In summary, it appears that the influx of metamorphic detritus into the Midcontinent represents sediment dispersal from the active Appalachian orogenic belt toward the southern margin of the continent, which was itself evolving from a passive margin into an active orogen (Ouachitas).

Diagenesis of the St. Peter Sandstone Along a Traverse from the Ozark Dome into the Deepest Illinois Basin

David W. Houseknecht, Paul E. Stackelberg, and Christoph Spötl (University of Missouri)

St. Peter Sandstone outcrop and core samples from a traverse that extends from the eastern margin of the Ozark Dome to the deepest part of the Illinois Basin provide the opportunity to evaluate depth-dependent diagenetic processes. The samples are spaced at nearly equal depth intervals from 0 to 2.4 km of present burial depth, and correspond to a systematic increase in thermal maturity of the New Albany Shale, which lies 500 to 800 m above the St Peter, from <0.5 to >0.7% vitrinite reflectance.

St Peter samples display various degrees of chemical compaction (intergranular pressure solution), both on local and regional scales. Locally, samples that are relatively fine grained and/or contain illitic grain coatings have undergone more intergranular pressure solution than samples that are relatively coarse grained and/or contain >10% cement precipitated during relatively shallow burial. There is a modest increase in the amount of intergranular pressure solution with increasing depth along the traverse. Significantly, samples from the vicinity of the Wabash Valley fault system, just east of the structural axis of the Illinois Basin, display more intergranular pressure solution than samples analyzed from any other location, including deeper in the basin.

Overall, quartz is the most abundant cement in the St Peter and at least two distinct phases of quartz cementation occurred, evidenced by cathodoluminescence zoning within quartz overgrowths combined with cement stratigraphy. The earlier phase apparently pre-dated most intergranular pressure solution whereas the later phase was either coeval with, or post-dated, most intergranular pressure solution. The volume of quartz cement (particularly the later phase) increases in the deeper part of the basin (>1.5 km depth) in a pattern similar to the increase in chemical compaction, suggesting that intergranular pressure solution in the deep basin may have provided much of the silica for quartz cementation.

The St. Peter also contains carbonate cements in locally variable volumes. Preliminary stable isotope analyses of carbonate cements from the shallow part of the sampling traverse suggest precipitation of early dolomite ($\delta^{18}O$ = -2 to -5‰ PDB; $\delta^{13}C$ = -6 to -9‰ PDB) from non-marine water. Isotopic compositions of later dolomite and calcite cements ($\delta^{18}O$ as light as -10‰ PDB) suggest that the C/O isotopic signature of pore water did not change significantly and can be explained by modest temperature increase associated with stratigraphic burial. These conclusions are consistent with burial reconstructions and observed levels of thermal maturity in younger strata.

Anhydrite is locally present in significant volumes. Cement stratigraphy indicates precipitation at various times during diagenesis, suggesting recurrent remobilization as burial progressed. Other cements present in small volumes include silica grain coatings, K-feldspar overgrowths, halite, illite, and pyrite. Local dissolution of grains and cements has also been documented in some samples.

Taken collectively, these observations suggest that St. Peter diagenesis mostly involved silica redistribution accommodated by chemical compaction and quartz cementation on relatively local scales. Other cements are present in such small volumes that significant mass transport is not suggested.

Assessment of the Clay and Shale Resources of the Paducah Quadrangle

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Absorbent clay from the Porters Creek Formation, currently produced for use in pet litter products, is the major clay resource within the Paducah Quadrangle and has the greatest potential for further development. This clay could be used more extensively in pet litter markets and as a feed pelletizer and agrichemical carrier. The Porters Creek and other clays with a high content of expandable clay minerals such as montmorillonite, mixed-layered illite/smectite, or vermiculite could also be used in constructing covers and barriers in waste disposal facilities or as solidifying absorbents in waste cleanup. High-expandable clay mineral resources include some Quaternary lacustrine deposits, Quaternary accretion gleys or clay-rich soils, some clays in the McNairy Formation, and gley-type coal underclays (mostly below the Illinois Herrin (No. 6) and Springfield (No. 5) Coals).

Surficial materials such as loess and non-calcareous lacustrine deposits; ball clays in the Claiborne, Wilcox, and McNairy Formations; Pennsylvanian underclays and shales; pre-Pennsylvanian shales; coal cleaning wastes; Anna ball clays, and hydrothermal clays such as at the Clay Diggings site can be used to produce various fired-clay products. The quality and value of fired products ranges from low for surficial materials to moderately high for ball clays, kaolinitic Pennsylvanian underclays, and coal cleaning wastes. The kaolinitic underclays are mainly those found below the Illinois Colchester (No. 2) Coal. Most of the clays with potential as fired-clay products could also be used for flux in cement making and some would contain sufficient kaolin to produce high-strength cement.

The need for clay-bearing materials to impound wastes is growing. This growth should add to the value of fine-grained materials in lacustrine deposits, expandables-rich facies of the McNairy Formation, and gley-type underclays. However, the overall prospect for new clay products industries in southern Illinois is low, partly because of low-grade resources and partly due to market factors such as distance from major cities, lack of low-cost fuel, and competition from the nearby Kentucky ball clay district. This district stretches from northern Mississippi through Tennessee and has its northernmost boundary near the southern edge of the Paducah Quadrangle in Kentucky. Mitigating factors favoring development of clay resources in the Paducah Quadrangle include low land and labor costs, potential for use of coal and captive natural gas to fire kilns and calciners, and transportation savings to some nearby metropolitan markets.

Waste materials represent possible byproduct opportunities. Moderately large tonnages of Porters Creek are left unmined due to color or unacceptably low absorbent properties, and most coal cleaning plants reject kaolinite-rich waste. The former might be physically processed and/or chemically modified to produce a fine-grained absorbent clay for agribusiness, and the latter for synthetic zeolites for markets such as removal of toxic metals from waste water, detergent builders, ammonium fertilizer carriers, catalysts, and many more products in a wide range of industries.

Assessments, using the ISGS-USGS Geographical Information System (GIS) have been made on four models: (1) absorbent clay, (2) ball clay, (3) underclays and shales, and (4) lacustrine clays. The diagnostic criteria utilized for each of the four clay models include: (1) distribution of potential sources (host rock); (2) location of mines, prospects, and informational outcrops and drill holes; and (3) overburden thickness. The diagnostic criteria for each clay model were weighted and analyzed using the GIS system. Areas of high-, medium-, and low clay mineral potential were derived from the sums of the weighted criteria.

The areas of high or moderate potential are described in the following paragraph. The surficial materials of highest potential are located in extensive Pleistocene lacustrine deposits that occur across much of the northern half of the quadrangle near the Mississippi and Ohio Rivers. Accretion gleys are typically thick on topographically low surfaces on Illinoian tills. The Wilcox and Claiborne Formations occur only in southernmost Illinois, west of Paducah in Kentucky, and in southeasternmost Missouri. Porters Creek clays are located in extreme southern Illinois, the central part of Kentucky, and in the southeastern part of Missouri. The McNairy Formation occurs across far southern Illinois, the northcentral part of Kentucky, and in Missouri as the oldest embayment deposit along the southwest-northeast line of the contact between embayment and Paleozoic deposits. Outliers of McNairy and equivalents lie east and northeast of its outcrop in Kentucky and north and northwest of its outcrop in Missouri. Thick Pennsylvanian shales are near the surface throughout Illinois, Indiana, and Kentucky on the northern half of the quadrangle. The most promising fireclay zone in the Pennsylvanian occurs below the Illinois Colchester (No. 2) Coal and its equivalent in Kentucky. In the western part of the quadrangle in Illinois, this fireclay zone includes the underclay of the Colchester Coal and the Cheltenham Formation. Several Mississippian shales and the New Albany and Maquoketa Group shales are accessible south of the Pennsylvanian outcrop line in Illinois and Kentucky, and in the northern three-fourths of the Missouri area included within the quadrangle.

Origin of Shallow Saline Groundwater in the Central and Southern Illinois Basin

Hue-Hwa Hwang (ISGS, University of Illinois)

The genesis of shallow, saline groundwaters and the relationship between those groundwaters and deep, sedimentary basin brines are poorly understood. In the south-central Illinois Basin, the occurrence of shallow, saline groundwater and deep basin brines provide us with a good opportunity for investigating the chemical and isotopic evolution of brines and groundwaters. The objectives of this study are to investigate (1) the chemical composition of the saline near-surface groundwater in south-central Illinois ; (2) vertical and lateral changes in the isotopic and chemical composition of shallow groundwater, (3) the source of the salinity in groundwater, in particular, the relationship between shallow saline groundwater and deep basinal brines, (4) the meteoric recharge rate of shallow aquifers, and (5) effects of water/rock interactions on groundwater chemistry.

The high salinity of formation waters in the Illinois basin has been ascribed to three processes: membrane filtration, entrapment of hypersaline connate waters, and halite dissolution. The Na, K, Ca, Mg and Cl concentration of brines in the Illinois Basin increase with depth. This phenomenon is most significant in Pennsylvanian and Mississippian units. These changes in brine composition with depth suggest an evolutionary trend which reflects the interaction of the shallow groundwater and deep brines. Previous studies of other basins suggest that the source of the salinity in shallow groundwaters could be the upward advection of basin fluids or the upward diffusion of the ions from those fluids.

I report here preliminary chemical and isotope results on fifteen shallow groundwaters from Cumberland, Fayette, Franklin, Hamilton, Jasper, Moultrie, Richland, and Shelby counties in south-central Illinois that were collected in July and August, 1991. The samples were collected from wells at depths of 20 to 330 ft. Total dissolved solids (TDS) range from 150 to 9500 mg/L and tend to increase with depth, although samples from some of the deeper wells are rather dilute (TDS < 2000 mg/L). Na and Cl are the most abundant species in the more saline groundwaters, and the Na/Cl ratio in these waters (0.50) is the same as that in Illinois Basin brines. However, in five of the water samples, sulfate is the dominant anion ($SO_4/Cl = 1 - 77$). These high-sulfate waters are also characterized by relatively high Ca and Mg concentrations and low Na concentrations compared to Na-Cl saline groundwaters. High-sulfate groundwaters have been reported elsewhere in south-central Illinois. Although the source of the "excess" sulfate has not been determined, my preliminary results suggest the dissolution of Ca-Mg sulfates in the aquifers.

Radiocarbon assays on seven of the water samples range from 0.2 to 53.27 PMC (percent of modern carbon). The 5 "older" samples are from well of 40 to 265 ft in depth. $\delta^{13}C$ values of total dissolved carbonates on seven of the waters range from -14.4 to +3.2 permil (PDB). The carbon isotopic compositions of most samples (-14.4 to -7.3) indicate that dissolved carbonate was derived from variable proportions of soil- produced CO_2 and marine carbonate. Two waters with the high $\delta^{13}C$ values (+3.2 to -2.7) contain appreciable methane (~ 80 % of total dissolved gases), suggesting that isotope effects associated with methanogenesis are responsible to the high $\delta^{13}C$ value of dissolved carbonate.

The hydrogen and oxygen isotopic compositions of the groundwater ($\delta D = -51$ to -37 permil and $\delta^{18}O = -7.1$ to -5.7 permil) lie on the "meteoric water line". The composition of these waters also plot on or slightly above the intersection of the δD - $\delta^{18}O$ trend of Illinois basin brines with the meteoric water line. Similarly, on a plot of δD versus Cl^-, saline groundwaters from Pennsylvanian aquifers and brines from deeper Paleozoic units form a broad, linear trend. This evidence suggests that saline groundwater in south-central Illinois is the mixing product of modern recharge waters with deep, basinal brine. Moreover my preliminary results imply that variations in the chemical and isotopic compositions of brines in the Illinois basin are due to dilution of the brines with waters having isotopic compositions essentially the same as modern groundwaters. Additional analyses of groundwater and brines will be needed to test these preliminary conclusions.

Digital mineral deposit models and Geographic Information Systems as resource assessment tools

Bruce R. Johnson (USGS), Robert R. Pool (ISGS), Gregory N. Green (USGS), and Barbara J. Stiff (University of Illinois)

During the initial stages of the Paducah CUSMAP project, it became apparent that there were a large number of mineral deposit types contained in the Paducah Quadrangle. To accommodate detailed analysis and deposit modeling, the project team decided to use computerized Geographic Information System (GIS) technology. The goal was to translate all available data into digital format and to use a GIS to map areas of relatively high and low mineral potential for each mineral deposit type. Techniques were developed for digitizing and translating numerous data types into a GIS-compatible format. ARC/INFO was selected as the GIS software for this project. Both the U.S. Geological Survey (USGS) and the Illinois State Geological Survey (ISGS) had experienced personnel and access to the software.

To produce a map depicting areas of relatively high and low mineral potential from the raw data sets, a digital mineral deposit model was created for each mineral deposit type. These digital models were created from descriptive deposit models, a process requiring quantification of numerous imprecise criteria used to describe ore deposits. For example, faults of various kinds are believed to be an important factor controlling the location of several types of mineral deposits. Descriptive models contain statements about the importance of proximity to faults. In applying GIS analytical tools to the digital fault map, the concept of proximity was quantified using a buffering process. Mineral deposit experts selected the distance from a fault that constituted "near" and determined the significance of proximity to a fault in comparison with other factors in the model. In many cases, several "proximity to fault" areas were created at various distances from the fault; narrow buffer zones were judged more important than broader areas. Similar approaches relying on expert opinion were used in weighing the relative importance of various types of criteria from the descriptive models; for example, permissive criteria, necessary criteria, and critical criteria are included in many descriptive models.

During the process of creating quantified, digital models from the descriptive models, it became apparent that a numeric weighting scheme was needed to reflect the relative importance of individual criteria. The weighting process involves selecting the most important diagnostic criterion (necessary for the occurrence of the mineral deposit being considered) and assigning its presence an arbitrary weight of 10. Each of the other criteria are then assigned weights relative to their individual importance in the model. Weights can be negative as well as positive. Weighted criteria can then be combined using numeric and Boolean operators. The models commonly have at least two levels of weighted criteria. The first level, or the major criteria, might include: (1) the presence of suitable host rocks, (2) the presence of suitable structures for passage of mineralizing fluids, (3) the proximity to known mineral deposits of the appropriate type, and (4) the existence of geochemical anomalies. Each of these primary criteria can be composed of a combination of any number of individual-criterion data layers. The original, raw data layers are commonly pre-processed by some combination of contouring and buffering to create the individual-criterion data layers. When all of the layers of a deposit model are combined using GIS overlay techniques, areas of higher and lower undiscovered mineral occurrence potential can be drawn based on the total model weight assigned to each area.

A number of problems were encountered in the process of applying this procedure to the Paducah Quadrangle. The first and probably the most difficult is that mineral deposits occur within the earth's crust, not only on its surface. Unfortunately, the GIS in use is fundamentally a two-dimensional system. Where the data were available, the models were divided into stratigraphic layers and each layer was treated as an individual deposit model.

In some instances, we did not have the data necessary for a full evaluation of a deposit model. Some types of data were not collected for this study (for example, surface geochemistry) and others had poor areal distribution. Areas of the quadrangle that have sparse data necessarily lack detail in the final assessment maps. The question of the model's reliability is multi-dimensional. There are uncertainties in contoured data sets based on the irregular distribution of drill holes and the variable quality of analyses from individual drill sites. The reliability of the bedrock geology map decreases in areas of thick drift where it is based on the density and quality of well control and geologic intuition. The uncertainty for each data layer is difficult to quantify and, after combining several layers, the problem of evaluating reliability becomes still more difficult. If it were possible to quantify the reliability of each data layer, then a weighted error model could be created.

The benefits of using a GIS for mineral resource assessment are many. The data sets and models are easily improved as new data become available, and they contribute to other spatial studies in this region. The GIS maintains a detailed history of each model that contains the sum of the criteria and the name and weight of each contributing criteria, which can be reviewed for any area of the map. Finally, GIS techniques offer a better method of easily visualizing and therefore understanding the complexity of the digital models and the underlying data sets.

The purpose of the assessment maps is to highlight areas which may have potential mineral resources, in other words, areas which are good targets for future research and exploration. Given the inherent uncertainties in the available information, there can be no guarantee that a designated area contains a commercially viable mineral deposit.

Determination of the Limits of Mid-Continental Brine Flow by Sulfur Isotopes from Mississippi Valley-Type Deposits

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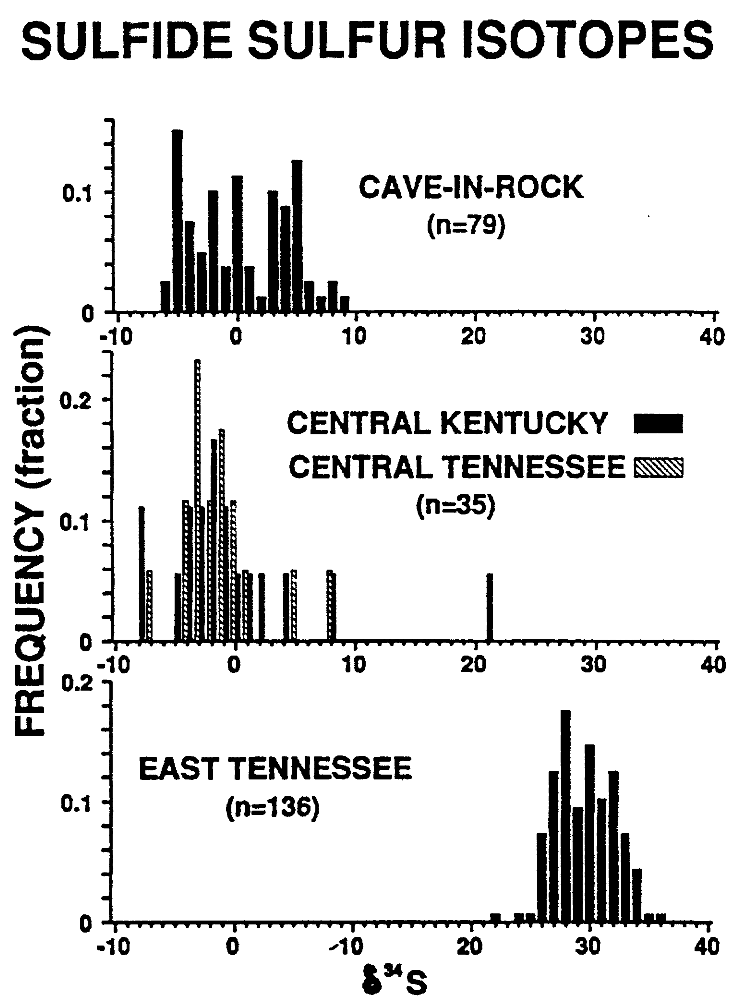
Mississippi Valley-type (MVT) deposits formed from basinal brines in many locations in the central and eastern United States, and the chemistry of their minerals and mineral fluid inclusions can be used to examine large-scale flow patterns of the mineralizing brines. We report here sulfide sulfur isotope compositions at sites ranging from the Cave-in-Rock (CIR) MVT district at the southern end of the Illinois basin, to the large MVT districts in the Valley and Ridge province of the Appalachians in east Tennessee (ET). On the basis of sulfur isotopes, we have delineated a possible boundary between regions inundated by basinal fluids from the west (possibly either Illinois basin brines or more southerly-sourced brines expelled during the Ouachita orogeny), and those mineralized by fluids from Appalachian-related basin(s) to the east.



The CIR district consists of several bedded replacement fluorspar deposits, hosted in the Downeys Bluff and Ste. Genevieve limestone formations (Mississippian). The deposits also contain moderate amounts of sphalerite, galena, and barite. To the south, in Kentucky, mineralization similar to that at CIR occurs in a few veins. Sulfides from throughout this area have $\delta^{34}S$ values ranging from about -6 to +10 per mil. This range does not uniquely constrain the origin or history of the sulfur, but is compatible with reduction of seawater sulfate in basinal fluids.

In both central Kentucky (CK) and central Tennessee (CT), MVT mineralization occurs primarily in veins above structural highs on the Cincinnati arch (the Lexington dome in CK, and the Nashville dome in CT). While some veins extend up into units as young as Mississippian, the probable aquifer for the region is the lower Ordovician upper Knox group, a carbonate (locally massively dolomitized) unit that was karstified during development of the overlying widespread Knox unconformity. Some of the larger deposits in CT are in stratabound breccias within the upper Knox. Sulfides from throughout this region have $\delta^{34}S$ values that range between -8 and about +3 per mil, with a few heavier values.

Mineralization in the 3 large MVT districts in ET is hosted entirely within the upper Knox group. In contrast to CT and CK, all ET sulfides have unusually high $\delta^{34}S$ values, generally ranging between +25 and +35 per mil. The inferred sulfur source is upper Precambrian-Lower Cambrian seawater sulfate, reduced to completion under closed conditions prior to sulfide precipitation. Basinal sedimentary units of that age were available to provide fluids during Appalachian tectonically-driven fluid expulsion events.

The vast difference in sulfide $\delta^{34}S$ values requires that ET mineralization did not form under the same conditions as sulfides in CT and CK. In contrast, the similar sulfur isotopic compositions at CT and CK suggest that both regions were part of one fluid system. Furthermore, the similarity of the sulfur isotopic compositions in both CT and CK with that of CIR, and even of the Tri-state district ($\delta^{34}S$ of about -10 to 0 per mil), suggests that mineralization in CT and CK may have formed from fluids sourced from the west, rather than from Appalachian basins as has sometimes been assumed. One possible conduit for fluids is the Rough Creek-Shawneetown fault system, which extends from the CIR region to the Lexington dome, and could have facilitated brine movement across that distance.

Evolution of the Illinois Basin

Dennis R. Kolata and W. John Nelson (ISGS)

The Illinois Basin is one of the major interior cratonic basins of North America, covering an area of approximately 110,000 mi^2 (285,000 km^2) in Illinois, Indiana, and Kentucky. It comprises about 120,000 mi^3 (500,000 km^3) of Paleozoic rocks containing a wealth of resources, including coal, oil and gas, ground water, and industrial minerals and metals.

The origin and evolution of the basin are closely related to the development of the Reelfoot rift and Rough Creek graben, a failed rift situated at the south end of the basin. The rift system formed during breakup of a supercontinent, apparently during late Precambrian to Early Cambrian time. Lithospheric extension within the rift system resulted in tensional block faulting and relatively rapid subsidence and sedimentation. By Late Cambrian the tectonic setting changed from a rift basin to a broad cratonic embayment centered over the rift. During the remainder of the Paleozoic Era, the proto-Illinois basin was a broad trough extending from the continental margin in central Arkansas northward through Illinois, Indiana, and western Kentucky. Sedimentation during the Paleozoic was dominated by deposition of carbonates and to a lesser extent by sandstone, shale and siltstone. Total Basin fill, after Pennsylvanian rocks were deposited, exceeded thicknesses of 20,000 ft (6,000 m) in the Rough Creek graben area of southern Illinois and western Kentucky and probably was even thicker within the Reelfoot rift. Structural deformation in the basin began during Mississippian time, concurrent with the initial accretion of continents that later formed the Pangea supercontinent. Compressional stresses emanating from the Allegheny and Ouachita orogenies were transmitted to the continental interior, reactivating faults within the Reelfoot rift and Rough Creek graben, and causing uplift of basement-block structures throughout the Illinois Basin. The compressional stress reactivated the ancient rift-bounding faults, upthrusting the northern edge of a crustal block within the rift approximately 1000 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.

The compressional phase was followed by a post-Early Permian episode of extension that apparently coincided with the breakup of Pangea. Tensional stresses reactivated faults within and adjacent to the Reelfoot rift and Rough Creek graben including the Fluorspar area fault complex (FAFC). Mineralization in the FAFC post-dates initial movements on the host faults, which displace and hence post-date the Early Permian dikes. Petroleum occurs in fluorite fluid inclusions and as seeps and coatings in fluorspar mines, indicating that hydrocarbons migrated through the FAFC during and after mineralization.

Post-Pennsylvanian, pre-Late Cretaceous uplift in the area of the Reelfoot rift structurally closed the southern end of the Illinois basin, creating the present basin geometry. By the end of the Mesozoic Era, this uplift had been beveled and overlapped by Late Cretaceous and early Tertiary rocks of the Mississippi Embayment. The midcontinent region, including the Illinois Basin, is presently experiencing east-west compressive stress that apparently is reactivating faults within the southern part of the basin, particularly in the Reelfoot Rift.

Subsurface Lithologic Mapping for Mineral Resource Potential Assessment of the Paducah CUSMAP Quadrangle

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Subsurface isopach and isolith maps were prepared for various Cambrian, Ordovician, and Devonian lithologic units determined to be potential host rocks, aquifers, or aquitards for Mississippi Valley type (MVT) mineralizing fluids in the Paducah CUSMAP quadrangle in the Southern Illinois Basin. Subsurface data from drillhole lithologic logs used to produce the maps were contained in INFO databases provided by the State geological surveys of Illinois, Missouri, and Kentucky. No outcrop measured sections were used. Data were selected for the stratigraphic interval of interest, edited, and run through the Interactive Surface Modelling program (ISM version 7.0) to generate formation isopach maps and limestone, dolostone, sandstone, or shale isolith maps. The contour data were then taken into ARC/INFO for preparation of final maps for Geographic Information Systems (GIS) mineral resource potential assessment. The computer approach provided objective mapping of isopach and isolith zero-edges between the sparse well control. The maps were then subjectively reviewed to correct any anomalies that were in conflict with the known subsurface geology. Outcrops of the mapped units and the northernmost faults of the Sainte Genevieve fault zone were added to the final maps to remove artificial contouring from areas where the units are missing by erosion and/or faulting. Some units, such as the Champlainian Dutchtown Formation and the Canadian upper Knox Megagroup, required pre-mapping regional correlation using lithologic drillhole fences to subdivide the units where more than one host rock layer was present or to determine equivalent units across the area. The poster shows the steps used to produce the final map of the Champlainian St. Peter Sandstone isolith and displays particular products, such as the Dutchtown Formation limestone isolith maps and the Knox Megagroup lithologic fence and limestone isolith maps.

The Dutchtown Formation is a complex of interlayered limestone and dolostone. The relationships between these lithologies could not be adequately represented by gross limestone and dolostone isolith maps of the entire Dutchtown section. Therefore, the Dutchtown was split into an upper 40%-of-total-thickness slice, a middle 20% slice, and a lower 40% slice based on lithologic drillhole fences connecting available well control to limit one limestone layer zero-edge per slice. The displayed limestone isolith maps present a clearer view of the complex distribution of potential limestone host rocks for MVT mineralization in the Dutchtown, particularly in the western part of the Paducah quadrangle.

The upper Knox Megagroup contains limestone intervals in six drillholes of the Paducah quadrangle. These limestones were mapped across the Paducah quadrangle using the formation terminology of Missouri. A regional lithologic drillhole fence was constructed to correlate Missouri terminology into wells in Illinois and Kentucky. Sandstone intervals representing the Roubidoux Formation and Gunter Sandstone could be correlated across the

Paducah quadrangle and allowed assignment of upper Knox limestones to specific formations using Missouri terminology. Limestone isolith maps of the Powell, Cotter/Jefferson City, and Gasconade Formations are presented. The Powell limestone isolith indicates a limestone zero-edge that may have potential for MVT mineralization near the outcrop area in the southwest corner of the Paducah quadrangle. The presence of more than 1000 feet of limestone in the Cotter/Jefferson City Formations and the trend of the isoliths to the south and southeast indicate correlation with the Mascot Formation limestone host rocks of the Central Tennessee MVT district. Limestones of the Cotter/Jefferson City and Gasconade may be potential hosts for MVT mineralization but are at depths in excess of 3000 feet where they are present beneath the Paducah quadrangle.

Modeling Fluid Flow and Brine Diagenesis in the Illinois Basin

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We use quantitative modeling techniques to study the origin of authigenic dolomite and K-feldspar cements found in deep aquifers and along the northern margin of the Illinois basin. Previous studies suggest that these cements formed when saline brines migrated through host rocks long after the rocks were deposited. The hydrologic system within which the brine migrated, as well as the transport and reaction processes that localized the cements remain poorly understood. In this study, we predict the rates of mass transport and diagenetic reaction that likely accompanied fluid migration in the basin, providing quantitative constraints on the duration and degree of diagenetic alteration.

We incorporate into a transient model of groundwater flow equations that describe heat transfer, solute transport, and chemical reaction of brine with sediment. The equations predict flow rates, the temperatures and salinities of migrating fluids, and the rates at which minerals dissolve and precipitate in basin strata through time. We apply the model to study the hydrologic and diagenetic consequences of uplift in the southern basin during the late Permian or Mesozoic.

Brines ascended northward from deep strata at rates of m/yr in our hydrologic model results, cooling from about 250 to 25°C over the flow paths of several hundred km. As brines cooled, our geochemical model indicates that, they reacted to form dolomite and K-feldspar at the expense of quartz, calcite, muscovite, and smectite. Reaction was most intensive at temperatures above 100°C, which agrees well with the results of fluid inclusion analyses.

The duration of brine diagenesis in the deep aquifers likely reflects the time interval over which warm brines migrated onto the basin's northern margin. According to the calculation, dolomite and K-feldspar precipitated in clastic and carbonate aquifers at rate as much as about 4 and 15 vol% per m.y., respectively. Late dolomite cements occupy up to about 2% of carbonate strata in the northern basin today. According to the model results, reaction over a period of about a half million years is needed to account for the volume of late dolomite in the basin. This interval agrees with a study of zinc distribution in carbonate rocks which suggests that mineralization in the Upper Mississippi Valley District formed over a period of about 0.25 million years (Lavery and Barnes, 1971). The result might also be compared to paleomagnetic studies on Paleozoic carbonates of the Appalachian foreland, which suggest that remagnetization, a process likely accompanying past brine migration in that basin, occurred during a relatively short interval of geologic time (Scotese et al., 1982; McCabe et al., 1983).

If chemical diagenesis began at the onset of brine migration and ceased as migration waned, the migration event probably lasted for less than 1 m.y. Migration would cease if the aquifer's solute content were depleted by freshwater recharge, or as erosion leveled the uplift that provided the hydrodynamic drive for flow. As well, the inferred chemical diagenesis might have reduced the permeability of the deep aquifers that served as conduits, thereby reducing the ability of brines to move rapidly enough to carry heat to the basin's northern margin.

Origin of Middle Ordovician Dolomites in the Illinois Basin

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To assess the effect of large-scale basin brine migration on the formation of dolomite in the Illinois Basin, limestones and dolostones from Ancell, Platteville and Galena Groups have been studied, using petrographic and geochemical techniques. The collected specimens include core samples from Illinois and outcrop samples from northern Illinois, Missouri, Iowa and Wisconsin.

Textures of limestones vary from micritic to calcarenitic and fossilfereous. Isotopic data of most limestones are in a relatively small range: $\delta^{13}C = +1.4$ to -1.4 permil (PDB), $\delta^{18}O = -4.5$ to -6.9 permil (PDB). Bulk limestones contain 1-4 mole% $MgCO_3$. Dolomites in dolostones and limestones have an average $MgCO_3$ content of 45 mole%. The dolomites are divided into seven types based on petrographic and isotopic characteristics.

Type A dolomite is pervasively distributed in most limestones and is fine-grained, often only slightly coarser than coexisting calcitic micrites. It can be identified on the surfaces of HCl-etched limestone or in the stained thin sections.

Type B dolomite occurs in the Ancell Group beneath the St. Peter sandstone. It is fine-grained, usually pure dolostone, and is characterized by low $\delta^{13}C$ values (-3.2 to -9.0). $\delta^{18}O$ values range from -2.5 to -5.1 permil.

Type C dolomite is from lower part of Platteville Group. It is fine-grained and often occurs with anhydrite or gypsum, occasionally with halite. It has higher carbon and oxygen isotopic ratios ($\delta^{13}C = +1.5$ to $+2.0$, $\delta^{18}O = -2.5$ to -5.0, respectively) than coexisting calcite.

Type D dolomite occurs in northern Illinois. It often makes up pure dolostones, with fine- to medium-grained dolomite domains of centimeter size. Fine-grained domains have low porosity, while the medium-grained domains have very high (up to 40%) intercrystalline porosity. Compared with limestones, it has similar $\delta^{13}C$ values (-0.9 to +1.0), but higher $\delta^{18}O$ values (-2.4 to -3.5).

Type E dolomite is from Stephenson County of northern Illinois. It is coarse-grained and are associated with lead-zinc ore deposits. It is characterized by $\delta^{13}C$ values (-1.0 to +0.9) similar to limestones, but considerably lower $\delta^{18}O$ values (-7.2 to -8.0).

Type F is saddle dolomite. It occurs as crystals in cavities or as cross-cutting veins. It is often associated with fluorite and was followed by late stage calcite cement. It has high $\delta^{13}C$ values (~ +3.0) but low $\delta^{18}O$ values (-6.5 to -9.0).

The dolomite types are interpreted to represent different stages of dolomitization. Type A dolomite may have precipitated directly from seawater during sedimentation or from pore water immediately after sedimentation. Types B and C dolomites are the dominant types. They are interpreted to have formed in marine environment, most likely during early diagenesis. Type D dolomite is also considered to have formed by early dolomitization of calcium carbonates, followed by recrystallization of the initially formed dolomites. Type E dolomite appears to have formed from the hydrothermal alteration of preexisting dolomites at relatively high temperature. Type F saddle dolomite may have precipitated during basin brine migration and degassing.

In search of the unconformity beneath the Mississippian

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The bounding surfaces of the Upper Devonian Grassy Creek Shale and the overlying Saverton Shale and Louisiana Limestone have figured prominently in the placement of the Devonian-Mississippian boundary in North America. The Louisiana was defined as the base of the Kinderhook Series (lowermost Mississippian; Meek and Worthen, 1861) based on paleontological studies conducted by the leading earth scientists of the day. In the original definition, it was uncertain how much, if any, of the shale underlying the Louisiana should be included in the Kinderhook. One hundred years later the Saverton and Louisiana were formally pronounced to belong in the Upper Devonian rather than in the Mississippian based primarily on the similarity of conodonts from the Saverton and the basal Louisiana to those of the Grassy Creek (Scott and Collinson, 1961).

The earliest conodont studies of the Grassy Creek, and Saverton were conducted in Missouri by E.R. Branson and M.G. Mehl (1934b). During the original investigation, and in many subsequent ones, it was assumed that the Grassy Creek and Saverton were lateral equivalents, primarily because of the similarity of their conodont faunas. Although Mehl (1960) later stated that the two units were stratigraphically distinct, the similarity of the faunas has led later workers to keep the Saverton within the Upper Devonian, and separate zones within it have been defined as part of the Upper Devonian (Collinson, Scott, and Rexroad, 1962).

Scott and Collinson (1961) placed the Devonian-Mississippian boundary at an unconformity between the Louisiana and the overlying Hannibal Formation. The unconformity between the Louisiana and Hannibal at Hamburg, Ill., however, was described by Williams (1943) as very poorly developed. Williams also noted that, based on macrofaunal studies, the Louisiana is probably the equivalent to part of the lower Carboniferous in Europe, such as the Avonian of Great Britain, part of the Tournaisian (lower Dinantian) of western continental Europe, part of the Lower Carboniferous of the U.S.S.R., a conclusion that disagrees with the conodonts studies.

The recent work of Ellison (1987) and Broadhead and Dreiss (1991) showing that conodonts are frequently reworked into younger sediments without signs of marked wear has made it necessary to look at physical evidence of unconformities within these sections. It can no longer be assumed that similarity of conodont fauna alone is sufficient criteria for estimating the time gap between succeeding stratigraphic units. The nature of the unconformities separating stratigraphic units must be reconsidered.

Study of the unconformity between the Grassy Creek and the overlying Saverton, or where the Saverton is missing, the Louisiana, offers an alternate conclusion to that of the conodont investigations. It has generally been assumed that black shales of the section are assignable to the Grassy Creek and that the gray shales are assignable to the Saverton. The Grassy Creek does includes a gray shale facies but it is not equivalent to the Saverton. This facies is most prominently displayed at the Monroe City, Mo., locality of Branson and Mehl (1934b) where it is separated from the overlying Louisiana by an unconformity and no Saverton is present. Near Saverton Station, in Ralls County, Mo., by contrast, a thick section (20 to 25 m) of Saverton Shale underlies the Louisiana Limestone and no unconformity is evident between the two units. At Clarksville, Mo., both the Grassy Creek and Saverton are well exposed beneath the Louisiana and an unconformity, recorded as a layer of well sorted medium-grained sand, is present between the black shale of the Grassy Creek and the gray shale of the Saverton. Again, there is no evidence of an unconformity between the Saverton and the overlying Louisiana. The similarity of conodont fauna on either side of the unconformity is probably the result of reworking conodonts from the Grassy Creek and older formations.

South of the occurrences of the Saverton and Grassy Creek, the Bushberg Sandstone at the base of the Sulphur Springs Formation, a lateral equivalent of the basal Hannibal, rests on units as old as Ordovician with an angular unconformity (Branson and Mehl, 1934a). The current investigation suggests that the restricted aerial extent of the Saverton and Louisiana Limestones is the result of local tectonism that disrupted the generally uniform sedimentary patterns of the Upper Devonian and was followed by Mississippian deposition in a paleotectonic setting unique to the Kinderhookian.

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Assessment of the Construction Sand and Gravel and Industrial Sand Resources of the Paducah 1° X 2° Quadrangle

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Sand and gravel deposits suitable for use as construction aggregate or as a source of quartz sand are locally abundant within the boundaries of the Paducah Quadrangle. Sand and gravel aggregate products have a relatively low-unit cost and markets close to the point of extraction are required to ensure profitability and minimize transportation costs. Sand and gravel production in the quadrangle is relatively low because of the modest needs of the low population in the area. Only high-quality sand dredged from the three major rivers is likely to be shipped out of the area to other markets, due to easy access to low-cost barge transportation. Industrial sand is a moderately priced commodity, but deposits in the Paducah Quadrangle are more areally restricted than the common sand and gravel resources, and would require beneficiation to bring their quality up to industry standards and face long hauls to potential markets in major industrial centers.

The assessment of sand and gravel and industrial sand includes the location of deposits and their potential. This assessment does not include legal requirements or current land use restrictions that may limit or prevent the development of some sand and gravel deposits. The sand and gravel resource map on which the assessments are based was derived from the surficial deposits (stack unit map) and the bedrock geology map of the Paducah Quadrangle. However, the resource map incorporates refinements and revisions based on (1) the authors' knowledge of the geology of the area, (2) unpublished field notes, reports and maps, (3) engineering tests, water wells and other drilling records, (4) modern soil maps and publications by the Soil Conservation Service of the United States Department of Agriculture, and (5) published reports and maps of the Kentucky, Illinois, Missouri and United States Geological Surveys.

There are several sedimentary deposits in the Paducah Quadrangle that may contain sand and gravel resources. They include: Cretaceous near-shore marine to fluvial-deltaic sand (McNairy Formation) and alluvial-fan chert-gravel (Tuscaloosa Gravel); Eocene fluvial deposits (Wilcox and Claiborne Formations); Pliocene-Pleistocene alluvial-fan chert-gravel deposits (Mounds Gravel of Illinois = Lafayette Gravel of Missouri = "continental deposits" of Kentucky); Pleistocene fluvial sand and gravel (Mackinaw Member of the Henry Formation), lacustrine slack-water deposits (Carmi Member of the Equality Formation), and wind-blown deposits (Peoria Loess); and Holocene fluvial sediments (Cahokia Alluvium).

Within the Paducah Quadrangle, Cretaceous and Eocene sands are known to have been mined only for use as fill material. Cretaceous chert-gravel was formerly used for railroad ballast, on secondary roads and for fill. The more wide-spread Plio-Pleistocene chert-gravel is commonly used for base construction of paved highways, as secondary road surfacing and as fill. None of the gravel in the area meets current specifications for use as aggregate in portland cement concrete. On the other hand, sand from Pleistocene-Holocene deposits, especially in-channel sand from the Mississippi, Ohio and Wabash Rivers, usually does meet these specifications as well as those for lesser-quality construction aggregate products. Aeolian sand (Peoria loess) is used as blend-sand in bituminous-based concrete and as fill. Chert-gravel in certain creek beds adjacent to areas of chert bedrock is used on secondary roads and as fill.

Diagnostic criteria used in the Geographical Information System (GIS) for assessment of the potential for chert gravel include: (1) presence and topographic position of potential sources; (2) overburden thickness; (3) thickness of source formation; (4) variation in particle size, and (5) pits and other occurrences. For construction sand and gravel from Pleistocene-Holocene deposits, the diagnostic criteria used are: (1) presence and relative position of source formation with respect to the water table; (2) overburden thickness; (3) deposit thickness; (4) location of pits and other occurrences; and (5) the occurrence of special depositional features. For industrial quartz sand, the diagnostic criteria are: (1) presence of potential source formation; (2) thickness of overburden, and (3) pits and other occurrences.

Map units from the basic sand and gravel map derived from the geologic and stack-unit maps were assigned values weighted with respect to the quality of potential products. Other weighted values were assigned to diagnostic features that can be used to predict the location, quality, and potential for exploration and exploitation within those map units. GIS analysis of the data defined the relative potential of specific resources within the map units in terms of high, moderate and low. Areas of moderate to high potential for each of the three categories of commodities—chert gravel, Pleistocene-Holocene sand and gravel, and industrial (quartz) sand—are depicted on a series of 1:250,000 scale maps.

Surface Geologic Mapping in Missouri: Look At It This Way

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Detailed surface geologic mapping is the cornerstone of all related deriv-ative studies and is the premier field technique to present geologic data. Growing demand for site-related information pertaining to water needs, discarding of hazardous and sewage wastes, building and bridge construction, subdivision developments and other applications necessitates a large-scale database. Regional studies of structural, mineral, stratigraphic and hydrologic data are more reliable if related to detailed rather than reconnaissance mapping. Geologic mapping at 1:24,000 scale optimizes the distribution of outcrops with a confident map position for most Missouri terrains, structural styles and stratigraphic control. While a geologic map is a subjective rendition of ground proof, the record of outcrops is perhaps the most basic and truthful tool which, with good notes, can be verified by others.

Geologic mapping used to produce the Missouri portion of the Paducah 1° x 2° Quadrangle came from various sources, but nearly all of it is from detailed field investigations. Thus the control used to field map on a large-scale base makes the accuracy of this small-scale map highly reliable.

Two important aspects of any map product are reproduction and protection. With the eventual incorporation of our geologic data into a Geo- graphical Information System, the long-term concerns of protection from any number of hazards and the immediate ease of placing valuable information in the public's hand are both addressed. Additional input of data at a later time or corrections to the original work are easily incorporated into exis- ting maps; after all, geologic maps are essentially progress reports which should be amended to reflect new insights or data.

Geochemical studies of the dilute HCl soluble fraction of subsurface samples from the Paducah 1° x 2° quadrangle

E.L. Mosier and M.B. Goldhaber (USGS)

Insoluble residues of carbonate rocks obtained by treating the rocks with cold 2.4N (20%) HCl has been demonstrated to be a valuable geochemical sample medium for mineral appraisal studies in the mid-continent U.S. (Erickson and others, 1978, 1981, and 1983). In this study, we report on the use of the soluble fraction of the rock to obtain additional geochemical data. In addition to the carbonate minerals, cold 2.4N HCl is capable of dissolving to varying degrees certain sulfide minerals (e.g. galena and sphalerite) and an array of sediment constituents including Fe, Mn, and Al oxides. The resulting solute from the preparation of insoluble residue samples from the cuttings of 38 drill holes in Illinois and 6 drill holes in Kentucky were analyzed for 33 elements using inductively-coupled plasma-atomic emission spectrometry. The analytical results were calculated to reflect element concentrations in the whole rock and the concentration values were normalized to anomalous metal feet (AMF). The reporting unit, AMF, is based upon normalizing the ratio of a reported anomalous metal content to the minimum anomalous metal content, which for this study was the statistically determined 90th percentile concentration level (Erickson and others, 1978).

The data suggests that valuable geochemical information may be gained by analyzing the solute fraction from the preparation of insoluble residue samples. In addition to calcium and magnesium, appreciable quantities of aluminum, iron, potassium, manganese, phosphorous, barium, cerium, cobalt, chromium, copper, lanthanum, lithium, molybdenum, nickel, lead, sodium, strontium, vanadium, yttrium, and zinc were dissolved by the 2.4N HCl treatment.

An example of AMF content in the solute fraction for cobalt, lead, nickel, and zinc from the dissolution of Ordovician carbonate rocks is given in figure 1. These rocks represent 1600 feet of strata below the Maquoketa Shale from the Trenton, Plattevile, and Knox Formations. The solute fraction of these samples also contained anomalous concentrations of copper and molybdenum. These results do not mirror the analytical results obtained from the insoluble residue fraction but instead provide additional information on the abundance of elements, some of which may be related to the passage of ore fluids. Anomalous concentrations of cobalt or zinc were not detected in the insoluble residue fraction of this suite of samples. Only two insoluble residue samples contained anomalous concentrations of copper and six insoluble residue samples contained anomalous concentrations of molybdenum and nickel. Even though as much as 10,000 AMF of lead was detected in the insoluble residue fraction of these samples, the insoluble residue AMF lead data, as well as data for other metals, is augmented by the AMF solute data. The AMF solute data will be used in developing a series of plan view maps showing the abundance and distribution of selected elements in Mississippian, Devonian/Silurian, and Upper and Lower Ordovician strata that may have a direct relation to the movement of metal rich fluids away from the New Madrid rift zone. For example, paired geochemical maps compiled for Ordovician and Mississippian strata show that zinc is most abundant in solute samples from Ordovician strata that is near the New Madrid rift zone in the southern part of the quadrangle while away from the rift zone, in the northern part of the quadrangle, zinc is most abundant in Mississippian strata.

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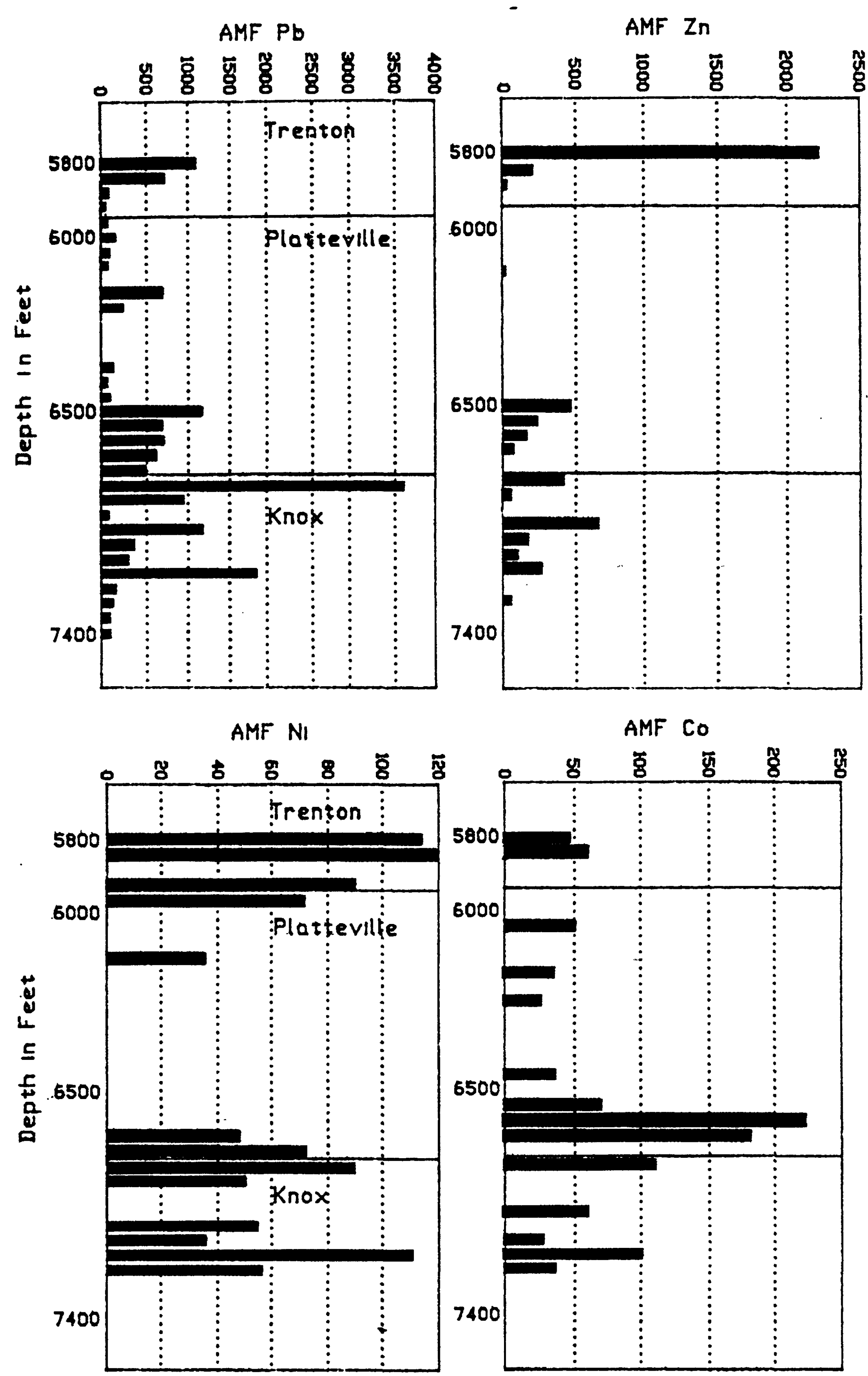

Figure 1. Contents of selected elements in solute fraction (2.4N cold HCl) of Ordovician strata from drill hole I98, Williamson, Co. Illinois.

Structural Geology of the Paducah Quadrangle

W. John Nelson (ISGS)

The Paducah Quadrangle encompasses parts of three major structural provinces. These are the eastern flank of the Ozark Dome, with Ordovician through Devonian sedimentary bedrock; the southern end of the Illinois Basin, with Mississippian through Lower Permian strata, and the northern tip of the Mississippi Embayment, with Upper Cretaceous through Eocene strata. Many fault systems have been mapped within the quadrangle. These faults have been recurrently active under a variety of stress regimes.

Three principal fault trends are mapped on the Ozark Dome: (1) Northwest-trending faults are post-Early Devonian, pre-Quaternary. Although dip-slip displacements across these faults are less than 60 m, breccia clasts and blocks within fault zones are down-dropped as much as 730 m. Such structure suggests pull-apart, possibly in a trans-tensional (divergent wrenching) stress regime. (2) Northeast-trending faults, mostly in the southern part of the area, apparently are normal faults and displace strata as young as Eocene. (3) Mapped faults on the Illinois portion of the Ozark Dome strike NNW and dip steeply. Mapping in progress suggests post-Cretaceous pull-apart.

The Ste. Genevieve Fault Zone separates the northeast flank of the Ozark Dome from the Illinois Basin. The fault zone underwent mid- to late-Devonian normal faulting, followed by post-Mississippian reverse faulting with opposite sense of throw.

Within the Illinois Basin, the Cottage Grove Fault System is a Pennsylvanian-Permian right-lateral wrench system. The Wabash Valley Fault System is composed of post-Pennsylvanian normal faults that may represent a broad, collapsed arch. The Du Quoin Monocline probably is the surface expression of a reverse fault in crystalline basement.

The complexly faulted area in the southeast part of the Paducah Quadrangle reflects late Paleozoic and younger reactivation of a dogleg-shaped Cambrian failed rift. The Rough Creek-Shawneetown Fault System and Lusk Creek Fault Zone outline the northwest boundary. These faults underwent (1) Cambrian normal faulting, (2) late-Paleozoic reverse faulting, and (3) Mesozoic normal faulting. The Tabb and Pennyrile Fault Systems, along the southeast margins of the rift, have undergone repeated episodes of normal, dip-slip displacement. Within the rift, reverse and oblique-slip faults are documented but high-angle normal faults predominate. Ultramafic igneous rocks were intruded during the Early Permian Period. Hicks Dome is the product of deep-seated explosive igneous activity.

The Mississippi Embayment occupies a structural trough that overlies the ancient Reelfoot Rift. Northeast-trending faults of relatively small displacement offset Cretaceous and Tertiary rocks along its margins. The currently active New Madrid Seismic Zone lies immediately south of the Paducah Quadrangle.

Fluorspar, lead, zinc, and associated minerals are mined from vein (fault) and bedded-replacement deposits in the southern part of the quadrangle. Metallic sulfides have been observed within and adjacent to the Ste. Genevieve fault zone. Intense tectonic fracturing may have played a role in the origin of commercial silica deposits of extreme southwestern Illinois.

Oil and Gas Potential in Paducah Quadrangle

D. F. Oltz and J. E. Crockett (ISGS), R. Mast (USGS), R. H. Howard (ISGS), J. Rupp (IGS), and M. C. Noger (KGS)

The preponderance of hydrocarbon production in the Paducah Quadrangle has come from the area north of the Cottage Grove and Rough Creek-Shawneetown Fault Systems at the southern margin of the Illinois Basin in Illinois. South of these faults in Illinois, exploration has been relatively sparse, limited in part by former drilling restrictions on large tracts of federally owned land. Whereas both Mississippian and Pennsylvanian reservoirs have been productive in Posey County, Indiana and western Union County, Kentucky, the greatest volume of hydrocarbon production in the Paducah Quadrangle has come from Mississippian reservoirs in Illinois, with lesser volumes from Pennsylvanian and Devonian reservoirs. No Silurian or Ordovician reservoirs have been discovered in the Paducah Quadrangle.

As federal lands become available for leasing, it is likely that exploratory drilling would focus in the Paducah Quadrangle. The exploration targets in this area may be (1) structural; for example, anticlinal traps caused by tectonic folding or drape over Silurian reefs, fault entrapment, fracturing of organic-rich source rocks, and fracturing of reservoir rocks, or (2) stratigraphic; for example, pinchout of porous clastic rocks, shale-sealed reservoir rocks beneath an unconformity, isolated carbonate shoals and reefs, isolated turbidites, updip pinchout of porous carbonates against anhydrite seals, and pinchout of reservoirs against paleostructures. Potential gas plays may be associated with fractured New Albany Shale within the Fluorspar Fault Complex in southeastern Illinois and western Kentucky, as well as with deeper strata within the Reelfoot Rift-Rough Creek Graben.

The primary hydrocarbon source rocks known in the area are the Devonian-Mississippian New Albany Shale, widely considered to be the main source rock for Illinois Basin hydrocarbons, and the upper Ordovician Maquoketa Shale. The quality and distribution of older source rocks are unsubstantiated by deep drilling, a factor that impedes analysis of plays in strata deeper than the middle Ordovician Galena Group, which comprises the oldest productive strata in the Illinois Basin. In the apparent absence of definitive evidence of older source rocks, deeper play analysis remains limited to speculation on the possibilities of various structural and stratigraphic plays analogous to those in other areas. These analogs include the deep St. Peter gas play and the Albion-Scipio diagenetic trap play of the Michigan Basin, Knox unconformity pinchout plays, and plays associated with fault blocks in the Reelfoot Rift/Rough Creek Graben.

Cambrian and Ordovician Stratigraphy and the Potential for Mississippi Valley-Type and Mount Isa-Type Base Metals, Western Paducah 1° X 2° Area

James R. Palmer (MGS)

Cambrian and some early Middle Ordovician rocks in the western Paducah 1° X 2° degree area have potential for two types of sediment-hosted base metal deposits: epigenetic Mississippi Valley-type (MVT) Pb-Zn-Cu, and synsedimentary-syndiagenetic Mount Isa-Type Ba-Zn-Pb-Cu-Ag. The potential for MVT deposits should be high near the Old Lead Belt district in the western part of the quadrangle. The emplacement of the MVT deposits was controlled by paleoaquifer/aquitard relationships such as shale windows, basement highs, or fracture systems where mineralizing brines migrated upward into host rocks. The Mount Isa-type deposits are generally thought to be related to synsedimentary hydrothermal activity in areas undergoing regional extension, such as rifted (passive) margin or failed-rift settings. Mount Isa-type deposits are localized along graben and horst margins in organic-rich shales, limestones, or dolostones, with mineralization and stratigraphy in both concordant and discordant relationships (Williams, 1978; Boast and others, 1981; Hitzman, 1986 McArdle, 1990). Evidence of early synsedimentary mineralization in the study area remains to be found.

The failed Reelfoot Rift produced a passive margin-like succession in eastern Missouri beginning with alluvial and fluvial redbeds (pre-Late Middle Cambrian). The initial early Paleozoic marine transgression occurred probably during latest Middle Cambrian. Deepest marine shelf sediments were deposited in the Mississippi Valley graben and a rimmed carbonate shelf sequence developed along the graben margin concurrently with an intrashelf basin-carbonate ramp system in the Ozarks (Dresbachian and Franconian Stages). The Late Upper Cambrian rimmed carbonate shelf margin (4700 ft thick) has eleven large-scale transgressive-regressive (t-r) cycles that are 120 to 600 ft thick. Within the Mississippi Valley graben, carbonate shelf equivalent black shales reach thicknesses of more than 1600 ft. The facies change from cyclic and rimmed carbonate shelf margin to graben basin shales may occurs within a distance of less than five miles. The carbonate shelf rim is believed to be controlled by large faults. In contrast to the shelf rim, there are only six large-scale t-r cycles (60 to 200 ft thick) to the north in the shelf and intrashelf basin-carbonate ramp sequence. Synsedimentary tectonic and volcanic activity in the Cambrian sequence is indicated by:

(1) Local accumulation of ultramafic lapilli tuffs (0 - 146 ft thick) interbedded with early Dresbachian, lower Bonneterre rocks (Snyder and Gerdemann, 1965; Wagner and Kisvarsanyi, 1969; Kisvarsanyi and Howe, 1983).

(2) Stratigraphic sequences which have conglomerates composed of Precambrian clasts above fine-grained quartz arenites, or within platform carbonates.

(3) The presence of deep-water, starved-shelf limestones, that correlate with nearby early paleokarsted tidal flat sequences and meter-scale fandelta cycles of sandstone paleokarsted carbonates.

(4) In southern Missouri the last intrashelf basin cycle began the late Dresbachian and continued into the Franconian (Palmer, 1989, 1991), unlike Cambrian sequences in the southern Appalachians which shoaled through the Dresbachian and Franconian (Read, 1989).

If the large-scale facies evidence presented here indicates rifting and post-rift thermal subsidence were active processes during much of the Upper Cambrian, then a variety of grabens should be present in eastern Missouri. One example has been identified in the southwestern part of the quadrangle at Scott City where a 400-ft-thick sequence of the Ordovician Plattin Limestone is present within an east-west oriented half graben (down-to-the-north about 600 ft) that becomes a monocline to the west in less than four miles. One or more south-dipping tilt blocks are nested within the half graben. Underlying Middle Ordovician rocks do not thicken within the graben, and the Plattin is absent on the south side of the half graben. However, the underlying early Middle Ordovician Dutchtown Formation is dominantly shaly limestones within the graben and dolostone in the footwall, indicating early Ordovician activation. This half-graben may have its origin during early Paleozoic rifting, and was reactivated during the Middle Ordovician.

Similarities between the early Paleozoic setting in the northern Mississippi Embayment region and Mount Isa-type districts suggests potential for syndiagenetic base metal mineralization near syn-rift fault zones. The most likely host rocks for Mount Isa-type mineralization are probably the earliest carbonate and shale sequences (early Dresbachian Bonneterre - Eau Clair) in areas near major fault zones. Middle Ordovician rocks in areas near some fault zones may have lesser potential for synsedimentary-syndiagenetic mineralization, but still serve as an example of half-graben and tilt block structures common in many Mount Isa settings. The potential for MVT deposits has been recognized by industry, because of the large numbers of cores were drilled just to the west of the study area during the 1960's to 1980's. MVT exploration targets include Bonneterre dolostones in areas where the Lamotte Sandstone pinches out against basement highs, a dominant control of the Fredericktown ores, and areas with Bonneterre limestone-dolostone interfaces along intrashelf basin facies margin, a feature prominent in the Viburnum Trend. The lack of abundant core data in the study area allows identification only in a general way of prospective ground. However, previous study of dolomites with quenched ultraviolet flourescence in a drillcore near Marble Hill, Missouri, suggests close proximity to undiscovered MVT ores (Hayes and others, 1989).

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Regional Diagenetic Patterns in the St. Peter Sandstone, Illinois Basin: Evidence for Multiple Episodes of Fluid Movement during the Late Paleozoic

Janet K. Pitman, Martin B. Goldhaber (USGS) and Tom Shaw (Queens College-Flushing)

Complex diagenetic alteration patterns in the Ordovician St. Peter Sandstone of the Illinois basin preserve a record of temporal and spatial fluid evolution in a large paleoaquifer system that also may have been a major conduit for fluids responsible for fluorine-zinc-lead mineralization in and adjacent to the basin. The origin and timing of fluid movement in the basin can be deciphered by knowing the relative age and chemical and isotopic characteristics of the authigenic minerals. Petrographic studies reveal that St. Peter sandstones were diagenetically modified by precipitation of secondary quartz, K-feldspar overgrowths and cement, multiple generations of ferroan and non-ferroan carbonate, the clay minerals illite, chlorite, and kaolinite and anhydrite. Extreme vertical variability in diagenesis occurs on a small-scale; however, mineral alteration often shows clearly defined trends regionally. Alteration in the St. Peter appears to be controlled by regional structural trends as well as by depth of burial. For example, in shallow to moderately buried rocks east of the La Salle Anticlinal Belt, authigenic K-feldspar (fig. 1), illite, and dolomite are relatively abundant. Hematite and kaolinite as well as primary and secondary porosity occur in addition to these minerals in the northern part of the basin near the outcrop where meteoric water infiltrated in recent times. The predominance of potassium-bearing minerals in the northern Illinois Basin may be related to potassium-rich brines that migrated long distances during Devonian and/or late Paleozoic time. Within and adjacent to the Fairfield basin, trending toward the Mississippi River Arch to the northwest, the St. Peter contains significant amounts of secondary quartz and non-ferroan and ferroan dolomite. Porosity also occurs but is less pronounced due to the effects of increased burial. Iron-bearing carbonates in the southern part of the basin overlie thermally mature, hydrocarbon-bearing shales suggesting that fluids produced during thermal maturation migrated upward along faults and fractures into the St. Peter where they moved northward within the aquifer to areas where they precipitated carbonate minerals. Stable isotope compositions of dolomite and calcite generally show a systematic decrease in $\delta^{13}C$ ratios (-3 to -7 per mil) toward the southern part of the basin inferring an increase in isotopically light carbon associated with decarboxylation of organic matter. The $\delta^{18}O$ compositions of carbonates tend to be fairly uniform (-2 to -3 per mil PDB) except in the southern part of the Fairfield basin where the values become more depleted. The lighter values can be explained by increased temperature and/or changes in fluid compositions near areas where there was upwelling of deep-seated brines.

Anhydrite preserves primary sedimentary textures in deeply buried rocks to the south basinward of the present limit of freshwater incursion, implying evaporative conditions prevailed during deposition. Partial to complete dissolution and subsequent recrystallization of this phase may have occurred late in the burial history as inferred

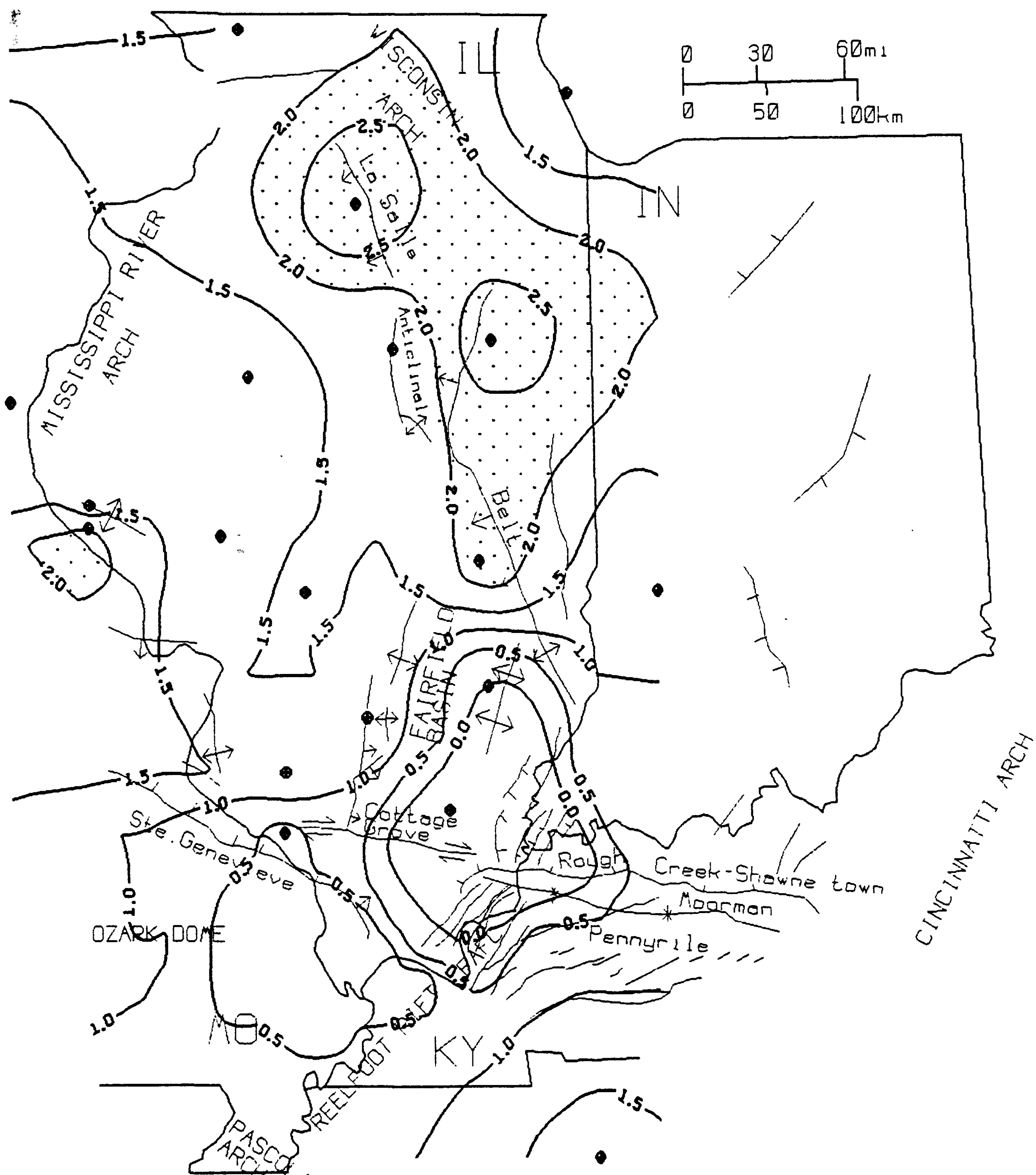

Figure. 1. Plot showing location of drill holes sampled for this study. Contours show average abundance of feldspar cement. Contoured amounts are semi-quantative: 0-absent, 1-slight, 2-moderate, 3-moderately abundant, 4-abundant. Contoured values greater than 2 are stippled.

from dolomite-anhydrite replacement textures in some sandstones.

There is evidence to suggest that a major regional brine-flow event occurred in the Illinois Basin during the late Paleozoic. Hydrologic modeling coupled with geochemical data (Bethke, 1990) demonstrate that long-distance oil migration was driven by these fluids. It is inferred that oil migration coincided in time with brine movement associated with the formation of the Illinois/Kentucky fluorspar district because fluorite contains primary oil-bearing inclusions. The broad northward dispersal of fluids from a presumed southern Illinois Basin source is demonstrated by the extent of trace fluorite mineralization in carbonate rocks immediately overlying the St. Peter as far north as the Mississippi River Arch. Studies are presently underway to determine the relationship between authigenic-mineral phases in St. Peter sandstones (as described above) and this late Paleozoic fluid-migration event.

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The possible role of magmatic gases in the genesis of Illinois-Kentucky fluorspar deposits: implications from chemical reaction path modeling

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There is increasing evidence that deposits of the Illinois-Kentucky fluorspar district (FSD) formed from a basinal-brine hydrothermal system (see Hayes and Anderson, this volume) shortly after emplacement of the Hicks Dome alkalic igneous complex (e. g., Taylor et al., this volume). In general, the FSD deposits are characterized by early extensive dissolution of limestone and replacement of limestone by fine grained fluorite; deposition of main-stage fluorite in open spaces occurred in multiple periods interspersed with periods of lesser calcite, quartz, and/or sulfide deposition (Richardson and Pinckney, 1984). In this paper, we present preliminary results of reaction path calculations which model possible fluorite deposition mechanisms in the FSD. These calculations suggest that the mineralizing fluids needed quite low pH values (below 4) and high F contents in order to produce fluorite dominant assemblages observed in the FSD; the fluids therefore may have interacted with HF-rich magmatic gases (possibly associated with the Hicks Dome Complex) at some point prior to forming the FSD deposits.

We used the chemical speciation and reaction path programs SOLVEQ and CHILLER (Reed, 1982) for our calculations. Chemical reaction path modeling is based on fundamental equilbrium thermodynamics. It predicts quantitative changes in fluid chemistry and amounts of minerals precipitated (and/or gases formed) at incremental steps during a specified chemical process (such as boiling, cooling, or water-rock interaction).

The reaction path calculations require, as input, the temperatures, salinities, concentrations of major cation and anions (Na, K, Cl, SO_4, etc.), and dissolved gases (H_2S, CO_2, etc.) in the hydrothermal fluids; fluid pH values and concentrations of fluorine and various metals can then be calculated assuming saturation with various observed hydrothermal minerals. Fluid inclusion and stable isotope data indicate that the mineralizing fluids were saline (as much as 20 weight % NaCl eq.), Ca-, Mg-, CO_2-, and CH_4-rich, basinal brines whose temperatures varied from 150°C near Hicks dome to less than 70°C on the fringes of the district (Richardson and Pinckney, 1984; Richardson et al., 1988; Hall and Friedman, 1963; Taylor et al., this volume). We used for our modeling an initial fluid composition with cation contents in the range of those measured by Hall and Friedman (1963), and with dissolved gas contents similar to those estimated by Leach et al. (1991) for the basinal brines which formed MVT deposits and related hydrothermal mineralization of the U. S. Ozark region. This fluid composition is relatively acidic (pH 4.5 to 5), CO_2-rich (0.3 molal), Ca-rich (0.3–0.5 molal), and saturated with fluorite, dolomite, quartz, muscovite (approximating illite), anhydrite, sphalerite, galena, and pyrite. The assumed mineral saturations are plausible given the observed ore mineralogies and the presence of extensive dolomitic carbonates with anhydrite, chert, and clays in the stratigraphic section below the FSD.

Fluorite ore deposition mechanisms which we initially modeled include (1) simple cooling (from 150 to 142°C, based on data and conclusions of Richardson and Pinckney, 1984), (2) reactions of the hydrothermal fluids with limestones (based upon the observed extensive replacement of limestones by fluorite), (3) combinations of cooling and limestone reaction, (4) isothermal or near-isothermal boiling of the fluids in response to pressure drops, and (5) mixing of two fluids with different Ca and F contents. Using the assumed initial fluid composition discussed above, the modeling predicts that none of these mechanisms accurately reproduce the observed fluorite-dominant mineralization stages and limestone replacement features. Cooling reaction paths come the closest, and predict precipitation of subequal fluorite and quartz ($<10^{-5}$ total moles of each precipitated over the 8° C T drop) with trace sulfides. Limestone replacement reaction paths predict formation of large amounts of dolomite and anhdydrite with several orders of magnitude less fluorite and quartz, and traces of sulfides. Boiling paths also predict precipitation of copious dolomite and anhdyrite with much less fluorite and quartz. Mixing paths of two fluids with different Ca and F contents generally predict a dolomite-dominant assemblage with lesser fluorite.

We then modeled how interactions of the hydrothermal fluids with HF and CO_2 (approximating a CO_2- and HF-bearing gas phase expelled from a crystallizing alkalic magma) might affect fluid chemistries and results of the above deposition mechanisms. Titration of 0.5 grams HF and 0.5 grams CO2 into 1 kilogram of the fluorspar fluid composition (discussed above) at temperatures ranging from 150 to 300°C produces extensive fluorite precipitation and acidic (pH 2.5 or lower), F-rich, Ca-poor fluids. Cooling of these fluids to 150°C leads to further fluorite precipitation. Paths modeling subsequent reactions of these fluids at 150°C with limestone (to produce the manto, Cave-in-Rock style ores) predict extensive replacement of limestone initially by large amounts of fluorite; when the pH increases to above 4.5, dolomite and anhydrite also precipitate. When cooled from 150 to 142°C, these fluids produce large amounts of fluorite with lesser quartz. Isothermal or near-isothermal boiling reaction paths predict formation of somewhat lesser amounts of fluorite. Reaction paths modeling the mIxing of the acidic, F-rich fluids with Ca-rich, F-poor fluids also predict copious fluorite precipitation with no associated minerals. Thus, cooling or mixing of a fluid previously acidified by HF could produce open-space, vein-style fluorspar mineralization.

Although preliminary, these results indicate that the fluids responsible for Illinois-Kentucky fluorspar mineralization were likely quite acidic (pH < 4) and rich in fluorine in order to produce the fluorite-rich mineral assemblages and extensive dissolution of host limestones. A possible source for the acid and flourine may have been HF-rich gases which were expelled from alkalic magmas and then incorporated by migrating basinal brines.

A possible sequence which fits the available data is an initial major gas explosion to form the Hicks Dome cryptovolcano, followed by continued, less-violent leakage of magmatic gases from alkaline igneous sources. These magmatic gases could have migrated upward not only in the immediate vicinity of Hicks Dome itself, but also along major FSD faults which cut crystalline basement (see Potter et al., this volume); titration of the gases into basinal brines at depth led to preferential mineralization of these structures. This hypothesis warrants further consideration, but must be tested extensively through careful intergration with geologic, mineralogic, fluid inclusion, and stable isotopic evidence. Many further reaction path calculations are also needed which incorporate more realistic fluid inclusion gas chemistry data and magmatic gas compositions for alkalic magmas.

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Interpretation of a regional seismic reflection line, southern Illinois basin: Cambrian rifting, Illinois-Kentucky fluorspar district faulting, and Hicks Dome genesis

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An 82.8 km segment of a high-quality seismic reflection profile across the northern Reelfoot rift provides subsurface constraints on a tectonically complex area of the southern Illinois basin. The dynamite-source seismic line has a record length of five seconds and trends northwest-southeast in southern Illinois and western Kentucky (fig. 1). The line segment extends from Saline County, Illinois, to Caldwell County, Kentucky and crosses the Ohio River near Hurricane Island. The seismic line crosses the Cambrian rift system where the Reelfoot rift makes an abrupt eastward bend to the Rough Creek graben. Prominent geologic structures along the line include the Rough Creek - Shawneetown fault zone, Hicks Dome, the Fluorspar area fault complex, and the Tabb and Pennyrile fault systems (fig. 1). The data provide new information on the development of the Cambrian rift system, on the origin of Hicks Dome, and on the relationship between faulting and mineralization.

The seismic data show that the general geometry of the Cambrian rift system along the profile is that of a half-graben that thickens to the southeast, as opposed to the northward-thickening geometry observed farther east in the Rough Creek graben. Northwest of the Ohio River, Middle and Lower Cambrian syn-rift sedimentary rocks occupy about 0.35 s (two-way travel time) on the seismic record (corresponding to a thickness of about 1160 m). This stratigraphic interval occupies about 0.45 s (1500 m) near the Ohio River, and is thickest against Pennyrile fault system in Kentucky where it occupies 0.7 s (2350 m). The reflections from this sequence have a southeast component of dip. This wedge of Cambrian sedimentary rocks terminates to the southeast against faults that project to the surface as the Tabb and Pennyrile fault systems. Here, several major steep normal faults offset crystalline basement to form the southeast margin of the rift. Near the northwest end of the seismic profile, normal faults offset Precambrian basement and Cambrian rocks slightly thicken southeastward across a zone that includes the Herod and Raum faults (northeastern extension of the Lusk Creek fault zone). We detect no significant basement offset or Cambrian sedimentary thickening at the Rough Creek-Shawneetown fault zone. However, disrupted reflections from late Paleozoic strata are prominent along this fault zone.

Interpretation of the base of the Paleozoic section is problematic near the Ohio River, between the Fluorspar area fault complex and Hicks dome (fig. 1) due to poor data quality northwest of the river. A thick section of Cambrian rocks is present southeast of the river in Kentucky, but on the northwest side of the river in Illinois, the Cambrian interval appears to be thinner. We suggest that there is a significant Cambrian normal fault (not shown on Figure 1) just northwest of the Ohio River, because: (1) strong continuous reflections from the Cambrian section on the Kentucky side of the river may continue across the river as weaker reflections that terminate just northwest of the Ohio river in Illinois; and (2) Bouguer gravity data show a distinct break of four mgal just northwest of the river. Further work is needed in this zone.

Reflection patterns near Hicks dome, a "cryptovolcano", are consistent with the hypothesis that the dome originated by explosive release of mantle-derived gases associated with alkali volcanism. Beneath Hicks dome, the entire section of Paleozoic rocks and the top of Precambrian basement are domed, which indicates that the uplift originated in the basement, rather than within the sedimentary section. Within the Paleozoic section, there is an upward tapering cone of highly disrupted reflections. We interpret this disruption to be caused by brecciation and

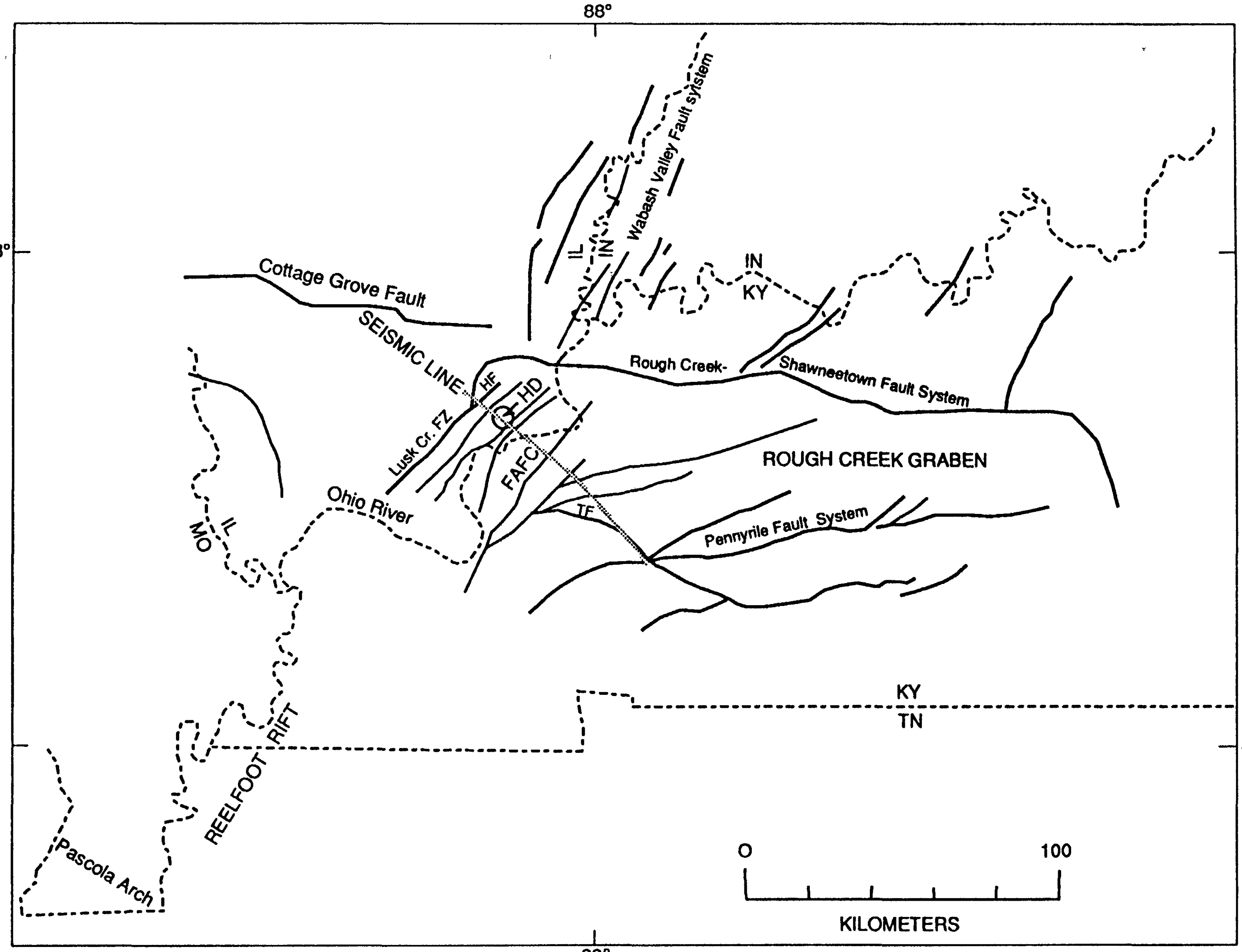

Figure 1. Map of the southern Illinois, southern Indiana western-Kentucky region showing location of the seismic line (stippled line). Major geologic features include the Reelfoot rift and Rough Creek graben, the Lusk Creek and Rough Creek-Shawneetown fault zones, Hicks dome (HD), the Fluorspar area fault complex (FAFC-shown schematically only, as the number of faults is too large to illustrate at this scale), and the Pennyrile fault system. The Herod fault (HF) is the northeastern continuation of the Lusk Creek fault zone, northwest of Hicks Dome and TF is the Tabb Fault.

fracturing of these layers, perhaps during the "cryptovolcanic" event that has been invoked to explain Hicks dome. Intra-basement reflectors terminate below the disrupted zone in the overlying sediments, suggesting that the disruption extends into the basement rocks. Disruption is most pronounced on the northwest side of the dome. Potential-field geophysical data contain no obvious signature of an intrusion at depth, suggesting that doming of the basement surface and disruption of basement and Paleozoic sedimentary strata are best explained by an explosive release of igneous volatiles. Alternatively, some reflection patterns in the uppermost basement may be interpreted as intrusive bodies that lack significant gravity or magnetic signature and contributed to the doming of overlying strata.

Correlation of the reflection data with surface mineralization patterns shows that in most cases mineralized surface faults clearly cut basement or are splays from faults that cut basement. This relationship between structure and mineralization implies that the fluorine source for the ores of the Illinois/Kentucky fluorspar district is within the basement.

Lower Ordovician Stratigraphy and Facies in and Adjacent to the Reelfoot Basin, Southern Midcontinent, U.S.A.

John E. Repetski (USGS)

Available Early Ordovician conodonts from the subsurface in the Reelfoot basin of westernmost Tennessee, northeastern Arkansas, southeastern Missouri, and southwestern Kentucky, permit some preliminary correlations with coeval exposed sequences of the U.S. Midcontinent region. Thus far, no samples of earliest Middle Ordovician age have been recovered in the subsurface south of the Pascola arch; apparently the early Whiterockian regional unconformity cuts out any earlier Whiterockian strata in the immediate area of the Reelfoot basin. For the lower, middle, and much of the upper part of the Ibexian Series, faunas are typical of shallow, warm-water platform carbonate depositional environments. Correlations can be made with the Knox (east), Arbuckle (west), and Prairie du Chien (northeast) Groups and the Ozark shelf sequence (northwest). Uppermost Ibexian rocks and faunas are quite different, however, from the adjacent Midcontinent sequences. The highest preserved Ibexian strata encountered in the subsurface is a dark-gray, argillaceous lime mudstone to wackstone containing numerous, but not all, species typical of the North American Midcontinent Province of the *Oepikodus communis* Zone, but also containing species indicative of cooler and (or) deeper environments, some of which are cosmopolititan in distribution and some of which are indicative of the North Atlantic Province *Oepikodus smithensis* Zone. Several of the species present in this interval are characteristic of the middle Arenigian sequence of the Precordilleran province of Argentina, where the sedimentological sequence also is dominated by cooler, deeper lithofacies and faunas. The conodont faunas from the upper Ibexian interval of the Reelfoot basin thus indicate that this area had free communication with the open ocean and limited influence from the restricted circulation shallow cratonic seas immediately to the west, north, and east.

Paleomagnetic Study of the Grants Breccia and the Downeys Bluff Sill—Implications for the Influence of Permian Igneous Activity on Mississippi-Valley Type (MVT) Mineralization in Southern Illinois

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Identical directions of remanent magnetization have been determined from the Grants carbonatitic breccia at Hicks dome and from the nearby Downeys Bluff sill, including from subjacent baked sediment, in southern Illinois (latitude≈37.5 °N, longitude≈88.4 °W). The paleomagnetic results, complemented by isotopic age determinations, support interpretations that link MVT mineralization to igneous activity in the district and thereby constrain the age of mineralization in southern Illinois.

The Grants breccia is dated at 272.7 ± 0.7 Ma by the $^{40}Ar/^{39}Ar$ age-spectrum method on biotite. The breccia includes igneous-rock fragments some of which contain petrographically observed magnetite commonly associated with ilmenite and titanium-dioxide-rich alteration products. Magnetite was not observed in the carbonate matrix. Iron sulfide minerals (pyrite, marcasite, and chalcopyrite) grew in the matrix and rock fragments after emplacement of the breccia. Alternating-field (AF) and thermal demagnetization of oriented specimens isolated remanent magnetization in magnetite with southeasterly declinations and shallow, negative inclinations. After AF demagnetization, the mean remanent direction (declination [D]=162°; inclination [I]=-12°; a_{95}=12°; number of specimens [N]=4) is less dispersed than that determined from thermal demagnetization (D=176°; I= -17°; a_{95}=16°; N=6), perhaps because of alteration of iron sulfide to magnetic oxide during laboratory heating.

The Downeys Bluff lamprophyric sill yielded an age of about 275 ± 24 Ma by the Rb-Sr method (recalculated from Zartman and others, 1967, using post-1977 decay constants). The sill contains relict magnetite in phenocrysts of iron-titanium oxide; some of the magnetite has been replaced by younger iron sulfide minerals, mainly pyrite and chalcopyrite. Both AF and thermal demagnetization isolated southeasterly, shallow remanent directions from magnetite in the sill, and from both magnetite and hematite in baked sediment of the Upper Mississippian Downeys Bluff Limestone. Magnetic behavior indicates that the most reliable results come from the baked sediment: D=160°; I=-15°; a_{95}=2.5°; N=6. This direction is statistically identical to that obtained after AF treatment of the Grants breccia.

The paleomagnetic, isotopic, and petrographic evidence favors the acquisition of thermal remanent magnetization by the Grants breccia and the sill during the Permian: (1) The northern-hemisphere projection of the virtual geomagnetic pole position (latitude≈55° N; longitude≈126° E) represented by the nearly identical paleomagnetic directions plots close to pole positions from other Permian rocks on the North American craton; (2) the reversed directions, carried by phenocrystic magnetite in the igneous bodies, are consistent with remanence acquisition during the Permo-Carboniferous long reversed superchron (320 to 250 Ma); and (3) the isotopic results indicate emplacement and cooling through isotopic closure temperatures (about 300 °C for the Grants breccia) during the Permian, as well as lack of severe post-emplacement alteration at elevated temperatures.

Because the Earth's magnetic field may return to a particular direction over many millions of years, the identical remanent directions from the Grants breccia and the Downeys Bluff sill do not require that these bodies were emplaced and cooled synchronously (within a few hundred years) or are otherwise related. Regardless, the results indicate that the breccia was emplaced at high temperatures (apparently greater than 580 °C, the maximum magnetization-blocking temperature of magnetite) in structurally shallow levels at Hicks dome. The paleomagnetic data thus reinforce fluid-inclusion studies on fluorite (Goldhaber and others, 1991) indicating that Hicks dome was a thermal center during fluorspar-district mineralization and implying that igneous activity influenced the mineralization in the district during the Permian.

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Sedimentary cycles in the Mississippian St. Louis Limestone, southwest Indiana

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Preliminary analysis of core from two complete and one partial sections through the lower part of the Mississippian St. Louis Limestone in southwest Indiana indicates the presence of numerous sedimentary cycles. Core from the lower 34 ft in the National Quarry section (Sec. 32, T. 8 N., R. 1 W., Monroe County) showed two partial cycles. Core from the State Drill Hole 16 section (Sec. 22, T. 3 N., R. 3 W., Martin County) consisted of 11 full or partial cycles. Core from the State Drill Hole 190 (Sec. 25, T. 4 S., R. 1 E., Crawford County) had 14 full or partial cycles. Each cycle consists of a basal transgressive and upper regressive component. The transgressive component of a cycle consists of normal-marine salinity, fossiliferous limestone deposited during maximum flooding that may be underlain by a thin sequence of nearshore marine limestone or dolomite. The regressive part of the cycle consists of progressively more depauperate faunal-bearing limestone characteristic of lagoonal or intertidal depositional settings to silty dolomites of possible supratidal environments. Within each cycle there may be small-scale transgressive-regressive oscillations.

Where evaporite minerals (anhydrite and gypsum) are present as primary to early diagenetic phases, they are mostly restricted to the regressive part of each cycle. Evaporites first appear in the transgressive limestone as large single crystals or crystal aggregates of anhydrite that poikilotopically enclose fossil tests. The anhydrite formed as replacement grains from pore brines locally supersaturated in calcium sulfate and is not a cement. The proportion of anhydrite aggregates increases upwards as a result of a greater concentration of calcium sulfate in the pore brines. In the upper intertidal rocks, gypsum or anhydrite textures are nodular or laminated and replacive or displacive. The textures result from the coalescence of numerous small crystals. Much of the gypsum/anhydrite is early diagenetic. Dolomite, as authigenic euhedral crystals, becomes an important carbonate mineral in these rocks. In possible supratidal environments, the rocks are dolomitic mudstones with or without anhydrite or gypsum beds or lenses. The dolomitic mudstones commonly contain the highest clastic and iron mineral (probably pyrite) content.

Fauna presence, size, and diversity change with position in a cycle. The maximum transgressive limestone in each cycle contains large, robust forms. Fragments of brachiopods, mollusks, foraminifers, bryozoans, crinoids, echinoderms, echinoids, and dasycladacean algae are the common rock-forming bioclasts. Ooids may be present at some horizons. Rock types are grainstones or packstones. Early cements are characteristic of submarine and not vadose environments.

Away from the maximum transgressive limestone, the diversity of fossil type and size decreases, upwards, in limestone of the regressive component and, downwards, in the transgressive component of a cycle. In these parts of the cycle, fossils consist of thin-shelled, small forms of ostracodes and mollusks characteristic of restricted marine environments. Rock types are wakestones to mudstones. Overlying these rocks are silty dolomite mudstones which are not fossiliferous.

Isotopic analyses of sulfur in sulfate (anhydrite and gypsum) in five samples from the St. Louis in State Drill Hole 16 show a systematic decrease in value from the base (δS^{34} values of 16.6 per mil) to the middle (δS^{34} values of 15.7 per mil) to the top (δS^{34} value is 14.1 per mil) of the formation. This decrease in δS^{34} values accompanies a decrease, upwards, in the proportion of the transgressive marine limestone in each cycle and indicates a change in composition of the sulfate reservoir that could result from brine mixing or bacterial reduction of sulfate.

Three Structural Cross Sections Through Selected Deep Wells Within and Adjacent to the Paducah 1° X 2° Quadrangle, Southern Illinois, Southeastern Missouri and Western Kentucky

Michael L. Sargent, Janis D. Treworgy, Stephen T. Whitaker (ISGS), and Martin C. Noger (KGS)

A set of three well-to-well cross sections through southern Illinois, southeastern Missouri and western Kentucky was prepared for the Conterminous United States Mineral Assessment Program (CUSMAP) evaluation of the Paducah 1° X 2° Quadrangle. These sections, which form a triangle on the index map (fig. 1), tie to important reference wells beyond the limits (37°-38°N and 88°-90° W) of the quadrangle. The west-east section, A-A', extends from the northwestern corner of Madison County, Missouri, an arbitrary point within the Precambrian terrane of the St. Francois Mountains, crosses through southern Illinois, and terminates at the Exxon #1 Duncan in western Webster County, Kentucky. The Duncan well penetrates 15,200 feet (4,633 m) of Paleozoic strata in the Rough Creek Graben without reaching crystalline basement. The southeast-trending section, B-B', extends from the Brehm #1 Bochantin, a 7,332-foot (2,235-m) test that drilled into Precambrian crystalline basement in southeastern Washington County, Illinois, to the Sun #1 Stephens, a 12,960-foot (3,950-m) test that bottoms in the Eau Claire Formation (Upper Cambrian) in northeastern Caldwell County, Kentucky. The northeast-trending section, C-C', extends from the Gypsy #1 McNew, a 2,702-foot (824-m) test that bottoms in Roubidoux Formation (Lower Ordovician) in central Scott County, Missouri, to the Union #1 Cisne, an 11,614-foot (3,540-m) test in north-central Wayne County, Illinois, that reached Precambrian crystalline basement.

WEST-EAST SECTION A-A'

Near its western end, the west-east section encountered two small basins containing Cambrian strata within the Precambrian crystalline paleotopographic terrane that was uplifted to form the St. Francois Mountains. The eastern flank of the Ozark Dome is characterized by a series of step faults that are mostly downthrown to the east. A faulted flexure, which was tested by the Humble #1 Pickel well (the intersection of A-A' with C-C'), occurs in western Union County, Illinois. East of this faulted flexure, dips steepen dramatically. True eastward dips of older stratigraphic units in this part of the cross section steepen as a result of the increasing burial depth that accompanies the eastward thickening of most of the strata.

As section A-A' continues to the east toward the Texas Pacific #1 Farley, in south-central Johnson County, Illinois, apparent dips diminish to essentially zero (vertical exaggeration = 52X). The section nearly parallels the strike of northward dipping units through much of Johnson County.

Through easternmost Johnson, Pope, and southernmost Hardin Counties, Illinois, and Livingston and Crittenden Counties, Kentucky, the section crosses through the Fluorspar Area Fault Complex. Where this section intersects the Dixon Springs Graben in western Pope County, Illinois, strata within the graben are downdropped more than 600 feet (180 m). Where the section intersects the Rock Creek Graben in Livingston County, Kentucky, and Hardin County, Illinois, the maximum offset is approximately 1,500 feet (450 m). The basal-Pennsylvanian Caseyville Formation is juxtaposed with the mid-Mississippian Ste. Genevieve Limestone near the Ohio River in northern Livingston County, Kentucky.

Continuing eastward, the section passes through the Tolu Arch. The Shell #1 Davis test was drilled to 8,821 feet (2,689 m) near the apex of the arch and bottomed in the Upper Cambrian Potosi Dolomite, near the middle of the Knox Supergroup.

On the eastern limb of the Tolu Arch, the section passes through the Commodore Fault System, the easternmost fault of the Fluorspar Area Fault Complex encountered in this section. East of the Shell #1 Davis, the rocks show continued eastward dip within the Rough Creek Graben to a point approximately six miles (10 km) from the eastern end of the section. From this point to the Duncan well, strata rise eastward from 200 to 800 feet (60-240 m) within these six miles (10 km) depending on their position in the section. Strata above the St. Peter-Everton rise approximately 200 feet (60 m) within these six miles, whereas those below the Everton rise as much as 800 feet (240 m) indicating uplift prior to Everton deposition. The top of the Lower Ordovician rocks appears to have undergone at least 600 feet (180 m) of erosion. The net result of this missing section is that rocks below the angular unconformity, the sub-Tippecanoe unconformity, dip more steeply than rocks above the unconformity.

SOUTHEAST-TRENDING SECTION B-B'

Section B-B' crosses six major structural elements in southern Illinois and western Kentucky. Near its northwestern end, the section passes through the DuQuoin Monocline, which forms the natural boundary between the Sparta Shelf and the portion of the central Illinois Basin known as the Fairfield Basin. Near the Brehm #1 Harris well, where it crosses section C-C', the section intersects the Cottage Grove Fault System. At this location the fault system forms a flower structure in which faults on either side of the Harris well merge within the Knox Supergroup into a single fault that continues into Precambrian crystalline basement. The master fault lies north of the well. The structural style of the Cottage Grove System is a right-lateral strike-slip fault. Net offset shown in the section is approximately 150 feet (45 m) down on the north across the zone. Between the faults at shallow depths, an arched horst, known as the Pittsburg Anticline, is upthrown slightly less than 100 feet (30 m) relative to the south side and somewhat more than 200 feet (60 m) relative to rocks to the north of the fault system.

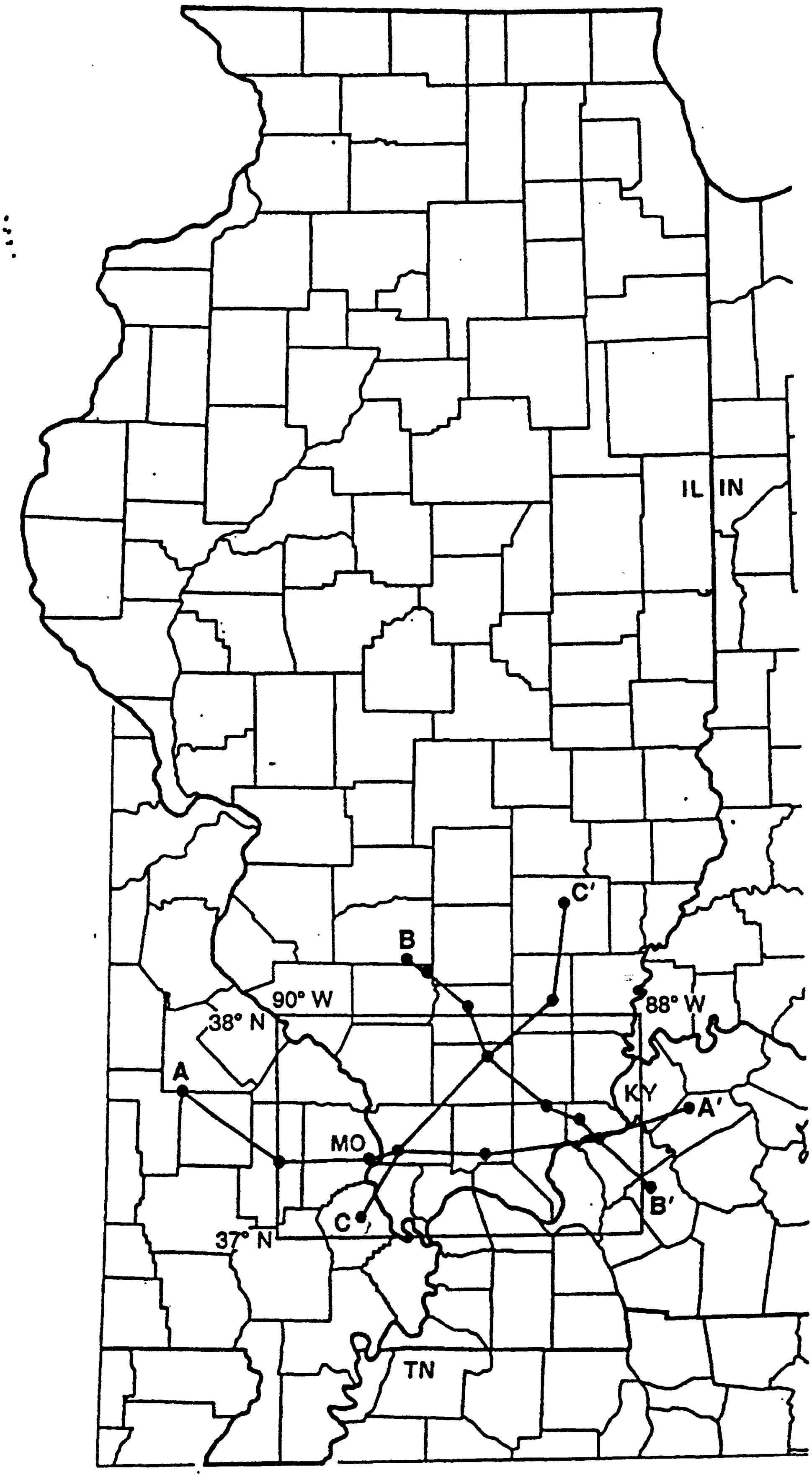

Figure 1. Index of cross sections.

After passing through a relatively flat-lying area, the section cuts through the McCormick Anticline, which was penetrated by the Texas Pacific #1 Streich. The anticline is a flexure caused by thrust faulting and is located to the northwest of the more intensely faulted part of the Fluorspar Area Fault Complex.

Continuing from the McCormick Anticline, the section passes through the Fluorspar Area Fault Complex including Hicks Dome and the Tolu Arch. It crosses the east-west section, A-A', at the Shell #1 Davis and terminates at the Sun #1 Stephens. In the vicinity of the Stephens well, the rocks show evidence of pre-Everton uplift and erosion that removed several hundred feet of dolomite—perhaps significantly more than a thousand feet—from the top of the Lower Ordovician Knox. This unconformity is similar to, but on a scale at least two to three times greater than, that described for the eastern end of section A-A'.

NORTHEAST-TRENDING SECTION C-C'

The northeast-trending section, C-C' passes through two major structural features already described: (1) the faulted flexure in Union County, Illinois, that was tested by the Humble #1 Pickel, and (2) the flower structure, the Pittsburg Anticline tested by the Brehm #1 Harris that lies along the Cottage Grove Fault System.

The southwestern end of the section begins near the north edge of the Mississippi Embayment where gently southerly dipping Late Cretaceous and Tertiary rocks were upturned slightly. These rocks are in angular unconformity with Silurian and older northerly dipping strata on the northern flank of the Pascola Arch. A major reversal in dip brings these rocks back up as the section approaches the Delta Fault, which has approximately 200 feet (60 m) of offset, down on the east, in northern Alexander County, Illinois. Northeast of the fault the strata have relatively steep apparent dips to the southwest. As the section approaches the Humble #1 Pickel well, where it intersects A-A', the southwest dip becomes gentle. Just northeast of the Pickel well, the section intersects the Atwood Fault, which has approximately 750 feet (225 m) of offset, downthrown on the east. Another major dip reversal occurs east of the Atwood Fault where the beds begin to dip steeply eastward into the Illinois Basin.

East of the Atwood Fault, the Mississippian Mammoth Cave Group carbonates thicken depositionally by more than 50 percent in less than 10 miles basinward from their cropline. This is due to penecontemporaneous tectonic subsidence of the basin.

Approximately eight miles to the northeast of the Atwood Fault, a pair of small faults were encountered that have 100-200 feet (30-60 m) of displacement, down to the east. Strata show diminishing apparent dips from the area of the pair of faults to the vicinity of the Cottage Grove Fault System. Within the flower structure of the fault zone, the strata form an anticlinal horst, the Pittsburg Anticline (also shown on B-B'). The horst shows only a few tens of feet of displacement, downward to the southwest. Along the master fault to the northeast, middle Mississippian Valmeyeran and older strata show approximately 300 feet (90 m) of downward displacement. Net displacement across the zone is slightly more than 250 feet (75 m). Chesterian and overlying Pennsylvanian strata show progressively less displacement upward. The net displacement across the zone has decreased to slightly less than 100 feet (30 m) at the Herrin (No. 6) Coal Member of the Carbondale Formation. This relationship suggests that the fault was continually active during and after this 50-million-year post-Valmeyeran interval.

Northeast of the Cottage Grove Fault System the apparent dips continue to diminish in strata above the Lower Ordovician. Dips of Lower Ordovician and older strata range from nearly horizontal in the upper part to the apparent southwestward dips of Cambrian strata and of the Precambrian crystalline surface as the older units thin to the northeast along the section.

The Dale Dome in south-central Hamilton County, which was tested to Precambrian crystalline basement at 12,967 feet (3,952 m) by the Texaco #1 Cuppy, is a major oil-producing structure in the basin. Structural closure on the Dale Dome is approximately 150 feet (45 m) on Mississippian and older strata. Closure on Pennsylvanian strata is only about half as much as on older rocks because thinning of the older strata causes apparent dips to decrease toward the northeast. The Eau Claire Formation rests on basement; pinchout of the Mt. Simon Sandstone around this Precambrian paleotopographic high is corroborated by proprietary seismic-reflection sections. The paleotopographic high may be fault controlled.

The Dale Dome is an important structural demarcation between strata to the south that were tilted northward by the uplift of the Pascola Arch and strata to the north that dip southward toward the post-Mt. Simon depocenter of the Illinois Basin, which is generally centered in the New Madrid Rift Complex.

Important general phenomena illustrated by these sections include the continued subsidence of the southern Illinois Basin due to tectonic stresses and sediment-loading that persisted throughout the Paleozoic. Movement on major faults appears to have been during mid- to late Mississippian and the Pennsylvanian Periods. Many of the faults may also have been active earlier but data are insufficient to detect such movements.

Potential for Magmatic-Hydrothermal Fe-REE-Cu-(Au?) Deposits in the Proterozoic Basement of the Paducah 1° x 2° Quadrangle

Cheryl M. Seeger and Eva B. Kisvarsanyi (MGS)

The western, Ozark highlands part of the Paducah quadrangle is underlain by the Middle Proterozoic (1.48 to 1.45 Ga) St. Francois granite-rhyolite terrane. The terrane is extensively exposed in the St. Francois Mountains of Southeast Missouri, hosts six major and several minor magnetite-hematite deposits, and is an iron-metallogenic province (Kisvarsanyi and Proctor, 1967; Kisvarsanyi, 1981). Seismic reflection profiling suggests that a Proterozoic layered assemblage, possibly an extension of the silicic igneous province, underlies the eastern Paducah sheet under the Illinois basin as well (Pratt and others, 1989). As there are no Precambrian outcrops and only one drillhole intercept in the quadrangle, its potential resources must be appraised indirectly from geophysical data and analogies with similar terranes.

The magnetite-hematite deposits of Southeast Missouri share many similarities with both the Swedish deposits of the Kiruna district and the South Australian deposits of the Stuart shelf, best known for its giant Olympic Dam Cu-U-Au deposit (Meyer, 1988; Hauck, 1990): subvolcanic, rifted continental tectonic settings and Middle Proterozoic, bimodal, silicic-alkalic host rocks. "Red" and rapakivi granites, rhyolites, iron-rich intermediate-alkalic rocks (trachyte), and iron-rich minerals (fayalite, biotite, ferro-hastingsite, etc.) are characteristic. The deposits in the three districts are diverse, but are dominated by iron oxides with ore grades of up to 60 percent Fe. Apatite is ubiquitous in most deposits; rare-earth-elements (REE), F, U, Cu, and Au are locally important.

Most major deposits in Southeast Missouri are within or near the margin of inferred cauldron subsidence structures with granite central plutons; ore tends to be associated with distinctive magnetite trachytes, containing as much as 20 percent by volume of primary disseminated magnetite, and intermediate-alkalic dikes. The deposits occur on both sides of a northwest-trending regional gravity lineament thought to be the geophysical expression of a major Proterozoic tectonic zone, possibly a transform fault (Kisvarsanyi, 1984). High-amplitude positive magnetic anomalies are associated with the magnetite-dominant deposits. Caldera-collapse breccias and permeable ash-flow tuffs are favorable ore hosts. As most known deposits are associated with erosional highs on the Precambrian surface, nearby basal conglomerates frequently contain abundant hematite clasts. The Pea Ridge deposit, the only one currently active in the district, is in a downfaulted block of megabreccia near the center of a collapsed caldera; it has an estimated 132 million tons of 57 percent Fe reserves with 200,000 tons of 12 percent REE and traces of gold. Recent work in the mine by a joint team of USGS and DGLS scientists supports a magmatic-hydrothermal origin for the ore (Day and others, 1991).

In the southwestern part of the Paducah quadrangle near Marble Hill, a single drillhole bottomed in medium-grained, slightly porphyritic, red rapakivi granite typical of the central plutons identified in the Rolla quadrangle. Near the bottom of the intercept, the granite is intruded by a fine-grained aplite dike. More than a dozen drillholes west of Marble Hill, all in the Rolla quadrangle, intercept rhyolite ash-flow tuff, rhyolite porphyry, rhyolite breccia, and, trachyte porphyry. In all of these drillholes, the Precambrian surface is directly overlain by tens of feet of basal conglomerate with clasts up to several feet in diameter; some clasts are hematite. The conglomerate and overlying sandstone are stained red by iron oxide cement; in some holes, sand-sized specular hematite grains have been observed tens of feet above the Precambrian surface in the Paleozoic section.

In the Marble Hill area, the aeromagnetic map shows a ring-shaped positive magnetic anomaly with an oval magnetic low, about 8 miles in diameter, at its center. The scale and shape of this magnetic pattern are very similar to those in the Rolla quadrangle where cauldron subsidence structures with ring dikes and central plutons have been identified (i.e. at Pea Ridge). The coincidence of thegeophysically inferred Marble Hill cauldron subsidence structure with favorablehost rocks in this area, and the occurrence of hematite in the overlyingsediments are considered to be permissive criteria for a magnetite-hematitedeposit in the southwestern part of the Paducah sheet. Similar deposits may be present elsewhere, but are more tenuous to infer.

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Early-Middle Ordovician Evolution of the Illinois Basin: Paleontologic and Sedimentologic Constraints

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Although the Ordovician lithostratigraphy of the Illinois Basin has been well established by previous workers, modern biostratigraphic and sedimentological studies are, for the most part, lacking, and detailed studies are limited to outcrop areas on the basin-bounding arches. This study was initiated to document the age and depositional relationships of the early-Middle Ordovician strata of the Illinois Basin. These data provide a basis for defining the geometry of the basin, to qualitatively evaluate the relationship of basin subsidence to the Taconic orogeny, and provide additional control for quantitative subsidence modeling.

The study contains four elements: development of a conodont-based biozonation for age control, description and interpretation of lithofacies, log-characterization of the lithofacies, and subsurface mapping based on well-logs and core material to determine the temproal and spatial relationship of depositional environments.

The conodont biozonation is based on conodont samples collected from eleven, cored subsurface sections and from outcrop studies. For each subsurface section, samples were collected from the lowermost post-Knox unit cored through the Galena Group, or its equivalents, and the ranges of species present graphically correlated to the Middle Ordovician composite standard. Outcrop material has been collected for units poorly represented in available core material, and/or for intervals characterized by low faunal recovery.

Lithofacies have been identified on the basis of detailed description and petrographic sampling of cores and outcrops. Where available, geophysical-logs have been compared to the lithic succession in cores to characterize the geophysical response of the differing rock types.

Based on these data, three genetic units can be identified within the Ancell sequence: (1) a transgressive unit made up of retrogradational, shallow-marine parasequences with a relative sea level maxima within the Dutchtown Formation; (2) a progradational unit that has a relative sea level minima represented by evaporite-bearing peritidal parasequences of the upper Joachim Dolomite; and (3) a predominantly subtidal aggradational unit including the uppermost Joachim, Starved Rock Sandstone and Glenwood Formation.

The Tonti Member of the St. Peter Sandstone is a time-transgressive sandstone lithotope that has a facies relationship with the Dutchtown Formation, Joachim Dolomite and Glenwood Formation.

The nature of the Everton Dolomite-St. Peter Sandstone contact is locally erosive, but the duration of the hiatus is undetermined. As a consequence, it is unclear if the Everton is a genetic sequence in its self, or if the Everton represents the low-stand facies tract of the Ancell sequence and therefore, the Everton should be included in the Ancell Group.

$^{40}Ar/^{39}Ar$ Geochronology of Intrusive Rocks and Mississippi-Valley-type Mineralization and Alteration from the Illinois-Kentucky Fluorspar District

Lawrence W. Snee and Timothy S. Hayes (USGS)

Determining the isotopic age of Mississippi-Valley-type (MVT) mineral deposits is difficult because datable phases with suitable isotopic integrity are generally absent from MVT ore. In the Illinois-Kentucky fluorspar district, numerous small igneous intrusions are exposed or have been intersected by drill core. Goldhaber and others (1991) presented new evidence supporting a thermal relationship between MVT deposits and igneous activity; their evidence includes the thermal zonation revealed by fluid inclusion homogenization temperatures in fluorites around Hick's Dome, Illinois. Biotite/phlogopite of lamprophyre and mica peridotite dikes and plugs of the district were visibly altered to sericite by the MVT mineralization. Many of the igneous rocks and two alteration phases in this area have been dated in the past but the isotopic dates range from 100 to nearly 400 Ma. Although many of these dates cluster in the mid-Permian, the analytical precisions generally span about 30 million years. We are using the $4^0Ar/^{39}Ar$ age-spectrum technique to date primary and alteration phases from the Grants intrusive breccia (Illinois), the Hamp mine intrusive breccia (Illinois), a dike at the Hutson mine (Kentucky) and alteration phases from the West Morrison and Annabelle Lee mines (Illinois).

$^{40}Ar/^{39}Ar$ plateau dates for hornblende and biotite from unaltered Grants intrusive breccia, which is located about 2.5 miles south-southwest from the crest of Hick's Dome, are concordant at 271.7±0.7 and 272.7±0.7 Ma, respectively (fig. 1). Slightly altered biotite from the Hamp mine intrusive breccia yields a disturbed age spectrum but is approximately the same age or slightly older; less altered biotite from the Hamp mine breccia will soon be analyzed in an attempt to improve the age determination. Sericite that formed from alteration of biotite in the Hamp breccia during MVT mineralization yields equivocal $^{40}Ar/^{39}Ar$ results and is also being re-analyzed.

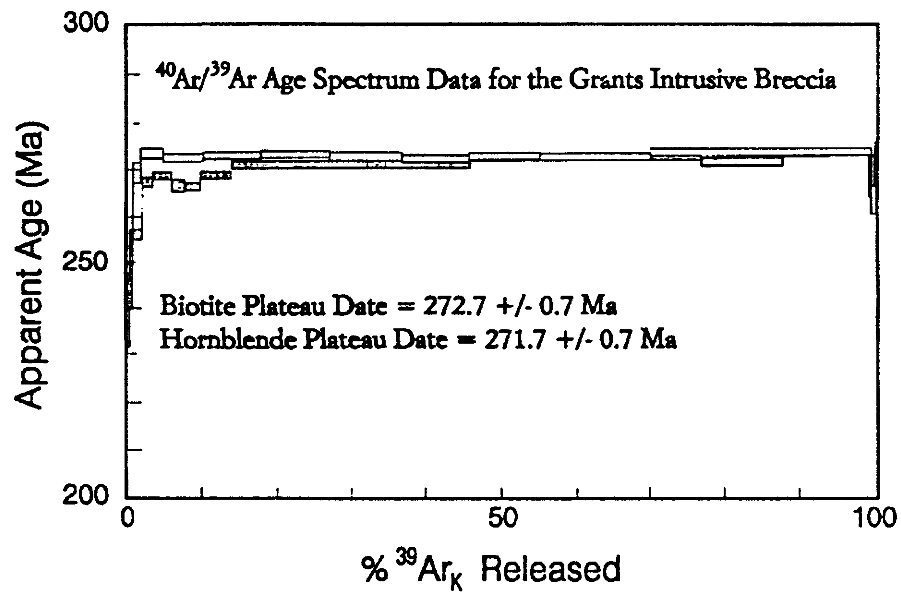

Figure 1. Composite $^{40}Ar/^{39}Ar$ age spectrum diagram for primary hornblende and biotite of the Grants intrusive breccia, Illinois-Kentucky fluorspar district.

Our preliminary $^{40}Ar/^{39}Ar$ data indicate that the best estimate for the emplacemaent age of the Grant intrusive breccia within the Illinois-Kentucky fluorspar district is 272±1 Ma. Because MVT mineralization altered primary phases within intrusive rocks of the district, the mineralization is younger. However, if the conclusions of Goldhaber and others (1991) that MVT mineralization is thermally related to these high-level intrusions is correct, the age of MVT mineral deposits is likely not much younger than 272 Ma.

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Sulfur Geochemistry of a Sphalerite-Bearing Illinois Basin Coal

E.C. Spiker, R.B. Finkelman, A.L. Bates, and J.R. Hatch (USGS) and R.D. Harvey (ISGS)

Epigenetic sphalerite in coals from the marginal platforms of the midcontinent sedimentary basins occurs mainly in veins, cleat, clastic dikes, and other small-scale structural features, and is commonly associated with kaolinite, pyrite, and calcite. Previous studies of the regional and stratigraphic distribution, mineralogy, paragenetic sequence, and fluid inclusion chemistry of the coal-hosted sphalerites suggest they were deposited from Mississippi Valley-type (MVT) basin brines (Hatch et al., 1976; Cobb, 1981; Whelan et al., 1988).

Although the zinc in these coals was probably derived from basin brines, the host coal may be the source of the sphalerite sulfur. A better understanding of the source of the sulfur in these coal beds and the timing and extent of interaction between the coal and basin brines is of great importance in the mining and utilization of the coal. Therefore, a detailed study was initiated of the sulfur geochemistry, mineralogy, and sulfur isotopic composition of sphalerite-bearing Illinois basin coals. This initial study is based on samples of the Colchester (Ill. No. 2) Coal bed that is exposed in the Industry mine, McDonough County, western Illinois.

At the locality sampled, the coal bed is 66 cm thick and sphalerite occurs in cleat at the base of the bed. Chemical analysis of six bench-channel samples indicates the total sulfur content of the coal bed ranges from 2.8

to 6.7 wt. %, except for a 1.5 cm thick pyrite-rich inertinite layer near the top of the coal bed which contains 21.3 wt. % total sulfur. Pyritic sulfur ranges from 0.8 to 2.9 wt. %, and organic sulfur ranges from 0.9 to 1.3 wt. %. Pyrite occurs mainly as cell fillings in inertinite and as cleat fillings. Isotopic ($\delta^{34}S$) values of the pyritic sulfur increase systematically from -7.0‰ at the top of the bed to +11.2 ‰ just below the middle of the bed, then decrease to +7.6 ‰ at the base of the bed. This large variation is partly the result of the abundance of cleat-filling pyrite. The $\delta^{34}S$ of the organic sulfur is not influenced by this late-epigenetic sulfidization and shows a near linear increase from +1.5 ‰ at the top of the bed to +7.2 ‰ at the base of the bed. In contrast, the δ34S of the cleat-filling sphalerite at the base of the bed is +4.7 ‰.

Chemical analyses also indicated the coal bed contains 0.01 to 0.38 wt. % acid volatile monosulfide sulfur, excluding the sphalerite at the base of the bed. Scanning electron microscopic (SEM) analyses show this monosulfide is galena, which appears to be epitaxial to the cleat-filling pyrite. Although galena is common in MVT mineralization, it has not been reported associated with coal-hosted sphalerite in the Illinois basin. This has been attributed to prior stripping of lead from the mineralizing solutions as a result of the coal's distance from the heart of the Upper Mississippi Valley Zn-Pb district (Whelan et al., 1988). The $\delta^{34}S$ of the galena ranges from -3.3 ‰ at the top of the bed to +7.1 at the base of the bed, similar to that of the pyritic sulfur.

SEM analyses indicate the cleat-filling pyrite is etched and, in some cases, appears to be replaced by kaolinite, providing evidence for sulfide remobilization. Cobb (1981) found that pyrite is extensively replaced by sphalerite in some coals. Our preliminary conclusion is that the cleat-filling pyrite is the source of the sphalerite sulfur in the samples studied.

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Shortcomings of Some Proposed Precipitation Mechanisms for Mississippi Valley-Type Deposits

Charles S. Spirakis and Allen V. Heyl (USGS)

Identifying the precipitation mechanisms for all minerals in the Mississippi Valley-type deposits (sulfides, disulfides, carbonates, sulfates, and fluorite) and explaining why all of these mechanisms affected the same sites are crucial to formulating a credible genetic model. Yet some of the most often cited models of ore formation do not even attempt to link various precipitation mechanisms to the same sites and are incompatible which geologic constraints.

Mixing of various cation- and anion-bearing solutions could produce some minerals, but such mixing could not have occurred uniformly enough to form the delicate banding in sulfides, carbonates, and fluorite that can be traced for several tens of kilometers in many districts. Dissolution of sulfides is also a problem for mixing models. These models avoid the low solubility of sulfide with metals (Pb, Zn) by transporting each in a separate solution to the sites of mineralization. However, removing sulfide and metals as sulfide minerals dissolve requires that both are carried in the same solution; it is impossible to unmix solutions to that each component is carried away separately. The many episodes of precipitation and dissolution recorded in the ores indicate that the volume of water needed to alternately carry metals and sulfide sulfur to the site of precipitation and then to partially dissolve highly insoluble sulfides and carry their components away is unreasonable. Mixing of calcium- and fluorine-bearing solutions actually hinders precipitation of fluorite because calcium and fluorine form a soluble complex,

CaF^+. Mixing models do not provide a source of -1 valent sulfur, which is required to precipitate pyrite; mixing models also do not explain why organic matter is a ubiquitous component of the ores.

Sulfate reduction by organic matter at the sites of mineralization could produce -1 valent sulfur for pyrite formation and is consistent with the association with organic matter, but existing kinetic data indicate, that at temperatures of MVT mineralization (typically 100° to 160°C), sulfate reduction is so slow that only a trivial amount of sulfide could be produced as the solution flowed through the ore zone at rate of a few meters of tens of meters in a year. Also, the oscillations between precipitation and dissolution in the ore require that the precipitation mechanism be readily reversible, but thermodynamic data show the sulfate reduction is not reversible.

The precipitation of carbonates by effervescence of carbon dioxide as the solution rises to lower pressure environments addresses only the precipitation of carbonates (none of the other ore stages), and decrease in CO_2 solubility due to release of pressure may be completely offset by the increase in solubility due to decrease in temperature. Also, the only evidence for effervescence, CO_2-rich inclusions, could have formed by other processes, such as calcite dissolution,m thermal degradation of organic matter, or oxidation of organic matter.

Cooling could cause some of the minerals in these deposits (not carbonates) to precipitate, but it is highly unlikely, that as the mineralizing solution migrated over long distances through the host rock, each mineral would cool to the point of saturation at exactly the same location as did each other mineral in the paragenesis. Mixing also fails to provide a reasonable explanation for the occurrence of all stages of the paragenesis at the same sites because it requires an improbable number of solutions all mixing at the same sites. Furthermore, the similarity in paragenesis from district to district requires the same series of mixing events in various districts. Sulfate reduction fares somewhat better in explaining why the ore minerals precipitate at the same sites because organic matter is necessary for sulfate reduction, and organic matter may trigger other ore mineral-forming reactions. If thiosulfate ($S_2O_3^=$), rather than sulfate, is the oxidized sulfur species in the mineralizing solution, then organic matter may link all stages of the paragenesis to the same sites by acting as (1) a reductant to form sulfides and disulfides, (2) a source of organic acids to dissolve carbonates, (3) a source of CO_2 at higher temperatures, which, in the presence of organic acids, precipitates carbonates, (4) a source of CO_2 to form $MgHCO_3^+$ at the expense of MgF^+ which, triggers fluorite precipitation, and (5) a substrate for bacterial metabolism of thiosulfate in the late cooler stages to form $SO_4^=$ and precipitate barite. Because many reactions involving thiosulfate and other partly oxidized sulfur species are readily reversible, they may account for sulfide dissolution.

A Relationship Between Hicks Dome and Temperature Zonation in Fluorite in the Illinois-Kentucky Fluorspar District, A Fluid Inclusion Study

Cliff D.Taylor, Elizabeth L. Rowan, Martin B. Goldhaber, and Timothy S. Hayes (USGS)

In order to evaluate the thermal influence of Hicks Dome on the Illinois-Kentucky fluorspar district (FSD), fluid inclusions were studied in fluorite from 17 mines spanning the presently recognized geographic limits of the district. The averaged filling temperatures of liquid dominant, two phase primary inclusions and hottest secondary inclusions in fluorite decline distinctly from the center of the dome (175°C), to the flanks of the dome (150°C), to the Cave-in-Rock subdistrict (132°-150°C), to the most distant mines on the southern margin of the district (35°-119°C, see fig. 1). High salinities (indicated by low temperatures of final ice melt) are consistent district wide and for all but the final stage of fluorite deposition (post-P7, using the nomenclature of Richardson and Pinckney, 1984), are in a narrow range of $-15.0°<Tm<-18.0°C$. Crushing studies and clathrate freezing behavior indicate the presence of a Ca-Mg rich fluid and a methane-CO_2 rich vapor phase. In two samples, one from the Rosiclare subdistrict and one from the Lucille mine (fig.1), which exhibit nearly complete fluorite paragenesis, filling temperatures rise to a maximum (162° and 147° C respectively) during early yellow and purple stages (Y2 to P3), followed by lower (124° and 121° C) and fairly consistent filling temperatures or slightly rising temperatures (132° and 135° C) prior to the collapse of the hydrothermal system after latest (P7) fluorite.

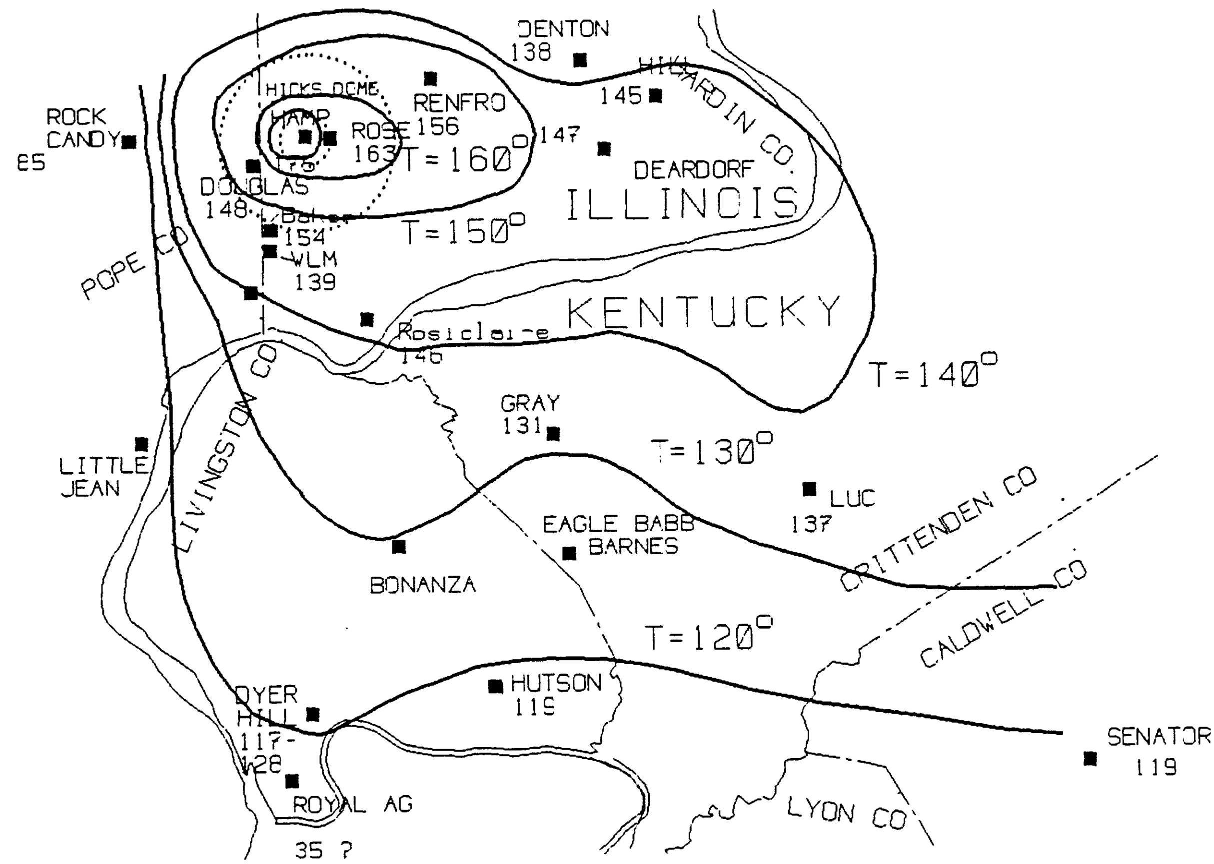

Figure 1. Mine locations and thermal zonation around Hicks dome in the Illinois-Kentucky fluorspar district.

The consistent similarity throughout the study area of observed inclusion types and fluorite ore and gangue mineral paragenesis to the well documented paragenetic relationships observed in the Cave-in-Rock subdistrict (see Hayes and Anderson, this volume), indicates that fluorite deposition in the FSD was the result of a single interconnected hydrothermal system. Late early Permian (272 Ma) age dates on igneous breccias related to the Hicks dome cryptovolcanic event (Snee and Hayes, this volume) coupled with the thermal zoning data of this study indicates that formation of the mineralized FSD fault complex was also late Paleozoic and suggests a relationship between igneous activity and FSD mineralization. Hicks dome has previously been suggested as a heat source for the FSD, and vitrinite reflectance studies in the New Albany shale surrounding the dome indicate a local area of thermal maturation greater than expected from reconstructions of New Albany burial history (Cluff and Byrnes, 1990). However, this study provides the first direct evidence for district-wide thermal zonation in the FSD with temperatures in fluorite decreasing away from Hicks dome.

Although our data clearly show that Hicks dome was an important thermal influence on the FSD it may not have been the fluoride source for the entire district. Recent seismic reflection studies (Potter and others, this volume) show a relationship between structures that offset basement and fluorite mineralization. These structural data may indicate that other sources and conduits for deep-seated fluoride-bearing fluids may have been present in addition to the Hicks dome system.

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Assessment of the Coal Resources in the Paducah Quadrangle

Colin G. Treworgy, Margaret H. Bargh, Russell J. Jacobson, and Gayla K. Coats (ISGS)

The Paducah Quadrangle covers the southwestern edge of the Illinois Basin Coal Field. Most of the coal field within the quadrangle is in Illinois; only a small area of the field lies within the Kentucky and Indiana portions of the quadrangle. The quadrangle has been an important area for coal mining since the early 1800's. In 1990, mines in the Paducah Quadrangle produced just over 22 million tons; about 33 percent of Illinois' coal production, 16 percent of the total coal field production, and more than 2 percent of total U. S. production.

Approximately 37 percent of the Paducah Quadrangle is underlain by Pennsylvanian-age strata. The Pennsylvanian strata thicken northward and eastward from their southern limit towards the centers of the Fairfield Basin in Illinois and the Moorman Syncline in western Kentucky. Within the quadrangle area these sediments have a maximum thickness of about 2200 feet. Sixteen coals have been mapped within the quadrangle. Total identified resources are 17 billion tons; about 7 percent of the total resources in the Illinois Basin Coal Field. Four seams account for more than 95 percent of the resources: the Herrin, Springfield, Dekoven, and Davis Coals. Two-thirds of the resources (11.3 billion tons) are in the Herrin and Springfield Coals. Most of these resources have a high (2.5 to 5 percent) sulfur content. Some resources with a lower sulfur content are found in the Herrin, Springfield, Murphysboro, Reynoldsburg, Bell, Oldtown and New Burnside Coals (Gluskoter and Simon, 1968; Hopkins, 1968; Nelson et al, 1991). Of these, only the Springfield Coal has a significant tonnage of relatively low-sulfur resources (1.3 billion tons).

The coal resources of the four major seams were ranked according to their potential for development in the foreseeable future. Criteria considered were thickness and depth of the seam, size of mining block, and proximity to towns, areas densely drilled for oil, and abandoned mines (Table 1; see Treworgy et al. 1978 and Treworgy and Bargh 1982 for a full explanation of this model). Deposits with characteristics similar to those currently mined were ranked as having a high potential for development. Deposits with less favorable characteristics were ranked moderate or low potential. Deposits that would be prohibitive to mine because of the size or configuration of the mine block or the proximity to towns, oil fields, or abandoned mines were ranked as having a restricted potential for development. Based on this model, 2.3 billion tons of the Herrin Coal, 1.3 billion tons of the Springfield Coal, 57 million tons of the Davis Coal, and 6 million tons of the Dekoven Coal have a high potential for development. Approximately 91 percent of these resources are recoverable only by underground mining. Only 381 million tons of the highest-ranked resources have a low to medium sulfur content (1 to 2.5 percent sulfur).

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Table 1. Coal Model

Diagnostic Criteria	Development Potential
Coal >150' deep, > = 28" thick within urban areas or oilfields or narrow blocks between abandoned mines Coal <150' deep, > = 18" thick within urban areas, public lands, interstates, or cemeteries	Restricted
Coal 150' to 400' deep and > = 54" thick Coal >400' deep and >66" thick Minimum block size 50 million tons Coal 18 to 29" thick and ≤50' deep; 30 to 47" thick and ≤75' deep; 48 to 71" thick and ≤100' deep; 72" or more thick and <125' Minimum block size 6 million tons	High
Coal that is not ranked high but is >150' deep and > = 42" thick or 18" or more thick and <150' deep	Moderate
Coal >150' deep and 28" to 42" thick	Low

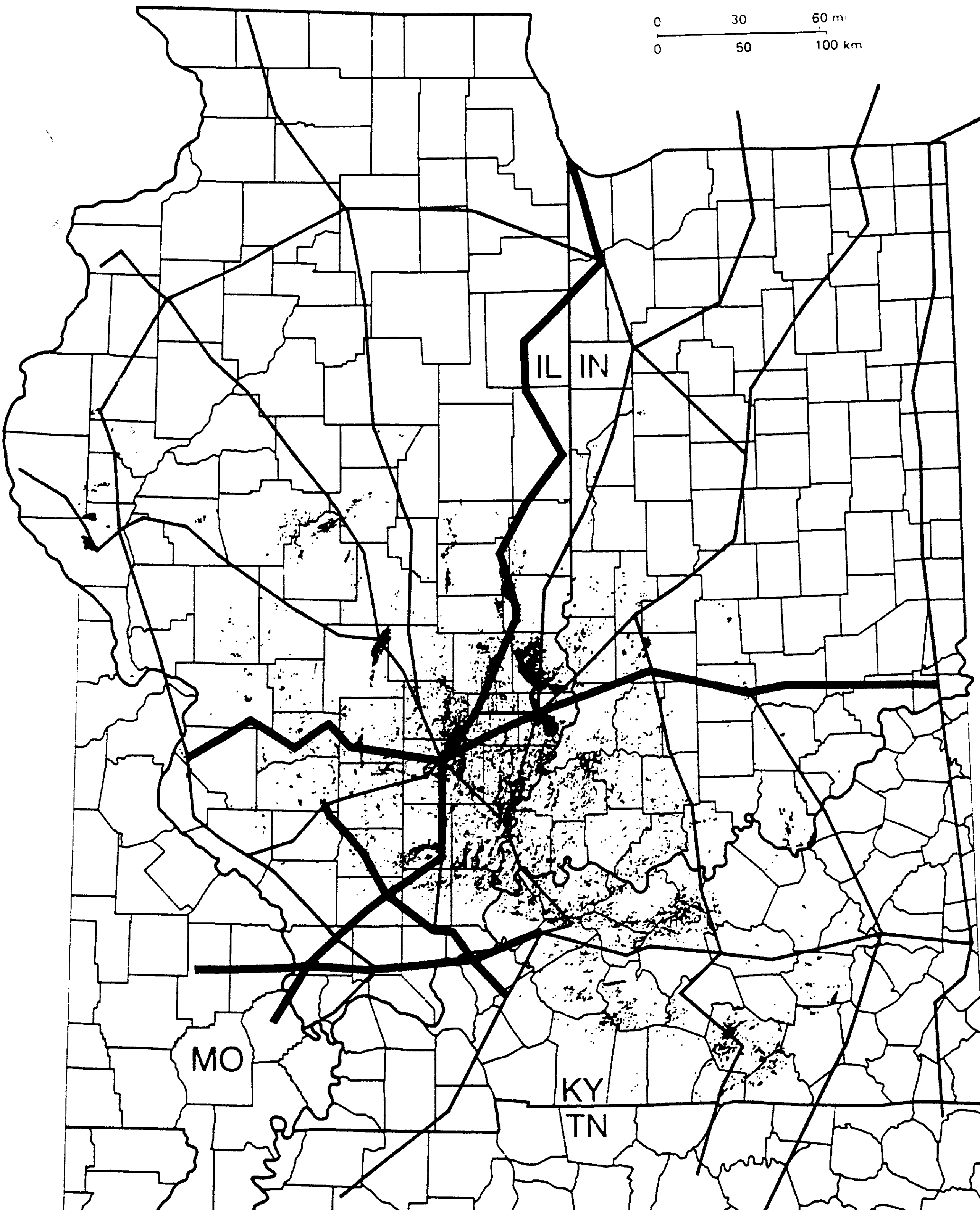
The Illinois Basin in Cross Section

Janis D. Treworgy and Stephen T. Whitaker (ISGS)

The structural and stratigraphic framework of the Illinois Basin is portrayed in a network of regional cross sections (see figure) being prepared by the Illinois Basin Consortium (Illinois, Indiana, and Kentucky Geological Surveys). The sections consist of wireline logs of the deepest wells and show formation boundaries and gross lithofacies of the entire stratigraphic column as well as possible structural and stratigraphic hydrocarbon plays. Available seismic data, sample and core descriptions, and existing structure, isopach, and facies maps are also being used in preparing the sections. The vertical scale is 1 in = 400 ft (1:4800); the horizontal scale is 1 in ≅4 mi (1:250,000).

Several stratigraphic and structural relations seen in the cross sections modify previous concepts of the basin's evolution. Recognition of a previously unreported stratigraphic unit below the lower Ordovician Everton suggests that there may have been continuous deposition across the Sauk-Tippecanoe Sequence boundary in the

CROSS SECTION NETWORK



Oil and gas fields in the Illinois Basin

cross sections completed to date

southernmost part of the Illinois Basin. Local absence of this unit and significant thinning of the underlying Shakopee Dolomite (Sauk Sequence) in parts of the Rough Creek Graben, suggests uplift and erosion of horst blocks in that area prior to deposition of the Everton Formation (Tippecanoe Sequence). Thinning of Mississippian Valmeyeran units along the La Salle Anticlinorium suggests that compressive forces began acting there earlier than previously thought.

Many units that have been considered discrete and sequentially stacked in one part of the basin are apparently in facies relation with one another in other areas. For example, the upper part of the Everton Dolomite and the lower part of the St. Peter Sandstone appear to be in facies relation. The same may be true of the overlying Dutchtown Formation, the upper part of which may be in facies relation with the lower part of the overlying Joachim Formation. Relatively pure Silurian carbonate bank deposits of the northern reaches of the basin are shown to be laterally equivalent to shaly carbonate basinal facies. The Borden Siltstone is interpreted here as being in facies relation with the Ft. Payne cherty limestone, and likewise the Ft. Payne with the Ullin Limestone. These and other facies relations indicated on these cross sections should stimulate further research.

Potential structural and stratigraphic hydrocarbon plays are apparent in many areas of the basin and at a number of horizons, including several that have received minimal exploration to date. The structural plays include anticlinal and fault entrapments and fracturing of organic-rich shales and of carbonate rocks. The stratigraphic plays include pinchouts of porous siliciclastic and carbonate rocks, sand bars within incised paleovalleys, reefs, onlap and pinchouts of reservoir rocks above unconformities and on paleostructures, and truncation of reservoir rocks below unconformities.

Origin, Evolution and Migration of Illinois Basin Brines

L.M. Walter (University of Michigan-Ann Arbor), A. Stueber (Southern Illinois University), T.J. Huston, A. Martini, V. Granath, and R.R. Blake (University of Michigan-Ann Arbor)

We report chemical analyses of subsurface formation waters from the evaporite-poor Illinois Basin in order to evaluate possible processes for the origin of solutes and water in these brines. Processes involved may include retention of evaporatively-concentrated seawater, evaporite mineral dissolution, carbonate and siliciclastic mineral diagenesis, and meteoric water recharge. Chemical systematics and regional patterns in hydrogeochemistry are also used to constrain the relative importance of these processes and provide a better understanding of fluid migration pathways within the Illinois and other cratonic basins. We compare chemistries of Illinois Basin formation waters with those of the neighboring evaporite-rich Michigan Basin. This comparison shows that significant reservoir compartmentalization exists in both basins and serves to illustrate some of the unique aspects of Illinois Basin brines.

Subsurface formation waters obtained from various Ordovician-Pennsylvanian reservoirs within the Illinois Basin differ significantly in elemental and isotopic composition. The New Albany Shale Group appears to retard exchange between the upper and lower stratigraphic segments of the Illinois Basin. Formation waters sampled from reservoirs underlying the New Albany Group (Ord.-Dev.) versus those sampled from overlying (Miss.-Penn.) strata have distinct Na-Cl-Br systematics. Ord.-Dev. strata have waters that have Na/Br and Cl/Br ratios nearly equivalent to seawater or seawater evaporated short of halite precipitation. Miss.-Penn. formation waters all have significant enrichment in Na and Cl, which suggests that halite dissolution has played an important role in providing salinity to reservoirs in this upper segment of the basin. Importantly, Illinois Basin waters are distinct from those of the Michigan Basin, which have up to 10 times lower Na/Br and Cl/Br ratios. Formation waters from the halite-rich Michigan Basin have chemistries consistent with seawater evaporated well into halite facies and show finer-scale stratigraphic differences in water chemistry. This is likely caused by more frequent interbedding of shales and evaporite strata in the Michigan Basin.

Strontium and boron isotopic compositions of Illinois Basin formation waters also exhibit distinct patterns between upper and lower stratigraphic segments. Sil.-Dev. formation waters exhibit mixing arrays on $^{87}Sr/^{86}Sr$

versus 1/Sr diagrams, whereas Miss.-Penn. show completely random distribution. Local siliciclastic rock/water interaction appears important in controlling Sr isotopic as well as Li and B contents of formation waters from Miss.-Penn. strata.

The Illinois Basin formation waters are interpreted as being derived from seawater concentrated by evaporation short of halite precipitation. These fluids have also experienced extensive rock/water interactions with carbonate and sulfate minerals. Interaction with halite is limited by the evaporite-poor nature of this basin. Only in the reservoirs adjacent to the evaporite-bearing St. Louis limestone are waters influenced by halite dissolution. Meteoric water invasion has affected units throughout the stratigraphic section, but has apparently not been sufficiently extensive to completely expel the dense formation waters from this basin.