Proceedings of the

Illinois Basin Energy and Mineral Resources Workshop

September 12-13, 1994

Evansville, Indiana

Edited by

Jennie L. Ridgley, James A. Drahovzal, Brian D. Keith, Dennis R. Kolata

Sponsored by the

Illinois Basin Consortium

Illinois State Geological Survey
Open-File Report 94-4

Indiana Geological Survey
Open-File Report 94-12

Kentucky Geological Survey
Open-File Report 94-12

and the

United States Geological Survey

Open-File Report 94-298

Introduction

The Illinois Basin, which covers about 110,000 square miles in Illinois, Indiana, and Kentucky, contains a wealth of energy and industrial- and metallic-mineral resources. These resources are an important constituent of the economies of states located in the basin. Because new deposits of these resources will be needed to sustain and enhance the economies of this region, there is a continued need to further our understanding of the geology of the basin and how it relates to energy and mineral resources and to environmental problems.

In 1989, the Illinois Basin Consortium (IBC), consisting of the Illinois, Indiana, and Kentucky state geological surveys, was formed to advance the understanding of the geology of the Illinois Basin, by coordinating the various state survey studies, and by utilizing the surveys' collective expertise. The IBC and the U.S. Geological Survey entered into a collaborative effort in 1990 to integrate their geochemical and fluid-flow expertise with ongoing state surveys' research. The IBC (surveys) continued to study problems related to the structural formation of the basin, sedimentology of strata filling the basin, and formation and distribution of hydrocarbon, and industrial- and metallic-mineral resources. The USGS focused on aspects of basin-scale fluid flow and its link to regional patterns of diagenesis, sedimentary metal deposits, and hydrocarbon accumulations. The ultimate goal of the cooperative program is to provide decision makers with geological information for current and future resource and environmental assessment.

Many new studies were initiated under the joint IBC-USGS agreement, including the acquisition and interpretation of regional seismic data not formerly available to all parties. These data are providing valuable new insights into the tectonic history of the basin and on the role of tectonism on sedimentation and formation of local structures that could be important new hydrocarbon exploration targets in the structurally complex, deep part of the basin.

The 41 abstracts in this volume represent results of some of the basin studies and were presented at this workshop. The workshop, which is the culmination of the 5-year cooperative research effort between the IBC and USGS, is a means for transferring information gained from this effort to the public. The workshop was also intended to provide a forum for those concerned with the geology, energy and mineral resources, geologic hazards, and geology-related environmental problems in the basin to discuss future directions for research and possible cooperative investigations.

Technical Program

OPENING SESSION (INDIANA B)

MONDAY SEPTEMBER 12
8:00AM-8:30AM

JAMES A. DRAHOVZAL **(KGS), WELCOME AND WORKSHOP FORMAT**

NORMAN C. HESTER **(IGS), IBC PROGRAM OVERVIEW**

JENNIE L. RIDGLEY **(USGS) USGS-ESB PROGRAM OVERVIEW**

FRANK MCCLOSKEY **(US HOUSE OF REPRESENTATIVES), COMMENTS**

TECHNICAL SESSION I (INDIANA B) - J. A. DRAHOVZAL, SESSION CHAIR

8:30am **D.R. Kolata**, History of the Illinois Basin: An Overview

9:00am **T.G. Hildenbrand, V.E. Langenheim,** and **P.C. Heigold**, Geophysical Setting of the Northern Reelfoot Rift and Southern Illinois Basin Region

9:30am **C.J. Potter** and **J.A. Drahovzal**, The regional configuration of the Cambrian Reelfoot-Rough Creek-Rome Rift System

10:00am Coffee break

10:30am **J.J. Lewis**, Tectonic History of the Wabash Valley Rift Using Seismic Reflection and Stress Field Effects

11:00am **D.C. Harris**, Lithostratigraphy and Hydrocarbon Potential of the Cambrian (Pre-Knox) Interval in the Conoco No. 1 Turner Well, Rough Creek Graben, Western Kentucky

WORKSHOP LUNCHEON (INDIANA A)
11:30AM-1:00PM GUEST SPEAKER—GORDON EATON (USGS)

TECHNICAL SESSION II (INDIANA B) - J.L. RIDGLEY, SESSION CHAIR

1:00pm **R.C. Burruss**, Alteration of Oils During Migration in the Illinois Basin: Geochemical Constraints on Paleohydrology

1:30pm **N.S. Fishman** and **J.K. Pitman**, Basin-wide paleofluid flow in Cambro-Ordovician siliciclastic rocks of the Illinois Basin: Diagenetic and geochemical evidence from the Mt. Simon and St. Peter Sandstones

2:00pm **C.S. Spirakis**, The Possible Role of Thermal Convection as a Result of Fracturing of Radioactive Basement Rocks and Implications for Fluid Flow, Heat Flow, and the Genesis of the Upper Mississippi Valley Zinc-Lead Ores

2:30pm **E.L. Rowan, M.B. Goldhaber,** and **J.R. Hatch**, Biomarker and Fluid Inclusion Measurements as Constraints on the Time-Temperature, and Fluid-Flow History of the Northern Illinois Basin, and Upper Mississippi Valley Zinc District

3:00pm **M. Goldhaber, E. Rowan, J. Hatch, R. Zartman, J. Pitman, R. Reynolds**, The Illinois Basin as a Flow Path for Low Termperature Hydrothermal Fluids

3:30pm Coffee break

3:30-6:30PM POSTER SESSION (INDIANA C)

Pennsylvanian and Coal

M.L. Barnhill, and **H. Zhou**, A Comprehensive Core Book of Pennsylvanian Rocks of the Illinois Basin: Its Construction and its Applications

J.G. Callis, and **J.A. Rupp**, Coal Resources of Daviess County, Indiana: A GIS-Based Resource Assessment

H. Cetin, C. Conolly, and **J.A. Rupp**, A GIS Approach to Calculate Available Coal Resources in Alfordsville 7.5 Minute Quadrangle, Indiana

C.A. Chenoweth, M.H. Bargh and C.G. Treworgy, The Illinois State Geological Survey's Digital Database of Underground Mines

J.A. Devera, Ichnology of Morrowan through Basal Desmoinesian Rocks in Indiana

P.L. Hansley, Diagnesis and Fluid Flow in Lower Pennsylvanian Rocks, Illinois Basin

C.L. Oman, S.J. Tewalt, and **L.J. Bragg**, Data from Illinois Basin Samples Contained in the U.S. Geological Survey's New Coal Quality CD-Rom

C.G. Treworgy, R.J. Jacobson, C.A. Chenoweth, and **M.H. Bargh**, Geological Constraints on the Mining of Coal in Illinois

L.Weber, Indiana Coal Mine Information Project

Petroleum Studies

J.M. Guthrie, Unexpected results from a geochemical approach to typing and correlation of Ordovician oils in the Illinois Basin

M.E. Henry, Porosity Loss in Mississippian Oolitic Grainstones, Southern Illinois: Implications for Hydrocarbon Migration

H.E. Leetaru, Seismic Character Analysis of a Mixed Siliciclastic-Carbonate Reservoir

Z. Lasemi, J.D. Treworgy, R.D. Norby, and **J.P. Grube**, Waulsortian Mounds and Hydrocarbon-Bearing Facies in the Ullin ("Warsaw") Limestone of the Illinois Basin

D.L. Macke, Hydrocarbon plays within the Illinois Basin Province for the National Petroleum Assessment

W.M. Mitchell, Assessment of the 3,000 and 10,000 ppm Total Dissolved Solids Boundaries in the Mississippian and Pennsylvanian Aquifers of Southwestern Indiana Using Geophysical Logs

J. L. Ridgley, and **V.F. Nuccio**, Character and depositional environments of potential source rocks in the lower part of the Mississippian St. Louis Limestone of the Illinois Basin

Miscellaneous Basin Studies

L.C. Furer, Basement Tectonics in the Eastern Illinois Basin of Indiana

J.W. Nelson, and **J.D. Treworgy**, Preliminary Identification of Transgressive-Regressive Depositional Cycles in the Chesterian Series in Southern Illinois

V.F. Nuccio, Thermal History Modeling in the Illinois Basin

Janet K. Pitman, Christoph Spötl, and Martin B. Goldhaber, Origin and timing of carbonate cements in the St. Peter Sandstone, Illinois Basin: Evidence for a genetic link to MVT-type mineralization

C.J. Potter, J.A. Drahovzal, M. Sargent, and **J. Lewis**, Structural and stratigraphic patterns on regional seismic data, southern Illinois Basin

J.L. Ridgley, F.A. Hills, and **C. Rice**, Sedimentology and trace element and stable isotope geochemistry of the lower part of the Mississippian St. Louis Limestone in the Illinois Basin

R.L. Wheeler and **S. Rhea**, Seismotectonic maps of the New Madrid area—A model for maps of the lower Wabash Valley

TUESDAY SEPTEMBER 13

TECHNICAL SESSION III (INDIANA B) - D.R. KOLATA, SESSION CHAIR

8:00am **D.K. Lumm**, Subsurface Geometry and Petrography of Clastic Rocks of the Beech Creek Limestone (Chesterian) to Springfield Coal (Desmoinesian) Interval of Part of the La Salle Anticlinorium, Lawrence County, Illinois.

8:30am **J.A. Drahovzal**, Basin-Floor Fan Complexes: A New Exploration Strategy for the Rough Creek Graben

9:00am **B. Seyler**, and **D.S. Beaty**, Diagenetic Alteration and Porosity Enhancement of Two Middle Mississippian Sandstone Reservoirs in the Illinois Basin

9:30am **E. Udegbunam** and **S.K. Sim**, Reservoir Simulation Studies of Aux Vases and Cypress Reservoirs in Illinois

10:00am Coffee break

TECHNICAL SESSION IV (INDIANA B) - B.D. KEITH, SESSION CHAIR

10:30am **T. Hamilton-Smith**, Western Kentucky Tar Sands and Illinois Basin Oil

11:00am **S.F. Greb, D.A. Williams, C.B. Eble, J.W. Nelson, J.A. Devera,** and **W.A. DiMichele**, Geology of the Elm Lick Zone, Tradewater Formation —A Low-sulfur Coal in the Western Kentucky Coal Field

11:30am Lunch break (on your own)

TECHNICAL SESSION IV (CONTINUED)

1:00pm **B.C. Nuttall** and **J.A. Drahovzal**, A Proposal For an Atlas of the Major Oil and Gas Plays of the Illinois and Michigan Basins

1:30pm **D.F. Oltz** and **L.D. Moore**, The Midwest Region of the Petroleum Technology Transfer Council

2:00pm Coffee break

2:15pm **Group Discussions**

Illinois Basin Petroleum Resource Issues (Indiana B)

Illinois Basin Coal Resource Issues (Orr Room-Green Annex)

Illinois Basin Mineral Resource Issues (Welsh Room-Green Annex)

A Comprehensive Core Book of Pennsylvanian Rocks of the Illinois Basin: Its Construction and its Applications

Mark L. Barnhill, Indiana Geological Survey, Indiana University
Huitang Zhou, Department of Geological Sciences, Indiana University

INTRODUCTION

J.C. Ferm and R.A. Melton coauthored a book in 1977 entitled *A Guide to Cored Rocks in the Pocahontas Basin.* This book consists of approximately 65 colored plates of Pennsylvanian age rock core with an introductory section explaining how to use the book, as well as its applications. The authors envisioned this core book to be used primarily by coal companies as an aid in the standardization of rock core descriptions.

The Pocahontas Basin core book by Ferm and Melton (1977), and core books for the northern and southern part of the Appalachian Basin which were published subsequently, are still used. Unfortunately, there is no comparable book available for the Illinois Basin in spite of the fact that it is one of the most important coal basins in North America. Indeed, many coal companies operating in the Illinois Basin have had to use one of the Appalachian Basin core books when describing their core.

The Indiana Geological Survey recognizes the need for a standard reference book of Pennsylvanian rock core, and has made substantial progress towards creating one. A total of 108 Pennsylvanian cores, representing more than 23,000 feet of section, have been examined for the purpose of collecting representative samples of rock core for this book.

CONSTRUCTION

The format chosen for the Illinois Basin core book is the result of the valued input of many people. We believe that the format selected represents a consensus of opinion regarding the elements necessary to produce a high quality core book of Pennsylvanian rocks for the Illinois Basin. These elements include: 1) a wide representation of facies, 2) an emphasis on roof rock and underclay variability, 3) a stratigraphic context within which to observe the core, 4) one-to-one scale true-color core photographs, 5) ease and practicality of use, and 6) durability.

At the top of each of the 75 colored plates, the location of the well from which the core sample was taken will be shown (Fig. 1). Below the location information are four rectangles. The two rectangles on the left will contain one-to-one scale color photographs of the uncut core, and the cut and polished core, respectively. The core will be photographed wet, and bar scales in inches and in centimeters, located in the slot between the photographs, will be included.

On the right side of each plate are two rectangles containing stratigraphic information. The rectangle on the left contains a gamma-ray log representing 100 feet of section (50 feet of section above and below the location of the core sample shown in the photographs). The rectangle on the right contains a vertical columnar profile showing grain size and sedimentary structures. Additional information on each plate will include alpha-numeric codes representing the classification schemes, a stippled pattern to the left of the columnar profile indicating the thickness of the facies represented by the photograph, and an arrow showing the location within this interval where the photographed sample was taken.

On the reverse side of each plate, the following information will be provided for each core sample: 1) a descriptive name, 2) the formation it represents, 3) a detailed description including texture, composition, sedimentary structures, and fossils, 4) gamma-ray well-log characteristics, 5) an interpretation of the depositional environment represented by the sample, 6) pertinent references where the rock type represented by the sample has been described in the literature, and 7) a map of the Illinois Basin showing the location of the well from which the sample was taken.

APPLICATIONS

We envision four major applications for this book: 1) as an aid in standardizing rock-core descriptions for the coal industry, 2) as a teaching tool to help undergraduates in geology recognize and identify sedimentary structures, 3) as an aid to petroleum geologists in recognizing gamma-ray well-log signatures of rock facies successions, and 4) as an aid to construction engineering companies in the identification of rock types that present stability problems for man-made structures.

We believe that the primary application of this book will be the standardization of rock core descriptions for the coal industry. We recognize that certain rock types associated with both underground and surface mining are problematic. For example, the presence of disturbed-bedding in roof rocks can result in severe problems with roof control in underground mining. It is essential, therefore, that rock core descriptions be standardized so that facies known to be problematic can be identified early on, and their thickness and lateral continuity determined. We also recognize that certain rock facies present problems with acid mine drainage. Standardizing rock core descriptions permits early recognition of these facies so that appropriate action can be taken to avoid acid mine drainage problems.

We also envision this book to be useful as a teaching guide for undergraduate students in geology. Many of the physical structures that are present in sedimentary rocks are readily observed in core. In fact, many are more easily observed in core than at the outcrop. This is particularly the case with fine-grained rocks where slabbing and polishing the core often reveals subtle but important structures and textures not observable at the outcrop.

This core book will also be useful to petroleum geologists working in the subsurface. Gamma-ray well-logs are an important tool for interpreting depositional environments. It is well known, for example, that many depositional environments produce recognizable gamma-ray well-log signatures. The core book will provide additional insight by showing the actual gamma-ray well-log response to specific facies represented in the core photographs. Moreover, by showing a 100-foot-thick vertical columnar profile, the gamma-ray well-log response to the facies 50 feet above and below the core sample can also be observed.

Finally, we believe that the core book will be helpful to engineers and geologists working for construction engineering companies. We recognize that there are many sedimentary rock facies, particularly fine-grained facies, that can cause structural problems to buildings, bridges, roads, etc.. This core book should be useful as a guide in the identification of those rock facies that present construction engineering problems.

We believe the core book of Pennsylvanian rocks of the Illinois Basin will be useful to geologists from a wide range in backgrounds. Presently, the book is almost complete, and should be available for purchase sometime during the end of the 1994 calendar year.

REFERENCES

Ferm, J.C., and Melton, R.A., 1977, A Guide to cored rocks in the Pocahontas Basin: Carolina Coal Group, Department of Geology, University of South Carolina, Columbia, South Carolina, 90 p.

Alteration of Oils during Migration in the Illinois Basin: Geochemical Constraints on Paleohydrology

R. C. Burruss, U.S. Geological Survey, Denver, CO

Crude oils in the Illinois basin generated from shales in the upper Devonian-lower Mississippian New Albany Group occur in reservoirs of Silurian to Pennsylvanian age and in fluid inclusions in fluorite from the southern Illinois fluorspar district. Gas chromatographic analysis of twenty-three whole oils (16 oils from Hatch, et al. (1990) and 7 fluid inclusion samples) reveals that the gasoline range compounds (C_4-C_8) of the oils are depleted in benzene and toluene. The least depleted samples are the oil inclusions in fluorite which contain oils generated locally in thermally mature rocks of the New Albany Group. None of the samples are biodegraded despite the fact that reservoir depths range from 866 m (2840 ft) to 196 m (643 ft).

A plot of toluene content of oils versus radial distance from Hicks Dome (fig. 1) located in the thermally mature region of the New Albany Group (see maps in Cluff and Byrnes, (1990) shows a general correlation of decreasing toluene content with increasing distance from the mature hydrocarbon source. Similar depletions in toluene versus distance from thermally mature source areas were documented by Burruss and Hatch (1989) for the Anadarko basin. Crude oils become depleted in benzene and toluene through water washing (Lafargue and Barker, 1988). This occurs whenever crude oil comes in contact with large volumes of water which removes the most water soluble compounds in the oil. Large volumes of water interact with crude oils during either local meteoric recharge of reservoir units or long-distance oil migration when oil moves through a large volume of water-wet carrier beds. Water washing due to meteoric recharge is commonly associated with biodegradation. Although biodegraded oils are present in the Illinois basin, they are not common (Hatch and others, 1990).

The geochemical variations in the oils are consistent with paleohydrologic models of the Illinois basin. Oils in Silurian reservoirs along the Sangamon arch are strongly depleted of toluene consistent with long distance migration of oil modelled by Bethke, et al., (1990). That model invoked migration from the base of thermally mature New Albany Group

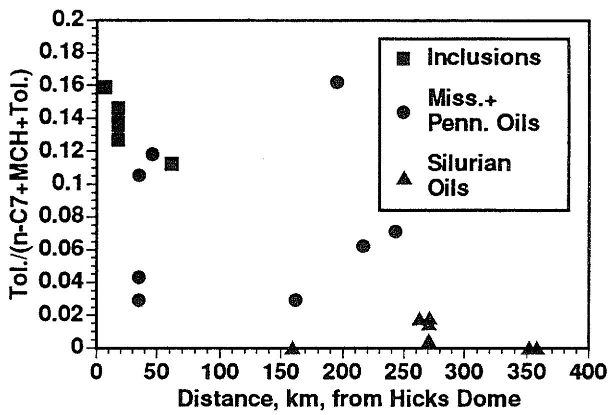


Figure 1. Plot of toluene content of whole crude oils, as fraction of toluene (Tol.) relative to the sum of toluene, methyl-cyclohexane (MCH), and normal heptane (n-C7), versus distance of the reservoir from Hicks Dome as a reference for the thermally mature New Albany Group source rocks in the southern Illinois basin.

rocks into older Paleozoic aquifers and then lateral, up-dip migration due to buoyancy and hydrodynamic forces beneath the New Albany aquitard. Oils in Mississippian and Pennsylvanian reservoirs show a wide range of depletions in toluene that do not correlate well with distance from thermally mature New Albany Group rocks in southern Illinois. The least depleted sample is about 30 km northeast of thermally mature New Albany Group source rocks in the northern Fairfield sub-basin (Cluff and Byrnes, 1990) whereas the two strongly depleted samples are south of the sub-basin, near the fluorspar district. The latter oils may have been affected by additional fluid flow during fluorspar mineralization (see Goldhaber, this volume). The fact that none of the oils are biodegraded indicates that there was no local meteoric recharge of reservoir units after the oils accumulated.

REFERENCES

Bethke, C.M., Reed, J.D., and Oltz, D.F., 1990, Long-range petroleum migration in the Illinois basin, *in* Leighton, M.W., Kolata, D.R., Oltz, D.F., and Eidel, J.J., eds., Interior Cratonic Basins: American Association of Petroleum Geologists, Memoir 51, p. 455-471.

Burruss, R.C., and Hatch, J.R., 1989, Geochemistry of oils and hydrocarbon source rocks, greater Anadarko basin: Evidence for multiple sources of oils and long-distance oil migration, *in* Johnson, K.J., ed., Anadarko Basin Symposium, 1988: Oklahoma Geological Survey, Circular 90, p. 53-64.

Cluff, R.M., and Byrnes, A.P., 1990, Lopatin analysis of maturation and petroleum generation in the Illinois basin, *in* Leighton, M.W., Kolata, D.R., Oltz, D.F., and Eidel, J.J., eds., Interior Cratonic Basins: American Association of Petroleum Geologists, Memoir 51, p. 425-453.

Hatch, J.R., Risatti, J.B., and King, J.D., 1990, Geochemistry of Illinois basin oils and hydrocarbon source rocks, *in* Leighton, M.W., Kolata, D.R., Oltz, D.F., and Eidel, J.J., eds., Interior Cratonic Basins: American Association of Petroleum Geologists, Memoir 51, p. 403-423.

Lafargue, E., and Barker, C., 1988, Effect of water washing on crude oil compositions: American Association of Petroleum Geologists Bulletin, v. 72, p. 263-276.

Coal Resources of Daviess County, Indiana: a GIS-based Resource Assessment

Joseph G. Callis and John A. Rupp, Indiana Geological Survey

Daviess County, Indiana, is located in the eastern part of the Illinois Basin. The county has an area of approximately 426 square miles. Coal resource calculations were performed in the county on 12 Pennsylvanian coal beds (assumed to be continuous) using GRASS, a workstation-based geographic information system (GIS). The resulting resource figures are to be further analyzed by a coal availability study (determining the amount of coal available for mining). The coals that were used in this resource assessment are, in ascending order: the Blue Creek and Mariah Hill Coal Members of the Mansfield Formation, the Lower Block, Upper Block and Buffaloville Coal Members of the Brazil Formation, an unnamed coal (associated with the Holland Limestone Member) and Seelyville Coal Members of the Staunton Formation, the Colchester and Survant Coal Members of the Linton Formation, the Houchin Creek and Springfield Coal Members of the Petersburg Formation, and the Bucktown Coal Member of the Dugger Formation.

Several sources of data were used to calculate coal resources in Daviess County. The main source of data was from the U.S. Geological Survey (USGS) National Coal Resources Data System (NCRDS). The NCRDS database has in it data collected by the Indiana Geological Survey (IGS) which includes measured sections, electric logs, borehole data, etc. Petroleum well logs (from the IGS) were included to fill in gaps in the data. The information regarding the location and distribution of the mined areas came from the Coal Mine Information System (CMIS) of the IGS.

We estimate that originally there were about 4.48 billion short tons of coal in place in Daviess County. As of 1985 (the latest date of the CMIS database) 17.0 million short tons of coal had been mined or lost in mining, leaving 4.46 billion short tons of coal *in situ*. Based on Indiana Bureau of Mines production figures, between 1985 and 1992 there were approximately 31.5 million short tons of coal mined which leaves a current (as of 1992) remaining resource tonnage for the county of 4.43 billion short tons. This and other resource tonnage numbers reflect all coals that have a thickness of 14 inches or greater, which was the criterion used by GRASS to determine minability. According to our model, 98.9 percent of the original coal in Daviess County is still in place.

A GIS Approach to Calculate Available Coal Resources in Alfordsville 7.5 Minute Quadrangle, Indiana

Haluk Cetin, Carol Conolly, and John A. Rupp, Indiana Geological Survey

Coal production in Indiana comes from the coal beds that occur within the Pennsylvanian System of southwestern Indiana. The Indiana coal field constitutes the eastern edge of Eastern Interior Coal Basin, a basin that covers parts of a three-state area, including Illinois and western Kentucky. The availability of coal resources in the Alfordsville 7.5 Minute Quadrangle in southwest Indiana was examined in this study. Resources defined as original coal in place, remaining after mining, and currently available considering restrictions were calculated for seven coal beds underlying the study area. In ascending stratigraphic order, the seven coal beds which belong to the Raccoon Creek Group of the Pennsylvanian System are: Blue Creek and Mariah Hill Coal Members, and an unnamed Mansfield coal bed of the Mansfield Formation; Lower Block, Upper Block and Buffaloville Coal Members of the Brazil Formation; and an unnamed Staunton coal bed of the Staunton Formation. Resources were calculated by combining two coal thickness categories, "14-28 inches" and "greater than 28 inches" with two overburden categories, "0-200 feet" and "200-1000 feet", and by combining four reliability categories (circles), measured (0-0.25 miles from a data point), indicated (0.25-0.75 miles), inferred (0.75-3.0 miles) and hypothetical (3.0-10.0 miles). Structure maps showed that no coals were covered by greater than 1000 feet overburden.

The coal availability concept was established because of the need to develop a more reliable resource database. This concern has manifested itself as a collaborative program between the U.S. Geological Survey and state geological surveys to estimate the amount and character of coal resources available for mining. The original, remaining, and available coal resources of the Alfordsville 7.5 Minute Quadrangle were calculated using GRASS software (Geographical Resource Analysis Support System), a raster-based (equal-size grid cells) Geographic Information System (GIS) software developed by the U.S. Army Corps of Engineers, the U.S. Geological Survey, and the Soil Conservation Service. The calculations took into account the amount of original coal in place, mined coal, coal lost during mining, and land-use and technological restrictions. Several initial steps were completed before calculating the resources: study area selection; collection and compilation of point source data; construction of cross sections for correlation of coals; digitization of outcrops, land-use in the area, and the extent of mined-out area maps. From these data sets technological restrictions, structure contour, and isopach maps were generated for the final resource calculations. Overburden rasters were created using Digital Elevation Model (DEM) data with 30x30 meter grid size and structure data. Thickness, outcrop, and location information for all seven coal beds was derived from geophysical well logs, NCRDS (National Coal Resource Data System), and coal company data.

One of the factors influencing the minability of a coal bed is coal quality. In general, coal quality includes ash and sulfur content, and Btu value of a coal. In the study area, the coal beds that are most attractive based on favorable quality values are those in the Brazil Formation: Lower Block, Upper Block, and Buffaloville Coal Members. These coals have been extensively mined and have very low sulfur content which is one of the most important coal quality factors. Overall the Lower Block Coal Member has the lowest sulfur content among the coals mined in the area (the sulfur content of this coal is as low as 0.44 percent; as-received basis).

Total original resources for the seven coal beds in the study area are 204 million short tons (table 1).

Of the 204 million short tons, 19.8 million short tons have been removed by mining or lost in the mining process, thus leaving remaining resources of 184 million short tons. Land-use and technological restrictions prevent the mining of 22 million short tons; thus leaving 162 million short tons (79.3% of the original resources or 87% of the remaining resources) available for mining in the area. However, it should be noted here that these numbers include all the reliability categories, measured, indicated, inferred, and hypothetical. Under the measured category, for example, the original resources for the seven coal beds are 38 million short tons (table 1).

Table 1. Coal Resources of Alfordsville 7.5 Minute Quadrangle (thousands of short tons).

	Measured 0-1/4 mi	Indicated 1/4-3/4 mi	Inferred 3/4-3 mi	Hypothetical 3-10 mi	Total
Original Resources	37,881	73,387	89,785	2,740	203,793
Remaining Resources	28,243	67,513	85,462	2,731	183,949
Available Resources	24,219	61,451	74,933	939	161,542

The Illinois State Geological Survey's Digital Database of Underground Mines

Cheri Chenoweth, Margaret H. Bargh and Colin Treworgy
Illinois State Geological Survey

Information on underground mined-out areas is useful for those involved in resource development, hazard assessment, planning, and scientific investigation. A study done by the Illinois State Geological Survey (ISGS) calculated that 178,000 acres of residential and other built-up areas, including more than 300,000 housing units, were in close proximity to undermined areas in Illinois.

The ISGS maintains a geographic information system (GIS) database, containing information for more than 4500 mines in Illinois, including all coal mines and most underground mines for limestone, clay, fluorospar, lead, zinc, and tripoli. The database contains mine locations and/or outlines as digitized from company maps or the best available source maps. Additional information in the database includes current and historical company and mine names, years of operation, coal seam mined, and type of mine. These data are suitable for statewide and regional mapping applications at a scale of 1:100,000 or smaller.

Portions of the database, particularly around urban areas and active mines, are being upgraded for applications requiring data at scales of 1:24,000. Each of the 1:24,000 series maps covers the area of a U.S. Geological Survey 7.5-minute quadrangle and contains various hydrographic and cultural features in addition to the boundary of the underground mines. The mine outlines are drawn using line symbols that indicate the relative precision and completeness of the source maps. Shade patterns and colors are used to indicate the mining method and differentiate between surface and underground mines. A directory accompanying each map interprets the map symbols, discusses the history of mining in the quadrangle, and gives detailed information for each mine, including the production history, reported geologic problems (faults, unstable roof or floor, presence of water and other factors that could influence long-term stability of the mine openings), and the scale and date of the source map from which the information was obtained.

Ten of these detailed maps are now available for public distribution, in addition to the existing 1:100,000-scale county maps for all coal producing counties in Illinois. The data is available in either digital format or as paper maps.

Ichnology of Morrowan through Basal Desmoinesian Rocks in Indiana

Joseph A. Devera, Ilinois State Geological Survey

Trace fossils from the Mansfield, Brazil and Staunton formations (Morrowan-basal Desmoinesian) have been found in over 50 locations in Indiana. The distribution of these ichnofossils appear to be tied to complex local environmental conditions rather than related solely to the Seilacherian bathymetry model. In most marine settings, depth is the limiting factor for the occurrence of specific ichnofossil assemblages (Seilacher, 1967). However, the Morrowan through basal Desmoinesian rocks of Indiana were deposited in marginal marine settings (Kvale and others, 1989, Kvale and Archer, 1990). Sedimentation rate, availability of oxygen and nutrients and depth all played key roles, but paleosalinity was the overriding environmental factor that controlled most of the trace fossil distributions in Indiana during this time.

Nine recurring ichnofossil assemblages discussed below, have been recognized, three as normal marine indicators, three as brackish to freshwater indicators and three as terrestrial based indicators that could have been subjected to marine incursions as well. The ichnofossil assemblages are named from the most common one or two trace fossils found in each assemblage. A brief lithologic description is followed by associated ichnofossils, evidence to support paleosalinity, diversity/abundance of the traces, and other associated environmental factors.

1) ***Zoophycos - Chondrites*** assemblage is commonly found in black shales, dark gray shales and silty mudstones and occasionally in organic-rich sandstones; associated ichnofossils are *Scalarituba and Planolites;* spiriferid brachiopods have been found within this assemblage in Indiana, as well as conodonts in Illinois; this assemblage displays low diversity and low abundance, other environmental factors are poorly oxygenated substrate and quiet water conditions; this assemblage shows definite affinities to the marine environment.

2) ***Olivellites - Curvolithus*** assemblage occurs in thin flaggy to medium bedded sandstones and ripple bedded sandstones containing clay partings; associated ichnofossils are *Scolicia, Aulichnites, Cruziana, Eione, Scalarituba and Rhizocorallium; this* assemblage has been found with trilobite remains in western Kentucky, gastropods, and crinoidal debris in southern Illinois, also these traces are commonly associated with calcareous sandstones and limestones laterally or vertically within close proximity; this assemblage shows high diversity and high abundance of trace fossils; bimodal current indicators, clay drape and tidal bundles associated with this ichnofossil and body fossil assemblage are also suggestive of holomarine conditions.

3) ***Conostlchus - Asterosoma*** assemblage is found in silty shales, thin bedded siltstones, shale units and heterolithic fine grained sandstone/shale sequences; associated traces are *Teichichnus, Gyrolithes, Lockeia, and Planolites;* associated fossils are conodonts and gastropods in southern Illinois; this assemblage shows moderate diversity with high abundance; tracemakers of this assemblage can tolerate moderate sedimentation rates; definite connections to the marine environment.

4) ***Lockeia - Planolites*** assemblage commonly occurs in heterolithic siltstone/shale or micaceous, fine grained sandstone/shale packages; associated ichnofossil is *Uchirites;* linguloid and orbiculoid brachiopods, myalinid bivalves and arenaceous foraminiferids have been associated with these traces in Indiana; this assemblage has low diversity and high abundance to patchy occurrences of traces, because local areas of high sedimentation rates inhibit tracemakers; this assemblage is indicative of brackish water environments.

5) ***Kouphichnium*** - "*shrimp* traces" assemblage is found in shaly sandstones, and thin bedded fine grained sandstones; associated trace fossils are *Lockeia, Uchirites* and other repichnia; thus far no supporting invertebrate or microfossil evidence has been associated with this assemblage; this assemblage shows low abundance and locally high diversity of traces, usually associated with tidal bundles; this assemblage is suggestive of brackish to freshwater environments.

6) ***Skolithos*** assemblage is rare and occurs in fine to coarse grained quartz arenites thin to thick bedded sandstones; rarely found with other traces, in one case, *Skolithos* was associated with amphibian repichnia in southern Indiana; no supporting body fossil evidence for salinity; very low diversity and high abundance in ichnofossil type; episodic high/low rates of deposition, possibly brackish to freshwater environments.

7) ***Treptichnus - Plangtichnus - Haplotichnus*** assemblage occurs in laminated siltstones, clean, well-sorted, rhythmically-bedded siltstones; associated ichnofossils are *Tasmanadia, Kouphichnium,* amphibian repichnia, and stigmarian root casts; associated fossils are insect wing impressions, *in situ* trees, impressions of ferns and cones, and conodonts were found in clay drapes; moderate diversity and high abundance of traces; occurs with well developed tidal bundles, terrestrial-based deposit that is influenced by tidal sedimentation and occasionally inundated by brackish water; thus far this assemblage is restricted to Indiana.

8) **Root cast** assemblage found in fine grained sandstones, gray laminated shales, underclays and heterolithic sandstone/shale sequences; associated fossils *in situ* trees, stigmarian roots, commonly found below coals, important horizons for mapping in place, terrestrial horizons.

9) **Diapsid repichnia** assemblage found in shaly fine grained sandstone intervals, siderite nodules common; no other ichnofossils were found in association with the trackways; well preserved fossil plant remains occur in the shales; low diversity and low abundance of trace fossils, the sandstones infills cracks within the shale along the trackways indicating exposure; this fossil plant/trackway association suggests a terrestrial based area that is flooded periodically.

REFERENCES

Kvale, E.P., Archer, A.W., and Johnson, H.R., 1989, Daily, monthly, and yearly tidal cycles within laminated siltstones of the Mansfield Formation (Pennsylvanian) of Indiana: Geology, v. 17, no. 4, p. 365-368.

Kvale, E.P., Archer, A.W., 1990, Tidal deposits associated with low-sulfur coals, Brazil Formation (lower Pennsylvanian), Indiana: Journal of Sedimentary Petrology, v. 60, no. 4, p. 563-574.

Seilacher, Adolf, 1967, Fossil behavior: Scientific American, v. 217, no. 2, p. 72-80.

Basin-Floor Fan Complexes: A New Exploration Strategy for the Rough Creek Graben

James A. Drahovzal, Kentucky Geological Survey

The Rough Creek Graben is more than 100 miles (160 km) in length and 25 to 45 miles (40-73 km) in width. Throughout most of its extent, it is a north-dipping half graben with Paleozoic sediment thickness of up to 30,000 feet (9,100 m) along its northern edge on the downthrown side of the Rough Creek Fault Zone. The graben shallows to the southwest, south, and east; exhibits a polarity change to the southwest; and terminates to the east on a presumed tectonic inversion structure. Rifting and subsidence occurred in the basin during the Cambrian, resulting in up to 18,000 feet (5,500 m) of pre-Knox sedimentary fill that is more than five times the thickness in the surrounding stable areas.

Most of the oil and gas drilling into the pre-Knox interval of the Rough Creek Graben has been near the Rough Creek Fault Zone in western Kentucky. Currently, a Cambrian test is drilling in the same relative position in southern Illinois. Apparent past and present exploration strategies include drilling Knox and younger anticlinal structures associated with Late Paleozoic compression, horst blocks downthrown to the boundary fault, and presumed roll-over anticlines on the downthrown side of the boundary fault. There are two basic problems with these exploration strategies: (1) reservoir seals are more likely breached and (2) mechanical drilling problems are more common in and near the boundary fault zone because of the extensive fracturing related to the complex, polyphase fault-movement history.

Recent investigations of limited seismic reflection data available to the Illinois Basin Consortium provide relatively strong evidence for basin-floor fan deposition at least in the western, basal part of the graben (fig. 1). Such deposition is consistent with current understanding of graben-fill histories and patterns associated with tectonic systems tracts. The basin-floor fans are characterized by bidirectional, downlapping, mounded reflector patterns. In the northern, deepest part of the graben, the mounded reflectors overlap one another to form two distinct sequences that onlap and pinch out onto south-rising Precambrian basement. At their maximum these two sequences total more than 6,800 feet (2,070 m) in thickness. Other seismic reflection data show thinner fan complexes to the south.

The geometry of the individual fans suggests that the transport direction was longitudinal to the axis of the basin. This orientation would suggest that sediment sources for the fans included both the Precambrian Granite-Rhyolite Province and the East Continent Rift Basin. The fans developing from these sources should be quartzose, but could include considerable arkosic or lithic fractions. Such compositions are consistent with recent well data in the area.

The fan complexes represent an important potential hydrocarbon reservoir facies that has not yet been tested in the graben. Future exploration strategies involving the deep potential should consider drilling the more southerly, less faulted parts of the graben where the fan complexes are present. Such a strategy would avoid the problems associated with past unsuccessful deep exploration attempts.

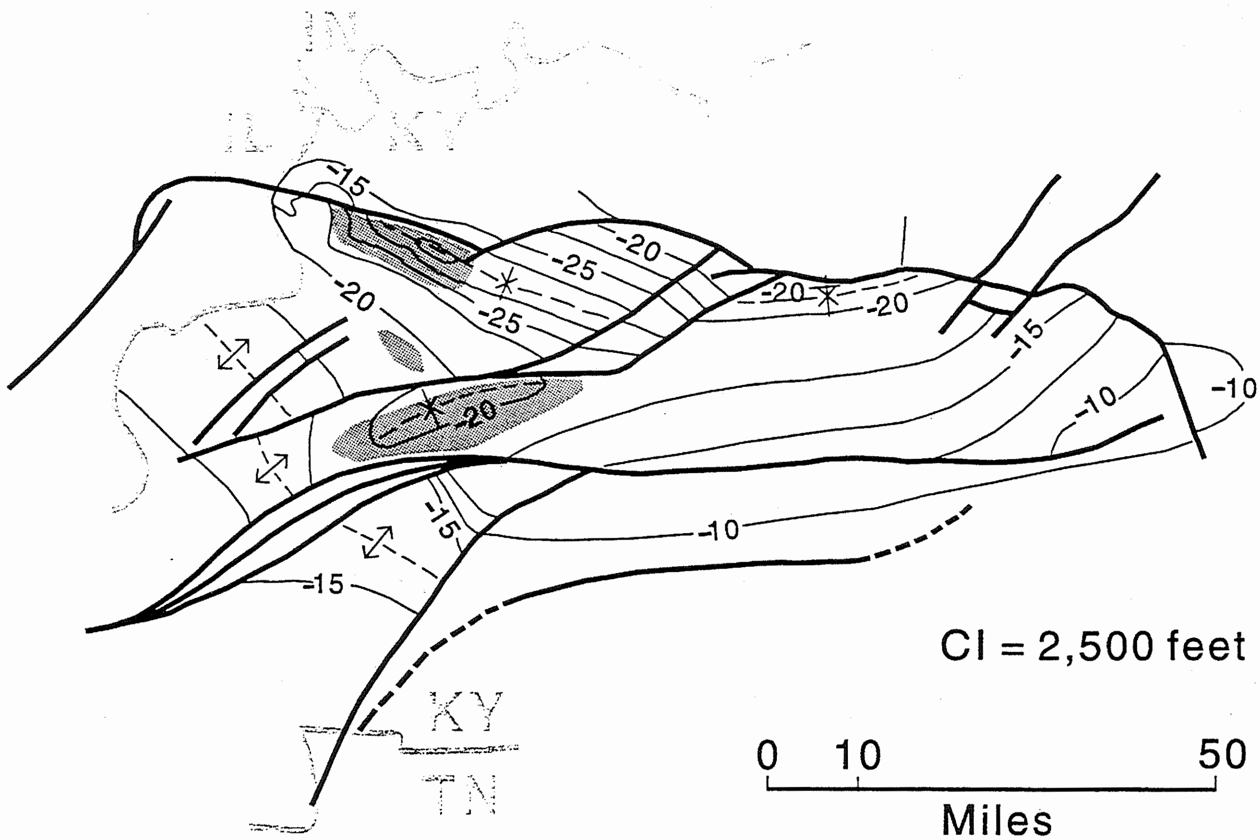


Figure 1. Preliminary map of the top of the Precambrian unconformity in the Rough Creek Graben, western Kentucky (in thousands of feet below sea level). Shaded areas represent approximate areas of basin-floor fan complexes interpreted from currently available reflection seismic data.

Basin-wide Paleofluid Flow in Cambro-Ordovician Siliciclastic Rocks of the Illinois Basin: Diagenetic and Geochemical Evidence from the Mt. Simon and St. Peter Sandstones

Neil S. Fishman and Janet K. Pitman, U.S. Geological Survey, Denver, Colorado

Diagenetic alterations in the Cambrian Mt. Simon Sandstone and Ordovician St. Peter Sandstone, two regionally extensive aquifers in the Illinois basin, Illinois and Indiana, record the nature, timing of migration, and dispersal pathways of fluids that have passed through them. Unraveling the nature and timing of these alterations is crucial to understanding paleofluid flow in both units throughout the basin, which in turn helps to constrain models pertaining to economically important lead-zinc mineralization and hydrocarbon migration in and around the Illinois Basin. In addition, understanding the present-day intraformational and interformational variability in porosity and permeability of the units is important in exploitation of the units as subsurface storage repositories of gas and/or waste.

Petrographic and SEM observations indicate that the paragenetic sequence of mineral cements is similar in both units; however, there is noticeable interformational variability in cement abundance.

The generalized paragenetic sequence for important authigenic minerals is, from oldest to youngest, illite → K-feldspar overgrowths ±rhombic K-feldspar cement → carbonate → quartz overgrowth → carbonate → anhydrite+fluorite → illite. Overgrowths of authigenic K-feldspar (now partly dissolved) and quartz, both of which formed after some compaction, are volumetrically minor (<5% each) in the St. Peter but significantly more abundant (20%, and up to 10%, respectively) in the Mt. Simon. In contrast, multiple generations of carbonate (dolomicrospar, planar dolospar, baroque dolospar, and calcite) occur throughout the St. Peter but paragenetically similar dolospar cements (both ferroan and non-ferroan) are the only identified carbonates in the Mt. Simon and they occur rarely. Rhombic K-feldspar cement (partly dissolved), some of which may have formed at the same time as K-feldspar overgrowths, also occurs in varying abundances in both units. Early, illitic clay rims are widespread in both units but late illitic pore-filling clays are more abundant in the Mt. Simon. Fluorite cement occurs sparsely in both units, principally in northern Indiana (Mt. Simon) and southern Illinois (St. Peter).

Variability of authigenic K-feldspar abundance appears to be controlled, in part, by the occurrence of detrital feldspar suggesting detrital grains served as nucleation sites for much of the growth of authigenic K-feldspar. Porosity, largely secondary in nature, also varies within each sandstone, probably due to precursor carbonate cement that was subsequently dissolved. Porosity, as determined petrographically, in the St. Peter varies from 0 to ~30%, whereas porosity in the Mt. Simon varies from 0 to ~25%. The variability in porosity is broadly regionally defined with greater porosities commonly in the northern part of the basin, where the units have not been buried too deeply, and a general decrease in porosity to the south in the central and southern parts of the basin, where the units have experienced deeper burial.

The similar paragenesis of alterations in the two units suggests that many alterations are due to pore fluids of similar chemical compositions that traveled widely throughout the basin in both sandstones; however, intraformational variability in cement abundance (porosity) points to additional controls on diagenesis. Not only were fluids widely traveled, but they varied significantly in chemical nature, which explains precipitation of minerals and their subsequent dissolution (released K may have been incorporated into late-stage illite). K-feldspar and illite authigenesis occurred throughout the mid-continent at about 400 Ma and perhaps about 270 Ma, respectively, as indicated from age dating on these phases in the Mt. Simon in northern Illinois (Duffin and others, 1989). Because lead-zinc mineralization in the region also has been dated at about 270 Ma (Parr and others, 1990; Brannon and others, 1992), the areally extensive Mt. Simon and St. Peter aquifers may well have hosted mineralizing solutions as they moved in the basin. However, the source(s) and possible flow paths are complex and are as yet not constrained on a basin-wide scale.

REFERENCES

Brannon, J.C., Podosek, F.A., and McLimans, R.K., 1992, Alleghenian age of the Upper Mississippi Valley zinc-lead deposit determined by Rb-Sr dating of sphalerite: Nature, v. 356, p. 506-511.

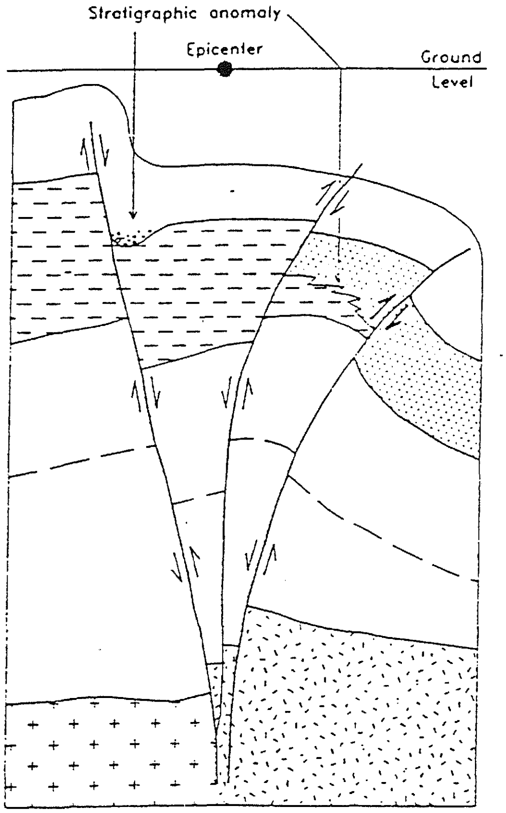
Duffin, M.E., Lee, M., Klein, G.V., and Hay, R.L., 1989, Potassic diagenesis of Cambrian sandstones and Precambrian granitic basement in UPH-3 Deep Hole, Upper Mississippi Valley, U.S.A.: Journal of Sedimentary Petrology, v. 59, p. 848-861.

Parr, H., Symons, D.T.H., and Sangster, D.F., 1990, Paleomagnetism of the Mississippi Valley-type ores and host rocks in the northern Arkansas and Tri-State Districts: Canadian Journal of Earth Science, v. 27, p. 923-931.

Basement Tectonics in the eastern Illinois Basin of Indiana

L. C. Furer, Indiana Geological Survey

Seismic and subsurface data provide indirect and some direct evidence that near-vertical strike-slip deep faulting in the crystalline basement rocks of the eastern part of the Illinois Basin has a significant effect on the thickness and facies distribution of overlying Proterozoic and Paleozoic sedimentary rocks. The evidence includes: alignment of earthquake epicenters, anomalous spring waters, magnetic anomalies, various isopach trends, facies patterns, as well as evidence from reinterpreting of published structure maps, and new structural mapping in fault-bounded oil fields. The predominant trend of these faults is northeast-southwest. A tectonic model is proposed in which epicenters of recorded deep earthquakes do not map directly above stratigraphic anomalies or shallow faults in the Paleozoic section,



but do define a spatial pattern that is consistent with that expected from a flower structure. The diagram below is of a flower structure along an oblique slip fault. It has been modified from a paper by N. Christie-Blick and K.T. Biddle in 1985.

Faulting was probably recurrent and not all basement faults were active at any given geologic time. Periods of maximum faulting activity were Proterozoic (1.3 - 1.1 Ba), Ordovician (Taconic Orogeny, 478-438 Ma), earliest Pennsylvanian (320-315 Ma), Middle Pennsylvanian-latest Permian (Alleghanian Orogeny, (290-245 Ma), and Holocene. Maximum faulting activity also appears to be associated with major regional unconformities. Three new faults have been mapped in northern Indiana in the past year in lower Paleozoic rocks. This model predicted the location and trend of two of these faults.

The tectonic model described above partially explains the thickness and distribution of the very thick Proterozoic Middle Run Formation in eastern Indiana, and the trend of major segments of Lower Pennsylvanian paleo-valleys in southwestern Indiana. More subtle tectonic activity likely affected the facies distribution of some other Paleozoic rocks of the Illinois Basin such as the Ordovician Trenton Limestone, Silurian reefs and Chesterian sandstone and limestones.

REFERENCES

Christie-Blick, N.H., and Biddle, K.T., 1986, Deformation and basin formation along strike-slip faults, *in* Biddle, K.T., ed., Strike-slip deformation, basin formation, and sedimentation: Society of Economic Paleotologists and Mineralogists Special Publication 37, p. 1-34.

The Illinois Basin as a Flow Path for Low Temperature Hydrothermal Fluids

M. Goldhaber, E. Rowan, J. Hatch, R. Zartman, J. Pitman, R. Reynolds*
U.S. Geological Survey, Denver CO
**U.S. Geological Survey, Menlo Park, CA*

The Illinois basin is partly surrounded by Mississippi Valley type (MVT) deposits, the fluids for which may have migrated through that basin. We present evidence that elemental and isotopic analyses, augmented by petrographic studies, can detect the "footprints" of the ore-forming brines in the Illinois basin sediments; fluid-flow modeling coupled with organic maturation studies reveals the thermal history of this regional fluid flow event.

Fluorine is a particularly useful tracer for the Illinois basin brine migration. Magmatic HF was released at the southern end of the basin by a major alkalic igneous event (at Hicks dome) which also produced the Illinois Kentucky fluorspar district (FSD) (Goldhaber, et al., 1992; Plumlee et al., 1994). Dating of both the igneous activity and Fluorspar District yields Permian ages. The Upper Mississippi Valley (UMV) District at the north end of the basin is likewise dated as Permian. Thus, fluids may have been migrating northwards through the Illinois basin towards the UMV district at the same time as fluorine was introduced into these fluids in the south end, potentially resulting in a northward directed plume of F-enriched brines. To test this hypothesis, we analyzed for F in rocks from wells which span the western and central Illinois basin. These analytical data are largely from Ordovician carbonate rocks above and below the St. Peter Sandstone aquifer. These horizons were studied because at Hicks dome, magmatic fluorite deposits formed in rocks of this age range, and the associated St. Peter Sandstone aquifer occurs over the entire basin area.

Geochemical data on samples from over 100 wells in the southernmost part of the basin and from 14 other wells broadly dispersed throughout the basin document a fluorine-enriched region south of the Iowa Missouri border. In individual wells, the F abundance tends to increase with proximity to the St. Peter Sandstone. The basinwide pattern can be contoured and shows systematically decreasing F content away from the Hicks dome igneous center (e.g. Fig 1). Petrographic studies of samples from the southern portion of the Illinois basin demonstrate that the F resides in the mineral fluorite. This fluorite is paragenetically associated with dolomite and possibly K-feldspar. The basinwide pattern of F distribution is consistent with the late Paleozoic transport of hydrothermal brines towards the UMV district in the north.

Enrichment in ore-related trace metals above regional background concentrations may also be a tracer of hydrothermal fluids. Many years of work by USGS and State Geological Surveys demonstrated that elemental analyses of the HCl insoluble residues of midcontinent Paleozoic carbonate rocks provide an excellent record of the passage of metal-rich fluids. Data from south to north transects through the Illinois basin indicate enrichment in Zn, Pb, Ag, Mo relative to regional background levels. Metal enrichment is most marked along the western edge of the basin. This enrichment, which is largely hosted by epigenetic FeS_2, is particularly striking in Cambro-Ordovician carbonates from the deepest southern portion of the basin, but the metal anomaly extends for nearly the entire length of the basin.

Lead isotopic data on the anomalously Pb-rich deeply buried Cambro-Ordovician carbonates of the southern Illinois basin match values for Pb isotopes in the overlying Mississippian hosted FSD, implying dominantly vertical Pb transport to form galena in the FSD. The deep Illinois basin Pb isotope data are also collinear on isotope plots with data for the UMV district and Pb data on epigenetic pyrite from wells lying between the two districts. The isotope systematics are thus permissive of an Illinois basin flow path for a component of the ore Pb. Similarly, Pb contained in epigenetic sulfides from the Reelfoot rift to the south of the present Illinois basin falls along this same trend. In striking contrast, Illinois basin hosted Pb has markedly higher $^{208}Pb/^{204}Pb$ for given

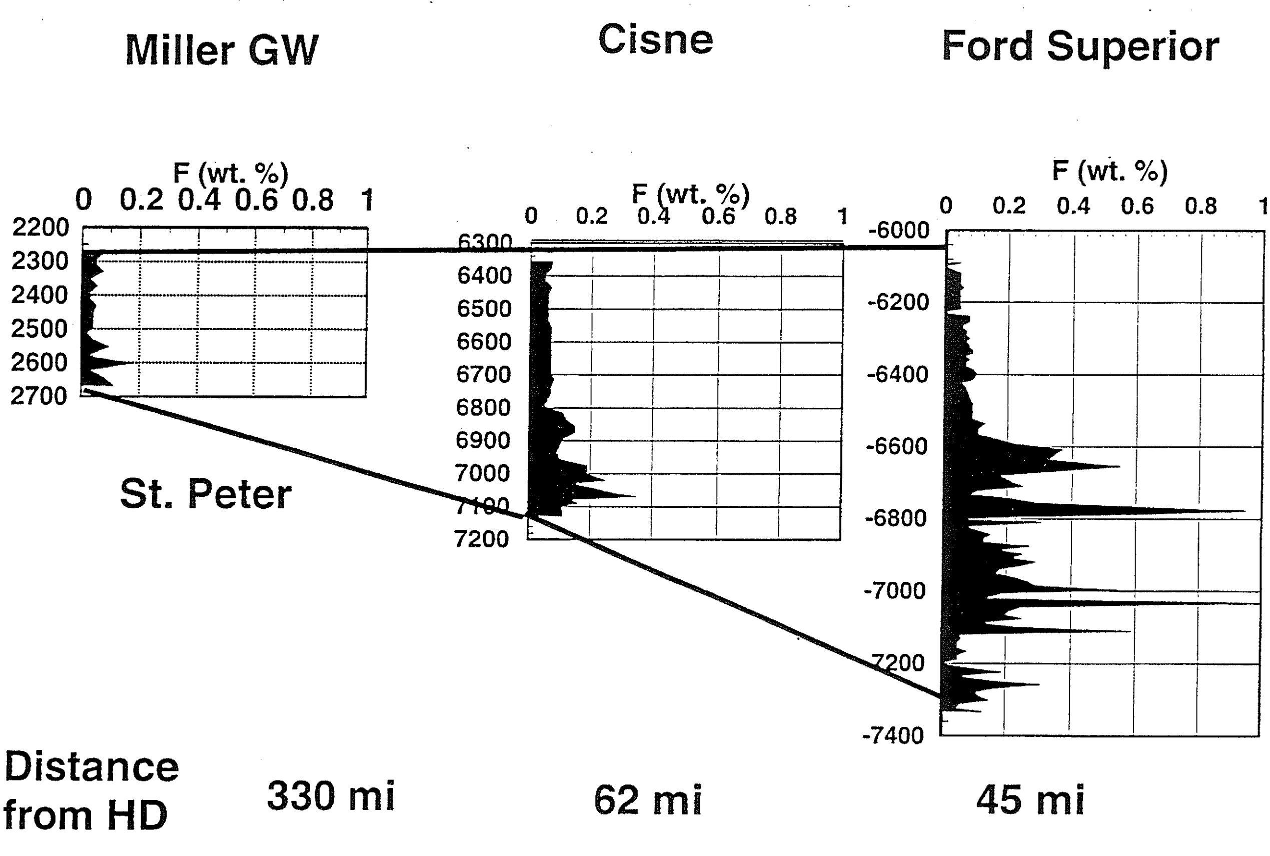


Figure 1. Fluorine abundance in the acid insoluble residues of a series of wells located progressively northward of Hicks dome (HD). The lower bold line marks the top of the St. Peter Sandstone, the upper one, the base of the Maquoketa Shale.

$^{206}Pb/^{204}Pb$ than galena from other MVT districts of the Ozark region, thus the Illinois basin was an unlikely source for Pb in districts to the west.

If as indicated above, a northerly fluid flow path through the Illinois basin was involved in the origin of the UMV district, then the time/temperature history of this district reflects the distal portion of the basinal hydrologic regime during the Permian. The maturation of organic matter, particularly biomarker compounds, can be combined with fluid inclusion and isotope equilibrium temperatures to constrain the thermal history of this late Paleozoic regional fluid flow event. The computer program GEOTHER has been used to model the thermal history of the district using as constraints the isomerization of C-29 5,24 ethyl-cholestane at the 20R position, and the isomerization of C-31 17, 21 -bishomohopane at the 22R position into the corresponding 20S and 22S products. The "best fit" to the fluid inclusion filling temperature data for the district when combined with the observed biomarker ratios indicates that the main stage of ore formation lasted for approximately 300K years at temperatures from 135 to 100 °C. A northerly fluid flow is further indicated by these same biomarker isomerization ratios plus T_{max} measures from Rock-Eval pyrolysis which both show a general decrease in thermal maturity of Ordovician organic matter from south to north in the area of the UMV district. The biomarker data demonstrate that some extremely high fluid inclusion filling temperatures (Th = 180-220 C) cannot have prevailed during ore deposition for periods longer than decades to centuries, and are more likely the result of artifacts in the data. Likewise, temperatures derived from galena-sphalerite isotope fractionation are consistent with only very short times of ore formation, on the order of a few x 10^3 years, that are unlikely given probable metal solubilities, and mass balance considerations.

The overall picture painted by our data and calculations is a major fluid-flow event during the Permian, which lasted about 300,000 years, and which left a strong chemical imprint on the Illinois basin.

REFERENCES

Goldhaber, M.B., Taylor, C.D., Rowan E.L, Hayes, T.S., Potter, C.J, and Mosier, E.L., 1992, Role of Igneous Processes in the Origin of the Illinois-Kentucky Fluorspar District, USA, International Geological Congress, Kyoto Japan, Abstracts v.. 3, p. 739.

Plumlee, G., Goldhaber, M.B., and Rowan, E.L., 1994; The potential role of magmatic gases in the genesis of the Illinois-Kentucky fluorspar district; Implications from chemical reaction path modeling, Economic Geology, accepted.

Geology of the Elm Lick Coal Zone, Tradewater Formation—A Low-sulfur Coal in the Western Kentucky Coal Field

S. F. Greb[1], D. A. Williams[1], C. B. Eble[1], W.J. Nelson[2], J. A. Devera[2], and W. A. DiMichele[3]

[1]Kentucky Geological Survey, Lexington, KY
[2]Illinois State Geological Survey, Urbana, IL
[3]Smithsonian Institution, Washington D.C.

Samples and measurements were taken from active surface mines in the Elm Lick coal zone of Kentucky by the Tradewater Working Group as part of a regional investigation of the geology of potential low-sulfur coal reserves in the Illinois Basin. The mined zone is approximately 85 feet thick and is divided into three intervals. The lower interval contains the double-benched Elm Lick coal (70 in.), a dark-gray shale (15-20 ft.), and a light-gray to greenish-gray shale (4-10 ft.) capped by a discontinuous, non-fossiliferous, bedded to nodular, rooted limestone (0-3 ft.). Where sampled the coal has a 14-inch top bench and a 42-inch bottom bench. Overall, the coal is low in ash yield (4.3%, dry basis) and sulfur content (1.1%, dry basis), although locally the coal has sulfur contents in excess of 5% where pyrite concretions occur in the roof shale. Analysis of closely spaced bench samples indicates that the upper 36 inches of the lower bench has the best quality, with a very low ash yield (2.8%) and sulfur content (0.8%). The top bench has an ash yield of 3.5% and sulfur content of 1.3%, while the basal 6 inches of the bottom bench had an ash yield of 9.6% and a sulfur content of 1.7%.

The Elm Lick coal is cut out by discontinuous, carbonaceous, shale-filled scours each 75 to 300 feet wide, oriented perpendicular and subparallel to a broader sandstone cutout just north of the mining operation. The basal part of the dark shale contains abundant in situ Calamites. The upper part of the dark shale contains lingulid brachiopods and disseminated plant material. Of significant importance was the discovery of seven caudal vertebrae of anembelomere amphibian in the roof shale of the Elm Lick coal. This is the first Pennsylvanian tetrapod fossil reported from the coal fields of Kentucky.

The middle part of the coal zone contained at least two relatively flat-lying coal beds separated by 12 to 15 feet of carbonaceous shale. Coals were extremely variable in thickness, pinching and swelling from less than 6 to more than 20 inches across lateral distances of less than 100 feet. These coals are overlain and laterally truncated by the upper part of the coal zone, which contains numerous discontinuous coal beds. At any one location as many as six coals overlay scours with more than 35 feet of relief on underlying strata. Coals also drape clastic lenses and wedges less than 400 feet wide and as much as 25 feet thick. Coals in this zone range in thickness from 2 to 30 inches, sulfur content from 1.5 to 3.1%, and ash yield from 7.4 to 20%.

Because this study is still ongoing, interpretations are tentative. The Elm Lick coal zone appears to have been a favorable period for peat accumulation along the eastern margin of the Illinois Basin. The lower bench of the Elm Lick coal represents accumulation of a mire relatively protected from clastic influence. Upward, the parting and increase in sulfur content and ash yield indicate clastic influences during accumulation, although the relatively low ash yield and sulfur content of the upper bench (where sampled) suggest that it was still relatively protected. The amphibian and in situ Calamites represent a clastic-dominated fresh-water swamp and the inundation of the Elm Lick mire. An upward change to lingulid-bearing shales with disseminated flora may indicate relative transgression and the influences of brackish, quiet-water environments. Laterally this brackish-water biofacies may truncate the fresh-water biofacies where sulfur balls occur in the roof of the coal.

The middle coal zone represents the accumulation of peats on successive, highly weathered exposure surfaces that formed after relative regressions of underlying brackish water bays or estuaries. The discontinuous limestone below the lower coal is rooted and did not contain marine fauna, and is interpreted as a carbonate paleosol. This could be miscorrelated as one of the marine marker beds in the upper Tradewater Formation.

The upper coals were more susceptible to clastic influx and appear to represent successive development of topogenous swamps above splay wedges and possibly abandoned crevasse or minor distributary channels on a highly dissected paleotopographic surface. Several large scours are inferred to represent abandoned channels that infilled with successive peats and clastic-dominated swamps.

Cross sections based on surface-mine, core, and downhole log data indicate that the Elm Lick coal zone occurs between the Lead Creek and Curlew Limestones. This suggests that the Elm Lick coal is correlatable to the Block Coal zone of southern Indiana, and the coals of the upper part of the zone may be correlatable to the Minshall/Buffaloville Coals of Indiana. Correlation of these beds may indicate a zone of possible low-sulfur coal reserves between Indiana and Kentucky, although it should be noted that individual coals are undoubtedly discontinuous and susceptible to lateral cutouts and rapid changes in coal thickness and coal quality.

REFERENCES

Gardner, J. H., 1912, The economic geology of the Hartford Quadrangle, Kentucky: Kentucky Geological Survey, ser. 3, v. 20, p. 1-25.

Gardner, J. H., 1927, The Elm Lick coal bed, in Geology of the Cave-in-Rock Quadrangle: Kentucky Geological Survey, ser. 6, v. 26, p. 129-154.

Greb, S. F., Williams, D. A., and Williamson, A. D., 1992, Geology and stratigraphy of the Western Kentucky Coal Field: Kentucky Geological Survey Bulletin 2, ser. 11, 77 p.

Johnson, W. D., Jr., 1971a, Geologic map of the Horton Quadrangle, western Kentucky: U.S. Geological Survey Geologic Quadrangle Map GQ-915.

Johnson, W. D., Jr., 1971b, Geologic map of the Rosine Quadrangle, western Kentucky: U.S. Geological Survey Geological Quadrangle Map GQ-928.

Norwood, C. J., 1880, A general account of the geology of a part of Ohio County: Kentucky Geological Survey, ser. 2, v. 5, pt. 5, 46 p.

Unexpected Results from a Geochemical Approach to Typing and Correlation of Ordovician Oils in the Illinois Basin

John M. Guthrie
Department of Geological Sciences, Indiana University, Bloomington, IN

A set of oil samples produced from Ordovician reservoirs (Galena Group-Trenton Limestone) in the Illinois and Indiana portions of the Illinois basin have been characterized geochemically. Two end-member oil groups (1 and 2) and one intermediate group (1A) are identified using conventional carbon isotopic analysis of the whole and fractionated oil, gas chromatography (GC) of the saturated hydrocarbon fraction, isotope ratio monitoring-gas chromatography-mass spectrometry (IRM-GC-MS) of *n*-alkanes ranging from C_{15} to C_{25}, and gas chromatography-mass spectrometry (GC-MS) of the aromatic hydrocarbon fraction.

Group 1 oils are characterized by high odd-carbon predominance in mid-chain *n*-alkanes (C_{15} to C_{19}), low abundance of C_{20+} *n*-alkanes, and absence of pristane and phytane. Group 1A oils are characterized by slightly lower odd-carbon predominance of mid-chain *n*-alkanes and greater abundance of C_{20+} *n*-alkanes, compared to Group 1. The isotopic composition of *n*-alkanes and the m/z 133 chromatograms of *n*-alkylarenes found in Group 1 and 1A oils indicate that these oils were sourced from Ordovician strata containing abundant *Gloeocapsomorpha prisca.* In contrast, Group 2 oils are characterized by low odd-carbon predominance in mid-chain *n*-alkanes and greater abundances of C_{20+} *n*-alkanes, pristane, and phytane. The isotopic composition of *n*-alkanes and the m/z 133 chromatograms of isoprenoidal alkylarenes (aryl isoprenoids) indicate a variety of possible sources for Group 2 oils.

Conventional oil-source rock correlations using stable carbon isotope type-curves and hopane (m/z 191) and sterane (m/z 217) distributions are of limited usefulness for distinguishing between Ordovician oils and for determining their sources. The use of GC, IRM-GC-MS, and GC-MS illustrates the power of using integrated molecular and isotopic approaches for correlating oils with source rocks.

Western Kentucky Tar Sands and Illinois Basin Oil

Terence Hamilton-Smith, Kentucky Geological Survey, Lexington, Kentucky

Numerous tar-sand deposits occur at or near the surface in western Kentucky, in various sandstones of Late Mississippian and Early Pennsylvanian age, dispersed around the eastern margins of the Moorman Syncline. Local deposits appear to be closely associated with faults, paleovalleys, or stratigraphic traps, and conventional oil production has been obtained locally from the same sandstones a few miles down dip. The tar sand deposits consist of well-consolidated sandstones with porosity between 10 and 28 percent, and permeability between 4 and 2,400 millidarcies. Between 15 and 80 percent of the pore space is filled with tar with a gravity between 6 and 18 API. Some of these deposits have local seeps that flow as much as 10 barrels a year.

Western Kentucky tar-sand deposits represent an in-place resource of over 3.4 billion barrels of tar. Over 2,000 feet of section have been removed from the tar-sand area by erosion, suggesting that the original volume of tar prior to erosion may have been over 11 billion barrels. If the tar is considered to be the degraded remnant of oil of 30 API gravity, then the western Kentucky tar-sand deposits may represent the residuum of over 33 billion barrels of original light oil. This figure compares to an estimated 13.4 billion barrels of oil originally in place in the Illinois Basin. The fact that the estimated original oil in place for the Illinois Basin is less than the estimated volume of oil required to produce the tar sands suggests that both must be taken into account in any mass balance study of hydrocarbons of the Illinois Basin.

The origin of the Kentucky tar sands is not well established. Previous workers suggested that the tar had migrated into its present position through the circulation of ground water, which had also contributed to its degradation. In contrast, there has been little agreement in the past concerning the source of the original oil. Organic geochemical analyses sufficient to match the tar with a parent oil and original source rock have not yet been done. The weight percent of sulfur and the ratio of vanadium to the sum of vanadium and nickel have both been suggested as source-dependent inorganic geochemical parameters. The average sulfur content of western Kentucky tar sand is 1.7 percent, comparable to 1.9 percent for the New Albany Shale, and in contrast to 5.4 percent for the Ohio Shale. Similarly, the average value of the ratio of vanadium to the sum of vanadium and nickel is 0.73 for the western Kentucky tar sands, comparable to 0.70 for the New Albany Shale, and in contrast to 0.60 for the Ohio Shale. Bitumen from western Kentucky tar sand has an unusually high uranium content, which also suggests derivation from the uranium-rich New Albany Shale.

Diagenesis and Fluid Flow in Lower Pennsylvanian Rocks, Illinois Basin

Paula L. Hansley, U.S. Geological Survey

Lower Pennsylvanian sandstones from the Illinois basin were examined petrographically for evidence of hydrothermal ground-water flow related to Mississippi Valley-type (MVT) deposits and (or) oil migration, because regional fluid pathways related to ore genesis and oil migration are not well understood (Spirakis, in press; Davis, 1990). Sandstones of Tradewater age from six cores in central and southern Illinois and from 14 cores in the Naval Surface Warfare Center on the eastern edge of the Illinois basin in Indiana were collected for this study. Slightly older sandstones of Caseyville age were sampled from four cores in the tar-sand district at the eastern edge of the Rough Creek graben in west-central Kentucky. All cores were from relatively shallow depths (6 to 285 m).

Lower Pennsylvanian sediments of Tradewater age in the Illinois basin were deposited on a tidally influenced coastal plain adjacent to an irregular northwest/southeast-trending shoreline (Kvale and Barnhill, in press). Because of rapid facies changes in this coastal setting, sandstones are generally discontinuous and either grade into or are surrounded by finer grained rocks that are less permeable and less porous. Relatively clean, quartzose sandstones were deposited in fluvial channels, tidally influenced fluvial/estuarine channels, or sand-dominated tidal flats. Clay- and organic-rich sandstones are closely associated with coal beds adjacent to the channels. Caseyville-age sandstones were deposited in deep fluvial channels, which were incised into underlying Mississippian rocks (Noger, 1984).

Tradewater-age sandstones are very fine to fine-grained, poorly to moderately well sorted subarkoses and sublitharenites (Folk, 1980). Quartz, chert, muscovite, chlorite, metaquartzite, low-grade metamorphic rock fragments, and relatively unaltered detrital plagioclase and potassium feldspar are the major framework constituents. Porosity and permeability trends are indigenous to individual sand bodies. The more quartzose sandstones contain abundant (up to 12 volume percent) early quartz overgrowths that locally have preserved good to excellent porosity. Remnants of calcite cement in optical continuity and vermicular kaolinite fill (late?) large secondary pores. On the other hand, the porosity and permeability of clay- and organic-rich sandstones are considerably lower. These sandstones, which are associated with low-sulfur coal beds, contain abundant muscovite with early siderite, calcite, and ankerite cements, and relatively small amounts of pyrite. The high amount of Mg (10 percent) substituting for Fe in some of the siderite indicates precipitation from brackish water (Mozley, 1990) and provides additional evidence for a coastal depositional setting.

Silica for quartz overgrowths in channel sandstones may have been imported from nearby peat beds and (or) sideritic sandstones because the margins of framework grains in these units are commonly deeply corroded. Anoxic, organic-bearing environments, which were near neutral in pH due to early microbial reactions, were favorable for the dissolution of silica because of the stability of organic acid-silica complexes under these geochemical conditions (Bennett and Siegel, 1987). Once in solution, these complexes transported silica from sites of dissolution into adjacent sandstones (Bennett and others, 1991).

The Caseyville-age, valley-fill sandstones are medium grained to conglomeratic and form more continuous sand bodies than the Tradewater-age sandstones. Long and sutured contacts between framework grains and stylolites indicate that these rocks have undergone more compaction due to deeper burial than have Pennsylvanian strata to the north. Preliminary examination of petrographic thin sections suggests that oil migrated into these reservoir rocks relatively early in their postdepositional history. Tar and pyrite are present at grain contacts, along stylolites, and under quartz overgrowths. Patches of (early) gypsum cement contain oil in dissolution vugs. Oil-saturated kaolinite, which occurs in secondary pores, replaced gypsum locally.

No petrographic evidence for hydrothermal fluid flow related to MVT-type deposits was found in any of the sandstones. Isolation of Tradewater-age sand bodies due to rapid facies changes apparently prevented hydrologic communication with a deep and (or) regional fault system. Diagenesis was influenced predominantly by early pore-water chemistry within and adjacent to sand bodies. The inherent stability of quartz and siderite enabled them to persist throughout burial diagenesis, and, thus, their distributions controlled patterns of later diagenesis and fluid flow within sand bodies. Secondary porosity formed only where more soluble early cements, such as calcite, dissolved when meteoric water invaded the sandstones. The paragenesis of authigenic phases strongly suggests that oil-bearing fluids migrated into the Caseyville-age tar sands before significant burial. This timing agrees with oil-source rock studies which suggest that peak oil generation and migration in the Rough Creek graben area occurred in the Late Pennsylvanian (Davis, 1990). Migration of hydrothermal fluids is thought to have occurred at approximately the same time (i.e., post-Early or Middle Pennsylvanian and pre-Late Cretaceous) into the Kentucky fluorspar district just to the west of the tar-sand district (Trace and Amos, 1984).

REFERENCES

Bennett, P.C., and Siegel, D.I., 1987, Increased solubility of quartz in water due to complexing by organic compounds: Nature, v. 326, p. 684-686.

Bennett, P.C., Siegel, D.I., Hill, B.M., and Glaser, P.H., 1991, Fate of silicate minerals in a peat bog: Geology, v. 19, p. 328-331.

Davis, H.G., 1990, Pre-Mississippian hydrocarbon potential of the Illinois basin, *in* Interior cratonic basins: American Association of Petroleum Geologists Memoir 51, p. 473-489.

Folk, R.L., 1980, Petrology of sedimentary rocks: Austin, Texas, Hemphill, 184 p.

Kvale, E.P., and Barnhill, M.L., in press, Evolution of Lower Pennsylvanian estuarine facies within two adjacent paleovalleys, Illinois Basin, Indiana: Society for Sedimentary Geology, Special Paper, 35 p.

Mozley, P.S., 1990, Relation between depositional environment and the elemental composition of early diagenetic siderite: Geology, v. 17, p. 704-706.

Noger, M.C., 1984, Tar-sand resources of western Kentucky *in* Eastern Oil Shale Symposium: Lexington, University of Kentucky Institute for Mining and Minerals Research, p. 151-177.

Spirakis, C.S., in press, Constraints on regional fluid flow in the Illinois basin from studies of the genesis of Mississippi Valley-type deposits: U.S. Geological Survey Bulletin 2094-B.

Trace, R.D., and Amos, D.H., 1984, Stratigraphy and structure of the western Kentucky fluorspar district: U.S. Geological Survey Professional Paper 1151-D, p. D1-D39.

Lithostratigraphy and Hydrocarbon Potential of the Cambrian (Pre-Knox) Intervalin the Conoco No. 1 Turner Well, Rough Creek Graben, Western Kentucky

David C. Harris, Kentucky Geological Survey, Lexington, Kentucky

In 1992 an important deep exploratory well was drilled by Conoco Inc. in the Rough Creek Graben of western Kentucky. The Conoco No. 1 Turner well was drilled in McLean County, and reached a total depth of 14,202 feet in Precambrian granite. The objective of this well was to test potential gas reservoirs in both an Eau Claire Formation carbonate buildup and syn-rift sandstones deposited in the Rough Creek Graben. This Early (?) to Middle Cambrian graben trends east-west across western Kentucky into southeastern Illinois, and is probably related to rifting in the Reelfoot Rift to the southwest, and in the Rome Trough of eastern Kentucky, West Virginia, and Pennsylvania. The Turner well encountered no commercial hydrocarbons, but provided new data on the evolution and hydrocarbon potential of the Rough Creek Graben. Encouraged by information from the Turner well, Conoco drilled a second well in Kentucky in 1993, and has recently permitted a third well to 17,500 feet in Gallatin County, Illinois.

The Turner well penetrated over 4,000 feet of pre-Knox sedimentary rocks. Based on sample examination, this interval can be divided into four depositional sequences. The oldest sequence (approximately 1,900 feet thick) consists of fine- to coarse-grained, glauconitic lithic sandstones; thin green shales; and minor oolitic limestones. This interval is sandstone dominated, and is interpreted to represent marine synrift deposits. Overlying the synrift clastics is an 1,150-foot-thick, heterolithic interval of fine- to medium-grained, glauconitic lithic sandstones; oolitic and fossiliferous limestones; and green shales. Smaller scale, shallowing-upward cycles can be recognized in this interval. All of these lithologies are nonporous, and are interpreted as late synrift to early postrift deposits. The uppermost two sequences consist of a 600-foot-thick zone of dolomitized, oolitic grainstones (nonporous) overlain by a 350-foot-thick, shale-dominated interval composed of green shales, siltstones, and oolitic limestones. These intervals are interpreted as a marine post-rift deposit.

Correlation of lithofacies in the Turner well with other wells in the Rough Creek Graben indicates that the basal synrift clastic and oolitic dolomite intervals are not present in the equivalent pre-Knox zones. The synrift clastics lack porosity in the Turner well (because of calcite and quartz cements), but may have reservoir potential in other parts of the basin. The oolitic dolomites contain dolomite cement, and also have no effective porosity. However, a black intercrystalline stain, interpreted to be bitumen, is present in the dolomite, indicating that oil moved through the interval.

The Conoco Turner well has proven that substantial thicknesses of synrift clastics and post-rift dolomites occur in the Rough Creek Graben, and that facies distribution is strongly tectonically controlled. Bitumen staining in the dolomites indicates that hydrocarbons were migrating in the basin. Prediction of effective porosity remains the final hurdle in the search for Cambrian reservoirs in the Rough Creek Graben.

Porosity Loss in Mississippian Oolitic Grainstones, Southern Illinois: Implications for Hydrocarbon Migration

Mitchell E. Henry, U.S. Geological Survey, Denver, Colorado

Mississippian carbonate rocks are of significant economic value in the Illinois basin. They are mined for cement manufacturing, host deposits of fluorite, lead, and zinc; and form important petroleum reservoirs. The most prolific Mississippian carbonate petroleum reservoirs are found in porous oolitic grainstones of the Meramecian Ste. Genevieve Limestone. Commercial quantities of petroleum are virtually absent in the Ste. Genevieve south of the Cottage Grove fault system and within and west of the Illinois-Kentucky fluorspar district on the south flank of the basin.

Original primary porosity of Mississippian oolitic grainstones from a core in the fluorspar district is estimated to have ranged from ~ 16 to 35% and averaged ~ 26% prior to early cementation. Petrographic evidence suggests that, in these grainstones, porosity loss due to mechanical compaction was minor, cementational porosity loss was great and there was little intergranular porosity available to transmit or trap fluids during the time that fluorite mineralization and petroleum migration took place.

The diagenetic history of the Ste. Genevieve grainstones in this core appears to follow a fairly regular pattern. Following deposition, isopachous cement formed as rims on the grains, binding them together in a somewhat rigid framework. These rims are usually ~ 10 to 20 µm thick but they occasionally continued growth to fill the remaining porosity, in what appears as a single generation of cement. Dolomitization of bioclasts, most frequently crinoid fragments, occurred early in the history of the grainstones. Silica mineralization in the form of replacement of bioclasts and quartz overgrowths appears to have taken place episodically during diagenesis of these rocks. Mechanical compaction features that postdate the formation of the isopachous rims and predate the pore-filling cement are present in some of these grainstones. However, these features are rare suggesting either that the thin cement rims resulted in a mechanically strong rock, or that the pores were nearly filled with cement at an early stage.

Following compaction, calcite cementation resulted in the near-complete loss of any remaining porosity. This cement is generally composed of large crystals of calcite; only a few crystals fill a pore. Individual crystals are generally clear and much larger than the crystals composing the earlier formed rims. This difference in size was the primary criterion used to identify multiple cementation events.

Fracturing occurred after pore-filling cementation. Evidence for this includes rupture of pore filling carbonate cement and the restriction of fracture fill carbonate minerals to the fracture. Most fractures are filled with calcite but dolomite also occurrs.

The grainstones are commonly stylolitized. Stylolites are generally parallel to bedding and are often at lithologic contacts; however, they are also present in homogeneous-appearing material. In a few examples, the stylolites appear to offset, and therefore postdate, near-vertical fractures. Dolomite rhombs commonly occur in masses associated with stylolites. The rhombs are uniform in size, averaging ~ 30 μm on an edge.

There is minor dissolution and mineralization related to fluorite emplacement in a few thin-sections. Stylolites and fractures apparently were the most efficient and continuous fluid conduits available during the fluorite mineralization and petroleum migration phase in what were once porous and permeable grainstones. Along the stylolites there commonly is a dark-colored amorphous material that resembles concentrated organic matter or bitumen. That this material is generally restricted to the stylolites suggests there was no open porosity at the time this material was concentrated or emplaced.

Little evidence exists for large-scale movement of hydrocarbons and/or mineralizing fluids through the intergranular space of what should have been some of the most transmissive parts of the Ste. Genevieve in the southern part of the basin. Opaque material resembling dead oil was seen in the intergranular space in only one thin-section. Petroleum generation may have occurred over a long period of time and significant quantities of petroleum may have migrated through these rocks prior to the deposition of pore-filling cements. If so, it continued to move through these rocks or was emplaced and subsequently removed south of the Cottage Grove fault system. If the core described in this study is representative of other carbonate grainstones in this barren area, then porosity loss may be a principal factor in the lack of significant petroleum accumulations here. Comparative studies of the oolite grainstone facies in petroleum productive areas north of the Cottage Grove fault system are underway to determine how the diagenetic history differed between the two areas.

Table 1. Relative sequence of events in the diagenesis of Ste. Genevieve ooid grainstones from the fluorspar district.

EARLY	LATE
Isopachous cement formation	
?——————Dolomitization—————— ?	
?——————Silicification——————?	
Minor compaction	
Petroleum migration	
Pore-filling sparry cement	
Fracturing	
Fracture filling cement	
Stylolitization	
Dissolution	
Fluorite mineralization and petroleum migration	

Geophysical Setting of the Northern Reelfoot Rift and Southern Illinois Basin Region

T. G. Hildenbrand and V. E. Langenheim, U.S. Geological Survey, Menlo Park, California
P. C. Heigold, Argonne National Laboratory

Magnetic and gravity data in the northern Reelfoot rift and southern Illinois Basin region provide a geologic picture of the subsurface that indicates a long and complex tectonic and magmatic history. The Reelfoot rift possibly developed along a pre-existing shear zone in early Paleozoic time and extends from east-central Arkansas to western Kentucky, where it seems to merge with the Rough Creek graben. At the juncture of the Reelfoot and Rough Creek grabens, interpreted NW-trending faults and a zone of intrusions form the Paducah gravity lineament (PGL), which may represent a block-faulted region. Paralleling the PGL to the northeast and extending from eastern Tennessee to Missouri is a pronounced magnetic lineament (called the south-central magnetic lineament—SCML), which possibly delineates a Precambrian shear zone with magnetic intrusions. The study area is structurally one of the most complex regions in the midcontinent.

Geophysical inversion models and filter applications lessen this complexity by defining crustal structures and subsurface distributions of density and magnetizations. For example, eight hundred estimates of maximum depth to magnetic basement clearly show basement descending to depths greater than 6 km in the Reelfoot and Rough Creek grabens but ascending in the St. Francois Mountains and central Arkansas regions. Calculated densities and magnetizations suggest that the upper crustal intrusions forming and lying along the PGL are more mafic (gabbro?) than those along the SCML (granodiorite?). Gradient analyses reveal several linear geophysical features that correlate with known fault zones. Such potential-field studies assist in understanding the

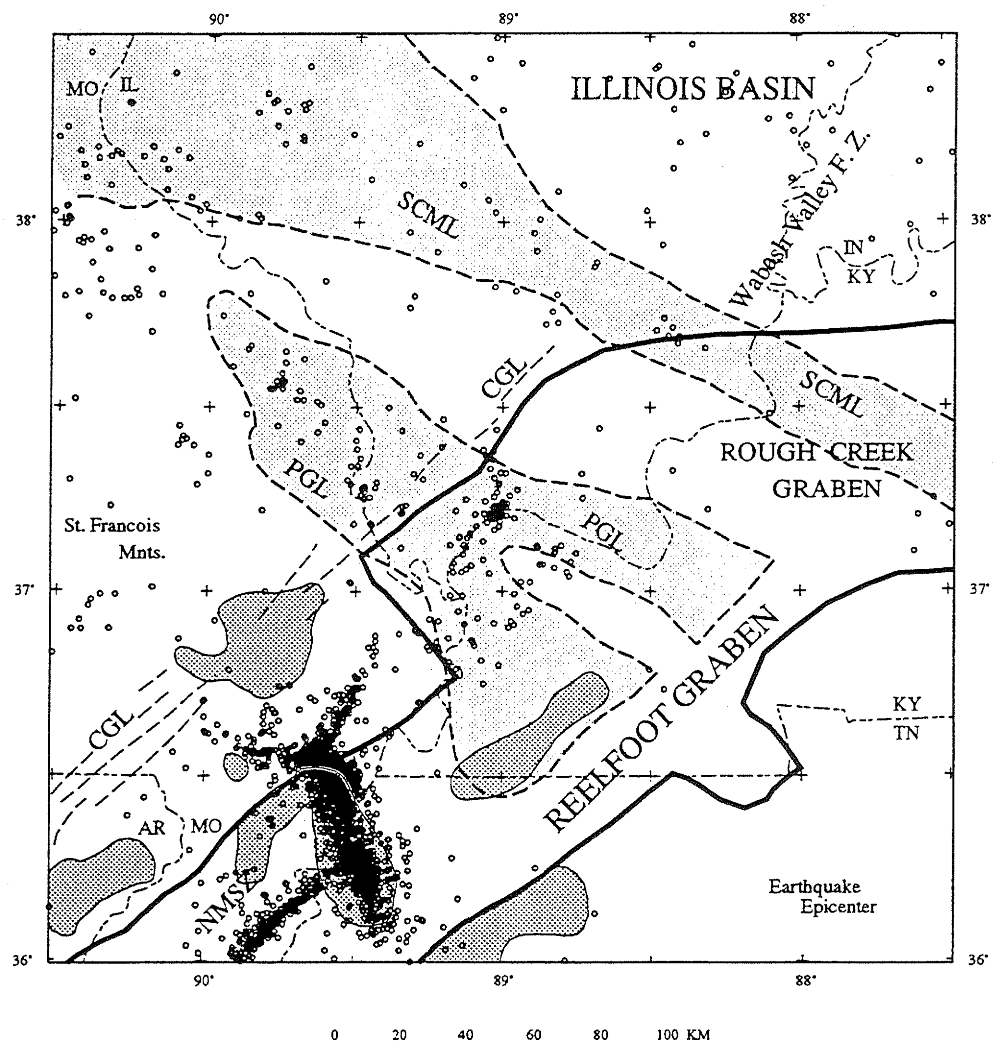


Figure. Regional geologic features expressed in the potential-field data of the southern Illinois and northern Reelfoot rift region. Heavy solid lines show the interpreted margins of the Reelfoot and Rough Creek grabens. Light shaded areas labeled PGL and SCML depict two prominent geophysical features, the Paducah gravity lineament and south-central magnetic lineament, respectively. Darker shaded areas represent subsurface igneous intrusions associated with the Reelfoot rift. NE-trending dashed lines depict linear gravity and magnetic features that form the Commerce geophysical lineament (CGL). Small circles are locations of earthquake epicenters detected by the Missouri Valley regional seismic network from 1975 to 1991.

regional geologic framework needed in assessments of energy resource, mineral resource, and earthquake hazards.

On a local scale, magnetic-anomaly data are useful in delineating Permian ultramafic alkalic plugs or laccoliths at shallow depths (<1 km). Of particular interest is that positive anomalies coincide with known or indicated shallow intrusive centers near Omaha Dome, Coefield, and Hicks Dome. Perhaps some of the other positive anomalies delineate shallow intrusions with mineral potential, similar to Hicks Dome.

Several structures expressed by the potential-field data appear to focus earthquake activity. For example, the remarkable geographic correspondence of the eastern lobe of an intrusive complex and the New Madrid seismic zone (NMSZ) in NW Tennessee and SE Missouri strongly suggests that the abrupt change in the seismicity trend from NE to NNW is related to a path of less resistance along the intrusive complex. Moreover, there is no apparent geophysical evidence for a continuous NE-trending structure linking the NMSZ and the approximately colinear Wabash Valley fault zone. To the contrary, the PGL and the SCML reflect structures trending NW in the intervening region. Because earthquakes are concentrated within the PGL but are rare immediately NE of the PGL, intrusive boundaries and NW-trending faults related to the PGL may be the preferred directions of strain release.

The Commerce geophysical lineament (CGL), near and parallel to the NW margin of the Reelfoot graben, is probably related to recent fault movement as well as to rifting. In southern Illinois the CGL coincides with the Commerce fault, with known Quaternary movement. Both the magnetic and gravity data express 5 km of apparent left-lateral offset along the CGL. Inversion models reveal a buried horst and graben topography dipping SE toward the Reelfoot rift. Apparently, the CGL expresses border faults of the Reelfoot rift, and some of these faults have been reactivated in recent geologic time.

History of the Illinois Basin: An Overview

Dennis R. Kolata, Illinois State Geological Survey

The Illinois Basin covers an area of approximately 285,000 km^2 in parts of Illinois, Indiana, and Kentucky, and contains about 500,000 km^3 of Cambrian through Pennsylvanian sedimentary rocks with a maximum thickness of more than 7,600 m. The southern end of the basin is underlain by the Reelfoot Rift/Rough Creek Graben, a rift system that formed during late Precambrian to Early Cambrian time. Geodynamic processes operating within the rift, significantly influenced by plate tectonic interactions from late Precambrian to the present, have controlled basin geometry, basin subsidence, sedimentation rates, position of depocenters, facies relations, structural styles, regional fluid flow systems, and localized intrusive activity during reactivation of the rift. In addition, the rift controlled development of the Mississippi Embayment during Mesozoic-Cenozoic time, and today, tectonic compressive stress is reactivating ancient faults within the rift, causing earthquakes.

The rift formed concurrently with breakup of a supercontinent during late Precambrian to Early Cambrian time, perhaps exploiting a pre-existing zone of weakness. Lithospheric extension within the rift system resulted in tensional block faulting and rapid subsidence. 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 northeastward through Illinois, Indiana, and western Kentucky. Open-marine circulation dominated, and depositional and diagenetic facies aligned with tectonically defined bathymetric zones. The primary depocenters for the Paleozoic sequences in the basin developed over the rift system.

During Late Cambrian through Early Ordovician time (about 30 million years), approximately 2,500 m of primarily carbonate rocks (Knox Group) were deposited in a depocenter situated over, but extending beyond, the rift system. This was the time of highest post-rifting subsidence in the proto-Illinois Basin. Regression of seas from the North American craton during the Early Ordovician resulted in subaerial exposure and formation of a widespread major unconformity. The region of the Reelfoot Rift/Rough Creek Graben, however, apparently continued to be a depocenter for marine sediments. Biostratigraphic evidence from the southern part of the basin suggests that there was continuous sedimentation across the Sauk/Tippecanoe sequence boundary. The relatively rapid rates of subsidence during this time have been attributed to thermal subsidence that accompanied and followed rifting. Mild structural deformation and slow subsidence rates characterized the basin during Middle Ordovician to mid-Mississippian time.

The basin experienced widespread structural deformation beginning in late Mississippian and continuing into Early Permian time, concurrent with the accretion of continents forming the Pangea supercontinent. Compressional stresses emanating from the Alleghenian and Ouachita orogenies were transmitted to the continental interior, reactivating faults within the rift system and evidently increasing subsidence rates within the proto-Illinois Basin. The compressional episode was followed by a post-Early Permian episode of extension coinciding with breakup of Pangea. Tensional stresses again reactivated faults within and adjacent to the rift system. Post-Pennsylvanian, pre-Late Cretaceous uplift of the Pascola Arch structurally closed the southern end of the Illinois Basin, creating the present basin geometry.

Waulsortian Mounds and Hydrocarbon-Bearing Facies in the Ullin ("Warsaw") Limestone of the Illinois Basin

Zakaria Lasemi, Janis D. Treworgy, Rodney D. Norby, and John P. Grube
Illinois State Geological Survey

The Middle Mississippian Ullin ("Warsaw") Limestone has been a prolific hydrocarbon producer in a number of fields in the Illinois Basin. Some wells have produced over 200,000 barrels of oil in just a few years. Recent discoveries indicate a greater reservoir potential for the Ullin than previously recognized. Depth to the Ullin ranges from 2400 to 4400 feet throughout Illinois. Our study of the various facies of the Ullin and their depositional environments has shown that the Ullin contains numerous Waulsortian-type mud mound complexes. Waulsortian mound facies similar to those in the Ullin Limestone are prolific hydrocarbon reservoirs elsewhere in North America.

Two stages of Ullin deposition are recognized. In the lower Ullin, Waulsortian-type carbonate mud mounds were initiated after a sea-level rise that accompanied cessation of Borden Siltstone deposition. The mounds developed below storm wavebase in a deeper water, outer ramp to basinal setting. The mound facies of the Ullin generally coalesce laterally and vertically into complex carbonate bodies that range from 50 to 500 feet wide and 20 to 60 feet thick in outcrop and thicken basinward. Mound facies include a massive mudstone and wackestone core flanked by 1) a bryozoan-crinoid bafflestone buildup facies that shows little evidence of current reworking and 2) a well-bedded, transported, bryozoan-crinoid wackestone and packstone/grainstone. The bafflestone facies was the potential source for skeletal sands deposited as aprons of packstone/grainstone debris in intermound areas. These facies grade basinward into the dark colored, argillaceous, spiculitic, and cherty lime mudstone of the Fort Payne Formation. The mound facies accreted vertically into storm wavebase.

The upper part of the Ullin includes a widespread storm-generated skeletal sandwave facies (grainstone) and an inter-sandwave facies. Isolated bryozoan bafflestone buildups, or bryozoan patch reefs, developed on pre-existing highs. The storm-generated sandwave facies includes fragmented and poorly sorted skeletal particles and is characterized by low-angle inclined bedding, hummocky cross-stratification, graded bedding, and escape burrows, all indicating rapid deposition. The upper Ullin accretes vertically into a fair weather wavebase setting and grades into the overlying Salem Limestone.

Because of excellent preservation of intra- and interparticle porosity, the bafflestone buildup facies has a high potential for reservoir development where permeable. High porosity is also characteristic of debris aprons and storm-generated sandwaves in the Ullin. The porosity, permeability, and reservoir quality of these carbonate sand bodies are highly variable and may be dependent on the relative abundance of crinoid fragments, which are susceptible to overgrowth cementation.

Seismic Character Analysis of a Mixed Siliciclastic-Carbonate Reservoir

Hannes E. Leetaru, Illinois State Geological Survey

Detailed reservoir characterization at King Field, Jefferson County, Illinois indicated that the Mississippian age Aux Vases Sandstone is part of a nearshore mixed siliciclastic-carbonate system. The intercalated sequence of reservoir sandstone and non-reservoir shales and calcareous facies form a compartmentalized reservoir. High resolution seismic can be used to predict some of the lithologic changes that contribute to reservoir compartmentalization.

The principle data at King Field are old wireline electric logs. Pseudo-velocity logs were created from these old electric wireline logs and subsequently used to create synthetic seismogram models of the facies changes. Synthetic seismogram modeling compared with actual seismic from King Field suggests that amplitude variations of the seismic reflectors can be used to differentiate reservoir from non-reservoir calcareous facies. This amplitude variation is due to destructive interference of the seismic wavelet created by the non-reservoir calcareous facies with high impedance reflectors beneath the reservoir interval. Seismic character analysis can be successfully applied to King Field because most of the compartmentalization in this field was due to the interrelationship of the calcareous facies with reservoir sandstones.

The application of seismic character analysis may be used to reduce the risk during reservoir development in mixed siliciclastic-carbonate systems. Seismic character analysis may also be used as an exploration tool in searching for new stratigraphic traps within the Aux Vases Sandstone.

Tectonic History of the Wabash Valley Rift Using Seismic Reflection and Stress Field Effects

Jennifer J. Lewis, Indiana University

The current understanding of the structural history from latest Precambrian through early Paleozoic time of southern Indiana is problematic. This is due in part to the fact that the Precambrian rocks are overlain by later Paleozoic rocks, thus structural relationships are concealed and can not be determined in outcrop. Borehole data offers a limited amount of information about the Precambrian-Paleozoic relationship because few wells in this area penetrate the Precambrian. One of the most valuable sources of information which can be used to define the Precambrian-Paleozoic relationship is seismic reflection data. Although interpretations determined on seismic reflection data are often referred to as non-unique, using this data in conjunction with the analysis of stress fields resulting from continental-scale orogenic events, a unique tectonic model can be established. Integration of the size, orientation, and timing of orogenic events constrain the type and geometry of structural features possible. The tectonic history of the midcontinent can be subdivided into multiple stages. Keller *et al.* (1983) suggested three major time periods of rifting in the mid-continent region: Keweenawan, Eocambrian, and early Mesozoic. It can be demonstrated that the Rough Creek Graben, which is one of the three arms of the Reelfoot rift, was affected by each of these periods. Eocambrian and Mesozoic tectonism resulted in reactivation and modification of the original rift. In the same way, a polystage tectonic model is generated for the Wabash Valley rift, which is a second arm of the Reelfoot rift. The initial major tectonic event affecting this area was the opening of Iapetus during latest Precambrian time, resulting in NE-SW trending normal faults. The Wabash Valley rift was additionally affected by the north-south stress field of the Ouachita orogeny that reactivated the NE-SW trending faults, resulting in transpressional motion. The latest major event was the renewal of the NE-SW striking dip-slip motion as observed in the system today.

REFERENCES

Keller, G.R., Lidiak, E.G., Hinze, W.J., and Braile, L.W., 1983, The role of rifting in the tectonic development of the Midcontinent, USA, *in* Morgan, Paul and others eds., Proceedings of continental rifting: Tectonophysics, v. 94, no. 1-4, p. 391-412.

Subsurface geometry and petrography of clastic rocks of the Beech Creek ("Barlow") Limestone (Chesterian) to Springfield Coal (Desmoinesian) stratigraphic interval of part of the La Salle Anticlinorium, Lawrence County, Illinois

Donald K. Lumm, Dept. of Geological Sciences, University of Kentucky, Lexington, Kentucky

The La Salle Anticlinorium is a 250-mile-long, north-northwest-striking feature of the Illinois Basin, and its extent and character have been progressively delineated from the accumulation of data derived from coal, oil, and gas exploration. For much of its extent the principal structural element is the Charleston Monocline, which separates an eastern shelf area consisting of enechelon anticlines and synclines from the deeper part of the Illinois Basin to the west. Ordovician through Pennsylvanian limestone, shale, sandstone, and coal are folded and dip to the west. Although previous studies report thinning of major rock units across the La Salle Anticlinorium, and that this thinning is the result of movement of the structure during sedimentation, how this thinning takes place has not been established. Of particular significance is the systemic unconformity reported at the base of the Pennsylvanian System; with increasing amounts of data applied to same size or smaller areas, aerial bedrock maps show greater complexity of the sub-Pennsylvanian (Chesterian) surface (Workman, 1940; Siever, 1951; Bristol and Howard, 1971). As data spacing becomes progressively smaller the number of alternative hypotheses to the Mississippian-Pennsylvanian unconformity and to the manner of sedimentary thinning across the anticlinorium tend to diminish. However, the fact remains that in distances of one well per half mile (average spacing used by Bristol and Howard, 1971) between boreholes, the character and correlation of the rocks could be subject to alternative explanations. Throughout much of the eastern part of the Illinois Basin where Chesterian sandstones are well developed, correlation of these sandstones using geophysical logs show that many are in apparent lateral equivalency with similar and presumed Lower Pennsylvanian sandstones. Hence, a four-township area (144 mi.2) of Lawrence County, Illinois, astride the La Salle Anticlinorium was selected for detailed examination because of the great concentration of data available, and for the presence of structural and stratigraphic features noted above. The specific objectives were to determine the geometry and petrographic character of some of the principal Carboniferous clastic units, and to interpret the manner in which these units were affected by structural movements or other geological events.

The primary source of data used in this study is 550 geophysical logs, which are predominately electric logs (SP/R). The logs that were selected for study show the entire sequence from the base of the Beech Creek ("Barlow") Limestone (Chesterian) to the Springfield Coal Member of the Carbondale Formation (Desmoinesian). The geophysical logs were used to construct a grid of 28 cross sections (average well spacing = 2,100 feet) to observe the general stratigraphic relationships. Isopach maps (scale 1:31,250) were produced for some stratigraphic intervals including the thick (greater than 60 feet) sandstone bodies observed on the cross sections. A second grid of 18 cross sections (average well spacing = 1,100 feet) was constructed perpendicular to the main trend of the sandstone bodies identified from the isopach maps in order better distinguish their shapes. Drill cuttings selected from 30 oil and gas tests representing more than 12,300 feet of stratigraphic section were examined under binocular microscope to provide additional details about sandstones and shales represented on geophysical logs.

The cross sections reveal that the thickness and continuity of the Chesterian limestones and sandstones is nearly constant, except for local absences; the youngest sub-Pennsylvanian unit varies from the Waltersburg Formation in the extreme west to the Beech Creek ("Barlow") Limestone. The conspicuous local absence of the Glen Dean Limestone, its replacement by shale or sandstone correlated with younger (Pennsylvanian) strata, and its preservation on opposite sides of the absent localities (with the same thickness and same structural position) gives indication for erosion of that unit prior to deposition of the younger strata.

Four vertically distinct and lenticular sandstone bodies positioned above the Glen Dean Limestone (Chesterian) and below the Colchester Coal (Desmoinesian) can be correlated in areas of dense well control. Three of the sandstone units are tentatively correlated with the Caseyville Formation (Morrowan) and are generally several thousand feet across; locally, the sandstones are stacked and up to 390 feet thick. The upper part of these sandstone bodies, where thick, tends to split laterally into one to three benches and pinch out. Isopach maps of these sandstone bodies indicate that "Sandstone A" (basal Caseyville Formation) and "Sandstone C" (upper part of the Caseyville Formation) do not have a preferred strike and are of the same thickness range on both sides of the monocline. However, "Sandstone B" (Caseyville Formation equivalent) and "Sandstone D" (Tradewater Formation equivalent) are oriented north-south and are much thicker (up to 120 feet) to the west of the structural axis of the monocline, whereas they are 0 to 20 feet thick east of that axis. These isopach patterns suggest separate episodes of uplift of the anticlinorium or rapid subsidence of the deeper part of the Illinois Basin during deposition of the Caseyville Formation and the Tradewater Formation.

The petrographic analysis of some Chesterian sandstones (e.g., Tar Springs and Hardinsburg) from drill cuttings indicates they are quartz-arenite composition and very fine to fine grained. In most cases, these sandstones cannot be positively distinguished from petrographically similar sandstones tentatively assigned to the Caseyville Formation. The general lack of quartz-pebble conglomerate in many Caseyville samples, and to a lesser degree, the small proportion of the coarse-grained sand fraction observed is atypical for sandstones of the Caseyville Formation.

Since shales are the most voluminous rock type and distributed throughout the stratigraphic sequence and because they are sensitive to depositional setting, a secondary analysis of the drill cuttings was directed to the shales. Shales admixed with sandstones, excluding caving material, were routinely described from the drill cuttings. A statistical analysis to quantify the association of color, the presence or absence of carbonaceous matter, mica (muscovite), and fissility of shales was performed. The results of chi-square (X2) tests applied to the petrographic data indicate that shales of the Tradewater Formation are abundantly micaceous (X2 = 9.7) and dominated by grayish-black (X2 = 7.9) and dark-gray (X2 = 2.8) colors. The shales of the Caseyville Formation tend to be sparsely micaceous (X2 = 11.1) and medium dark-gray (X2 = 3.4) and medium-gray (X2 = 3.3) in color. These results are in general agreement with the shale mineralogy of the Caseyville and Tradewater formations as are known for Illinois (Kosanke et al., 1960; Willman et al., 1975).

REFERENCES

Bristol, H. M., and Howard, R. H., 1971, Paleogeologic map of the sub-Pennsylvanian Chesterian (upper Mississippian) surface in the Illinois Basin: Illinois Geological Survey Circular 458, 14 p.

Kosanke, R. M., Simon, J. A., Wanles, H. R., and Willman, H. B., 1960, Classification of the Pennsylvanian strata of Illinois: Illinois Geological Survey Report of Investigations 214, 84 p.

Siever, R., 1951, Mississippian-Pennsylvanian unconformity in southern Illinois: American Association of Petroleum Geologists Bulletin, v. 35, no. 3, p. 542-581.

Willman, H. B., Atherton, E., Buschbach, T. C., Collinson, C., Frye, J. C., Hopkins, M. E., Lineback, J. A., and Simon, J. A., 1975, Handbook of Illinois stratigraphy: Illinois State Geological Survey Bulletin 95, 261 p.

Workman, L. E., 1940, Subsurface geology of the Chester Series in Illinois: American Association of Petroleum Geologists Bulletin, v. 24, no. 2, p. 209-224.

Hydrocarbon plays within the Illinois Basin Province for the National Petroleum Assessment

David L. Macke, U.S. Geological Survey, Denver, Colorado

The Illinois Basin Province, as defined for the National Petroleum Assessment, includes the Illinois Basin and the northern Mississippi Embayment. The Illinois Basin is an interior cratonic basin primarily in Illinois, Indiana, and Kentucky and small areas in Tennessee and Missouri. The northern Mississippi Embayment, an area of subsidence centered on the Late Proterozoic Reelfoot Rift and related to subsidence of the Gulf Coast, lies at the southern end of the Illinois Basin in Arkansas, Kentucky, Missouri, Tennessee, and Mississippi. Eight petroleum plays have been defined within the Illinois Basin: four confirmed, two hypothetical, and two unconventional plays. The confirmed plays are the Post-New Albany, Hunton, Silurian reef, and Middle and Upper Ordovician carbonate plays. The hypothetical plays are the Pre-Middle Ordovician and Rough Creek Graben plays; and the unconventional plays are the Devonian Shale gas and (8) Pennsylvanian coal gas plays. Three hypothetical plays have been defined within the Mississippi Embayment: the Reelfoot Rift, the Late Paleozoic, and the Post-Middle Cambrian fold and thrust plays. The first phase of the assessment dealt only with the conventional plays.

The Post-New Albany play includes all Mississippian and Pennsylvanian reservoirs within the Illinois Basin and produces oil and minor amounts of gas and associated wet gas principally in large structural, stratigraphic, and combination traps. It accounts for greater than 95 percent of the hydrocarbon production within the basin. Although this play could have been subdivided into a large number of subplays, the entire sample population was treated as a single sample set.

The Hunton play involves structural and combination traps and some unconformity traps. It includes Silurian and Devonian age reservoirs below the New Albany Shale but excludes Silurian reef reservoirs. The play occurs throughout the basin but is most favorable south of the Sangamon arch, where the source potential of the New Albany Shale is the greatest. However, the area south of the Rough Creek fault zone and east of the fluorspar district in Kentucky is both a productive and prospective part of the play.

The Silurian reef play includes oil accumulations in pinnacle reef carbonate reservoirs or in younger reservoirs that are draped over reefs; both types of reservoirs contain oil sourced from the New Albany Shale. The play includes the area of pinnacle and interstratal reef limestone occurrences that are overlain by the New Albany Shale.

The Middle and Upper Ordovician carbonate play includes all reservoirs of Middle and Upper Ordovician age (the lower Tippecanoe sequence). The known production of both the Western Shelf area and the La Salle anticline occur in limestone found as localized carbonate grainstone shoals where intergranular porosity has been preserved. The traps are primarily anticlines, with minor stratigraphic traps involving facies changes.

The Pre-Middle Ordovician play is a mixed structural and stratigraphic hypothetical play consisting of the Upper and Middle Cambrian and Lower Ordovician rocks within the Illinois Basin exclusive of the Reelfoot Rift and Rough Creek grabens.

The Rough Creek Graben (Illinois Basin) and Reelfoot Rift (Mississippi Embayment) early Paleozoic rift-graben plays are hypothetical plays involving principally fault and fault-related structural traps in clastic reservoirs.

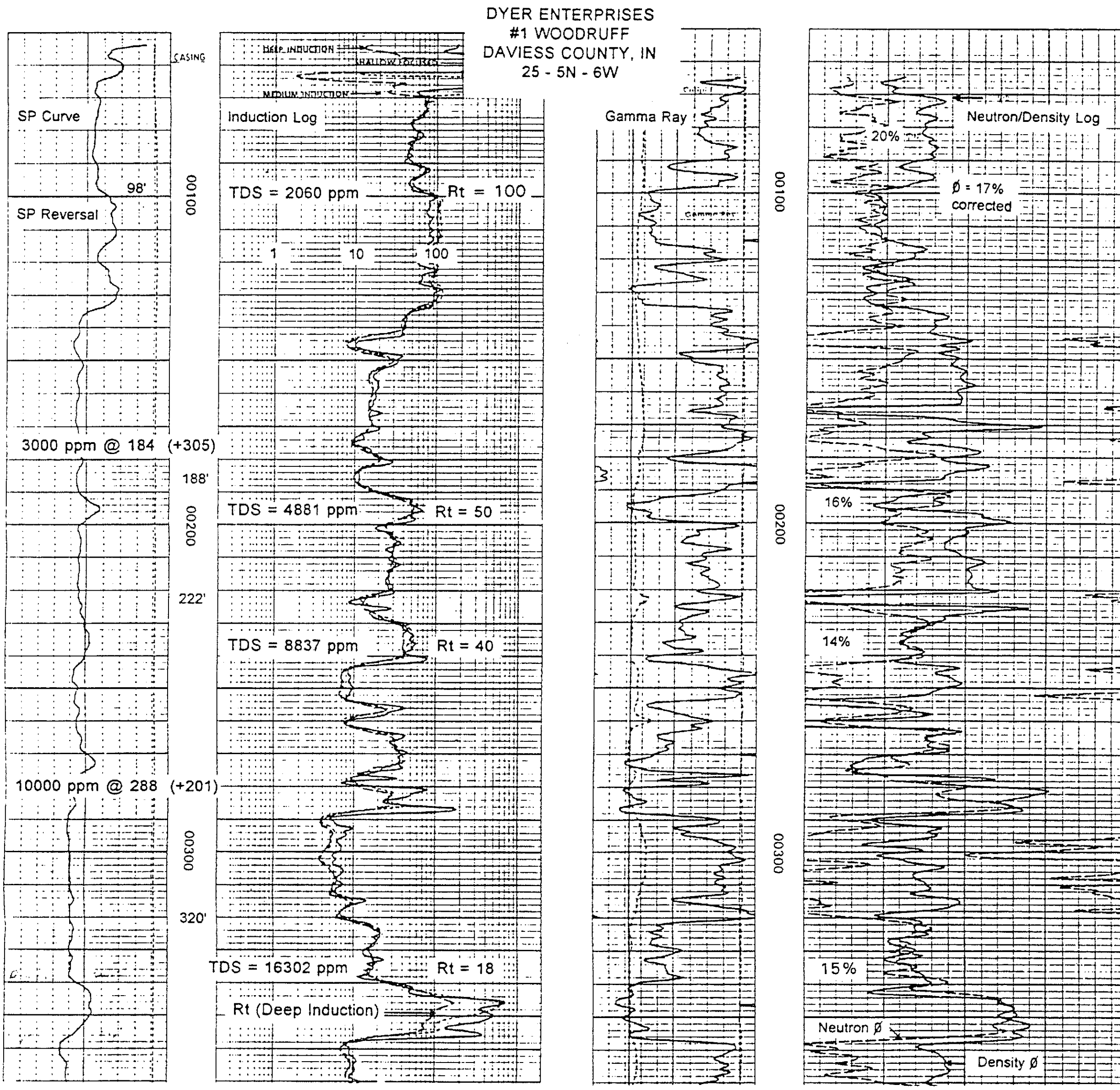
The hypothetical Late Paleozoic play includes all post-Middle Cambrian rocks subcropping beneath the Cretaceous sedimentary section within the Mississippi Embayment. This play is analogous to the Pre-Middle Ordovician, Middle and Upper Ordovician carbonate, Silurian reef, Hunton, and Post-New Albany plays within the Illinois Basin. The rocks of this play subcrop radially around the Pascola Arch, beneath the Cretaceous sedimentary cover. Petroleum accumulations within the play would occur within structural, stratigraphic, and diagenetic traps.

The hypothetical Post-Middle Cambrian fold and thrust play includes Late Cambrian through Pennsylvanian rocks within the Mississippi Embayment. This play has analogs in the Arkoma Basin to the west (a lower Paleozoic through Mississippian eastern Arkoma gas play and a Morrowan clastic wedge gas play) and partial analogs in the Black Warrior Basin to the east (a Cambrian and Ordovician carbonate play). The play contains potential gas and local oil trapped in basement-controlled fault blocks, ramp anticlines associated with frontal thrust faults of the Ouachita fold belt, and facies changes.

Assessment of the 3,000 and 10,000 ppm Total Dissolved Solids Boundaries in the Mississippian and Pennsylvanian Aquifers of Southwestern Indiana Using Geophysical Logs

W. M. Mitchell, Indiana Geological Survey

The Indiana Geological Survey (IGS), in cooperation with the Indiana Department of Natural Resources' Division of Oil and Gas, conducted a study of Mississippian and Pennsylvanian aquifers in southwest Indiana to identify the 3,000 and 10,000 ppm total dissolved solids (TDS) boundaries, using geophysical logs. These boundaries, particularly the 10,000 ppm TDS level, are used to define the limits of aquifers classified as Underground Sources of Drinking Water (USDW); under current federal



Depth	(Subsea)	Formation	Rtdeep	Porosity	BHT	Formation Temperature	TDS
98	(+391)		100	0.17	72	58	2060
188	(+301)		50	0.16	72	59	4861
222	(+267)		40	0.14	72	60	8337
320	(+169)		18	0.15	72	62	16302
358	(+131)	Cypress	16	0.15	72	62	18295
379	(+110)	Cypress	12	0.18	72	63	16241

Figure Showing Typical Neutron/Density and Resistivity Log Responses with Salinity Calculations

regulations these aquifers must be protected to prevent contamination.

The TDS values of the water in individual formations were obtained from two sources: groundwater samples and calculations using the resistivity and porosity readings from geophysical surveys that were conducted in petroleum industry wells. Approximately 10,000 individual-formation TDS calculations from more than 2,500 oil and gas industry wells, and 245 groundwater samples were used to make isosalinity maps depicting the elevations of the 3,000 and 10,000 ppm TDS boundaries.

Water samples from 13 zones in 5 boreholes were analyzed for TDS in order to calibrate the geophysical calculations. None of the groundwater samples exceeded 2,000 ppm TDS. Fifty percent of the measured values correlated favorably with the calculated values. The relatively low TDS and the presence of gas are thought to be responsible for the reduced correlation found in the remaining fifty percent.

The study demonstrated that TDS values from geophysical logs can be used to predict salinity trends with some reliability; however, accurate TDS concentrations cannot be as reliably determined from log-determined data alone when formation fluids have TDS less than 5,000 ppm.

The 3,000 and 10,000 ppm TDS isosalinity surfaces generally dip basinward and are irregular. The 3,000 and 10,000 ppm TDS surfaces occur in southwestern Indiana at greater depths than anticipated. Numerous salinity anomalies and salinity inversions were observed within the study area. These anomalies and inversions suggest several possible conditions, including the upwelling of deep fluids, faulting, the circulation of shallow subsurface fluids, or perhaps the mixing of surface water and deep aquifers.

Present address: ATEC Associates, Inc., 920 Frederica Street, Midtown Building, Suite 1040C, Owensboro, Kentucky 42301

Preliminary Identification of Transgressive-Regressive Depositional Cycles in the Chesterian Series in Southern Illinois

W. John Nelson and Janis D. Treworgy, Illinois State Geological Survey

The Pope Group (primarily of Chesterian age) includes some of the most prolific hydrocarbon producing units in the Illinois Basin. Determining genetically related lithologic units is a key to mapping and correlating potential producing units. Here we show transgressive-regressive depositional cycles within the Pope in southern Illinois as a first attempt at identifying and correlating these cycles basinwide.

The Pope Group in southern Illinois is divisible into multiple transgressive-regressive depositional cycles that range from 1 m to more than 30 m thick but commonly are about 10 m thick. Many of the shallow marine limestone units, including the Beech Creek, Haney, upper Glen Dean, Vienna, and Negli Creek, consist of a shallowing-upward, regressive sequence, initiated by marine transgression. Locally, these regressive limestone units are capped by a low-relief scour surface, which, in isolated cases, may be cut by an incised valley. Elsewhere the limestones grade upward into the overlying siliciclastic unit. Overlying some regressive limestone intervals are thick sandstone units that appear to be marine. These sandstones include the Cypress, Big Clifty, Hardinsburg, and Degonia. Two possible explanations regarding sea level shifting at the contact of the limestones and sandstones are plausible. Where the scour surfaces are accompanied by pedogenic features, including root zones and breccias, there was subaerial exposure and there must have been a subsequent marine transgression to allow for deposition of the overlying marine sandstones. However, scour surfaces on top of the limestones that lack evidence of subaerial exposure may be due to marine tidal activity, and the incised valleys may have formed later during a time of subaerial exposure near the top of the overlying siliciclastic unit. In this case and in the case where the contact between the limestone and the overlying siliciclastic unit is transitional, a marine transgression is not necessary at the inception of siliciclastic deposition. The bulk of these siliciclastic units are regressive, or shallowing-upward, marine deposits that commonly include coal, rooted zones, paleosols, or tidal flat sediments near the top. Some carbonate units (Menard, Cave Hill) and siliciclastic units (Upper Valmeyeran Aux Vases, Tar Springs) are more complex and may contain several transgressive-regressive cycles.

We believe that sediment supply was the primary control on carbonate versus siliciclastic sedimentation. Sediment supply, in turn, was controlled chiefly by climate and/or tectonic activity in the source areas.

Thermal History Modeling in the Illinois Basin

Vito F. Nuccio, U.S. Geological Survey, Denver, Colorado

Vitrinite reflectance (R_o) is commonly used to calibrate thermal history and petroleum generation models in sedimentary basins. Laboratory-derived kinetic-R_o profiles are adjusted to match measured R_o values by varying geologic parameters such as paleogeothermal gradients, paleo-surface temperatures, heat flow, and burial history. However, if calibrated to problematic measured R_o values, the resulting thermal-history model may not represent the "true" geologic history of the study area. It is obvious, therefore, that recognition and remediation of problems with R_o data are critical when modeling the thermal and petroleum generation history of a basin.

During thermal-history reconstruction of the Illinois Basin of Illinois, Indiana, and Kentucky, we observed that the level of thermal maturity in R_o profiles (constructed from Pennsylvanian Herrin no. 6 coal bed and Upper Devonian-Lower Mississippian New Albany Shale samples) do not always increase with increasing depth of burial and, in some instances, actually decrease with increasing depth. For example, in Wayne County, Illinois, in the central part of the basin, R_o of the Herrin coal is 0.65 percent and R_o of the New Albany Shale, 2,600 ft below, is also 0.65 percent. However, pyrolysis temperature (T_{max}) values for the New Albany in Wayne County average 450°C; these equate to an R_o equivalent of approximately 0.90-1.0 percent. The kinetic-R_o model for this area also indicates an R_o of about 1.0 percent for the New Albany, in agreement with other organic geochemical data. Therefore, vitrinite reflectance suppression appears to be around 0.35 percent for the New Albany in this part of the basin.

Rock-Eval and extraction organic geochemical data indicate that the level of suppression for the New Albany is variable throughout the basin, depending on the quality of the organic matter and level of maturation. Measured R_o values are consistently lower than R_o equivalents estimated from T_{max} up to a T_{max} of approximately 455°C, at which point measured R_o seems to converge with and is comparable with T_{max} values. Also, R_o values show an inverse relationship to hydrogen indices (HI).

The present study determines the amount of R_o suppression for the New Albany Shale and uses the corrected values to model the thermal history of the Illinois Basin. The following model of the Fairfield basin area (in the central to south-central part of the Illinois Basin) illustrates how the corrected R_o values for the New Albany Shale are used. Measured R_o values in the Fairfield basin area range from around 0.50 percent for coals in the upper part of the Pennsylvanian to 0.65 percent in the Upper Devonian-Lower Mississippian New Albany Shale (dashed line in Figure 1). For this study, it is assumed that the Pennsylvanian coals yield a fairly representative, non-suppressed R_o. Based on T_{max} values and other organic geochemical indicators, the amount of R_o suppression for the New Albany Shale in this part of the basin is around 0.15 percent and should be about 0.80 percent.

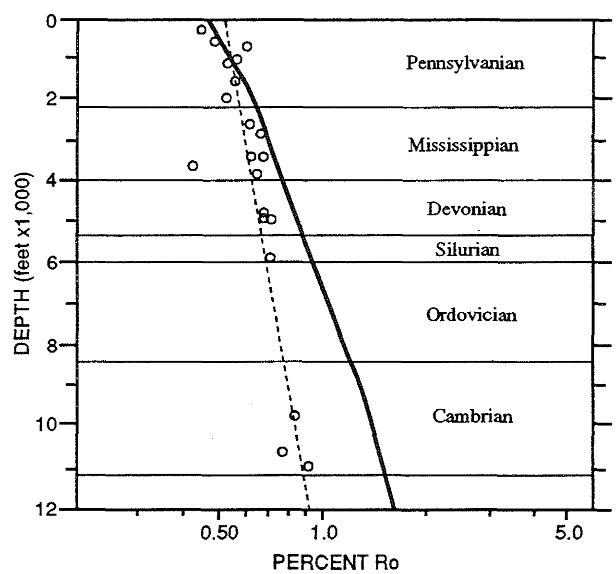


Figure 1. Measured and modeled vitrinite reflectance profiles for the Fairfield basin, central to south-central Illinois Basin. Individual R_o data points are represented by (+). The dashed line is the measured profile, and the solid line is the modeled profile. The difference between the measured and modeled profiles represents the amount of vitrinite suppression. (Measured profile is unpublished data of M.H. Barrows; provided by R.D. Harvey, Illinois State Geological Survey).

Several scenarios, using varying amounts of erosion and heat flow were tried until the vitrinite kinetic model matched the non-suppressed Pennsylvanian coals (around 0.50 percent) and the corrected R_o (around 0.80 percent) for the New Albany (solid line in Figure 1). In order to make this match, 4,000 ft (1,220 m) of overburden was required, and a variable heat flow of 38 mW/m^2 from 570-100 Ma, and a linearly increasing heat flow from 38 mW/m^2 to 55 mW/m^2 from 100 Ma to present. Based on these factors, the New Albany Shale in the Fairfield basin reached a maximum temperature of 130°C at maximum burial 260 Ma. If the suppressed R_o values were used to calibrate the thermal history of this part of the basin, burial thicknesses and temperatures would be greatly underestimated.

Reinterpretation of the vitrinite reflectance of the New Albany Shale in the Illinois Basin has some important consequences to determining basinal maximum temperature and petroleum generation. The corrected R_o indicates that the New Albany was hot enough (mature enough) to generate oil over a larger area in the Illinois Basin than previously thought. Oil found in the central to northern part of the basin may have been generated in place, and not necessarily deposited by long-range migration from the southern part of the basin.

A Proposal for an Atlas of the Major Oil and Gas Plays of the Illinois and Michigan Basins

B. C. Nuttall and J. A. Drahovzal, Kentucky Geological Survey, Lexington, Kentucky

The Illinois and Michigan Basins are two Eastern Interior, cratonic, sag basins lying dominantly in the states of Illinois, Kentucky, Indiana, Ohio, and Michigan and covering more than 200,000 square miles. Oil and natural gas reserves of the two basins represent an important national energy resource. Useful data on the plays of the basins are scattered or nonexistent, making it difficult for industry to devise exploration and development strategies. Basic data and a comprehensive review of the major oil and gas plays are needed for future exploration and development. These needs could be best met with the creation and implementation of a comprehensive data base and an oil and gas atlas for the two basins.

Currently, more than 2,000 oil and gas fields are distributed throughout the basins, representing more than 7,200 reservoirs. The two basins have produced more than 6 billion barrels of oil, and there is an estimated 20.7 billion barrels of original oil in place. Of this original resource, only about 6.7 BBO are accounted for in the DOE TORIS data base. More than 6 TCF of gas have been produced in the basins, and 162 TCF is thought to be in place in the Devonian black shales alone.

In addition, potential exists for deep-basin gas in the unpenetrated parts of the basins. The two basins are filled, on average, with about 15,000 feet of sediment. An exception is the southern part of the Illinois basin where locally up to more than 27,000 feet of sediment is present. Yet, in both basins, the average oil and gas test is drilled to less than 3,000 feet, leaving more than three-quarters of the sedimentary section inadequately explored for hydrocarbons.

A preliminary survey indicates the atlas would contain data for 27 plays (Table 1). Data collected for plays would include field or pool names, locations, and area; reservoir name, age, depositional environment, and heterogeneity; structural and lithologic information; number of producing and abandoned wells; original resource, production, and reserves; porosity, permeability, pay depth and thickness, water, oil, or gas saturation; and completion and logging practices. Each play would appear as a chapter in the atlas and would be described by a text with accompanying charts, figures, and tables that present the key features essential to understanding the play. An electronic data base of the data collected by field and reservoir would also be compiled.

By upgrading the oil and gas data base and developing an oil and gas atlas for the basins, several needs would be served. The private sector would benefit in formulating better exploration and development strategies. The government sector would benefit in developing energy-related research, economic, and national-security information necessary to the well-being of the Nation and the region.

Table 1: Preliminary Classification of Oil and Gas Plays Within the Illinois and Michigan Basins

SYSTEM	PLAY	*Illinois Basin*				*Michigan Basin*
		KENTUCKY	ILLINOIS	INDIANA	OHIO	MICHIGAN
Pennsylvanian	Fluvial Deltaic Clastics	Tradewater to Sturgis	Abbot to Modest			
	Fluvial Sandstones	Caseyville	Caseyville	Pennsylvanian		
	Coal-bed Methane	*This is a speculative play which must be evaluated for possible inclusion in the atlas*				
Mississippian	Fluvial Deltaic Clastics	Chester sands	Chester sands	Chester sands		
	Tide-Dominated Deltaic	Walterburg, Aux Vases	Waltersburg, Aux Vases, and Rosiclare	Walterburg and Aux Vases		
	Shallow Shelf & Ramp Carbonates	Chester carbonates	Chester carbonates			
	Oolite Banks	Ste. Genevieve (O'Hara & McClosky)	Ste. Genevieve (O'Hara, McClosky, and Oblong)	Ste. Genevieve		
	Restricted Shelf to Peritidal carbonates	St. Louis	St. Louis	Ste. Genevieve and St. Louis		
	Shallow Open Shelf	Salem-Warsaw	Salem-Warsaw	Salem-Harrodsburg		
	Siliceous Carbonates		Fort Payne and Ullin	Muldraugh		Michigan (Stray Sand)
	Distal Deltaic Clastics	Borden	Borden (turbidites)	Carper (turbidites ?)		
	Deltaic Clastics					Marshall and Berea
	Bioherms (crinoid mud mounds)	Fort Payne				
Devonian	Fractured Black Shale	New Albany	New Albany	New Albany	New Albany and Ohio Shales	Antrim
	Shelf Sands (lag/detrital)	Knob Lick and Hardin				
	Standplain		Lingle			
	Open Shelf Carbonates	Sellersburg, Jeffersonville, and Clear Creek	Grand Tower	Muscatatuck		Travers, Rogers, and Dudee
	Shelf Sands	Dutch Creek	Dutch Creek			
	Evaporites					Lucas
Devonian-Silurian	Eroded Shelf Carbonates	Clear Creek, Louisvile, Laurel, and Brassfield		New Harmony		
Silurian	Shallow Shelf Carbonates	Decatur to Brassfield	Sexton and Kankakee			Clinton Group
	Pinnacle Reefs		Moccasin Springs			Salina and Niagra
Ordovician	Shallow Shelf Carbonates	Leipers and Granville				
	Fractured Shelf to Supratidal Carbonates	Lexington to Knox	Galena	Ft. Atkinson and Trenton	Trenton and Black River	Trenton and Black River
	Transgressive Shelf Sands					St. Peter
	Paleokarstic Shelf Carbonates	Knox		Knox	Knox	Trenton, Black River, and Praire du Chien
Cambrian	Pre-Knox Structural and Stratigraphic Plays	*This is a speculative play which must be evaluated for possible inclusion in the atlas*				

The Mid-West Region of the Petroleum Technology Transfer Council

D. F. Oltz, Illinois State Geological Survey
Lester D. Moore, MEPCO, Inc.

The Petroleum Technology Transfer Council (PTTC) is a new national "umbrella" organization formed this year. The mission of the PTTC is to foster effective transfer of exploration and production technology to domestic petroleum producers and operators in all producing regions of the USA. The technical information will be transferred from the research and development community and intermediate providers of technology, including: government, universities, national labs, major companies, service industry, geologic surveys, etc.

The PTTC is intended to be a national clearinghouse to address all of the upstream technology needs of the U.S. oil and gas producing companies and identify the best mechanisms for improving near-term and long-term technology transfer to domestic operators. Providers of technology and research and development should be able to use the PTTC in a marketing sense. One of the most important functions of the program will be to provide a feedback loop so that the needs and concerns of producers can be communicated effectively to the entire research community and to the Department of Energy.

The PTTC has three main components:

1. Problem identification workshops will be held in all producing areas to identify and prioritize the operators most common problems in specific regions, specific types of reservoirs, and environments.
2. Focused technology workshops will provide information and solutions to address specific problems identified in the earlier workshops. Regional and national experts will meet with producers to discuss focused solutions to their real world technical problems.
3. Regional Resource Centers will be established in existing facilities around the producing areas to provide operators with access to a library, technical and referral assistance, computer workstations with data covering project histories, field and reservoir data, and analytical software which will help operators evaluate their reservoirs and technical problems. The regional structure has divided the United States into ten regions. The mid-west region is comprised of the Illinois and Michigan Basins, and includes the States of Illinois, Indiana, Michigan, and western Kentucky.

A Producer Advisory Group (PAG) has been formed in the Mid-west region. Lester Moore is the Director of the Mid-west PAG. The purpose of the PAG is to help set the direction for the regional technology transfer activities, develop budgets and plans, and coordinate industry cost-sharing.

Each region must have a Regional Lead Organization (RLO) that is a 501(C) corporation suitable for managing the regional PTTC program. The RLO for the mid-west region has been elected and is the Illinois State Geological Survey (ISGS) in Champaign, Illinois. The RLO will develop and carry out a comprehensive program of technology transfer activities with the advice and consent of the regional PAG. The RLO has made a proposal to the PTTC Board for inclusion of activities in Phase II of the PTTC plan. The ISGS, in that proposal, will serve as the RLO to implement the mid-west PAG program. The ISGS will conduct problem identification and workshops at the ISGS or at remote sites. The ISGS will conduct focused technology workshops and will recruit experts to aid in making the workshops problem solving. The ISGS will also work with the State of Michigan to budget a satellite resource center at a location to be determined in Michigan. Conversations with other data providers in the mid-west area, notably the Indiana and the Kentucky Geologic Surveys, indicates that a program to network the three Surveys to provide access to the Survey's data needs also to be budgeted in the long-term program.

The schedule of activities includes two problem identification workshops in Year 1, and two more held in Year 4. It is possible that budget allocations may allow other workshops to be held as the budget permits. Workshops will be held in areas of geographic and geologic diversity. The PAG will ensure that invitees in each region represent the knowledge and experience necessary to adequately discuss geological and reservoir development completion, production, and equipment problems. Notices of meetings will be made in all professional society and industrial newsletters. Summaries of the meetings will be printed and circulated. One focused technology workshop is scheduled to be held in Year 1, and again providing budget allocations, we intend to hold as many as we can. The problems that have been identified in the initial round of problem identification workshops will then be addressed in the focused technology workshops.

Data from Illinois Basin Samples contained in the U.S. Geological Survey's New Coal Quality CD-Rom

Charles L. Oman, Susan J. Tewalt, and Linda J. Bragg
U.S. Geological Survey, Reston, Virginia

The U.S. Geological Survey has produced a CD-ROM Open-File Report 94-205 entitled "U.S. Geological Survey Coal Quality (COALQUAL) Data base: Version 1.3" on a CD-ROM. This CD-ROM contains the COALQUAL data base, which consists of analyses of approximately 7,400 coal samples. Each record in the data base contains up to 136 fields of data representing the composition of a complete core or channel sample. The data include geographic (State, county, latitude, longitude, and map name) and geologic (system, series, group, formation, bed and member names) information as well as chemical data. Chemical data for the samples are stored on an as-received, whole-coal basis, except for major element oxides that are on an "ash" basis. The COALQUAL data base is a subset of the 13,035 coal quality samples contained in the National Coal Resources Data System, USCHEM (USgeoCHEMical) data base.

Details of sampling methods and analytical procedures can be obtained from the viewable documents on this CD-ROM. Flowcharts in the documents provide the analytical method(s) for each field of coal quality data. The user is cautioned to utilize only the correct number of significant figures for any final results of calculations or summaries of data in reports. Significant figures for data are discussed in technical documents on the CD-ROM.

Two hundred and ninety eight samples from more than 35 counties in the Illinois Basin are available on the CD-ROM. Sixteen samples are from Illinois (representing three beds), 158 samples are from Indiana (representing 16 beds) and 124 samples are from Kentucky (representing 22 beds).

The 1990 Clean Air Act Amendments list a number of Hazardous Air Pollutants (HAPs). The data from the Illinois Basin were used to determine arithmetic means for 12 of the HAPs in coals from the Illinois Basin on a whole-coal basis. The means are as follows: arsenic, 3.5 ppm; beryllium, 3.2 ppm; cadmium, .61 ppm; cobalt, 7.4 ppm; chromium, 17 ppm; mercury, .098 ppm; manganese, 41 ppm; nickel, 29 ppm; lead, 20 ppm; antimony, 1.5 ppm; selenium, 2.9 ppm; and sulfur, 3.6 percent.

REFERENCES

Bragg, L.J., Oman, J.K., Tewalt, S.J., Oman, C.L., Rega, N.H., Washinton, P.M., and Finkelman, R.B., 1994, U.S. Geological Survey coal quality (COALQUAL) data base: version 1.3: U.S. Geological Survey Open-File Report 94-205, CD-ROM.

Origin and Timing of Carbonate Cements in the St. Peter Sandstone, Illinois Basin: Evidence for a Genetic Link to MVT-type Mineralization

Janet K. Pitman, U.S. Geological Survey, Denver, Colorado
Christoph Spötl, Munzergasse 6, 6060 Hall in Tirol, Austria
Martin B. Goldhaber, U.S. Geological Survey, Denver, Colorado

The Ordovician St. Peter Sandstone in the Illinois Basin has undergone complex diagenetic alteration involving regionally extensive dolomite formation and local quartz, anhydrite, and calcite precipitation. Petrographic, isotopic, and geochemical analysis reveals multiple generations of carbonate cement including dolomicrospar, planar and baroque (saddle) dolospar and late-stage poikilotopic calcite. The timing of carbonate diagenesis in the St. Peter is broadly constrained to have occurred between the Devonian and early Permian based on isotopic age dates of authigenic K-feldspar and illite in Ordovician rocks adjacent to the basin. In northern Illinois where there is authigenic K-feldspar dated at about 400 Ma, the earliest possible timing of dolomite formation would be the Devonian. There, burial and thermal reconstruction indicates early dolomite precipitation occurred when the rocks were at shallow burial depths and low temperatures approximating present-day conditions (<500 m and <50° C). In southern Illinois, authigenic illite in Ordovician rocks has been dated at 215-230 Ma (late Triassic). Assuming that late-diagenetic illite in the St. Peter in the Fairfield subbasin formed at about the same time, then planar and baroque dolospar and associated quartz, anhydrite, and calcite predating illite precipitated before the late Triassic when the rocks were at or close to their maximum burial depth and temperature, i.e., 2,700 m and 140° C.

The paragenesis of burial-related carbonates in the St. Peter and their estimated time of emplacement is consistent with the nature and timing of replacement dolomites and dolomite cements in regionally extensive superjacent carbonate rocks with localized lead-zinc-fluorite mineralization. Baroque dolomite in the St. Peter is restricted to the southern part of the basin where trace-fluorine anomalies in overlying carbonate rocks are highest. In these carbonate strata, baroque dolomite (also referred to as late-dolomite cement or hydrothermal dolomite) occurs locally as cross-cutting veins, as a cement in solution collapse features, as a cement in vugs and moldic pores in early-formed replacement dolomite, and its precipitation overlaps lead, zinc, and fluorite mineralization. Paleomagnetic dating constrains the age of major ore-forming events in the southern midcontinent to Late Pennsylvanian-Early Permian (Pan et al., 1990). This implies that the earliest possible timing of the dolomites that host the ore minerals also is Late Pennsylvanian-Early Permian, which is consistent with the late Paleozoic age suggested for late-stage dolomite precipitation in the St. Peter. The genetic link between late-diagenetic dolomites in the St. Peter and MVT-type mineralization suggests that planar and baroque dolospars in sandstones in the southern portion of the Illinois basin could have been influenced by hydrothermal activity.

The diagenetic history of the St. Peter Sandstone puts constraints on the nature and timing, and the source, of paleofluids that moved through the Illinois Basin. We favor the interpretation that fluids involved in dolomite precipitation and locally in ore-formation were derived from multiple sources rather than from a single source during the late Paleozoic. Several lines of evidence indicate that the St. Peter was a major conduit system that focused hot fluids in the southern part of the basin. First, the age and origin of planar and baroque dolospar in deeply-buried sandstones is comparable to that of dolomite associated with MVT-type mineralization in overlying carbonate rocks, implying that the fluids involved in dolomite precipitation in sandstones were part of the same hydrologic system responsible for ore deposition. Second, fluid inclusion data suggest that the dolomitizing fluids were brines with compositions (>20 wt.% NaCl eq.) similar to those involved in ore-formation. Third, baroque and planar dolospars in wells immediately north of Hicks dome and the Illinois-Kentucky fluorspar district at the southern margin of the basin have $\delta^{18}O$ ratios as light as -10‰ PDB, which suggests precipitation from hydrothermal fluids. Corresponding light $\delta^{13}C$ ratios in these dolomites (-8‰PDB) reflect an input of ^{13}C-depleted CO_2 derived from the decarboxylation of organic matter indicating hydrocarbon generation and migration were active in the southern part of the basin during dolospar precipitation. Various fluid sources were possible, including intrabasinal fluids from the Illinois basin itself, fluids from sediments beneath the extensively folded and faulted terrane along the southern margin of the basin, or fluids from sedimentary basins adjacent to the Illinois Basin.

In northern and eastern Illinois, along the Kankakee-Wisconsin Arch and the faulted La Salle Anticline, shallow-buried rocks with dolospar $\delta^{18}O$ ratios averaging -4 to -5‰ (PDB) in the St. Peter are in close proximity to extensively dolomitized strata in the Upper Mississippi Valley lead-zinc district. In contrast, the $\delta^{18}O$ ratios of planar dolospars in more deeply buried rocks in the central part of the basin average - 2 to -3‰ (PDB). The 2 ‰ $\delta^{18}O$ depletion in dolomites in the shallow-buried strata suggests that fluids involved in dolomite formation in northern Illinois had a different geochemistry or flow vector than dolomite-precipitating fluids focused through the Illinois basin. This raises the possibility that ore-depositing fluids in the Upper Mississippi district may not have been solely related to the brine-migration event responsible for ore-deposition some 600 km to the south.

REFERENCES

Pan, H., Symons, D.T.H., and Sangster, D.F., 1990, Paleomagnetism of the Mississippi Valley-type ores and host rocks in the northern Arkansas and Tri-State districts: Can. J. Earth Sci., v. 27, P 923-931.

The Regional Configuration of the Cambrian Reelfoot-Rough Creek-Rome Rift System

Christopher J. Potter, U.S. Geological Survey, Denver, Colorado
James A. Drahovzal, Kentucky Geological Survey, Lexington, Kentucky

Regional seismic reflection and gravity-model data provide new information on the regional variation in the geometry of the Cambrian rift system (fig. 1) that comprises the Reelfoot rift (RFR), Rough Creek graben (RCG), and Rome trough (RT). This paper examines the rift system along a 1,000-km-long segment extending from western Arkansas to southern West Virginia. The northeast-oriented RFR and the northern RT appear to be linked by the east-west oriented RCG and southern RT. The western dogleg-shaped pattern linking the RFR and the RCG underlies the southern Illinois Basin, but the relationship of this rift system to the early development of the Illinois Basin is not well understood.

In the RFR segment, historic and contemporary New Madrid seismicity occurs along the Mississippi Valley within a relatively symmetric segment of the Cambrian rift. An anomalous thickness (up to 6.1 km) of Lower(?) and Middle Cambrian clastic sediment accumulated in this 20-km-wide medial graben. The trough was inverted into a structural high (Blytheville arch) in the late Paleozoic. Major Cambrian accommodation zones bounded the southwest and northeast ends of the medial Cambrian graben. Reflection profiles near the southwest end of the RFR (eastern Arkansas, western Tennessee) show an along-strike change in Cambrian rift geometry to one of simple half-grabens that appear to change tilt di-

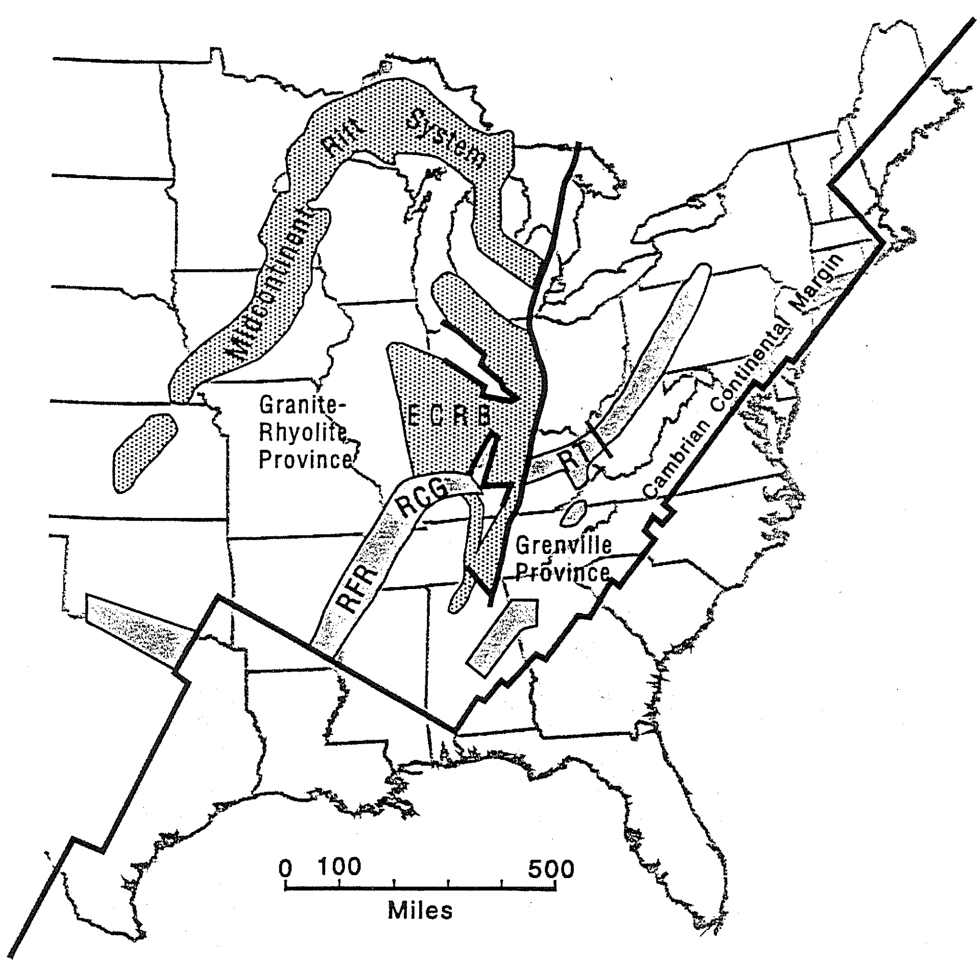


Figure 1. Precambrian (dotted) and Cambrian (shaded) basins, showing Reelfoot (RFR) - Rough Creek (RCG) - Rome (RT) rift system, and its relationship to Precambrian provinces. East Continent Rift Basin is ECRB.

rection along the rift axis with no pronounced axial thickening. The present depth to basement in these half-grabens may be as great as 9 km.

To the north, the RFR bends easterly into the RCG; in the bend area is a southeast-tilted, asymmetric graben, with the maximum graben fill on the southeast side of the rift. A segment of a northwest-southeast seismic reflection profile in southeastern Illinois and western Kentucky shows that, near Hicks Dome, Illinois, Middle and Lower(?) Cambrian pre-Knox, syn-rift sedimentary rocks are about 1.1 km in thickness and thicken southeasterly to about 3.1 km against the Tabb fault system (TFS) in Kentucky. On the upthrown (southeast) side of the TFS, the pre-Knox interval thins markedly to about 1.6 km. Farther southeast, the interval presumably thins across several other down-to-north normal faults.

To the east of the "bend area" in western Kentucky, available reflection seismic data exhibits a dramatic change in polarity of the rift system. Here, the RCG, a 160-km-long by 40-75-km-wide feature, is characterized by a deep, north-tilted half-graben bounded on the north by the Rough Creek fault zone (RCFZ) whose displacement on basement is as much as 4 km. The pre-Knox syn-rift sediments show a growth factor of more than five across the RCFZ at the northern margin of the RCG. Within the RCG, the pre-Knox syn-rift sedimentary rocks range in thickness from nearly 5.5 km just south of the RCFZ to about 1.5 km, just north of the Pennyrile fault zone (PFZ). South of the PFZ, the pre-Knox thins to about 0.7 km thickness. The RCFZ loses throw to the east and terminates on a presumed Late Proterozoic inversion structure underlain by the Precambrian Granite-Rhyolite Province and the Keweenawan East Continent Rift Basin.

The RT extends eastward across Kentucky from the east side of the inverted East Continent Rift Basin in central Kentucky. In contrast to the RCG, available seismic data in eastern Kentucky shows the RT to be a stepped, flat-bottomed graben that is bounded on the north by the Kentucky River fault zone and thickens to the south across a medial fault zone, the Irvine-Paint Creek fault zone. Each of the two fault zones displace basement by as much as 1.4 km locally, and the pre-Knox syn-rift sediment range in thickness from 1.2 km on the downthrown side of the Kentucky River fault zone to more than 2.7 km south of the Irvine-Paint Creek fault zone. Several basement highs bounded by down-to-north normal faults limit most of the graben to the south, but farther southeast, basement drops into the Appalachian Basin and the pre-Knox interval thickens again.

Near the Kentucky-West Virginia line, the strike of the RT changes to northeast and its cross sectional geometry also changes to that of a graben bounded on the southeast by a major bounding fault, the Warfield fault zone (WFZ). Gravity modeling indicates that the WFZ has as much as 2.1 km of displacement on basement. The pre-Knox syn-rift interval forms a faulted wedge that thins to the northwest, ranging from more than 3 km immediately downthrown of the WFZ to 0.15 km along the northwest edge of the graben.

Structural and stratigraphic patterns on regional seismic data, southern Illinois Basin

Christopher J. Potter, U.S. Geological Survey, Denver, Colorado
James A. Drahovzal, University of Kentucky, Lexington, Kentucky
Michael Sargent, Illinois State Geological Survey, Champaign, Illinois
Jennifer Lewis, Indiana University, Bloomington, Indiana

Four high-quality seismic reflection lines in the southern Illinois Basin (fig. 1), totaling 245 km in length, provide an excellent regional subsurface stratigraphic and structural framework for hydrocarbon exploration and assessment, and other regional geologic studies. Our principal preliminary interpretations from these data are listed here in order of geologic age, from oldest to youngest: (1) Prominent Proterozoic layering has undergone several phases of deformation; these strata are possibly equivalent to the Middle Proterozoic (1 Ga) Middle Run and associated volcanic rocks of the East Continent Rift Basin or they may represent Late Proterozoic (600 Ma?) rifting associated with continental breakup. (2) A gentle flexure exists at the top of the Proterozoic across the Wabash Valley fault zone, unlike the major offset that has been previously suggested. (3) A well-defined angular unconformity is

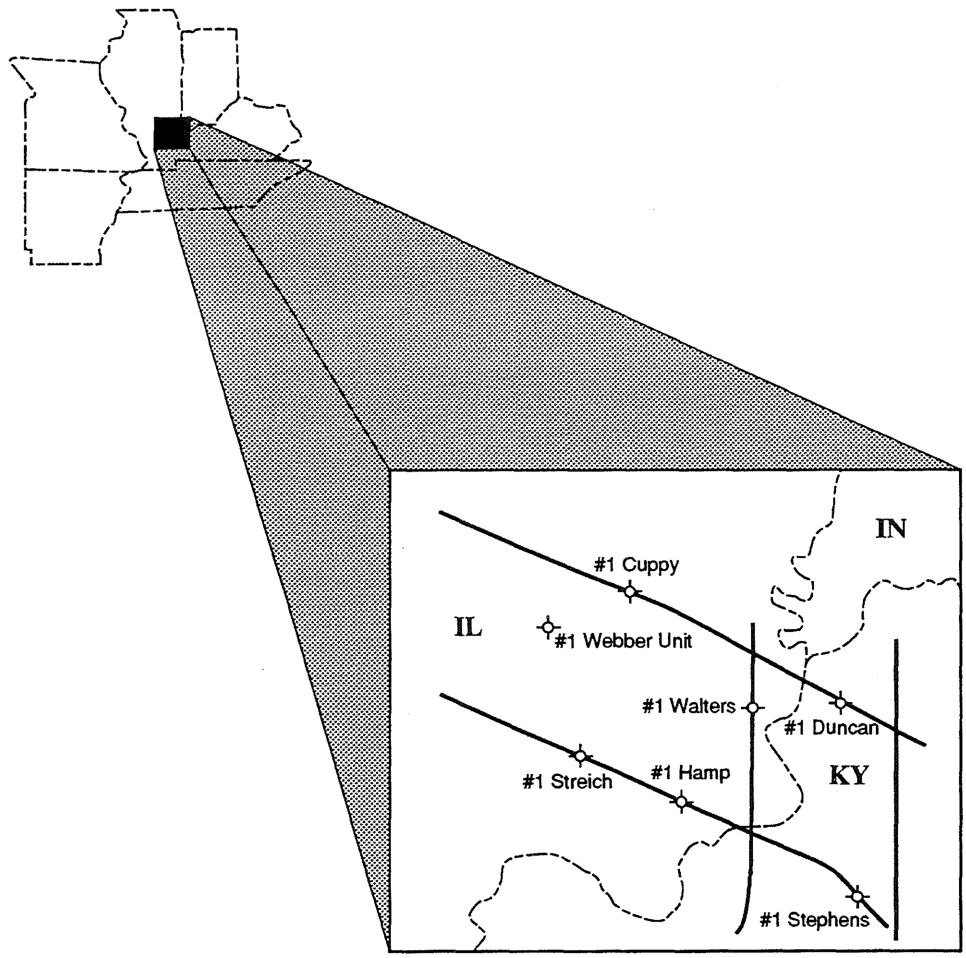


Figure 1. Deep well and seismic line locations.

seen in many places between Proterozoic and Cambrian(?) strata. (4) We infer a major reversal in Cambrian rift polarity (accommodation zone) in the Rough Creek graben in western Kentucky. (5) Seismic facies analysis suggests the presence of basin-floor fan complexes at and near the base of the Cambrian interval in several parts of the Rough Creek graben. (6) There is an abrupt pinchout of the Mount Simon Formation against the basement below Dale dome (near the Texaco No. 1 Cuppy well, Hamilton Co.) in southeastern Illinois and a more gradual Mt. Simon pinchout to the southeast. (7) We recognize seismic expression of the clastic-to-carbonate facies transition in the Upper Cambrian Eau Claire Formation, north of the Rough Creek graben in northwestern Kentucky (although definition of this transition is complicated by data-acquisition problems). (8) The data show clear evidence of late Paleozoic reverse faulting, particularly evident in the Pennyrile fault system of western Kentucky, that is probably related to Ouachita deformation; such faulting is also evident on previously published seismic sections and at the surface along the Rough Creek fault zone in western Kentucky. (9) Chaotic reflection patterns in the lower and middle Paleozoic strata near Hicks Dome, southern Illinois, are related to a combination of intrusive-related brecciation, intense faulting, and alteration of carbonate strata by acidic mineralizing fluids, all of which occurred in the Permian. (10) Late Paleozoic(?) reverse faulting on one flank of the Rock Creek "graben," southern Illinois. (11) Permian and Mesozoic(?) extensional faulting in the Fluorspar area fault complex.

Sedimentology and Trace Element and Stable Isotope Geochemistry of the Lower Part of the Mississippian St.Louis Limestone in the Illinois Basin

J.L. Ridgley, F.A. Hills, and C. Rice, U.S. Geological Survey, Denver, Colorado

The lower part of the Mississippian St. Louis Limestone in the Illinois Basin was deposited during a world-wide sea-level low and is characterized by the presence of evaporite (anhydrite and gypsum) beds in as many as 19 thin (commonly <10 m), fourth-order cycles; rhythmic changes in major- and trace-element concentrations that reflect upward changes in sedimentology within and between cycles; and the gradual upward lightening of sulfur isotope values in anhydrites between cycles. The top of the lower part of the St. Louis is an unconformity and represents a third-order cycle boundary.

Cycles within the St. Louis have transgressive and regressive components that vary in thickness depending, in part, on whether a complete cycle is present. The part of a cycle representing maximum transgression is characterized by thinly laminated calcareous shale or micrite or by fossiliferous limestone indicating normal-marine salinity. The fossils, which are mostly stenohaline, include frond-type bryozoans, echinoderms, and solitary corals. Rocks characteristic of the maximum flooding event are more organic rich than immediately underlying transgressive or overlying regressive carbonates. Euryhaline fossil-bearing limestone, dolomite, or anhydrite (gypsum) commonly underlie and overlie maximum transgressive rocks, depending whether a complete or partial cycle is present (Ridgley, 1992).

The depositional facies interpreted from cores and as expressed in the transgressive and regressive portions of cycles indicate shallow-water, open-shelf (or open-lagoon), restricted-lagoon, and supratidal environments. The oscillations in depositional environments reflect a change in water depth during fourth-order sea-level rises and falls.

The cycles are also denoted by changes in chemistry of the rocks. Major- and trace-element content for 35 samples, representing various lithofacies in the St. Louis, was determined by the induction coupled plasma (ICP) emission method of analysis. Ranges for major-element concentrations in weight percent are: Ca (0.22 to 38), Mg (0.39 to 12), Al (0.14 to 9), Fe (0.06 to 3.1), and K (0.07 to 3.6) and their distributions reflect the changes in proportion of calcite, dolomite, and clay as a function of depositional environment.

The trace-element chemistry shows some differences between organic-rich [>0.5 percent total organic carbon (TOC)] and organic-poor (<0.5 percent TOC) rocks. Ranges and arithmetic means in parts per million for important trace elements in 15 organic-carbon-rich samples are: arsenic (<20-23; <20, but three samples contained 20, 22, and 23 ppm), chromium (28-200; 66), cobalt (10-86; 29), copper (5-98; 26), lead (7-64; 18), lithium (13-180; 54), manganese (57-190; 112), molybdenum (4-110; 24), nickel (14-110; 37), vanadium (23-500; 88), and zinc (4-160; 59). Ranges and arithmetic means in parts per million for the same trace elements in 20 organic-carbon-poor samples are: arsenic (all samples <20), chromium (3-68; 25), cobalt (4-45; 23), copper (2-31; 7), lead (6-18; 9), lithium (4-100; 54), manganese (37-290; 117), molybdenum (3-13; 5), nickel (3-36; 14), vanadium (6-100; 29), and zinc (3-65; 18). The higher average concentrations and greater ranges in values for most of these elements in the organic-rich rocks is expected because organic matter is efficient at scavenging these elements from sea water. The means for the above elements are commonly greater in both populations than those reported for coals in the basin (see Oman, this volume). Thus, the chemical variations in the St. Louis need to be evaluated if the St. Louis Limestone is considered for use in coal-scrubbing operations, especially if there are tolerances mandated for the 1990 Clean Air Act Amendments Hazardous Air Pollutants.

Establishing the cyclicity within the lower part of the St. Louis is important because there are no internal, reliable marker beds that can be used as datums for regional correlations. It was originally thought that evaporite beds might be useful regional datums; however, the number of evaporite beds vary between localities due to nondeposition or later dissolution. Although no physical regional marker beds were found, the sulfur-isotope distributions among anhydrite beds in the various cycles at the same locality as well as between localities suggest that they might be useful in regional correlations. The sulfur isotopes are typical of Mississippian marine evaporites; their values relative to PDB range from 19.7 to 13.8 per mil δ^{34}S. In three cores from different parts of the basin, the sulfur-isotope values tend to become lighter from the base to the top of the section. This consistent trend to lighter and similar sulfur isotope values between sections indicates that the marine body of water evolved with time such that heavy sulfur isotopes were removed early and (or) light sulfur isotopes were introduced in significant quantities due to input of meteoric water, resulting in brine mixing.

The influx of meteoric water and the extent of cyclicity can also be assessed by examining strontium-isotope ratios. The $^{87}Sr/^{86}Sr$ in the bedded anhydrite-gypsum range from 0.70766 (more marine?) to 0.70787 (less marine?) ($\sigma=\pm 0.00001$). Observed systematic variations within individual transgressive-regressive cycles may be related to a change in the ratio of marine to nonmarine waters as the basin became progressively more landlocked.

As the basin became more landlocked during the sea-level low, precipitates from the brine should have moved from the calcium sulfate field into the sodium chloride field; however, no halite deposits are reported from the St. Louis. Halite absence could be due to dissolution or to increased meteoric water input to the basin, as suggested by the sulfur isotope values. To test if there is any residual NaCl present, NaCl content on a whole-rock basis was determined for 15 samples of cored, unslabbed gypsum and anhydrite and one sample of dolomite from Survey Drill Hole (SDH) 16 from Martin County, Indiana, in the Illinois Basin. The NaCl content of the anhydrite (gypsum) ranged from 11 to 350 ppm with a mean of 150 ppm. The dolomite had a NaCl content of 890 ppm. The values for NaCl content of anhydrite (gypsum) samples from the SDH-16 core are similar to values of NaCl content reported by Saxby and Lamar (1957) for samples of anhydrite (gypsum) from 5 cores from Illinois (range: 100-400 ppm; mean: 200 ppm). The values reported here and by Saxby and Lamar are significantly lower than values reported by McGrain and Helton (1964) for anhydrite (gypsum) from a core from Kentucky (range: 4,100-19,000 ppm; mean: 9,700 ppm). The difference in NaCl values between the Indiana, Illinois, and Kentucky anhydrites (gypsums) may be attributed to one or more of the following:

1. Differences in drilling or sampling techniques (washing or contamination).
2. Errors in NaCl determination (different assumptions or techniques).
3. Different fluids altering the St. Louis Limestone at different locations since deposition.
4. Different fluid compositions present at time of deposition within basin.

Using the NaCl content determined in this study, an attempt was made to estimate the origin of the NaCl. Assuming a 5 percent porosity in the gypsum rock, an average rain water would leave a residue of about 30 ppb NaCl, an average river water would leave about 400 ppb, and seawater concentrated to gypsum saturation would leave about 2,300 ppm on a whole-rock basis if evaporated. The mean NaCl content in gypsum and anhydrite samples from core SDH-16 is 150 ppm, considerably higher than what would be expected from unaltered meteoric or river water, but also considerably lower than what would be expected from seawater concentrated to gypsum saturation. The NaCl content might be a seawater residual, but partial flushing of the rocks by dilute waters or the use of water during drilling may have removed most of the residual. Alternatively, the intermediate NaCl content of the gypsums and anhydrites from SDH-16 could result from precipitation from brines that are a mixture of meteoric water and dissolved halite from other portions of the basin, as suggested by the sulfur- and strontium-isotope distributions.

REFERENCES

McGrain, Preston, and Helton, W.L., 1964, Gypsum and anhydrite in the St. Louis Limestone in northwestern Kentucky: Kentucky Geological Survey Information Circular, Series X, 27 p.

Ridgley, J.L., 1992, Sedimentary cycles in the Mississippian St. Louis Limestone, southwest Indiana, *in* Goldhaber, M.B., and Eidel, J.J., eds., Mineral resources of the Illinois Basin in the context of basin evolution: U.S. Geological Survey Open-File Report 92-1, p. 52-53.

Saxby, D.B, and Lamar, J.E., 1957, Gypsum and anhydrite in Illinois: Illinois State Geological Survey Circular 226, 26 p.

Character and Depositional Environments of Potential Source Rocks in the Lower Part of the Mississippian St. Louis Limestone of the Illinois Basin

Jennie L. Ridgley and Vito F. Nuccio, U.S. Geological Survey, Denver, Colorado

The carbonate-evaporite sequence in the lower part of the Mississippian St. Louis Limestone of the Illinois Basin in south-central Indiana contains as many as 19 fourth-order transgressive-regressive sedimentary cycles and has a maximum thickness of 73 m. Organic-rich strata in each of these cycles were deposited during peak transgression (maximum flooding) or in restricted lagoonal environments commonly associated with gypsum/anhydrite precipitates when clastic input decreased and anoxic conditions were prevalent. The most organic-rich strata have laminated fabrics of primary or secondary origin. In thin section, the organic-rich, laminated fabrics may consist of abundant horizontal microstylolites that result from compaction of organic matter. These intervals range from a few centimeters to as much as 1 m in thickness; cumulative thickness may represent as much as 5-20 percent of the lower part of the St. Louis Limestone.

Rock-Eval pyrolysis analysis indicates that selected samples in cores from several parts of the basin contain from <0.1 to 15.7 percent total organic carbon. Plots of hydrogen versus oxygen indices indicate type III and mixed type II-III organic matter. The hydrogen indices are less than 300, which suggests that the rocks are gas/oil or gas prone. A number of samples have a genetic potential [(S1+S2) milligrams hydrocarbons/gram of sample] >3.0 (3,000 ppm), production indices (PI) greater than 0.10, and Tmax values up to 440 °C, indicating a fair to excellent source-rock potential of low to moderate maturity. The distribution of PI and Tmax from this study indicate a relative decrease in thermal maturity of the rocks from south to north in the basin, except in the vicinity of the Wabash fault zone where there is a slight increase in thermal maturity. This is consistent with the regional thermal maturity based on vitrinite reflectance in shales of the Devonian-Mississippian New Albany Group and Pennsylvanian coals.

No oils have been correlated to organic-rich strata in the St. Louis or to other Mississippian rocks. Mississippian-age reservoir rocks are considered to contain oil sourced from the New Albany Group. In order to determine the character of the organic matter in the St. Louis, bitumen was extracted from the lower St. Louis in Survey Drill Hole 190 (Sec. 25, T. 4 S., R. 1 E., Crawford County, Indiana) at 381.7 ft and from Survey Drill Hole 16 (Sec. 22, T. 3 S., R. 3 W., Martin County, Indiana) at 451.9 ft. Total organic carbon based on Rock-Eval pyrolysis of these samples is, respectively, 15.7 and 8.2 percent. The sample from Survey Drill Hole 16 is from a restricted lagoonal setting associated with evaporites. The sample from Survey Drill Hole 190 is from restricted lagoonal environments, but evaporites are absent. Both samples are from the regressive part of a cycle.

The saturate and aromatic fractions of the bitumen extracts were analyzed by gas chromatography-mass spectrometry. Biomarker data from the bitumen extracts are distinctly different from those reported for Ordovician Maquoketa Group and Devonian-Mississippian New Albany Group extracts. Saturated hydrocarbon distributions in extracts from both St. Louis samples show a lack of n-alkanes below C_{17}, except for a few very low carbon number n-alkanes, and a predominance of n-alkanes from C_{17} to C_{32}. These distributions do not match any saturated hydrocarbon distributions reported for extracts from the New Albany or Maquoketa Groups. Both samples have a pristane/phytane ratio of less than 1 and a Tm/Ts ratio much greater than 1 which is consistent with a carbonate source rock. Pristane/phytane ratios for New Albany Group source rocks range from 1.7 to 2.1 and for Maquoketa Group source rocks are 1.4 to 2.0 (Hatch and others, 1990). Triterpane distributions of hopanes and non-hopanes (including tricyclic terpanes) have been used to distinguish source rocks from different formations (Hatch and others, 1990; Mackenzie, 1984). The triterpane distributions on the mass fragmentogram m/z 191 for both St. Louis samples indicates they are similar, suggesting that they are from the same formation.

Sterane distributions on mass fragmentogram m/z 217 are often used to indicate relative differences in maturity and depositional environments (see discussion in Mackenzie, 1984, p. 181-183). A comparison of the sterane distributions between the two samples suggests that they are similar in maturity. However, the ratios of the C_{27}:C_{28}:C_{29} steranes are different between the two samples, suggesting that there is some difference in the depositional environment.

Rock-eval data coupled with paleogeographic and sedimentologic reconstructions suggest that there are fair to excellent source rocks in the lower part of the St. Louis. These source rocks could have produced oil or gas in the more thermally mature part of the basin where favorable source-rock facies are found. Preliminary evaluation of biomarkers in bitumen extracts from two samples of the St. Louis indicate they are distinctly different from biomarkers in bitumen extracts in Ordovician and Devonian-Mississippian source rocks. Perhaps oils, especially those in Mississippian reservoirs, should be reevaluated to see if there is a St. Louis source component.

REFERENCES

Hatch, J.R., Risatti, J.B., and King, J.D., 1990, Geochemistry of Illinois Basin oils and hydrocarbon source rocks, *in* Leighton, M.W., Kolota, D.R., Oltz, D.F., and Eidel, J.J., eds., Interior Cratonic Basins: American Association of Petroleum Geologists Memoir 51, p. 403-423.

Mackenzie, A.S., 1984, Application of biological markers in petroleum geochemistry, *in* Brooks, J., and Welte, D., eds., Advances in Petroleum Geochemistry, Academic Press, London, p. 115-214.

Biomarker and fluid inclusion measurements as constraints on the time-temperature and fluid-flow history of the northern Illinois basin and Upper Mississippi Valley zinc district

E.L. Rowan, U.S. Geological Survey, Menlo Park, California
M.B. Goldhaber and J.R. Hatch, U.S. Geological Survey, Denver, Colorado

The Upper Mississippi Valley (UMV) zinc district is hosted by Ordovician carbonate formations at the northern margin of the Illinois basin. Biomarker maturities and fluid-inclusion temperatures in the district are believed to reflect the temperature and duration of regional fluid circulation through the Cambrian and Ordovician aquifers of the Illinois basin. This regional flow system was responsible for mass transport which drove physical processes (e.g., hydrocarbon migration, transport of metals in solution) and energy (heat) transport which drove chemical reactions (e.g., maturation of organic matter, mineralization, diagenetic reactions) within the Illinois basin and at its margins.

Biomarkers are organic compounds which undergo chemical transformation at a rate that increases exponentially with temperature (an Arrhenius reaction). Using recently published kinetic constants for the biomarker Arrhennius reactions, and temperatures from fluid inclusion measurements, we are able to place new, more precise constraints on the duration of the heating event at the northern end of the Illinois basin. Fluid inclusion temperatures for sphalerite in the UMV district were measured primarily by McLimans (1977). Rb-Sr isotopic dates give an age of 270 m.y. for these sphalerites (Brannon, et al., 1992). Hatch, et al. (1986) measured biomarker product/reactant ratios in samples of unmineralized country rock between the Thompson and Temperly mines in the UMV district.

We use numerical fluid/heat flow modeling to simulate fluid circulation through the ore zones at the Thompson and Temperly mines, with temperatures constrained by fluid-inclusion measurements. The barren country rock between the two mines is a sublithographic limestone with few observed fractures and overall very low permeability. Heat is therefore transferred to the country rock predominantly by conduction. For each time step we calculate incremental and cumulative thermal maturities for the biomarkers sampled within the mines, and at increasing distances from the ore zones.

Most of the fluid-inclusion homogenization temperatures measured in sphalerites in the UMV district range from 90-150°C. Yet previous estimates of maximum burial depth are relatively shallow, < 1 km. Simple burial, and a geothermal gradient typical of the continental interior (25°C/km, Cluff and Byrnes, 1991) controlled by basement heat flow, cannot alone explain the fluid-inclusion temperatures. Elevated fluid inclusion temperatures are a regional phenomenon not restricted to the UMV district. Magmatic rocks at least as young as the formations that host ore have not been identified in the UMV region. The fluid-inclusion temperatures are thus not likely explained by point sources of heat, such as undetected individual plutons.

Several studies have shown that circulation of groundwater through regional aquifers, given sufficient flow rates, can redistribute heat from deep in a sedimentary basin, to the shallower margins (e.g., Garven, 1985; Bethke, 1986). A late-Paleozoic episode of brine migration is recognized as a regional phenomenon affecting much of the sedimentary section of the U.S. midcontinent. Recharge in the Appalachian-Ouachita mountain belt and northward flow through the Reelfoot rift into the proto-Illinois basin represents one plausible flow path. Evidence for broad scale circulation of fluids comes from paleomagnetic studies, regionally correlatable zoned dolomites, and the common occurrence of fluid inclusions, and organic material that indicate anomalously high temperatures, given a maximum burial depth estimated from stratigraphy. We consider regional fluid circulation to be the most plausible explanation for the steep thermal gradient in the UMV district, and for the elevated fluid inclusion temperatures (relative to maximum estimated burial depth) regionally across the northern end of the Illinois basin. Warm fluid circulating through Cambro-Ordovician aquifers would move vertically upwards through the fractures that control sphalerite mineralization in the UMV district. Fluid inclusion temperatures measured in these sphalerites represent a lower limit on fluid temperatures in the aquifers below.

Gravity driven fluid flow is virtually required to explain the broad distribution of elevated fluid inclusion temperatures in the UMV district and regionally across the northern Illinois basin, e.g., in sphalerites hosted by Pennsylvanian coals. However, fluid/heat flow modeling by Bethke (1986) shows that fluid inclusion temperatures above 90°C (most of the data) require elevated basement heat flow. This appears most likely in the southern portion of the Illinois basin where the Hicks Dome igneous intrusion, radiometrically dated as contemporaneous with the UMV district, and possibly other similar intrusions injected a significant pulse of heat into the circulating groundwater.

The fluid-flow and thermal history of the UMV district at the northern margin of the Illinois basin, provides information about regional-scale fluid circulation. Additional geochemical evidence suggests that the predominant flow direction was from south to north, through the deep aquifers in the Illinois basin, but fluid contributions from sources such as the Michigan basin should not be excluded. Regardless of flow direction, the biomarker measurements enable us to interpret the fluid inclusion measurements in terms of time, at a given temperature, or series of temperatures, required to produce the observed thermal maturities.

We tested three temperature histories, each consistent with the fluid inclusion measurements: high and low temperature paths, and a 'best fit' through the fluid inclusion data. The high and low temperature paths correspond to durations of approximately 50,000 and 3 million years, respectively, and bracket the range of plausible durations for exposure of the biomarker samples to warm fluids. The 'best fit' temperature path gives a duration of approximately 300,000 years; this represents the best estimate' for the duration of mineralization in the UMV district, and the time span over which fluid circulated at elevated temperatures through the northern Illinois basin. At the end of this time period, flow rates likely decreased, causing temperatures to decline. Calcite crystals dated as 110 m.y. younger than the sphalerites in the UMV district (Brannon et al., 1992) have fluid inclusion temperatures of approximately 50°C; we interpret these temperatures to reflect the reestablishment of a conductive thermal regime and a basement heat flow controlled thermal gradient.

REFERENCES

Bethke, C.M.,1986, Hydrologic constraints on the genesis of the Upper Mississippi Valley mineral district from Illinois basin brines, Economic Geology, v. 81, p. 233-249.

Garven, G., 1985, The role of regional fluid flow in the genesis of the Pine Point deposit, Western Canada sedimentary basin, Economic Geology, v. 80, p. 307-324.

Brannon, J.C., Podosek, F.A., and McLimans, R.K., 1992, Alleghenian age of the Upper Mississippi Valley zinc-lead deposit determined by Rb-Sr dating of sphalerites, Nature, v. 356, p. 509-511.

Cluff, R.M., and Byrnes, A.P., 1991, Lopatin analysis of maturation and petroleum generation in the Illinois Basin, in Leighton et al., eds., Interior Cratonic Basins: American Association of Petroleum Geologists Memoir 51, chapter 25, p. 425-437.

Hatch, J.R., Heyl, A.V., and King, D., 1986, Organic geochemistry of hydrothermal alteration, basal shale and limestone beds, Middle Ordovician Quimby's Mill Member, Platteville Formation, Thompson-Temperly Zinc-Lead mine, Lafayette County, Wisconsin, *in* W.E. Dean, editor, Organics and Ore Deposits, Proceedings of the Denver Regional Exploration Geologists Society, p. 93-104.

McLimans, R.K., 1977, Geochemical, fluid inclusion, and stable isotope studies of the Upper Mississippi Valley zinc-lead district, southwest Wisconsin, Ph.D. dissertation, Pennsylvania State University, State College, Pa., 175 p.

Diagenetic Alteration and Porosity Enhancement of Two Middle Mississippian Sandstone Reservoirs in the Illinois Basin

Beverly Seyler, Illinois State Geological Survey
D. Scott Beaty, Kansas Geological Survey

Two highly productive Middle Mississippian siliciclastic units, the Aux Vases and Cypress formations, currently at 1,000 to 3,000 feet subsea and separated vertically by approximately 150 feet, have responded differently to similar burial conditions and diagenetic processes. Middle- and late- stage diagenetic alterations have enhanced porosity and permeability in both reservoirs. These alterations were controlled by initial sandstone composition, which is a function of both provenance and depositional facies. Most Aux Vases reservoirs were deposited in shallow marine, mixed siliclastic-carbonate tidal bars and channels. Many Cypress reservoirs were deposited in deltaic environments subjected to later reworking by marine processes.

In reservoir intervals, the Aux Vases sandstone is a friable unit, loosely cemented by diagenetic clay minerals. It is highly productive and typically possesses porosities greater than 22% and permeabilities greater than 300 md in the best reservoir sandstones.

The Cypress sandstone, a Chesterian siliciclastic unit that overlies the Aux Vases sandstone, has responded differently to a similar diagenetic history. Due to the absence of clay rims, good Cypress sandstone reservoirs are highly cemented with quartz-overgrowths and are less porous and less permeable than Aux Vases reservoirs. Porosity-enhancing diagenetic alterations in these reservoirs include dissolution of original carbonate cement, dissolution of feldspars, and dissolution of quartz overgrowths. Other diagenetic events include late-stage carbonate cement and quartz overgrowths and the precipitation of diagenetic clay minerals which occlude porosity. Together, these diagenetic alterations control the development and distribution of porosity and permeability and are responsible for varying pore geometries and mineralogies within these two reservoirs.

The Possible Role of Thermal Convection as a Result of Fracturing of Radioactive Basement Rocks and Implications for Fluid Flow, Heat Flow, and the Genesis of the Upper Mississippi Valley Zinc-Lead Ores

Charles S. Spirakis, U.S. Geological Survey, Denver, Colorado

Faulting may produce fracture permeability of basement rocks and increase their permeability by orders of magnitude. Because of the increase in permeability, heat from radioactive decay, which prior to fracturing had slowly escaped by conduction, may now escape quickly through convection. A consequence of this change to convective heat loss is the generation of short-lived thermal anomalies in the overlying sediments (Fehn et al., 1978). These thermal convection systems are likely sources of energy for the formation of Mississippi Valley-type (MVT) zinc-lead deposits.

Conditions required for this type of thermal convection were present in the Upper Mississippi Valley district. Strike-slip faults in the district offset magnetic patterns in the basement rocks (Heyl and King, 1966) and have offsets in the mines of up to 330 meters. These faults were active during mineralization (Heyl et al., 1959) and thus provided fracture permeability at that time. Potential heat-generating rocks are also present. Granitic rocks intersected in a well on the edge of the district contain an average of 46 ppm U and 114 ppm Th (Doe et al., 1983), much more than the 15 ppm U and 57 ppm Th in the heat-generating granite modeled by Fehn et al. (1978). Furthermore, there is evidence that the area was affected by a thermal convection system. Radiogenic lead, with similar isotopic ratios to the lead in the ores of the district, was leached from the basement rocks at about the time of mineralization (Doe et al., 1983); this indicates that the mineralizing fluids probably did flow through these rocks, which now have a very low permeability. Traces of basinal brines (Couture et al., 1983) and oil (Couture and Seitz, 1986) in the basement hundreds of meters beneath the sediments also indicate flow of basinal brines through the basement. Fehn et al. (1978) pointed out that once convection ceased and the fracture permeability of the basement sealed, heat would again begin to build up in the basement, and because faults are likely to be reactivated periodically, several ages of thermal events are likely to occur in relation to any area of faulting of radioactive basement rocks. The Upper Mississippi Valley district may be one such area, in that several episodes of potassic alteration, one or more episodes of mineralization, and annealing of fission tracks in apatite are all focused on the district. The present-day unusually low heat flux from the basement in the district may be an indication that the basement is still recovering from the latest cooling due to invasion of basinal brines.

In this model, fracturing of the radioactive granite beneath the district increased the permeability of the basement, which initiated the thermal convection of basinal brines. Salinity was provided by the circulating brine; sulfur was obtained from the brine or from the sediments, and metals were leached from the basement rock. The ability of the convecting brine to leach lead indicates the brine did not contain sulfide; such low-sulfide brines are more common on the edges of basins than in the deep parts of basins. The common occurrence of radiogenic lead in MVT deposits and the fact that radiogenic lead can only be obtained from uranium- and thorium-enriched rock, suggest that radiogenic granites may be present to provide heat and fluid flow for many MVT districts.

The proposed relation between thermal convection systems and MVT districts suggests that areas above faulted radioactive basement rocks on the edges of basins are exploration targets for MVT districts. Within the districts, ore deposits formed where concentrations of organic matter in the host rocks triggered ore-forming reactions (Spirakis and Heyl, 1993).

REFERENCES

Couture, R.A., and Seitz, M.G., 1986, Movement of fossil pore fluids in granite basement, Illinois: Geology, v. 14, p. 831-834.

Couture, R.A., Seitz, M.G., and Steindler, M.J., 1983, Sampling brines in cores of Precambrian granite from Northern Illinois: Jour. Geophysical Research, v. 88, no. B9, p. 7331-7334.

Doe, B.R., Stuckless, J.S., and Delevaux, M.H., 1983, The possible bearing of the granite of the UPH drill holes, northern Illinois, on the origin of the Mississippi Valley ore deposits: Jour. Geophysical Research, v. 88, no B9, p. 7335-7345.

Fehn, U., Cathles, L.M., and Holland, H.D., 1978, Hydrothermal convection and uranium deposits in abnormally radioactive plutons: Economic Geology, v. 73, p. 1556-1566.

Heyl, A.V., Agnew, A.F., Lyons, E.J., and Behre, C.H., 1959, The geology of the Upper Mississippi Valley zinc-lead district: U.S. Geological Survey Professional Paper 309, 310 p.

Heyl, A.V., and King, E.R., 1966, Aeromagnetic and tectonic interpretation of the Upper Mississippi Valley zinc-lead district: U.S. Geological Survey Bulletin 1242A, p. A1-A16.

Spirakis, C. S., and Heyl, A.V., 1993, Organic matter (bitumen and other forms) as the key to localisation of Mississippi Valley-type ores, *in* Parnell, J., Kucha, H., and Landais, P., eds., Bitumens in ore deposits: New York, Springer-Verlag, p. 381-398.

Geological Constraints on the Mining of Coal in Illinois

Colin G. Treworgy, Russell J. Jacobson, Cheri A. Chenoweth, Margaret H. Bargh
Illinois State Geological Survey

To be successful, a mining company must produce a marketable coal product at a competitive price. One of the keys to being a low-cost producer is locating coal resources that have geologic characteristics favorable for mining. Geological factors such as bedrock overburden thickness, size of mining block, stripping ratios, and coal seam thickness influence mining costs and may completely prevent the mining of some deposits. Companies that are acquiring reserves for mining need to know the location and quantity of coal that has the most favorable characteristics for mining.

Geologists at the Illinois State Geological Survey are identifying geological and other factors that limit the availability of coal for development. To date, coal resources have been evaluated in detail for three 7.5-minute quadrangle study areas in central, southern, and southeastern Illinois. The amount of coal found to be available for mining in each quadrangle ranged from 36 to 56% of the original resources. In the central Illinois study area, thickness of bedrock overburden was a significant factor limiting development of more than 25% of the original resources in the quadrangle. In the southern and southeastern Illinois study areas, geologic conditions associated with the Galatia Channel limit the minability of significant resources of low- to medium sulfur Springfield Coal. Results from these and additional individual quadrangle studies will be extrapolated to characterize larger regions and will ultimately be used to produce statewide information on the availability of coal for future development.

Reservoir Simulation Studies of Aux Vases and Cypress Reservoirs in Illinois

Emmanuel Udegbunam, Illinois State Geological Survey

Reservoir characterization studies by the Illinois State Geological Survey (ISGS) show that heterogeneity is a major contributor to recovery inefficiencies from Illinois Aux Vases and Cypress reservoirs. Computer-assisted simulations of a number of Aux Vases and Cypress reservoirs reveal that oil recovery is improved when reservoir development and management are guided by a good understanding of reservoir geology and heterogeneity. Strategies for future improved oil recovery and simulated results from five field studies are summarized below:

Thompsonville units - Dale Consolidated field (south-west). Pre-waterflood oil recovery from these two Aux Vases Sandstone bars was 18.9% of the original oil-in-place (OOIP). Initially the waterflood program produced only 0.56% of OOIP after 14 months of operation. Reservoir simulation results showed that oil recovery was adversely affected by fractures induced by hydraulic fracturing and by a highly permeable upper sandstone interval. Suggested strategies for oil recovery improvement included reservoir tests, well recompletions, realignment of oil producing and water injecting wells, a selective plugging program and infill drilling. Field production rose from 12 barrels of oil/day (BOPD) to about 60 BOPD over 10 months after realigning the water-injecting and oil-producing wells.

Energy field consists of two stacked Aux Vases Sandstone bars separated by an impermeable shale interval in two separately-owned leases. Only 15% of the OOIP has been recovered after 23 years of primary oil production. Simulated options for future improved oil recovery from the Energy field included (1) no waterflooding, (2) separate waterflood and infill drilling programs in the leases, and (3) unitized waterflooding and infill well development. Comparison among the options for improving future recovery of mobile oil from Energy field show that unitized waterflooding with one or more infill wells would yield the greatest oil recoveries.

Plumfield lease, Zeigler field, a mature Aux Vases reservoir, has undergone successful primary and secondary oil recovery operations. Because of the ample available reservoir and production data, this study is a good analog that can be applied in similar reservoirs. Estimates from reservoir analyses showed that Plumfield lease contained 4.56 millions of stock tank barrels of oil (MMSTBO) of which 43.1% was produced during the primary and secondary production stages. Continuous reservoir surveillance efforts guided optimum placement of water injectors in the field. Simulations of alternative reservoir management scenarios only recovered about 1.05% more oil than the historical case showing that this lease was optimally managed.

Lawrence field. The study area of Lawrence field consists of 5 distinct Cypress Sandstone intervals separated by impermeable shaly sandstones. Out of the initial reserve estimate of 780 stbo/ac-ft within the study area, only 39.5% has been produced after 85 years of oil production. The bypassed mobile oil volume is estimated as 14% of OOIP while the immobile oil volume is 46.5% of OOIP. Of the several waterflood patterns simulated, the line-drive pattern produced the most incremental oil from waterflooding with both 10-acre and 5-acre well spacings. Predictions of future production potential with the reservoir simulator showed that the Cypress Sandstones at Lawrence field may be drained more effectively with closer well spacings and the line-drive well pattern.

Mattoon field. Reservoir studies of the Mattoon field included simulations of water-alternating gas (WAG) in the Sawyer unit, straight CO_2 injection into the Pinnell unit and cyclic CO_2 injection (huff 'n puff) in the Strong unit. Parameters used for the simulations were derived from the field injectivity tests and from laboratory experiments. Simulation results show a significant improvement in oil recovery through implementation of a WAG injection program with 8 or more wells in the Sawyer unit. Parameters affecting oil recoveries from cyclic CO_2 injection wells have been investigated by simulations of a single well. Simulation results of the cyclic CO_2 injection process demonstrate that the "rule of thumb" value of 20 tons of CO_2 per perforated foot of pay can be too large; lower amounts of CO_2 resulted in higher oil recovery per unit volume (Mcf) of CO_2. Furthermore, simulation results show that the water-alternating gas process recovers more oil per unit volume of CO_2 than straight CO_2 injection.

Indiana Coal Mine Information Project

Licia Weber
Indiana Geological Survey at Indiana University

The Indiana Coal Mine Information System (Phases I-V) began in 1981 in cooperation with the Indiana Department of Natural Resource's Division of Reclamation. The System's purpose was to map Indiana's coal mines and to organize and compile mine information in a database format, which would be easily accessible to the public. Phases I and II of the project produced 97 USGS 7 1/2 minute quadrangle maps showing locations of underground coal mines, 85 quadrangle maps showing locations of abandoned surface coal mines, 34 county maps published by the Indiana Geological Survey at a scale of one inch to a mile showing locations of surface and underground coal mines, and a database containing all available surface and underground coal mine information. Phase III produced 97 quadrangle maps characterizing potential mine subsidence areas in Indiana, and improved, maintained, and managed the information system already in place. Phase IV produced a Geographic Information System (GIS) containing all mining information and Abandoned Mine Land sites. Phase V is currently in the first year of a three-year project to scan original coal company mine maps of underground workings, enhance the images, and add them to the GIS to make these maps accessible and available to the public, industry, and government agencies.

Seismotectonic maps of the New Madrid area—A model for maps of the lower Wabash Valley

Russell L. Wheeler and Susan Rhea, U.S. Geological Survey, Denver, Colorado

Recent discoveries of sand-filled dikes formed by shaking-induced liquefaction in the lower Wabash Valley show that the area has had large Holocene earthquakes. These findings and moderate-magnitude historic seismicity demonstrate the need to make existing, non-proprietary, geologic and geophysical information on the lower Wabash area accessible in a form that will help scientists to understand earthquake frequency and distribution. We present existing seismotectonic maps of the adjacent New Madrid area as examples to illustrate what can and should be produced for the lower Wabash Valley. Generally, such maps would not be used directly by engineers, emergency-response planners, or elected officials for hazard mitigation or loss estimation; instead, they represent some of the basic data needed by earth scientists to assess the hazard.

The examples from the New Madrid area are five 1:250,000-scale GIS maps that show an area (lat. 35°-37°N., long. 89°-91°W.) that includes most of the seismically active Reelfoot rift. Information on the five maps is grouped thematically: (1) The seismicity map shows epicenters of large historical earthquakes and of more recent instrumentally located seismicity, stress indicators, seismograph locations, and sand blow intensities from the great 1811-12 New Madrid earthquakes. (2) The crustal structure map integrates geophysical interpretations of the complex Reelfoot rift. (3) The geophysical profiles map shows lines of geophysical surveys and models. (4) The bedrock geology map shows contacts, wells, faults, structure of the Mississippi Valley graben, and structure contours drawn on an unconformity between bedrock and softer strata that might amplify shaking. (5) The surficial and hydrologic features map shows earthquake-induced landslides, fluvial and hydrologic anomalies, topographic features, GPS monuments, and the Bootheel lineament as interpreted separately from aerial photographs and Landsat images.

Seismotectonic maps have several uses, and the New Madrid maps illustrate them. The New Madrid maps reveal previously unrecognized spatial relations between seismicity and other data, which can suggest hypotheses about causal processes. Several kinds of data show coincident anomalies at the seismically active Lake County uplift and Blytheville arch and at some inferred intrusions, thereby constraining structural interpretations. The maps also show information bearing on recent tectonism and hazards from shaking, liquefaction, amplification, and ground failure. Other workers can use the maps as bases on which to plan surveys and plot their own data. Finally, others can incorporate the digital data into their own maps and figures.

It may be feasible to fit the lower Wabash data onto only two or three maps, fewer than for New Madrid. In particular, probably fewer data are available for the lower Wabash Valley on seismicity, on geomorphology, and on the geophysics of the middle and lower crust. However, more data may be available on faults, wells, structure contours, and geologic contacts. The data compiled for the New Madrid maps were all made available electronically and we hope to publish them as a CD-ROM. It should be possible to do the same for any lower Wabash Valley maps.

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