USGS
science for a changing world

Diagenesis and Reservoir Quality of the Upper Mississippian Aux Vases Sandstone, Illinois Basin

U.S. Geological Survey Professional Paper 1609

U.S. Department of the Interior
U.S. Geological Survey

Availability of Publications of the U.S. Geological Survey

Order U.S. Geological Survey (USGS) publications from the offices listed below. Detailed ordering instructions, along with prices of the last offerings, are given in the current-year issues of the catalog "New Publications of the U.S. Geological Survey."

Books, Maps, and Other Publications

By Mail

Books, maps, and other publications are available by mail from—

USGS Information Services
Box 25286, Federal Center
Denver, CO 80225

Publications include Professional Papers, Bulletins, Water-Supply Papers, Techniques of Water-Resources Investigations, Circulars, Fact Sheets, publications of general interest, single copies of permanent USGS catalogs, and topographic and thematic maps.

Over the Counter

Books, maps, and other publications of the U.S. Geological Survey are available over the counter at the following USGS Earth Science Information Centers (ESIC's), all of which are authorized agents of the Superintendent of Documents.

- Anchorage, Alaska—Rm. 101, 4230 University Dr.
- Denver, Colorado—Bldg. 810, Federal Center
- Menlo Park, California—Rm. 3128, Bldg. 3, 345 Middlefield Rd.
- Reston, Virginia—Rm. 1C402, USGS National Center, 12201 Sunrise Valley Dr.
- Salt Lake City, Utah—2222 West, 2300 South (books and maps available for inspection only)
- Spokane, Washington—Rm. 135, U.S. Post Office Bldg., 904 West Riverside Ave.
- Washington, D.C.—Rm. 2650, Main Interior Bldg., 18th and C Sts., NW.

Maps only may be purchased over the counter at the following USGS office:

- Rolla, Missouri—1400 Independence Rd.

Electronically

Some USGS publications, including the catalog "New Publications of the U.S. Geological Survey," are also available electronically on the USGS's World Wide Web home page at **http://www.usgs.gov**

Preliminary Determination of Epicenters

Subscriptions to the periodical "Preliminary Determination of Epicenters" can be obtained only from the Superintendent of Documents. Check or money order must be payable to the Superintendent of Documents. Order by mail from—

Superintendent of Documents
Government Printing Office
Washington, D.C. 20402

Information Periodicals

Many Information Periodicals products are available through the systems or formats listed below:

Printed Products

Printed copies of the Minerals Yearbook and the Mineral Commodity Summaries can be ordered from the Superintendent of Documents, Government Printing Office (address above). Printed copies of Metal Industry Indicators and Mineral Industry Surveys can be ordered from the Center for Disease Control and Prevention, National Institute for Occupational Safety and Health, Pittsburgh Research Center, P.O. Box 18070, Pittsburgh, PA 15236-0070.

Mines FaxBack: Return Fax Service

1. Use the touch-tone handset attached to your fax machine's telephone jack. (ISDN [digital] telephones cannot be used with fax machines.)
2. Dial (703) 648-4999.
3. Listen to the menu options and punch in the number of your selection, using the touch-tone telephone.
4. After completing your selection, press the start button on your fax machine.

CD-ROM

A disc containing chapters of the Minerals Yearbook (1933–95), the Mineral Commodity Summaries (1995–97), a statistical compendium (1970–90), and other publications is updated three times a year and sold by the Superintendent of Documents, Government Printing Office (address above).

World Wide Web

Minerals information is available electronically at **http://minerals.er.usgs.gov/minerals/**

Subscription to the Catalog "New Publications of the U.S. Geological Survey"

Those wishing to be placed on a free subscription list for the catalog "New Publications of the U.S. Geological Survey" should write to—

U.S. Geological Survey
903 National Center
Reston, VA 20192

U.S. Department of the Interior
Bruce Babbitt, Secretary

U.S. Geological Survey
Charles G. Groat, Director

For sale by U.S. Geological Survey, Information Services
Box 25286, Federal Center
Denver, CO 80225

Library of Congress Cataloging-in-Publication Data

Pitman, Janet K.
Diagenesis and reservoir quality of the Upper Mississippian Aux
Vases Sandstone, Illinois Basin / Janet K. Pitman, Mitchell Henry,
and Hannes Leetaru.
p. cm. — U.S. Geological Survey professional paper ; 1609)
Includes bibliographical references.
1. Geology, Stratigraphic—Mississippian. 2. Diagenesis—Illinois
Basin. 3. Petroleum—Geology—Illinois Basin. 4. Aux Vases
Formation. I. Henry, Mitchell E. II. Leetaru, Hannes E.
III. Title. IV. Series.
QE672.P58 2000
553.2′8′0977—dc21 99–39834
CIP

Diagenesis and Reservoir Quality of the Upper Mississippian Aux Vases Sandstone, Illinois Basin

By Janet K. Pitman, Mitchell Henry, *and* Hannes Leetaru

U.S. Geological Survey Professional Paper 1609

U.S. Department of the Interior
U.S. Geological Survey

Contents

Figures

Tables

Diagenesis and Reservoir Quality of the Upper Mississippian Aux Vases Sandstone, Illinois Basin

By Janet K. Pitman,[1] Mitchell Henry,[1] *and* Hannes Leetaru[2]

Abstract

The Aux Vases Sandstone (Upper Mississippian) is extensively cored in the Illinois Basin and thus offers the opportunity to study diagenetic processes that occurred under different temperatures and burial conditions. Major diagenetic events observed in the Aux Vases Sandstone interval include (1) precipitation of precompactional illite and grain-rimming chlorite, (2) quartz overgrowth, syntaxial calcite and dolomicrospar cementation, (3) carbonate-cement and framework-grain dissolution, (4) illite and chlorite authigenesis, (5) ankerite precipitation and (6) hydrocarbon emplacement. On the basis of petrographic and stable-isotope analysis, early diagenetic quartz, syntaxial calcite, and dolomicrospar formed at relatively low temperatures (~20°–90°C) in a generally freshwater burial environment, whereas late-diagenetic ankerite precipitated at elevated temperatures (~120°C) in a diagenetic system dominated by basinal brines. Porosity reduction in sandstones was predominantly caused by mechanical compaction and cementation by carbonate and quartz overgrowths. Enhanced porosity, which is mostly of secondary origin, is due to carbonate cement and framework-grain dissolution; only minor primary porosity is preserved by early grain-rimming clay. Secondary porosity was mostly caused by acidic meteoric waters and (or) deep basin brines carrying organic and inorganic acids released during maturation of organic-rich shales. On the basis of burial-thermal reconstruction, sandstone diagenesis took place over a short time interval, culminating in the Late Pennsylvanian to Early Permian when the rocks were at or close to their maximum burial (~2 km). In southern Illinois, combined igneous and hydrothermal heat transport during the late Paleozoic influenced source-rock maturation and subsequent migration of large amounts of petroleum into reservoir sandstones.

Introduction

The Illinois Basin is a mature, hydrocarbon-producing province, and most of the oil that has been produced (approximately 60 percent) comes from Upper Mississippian siliciclastic and carbonate rocks (fig. 1). The Aux Vases Sandstone, deposited during Late Mississippian time, is an important reservoir unit that has yielded an estimated 1 billion barrels of oil (Seyler, 1984). To date, the diagenesis and reservoir quality of the Aux Vases generally have been studied on a field basis rather than a regional scale, and potential mechanisms and timing of diagenesis have received little attention. In this study we attempt to (1) document the depositional history and framework mineralogy of major clastic sequences within the Aux Vases Sandstone proper, (2) formulate a generalized diagenetic model and examine the extent to which diagenetic processes affected the reservoir quality of sandstones, (3) construct regional reservoir-quality trends by mapping porosity and permeability variations across the area of deposition, and (4) relate the diagenetic history of the unit to the migration and entrapment of hydrocarbons in the basin. Results of the study revealed that early- and late-diagenetic cements are good indicators of the types of fluids that migrated through the sandstone interval. The processes that controlled porosity enhancement and porosity reduction in potential reservoir units were constrained by identifying the origin and timing of these cements. A knowledge of the major controls on porosity and permeability distribution is necessary in order to develop reliable porosity-prediction models in underdrilled areas of the basin.

Methods

The regional stratigraphic framework of the Aux Vases Sandstone was defined by the correlation of wireline logs from more than 1,400 wells (Leetaru, 1997). Representative core samples of sandstones were taken from approximately 70 wells for petrographic study (fig. 2; table 1). The wells selected for analysis span a depth interval of ~305–1,000 m and cover a wide geographic area. Thin sections of the sandstone samples were impregnated with blue epoxy for porosity recognition and stained with a combination of Alizarin red-S and potassium ferricyanide to distinguish Fe-free and Fe-bearing carbonate; thin sections were also stained with sodium cobaltinitrate to aid in the identification of K-feldspar. Three hundred counts were made on each sample to quantify rock composition and thin-section porosity. In this study, the classification scheme of Folk (1974) was modified so that the quartz category consisted of monocrystalline grains—polycrystalline quartz grains were included as rock fragments. Grain size, defined as the long axis of random framework grains, was computed for each sample.

Samples containing end-member carbonate were analyzed for their carbon and oxygen isotopic composition by Global Geochemistry (Canoga Park, Calif.) and Mountain Mass

---

[1] U.S. Geological Survey, Mail Stop 939, Box 25046, Denver, Colorado, 80225.

[2] Illinois State Geological Survey, 615 East Peabody Drive, Champaign, Illinois, 61820.

Spectrometry (Evergreen, Colo.). Carbon- and oxygen-isotope ratios were obtained by a timed-dissolution procedure based on different reaction rates for chemically distinct carbonate phases (Walters and others, 1972). Upon reaction with phosphoric acid, CO_2 gas that was evolved in the first hour was attributed to calcite, and CO_2 gas evolved after several hours was assigned to dolomite. Isotope results are reported as the per mil (‰) difference relative to the PDB (Peedee belemnite) standard using the delta (δ) notation. Data reproducibility is precise to ±0.2‰.

Conventional porosity and permeability analyses from 96 wells that penetrated the Aux Vases Sandstone were compiled into a reservoir-quality database. The data were taken from the Illinois State Geological Survey's Well Inventory System. In order to minimize large variations in porosity and permeability within a well, median values were calculated for the cored interval. Determining a median value for a whole interval rather than a specific facies eliminated problems associated with complex lithogenetic relationships, which are difficult to distinguish on well logs and in drill cores.

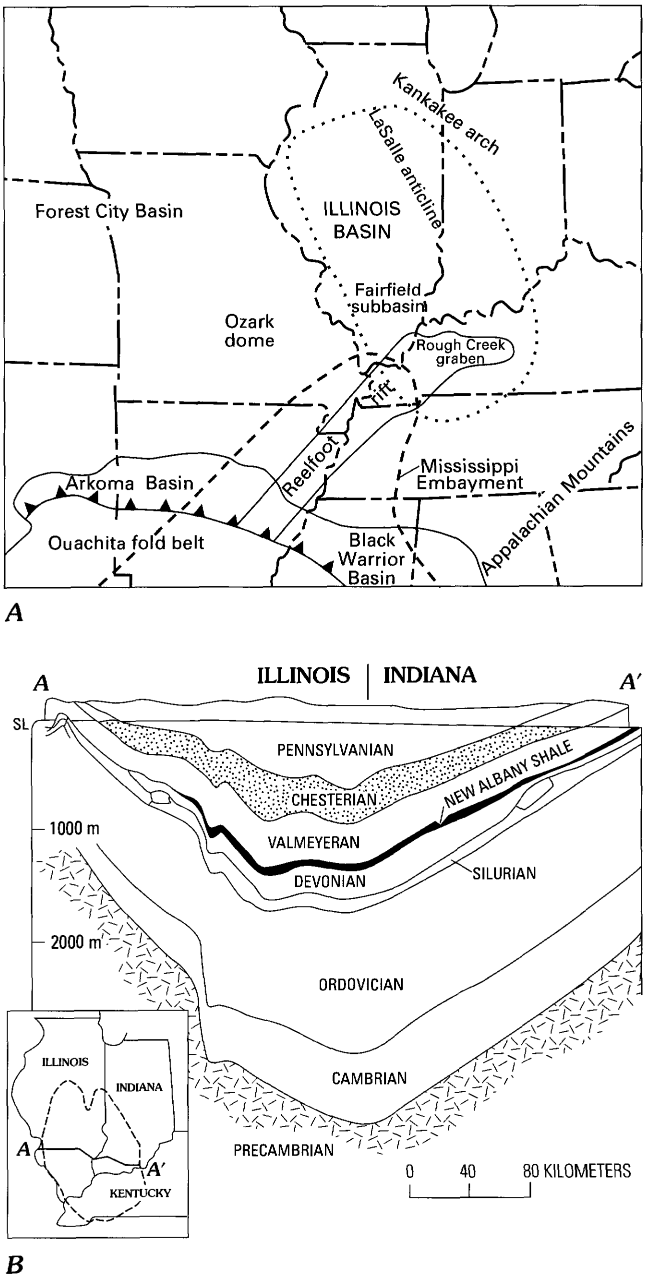


Figure 1. *A*, Location map showing the Illinois Basin. *B*, East-west cross section depicting Upper Mississippian Chesterian Series and Upper Devonian and Lower Mississippian New Albany Shale; subcrop of the Chesterian Series is shown as a dashed line on inset map (modified from Swann, 1967).

Geologic History and Depositional Framework

The Aux Vases Sandstone was deposited during Late Mississippian time as part of a tidally influenced mixed carbonate-siliciclastic system. The unit is composed of alternating carbonate and siliciclastic rock and is bounded by major sequence boundaries (Leetaru, 1997) (fig. 3). The base of the Aux Vases, which corresponds to the lower sequence boundary, generally is at the top of the Upper Mississippian Ste. Genevieve Limestone, but, in some areas, the Ste. Genevieve has been eroded and the Aux Vases unconformably overlies the Upper Mississippian St. Louis Limestone. Where present, the Upper Mississippian Joppa Limestone forms the lower part of the Aux Vases Sandstone (Leetaru, 1997). The Joppa is composed of thinly interbedded limestone, shale, siltstone, and sandstone and corresponds to a marine transgressive event. No hydrocarbons have been recovered from the Joppa because of the lack of good reservoirs. The principal hydrocarbon reservoirs within the Aux Vases occur in sandstone sequences within the upper part of the unit. The upper part of the Aux Vases is predominantly a siliciclastic unit that was deposited during a marine highstand. A relative drop in sea level followed deposition and resulted in widespread erosion. The upper sequence boundary of the Aux Vases is represented by paleosols, mudcracks, and root traces, which are indicators of this erosional event.

On a regional scale, the Aux Vases Sandstone shows variations that correspond to different depositional environments within the siliciclastic-carbonate system (fig. 4). The Aux Vases in the western part of the study area is dominated by massive, crossbedded sandstone beds that are locally fossiliferous and conglomeratic at their bases. Stratigraphic and sedimentologic studies suggest that these fluvial and estuarine sandstones formed as valley-fill deposits during a period of sea-level change (Leetaru, 1997). At shallow depths, these sandstones are important aquifers; however, they have not been found to contain oil and gas. On the basis of sandstones geometries (fig. 4), the Aux Vases in the central region formed from northeast-southwest-trending offshore bars that were deposited parallel to the paleoshoreline. There is only minor oil production from the Aux Vases in this region. Most oil in the Aux Vases is found in a crossbedded sandstone facies in the eastern part of the region. The reservoir facies contains isolated shale clasts and was deposited in a tidally influenced system (Seyler, 1998). In contrast, stratigraphically equivalent nonreservoir sandstones, including rhythmically bedded, and lenticular and flaser-bedded sequences, formed in a tidal-flat environment. The Aux Vases Sandstone generally becomes more calcareous to the east and southeast of the study area, and, at some localities, sandstones were deposited as channels that eroded into the underlying carbonate-rich facies of the

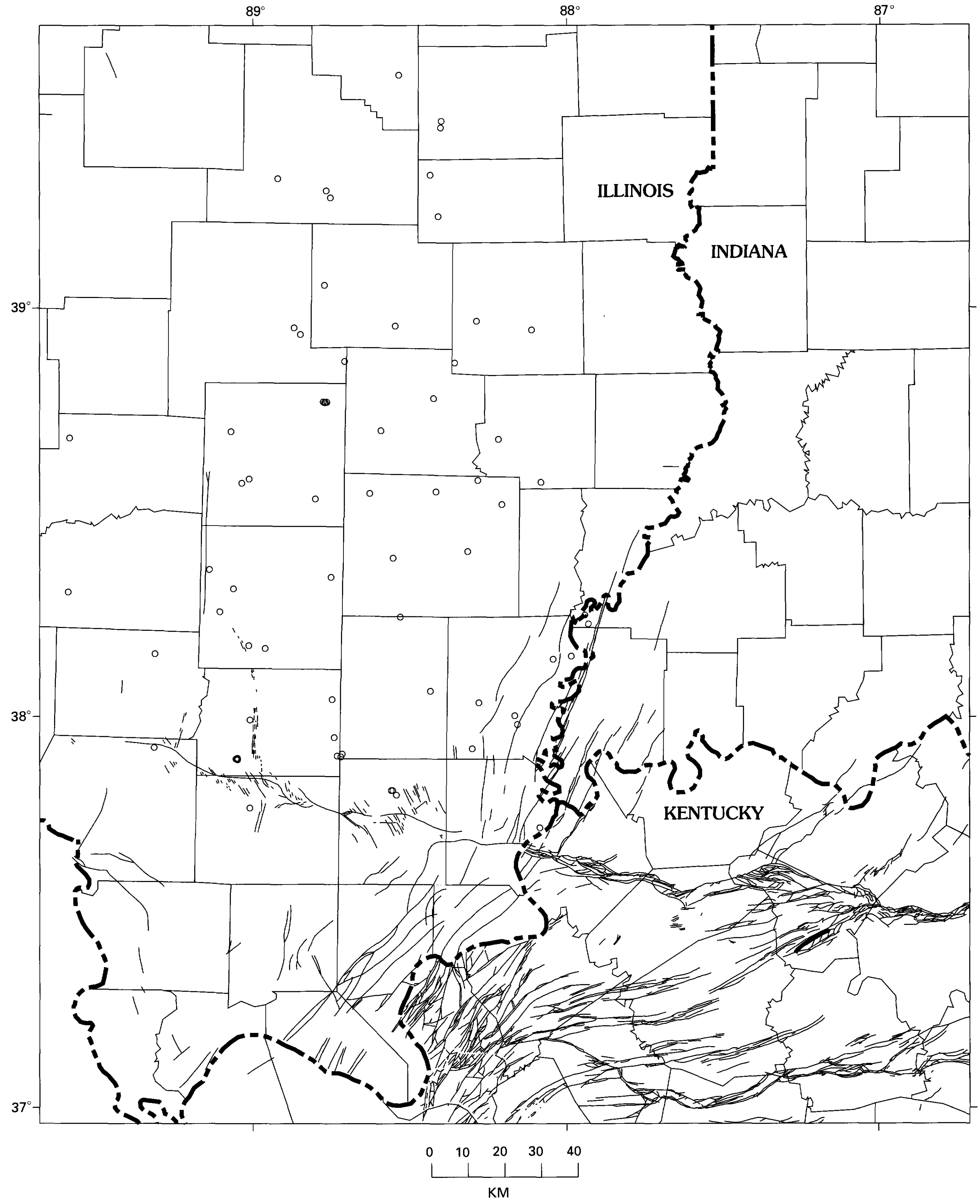


Figure 2. Map showing location of core holes sampled for petrographic and geochemical analysis.

Joppa (Leetaru, 1991). The crossbedded sandstone facies in the eastern region may contain limestone with carbonate grains that were transported into a predominantly siliciclastic environment by storms. These impermeable limestones commonly create lateral and vertical seals that compartmentalize oil reservoirs (Oltz, 1994). Reservoir compartmentalization is recognized by multiple oil-water contacts and higher-than-expected initial flowing pressures within the Aux Vases interval (Leetaru, 1993).

Table 1. Location of well samples.

Core ID	API	State	Latitude	Longitude
C00071	1207700603	Illinois	37.928828	89.283433
C00285	1214502037	Illinois	38.158661	89.285138
C00345	1208102322	Illinois	38.320668	89.042866
C00381	1217300063	Illinois	39.326528	88.916095
C00433	1219100109	Illinois	38.399507	88.544023
C00460	1219306796	Illinois	37.933664	88.294968
C00467	1219304604	Illinois	38.160159	87.986364
C00494	1219100012	Illinois	38.556896	88.618865
C00592	1219300424	Illinois	38.153027	88.043539
C00597	1207900017	Illinois	38.878071	88.352995
C00598	1208100799	Illinois	38.174662	88.941924
C00606	1207900128	Illinois	38.980093	88.284636
C00627	1206500251	Illinois	38.073224	88.424937
C00674	1206500043	Illinois	38.254823	88.520667
C00735	1212101296	Illinois	38.705799	89.055451
C00752	1215900014	Illinois	38.586007	88.081222
C00771	1207901699	Illinois	38.958428	88.110717
C00946	1212103995	Illinois	38.589738	88.997243
C00992	1218900369	Illinois	38.306769	89.559301
C01049	1213900006	Illinois	39.581258	88.534095
C01064	1212104128	Illinois	38.579448	89.020696
C01136	1205100944	Illinois	38.945236	88.840027
C01203	1219106348	Illinois	38.416416	88.310185
C01235	1204900446	Illinois	38.967613	88.541509
C01236	1205500679	Illinois	37.959383	88.723707
C01243	1219101768	Illinois	38.561880	88.410092
C01266	1205100167	Illinois	38.880339	88.69996
C01279	1205900360	Illinois	37.739878	88.084803
C01322	1202701515	Illinois	38.683297	89.562707
C01387	1219101118	Illinois	38.531865	88.203934
C01396	1208100709	Illinois	38.366666	89.11894
C01439	1208100764	Illinois	38.263679	89.085271
C01445	1219101791	Illinois	38.589686	88.279198
C01511	1204900140	Illinois	39.065321	88.765539
C01546	1202500525	Illinois	38.789958	88.419539
C01626	1219303068	Illinois	38.045577	88.27385
C01635	1205101009	Illinois	38.961306	88.860722
C01697	1202901120	Illinois	39.469346	88.398547
C01742	1215900748	Illinois	38.691761	88.21526
C01813	1203500074	Illinois	39.337077	88.433253
C02055	1212900326	Illinois	39.453137	88.400827
C02059	1212101476	Illinois	38.779823	88.767094
C02085	1212104968	Illinois	38.779868	88.755532
C02096	1212101475	Illinois	38.778051	88.762495
C02114	1202500549	Illinois	38.710497	88.584495
C02157	1212104966	Illinois	38.778053	88.760168
C02170	1212101410	Illinois	38.541994	88.788652
C02235	1203500090	Illinois	39.235724	88.407222
C02253	1219306226	Illinois	37.992952	88.1545
C02323	1217300392	Illinois	39.296958	88.76281
C02341	1208100199	Illinois	38.181586	88.992598
C02521	1216501397	Illinois	37.818689	88.529178
C03339	1205501226	Illinois	38.052249	88.732005
C04683	1217300078	Illinois	39.280430	88.74881
C05279	1218502475	Illinois	38.260543	87.944239
C05817	1216503280	Illinois	37.829886	88.540589
C06040	1216503273	Illinois	37.829917	88.545221
C06069	1206503364	Illinois	37.918572	88.698900
C06071	1206503362	Illinois	37.911432	88.703276
C13071	1205523456	Illinois	37.913560	88.71468
C13892	1219923491	Illinois	37.783680	88.98479
C13974	1205523596	Illinois	37.999733	88.987413
C13975	1219331131	Illinois	38.014470	88.16316
C13976	1205523768	Illinois	37.903527	89.029376
C13977	1205523769	Illinois	37.905350	89.0246
C14007	1205523753	Illinois	37.901550	89.02454
C14011	1205523750	Illinois	37.903550	89.0269
No #	1205523744	Illinois	37.903550	89.02454
No #	1208124399	Illinois	38.351390	88.73697
IN133	No data	Indiana	38.238589	87.932857

Mineralogy and Diagenesis

The Aux Vases Sandstone is predominantly composed of well-sorted to poorly sorted, subangular to subrounded, very fine to medium-grained subarkoses and sublitharenites (fig. 5). Quartzarenites and lithic arkoses also are present within the sandstone interval but in subordinate amounts. Framework-grain compositions of individual sandstones average 81 percent quartz, 9 percent feldspar, and 10 percent rock fragments (table 2). Detrital quartz, the major framework constituent, consists mostly of monocrystalline grains that commonly display small, rounded overgrowths, which suggests that they were derived from reworked, second-cycle sediments. Orthoclase is the dominant feldspar type in the sandstones, but minor amounts of plagioclase feldspar and microcline occur locally. Some feldspar grains have been altered to clay or exhibit a honeycombed (dissolution) texture, whereas other grains have been partially replaced by carbonate cement. Sedimentary rock fragments consisting of chert and carbonate rip-up clasts are common lithic types in sandstones. Bioclastic grains, which also occur in the underlying upper Valmeyeran Series (Pryor and others, 1991), may comprise as much as 15 percent of the whole rock in sandstones adjacent to carbonate beds. Plutonic rock fragments and metamorphic polycrystalline quartz grains are present but in very minor amounts. Heavy minerals—including rutile, tourmaline, and apatite—generally are rare.

On the basis of petrographic analysis, the framework-grain mineralogy of the Aux Vases Sandstone interval remains relatively constant throughout the area of deposition with no distinct variations between individual facies. Outcrop studies and facies analysis suggest that the detrital assemblage was derived from a northwesterly source, possibly the Transcontinental arch or Wisconsin arch; the Ozark uplift also may have been a source for some of the siliciclastic sediment (Leetaru, 1997). In contrast, the Canadian Shield to the north and Appalachian Mountain belt east of the basin are reported to be the source of the sediment in younger Chesterian sandstones, which are also reservoirs for oil

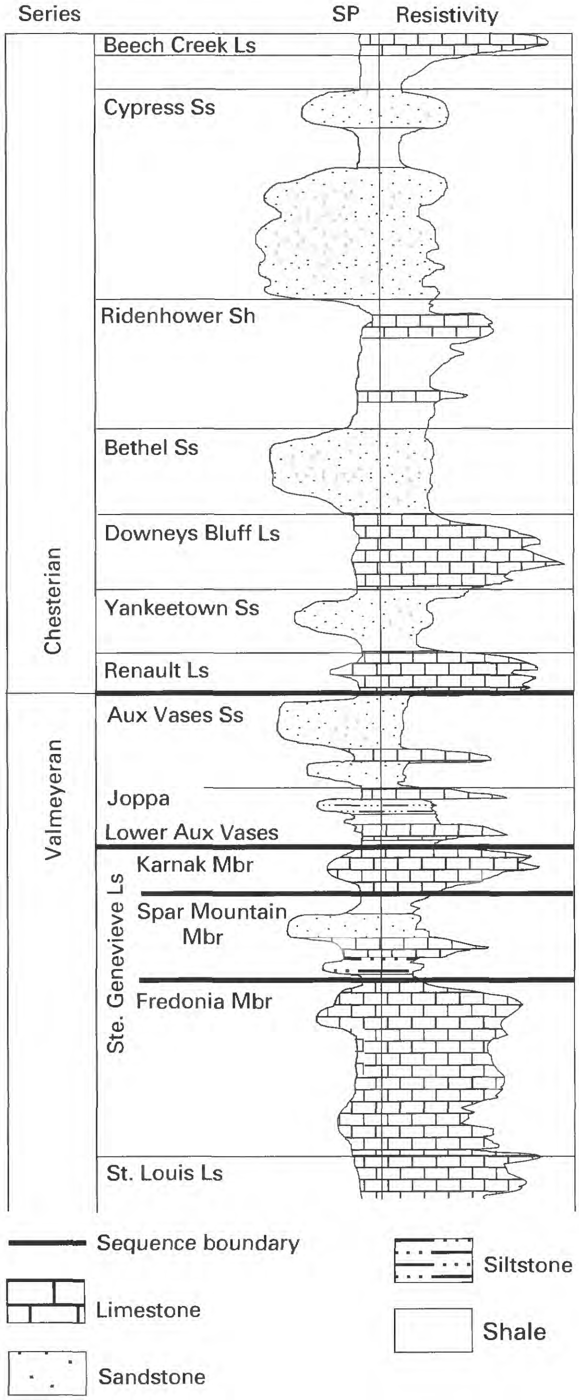


Figure 3. Stratigraphic column depicting the interval between the Beech Creek Limestone and the St. Louis Limestone (modified from Leetaru, 1998).

and gas (Swann, 1963). Our studies indicate that source-area differences are the most likely cause for the variations in framework-grain composition (and subsequent diagenetic alterations) observed in Chesterian-age reservoir sandstones.

The Aux Vases Sandstone was affected by a series of physical and diagenetic alterations during burial that included mechanical compaction, early quartz and carbonate cementation, framework-grain and cement dissolution, clay mineral precipitation, late-diagenetic carbonate development, and hydrocarbon emplacement (fig. 6). On a regional scale, there are no substantial variations in authigenic mineral type or abundance among individual sandstone samples nor are there any obvious depth-related trends. Minor variations that occur on a local scale most likely reflect the varied lithologies that comprise the unit. It is noteworthy that the paragenetic sequence in the Aux Vases generally is comparable to that found in other Chesterian sandstones despite variations in framework-grain mineralogy (Pitman and others, 1998).

Compaction and Pressure Solution

Most sandstones in the Aux Vases were affected by mechanical compaction, as indicated by the presence of long and concave-convex grain contacts. In the southern part of the basin, sandstones underwent substantial mechanical compaction, which resulted in only minor early-diagenetic cementation and subsequent dissolution porosity. Compaction in these sandstones occurred by means of increased grain-packing density due to grain rotation and deformation of ductile components. In some parts of the basin, quartz grains display interdigitated, presolved contacts, indicating that they experienced pressure solution. Grain-to-grain contact dissolution is most extensive in fine-grained sandstones that contain precompactional, grain-rimming clay. Although pressure solution may occur without clay, clay coats have been shown to accelerate the dissolution process at framework-grain contacts (Heald, 1955; Weyl, 1959).

Mineral Cements

Total authigenic cement in the Aux Vases Sandstone ranges from approximately 2 percent in the most porous samples to about 48 percent (mean 14 percent) in pervasively cemented beds (table 2). Dominant authigenic mineral cements consist of calcite, dolomite, and quartz. Stable-isotope compositions of the major carbonate phases are reported in table 3 and shown in figure 7.

Calcite and dolomite are the dominant pore-fill cements in reservoir sandstones and are present in amounts ranging from 0–45 percent, mean 7 percent (calcite), and 0–47 percent, mean 6 percent (dolomite) (table 2). On the basis of petrographic analysis, multiple generations of carbonate, including nonferroan and ferroan calcite, dolomicrospar, planar dolospar, and planar ankerite formed during early and late stages of diagenesis. The complex textural relations between individual carbonate phases suggest that other carbonate cements that are not recognized may also occur.

Nonferroan calcite predates other carbonate cements and is most abundant in sandstones containing bioclasts. The syntaxial nature of this calcite indicates that fossil fragments and detrital carbonate grains reworked from nearby carbonate environments served as nucleation sites for early carbonate growth. The carbon- and oxygen-isotope compositions of syntaxial calcite vary over a relatively narrow range, from +1.02 to –3.40‰ ($\delta^{13}C$) and –5.87 to –8.63‰ ($\delta^{18}O$) (table 3; fig. 7). In well-cemented sandstones, ferroan calcite comprises optically continuous crystals that form a poikilotopic, pore-fill cement with little to no intergranular porosity. The relatively high intergranular volumes characterizing these rocks (4–40 percent, average 25 percent) suggest that only minor mechanical compaction occurred prior to cementation.

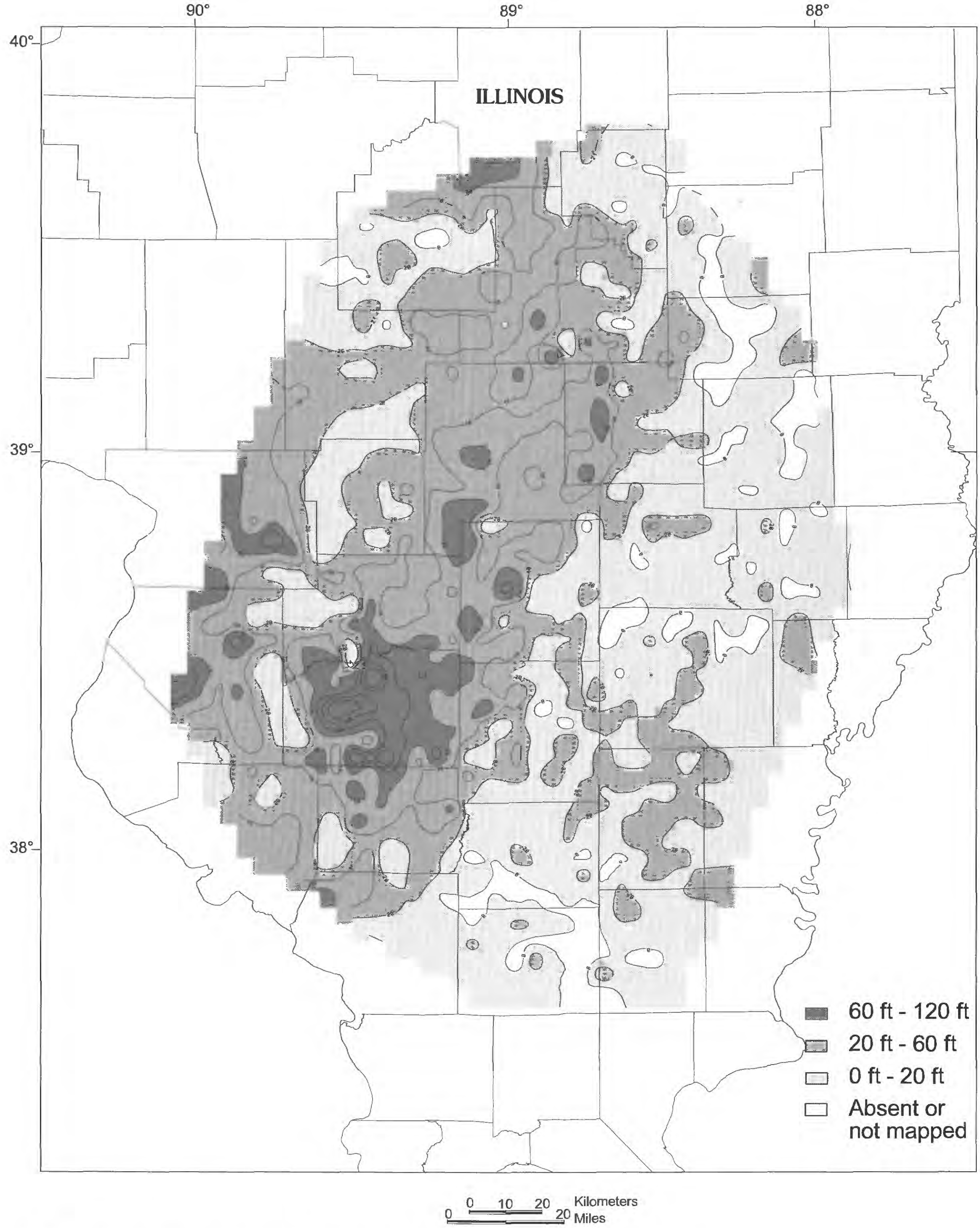


Figure 4. Isolith map for the Aux Vases Sandstone. Contours depict net sand thickness.

More commonly, ferroan calcite has irregular grain boundaries and is distributed in irregular patches, or as remnant cement in sandstones that are porous and permeable. Such features suggest that ferroan calcite formerly may have been more widespread in reservoir sandstones. Locally, ferroan calcite replaces relict nonferroan calcite and is in contact with early quartz overgrowths; ferroan calcite commonly does not replace feldspar. Representative samples of poikilotopic calcite have $\delta^{13}C$ values ranging from +0.49 to –0.82‰ and $\delta^{18}O$ values varying from –8.00 to –8.88‰ (table 3; fig. 7).

Dolomicrospar in reservoir sandstones comprises nonplanar interlocking crystals of nonferroan dolomite and, less commonly, tiny (~5–25 μm) planar crystals that occupy primary intergranular pores. The $\delta^{13}C$ values of dolomicrospar tend to be heavy, from +1.54 to +0.52‰. The $\delta^{18}O$ values range from –6.51 to –3.63‰ (table 3; fig. 7). A large fraction of dolomite in the southern part of the basin is coarse-crystalline (~20–300 μm) planar dolospar that may or may not coexist with quartz and calcite. Most planar dolospar forms compositionally homogeneous euhedral crystals but some (detrital?) planar dolospar grains are

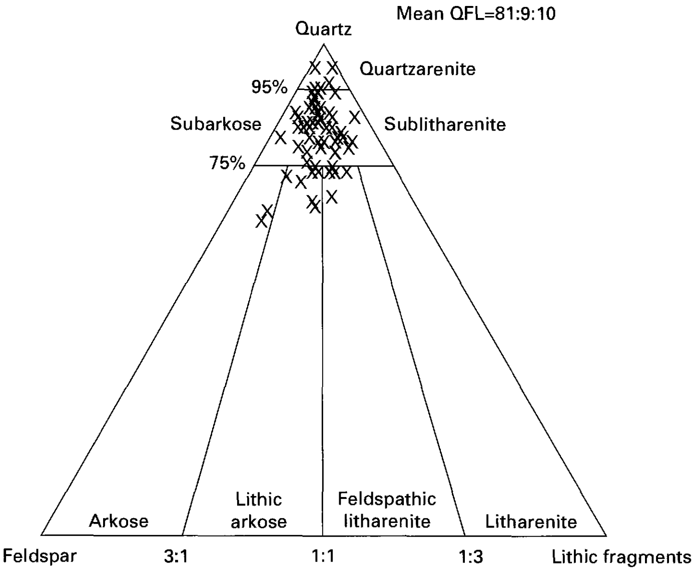


Figure 5. Ternary QFL (quartz, feldspar, lithic fragments) plot for the Aux Vases Sandstone based on the classification of Folk (1974).

partially rounded and exhibit Fe-rich overgrowths. The intergrown nature of planar ferroan and nonferroan dolospar and the small amounts of planar dolospar in most samples prevented stable-isotope analysis of these phases.

Planar ankerite postdates other carbonate cements in reservoir sandstones and is most abundant in southern Illinois in areas that are faulted. Most ankerite occurs as discrete or clustered rhombs with straight boundaries, but in well-cemented sandstones it forms a poikilotopic cement that infills secondary pores and replaces framework grains such as K-feldspar. One sample of planar ankerite analyzed isotopically has values of +0.04‰ (δ^{13}C) and –7.58‰ (δ^{18}O) (table 3; fig. 7). In a few samples, a small component of ankerite is anhedral to subhedral in habit and displays slightly curved crystal faces with broad sweeping extinction, which classify it as saddle ankerite. Unfortunately, it could not be sampled for isotopic analysis.

Authigenic quartz in reservoir sandstones constitutes discrete euhedral overgrowths that are partially developed or embayed. In a few samples, authigenic chlorite and illite are engulfed by quartz overgrowths. Generally, authigenic quartz averages a few percent, but in some coarser grained sandstones, commonly in the vicinity of major bounding faults in the southern portion of the basin, authigenic quartz cement is locally widespread (greater than 10 percent), which resulted in significant porosity reduction.

Clay Minerals

The clay-mineral assemblage in the Aux Vases Sandstone (0–18 percent, average 3 percent) is composed of illite, interstratified illite-smectite(?), and chlorite. In thin section, discrete clay phases are difficult to distinguish because they tend to be complexly intergrown. Illite and illite-smectite are predominantly precompactional clays that occur as thin tangential coatings on framework grains devoid of grain overgrowths. In sandstones where precompactional illite and illite-smectite are widespread, interdigitated, presolved grain contacts and incipient stylolites are common features. In a few samples, wispy flakes of illite (and chlorite) are engulfed in quartz overgrowths.

Authigenic chlorite occurs as platelets that are oriented perpendicular to detrital grain surfaces and as discontinuous rims that bridge framework grains in sandstones devoid of early secondary quartz overgrowths. In some sandstones with secondary porosity, dispersed chlorite crystals form loose aggregates in residual pores.

Other Phases

Authigenic phases present in volumetrically minor amounts in the Aux Vases Sandstone include anhydrite, pyrobitumen, hematite, and pyrite. Occurrences of anhydrite vary from scattered patches to individual euhedral crystals that replace earlier formed

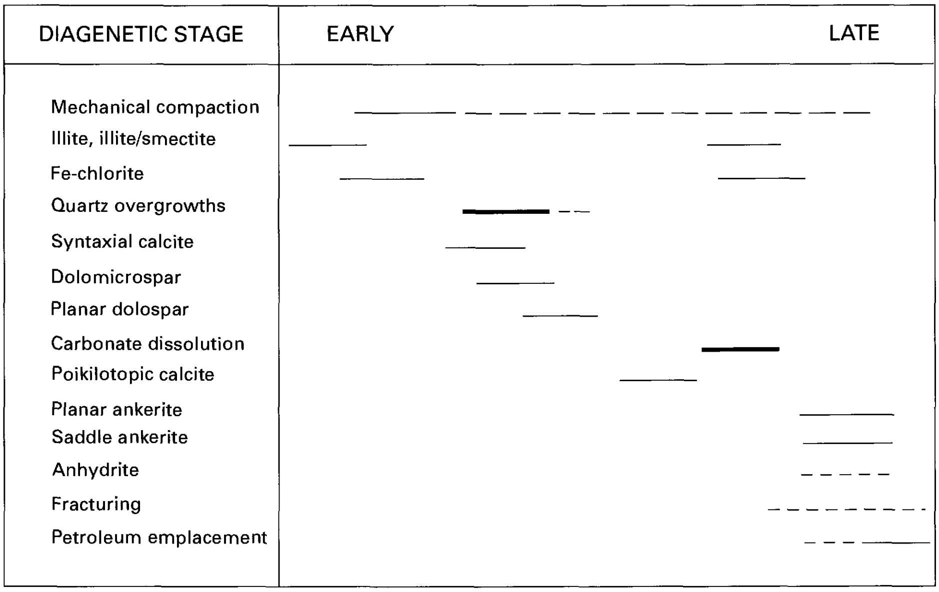


Figure 6. Paragenetic sequence of diagenetic events in the Aux Vases Sandstone. Thick bar represents major period of diagenesis; dashed line indicates probable diagenesis.

Table 2. Mineralogic composition of Aux Vases sandstones.

[Data reported in volume percent. feld, feldspar; lith, lithics; Qtz, quartz; cmt, cement; dolo, dolomite; carb, carbonate; IGV, intergranular volume]

Core ID	State	Latitude	Longitude	Quartz	Na-feld	K-feld	Total feld	Total lith	Qtz cmt	Total calcite	Total dolo	Total carb	Clay	Porosity	IGV	Total cmt
C00071	Illinois	37.928828	89.283433	65	1	4	5	2	6	2	0	2	1	18	27	9
C00285	Illinois	38.158661	89.285138	58	1	10	11	8	1	0	0	0	18	3	22	19
C00345	Illinois	38.320668	89.042866	63.0	2.5	4.5	7.0	5.5	4.5	0.0	0	0.0	5.0	13.5	23.0	9.5
C00381	Illinois	39.326528	88.916095	60	1	4	5	9	4	11	1	12	1	8	25	17
C00433	Illinois	38.399507	88.544023	48	5	1	6	6	0	2	2	4	2	20	26	6
C00460	Illinois	37.933664	88.294968	53	1.5	6	7.5	10	0	10	0	10	4.5	13	27.5	14.5
C00467	Illinois	38.160159	87.986364	54	4	6	10	9	1	19	0	19	4	2	26	24
C00494	Illinois	38.556896	88.618865	67	2	1	3	6	8	6	2	8	2	5	23	18
C00592	Illinois	38.153027	88.043539	52	0	10	10	8	0	26	3	29	0	0	29	29
C00597	Illinois	38.878071	88.352995	49.0	2.5	4.5	7.0	10.0	3.0	22.5	1.0	23.5	4.0	2.5	33.0	30.5
C00598	Illinois	38.174662	88.941924	52	1	0	1	11	7	28	0	28	0	0	35	35
C00606	Illinois	38.980093	88.284636	52.0	3.0	0.0	3.0	5.0	19.0	0.0	10.0	10.0	3.0	4.0	36.0	32
C00627	Illinois	38.073224	88.424937	62	8	2	10	7	2	2	1	3	2	11	18	7
C00674	Illinois	38.254823	88.520667	57.0	4.0	1.0	5.0	5.0	0.0	0.5	0.0	0.5	3.0	24.5	28.0	3.5
C00735	Illinois	38.705799	89.055451	60	3	6	9	2	7	2	0	2	2	17	28	11
C00752	Illinois	38.586007	88.081222	63	6	1	7	9	3	8	0	8	4	5	20	15
C00771	Illinois	38.958428	88.110717	46	3	2	5	21	4	8	10	18	0	5	27	22
C00946	Illinois	38.589738	88.997243	68	1	2	3	4	4	1	0	1	4	14	23	9
C00992	Illinois	38.306769	89.559301	72	1	2	3	1	2	0	0	0	1	20	23	3
C01049	Illinois	39.581258	88.534095	59	3	3	6	10	0	19	1	20	1	2	23	21
C01064	Illinois	38.579448	89.020696	55.0	0.0	3.5	3.5	4.5	1.5	29.0	1.0	30.0	1.0	4.0	36.5	32.5
C01136	Illinois	38.945236	88.840027	65	1	6	7	6	3	4	0	4	4	9	20	11
C01203	Illinois	38.416416	88.310185	56	4	1	5	6	7	4	0	4	2	8	21	13
C01235	Illinois	38.967613	88.541509	64	2	1	3	6	7	0	0	0	14	4	25	21
C01236	Illinois	37.959383	88.723707	63.0	3.0	2.0	4.0	9.0	1.0	7.0	4.0	11	1.0	6.0	19.0	13
C01243	Illinois	38.561880	88.410092	38.0	2.0	1.0	3.0	7.0	0.5	45.0	2.5	47.5	0.0	3.5	51.5	48
C01266	Illinois	38.880339	88.69996	57	7	6	13	7	5	0	0	0	7	8	20	12
C01279	Illinois	37.739878	88.084803	38.0	1.5	6.0	7.5	2.5	0.0	13.0	31.5	44.5	1.0	5.5	51.0	45.5
C01322	Illinois	38.683297	89.562707	62	0.5	3	3.5	2	2	16.5	0.5	17	0	12	31	19
C01387	Illinois	38.531865	88.203934	54	5	0	5	15	0	13	1	14	9	0	23	23
C01396	Illinois	38.366666	89.11894	54	5	3	8	4	0	0	0	0	5	27	32	5
C01439	Illinois	38.263679	89.085271	58	3	10	13	7	5	0	0	0	3	10	18	8
C01445	Illinois	38.589686	88.279198	45.5	5.5	4.5	10.0	12.0	0.5	9.0	1.0	10.0	7.0	8.0	25.5	17.5
C01511	Illinois	39.065321	88.765539	61	4	5	9	4	3	1	1	2	1	19	25	6
C01546	Illinois	38.789958	88.419539	62	2	5	7	13	5	1	3	4	1	7	17	10

Table 2. Mineralogic composition of Aux Vases sandstones—*Continued.*

Core ID	State	Latitude	Longitude	Quartz	Na-feld	K-feld	Total feld	Total lith	Qtz cmt	Total calcite	Total dolo	Total carb	Clay	Porosity	IGV	Total cmt
C01626	Illinois	38.045577	88.27385	54	4	5	9	10	0	6	1	7	4	16	27	11
C01635	Illinois	38.961306	88.860722	40	0	4	4	17	0	37	1	38	0	0	38	38
C01697	Illinois	39.469346	88.398547	69.5	0	2.5	2.5	9.5	1	4.5	0	4.5	1.5	11.5	18.5	7
C01742	Illinois	38.691761	88.21526	46	3	2	5	3	3	0	37	37	0	5	45	40
C01813	Illinois	39.337077	88.433253	58	6	0	6	6	4	0	0	0	6	20	30	10
C02055	Illinois	39.453137	88.400827	58	4	0	4	8	6	6	0	6	0	15	27	12
C02059	Illinois	38.779823	88.767094	62.5	2.5	3.5	6.0	4.0	7.0	0.0	0.0	0.0	6.0	11.0	24	13
C02085	Illinois	38.779868	88.755532	44.0	1.0	5.0	6.0	10.5	3.0	23.0	0.5	23.5	6.0	5.0	37.5	32.5
C02096	Illinois	38.778051	88.762495	58.0	3.0	5.5	8.5	5.5	5.0	0.0	0.0	0.0	3.0	6.0	14	8
C02114	Illinois	38.710497	88.584495	59.5	3.5	6.5	10.0	7.0	2.0	8.5	0.0	8.5	7.0	2.0	19.5	17.5
C02157	Illinois	38.778053	88.760168	58	4	5	9	5	5	0	0	0	3	10	18	8
C02170	Illinois	38.541994	88.788652	57	6	5	11	3	4	0	4	4	6	5	19	14
C02235	Illinois	39.235724	88.407222	64	3	8	11	7	2	0	0	0	7	7	16	9
C02253	Illinois	37.992952	88.1545	45	5	6	11	9	0	5	2	7	1	26	34	8
C02323	Illinois	39.296958	88.76281	59	0	3	3	5	3	0	1	1	1	27	32	5
C02341	Illinois	38.181586	88.992598	72	0	1	1	3	9	2	0	2	0	10	21	11
C02521	Illinois	37.818689	88.529178	53.0	3.0	8.0	11.0	8.0	4	6	9	15	4	1	24	23
C03339	Illinois	38.052249	88.732005	59.5	5.5	3	9	6	5	8	0.5	8.5	3	5	21.5	16.5
C04683	Illinois	39.280430	88.74881	61	0	4	4	8	3	6	0	6	1	6	16	10
C05279	Illinois	38.260543	87.944239	52.0	2.5	4.0	6.5	4.0	1.5	1.0	16.0	17.0	3.0	12.0	33.5	21.5
C05817	Illinois	37.829886	88.540589	60.5	3.5	5.5	9.0	5.5	1.0	6.0	1.0	7.0	4.5	7.5	20	12.5
C06040	Illinois	37.829917	88.545221	58	1	6	7	8	1	15	0	15	2	8	26	18
C06069	Illinois	37.918572	88.698900	60	1	3	4	6	0	1	1	2	0	25	27	2
C06071	Illinois	37.911432	88.703276	54	0	3	3	7	0	3.5	0	3.5	0	21	24.5	3.5
C13071	Illinois	37.913560	88.71468	65	1	2	3	5	0	0.5	1.5	2	0	22	24	2
C13892	Illinois	37.783680	88.98479	64	0	2	2	5	13	6	2	8	0	4	25	21
C13974	Illinois	37.999733	88.987413	64	2	1	3	4	5	6	0	6	0	17	28	11
C13975	Illinois	38.014470	88.16316	54	1	3	4	6	1	6	1	7	1	24	33	9
C13976	Illinois	37.903527	89.029376	71	1	1	3	5	12	0	3	3	0	1	16	15
C13977	Illinois	37.905350	89.0246	70	0	1	2	5	3	0	0	1	2	4	9	5
C14007	Illinois	37.901550	89.02454	61	1	2	3.5	8	0	2	1	3	0.5	16	19.5	3.5
C14011	Illinois	37.903550	89.0269	65.5	0.5	2.5	3	10	0	1	0.5	1.5	0	14.5	16	1.5
No #	Illinois	37.903550	89.02454	64	1	2	3	4	0	1	0	1	0	21	22	1
No #	Illinois	38.351390	88.73697	52	0	1.5	1.5	7	0.5	0	31	31	1	6.5	39	32.5
IN133	Indiana	38.238589	87.932857	54	4	7	11	14	1	1	16	17	0	1	19	18

carbonate cements. There is no evidence that anhydrite was affected by dissolution processes or that it was a pervasive cement.

Pyrobitumen is present locally as an opaque material in porous reservoir sandstones. In oil zones, bitumen occupies moldic and secondary intergranular pores and coats authigenic mineral cements. Authigenic minerals in oil-saturated sandstones generally are restricted to minor quartz overgrowths and relic carbonate cement. Fluorescent hydrocarbon inclusions were not observed in any diagenetic phase in the Aux Vases.

Dissolution

On the basis of visual estimates, approximately 95 percent of the porosity in the Aux Vases Sandstone is intergranular and less than 5 percent of the porosity is intragranular. Thus, in most porous sandstones, intergranular porosity dominates and intragranular porosity is minor. Although some workers have interpreted Chesterian sandstones as dominantly primary porosity reservoirs (Pryor and others, 1991), our studies indicate that most porosity in the Aux Vases sandstone interval is of secondary origin, resulting from the removal of carbonate cement and, to a lesser extent, framework grains, principally feldspar (fig. 8). In thin section, evidence of carbonate-cement dissolution includes embayed quartz overgrowths, well-developed carbonate cement adjacent to extensively leached areas, dissolution voids in tightly cemented sandstones, and relic carbonate cement in otherwise porous sandstones. Petrographic observations indicate that one or more generations of carbonate cement are present in various amounts in some reservoir sandstones, whereas other sandstones are still tightly cemented by carbonate.

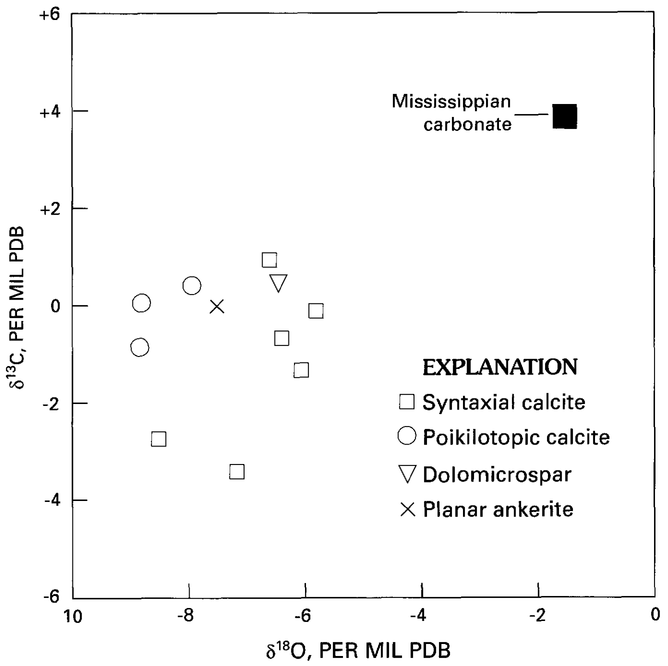


Figure 7. Stable-isotope compositions of diagenetic carbonate cements in reservoir sandstones. Black square represents approximate composition of carbonate cement in equilibrium with Mississippian seawater (from Meyers and Lohmann, 1985). PDB, Peedee belemnite standard.

Intragranular porosity resulting from partial dissolution of detrital grains is present throughout the Aux Vases Sandstone in variable but small amounts. Overall, grain-dissolution porosity did not significantly enhance the total sandstone porosity. Leaching of framework grains affected mainly K-feldspar and resulted in the development of oversized and moldic pores. In sandstones where authigenic clay fills these voids, porosity is moderate and permeability is low.

Table 3. Stable-isotope compositions of carbonate cements in Aux Vases sandstones.

[Values in parentheses are repeat analyses. PDB, Peedee belemnite standard]

Sample ID	State	Depth (m)	$\delta^{13}C$ (per mil, PDB)	$\delta^{18}O$ (per mil, PDB)
		Syntaxial calcite		
C0078	Illinois	1,946	−1.27 (−1.29)	−6.14 (−6.12)
C1064	Illinois	1,837	−3.40	−7.29
C1064	Illinois	1,834	−2.74	−8.63
C1279	Illinois	2,665	−0.07	−5.87
C13977	Illinois	2,624.9	0.62	−6.46
C13977	Illinois	2,624	1.02 (0.60)	−6.64 (−7.17)
		Poikilotopic Fe-calcite		
C3339	Illinois	3,138.5	−0.82	−8.91
C3362	Illinois	3,042	0.49 (0.49)	−8.00 (−8.00)
C13977	Illinois	2,623	0.10 (0.10)	−8.88 (−8.88)
		Dolomicrospar		
C1742	Illinois	2,921	1.54	−3.63
IN133	Indiana	2,825	0.52 (0.52)	−6.51 (−6.59)
		Planar ankerite		
C4399	Illinois	2,891	0.04 (0.04)	−7.58 (−7.58)

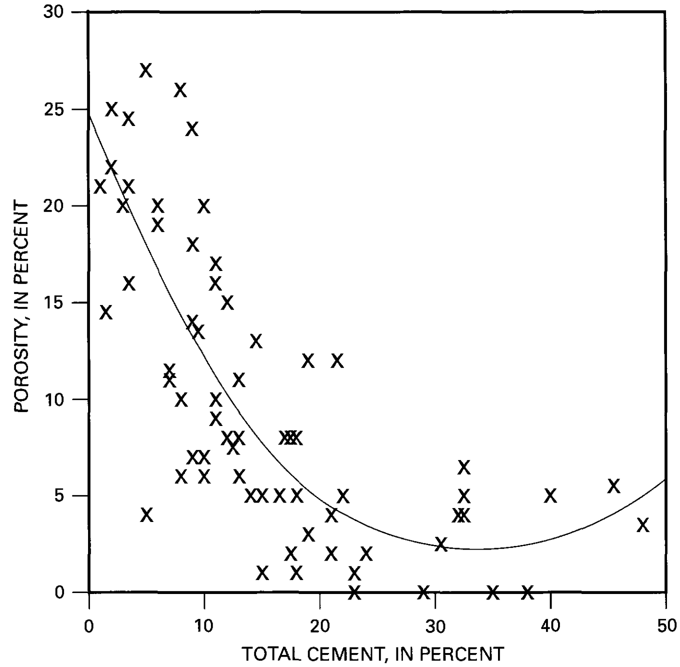


Figure 8. Relationship between thin-section porosity and total cement. The curve is a third-degree polynomial fit to the data.

Time-Temperature History

Generalized burial- and thermal-history curves of the Aux Vases Sandstone sequence (fig. 9) were generated using the 2-dimensional, finite-difference program, Basin2. The burial-thermal model takes into account differences in deposition and erosion, variations in porosity and permeability, and the thermal effects of fluid flow during the basin's history (Bethke and others, 1993). Thermal data incorporated in the model constrained the amount of eroded section in southern Illinois to approximately 1 km. Coupled numerical and heat-flow calculations were used to model paleotemperatures in the Aux Vases Sandstone because they have been shown to reconcile observed biomarker and vitrinite-reflectance maturities, and measured fluid-inclusion homogenization temperatures in the basin fill (Rowan and others, in press). The modeled temperatures based on these calculations (see temperature profile in fig. 9) reflect the strong influence that heat related to late Paleozoic hydrothermal and igneous activity had on the basin's thermal regime during late-stage diagenesis. Hypothetical temperatures calculated for the conductive heat-flow model (see fig. 9) are significantly lower than the observed thermal values determined from the rock record (i.e., biomarker and vitrinite maturities, fluid-inclusion temperatures). This suggests that conductive heat flow from the basement played a relatively minor role in the overall thermal history of the basin.

Diagenetic Evolution of Reservoir Sandstones

In this section, we place the diagenetic processes that may have influenced the reservoir quality of the Aux Vases Sandstone in a time-temperature framework. We then use this framework to constrain our hypothesis that porosity evolution in individual sandstones was controlled by the combined effects of mechanical compaction and mineral cementation.

The evolution of the Aux Vases diagenetic system is shown relative to its time-temperature history in figure 9. The temperatures that bracket individual diagenetic events were taken from Surdam and others (1989) and correlated with the temperature profile based on igneous and hydrothermal heat flow. The absolute age of individual diagenetic events is difficult to establish because Mississippian sandstones generally lack minerals suitable for isotopic dating; however, the upper limit can be constrained to Early Permian based on the age of peak hydrocarbon generation and migration in the basin (Cluff and Byrnes, 1991).

Sandstones in the Aux Vases were affected by multiple episodes of carbonate-mineral precipitation and dissolution, quartz cementation, and clay-mineral authigenesis. On the basis of petrographic analysis, precipitation of nonferroan and ferroan carbonate began soon after deposition and continued until hydrocarbons were emplaced in the Late Pennsylvanian and Early Permian. The temperature regime during carbonate precipitation varied widely (~30°–120°C) and was governed by the combined effects of burial heat flow, and coupled igneous and hydrothermal heat sources (Pitman and others, 1998). During early burial diagenesis, carbonate formed at low temperatures (~30°–80°C) in a meteoric environment, but later, during deeper burial, it precipitated at elevated temperatures (~80°–120°C) under conditions of high P_{CO_2} when the pore-water alkalinity might have been buffered by organic acids. Burial-history reconstruction suggests that carbonate precipitation did not occur after Early Permian time (see fig. 9).

The carbonate for calcite and dolomite cements was derived mostly from the dissolution of detrital marine carbonate rock, as indicated by the relatively uniform carbon-isotope compositions of early- and late-diagenetic carbonate cements (average 0.3‰; table 3). The narrow range of carbon values (~+1 to +3‰) further suggests recrystallization without CO_2 exchange. The later carbonate cements (ferroan calcite and ankerite) formed in a rock-buffered system by remobilization of preexisting cements with little change in $\delta^{13}C$.

Fractionation equations for calcite and dolomite (Friedman and O'Neil, 1977; Fritz and Smith, 1970) suggest that carbonate in sandstones precipitated in a burial regime that evolved from freshwater to saline conditions over a relatively short period of time. Paleosols, red beds, and root traces near the top of the Aux Vases (Leetaru, 1997) indicate a period of subaerial exposure during which meteoric water infiltrated the sandstone, precipitating the freshwater component of carbonate cement. Petrographic evidence of shallow burial at the time of syntaxial calcite cementation suggests that water of negative oxygen isotope composition was involved in the precipitation of early calcite cement. Assuming early calcite cementation was related to invasion of meteoric water at the end of Aux Vases deposition, burial temperatures probably would have been on the order of 30°C, which predicts pore-water oxygen-isotope compositions between –3 to –6‰ SMOW (standard mean ocean water) (fig. 10).

Dolomicrospar, which formed in a shallow burial regime at about the same time as early calcite, is interpreted to have precipitated from waters with $\delta^{18}O$ values (–4 to –7‰ SMOW) comparable to those that precipitated calcite (fig. 10). The development of poikilotopic ferroan carbonate postdated the

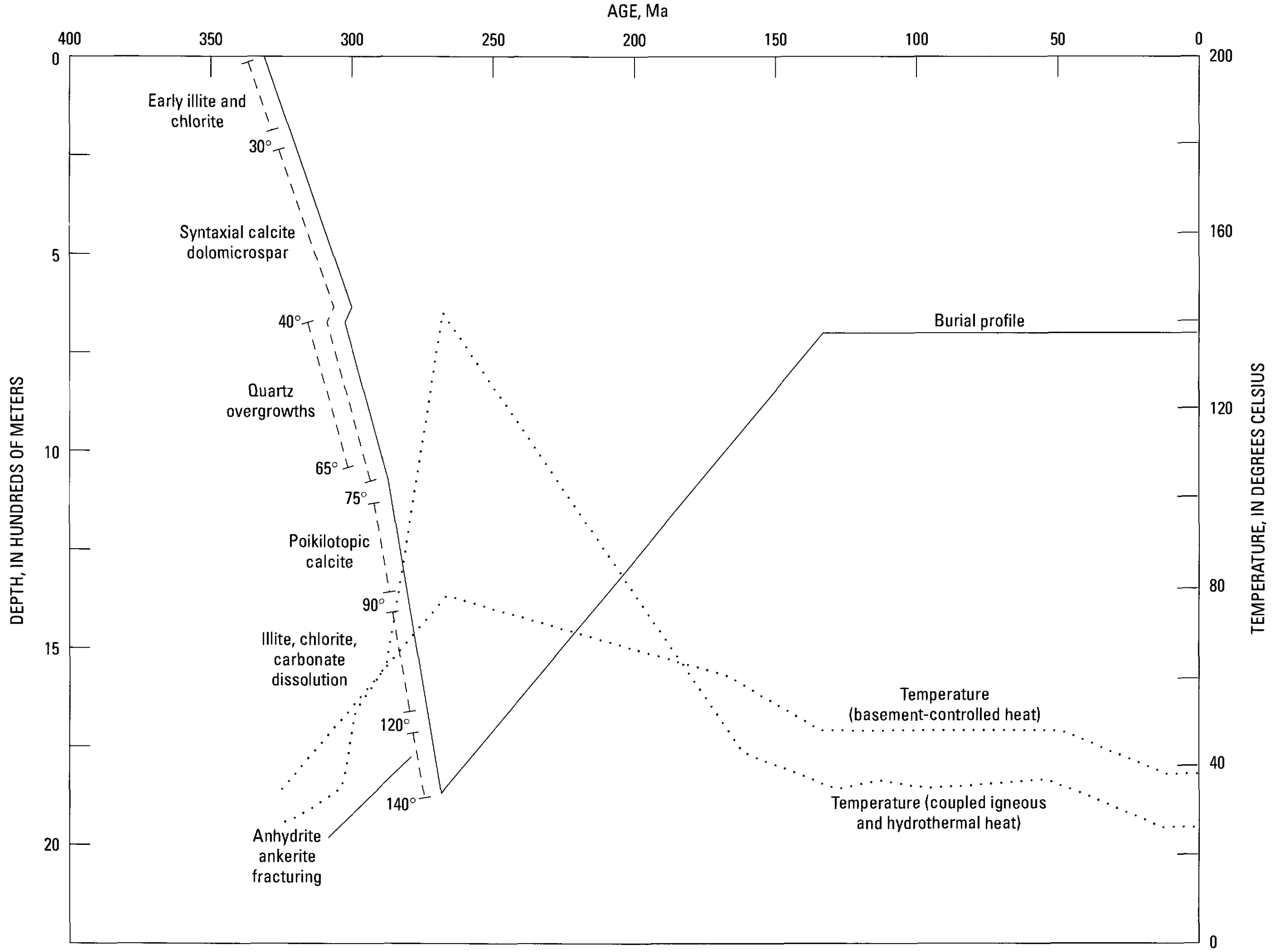


Figure 9. Burial- and thermal-history curves for the Aux Vases Sandstone interval showing relative timing of major diagenetic events in southern and central Illinois. Age of hydrocarbon generation and petrographic features constrain timing of diagenesis. Paleotemperature profiles (igneous plus hydrothermal heat flow and burial-only heat flow) were determined using the coupled fluid-flow and burial heat-flow model, Basin2. Note that thermal curves are depicted relative to geologic age, not burial depth. Temperatures bracketing diagenetic events modified from Surdam and others (1989).

formation of early syntaxial calcite but predated late-stage hydrocarbon emplacement, suggesting precipitation in a burial environment at temperatures as high as 90°C. Pore-water compositions at a temperature of 90°C should be slightly enriched in $\delta^{18}O$, from +4 to +3‰ SMOW (fig. 10). Late-diagenetic planar ankerite formed when the sandstone interval was close to its maximum burial depth (~2 km) and at about the same time that hydrocarbons entered the unit. Assuming crystallization temperatures approximating 120°C, ankerite formed from reducing, $\delta^{18}O$-enriched waters with compositions on the order of +4‰ SMOW (fig. 10). Saddle ankerite, also a late-diagenetic phase, may have precipitated from fluids with even heavier values if temperatures as high as 140°C were involved in cementation.

On the basis of petrographic observations, most quartz cement in the Aux Vases Sandstone precipitated at shallow burial depths early in the burial history before other mineral cements. In contrast to early quartz, which is the dominant cement in younger Mississippian sandstones, secondary quartz, is a minor diagenetic phase in the Aux Vases compared to early- and late-stage carbonate cements. According to Surdam and others (1989), early quartz overgrowths generally form at fairly low temperatures, which, in the Aux Vases, might have ranged from about 40° to 65°C (see fig. 9). Silica derived from external and internal sources likely was involved in early quartz cementation. As in the early carbonate cement, much of the silica might have originated from saturated meteoric ground waters circulating through the sandstone interval soon after deposition. Upon deeper burial, pressure solution along stylolites and framework-grain contacts might have added additional silica to pore fluids, which subsequently moved by diffusion to nearby sites of precipitation. Incipient stylolitization and grain-to-grain contact dissolution are observed in many sandstones in the Aux Vases and are features commonly associated with thin, illitic clay coats. According to Heald (1955) and Weyl (1959), even though pressure solution at grain contacts can occur without clay, clay coatings tend to accelerate the grain-contact dissolution process, which results in the release of silica into solution for uptake by quartz cement. The presence of interstratified illite and illite-smectite in small yet consistent amounts suggests that the illite-smectite

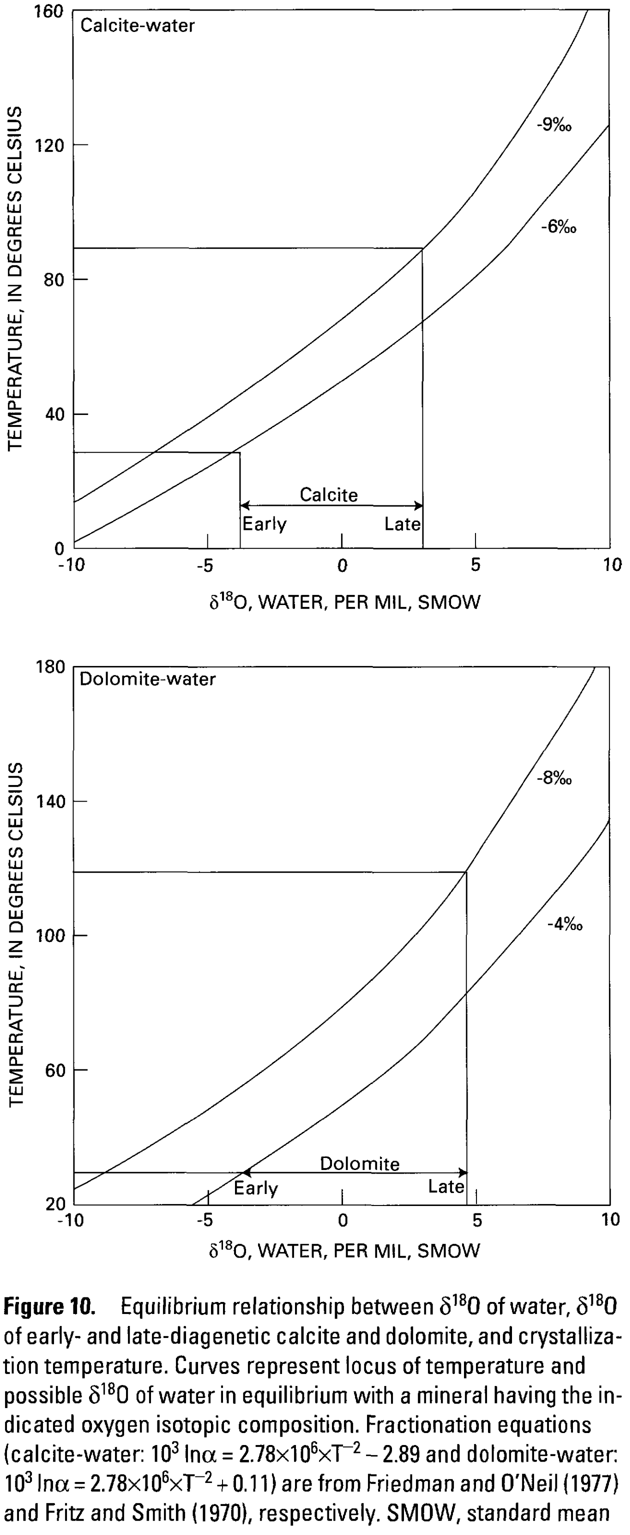


Figure 10. Equilibrium relationship between $\delta^{18}O$ of water, $\delta^{18}O$ of early- and late-diagenetic calcite and dolomite, and crystallization temperature. Curves represent locus of temperature and possible $\delta^{18}O$ of water in equilibrium with a mineral having the indicated oxygen isotopic composition. Fractionation equations (calcite-water: $10^3 \ln\alpha = 2.78\times10^6\times T^{-2} - 2.89$ and dolomite-water: $10^3 \ln\alpha = 2.78\times10^6\times T^{-2} + 0.11$) are from Friedman and O'Neil (1977) and Fritz and Smith (1970), respectively. SMOW, standard mean ocean water.

transformation process may have contributed minor silica to secondary quartz. Dissolution of framework grains such as feldspar was not a likely source of silica because quartz precipitation generally predated the main stage of framework-grain leaching.

Clay mineral authigenesis in the Aux Vases Sandstone commenced before significant mechanical compaction and continued until late in the burial history (see fig. 9). The earliest formed clays are precompactional illite rims, regarded to be syndepositional or early diagenetic precipitates, and chlorite grain-rimming cement, which formed during shallow burial and before appreciable compaction. Iron oxide grain coatings on some detrital grains and the dewatering of shales may have provided the iron that was incorporated into chlorite. Minor void-filling and grain-replacement illite precipitated following moderate amounts of mechanical compaction. The potassium and silica released into solution upon dissolution of K-feldspar and other framework grains may have been a source of the ions necessary for late-stage illitization.

A combination of processes is required to explain the dissolution of carbonate cement and framework grains, which together account for most of the porosity enhancement in the sandstones studied. In the shallow subsurface, through-flowing meteoric waters generally are acidic and undersaturated with respect to carbonate; thus, they may have been important in the dissolution process. However, in the deeper subsurface, the leaching capacity of meteoric waters is limited because, in addition to being undersaturated with respect to carbonate, the waters tend to be neutralized by reactions along the flow paths.

The Aux Vases Sandstone interval is among the principal reservoirs for hydrocarbons in the Illinois Basin. Thus, it follows that the release of organic acids and the production of CO_2 during the early stages of hydrocarbon generation might have been involved in the dissolution of carbonate cement and framework grains. Studies by Carothers and Kharaka (1978) have shown that organic acids are present in formation waters throughout the 80°–200°C temperature range and dominate the fluid alkalinity at temperatures of ~80°–120°C. Typically, production of organic acids, which reaches a maximum in the 80°–100°C temperature interval, gradually declines as a result of decarboxylation reactions (Surdam and others, 1989). From 80°–100°C, organic acids buffer the alkalinity at relatively low P_{CO_2}, which increases carbonate solubility, but, at temperatures of about 100°C, carboxylic acids dominate the fluid alkalinity at a high P_{CO_2}, which are conditions that promote dolomite or ferroan carbonate stability (Surdam and Crossey, 1987; Crossey and others, 1986). The organic-inorganic model for clastic diagenesis proposed by Surdam and others (1989) predicts that porosity-producing reactions occur throughout the same temperature range in which organic acids are present in formation waters (~80°–120°C), suggesting that early-formed carbonate cements and framework grains in the Aux Vases Sandstone interval were subject to dissolution. At temperatures approaching 100°C, iron and aluminum commonly are mobile due to complexing with organic acids, which results in an environment that is generally reducing. Such conditions favor the formation of iron-bearing mineral phases such as ferroan carbonate and chlorite. Some chlorite that formed at temperatures of 100°C may have nucleated on early chlorite that developed from clay/iron-oxide rims. In summary, the organic-inorganic model of sandstone diagenesis predicts that dissolution of calcite cement and feldspar followed by the formation of chlorite and dolospar cement took place when the sediments experienced temperatures of ~80°–120°C. Petrographic and stable-isotope data are consistent with this interpretation.

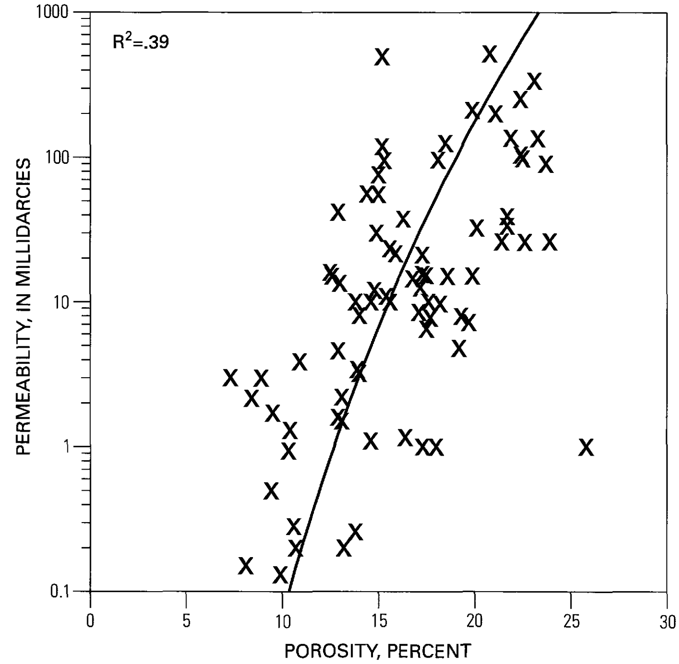


Figure 11. Relationship between percent core porosity and log permeability. R^2 is the variance of the power curve fit to the data.

Hydrocarbon Generation and Migration

The entrapment of petroleum generated from source rocks in the Upper Devonian–Lower Mississippian New Albany Shale was the last major diagenetic event that affected reservoir sandstones in the Aux Vases interval (see fig. 9). Petrographic observations suggest that the influx of hydrocarbons into reservoir sandstones inhibited mineral diagenesis in oil zones. In central and southern Illinois, the migration of oil into Aux Vases reservoirs began in the Middle to Late Pennsylvanian and reached its peak when the sedimentary section was close to its maximum burial in the Early Permian. The majority of oil in the Aux Vases Sandstone resides in combination (structural and stratigraphic) traps that overlie (by about 600 m) the generative portion of the New Albany Shale (M.D. Lewan, 1997, unpub. data), and the largest fields (i.e., Salem, Clay City, Dale Consolidated) are predominantly associated with faulted anticlines and related structural features that formed or were reactivated during the late Paleozoic (Howard, 1991). The spatial relationship between major oil accumulations in the Aux Vases and mature New Albany source rock suggests that the bulk of the oil moved vertically, by buoyancy, along faults and fractures into lenticular sandstone units and then migrated laterally updip until it reached a sealing unit.

Reservoir Quality

The Aux Vases Sandstone in the Illinois Basin has whole-core porosities as high as 24 percent, but most samples vary from 4–20 percent (fig. 11). Generally, measured core porosity increases with the log of permeability (fig. 11) but shows no systematic trend with present burial depth (fig. 12), as do other Chesterian sandstone units in the basin (Pitman and others, 1998). A combination of depositional and diagenetic factors (i.e., grain-size differences, postdepositional alterations) therefore must have influenced porosity preservation in reservoir sandstones.

Whole-core porosities (4–24 percent, median 15 percent) fall within the range of porosities determined in thin section (1–27 percent, mean 10 percent) but thin-section porosities generally are lower because microporosity (associated with authigenic and detrital clay) is difficult to quantify. Visible porosity in thin section usually classifies as macroporosity; thus, the amount of microporosity in a sandstone sample can be considered to be the difference between core porosity and thin-section porosity. The Aux Vases Sandstone average core porosity differs from thin-section porosity by ~5 percent, hence microporosity in these rocks may be quantitatively significant.

Intergranular volume (IGV) is a means of evaluating the importance of compaction versus cementation in initial porosity loss in sandstones (Houseknecht, 1987). The IGV in moderately to well-sorted sandstones in the Aux Vases averages 25 percent (fig. 13) and falls within the range of values (24–26 percent) that represents the configuration of grains at closest packing. Several studies have shown that the initial porosities of well-sorted sandstones approximate 40 percent (Beard and Weyl, 1973; Atkins and McBride, 1992; Ehrenberg, 1995). Assuming that depositional porosity in the Aux Vases was on the order of 40 percent, approximately 38 percent of the original porosity was destroyed by mechanical compaction and an additional 36 percent was lost due to mineral cementation (fig. 13). Mechanical compaction and mineral cementation thus were of nearly equal importance in reducing the reservoir quality of sandstones during burial. A comparison of IGV versus thin-section porosity (fig. 14) confirms the interpretation that low-porosity, well-cemented sandstones are no more or less compacted than are the high-porosity, noncemented sandstones. Figure 14 also shows that high-porosity sandstones contain less cement, whereas low-porosity sandstones contain more cement.

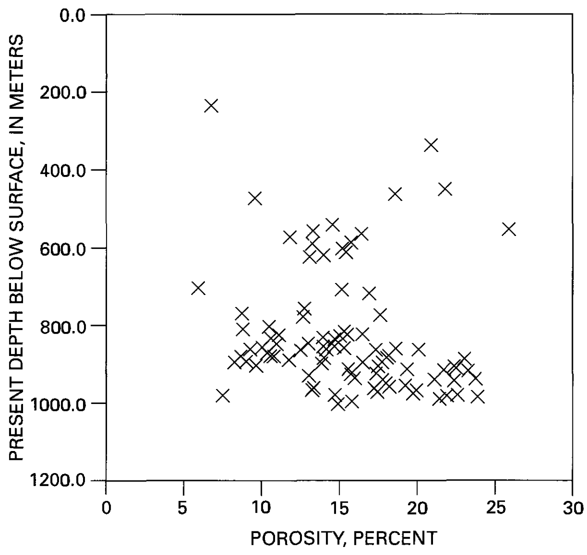


Figure 12. Plot of core porosity versus present depth for sandstones. Note absence of porosity-depth trend.

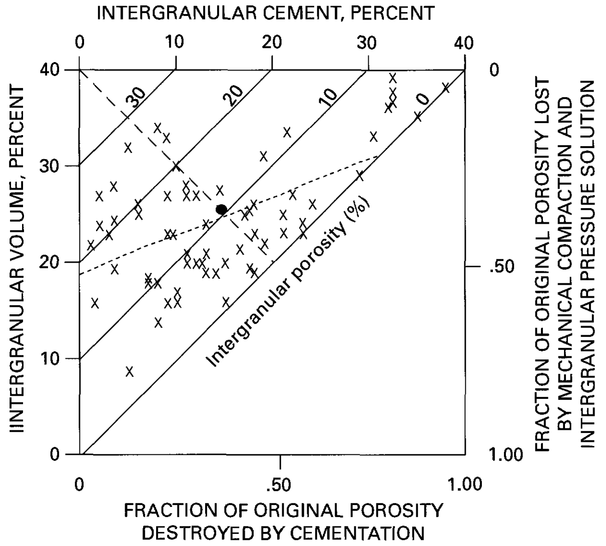


Figure 13. Relationship between compactional and cementational porosity loss in sandstones (after Houseknecht, 1987). Solid circle is the mean intergranular volume (IGV) value. Short-dashed line represents linear fit to the data.

Core permeability in the Aux Vases Sandstone ranges from 0.1 to about 250 mD and varies markedly at any given depth (fig. 15). Variations in permeability likely reflect differences in grain size, total cement volume, and amount of primary versus secondary porosity. As would be expected, the coarser grained sandstones initially had higher permeability than the finer grained sandstones (Beard and Weyl, 1973). According to petrographic observations, some of the original permeability variations due to grain size differences are preserved despite varying degrees of diagenesis subsequent to deposition.

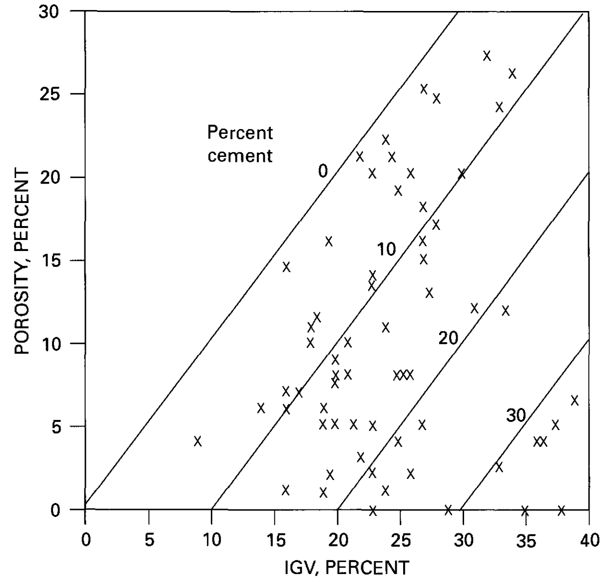


Figure 14. Plot showing percent IGV (intergranular volume) versus percent thin-section porosity in sandstones.

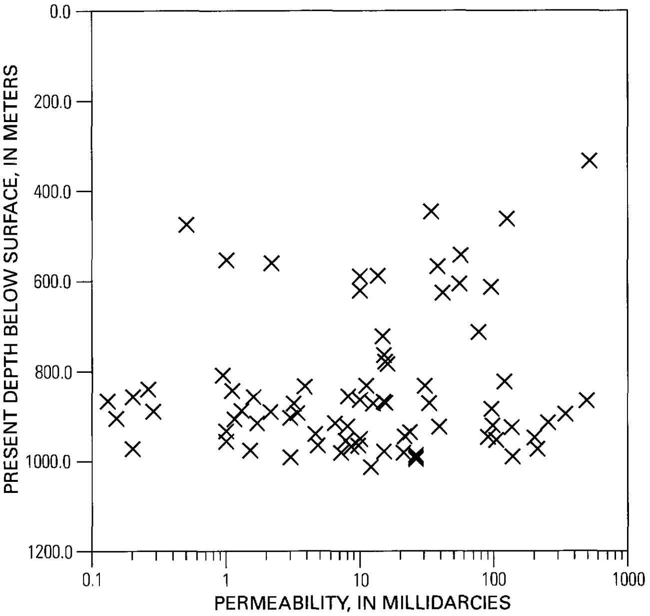


Figure 15. Plot of core permeability versus present burial depth for sandstones.

In well-cemented sandstones, authigenic cements and clays decrease permeability by occluding porosity in intergranular pores. On the basis of textural relations, total cement volume played a greater role in decreasing permeability than did one or more mineral phases alone. For example, sandstones with large amounts of carbonate cement typically have low permeability, but sandstones with little or no carbonate cement also can have low permeability because they have large amounts of secondary quartz. The extent to which clay content affected sandstone permeability is less clear because most samples that have permeability values were not analyzed for their clay content. We speculate that reservoir sandstones with a significant component of detrital and authigenic clay overall have low permeability.

In moderately to highly porous sandstones, higher porosity and permeability correspond to increasing secondary porosity, but primary and secondary porosity are difficult to distinguish; thus, some porosity preserved locally may be of primary origin. In most sandstones, primary pores have better connectivity than secondary pores and should provide a greater contribution to permeability, if present.

Regional variations in porosity and permeability in the Aux Vases Sandstone interval (fig. 16) are generally comparable to the reservoir-quality trends that have been reported for younger Mississippian sandstones in the basin (Pitman and others, 1998). Porosity and permeability increase in western Illinois, reaching a high of 20 percent and 200 mD, and high porosity and permeability occur locally in southwestern Indiana (fig. 16). Reservoir quality in the Aux Vases declines downdip to the south to ~4 percent porosity and 50 mD in southern Illinois near the Cottage Grove fault system (fig. 16). On the basis of petrographic observations, sandstone porosity near faults decreases in response to extensive mechanical compaction and diagenetic cementation, whereas, away from faults, porosity significantly increases due to the development of secondary porosity.

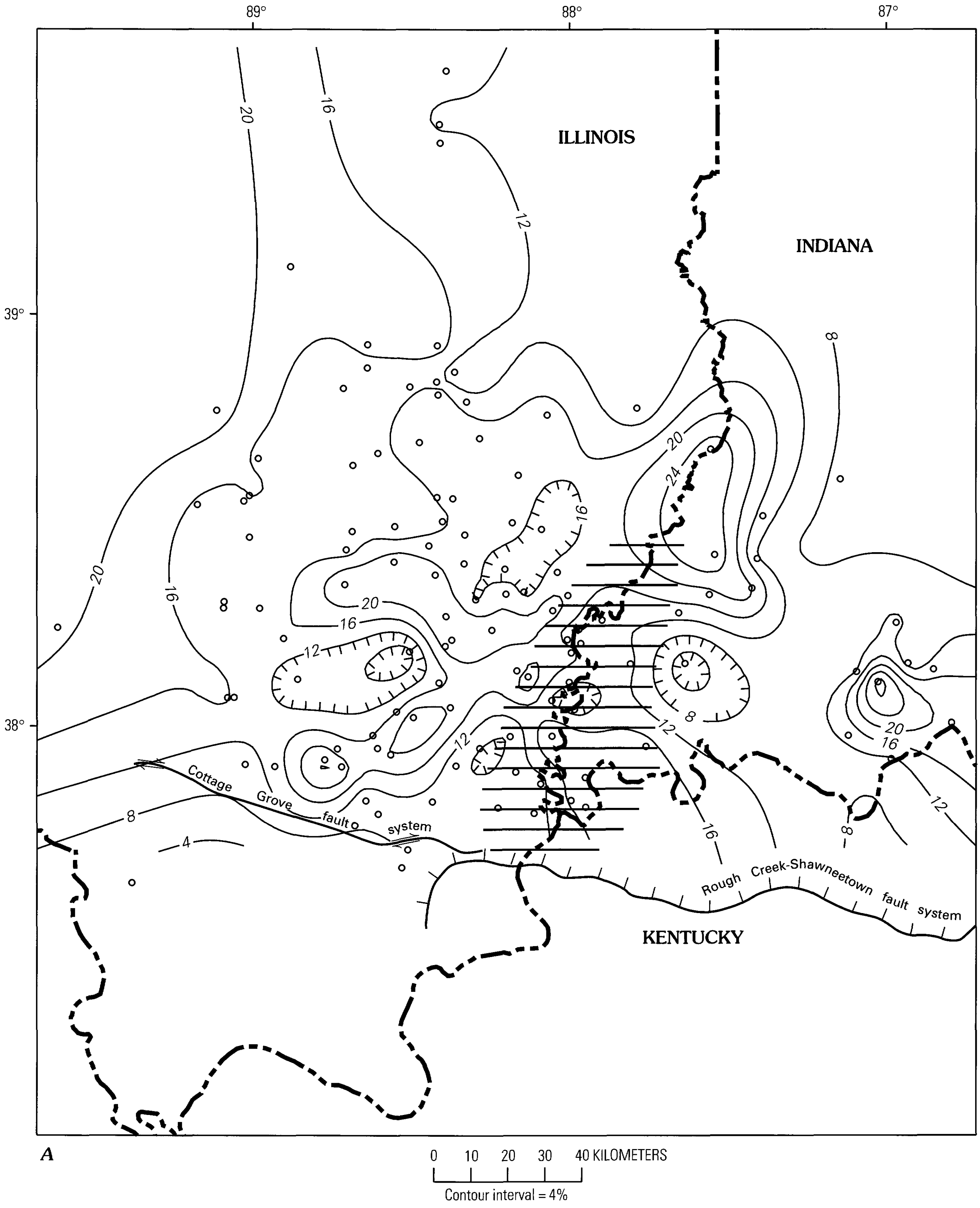
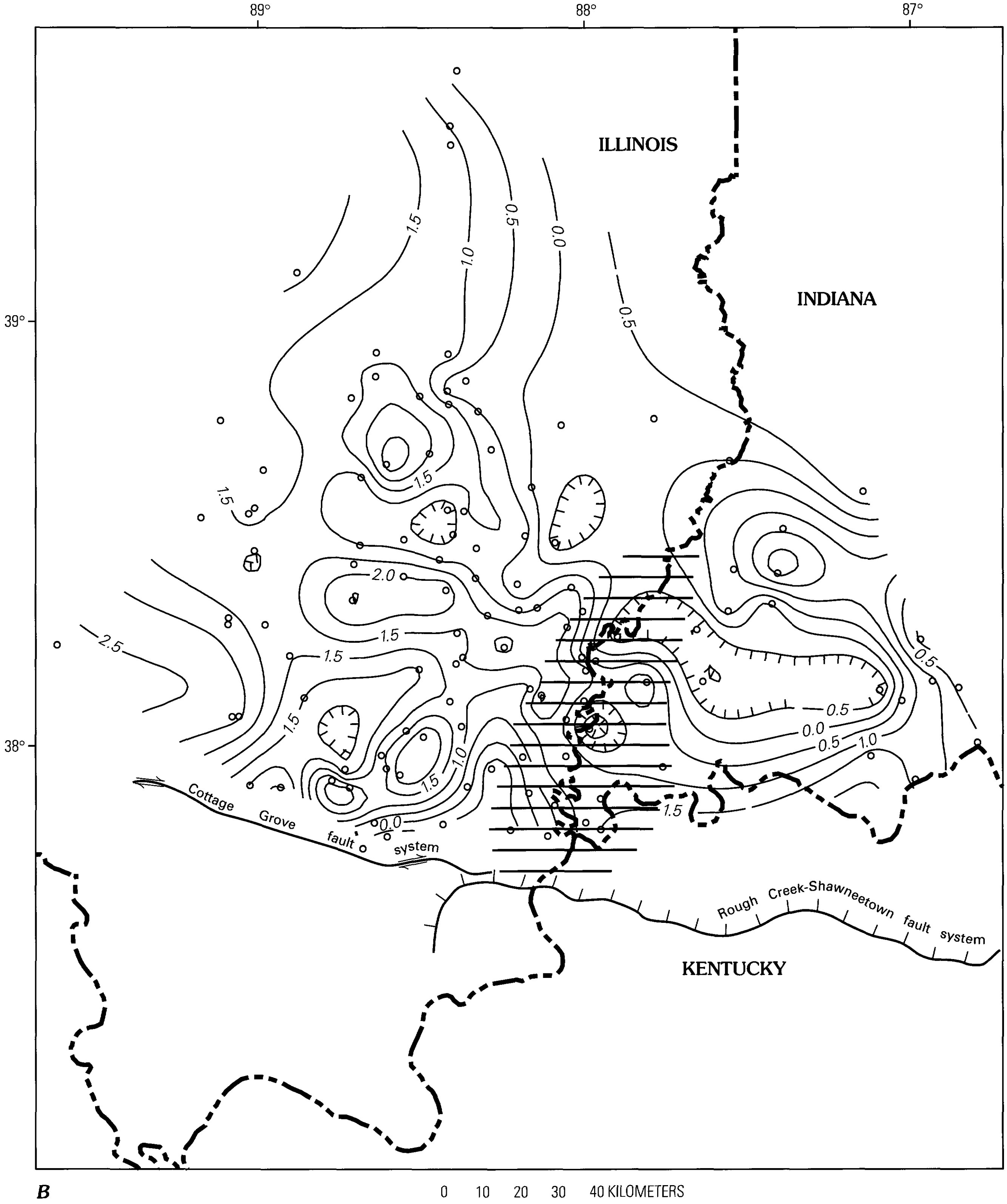


Figure 16 (above and facing page). Isocontour maps depicting regional variations in reservoir quality of sandstones in the Aux Vases interval. Horizontal lines indicate area of Wabash Valley fault system. *A*, percent porosity; *B*, log permeability.



Contour interval = 0.5 log mD unit

Conclusions

Diagenetic alteration in the Aux Vases Sandstone began soon after burial in the Late Mississippian and continued until oil entered the sandstones in the Late Pennsylvanian and Early Permian when the rocks were near maximum burial. Major diagenetic events observed in sandstones in the Aux Vases include (1) precipitation of precompactional illite and grain-rimming chlorite, (2) quartz overgrowth, syntaxial calcite, and dolomicrospar cementation, (3) carbonate cement and framework-grain dissolution, (4) illite and chlorite authigenesis, (5) ankerite precipitation, and (6) hydrocarbon emplacement. On the basis of petrographic and stable-isotope analysis, early diagenetic quartz, syntaxial calcite, and dolomicrospar formed at relatively low temperatures (~20°–90°C) in a dominantly freshwater environment, whereas late-diagenetic ankerite precipitated at elevated temperatures (~120°C) in a diagenetic system dominated by basin brines.

The reservoir quality of the Aux Vases Sandstone varies spatially, ranging from 4 to 24 percent, porosity and 0.1 to 250 mD permeability. Porosity reduction in sandstones is due to the effects of mechanical compaction and quartz and carbonate cementation, whereas porosity enhancement reflects dissolution of framework grains and carbonate cements. Initially, secondary-porosity development was caused by acidic meteoric waters, but, later, organic acids and CO_2 produced during the early stages of hydrocarbon generation promoted more extensive dissolution. The burial-thermal model presented in this study demonstrates that heat associated with igneous activity and heat transported by hydrothermal fluids elevated the basin's heat regime above the level based on normal basement heat flow alone. This added source of heat significantly increased the thermal maturity of organic-matter-rich source rocks, which subsequently resulted in greater rates of hydrocarbon expulsion and oil accumulation in the basin.

The presence of freshwater carbonate and silica cements provides an alternative method of delineating sequence boundaries in marine cratonic basins. Frequently, good evidence for subaerial exposure such as paleosols and root traces are eroded after formation and are not present in core. Results of this study suggest that diagenetic alterations may, at times, be the only evidence of sequence boundaries in the local rock record.

Acknowledgments

This study was supported by the U.S. Geological Survey's Energy Resources Program in cooperation with the State Geological Surveys of Illinois, Indiana, and Kentucky. The authors are indebted to Marty Goldhaber for generating burial-thermal curves using Basin2. We also are grateful to Joe Hatch and Jim Schmoker for reviewing the manuscript and providing many helpful suggestions.

References Cited

Atkins, J.E., and McBride, E.F., 1992, Porosity and packing of Holocene river, dune, and beach sands: American Association of Petroleum Geologists Bulletin, v. 76, p. 339–355.

Beard, D.C., and Weyl, P.K., 1973, Influence of texture on porosity and permeability of unconsolidated sand: American Association of Petroleum Geologists Bulletin, v. 57, p. 349–369.

Bethke, C.M., Lee, M-K., Quinodoz, H.A.M., and Kreiling, W.N., 1993, Basin modeling with Basin2, the Hydrogeology Program: Urbana-Champaign, University of Illinois, 225 p.

Carothers, W.W., and Kharaka, Y.K., 1978, Aliphatic acid anions in oil-field waters—Implications for the origin of natural gas: American Association of Petroleum Geologists Bulletin, v. 62, p. 2441–2453.

Cluff, R.M., and Byrnes, A.P., 1991, 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. 425–454.

Crossey, L.J., Surdam, R.C., and Lahmann, R., 1986, Application of organic/inorganic diagenesis to porosity prediction, *in* Gautier, D.L., ed., Roles of Organic Matter in Sediment Diagenesis: Society of Exploration Paleontologists and Mineralogists Special Publication 38, p. 147–156.

Ehrenberg, S.N., 1995, Measuring sandstone compaction from modal analyses of thin sections: How to do it and what the results mean: Journal of Sedimentary Research, v. A64, p. 369–379.

Folk, R.L., 1974, Petrology of Sedimentary Rocks: Austin, Texas, Hemphill, 182 p.

Friedman, I., and O'Neil, J.R., 1977, Compilation of stable isotope fractionation factors of geochemical interest, *in* Fleischer, M., ed., Data of Geochemistry, (6th ed.): U.S. Geological Survey Professional Paper 440-KK, 12 p.

Fritz, P., and Smith, D.C.W., 1970, The isotopic composition of secondary dolomite: Geochimica et Cosmochimica Acta, v. 34, p. 1161–1173.

Heald, M.T., 1955, Stylolites in sandstones: Journal of Geology, v. 63, p. 101–114.

Houseknecht, D.W., 1987, Assessing the relative importance of compactional processes and cementation to the reduction of porosity in sandstones: American Association of Petroleum Geologists Bulletin, v. 71, p. 633–642.

Howard, R.H., 1991, Hydrocarbon reservoir distribution 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. 299–329.

Leetaru, H.E., 1991, Reservoir heterogeneity and improved oil recovery of the Aux Vases (Mississippian) Formation at King field, Jefferson County, Illinois: Illinois Petroleum, v. 135, 49 p.

Leetaru, H.E., 1993, Reservoir heterogeneity and improved oil recovery of the Aux Vases (Mississippian) Formation at Boyd field, Jefferson County, Illinois: Illinois Petroleum, v. 142, 30 p.

Leetaru, H.E., 1997, Sequence stratigraphy and resource assessment of Aux Vases Sandstone in Illinois: Champaign, University of Illinois, Ph.D. dissertation, 161 p.

Leetaru, H.E., 1998, Sequence stratigraphy and regional geology of the Aux Vases Sandstone, chap. C *of* Leetaru, H.E., Seyler, B. and Morse, D.G., organizers, Focused Technology Workshop: Petroleum Resources of the Aux Vases Sandstone, Marion, Illinois: Champaign, Illinois, Illinois State Geological Survey and Midwest Office of the Petroleum Technology Transfer Council, p. C1–C20.

Meyers, W.J., and Lohmann, K.C., 1985, Isotope geochemistry of regionally extensive calcite cement zones and marine components in Mississippian limestones, New Mexico, *in* Schneidermann, N., and Harris, P.M., eds., Carbonate Cements: Society of Economic Paleontologists and Mineralogists Special Publication 36, p. 223–239.

Oltz, D.F., 1994, Improved and enhanced oil recovery in Illinois through reservoir characterization: U.S Department of Energy Final Report, DE-FG22-89BC14250.

Pitman, J.K., Henry, M., and Seyler, B., 1998, Reservoir quality and diagenetic evolution of Upper Mississippian rocks in the Illinois Basin: Influence of a regional hydrothermal fluid-flow event during late diagenesis: U.S Geological Survey Professional Paper 1597, 24 p.

Pryor, W.A., Lambourg, A.D., Roberts, M.J., Tharp, T.C., and Wilsey, W.L.M., 1991, Geologic controls on porosity in Mississippian limestone and sandstone reservoirs 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. 329–359.

Rowan, E.L., Goldhaber, M.B., and Hatch, J.R., in press, The role of regional fluid flow in the Illinois Basin's thermal history: Constraints from fluid inclusions and the maturity of Pennsylvanian coals: American Association of Petroleum Geologists Bulletin.

Seyler, B.J., 1984, Role of diagenesis in formation of stratigraphic traps in Aux Vases of Illinois Basin [abs.]: American Association of Petroleum Geologists Bulletin, v. 68, p. 526–527.

Seyler, B., 1998, Geologic and engineering controls on Aux Vases Sandstone reservoirs in Zeigler field, Illinois: Illinois Petroleum, v. 153, 79 p.

Surdam, R.C., and Crossey, L.J., 1987, Integrated diagenetic modeling: A process-oriented approach for clastic systems: Annual Reviews, Earth and Planetary Sciences, v. 15, p. 141–170.

Surdam, R.C., Crossey, L.J., Hagen, E.S., and Heasler, H.P., 1989, Organic-inorganic interactions and sandstone diagenesis: American Association of Petroleum Geologists Bulletin, v. 73, p. 1–23.

Swann, D.H., 1963, Classification of Genevievian and Chesterian (Late Mississippian) rocks of Illinois: Illinois State Geological Survey Report of Investigation 216, 91 p.

Swann, D.H., 1967, A summary geological history of the Illinois Basin, *in* Geology and Petroleum Production of the Illinois Basin: Illinois Geological Society, p. 3–21.

Walters, L.J., Claypool, G.E., and Choquette, P.W., 1972, Reaction rates and $\delta^{18}O$ variation for the carbonate-phosphoric acid preparation method: Geochimica et Cosmochimica Acta, v. 36, p. 129–140.

Weyl, P.K., 1959, Pressure solution and the force of crystallization: A phenomenological theory: Journal of Geophysical Research, v. 64, p. 2001–2025.

Published in the Central Region, Denver, Colorado
Manuscript approved for publication January 14, 1999
Edited by Richard W. Scott, Jr.
Graphics prepared by Norma J. Maes, David G. Walters, and
Carol A. Quesenberry. Use made of author-drafted material
Photocomposition by Carol A. Quesenberry

☆ U.S. GOVERNMENT PRINTING OFFICE: 1999 — 773-051 / 20161 Region No. 8

Selected Series of U.S. Geological Survey Publications

Books and Other Publications

Professional Papers report scientific data and interpretations of lasting scientific interest that cover all facets of USGS investigations and research.

Bulletins contain significant data and interpretations that are of lasting scientific interest but are generally more limited in scope or geographic coverage than Professional Papers.

Water-Supply Papers are comprehensive reports that present significant interpretative results of hydrologic investigations of wide interest to professional geologists, hydrologists, and engineers. The series covers investigations in all phases of hydrology, including hydrogeology, availability of water, quality of water, and use of water.

Circulars are reports of programmatic or scientific information of an ephemeral nature; many present important scientific information of wide popular interest. Circulars are distributed at no cost to the public.

Fact Sheets communicate a wide variety of timely information on USGS programs, projects, and research. They commonly address issues of public interest. Fact Sheets are generally two or four pages long and are distributed at no cost to the public.

Reports in the **Digital Data Series (DDS)** distribute large amounts of data through digital media, including compact disc read-only memory (CD-ROM). They are high-quality, interpretative publications designed as self-contained packages for viewing and interpreting data and typically contain data sets, software to view the data, and explanatory text.

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

Open-File Reports can consist of basic data, preliminary reports, and a wide range of scientific documents on USGS investigations. Open-File Reports are designed for fast release and are available for public consultation at depositories.

Maps

Geologic Quadrangle Maps (GQ's) are multicolor geologic maps on topographic bases in 7.5- or 15-minute quadrangle formats (scales mainly 1:24,000 or 1:62,500) showing bedrock, surficial, or engineering geology. Maps generally include brief texts; some maps include structure and columnar sections only.

Geophysical Investigations Maps (GP's) are on topographic or planimetric bases at various scales. They show results of geophysical investigations using gravity, magnetic, seismic, or radioactivity surveys, which provide data on subsurface structures that are of economic or geologic significance.

Miscellaneous Investigations Series Maps or Geologic Investigations Series (I's) are on planimetric or topographic bases at various scales; they present a wide variety of format and subject matter. The series also includes 7.5-minute quadrangle photogeologic maps on planimetric bases and planetary maps.

Information Periodicals

Metal Industry Indicators (MII's) is a free monthly newsletter that analyzes and forecasts the economic health of five metal industries with composite leading and coincident indexes: primary metals, steel, copper, primary and secondary aluminum, and aluminum mill products.

Mineral Industry Surveys (MIS's) are free periodic statistical and economic reports designed to provide timely statistical data on production, distribution, stocks, and consumption of significant mineral commodities. The surveys are issued monthly, quarterly, annually, or at other regular intervals, depending on the need for current data. The MIS's are published by commodity as well as by State. A series of international MIS's is also available.

Published on an annual basis, **Mineral Commodity Summaries** is the earliest Government publication to furnish estimates covering nonfuel mineral industry data. Data sheets contain information on the domestic industry structure, Government programs, tariffs, and 5-year salient statistics for more than 90 individual minerals and materials.

The Minerals Yearbook discusses the performance of the worldwide minerals and materials industry during a calendar year, and it provides background information to assist in interpreting that performance. The Minerals Yearbook consists of three volumes. Volume I, Metals and Minerals, contains chapters about virtually all metallic and industrial mineral commodities important to the U.S. economy. Volume II, Area Reports: Domestic, contains a chapter on the minerals industry of each of the 50 States and Puerto Rico and the Administered Islands. Volume III, Area Reports: International, is published as four separate reports. These reports collectively contain the latest available mineral data on more than 190 foreign countries and discuss the importance of minerals to the economies of these nations and the United States.

Permanent Catalogs

"Publications of the U.S. Geological Survey, 1879–1961" and "Publications of the U.S. Geological Survey, 1962–1970" are available in paperback book form and as a set of microfiche.

"Publications of the U.S. Geological Survey, 1971–1981" is available in paperback book form (two volumes, publications listing and index) and as a set of microfiche.

Annual supplements for 1982, 1983, 1984, 1985, 1986, and subsequent years are available in paperback book form.