Regional Diagenetic Patterns in the St. Peter Sandstone: Implications for Brine Migration in the Illinois Basin

By Janet K. Pitman, Martin B. Goldhaber, and Christoph Spöetl

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CONTENTS

FIGURES

Regional Diagenetic Patterns in the St. Peter Sandstone: Implications for Brine Migration in the Illinois Basin

By Janet K. Pitman,[1] Martin B. Goldhaber ,[2] and Christoph Spöetl[3]

ABSTRACT

Diagenetic minerals and alteration patterns in the Ordovician St. Peter Sandstone, Illinois Basin, record varied hydrologic and chemical conditions during the basin's long and complex geologic history. Major diagenetic events modifying the St. Peter Sandstone include (1) mechanical compaction, (2) early K-feldspar overgrowth and dolospar precipitation, (3) burial quartz, dolospar, anhydrite, and calcite cementation, and (4) carbonate-cement and K-feldspar grain dissolution. Radiometric age dates of authigenic K-feldspar and illite in combination with the reconstructed burial history of the St. Peter reveal that early-diagenetic K-feldspar and dolospar precipitated at shallow to moderate depths in the Devonian, whereas late-diagenetic quartz, dolospar, anhydrite, and calcite formed during deep burial in the Late Pennsylvanian to Early Permian. Stable-isotope geochemistry and fluid-inclusion paleothermometry suggest that burial cements precipitated from saline fluids over a wide temperature range. In the southern part of the basin, burial cements preserve a record of diagenetic effects that were in part controlled by fractures and hydrothermal-fluid circulation. Baroque dolospar cementation is the most significant of these effects.

INTRODUCTION

The Middle Ordovician St. Peter Sandstone in the Illinois Basin (fig. 1) was examined to establish regional diagenetic patterns and to evaluate the possibility that the unit acted as an aquifer for fluids that produced the zinc-lead-fluorine mineral deposits of the Mississippi Valley type (MVT) adjacent to the basin. An important aspect of the study involved deciphering the nature and timing of dolomitization in relation to major hydrothermal brine migration and associated ore-forming events. The St. Peter Sandstone in the Illinois Basin area previously has been studied regionally, including evaluation of the detrital mineralogy and reservoir quality (Odom and others, 1979; Hoholick and others, 1984); however, potential mechanisms of diagenesis and the timing of diagenesis have received little attention until recently (Pitman and Spöetl, 1996). The diagenetic minerals preserved in Ordovician sandstones are indicators of the types of fluids that migrated through the basin. Therefore, knowledge of the age and origin of the authigenic assemblage and its regional distribution pattern places constraints on the nature and timing of diagenetic fluids and the extent of fluid migration in the basin. The origin and timing of mineral alterations also provide insight into the role of hydrothermal ore-forming fluids in porosity reduction and enhancement and the timing of petroleum migration and entrapment.

GEOLOGIC AND TECTONIC HISTORY

The Illinois Basin is an elongate structure whose north-south-trending axis lies immediately west of the LaSalle anticline in Illinois (fig. 1). The basin is bounded on the northwest by the Mississippi River arch, on the northeast by the Kankakee arch, and on the south by the Cincinnati arch, the Pascola arch, and the Ozark uplift. Basin strata extend across Illinois into western Indiana and western Kentucky. The deepest part of the basin is situated near the Rough Creek graben in western Kentucky where more than 7,000 m of sediment are preserved. Overall, the stratigraphy, structure, and tectonic history of the basin are well known because the basin has been extensively explored for hydrocarbon resources and is adjacent to MVT deposits.

The Illinois Basin initially was a broad intracratonic embayment that formed as a result of rifting in the early Paleozoic (Burke and Dewey, 1973; Ervin and McGinnis, 1975). From Late Cambrian through the Middle Ordovician, sediment accumulated in the depocenter of the basin overlying the rift complex, which encompassed the intersection of the Reelfoot rift and the Rough Creek graben (fig. 1). During the remainder of the Paleozoic, the basin experienced multiple

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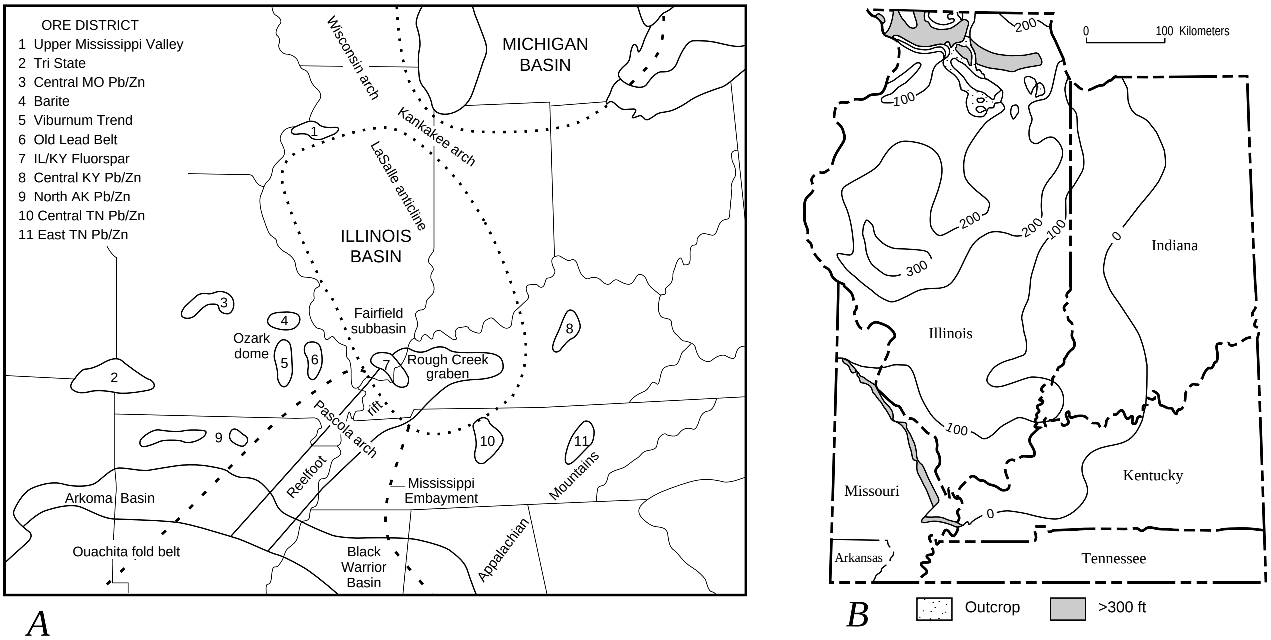


Figure 1. *A*, Location of the Illinois and Michigan Basins, major structural features, and principal ore-forming districts in the Midcontinent region. *B*, Isopach map (modified from Kolata, 1991) showing regional thickness variations in the St. Peter Sandstone in the Illinois Basin (contour interval in feet).

periods of tectonic deformation in response to the Taconic, Acadian, and Ouachita orogenies. In the Mississippian and Pennsylvanian, uplift of the LaSalle anticline occurred across east-central Illinois causing the St. Peter Sandstone in that area to be exposed and folded (Kolata and Nelson, 1991). Later, in Pennsylvanian and Permian time during the Ouachita orogeny, compressional stresses near the intersection of the Reelfoot rift and Rough Creek graben led to extensive folding, faulting, and igneous intrusion at the southern margin of the basin (Nelson, 1991). Major ore-forming events related to MVT mineralization (Plumlee and others, 1995) also occurred on the southern tectonic flank of the basin and were associated with Ouachita tectonism in the Permian (270 Ma; Pan and others, 1990; Snee and Hayes, 1992; Chesley and others, 1994). Isotopic dating indicates the MVT mineralization at the north end of the basin also occurred in the Permian (Brannon and others, 1993). The Illinois Basin attained its present structural configuration following the uplift of the Pascola arch in the late Paleozoic and early Mesozoic (Kolata and Nelson, 1991). The arch is now covered by Late Cretaceous and Early Tertiary siliciclastics of the Mississippi Embayment (Kolata and Nelson, 1991).

DEPOSITIONAL FRAMEWORK

The St. Peter Sandstone is a laterally continuous unit that extends across the entire Illinois Basin, reflecting the broad, relatively flat topography that existed during the Ordovician in the southern Midcontinent (fig. 2). The sequence thins southward, and varies from about 10 to 200 m thick, although typically it averages 30–60 m thick (Willman and others, 1975). Within the basin, Ordovician sandstones are buried at depths less than 1,000 m at the shallow northern margin in the vicinity of the Upper Mississippi Valley (UMV) ore district and more than 2.5 km in the Fairfield basin, a major subbasin in southern Illinois. In the Fairfield subbasin, the St. Peter Sandstone unconformably overlies the Everton Dolomite and underlies the Joachim Dolomite and Dutchtown Limestone; in northern Illinois, the St. Peter unconformably rests on the Prairie du Chien Group (Willman and others, 1975; see fig. 2). Within the Illinois Basin proper, the St. Peter comprises three members. The basal Kress Member locally contains chert conglomerate in a sandstone matrix. In some areas it consists of red and green shale and argillaceous sandstone (Buschbach, 1964). The middle Tonti Member generally forms the main body of the St. Peter and, except in western Illinois, is composed of fine-grained, well-sorted, porous and permeable sandstone (Templeton and Willman, 1963). The upper Starved Rock Member is mainly a well-sorted, medium-grained sandstone. This sandstone sequence, interpreted to be an offshore bar deposit (Willman and others, 1975), is confined to a belt trending northeast-southwest across the basin.

METHODS

Samples representative of the St. Peter Sandstone were collected from 113 wells throughout the Illinois Basin in

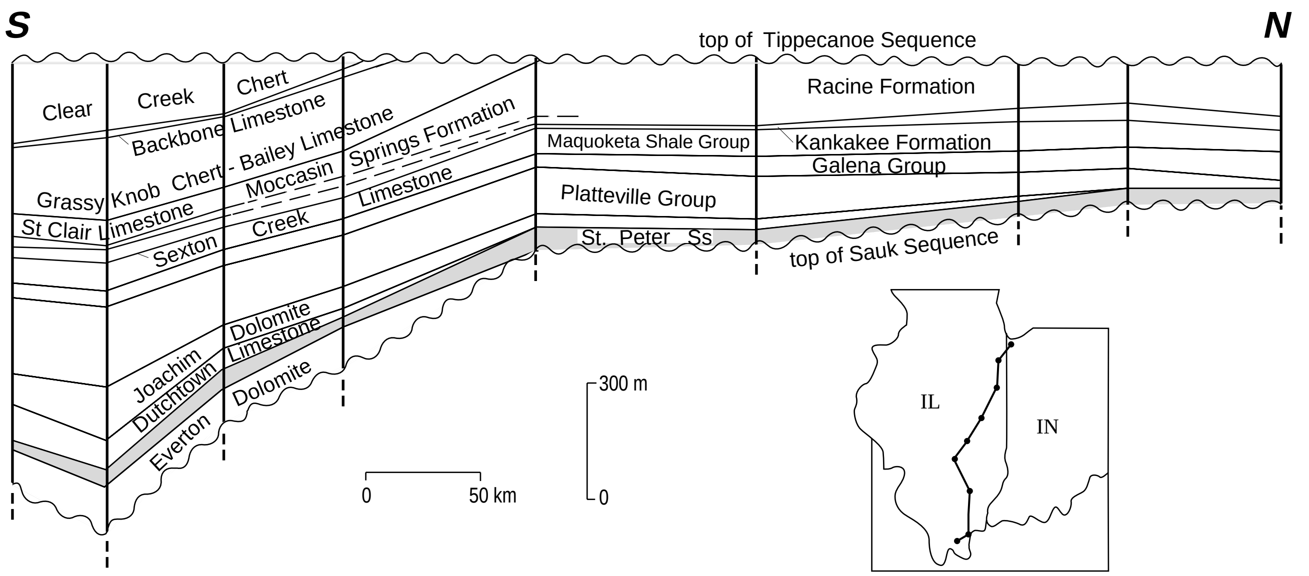


Figure 2. North-south cross section of lower Middle Ordovician (Whiterockian) through Lower Devonian (Ulsterian) rocks in Illinois (Tippecanoe sequence of Kolata, 1991).

Illinois and Indiana. The sample suite covers the range of present subsurface depths, ~50–3,300 m, and spans the thickness of the formation. The deepest samples (at ~ 3,300 m) are from the Fairfield subbasin. Individual sandstone samples were studied using a combination of techniques, including optical petrography, scanning electron microscopy (SEM), cathodoluminescence (CL) microscopy, electron microprobe analysis, fluid-inclusion microthermometry, and stable-isotope analysis.

Standard thin sections of sandstones were impregnated with blue-dye epoxy to identify porosity and stained to facilitate mineral identification. Staining with Alizarin red-S and potassium ferricyanide permitted Fe-free carbonate minerals to be distinguished optically from Fe-bearing carbonate minerals, and sodium cobaltinitrite stain aided in the identification of K-feldspar. Detailed point counts (300 counts per section) were performed on representative sandstones in each well to compare with previous studies; relative mineral abundances were determined visually in the remainder of the sandstones. CL microscopy was employed to qualitatively evaluate carbonate paragenesis in carbonate-bearing samples. A cold-cathode Technosyn 8200 Mk II model operating at ~20 kV, 500–600 mA and ~7 Pa pressure was used in the analysis. SEM was also routinely employed to identify mineral phases in back-scattered-electron mode and using an energy-dispersive X-ray analytical system. In addition, growth relationships of individual cements were studied on freshly broken sandstones in secondary-electron mode. Fluid-inclusion-microthermometric measurements were performed on doubly polished wafers of a few selected samples using a U.S. Geological Survey-type gas-flow-heating/freezing system calibrated against known melting point standards (analyst, T.J. Reynolds, Fluid Inc., Englewood, Colo.). Homogenization temperatures (T_h) were not pressure corrected. Representative samples of calcite and morphologically distinct dolomite (dolomicrospar, planar dolospar, baroque dolospar) were analyzed isotopically in the Branch of Petroleum Geology (analyst, Augusta Warden), U.S. Geological Survey, Denver, Colo.. Carbon and oxygen isotope ratios were obtained by a timed-dissolution procedure based on different reaction rates for chemically distinct carbonate phases (i.e., calcite vs. dolomite; Walters and others, 1972). To prevent contamination by CO_2 from organic matter during acid digestion, kerogen was isolated from the samples. Upon reaction with phosphoric acid, CO_2 gas evolved in the first hour was attributed to calcite and CO_2 gas evolved after several hours was assigned to dolomite. Isotope analyses on evaporite sulfur was carried out by Global Geochemistry Corp. using standard techniques. Sulfide was dissolved in acid, reprecipitated as $BaSO_4$ and combusted to produce SO_2 gas. All carbon and oxygen isotope results are reported as the per mill (‰) difference relative to the Peedee belemnite (PDB) standard using the delta (δ) notation. Sulfur isotope data are reported relative to the Canyon Diablo Troilite standard. Data reproducibility is precise to ± 0.2 ‰.

DETRITAL MINERALOGY

Detrital framework constituents in the St. Peter Sandstone consist of quartz and minor feldspar, lithic fragments, and matrix material (Dapples, 1955; Odom and others, 1979; Hoholick and others, 1984). Overall, the sandstones are texturally and compositionally mature, and moderately to well sorted. Based on the classification scheme of Folk (1974), the St. Peter Sandstone comprises predominantly quartzarenites and subarkoses.

Quartz constitutes the major proportion of the detrital fraction in the sandstones. Most grains are monocrystalline fragments that are subrounded to well rounded in shape and fine to medium grained in size. Grain contacts generally are concave to convex, although long and sutured contacts are common in some more deeply buried sandstones. Secondary overgrowths tend to be minor and are best developed in sandstones in the deep, southern part of the basin.

Detrital feldspar is a common constituent in shallow-buried sandstones in the northern part of the basin. On the basis of (bright yellow) staining by sodium cobaltinitrite, most feldspar is potassium rich, although rare sodic varieties are present locally. Potassium feldspar is distributed as twinned and untwinned fragments that vary in their morphology and degree of alteration. In the northern part of the basin, K-feldspar comprises subangular to subrounded, silt to very fine sand-size grains that commonly display optically continuous overgrowths. Along the LaSalle anticline, K-feldspar grains and grain overgrowths show the effects of dissolution. In more deeply buried sandstones to the south, detrital K-feldspar grains and authigenic overgrowths are rare except in dolomicrospar where tiny K-feldspar grains devoid of overgrowths are abundant.

Other constituents in the sandstones include illitic matrix and lithic grains, mainly finely crystalline chert, polycrystalline quartz, and granitic fragments. Matrix material, which is present in varying amounts, has been replaced by authigenic K-feldspar, clay minerals, and carbonate.

SEDIMENTARY DIAGENESIS

MINERAL AUTHIGENESIS

The St. Peter Sandstone displays a variety of diagenetic minerals, most notably multiple generations of carbonate cement, potassium feldspar and quartz overgrowths, anhydrite, and illite. The relative timing of these diagenetic events is depicted in figure 3. Other authigenic minerals in the sandstones include minor barite, hematite, illite, chlorite and kaolinite, and traces of sphalerite and fluorite. Mechanical compaction, chemical compaction (including styolitization and pressure solution), and dissolution textures are features common in some parts of the St. Peter. Spatial variations in authigenic mineral abundance and reservoir quality are shown in figure 4. It is noteworthy that mineral abundances vary on a basin-wide scale and that differences in mineral content can be found over short intervals within individual wells. Overall, the distribution of cements is similar to previously reported authigenic mineral patterns (Hoholick and others, 1984), although locally there are some differences in the occurrence of K-feldspar, quartz, and calcite compared to earlier work (see fig. 4). In the southern part of the basin, there is a broad geographic zonation of late-diagenetic quartz, dolomite, calcite, and anhydrite. Authigenic mineral development is more restricted in the shallow, northern part of the basin. Potassium feldspar and illite are geographically widespread, whereas dolomite tends to be localized. Primary and secondary porosity is well preserved in the northern portion of the basin but is not uniformly distributed.

The range in carbon and oxygen isotopic composition of individual carbonate phases in the St. Peter is illustrated in figure 5 and the basinal distribution pattern of oxygen-isotope ratios of dolomite cements is shown in figure 6. Figure 5 reveals that there is significant compositional overlap between various carbonate phases. In figure 6, regional variations in the $\delta^{18}O$ of dolomite, in part, correspond to major structural trends in the basin. The stable-isotope geochemistry of authigenic carbonate (i.e., dolomite) together with the carbonate-mineral paragenesis provide insight into the processes and possible fluid sources responsible for burial dolomitization. In the following sections, the petrographic characteristics, relative chronology, and geographic distribution of the main diagenetic constituents are discussed, and stable isotopic compositions together with limited microthermometric data are presented.

CARBONATE CEMENTS

On the basis of optical properties and crystal size, four major varieties of authigenic carbonate—dolomicrospar, planar dolospar, baroque dolospar, and poikilotopic calcite—have been identified in the St. Peter Sandstone. Variations in total dolospar abundance and calcite contents are shown in figure 4. Finely crystalline (4–25 μm) dolomicrospar is a locally abundant cement (2–10 percent, locally 20 percent by volume) in the northern and central portions of the basin. Minor dolomicrite (crystal size ≤ 4 μm) also was observed. Textural evidence indicates that dolomicrospar formed early, before most other mineral cements; however, dolomicrospar samples commonly exhibit clear-cut evidence of recrystallization, indicating that this early carbonate phase underwent diagenetic alteration. Dolomicrospar is composed of individual planar crystals and, less commonly, interlocking nonplanar crystals of nonferroan dolomite. Some dolomicrospar samples reveal distinct microfacies features, including dark, micritic, rounded components and patches, and peloidal and mottled textures. Other samples show rare elongate features that strongly resemble root casts known from calcretes and related carbonates (e.g., Esteban and Klappa, 1983; Wright, 1990). Silt-size, subrounded, detrital K-feldspar crystals devoid of authigenic overgrowths commonly are inclusions within dolomicrospar. Pyrite, distributed as individual cubes (5–30 μm), or as clusters of euhedral crystals, are associated with the mineral. Stable isotopic compositions of

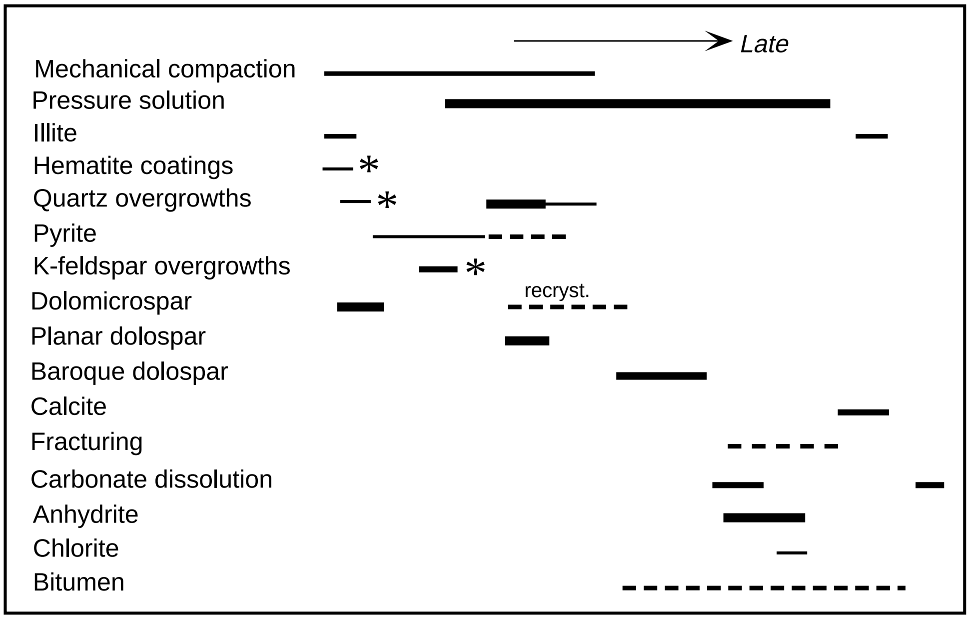


Figure 3. Mineral paragenesis in the St. Peter Sandstone. Diagenetic phases marked by an asterisk are largely confined to the northern part of the basin; relative thickness of bar reflects significance of diagenetic event. Recryst., recrystallized.

dolomicrospar (45 analyses) are depleted in $\delta^{13}C$ (–0.5 to –9.2 ‰ PDB) and $\delta^{18}O$ ratios (–1.4 to –6.8 ‰ PDB) (fig. 5). The lightest $\delta^{18}O$ ratios are in the southern part of the Michigan Basin and along the north-south-trending LaSalle anticline (see fig. 6).

A large fraction of dolomite (2–10 percent, locally 15–20 percent) in the central and southern parts of the Illinois Basin and a small component of dolomite in the northern portion of the Illinois Basin and southern part of the Michigan Basin is planar dolospar (referred to as "planar-e" by Sibley and Gregg, 1987). In well-cemented sandstones, planar dolospar postdates mechanical compaction and comprises equant crystals that form an interlocking mosaic with little or no intercrystalline porosity. Some planar dolospar locally contains abundant solid inclusions, giving rise to a cloudy appearance in transmitted light. Rare detrital K-feldspar grains and authigenic pyrite also may be included within planar dolospar. In many samples, there is evidence that a significant fraction of planar dolospar is a replacement of dolomicrospar. Coarse (20–300 µm) euhedral crystals of planar dolospar commonly float in a groundmass of dolomicrospar, which suggests that planar dolospar grew at the expense of dolomicrospar. Other samples display euhedral, inclusion-poor planar dolospar crystals protruding into open pores, which clearly indicate they are neoformed. In the southern part of the basin, planar dolospar coexists with authigenic quartz, calcite, and anhydrite and may be overgrown by a later generation of ferroan dolomite. Stable $\delta^{13}C$ and $\delta^{18}O$ isotope ratios of 24 samples of planar dolospar fall between –6.5 to –0.9 ‰ ($\delta^{13}C$) and –9.2 to –1.2 ‰ ($\delta^{18}O$) and are similar to the values that characterize dolomicrospar and baroque dolospar (fig. 5). This range in the data in part arises from mixing of end-member carbonate phases in varying proportions. Light $\delta^{18}O$ ratios of planar dolospar occur in the southern Michigan Basin, and $\delta^{18}O$-depleted mixtures of planar and baroque dolospar are found along the LaSalle anticline and in the Fairfield subbasin, close to Hicks dome and the Illinois-Kentucky Fluorspar district (fig. 6).

A small fraction of dolomite (< 5 percent) in sandstones predominantly from the southern portion of the Illinois Basin (Fairfield subbasin) has optical properties characteristic of baroque (or saddle) dolospar (equivalent to "nonplanar dolomite" of Sibley and Gregg, 1987). Crystals are coarsely crystalline, have slightly to moderately curved crystal faces, and display broad sweeping extinction. Locally, saddle dolomite forms ferroan overgrowths on planar dolospar crystals. The development of sweeping extinction seems to be unrelated to the formation of ferroan overgrowths because incipient sweeping extinction also occurs in some of the larger planar dolospar crystals. In addition, there is no correlation between the development of sweeping extinction and the stoichiometry of baroque dolospar. Petrographic observations show that baroque dolospar postdated quartz overgrowths and predated anhydrite, which indicates that it formed during deep-burial diagenesis. The isotope ratios of 7 baroque dolospar samples, –7.5 to –3.4 ‰ ($\delta^{13}C$) and 7.5 to –4.6 ‰ ($\delta^{18}O$), span the range of values for planar dolospar and represent mixtures of planar dolospar cores and ferroan baroque dolomite rims (fig. 5). A few samples of baroque dolospar from northern Illinois contain two-phase fluid inclusions. In one

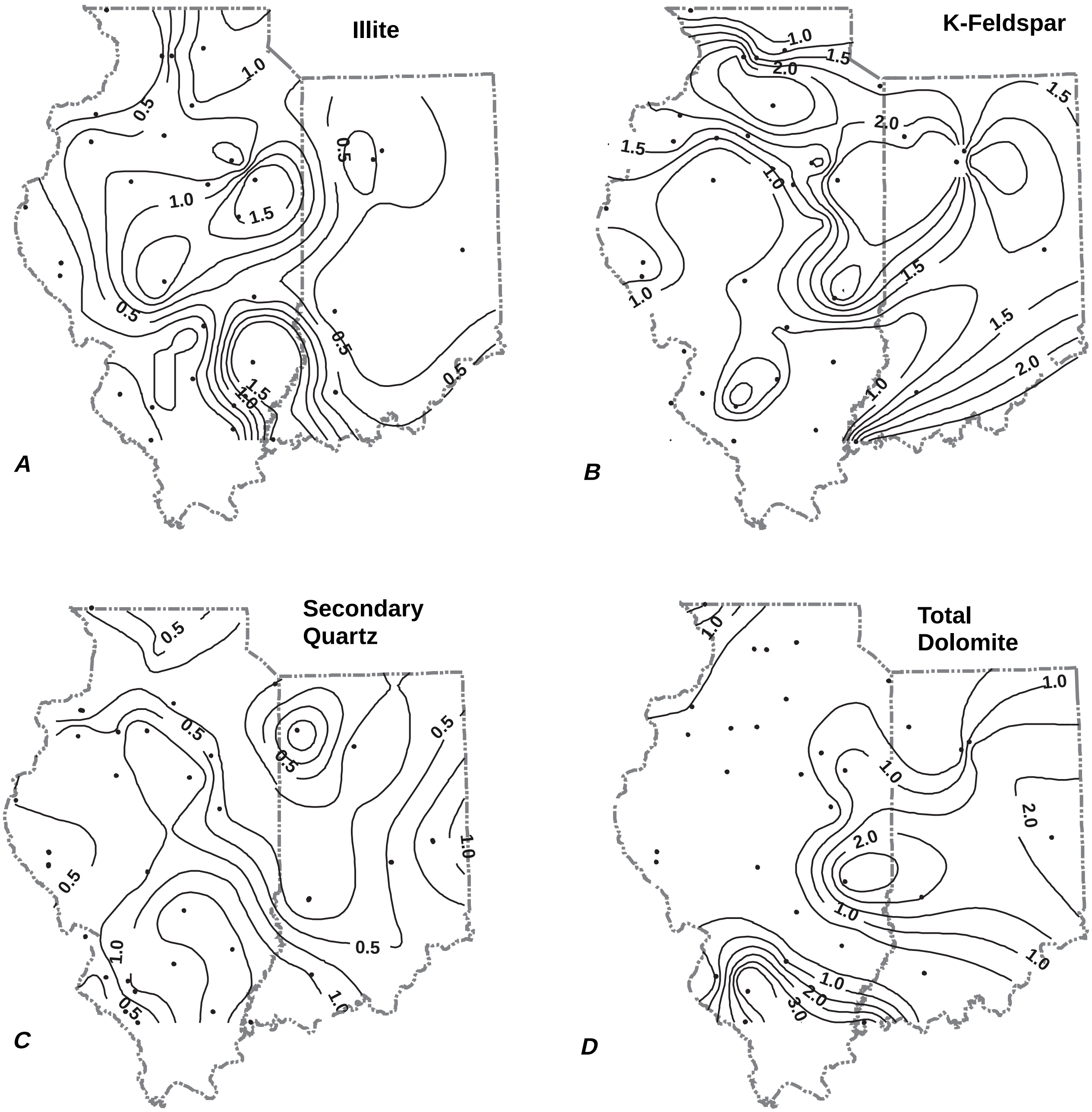
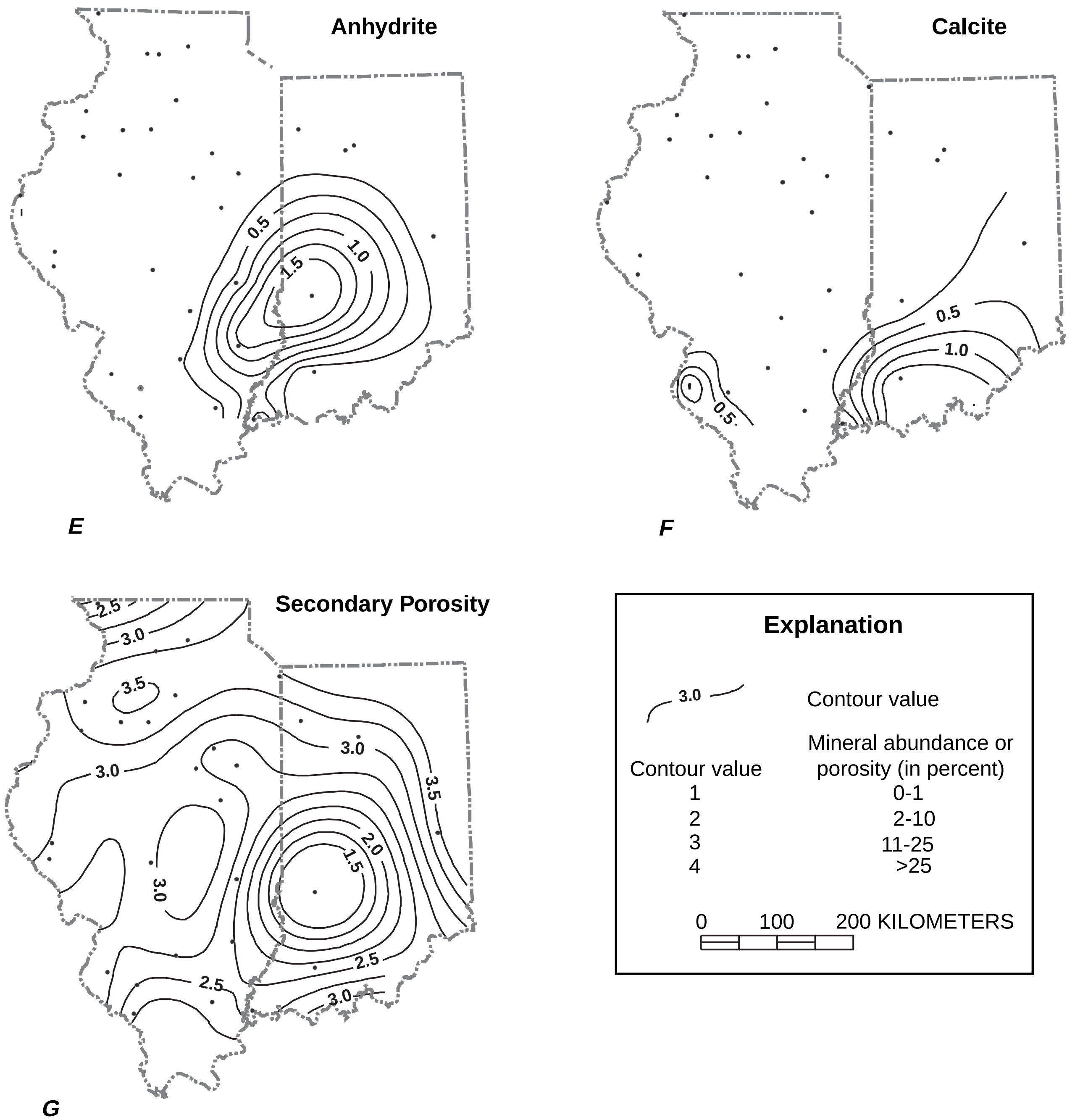


Figure 4 (above and facing page). Regional distribution of authigenic mineral cements and porosity in the St. Peter Sandstone. *A*, Illite; *B*, K-feldspar; *C*, Secondary quartz; *D*, Total dolomite; *E*, Anhydrite; *F*, Calcite; *G*, Secondary porosity. Mineral abundances reflect combined early- and late-diagenetic phases.

sample, very small (< 3 µm) primary fluid inclusions located at the boundary between planar dolospar and baroque dolospar overgrowths displayed consistent liquid-to-vapor ratios and yielded homogenization temperatures from 110°–115°C. However, most of the inclusions on growth features in planar and baroque dolospar had significantly lower temperatures, ~65°C. Final ice melting temperatures of all inclusions were consistently less than –20°C, which suggests formation from highly saline pore waters with compositions > 20 weight percent NaCl equivalent. Hydrocarbon-bearing fluid inclusions were not observed in the samples studied.

Calcite in the St. Peter Sandstone occurs in minor amounts (< 5 percent by volume average) in the southwest part of the basin (fig. 4). The mineral is distributed as a poikilotopic, nonferroan to slight ferroan, pore-filling cement; less commonly, it occurs as a framework grain replacement. Locally, calcite shows evidence of leaching.



In some sandstones, calcite contains trace amounts of micrometer-size fluorite and sphalerite. It is noteworthy that this fluorite- and sphalerite-bearing calcite occurs in areas where trace fluorine anomalies in carbonate rocks are highest (Rowan and Goldhaber, 1996). Calcite in sandstones postdates quartz cement as well as baroque dolospar and other authigenic mineral phases; thus, it appears to be one of the latest cements to have formed in the St. Peter. Carbon and oxygen isotopes of 19 calcite samples vary from –3.1 to –6.6 ‰ ($\delta^{13}C$) and –6.5 to –10.6 ‰ ($\delta^{18}O$), respectively. The $\delta^{18}O$ ratios of calcite tend to be lighter than the $\delta^{18}O$ ratios of burial dolospar cements, whereas the $\delta^{13}C$ ratios of calcite are within the range of dolomite cements (fig. 5).

SECONDARY QUARTZ

Authigenic quartz, formed as syntaxial overgrowths on detrital grains, occurs in minor amounts (< 5 percent by volume average), predominantly in the southern part of the basin (fig. 4). The majority of sandstones examined lacked

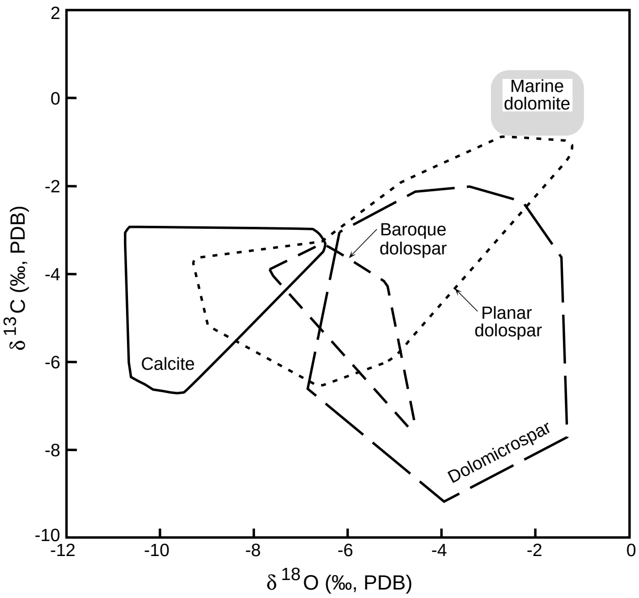


Figure 5. Stable isotopic composition of carbonate cements in the St. Peter Sandstone. Data used to construct the diagram are reported in Pitman and Spöetl (1996). The approximate composition of dolomite in isotopic equilibrium with Ordovician seawater is taken from Lohmann and Walker (1989).

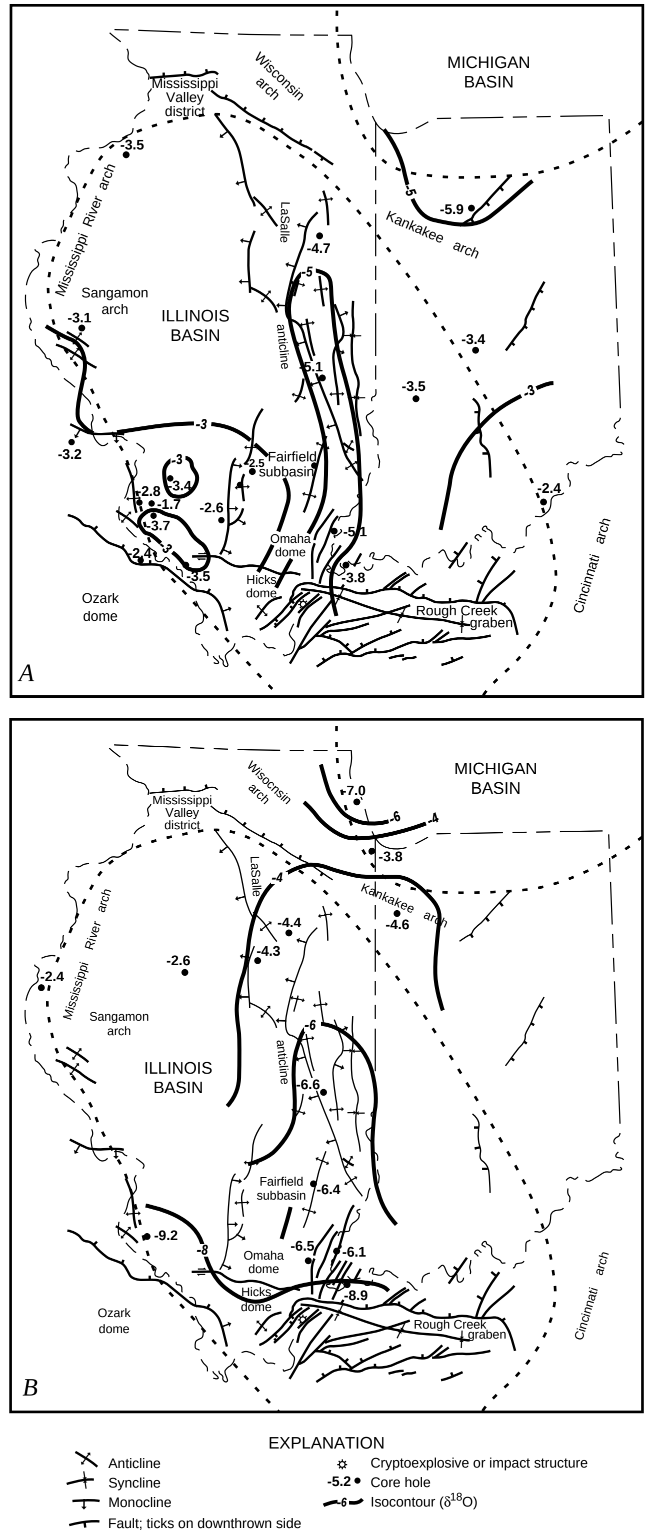


Figure 6. Regional variations in the mean oxygen-isotope compositions of dolomite in the St. Peter Sandstone. *A*, $\delta^{18}O$ ratios in dolomicrospar. *B*, $\delta^{18}O$ ratios in planar and baroque dolospar. Note similarity in isotopic pattern of dolospars on a basin-wide scale. Major structural features taken from Nelson (1991).

authigenic quartz or displayed incipient and incomplete overgrowths; however, the deeper portions of some wells (below ~1,500 m) contain abundant quartz cement (as much as 20 percent). Textural relations indicate that quartz formation postdated K-feldspar authigenesis but predated burial dolospar precipitation. Sandstones that exhibit porosity enhancement often contain quartz overgrowths that are corroded or have residual voids with partially dissolved mineral cements. Quartz cement also may occur immediately adjacent to millimeter- to centimeter-thick zones showing extensive pressure solution, which suggests that at least some silica was sourced from chemical compaction of framework grains. Primary fluid inclusions in quartz overgrowths from one well in the Fairfield subbasin yielded homogenization temperatures of 90°–110°C. Fluid compositions based on ice melting temperatures are highly saline, ~15 weight percent NaCl equivalent. No hydrocarbon-bearing fluid inclusions were observed.

AUTHIGENIC POTASSIUM FELDSPAR

Authigenic K-feldspar is a common but volumetrically minor constituent (< 5 percent by volume average) in the northern part of the basin and along the LaSalle anticline in east-central Illinois (fig. 4). K-feldspar occurs as clear, euhedral, non-luminescent overgrowths on subrounded, fine-grained detrital cores that luminesce bright blue. Where abundant, the overgrowths generally are untwinned and continuous around detrital grains. Authigenic K-feldspar also occurs as rhombs, relict cement, and subhedral to anhedral aggregates replacing illitic matrix. The cement and aggregate crystals commonly lack detrital cores (cf. Odom and others, 1979). Based on electron microprobe analysis, no distinct compositional differences exist between grain and feldspathitized overgrowths, which suggests that the detrital cores may have been diagenetically altered at the time of overgrowth precipitation. K-feldspar overgrowths predate planar dolospar and appear to be as early as dolomicrospar. In wells along the LaSalle anticline, K-feldspar overgrowths often display a skeletal morphology indicative of dissolution, whereas the detrital cores are unaltered. In the same samples, K-feldspar cement is distributed as patches, suggesting that it also might be dissolution controlled.

CLAY MINERALS

Authigenic clay minerals in the St. Peter Sandstone comprise minor illite (as much as a few percent, locally as high as 10 percent; fig. 4) and rare kaolinite. Illitic clay minerals comprise two generations, an early grain-rimming illite, and a later stage fibrous-filamentous illite. The micromorphology of these two generations suggests they are both probably illite/smectite mixed-layer clays. Illite grain coats are composed of webby to flakey growths oriented tangential to framework grain surfaces. In the northern and central portions of the basin, early illite is ubiquitous and is commonly distributed between framework grain contacts—this indicates that it formed before mechanical compaction and quartz overgrowths. Late-stage fibrous illite, in contrast, tends to be scarce and occurs as delicate lath-shaped projections and as pore bridges. Locally, it fills secondary intergranular pores caused by carbonate dissolution, which suggests a close association between carbonate leaching and illite precipitation. In some sandstones, pressure solution is highly variable (even on a millimeter scale) and clearly was promoted by illitic grain coatings (detrital and authigenic) as well as finer grain sizes of detrital constituents (Stackelberg, 1987).

Minor diagenetic kaolinite, distributed as randomly oriented, euhedral, pseudohexagonal crystals, occurs as a pore fill in sandstones near recharge zones in the northern part of the basin. The origin of the voids occupied by kaolinite is uncertain, although textural observations suggest that primary as well as secondary pores contain the mineral.

ANHYDRITE

Anhydrite is a late diagenetic mineral phase that occurs sparsely in the Fairfield subbasin (fig. 4), although textural features in sandstones suggest it was formerly more widespread (T. Shaw, Unocal Corp., 1994, oral commun.). The mode of occurrence of anhydrite ranges from small scattered patches to large euhedral crystals that preferentially replace mineral cements, including planar dolospar, baroque dolospar, and quartz. Anhydrite also replaces calcite, although, in most samples, the paragenesis of anhydrite and calcite is ambiguous.

OTHER PHASES

Miscellaneous constituents in sandstones consist of finely crystalline iron oxide, rare lithic fragments of chert, polycrystalline quartz, granite, and matrix material. Iron-oxide cement (hematite) forms a brownish-red matrix that predates quartz in some sandstones near the northern edge of the basin. Matrix often shows the effects of replacement by authigenic clay and K-feldspar. Solid bitumen is observed in a few samples in the deeper part of the basin and is intergrown with ferroan planar dolospar cement.

MINERAL DISSOLUTION

The amount and distribution of porosity (primary and secondary) in the St. Peter Sandstone varies regionally and with decreasing burial from south to north across the basin (fig. 4) (see also Hoholick and others, 1984). In the northern part of the basin, sandstones buried to a shallow depth contain large, well-developed intergranular and intragranular pores that locally exceed 20 percent by volume of the rock. Porosity loss due to compaction generally is minor. Two types of secondary porosity, leached framework grain overgrowths and partly dissolved diagenetic cements, are observed in the sandstones. Dissolution of framework grains mainly affected authigenic overgrowths on detrital K-feldspar. Several stages ranging from minor corrosion to complete dissolution (i.e., moldic pores) are observed, but, in most samples, K-feldspar overgrowths show only partial leaching. Sandstones that contain leached K-feldspar overgrowths commonly display K-feldspar cement distributed as patches, suggesting its occurrence also might be dissolution controlled. Secondary pores devoid of cement, or that contain remnant carbonate grains with etched serrated boundaries, also occur. Textural features suggest that some of the preserved porosity probably is of primary origin, although the exact amount is difficult to quantify. Quartz grains in sandstones near the outcrop often contain well-developed euhedral overgrowths that project into pores, which strongly suggests that the porosity is primary. However, in porous sandstones, it is difficult to determine if pore-fill cement was dissolved or if cementation never occurred. Thus, it is possible that the amount of primary porosity may be volumetrically greater than can be documented texturally.

In the southern part of the basin, more deeply buried sandstones display substantial porosity reduction due to mechanical compaction and mineral cementation; porosity varies from 0 to 10 percent and averages 5 percent. At depths of ~2,000 m, preserved porosity is exclusively of secondary origin caused by the dissolution of preexisting cement, mainly dolospar and possibly calcite. In well-cemented sandstones at these depths, high pre-cement porosities (20 percent average) indicate that only minor to moderate amounts of mechanical compaction occurred prior to emplacement of authigenic cement. Burial cements, principally dolospar and quartz, and minor calcite and anhydrite occlude intergranular pores, which accounts for the substantial reduction in porosity. Partly dissolved carbonate cement and evidence for repeated episodes of carbonate dissolution occur locally in some of the deeper sandstones, although the exact timing of these dissolution events is not well constrained petrographically. In dolospar-cemented samples, solution features such as discontinuous (corrosive) contacts between successive carbonate phases and relict cement in pores are common, suggesting that carbonate dissolution, burial dolomitization, and calcite precipitation were closely spaced diagenetic events.

TIME AND TEMPERATURE OF MAJOR DIAGENETIC EVENTS

The generalized paragenetic sequence of cementation and dissolution events that affected the St. Peter Sandstone is shown integrated with a decompacted burial curve constructed for the Fairfield subbasin in southern Illinois (fig. 7). Data and assumptions used to generate the curve (i.e., heat-flow conditions and stratigraphic configurations) are reported in Pitman and Spöetl (1996). The curve depicts periods of subsidence, changing subsidence rates, uplift and erosion, maximum burial depth, and paleothermal conditions. Radiometric ages of early-authigenic K-feldspar, and early- and late-diagenetic illite in Ordovician sandstones and K-bentonites adjacent to the basin (authigenic minerals within the Illinois Basin have not been dated) were used to constrain the timing and depths of formation of burial-related quartz, dolospar, and anhydrite. The age of MVT mineralization discussed above (~270 Ma, Early Permian) is shown on the curve for comparison. In the southern part of the basin, burial reconstruction indicates that the St. Peter was more deeply buried and experienced higher temperatures in the past. According to the reconstruction, the St. Peter attained its maximum burial depth and temperature (3,300 m and 140°C) in the Late Pennsylvanian and Early Permian when igneous activity and major ore-forming events were taking place in the region.

The mineral paragenesis in the context of burial reconstruction can be deduced from isotopic age dates and suggests a multistage precipitation history that commenced after the emplacement of authigenic K-feldspar and continued through the formation of late-stage illite and calcite. Radiometric dates reported for authigenic K-feldspar in Ordovician strata consistently yield Devonian ages that average ~400 Ma with a large uncertainty (Krueger and Woodard, 1972; Marshall and others, 1986; Elliott and Aronson, 1987, 1993; Barnes and others, 1992; Hay and others, 1988; Lee and Aronson, 1991; Hay and Liu, 1994). The ages suggest that feldspar authigenesis in the St. Peter, assuming it is coeval with the dated feldspars, took place during early diagenesis at shallow to moderate burial depths (< 1,500 m; see fig. 7).

The timing of illite precipitation in the St. Peter is more difficult to constrain because the range of ages that has been reported (360–215 Ma) varies widely (Hay and others, 1988; Lee and Aronson, 1991; Elliott and Aronson, 1993). In the Mississippi Valley area, two episodes of illitization have been reported for Middle Ordovician bentonites: an early Devonian–Mississippian episode dated at ~360 Ma north of the Illinois Basin and a later Permian event on the west edge and the east edge of the basin dated at ~265 Ma (Hay and others, 1988; Lee and Aronson, 1991). In the UMV district, illite-rich clays in the upper part of the St. Peter Sandstone yield Mississippian ages of ~340 Ma (Lee and Aronson, 1991). This illite however, has been dated at ~310 Ma (Pennsylvanian) in the most mineralized part of the district and is as young as 230–215 Ma (Triassic) on the Wisconsin arch (Lee and Aronson, 1991). There is some evidence indicating that early illite (~375–351 Ma) in the northern part of the region comprises detrital and authigenic clay intergrowths (R. Hay, Univ. of Illinois, 1995, oral commun.). If so, the previously reported ages for this bulk illite may reflect the older detrital value, in which case the actual ages of authigenic illite may be closer to those of the younger illites in the region. In the St. Peter Sandstone, textural evidence indicates two generations of illite—an early grain-rimming phase that predated the growth of authigenic K-feldspar and a late pore-fill phase that postdated the formation of quartz, burial dolospar, and anhydrite. The early illite phase is more prevalent in the northern portion of the basin, as noted above, although its age is uncertain. In the southern part of the basin, late stage pore-fill illite is assumed to have formed in the late Paleozoic at about the same time as the illites dated at 265 Ma or younger (see fig. 7). If so, then according to the burial-history model, late diagenetic quartz, dolospar, calcite, and anhydrite, which are bracketed in time by early authigenic K-feldspar and late-stage illite, also formed during the late Paleozoic after the rocks had undergone significant burial (fig. 7). It is noteworthy that the age for these burial diagenetic events is consistent with the timing of main-stage ore formation in both the Illinois-Kentucky

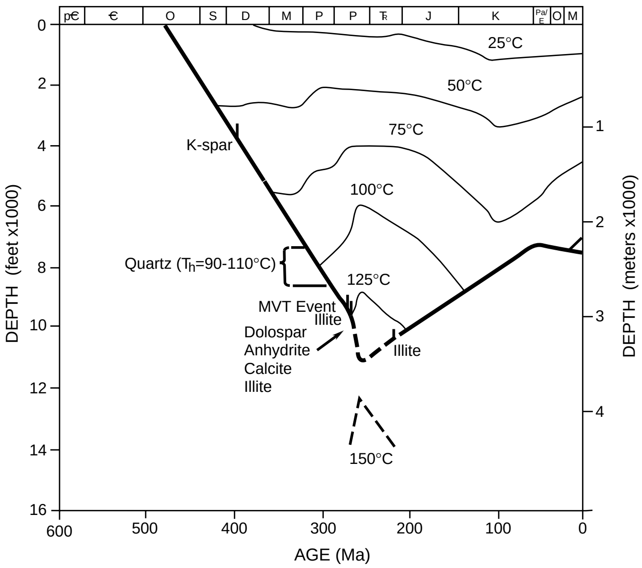


Figure 7. Burial-history curve of the St. Peter Sandstone showing timing of major diagenetic events in the Fairfield subbasin, southern Illinois. The interval was modeled kinetically with BASINMOD™ using the maturation kinetics of Sweeney and Burnham (1989). Moderate erosion (1,200 m) and variable heat flow (570 to 100 Ma = 38 mW/m2; 100 Ma to present = 55 mW/m2) were assumed in the model. Isotopic ages of early authigenic K-feldspar and early and late diagenetic illite (age range shown as dashed line) together with homogenization temperatures of secondary quartz constrain timing of burial diagenesis; age of lead-zinc-fluorine mineralization (MVT event) is shown for comparison. Note that most diagenesis took place when rocks were near maximum burial (see text for discussion).

Fluorspar district south of the basin and the UMV district north of the basin.

There is some uncertainty about the age of calcite in the St. Peter because the relationship between isotopically dated calcites and calcite cements in sandstones is unknown. In the UMV district, U-Pb systematics indicate that late vein-filling calcite in Ordovician carbonate rocks (post main-stage ore formation) formed at ~162 Ma (Middle Jurassic), approximately 100 m.y. after MVT mineralization (Brannon and others, 1993). There is presently no way to correlate the age of this vein-fill calcite and the calcite cement in the St. Peter. Moreover, there is no direct evidence that links calcite precipitation in the St. Peter to vein-calcite development in superjacent carbonate strata. However, localized micrometer-size fluorite and sphalerite inclusions in calcite cement in the St. Peter (see earlier discussion) are consistent with calcite precipitation from fluids enriched in ore-related constituents, suggesting that the minimum age of sphalerite/fluorite-bearing calcite is Permian, which is in accord with the burial-history model.

In southern and central Illinois, solid bitumen intimately associated with (ferroan) planar dolospar and baroque dolospar suggests that precipitation of late-diagenetic carbonate was closely related to migration of hydrocarbons into reservoir sandstones. The time of hydrocarbon migration within the St. Peter is tentative; however, hydrocarbon transport (and regional brine migration) presumably occurred during the Permian, assuming that the Pennsylvanian New Albany Shale was the primary source of oil (Barrows and Cluff, 1984).

Several lines of evidence indicate that burial diagenesis in the St. Peter Sandstone occurred when the unit was at or close to maximum burial in the Permian. Organic-maturation kinetics (Sweeney and Burnham, 1989) were used in conjunction with the reconstructed burial history to model the thermal conditions in the southern part of the Illinois Basin (Pitman and Spöetl, 1996) (fig. 7). Predicted paleotemperatures (shown as isotherms on the burial curve) were calculated assuming that basement-derived (conductive) heat flow was the major heat source during burial—the paleotemperatures do not take into account a potential heat source related to advective heat transfer by migrating hydrothermal fluids (e.g., Bethke, 1986; Garven and others, 1993; Rowan and Goldhaber, 1996). Silicate-mineral age dates (i.e., K-feldspar and illite) in the context of the thermal history suggest that burial diagenesis in the St. Peter occurred over a temperature range of ~65°–140°C (see fig. 7). The minimum temperature of diagenesis, ~65°C, corresponds to the Devonian age assigned to K-feldspar overgrowth precipitation; whereas the maximum (calculated) temperature of diagenesis, 140°C, conforms to the timing of late-diagenetic illite, regarded to be Permian. Fluid-inclusion homogenization temperatures indicate that secondary quartz precipitated at temperatures as high as 110°C. Thus, dolospar (and anhydrite) postdating quartz overgrowths may have precipitated at temperatures between 110°–140°C, assuming that they formed in a burial regime governed by conductive heat flow.

There is some evidence that suggests the modeled temperatures shown in figure 7 may be minimum values. Radiometric age dates on ores and igneous rocks (Snee and Hayes, 1992; Chesley and others, 1994; Brannon and others, 1993) indicate that hydrothermal fluids involved in ore formation were migrating through the Illinois Basin during the Permian (~270 Ma). According to fluid-inclusion studies, the temperatures of these fluids in the Fluorspar and UMV districts (~75°–180°C; McLimans, 1977; Richardson and others, 1988) approximate the range of burial temperatures (~65°–140°C) estimated for the St. Peter. However, the Fluorspar district ores are hosted in Mississippian-age carbonate rocks, which in Permian time were at shallower burial depths (by about 1.2 km) than the St. Peter Sandstone. The actual peak temperatures experienced by the St. Peter in the Fairfield subbasin thus might have been somewhat hotter than the temperatures predicted by the burial model, assuming that the sandstones were conduits for hydrothermal fluid flow.

In northern Illinois, maximum burial depths and temperatures of the St. Peter (including the south flank of the Michigan Basin) are estimated to have been ~1,000 m and

~50°C (Cluff and Byrnes, 1991; Rowan and Goldhaber, 1996 and included references). A few dolospar samples in these shallowly buried sandstones, however, have light $\delta^{18}O$ ratios (see fig. 6) that correspond to temperatures exceeding those of maximum burial (see below). In addition, some dolospar crystals in this area have fluid-inclusion crystallization temperatures (110°–115°C) that fall within the range reported for ore and gangue minerals in the UMV district (~80°–180°C; McLimans, 1977) and that are considerably higher than can be readily explained by burial alone. The combined burial-history curve and isotopic age dates depicted for the deep Fairfield subbasin (discussed above) suggest that the hot temperatures experienced by the St. Peter Sandstone in the southern part of the basin coincided with maximum burial as well as a hydrothermal fluid-flow event in the Permian. Although deep burial alone was capable of generating elevated temperatures (>100°C) in southern Illinois, this mechanism cannot explain temperatures in excess of 100°C in northern Illinois. Hydrologic modeling has shown that hydrothermal fluid flow was capable of producing the elevated temperatures observed in the northern portion of the study area (Bethke, 1986; Garven and others, 1993; Rowan and Goldhaber, 1996). Thus, in the absence of Paleozoic igneous activity, we conclude that the fluids involved in the diagenesis of the St. Peter in northern Illinois were, in part, related to the Permian hydrothermal flow event that was responsible for ore formation in the UMV district.

EVOLUTION OF PORE FLUIDS

COMPOSITION OF PRECIPITATING WATERS

Isotopic analyses of cements in the St. Peter Sandstone suggest that pore fluids with variable isotopic composition and (or) elevated temperature controlled the nature and extent of authigenic mineral precipitation during burial diagenesis. The $\delta^{18}O$ values of carbonate-precipitating pore waters that existed during burial were estimated using the dolomite-water fractionation equation of Fritz and Smith (1970) and the calcite fractionation equation of Friedman and O'Neil (1977). Temperatures assumed in the calculations (65°–140°C) were extrapolated from the burial-thermal curve (fig. 7), constrained by isotopic ages of the silicate mineral phases, K-feldspar and illite. The compositional range of the hypothetical pore waters is shown in figure 8. Based on the calculations, the $\delta^{18}O$ values of dolomitizing water varied from –3.3 to +12.7 ‰ (SMOW—standard mean ocean water) during the course of burial diagenesis. The most positive $\delta^{18}O$ water compositions correlate with (late diagenetic) baroque dolospar, which precipitated near the estimated upper temperature limit (~100°–140°C); negative $\delta^{18}O$ water compositions correspond to (early diagenetic) dolomicrospar, which precipitated at the lower temperature limit (~65°C). Some calculated $\delta^{18}O$ water compositions overlap the range reported for Ordovician seawater (~–1 to –3 ‰; Lohmann and Walker, 1989), indicating a potential for an "original" source of marine water. However, the majority of compositions are moderately to highly positive and exceed seawater values, implying that most dolospar precipitated from pore fluids elevated in temperature and (or) significantly enriched in $\delta^{18}O$. Based on the estimated timing of calcite crystallization (fig. 7), there should not have been a significant temperature change in the burial system between the time of planar/baroque dolospar formation and calcite precipitation. Thus, the composition of calcite-precipitating water was in the range of +2.7 to +10.5 ‰ (SMOW), assuming that crystallization temperatures were similar to those of quartz and baroque dolospar (~100°–140°C; fig. 8).

Geochemical and petrographic data provide strong evidence that the pore waters involved in burial cementation of the St. Peter were brines similar in composition to Permian ore-forming brines and modern Illinois Basin brines. The salt content of fluid inclusions in quartz and carbonate cements (~15–20 weight percent NaCl equivalent) indicates a saline fluid source as does the occurrence of late-diagenetic anhydrite in deeper portions of the basin. Further, the range of $\delta^{18}O_{water}$ values estimated for the St. Peter (+3 to +10 ‰) is similar to the $\delta^{18}O$ ratios of modern Illinois Basin brines (~0 to +6 ‰ SMOW; Clayton and others, 1966; Stueber and Walter, 1991) and is broadly comparable to the range of $\delta^{18}O$ ratios measured for fluid-inclusion waters from the UMV ore district (–5.1 to +5.7 ‰; McLimans, 1977). According to Stueber and Walter (1991), $\delta^{18}O$ (and δD) ratios of deep Illinois Basin brines reflect varying degrees of water-rock interaction and (or) brine and meteoric water mixing. It is noteworthy that the salinity of the brines responsible for dolospar and quartz cementation in the St. Peter closely approximates the salinity of the fluids involved in MVT mineralization (> 20 weight percent NaCl equivalent; McLimans, 1977; Richardson and others, 1988) and of modern formation waters in the basin (~20 weight percent NaCl equivalent; Stueber and Walter, 1991). Cl/Br values of present-day formation waters (290±18) reflect a brine more evaporated than seawater but undersaturated with respect to halite (Stueber and Walter, 1991). Kesler and others (1995) reached a similar conclusion regarding the composition of ore-forming fluids in the Illinois Basin region. Thus, the Permian hydrothermal brines were similar geochemically to modern, deep, Illinois Basin brines, although these modern and ancient fluids are not likely to be related (Ranganathan, 1993).

ORIGIN OF PRECIPITATING FLUIDS

The spatial distribution pattern of early- and late-diagenetic cements in the St. Peter Sandstone provides a record of

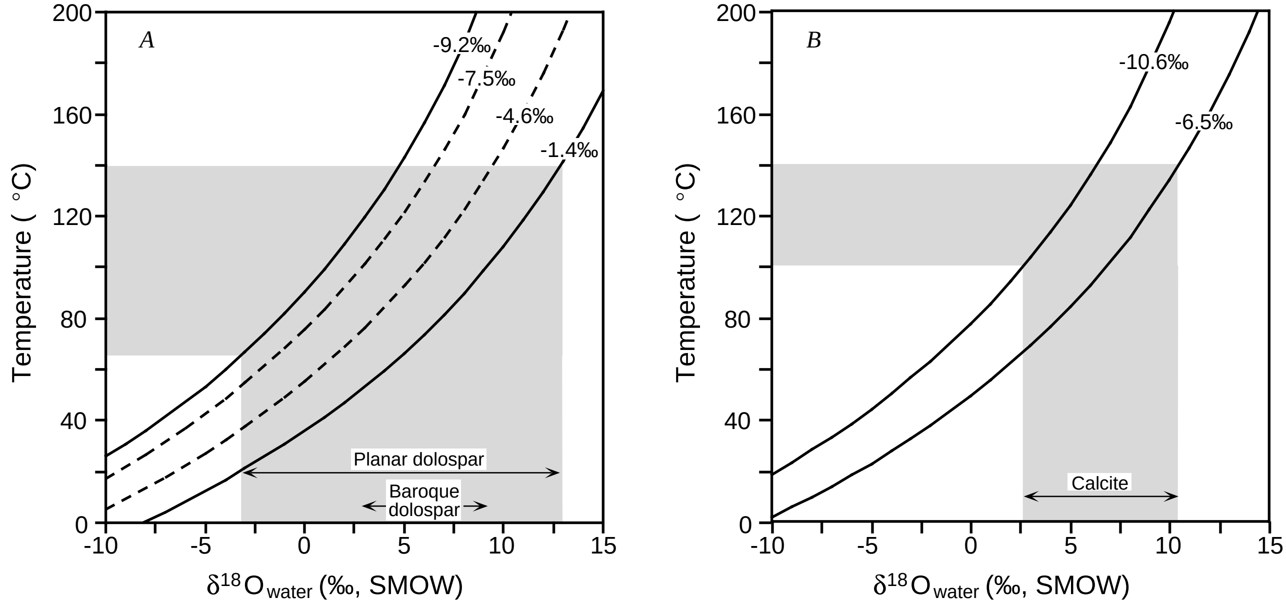


Figure 8. Relationship between the oxygen isotopic composition of pore water, temperature of mineral precipitation, and measured range in $\delta^{18}O$ ratios of carbonate cements in the St. Peter Sandstone. Note that pore-water $\delta^{18}O$ compositions are reported relative to SMOW, whereas $\delta^{18}O$ ratios of carbonate cements are reported in PDB. *A*, diagram showing possible parent pore-water compositions in isotopic equilibrium with planar dolospar (continuous lines) and baroque dolospar (dashed lines) using the fractionation equation of Fritz and Smith (1970). For details about temperature assessment, see text. *B*, same diagram for calcite based on the relationship of Friedman and O'Neil (1977). A 100°–140°C temperature window was assumed for late-stage calcite precipitation. See text for further details.

the sources and migration pathways of fluids that passed through the Illinois Basin during its burial history. Saline fluids from multiple sources internal and external to the basin were potentially involved in sandstone diagenesis. However, the relationship between late Paleozoic ground-water recharge, brine evolution, and sediment diagenesis has not been well constrained. On the basis of present-day formation-water data, Stueber and Walter (1991) concluded that modern Illinois Basin brines contain residual (evaporated) marine water that was not completely expelled or replaced by meteoric water recharge. Kesler and others (1995) have shown from fluid-inclusion studies of ore minerals in the Fluorspar district and UMV district that the ore fluids did indeed originate from evaporated seawater. Yet the relationship between modern and ancient brine is unclear because it is highly unlikely that fluids as old as the Paleozoic would have remained unaltered in a basin with a geologic and tectonic history as complex as that of the Illinois (Ranganathan, 1993). Within the Illinois Basin proper, a component of the basin brines might have been influenced by sulfate evaporite beds older than the St. Peter that underwent solution-precipitation reactions during burial. Occurrences of evaporite minerals in Paleozoic rocks older than the St. Peter today are sparse; nevertheless, peritidal environments promoted penesaline conditions and the formation of evaporite deposits consisting of bedded gypsum and anhydrite in some parts of the basin (T. Shaw, Unocal Corp., 1995, oral commun.). Subsequent dissolution of these minerals may have produced a sulfate-enriched fluid that conceivably could have migrated into Ordovician sandstones during the Permian fluid-migration episode. Textural relations clearly indicate that anhydrite in Ordovician sandstones was a late diagenetic phase—this precludes its formation from a pore fluid deposited with the sediment. Thus, we conclude that sulfate-rich brines (i.e., marine-derived sulfate) must have been imported into Ordovician strata when they were at or close to maximum burial.

Contributions of brine from sources external to the present Illinois Basin may have played an important role in burial cementation of the St. Peter Sandstone (fig. 9). Fluid-flow models have postulated that tectonic compression, sediment loading, and topographic relief associated with uplift are mechanisms that can transport warm fluid through the interior portions of sedimentary basins (Cathles and Smith, 1983; Bethke and others 1988; Bethke and Marshak, 1990; Garven and others, 1993). In the Illinois Basin, there is compelling evidence for a short (~200,000 year), intense, regional, hydrothermal brine-flow event during the late Paleozoic that was initiated by tectonism at the southern margin of the continent (Bethke, 1986; Bethke and others, 1988; Rowan and Goldhaber, 1996). Based on paleohydrologic reconstructions, deformation-induced gravity flow drove hydrothermal brines northward in the basin. Brine influx into the St. Peter in southern Illinois probably began in the Late Pennsylvanian when Ordovician strata were near maximum burial (~3,300 m) and continued through the

Permian during the period that regional tectonism was most intense. Ultimately, these fluids localized fluorine-lead-zinc mineralization along the southern basin margin and have been inferred to be responsible for the UMV district north of the basin (Bethke, 1986; Goldhaber and others, 1994). Hydrothermal fluid flow paths might have included uplifted and extensively folded and faulted terrane associated with the late Paleozoic Ouachita and Appalachian mountain belts (Brecke, 1979; Farr, 1989; Garven and others, 1993). There also is some evidence that a component of these fluids may have been expelled from the Arkoma and Black Warrior Basins, which underlie Mississippi Embayment sediments (Rowan and Leach, 1989) (see fig. 9). These fold-and-thrust belts, and foreland basins, are conduits for the flow pathways because late Paleozoic tectonics in conjunction with Ouachita/Appalachian orogenesis significantly altered basin hydrodynamics.

In the absence of significant igneous activity, advective fluid flow driven by topographic relief is an effective means of transporting heat in the subsurface and, therefore, is a feasible model to explain many of the observed diagenetic and geochemical trends in the St. Peter Sandstone. Anomalously warm basinal brines (relative to burial temperature) focused through aquifer sandstones are required to account for the high-temperature saline inclusions in dolospar in the northern part of the basin, and they provide an explanation for the systematically light $\delta^{18}O$ values of burial dolospar near the Fluorspar district in the deeper southern part of the basin. The local focusing of hot fluids could also explain the $\delta^{18}O$-depleted burial dolospar concentrated in Ordovician sandstones along the LaSalle anticline in the east-central Illinois (fig. 6). As fluids moved updip into the basin, presumably they cooled, which, in turn, resulted in heavier $\delta^{18}O$ values of burial dolospar northward along the flow path.

Present ground-water flow in the Illinois Basin is from northeast to southwest, and recharge zones are to the north (Young, 1992). The modern regional flow patterns coincide with extensive late-stage leaching of authigenic K-feldspar and carbonate cement in and adjacent to the northern part of the LaSalle anticline, suggesting that freshwater recharge into the subsurface promoted mineral dissolution. The presence of hematite and kaolinite in the shallow subsurface further indicates there was a shift to more dilute and oxygenated waters.

CONCLUSIONS

The St. Peter Sandstone was diagenetically altered by authigenic K-feldspar and illite, multiple generations of carbonate cement, secondary quartz, and anhydrite. Minor fluorite and sphalerite and dissolution features are also present. On the basis of the reconstructed burial history constrained by isotopic age dates of silicate minerals, precipitation of deep-burial planar and baroque dolospar, calcite, and quartz and anhydrite in southern Illinois probably occurred in the Late Pennsylvanian to Early Permian when the rocks were at or close to maximum burial. Deep burial suggests that elevated temperatures found in fluid inclusions were, in part, related to conductive heat flow. However, regional variations in the oxygen-isotope geochemistry of dolospar and occurrences of baroque dolospar north of the Illinois-Kentucky Fluorspar district indicate that hydrothermal fluids associated with (Permian) ore-forming events also may have been involved in dolomitization and contributed to elevated temperatures.

Carbonate-hosted lead-zinc deposits in the Midcontinent region are postulated to have formed from brines expelled from tectonically active terrane south and east of the present Illinois Basin (Richardson and Pinkney, 1984; Leach and Rowan, 1986; Richardson and others, 1988; Rowan and Leach, 1989; Leach and others, 1991; Garven and others, 1993). According to isotopic and paleomagnetic age dates of ore minerals (~270 Ma), these fluids migrated in the Permian. Ordovician aquifer sandstones and adjacent carbonate rocks were among the conduits for the passage of these fluids. In shallowly buried sandstones in the northern portion of the basin near the UMV district, the temperature and composition of fluid inclusions in dolospar (~110°–115°C; >20 weight percent NaCl equivalent) are comparable to those of ore minerals (~80°–180°C, >20 weight percent NaCl equivalent; McLimans, 1977). The similarity in temperature and salinity between ores and dolomite cements is permissive evidence that the same fluid-flow event was involved in mineralization and cementation. Further, the elevated formation temperatures for ore and burial dolomite formation are well above values that could be achieved through simple burial and normal crustal heat flow, which suggests that dolospar precipitation in the St. Peter was influenced by an advective hydrothermal heat source. In the deeper, southern part of the basin, the oxygen isotopic compositions of burial cements suggest that advective heat transfer along flow paths originally outside the basin coincided with elevated (conductive) heat flow within the basin. Evidence for an advective hydrothermal fluid and heat-transport mechanism is a decrease in $\delta^{18}O$ ratios of planar and baroque dolospar along structural features such as the LaSalle anticline and the clustering of highly depleted $\delta^{18}O$ values immediately north of the Illinois-Kentucky Fluorspar district. The $\delta^{18}O$-depletion trend along the anticline can best be explained by the movement of gravity-driven hydrothermal fluids northward through the structure. Thus, the evidence provided in this study links many of the diagenetic events in the St. Peter Sandstone to basin-scale and even continental-scale tectonic events.

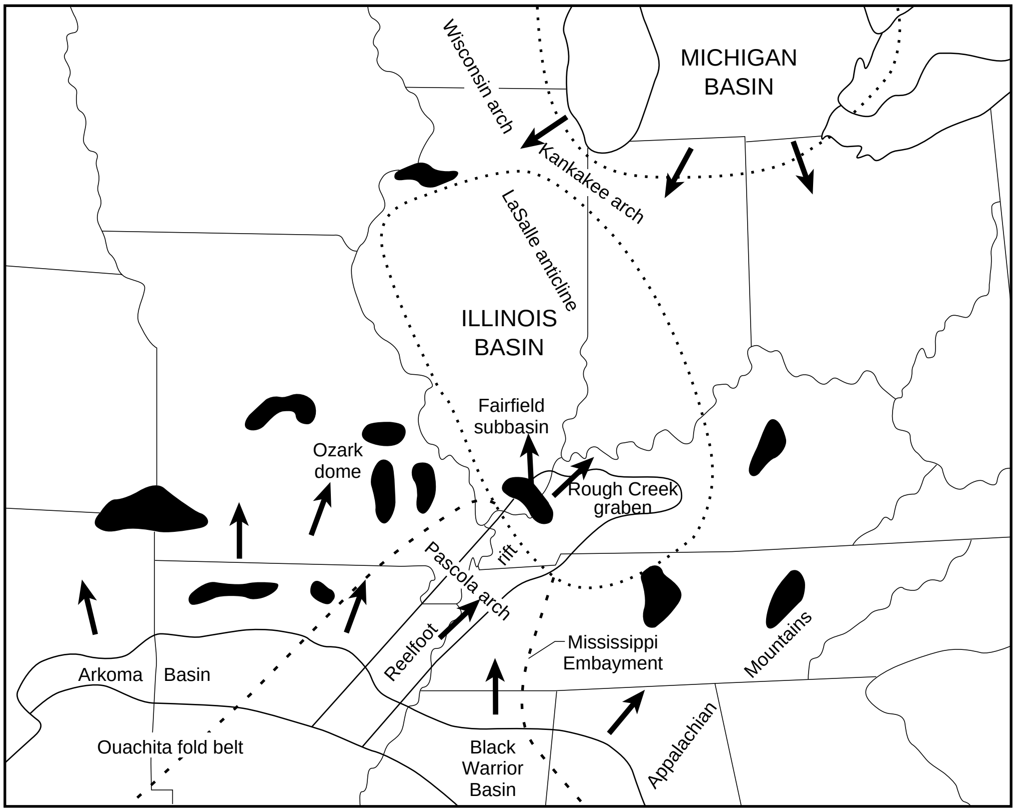


Figure 9. Paleoflow directions (arrows) in the Illinois Basin area. Dominant flow component was from the south; a smaller component of flow may have come from the north. Areas shown in back are major ore districts.

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