Mississippian (Osagean) Shallow-water, Mid-latitude Siliceous Sponge Spicule and Heterozoan Carbonate Facies: An Example from Kansas with Implications for Regional Controls and Distribution of Potential Reservoir Facies

by
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Abstract

Mixtures of biosiliceous and heterozoan-dominated carbonate deposits are commonly interpreted as recording cold-water polar or deep basinal conditions. However, a growing body of literature is documenting examples from the rock record that show these deposits accumulated in shallow-water middle- to low-latitude environments. The continued recognition of ancient neritic heterozoan carbonate and biosiliceous accumulations is broadening our understanding of the various paleoenvironmental controls on their development.

Early-Middle Mississippian time was characterized by the development of biosiliceous and carbonate accumulations in North America. This study focuses on Osagean cherty dolomitic strata in cores from the Schaben field in Kansas, which is located in Ness County on the southwest flank of the Central Kansas uplift (CKU). During the Osagean, Kansas was located at approximately 20° S latitude, within the tropical to subtropical latitudinal belt. Study area strata are characterized by shallow-water inner-shelf carbonates that were deposited on a gently southward-sloping shelf (ramp). Two depositional sequences (DS1 and DS2) are identified in cores and are separated by a sequence boundary (SB1) that evidences subaerial exposure. The primary facies in the two depositional sequences include 1) Mudstone-Wackestone (MW); 2) Sponge Spicule-Rich Wackestone-Packstone (SWP); 3) Echinoderm-Rich Wackestone-Packstone-Grainstone (EWPG); and 4) Dolomitic Siltstones and Shale facies. Other features identified in cores include 1) Silica Cementation and Replacement; 2) Silica Replaced Evaporites; 3) Brecciation and Fracturing; and 4) Calcite Cementation and Replacement.

The abundance of echinoderm facies with other diverse fauna, evidence of extensive reworking by burrowing organisms, and only rare occurrence of evaporites suggest subtidal deposition in a normal to slightly restricted marine inner-shelf setting for DS1. After the SB1 subaerial exposure event, marine conditions returned but the depositional environment over the study area changed compared to that for much of DS1 deposition. The volumetric increase of sponge-spicule wackestone and packstone (SWP) with less diverse fauna, abundance of early evaporites (replaced by silica), and evidence for shallowest water to subaerially exposed conditions throughout DS2 suggest deposition in more restricted environments that likely ranged from restricted inner shelf/protected embayment to evaporative lagoon and possibly supratidal flat.

One of the more significant characteristics in DS2 is the dominance of siliceous sponge spicule facies and heterozoan carbonates that were deposited in shallow-water and restricted environments. This study and others from numerous periods in the geologic record are indicating that shallow-marine, mid-latitude biosiliceous and heterozoan carbonates may be more common than previously thought. Especially interesting are the examples from Mississippian (Osagean–Meramecian) strata in North America that show similar facies associations with DS2 strata of this study.

The predominance of Early-Middle Mississippian heterozoan carbonate and biosiliceous (spiculitic) deposits, and lack of photozoan deposits, in the mid-latitude shallow-shelf setting in Kansas and surrounding areas was likely due to abundant nutrients and dissolved silica derived from basinal and/or terrestrial sources. Based on available evidence, upwelling of basinal waters rich in nutrients and dissolved silica appears to have been a primary control on shelf margin and shelf facies. Upwelling even may have had a primary imprint on shallow-water, inner-shelf areas, especially during transgression(s). Nutrients and dissolved silica from terrestrial sources may have contributed to the facies associations in shallowest water, inner-shelf areas. However, the available evidence suggests that terrestrial sourced nutrients and dissolved silica were not the dominant control.

The results of this study have implications from a petroleum reservoir standpoint. The DS2 sponge spicule, heterozoan carbonate, and silica-replaced evaporite facies in this study form reservoirs in Schaben field and another nearby field composed of similar facies. Because regional upwelling is likely to have had at least some control, facies similar to DS2 strata may form important reservoirs in Lower-Middle Mississippian strata that were deposited in shallow-water inner shelf/ramp settings elsewhere in Kansas and North America.

Continuing studies of the controls on biosiliceous and heterozoan carbonate deposition and diagenesis in mid-latitude neritic settings will improve our understanding and predictive capabilities.

Introduction

Environmental interpretations of carbonate facies in the rock record are commonly driven by equivalent facies occurrences in modern ocean environments. For example, Heterozoan Association carbonates (an association of benthic carbonate particles produced by organisms that are light-independent plus or minus red calcareous algae; James, 1997) are a characteristic component of modern cool-water carbonate shelves where sea-water temperatures are less than 20° Celsius for prolonged periods and influx of terrigenous sediment is relatively low (Lees and Buller, 1972; Nelson, 1988; James, 1997; James and Bone, 2000). In contrast, Photozoan Association carbonates (an association of benthic carbonate particles including light-dependent organisms, and/or nonskeletal particles such as ooids and peloids, plus or minus skeletons from the Heterozoan Association) are characteristic of modern warm, shallow-water tropical carbonate shelves. Heterozoans are an important component in most marine environments, and in addition to cool-water areas, can predominate even in low-latitude, warm-water settings where environmental conditions limit the supply of siliciclastic and pelagic sediments, and where photic zone and nutrient conditions prevent the development of photozoans (James, 1997).

Similarly, interpretations of biosiliceous rocks rich in sponge spicules or sponge body fossils are strongly influenced by the distribution of siliceous sponges in the modern ocean, where they thrive in the deep sea and/or on shallow polar shelves (Gammon et al., 2000). Gammon et al. (2000) point out that siliceous spiculites do not occur on the inner portions of modern shelves, especially those in subtropical and tropical environments.

Mixtures of biosiliceous (particularly those rich in sponge spicules) and heterozoan-dominated carbonate deposits occur in the rock record. The occurrences in the modern of similar facies, as mentioned above, have led to these deposits usually being interpreted as recording cold-water polar or deep basinal conditions (James, 1997). However, a growing body of literature documents biosiliceous and heterozoan carbonate deposits, and specifically sponge-rich deposits, in the rock record that are interpreted to have been deposited in shallow-water middle- to low-latitude environments (e.g. Cavorac and Ferm, 1968; Folk, 1973; Chowns and Elkins, 1974; Geeslin and Chafetz, 1982; Maliva et al., 1989; James and Bone, 2000; Gammon et al., 2000). The increasing documentation of these deposits is aiding in understanding the paleoenvironmental attributes of ancient neritic carbonate/spiculite accumulations. However, as pointed out by Gammon and James (2000), the depositional environments and sedimentology of such shallow-marine deposits are still poorly understood.

Early-Middle Mississippian time was characterized by extensive development of biosiliceous and carbonate accumulations in some areas of North America (Lowe, 1975; Gutschick and Sandberg, 1983). During this time a shallow tropical sea covered most of the southern North American continent and was the site of a broad carbonate platform (Gutschick and Sandberg, 1983). Most of present-day Kansas was part of the platform area. Paleogeographic studies place that area at about 20° S latitude, within the tropical to subtropical latitudinal belt during Early-Middle Mississippian time (Parrish, 1982; Witzke, 1990; Golanka et al., 1994; Scotese, 1999). Osagean deposition in the region was characterized by shallow shelf carbonates deposited on a gently sloping shelf (ramp) to the south (Rogers et al., 1995), with the shelf edge (bordering the Anadarko basin) located near the Kansas-Oklahoma border (Selk and Ciriaks, 1968; Lane and DeKeyser, 1980; Gutschick and Sandberg, 1983). Generally, shelf facies consist of limestones, dolomites, and cherts (Lane and DeKeyser, 1980; Gutschick and Sandberg, 1983). Previous detailed studies of Osagean strata in Kansas have focused on shelf-margin areas where thick accumulations of sponge-rich chert deposits occur (informally termed "chat") and form significant reservoir facies (e.g. Rogers et al., 1995; Colleary et al., 1997; Montgomery et al., 1998; Watney et al., 2001). In comparison, relatively little detail is known about equivalent Osagean deposits in inner shelf (as used by Lane and DeKeyser, 1980) locations in Kansas. The purpose of this paper is to 1) document Osagean biosiliceous and heterozoan carbonate and original evaporite facies that were deposited in a shallow-water, inner-shelf area in Kansas; 2) provide examples in the rock record of similar biosiliceous and heterozoan carbonate deposits to help illustrate that these types of facies are more common in shallow-water, tropical/subtropical settings than commonly thought; 3) show that similar shallow-water biosiliceous and heterozoan carbonate deposits occurred elsewhere in North America during Early-Middle Mississippian time; and 4) use the example from this study along with other documented examples in North America to examine paleoenvironmental conditions that may have controlled deposition of biosiliceous and heterozoan carbonate deposits in this Osagean subtropical/tropical shallow-water, mid-latitude setting.

Recognition of these facies and understanding controls on their distribution has additional significance in that these facies form reservoirs in several areas of Kansas and could be important potential reservoir facies elsewhere in Kansas and North America.

Geologic Setting

In earliest Mississippian time, the southern margin of North America delineated the northern boundary of a transequatorial seaway connecting the Iapetus and Panthalassic seas (Noble, 1993). The convergence of Laurasia and Gondwana closed off the transequatorial seaway in the Late Carboniferous, forming a series of borderland basins that filled with clastic sediments and were subsequently overlain by Permian carbonates and evaporites (Noble, 1993).

Although most of the major tectonic phases are thought to be much later, Noble (1993) provides evidence indicating that the Ouachita deformation started in the Late Devonian to earliest Mississippian. Evidence for Early-Middle Mississippian tectonism is present in Kansas as well. Goebel (1968) indicated that the eastern flank of the Transcontinental arch in western Kansas should be recognized as having been a positive area in Early Mississippian time. Similarly, Lane and DeKeyser

(1980) showed that the Transcontinental arch was a subaerial physiographic element during much of the Paleozoic and that associated subaerial areas along the eastern margin included the Nemaha ridge and Central Kansas uplift (CKU). They also indicate that the Transcontinental arch areas were near base level and intermittently subaerially exposed and submerged during Early-Middle Mississippian time.

The study focuses on Ness County, which is located on the upper shelf of the Hugoton embayment of the Anadarko basin, on the southwest flank of the Central Kansas uplift (CKU), at the western edge of the Mississippian (Osagean) subcrop beneath the sub-Pennsylvanian unconformity (fig. 1A). The CKU is the southeastward extension of the Transcontinental arch (see Goebel, 1968; Lane and DeKeyser, 1980). Several authors indicate that the CKU started to become a structurally positive element before and during Early Mississippian deposition but that the structural movements were minor compared with later tectonic events (e.g. Goebel, 1968; Thomas, 1982; Rogers et al., 1995). Montgomery et al. (1998) and Watney et al. (2001)

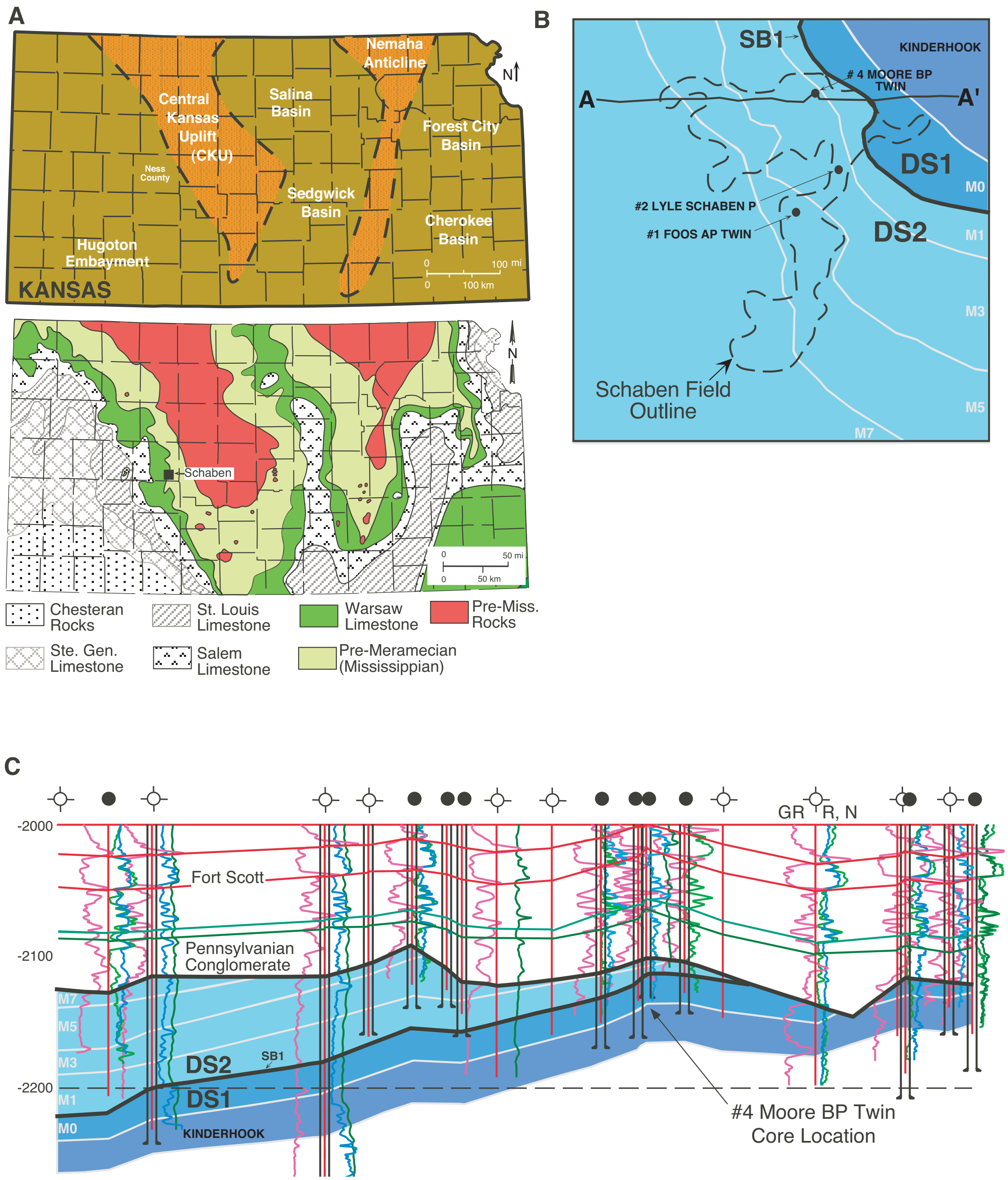

FIGURE 1—A) Maps showing structural elements (top) and Mississippian subcrop pattern (bottom) for the state of Kansas. Note location of Ness County and Schaben field. B) Mississippian subcrop map of Schaben field area with Kinderhook and Osagean sequences (DS1, DS2) defined in cores and units defined on electric logs (M0-M7). Note locations of three cores that were studied in detail and location of the west to east (A-A´) cross section shown in fig. 1C. C) A-A´ cross section with Kinderhook and Osagean stratigraphic units defined in cores and electric logs. These units are unconformably overlain by Pennsylvanian strata. Post-depositional regional uplift, subaerial exposure, and differential erosion of the ramp strata at the post-Mississippian unconformity resulted in paleotopographic highs (buried hills). Logs consist of gamma ray (GR) and suites of resistivity and neutron logs (R, N).

suggest that features associated with these Early Mississippian events may have influenced depositional patterns.

Mississippian rocks are successively younger in a southwestward direction away from the CKU where Mississippian rocks are absent (fig. 1A). This pattern is due mainly to Late Mississippian-Early Pennsylvanian structural uplift related to the Ouachita orogenic event. This resulted in an extensive period of subaerial exposure and erosion of Mississippian strata forming a regionally significant unconformity that separates Mississippian from overlying Pennsylvanian rocks. The inner shelf strata in the study area were differentially eroded at the post-Mississippian unconformity resulting in variable paleotopography (fig. 1C).

Osagean-Meramecian deposition in the region was characterized by shallow shelf carbonates deposited on a gently southward-sloping shelf (ramp). The immediate study area of this paper is in the inner shelf facies (as defined by Lane and DeKeyser, 1980), whereas the shelf edge (bordering the Anadarko basin) is generally mapped several hundred kilometers to the south-southeast, near the Kansas-Oklahoma border (Selk and Ciriaks, 1968; Lane and DeKeyser, 1980; Gutschick and Sandberg, 1983). Generally, shelf facies consist of limestones, dolomite, and cherts whereas basin facies are predominantly argillaceous limestones and shales with minor amounts of chert (Lane and DeKeyser, 1980; Gutschick and Sandberg, 1983). Rogers et al. (1995) emphasized that it is most difficult to identify a shelf margin with significant topographic relief and instead characterize the margin as a facies boundary marking a transition from "shallow" oxygenated waters to "deeper" less oxygen-rich waters (their quotes). Along the shelf margin, irregular or oval sponge bioherms, 15-48 m thick, consisting mostly of sponge spicule-rich mud, developed below wave base (Montgomery et al., 1998). According to Montgomery et al. (1998), fossiliferous burrowed lime wackestone and mudstone was deposited on the inner and middle shelf (Osagean limestone and equivalents), grading into finer-grained carbonate and interbedded shale downdip (Cowley Formation). As shown in this study, inner shelf areas were also sites of shallow-water biosiliceous and heterozoan carbonate (mostly dolomite) accumulations.

Study Area Stratigraphy

Osagean strata in Kansas comprise a number of formations and members, including the Burlington Limestone, Keokuk Limestone, and undifferentiated Burlington-Keokuk Limestone (fig. 2). This study focuses on cores from the Schaben field area in Ness County (fig. 1). Based on conodont data, Osagean rocks west of the CKU, including those of this study, probably belong to the Keokuk Limestone (Goebel, 1968). The cores are subdivided into two major units, Depositional Sequence 1 (DS1) and Depositional Sequence 2 (DS2) (fig. 3). The two sequences are separated by a regional surface of subaerial exposure that resulted from a relative sea-level fall and forms a sequence boundary (SB 1).

Facies and Other Core Features

The main facies identified in cores from the Schaben field include 1) Mudstone/Wackestone (MW); 2) Sponge Spicule-Rich Wackestone-Packstone (SWP); 3) Echinoderm-Rich Wackestone-Packstone-Grainstone (EWPG); and 4) Dolomitic Siltstone & Shale Facies. Other features identified in cores include: 1) Silica Cementation & Replacement; 2) Silica Replaced Evaporites; 3) Brecciation & Fracturing; and 4) Calcite Cementation & Replacement. The facies and other features are described in tables 1 and 2, and shown in figs. 4-10. Evidence for early silicification, evaporites, and dolomitization is included in table 3 as these are particularly important for depositional environment interpretations.

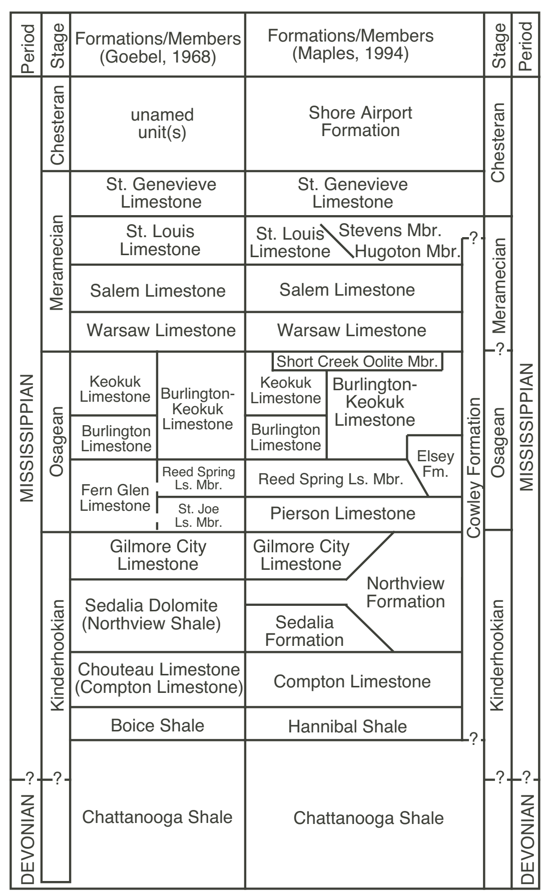

FIGURE 2 (right)—Mississippian stratigraphic units as defined for the state of Kansas. This study focuses on Osagean (Keokuk Limestone) strata. From Maples (1994).

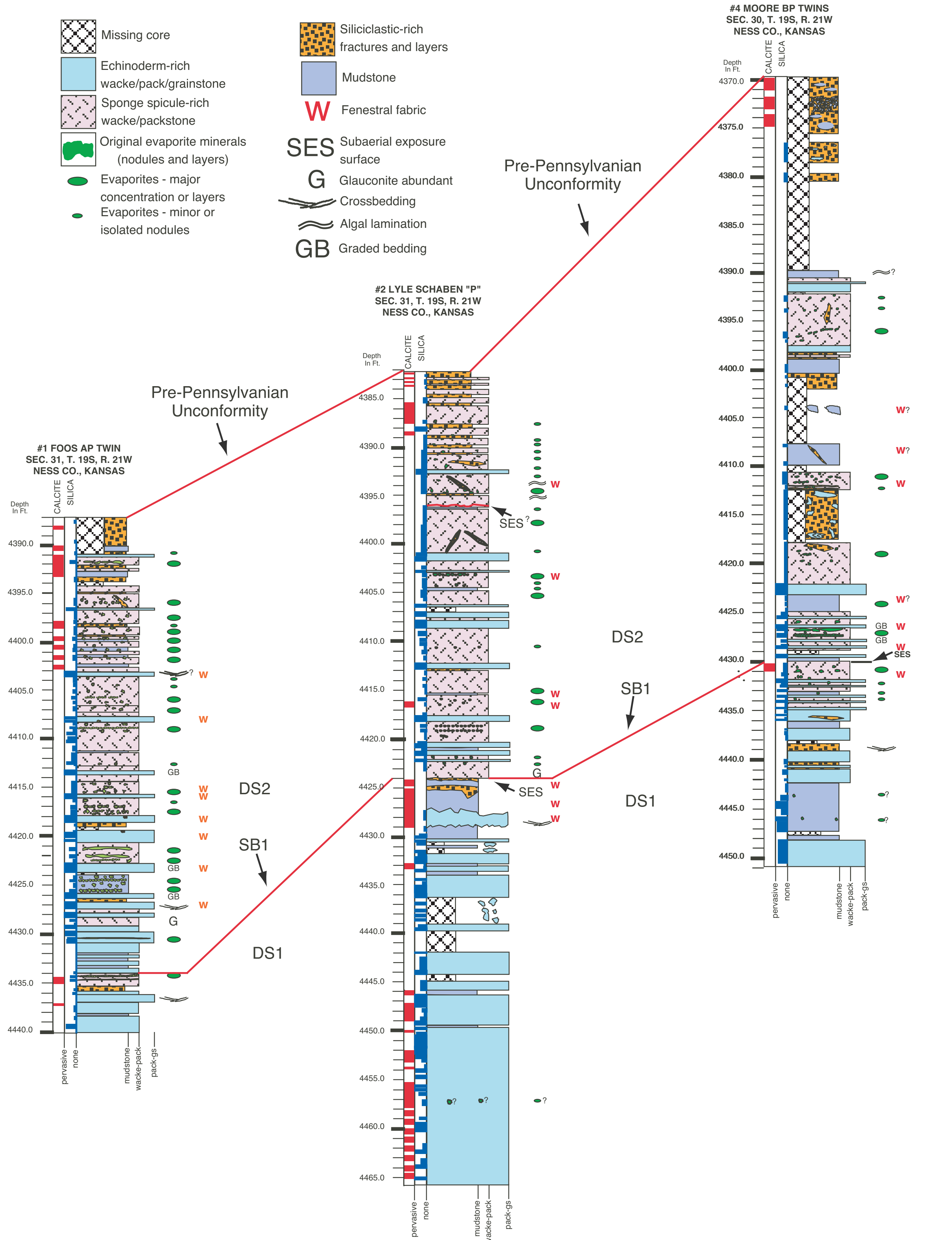

FIGURE 3—Core descriptions for the three cores from the Schaben field area showing depositional facies (see fig. 1B for locations). Also shown are relative abundance of calcite and silica replacements and cements. SB1 is identified in all cores based on evidence of subaerial exposure and associated calcite replacement and cementation fabrics. This surface is used for correlation and separates DS1 (below) from DS2 (above).

TABLE 1—Depositional facies.

Facies Name	Grain Types	Sedimentary Features	Other Characteristics
Mudstone/ Wackestone (MW)	Identifiable grains rare. Sponge spicules (mostly monaxon) and their molds are most identifiable grain type; echinoderm, bryozoan, brachiopod, gastropods, peloids, glauconite locally present. Rare concentrations of very fine grained (~100 μm) detrital quartz grains. Pyrite occurs as accessory mineral.	Typically laminated or wavy to wispy laminated (**fig. 4A**). Locally massive. Local mottled texture from burrowing results in local concentrations of sponge spicules in pockets on microscopic scale. Local dark blebs and clotted areas likely are from organic matter and may indicate microbial structures. Local soft sediment. Local fenestral fabric.	Typically tight or has moldic, intercrystalline, and minor vuggy porosity locally developed (6-22%, Byrnes and Franseen, 2000). Mottling texture and lamination locally results in variable tight and porous areas at a thin-section scale. Dolomite occurs as very finely crystalline to micrite size (~20 μm to <100 μm), subhedral to anhedral crystals; euhedral crystals locally. Commonly contains silica-replaced evaporites. Silica locally replaces matrix and grains.
Sponge Spicule-Rich Wackestone-Packstone (SWP)	Sponge spicules (mostly monaxon) and their molds are predominant grains commonly exclusive (**fig. 4B, C**). Sponge spicules are originally siliceous (central axial canal locally identifiable; **fig. 4B**). Rare identifiable triaxon spicules. Echinoderm, bryozoan, gastropod, peloids, and glauconite grains occur more rarely. Pyrite is locally an abundant accessory mineral.	Mottled, wispy horizontal laminated, and wavy horizontal laminated and textures are common; sponge spicules locally concentrated in layers. Laminations imparted locally by green/gray shale/siltstone and horsetail stylolites. Mottled textures from burrowing result in local concentrations of grains in pockets on microscopic scale.	Moldic (**fig. 4C**), intercrystalline, and minor vuggy porosity ranges from 18 to 25% (Byrnes and Franseen, 2000). Fenestral fabric occurs locally. Mottling texture and concentration of grains in layers locally results in variable tight and porous areas. Dolomite occurs as very finely crystalline to micrite size (~20 μm to <100 μm), subhedral to anhedral crystals. Commonly contains silica-replaced evaporites. Silica locally replaces matrix and grains (**fig. 4B, D**).
Echinoderm-Rich Wackestone-Packstone-Grainstone (EWPG)	Echinoderm fragments dominant; abundant sponge spicules, bryozoan fragments, brachiopods, solitary coral fragments, gastropods, ostracods, peloids, calcispheres, skeletal debris; minor complex grains and oncolites. Skeletal fragments generally disarticulated but not highly abraded or micritized. Very fine to fine-grained detrital quartz grains occur locally. Where replaced by silica, the grain textures may be preserved or are molds filled with chert, silica or calcite cement (**fig. 5A**). Where dolomitic, skeletal grains typically preserved as molds (**fig. 5B**).	Where dolomitic, typically has a wispy laminated or mottled texture; locally it has a massive texture. Locally, interbedded skeletal rich layers (more porous) and skeletal poor layers (tighter) result in an alternating porous and tight layering within this facies. Horizontal laminations and low-angle cross laminations locally. Local sorting of grains into fine-grained layers and coarser-grained layers; local normal grading of grains. Typically not much evidence for over compaction or early compaction. Grains locally show compromise boundaries, overly close packing, grain breakage and flat, horizontal alignment of skeletal fragments, Only minor occurrences of original calcite syntaxial overgrowths. Grainstones locally have isopachous chalcedony cement that coats grains and lines primary pores (**fig. 5C**). Some original molds, fenestrae, and vugs contain a floored (geopetal) internal sediment that was silicified with remainder of pore space filled with silica cement (**fig. 5C**).	Commonly partially or pervasively replaced with porcelaneous (tight) or, locally, tripolitic (porous) chert/megaquartz. Abundant vuggy and microcrystalline porosity in tripolitic chert areas and both tripolitic and porcelaneous chert typically contains micro- and mega-fracture porosity. Vugs locally developed within chert areas and partially or fully filled with silica cement. Fenestral pores either partially or fully filled with silica cement occur locally (**fig. 5D**). Some pores contain a silicified internal marine sediment and a later pore filling, or partially filling silica cement. Where dolomitic, porosity in this facies can exceed 22% (Byrnes and Franseen, 2000). Common porosity types include moldic, moldic reduced, intercrystalline, and vugs. Dolomite typically very finely crystalline (~50 μm or less) but locally exceeds 150 μm. Crystals are typically subhedral to euhedral. Some crystals zoned with a clear to turbid (locally calcian) center and clear dolomite rim. Some dedolomite.
Dolomitic Siltstones & Shale	Composed predominantly of very fine grained sand (~100 μm) to silt-sized (<50 μm) quartz grains and clays; sand- to pebble-size grains occur locally (**fig. 6**).	Wavy to wispy laminated and locally displays low-angle lamination. Shale locally occurs as wispy layers in dolomitic mudstone or wackestone facies.	Occurs as interbedded layers or as fracture fill and breccia matrix containing clasts of carbonate facies and replacive silica (**fig. 3**).

TABLE 2—Other core features.

Core Feature	Characteristics
Silica	Replacement silica and silica cements abundant throughout all three cores (**fig. 3**). Convoluted nodular, anastamozing bedded and bedded replacements (terminology of Nolte and Benson, 1998) are characteristic in EWPG facies (**fig. 7**). Disseminated silica, characterized by "ragged" boundaries with unsilicified strata of the same facies, is most common in the MW and SWP facies (**fig. 7**). Silica replacement occurs either as pervasive or partial replacement of original facies, textures or grains. Silica typically white to light gray in hand sample with a porcelaneous (tight) or more rarely a chalky porous (tripolitic) texture. Much of the chert replacement appears to follow original burrows or bedding planes. Silicified areas commonly exhibit a fracture and brecciated texture with variable micro-and macro-fracture porosity. Silica occurs as microquartz, megaquartz, chalcedony (both length-fast and length-slow), and zebraic chalcedony. Some microspherules (approximately 25-40 μm diameter) occur and may represent original cristobalite lepispheres. Silica replacement and cementation appear to have occurred in stages with early microquartz and chalcedony replacement of facies and grains, isopachous brown chalcedony cement lining pores and megaquartz as a later stage replacement or pore-filling cement (**fig. 5A, C**). Ghosts of micron-sized microstructural features in some silicified grains that were originally carbonate, such as echinoderms, indicate that silica precipitation and carbonate dissolution occurred simultaneously along thin solution films (**fig. 5A**; Maliva and Siever, 1989). Void-filling silica indicates a more rapid volumetric calcite dissolution rate than the volumetric silica precipitation rate (**fig. 5C**). Silica in the form of microquartz or chalcedony locally preferentially replaces spicules (**fig. 4B**) or replaces the matrix surrounding the spicules and leaves the spicules as molds (**fig. 4D**).
Silica-Replaced Evaporites	Silica-replaced evaporite textures include individual crystals, initial nodule development, complete nodule development, laterally coalesced nodules forming horizontal layers, some of which are composed of coalesced vertically elongate nodules (**fig. 8**), and local chicken-wire structure (**fig. 9A**). Individual nodules are generally <0.5 to 5 cm in size. Nodules and crystals preserve a bladed, radiating bladed, and twinned crystal morphology (**fig. 9B**), indicating replacement of anhydrite or gypsum. Individual bladed crystals, many with blunt ends, are typically between 100 μm-300 μm in length (20-60 μm width) with some blades over 500 μm in length (**fig. 9B, C**). Some megaquartz crystals in replaced evaporites contain abundant inclusions of evaporite minerals (anhydrite). Some preserved fabrics of pseudomorphed evaporites show crystal fabric evolution characteristic of different modes of nodular anhydrite growth as depicted by Shearman and Fuller (1969). Crystals show a d-decussate and sub-parallel arrangement of laths within the more central portion of the nodules, and the laths become "bent" and sub-parallel to the periphery of the nodule at the contact with the host sediment (**fig. 9C**).
Brecciation & Fracturing	Macro- and micro-scale brecciation and fracturing are ubiquitous throughout the three cores (**fig. 10**) resulting in fracture and mosaic breccias. Textures range from little to no rotation on clasts to matrix-supported and clast-supported chaotic breccias that represent mixtures of autochthonous and allochthonous materials resedimented by gravitationally driven processes. Fracture fill and breccia matrix includes shale, subangular to rounded, silt- to coarse-grained size detrital quartz, chert, megaquartz, chalcedony grains, carbonate micrite, carbonate grains, and skeletal grains. Clasts (ranging from rounded to angular) include chert/chalcedony/megaquartz fragments, clasts of original carbonate facies, replacive poikilotopic calcite clasts, coarse calcite cement fragments, and rubble of red and greenish limy clay. Porosity associated with fracturing and brecciation is quite variable, ranging from tight to very porous. Interparticle, intercrystalline, vuggy, and fracture porosity are common porosity types in breccia matrix.
Calcite Cementation & Replacement	Several different stages of calcite cementation and replacement occur. One event is associated with subaerial exposure (SB1 surface) (**figs. 3, 10, 12**) and results in locally extensive calcite replacement and cementation of DS1 strata. A later stage of calcite cementation and replacement is associated with post-Mississippian subaerial exposure that affects facies in the upper portions of cores (**fig. 3**).

TABLE 3—Evidence for early silicification, evaporites, dolomitization.

1) Close association of silicification and burrowing suggesting that burrows may act as a site for the initiation of the process. Lawrence (1993) noted that the same relationships have been made from DSDP sediments and indicated that higher organic content and a high porosity and permeability of burrow fill may predispose burrows to early chertification.

2) Although minor grain interpenetrations and shell breakage occur, there is an overall lack of compaction evidence in EWPG facies prior to silicification. Meyers (1977) noted similar relationships in Mississippian chertified facies in New Mexico that he interpreted as indicating early chert.

3) Very little original calcitic syntaxial or epitaxial cements have been identified in EWPG facies to date. Instead, isopachous chalcedony cement lines primary pores that contain later pore-filling silica cements. The lack of calcite cements in these facies, which typically are characterized by early calcite cements, and the presence of isopachous chalcedony cements in primary intergranular pores indicates early silicification.

4) The loose packing of much of the relict sponge spicules and their molds suggests dissolution and reprecipitation of silica prior to deep burial.

5) Evidence of early differential compaction characterized by brittle fracturing of silicified areas (including original evaporite minerals) and soft-sediment deformation of surrounding dolomite sediment. Fractures in silicified areas are commonly filled with dolomitic sediment. Meyers (1977; Mississippian strata) and Saller et al. (1991; Devonian strata) noted similar features that they used as lines of evidence for early silicification.

6) Stylolites commonly occur within dolomite facies or at the contacts of carbonate sediment and silicified areas (but not within silicified areas) indicating greater compaction after silicification.

7) Anhydrite in ancient evaporites is readily compacted (Maiklem et al., 1969; Shearman and Fuller, 1969). The preservation of radiating bladed evaporite crystal and nodule textures without much breakage or compaction is supportive of early evaporite emplacement and silica replacement prior to a heavy overburden. Similar preservation has been documented by Chowns and Elkins (1974) in Mississippian strata and Geeslin and Chafetz (1982) in Ordovician strata, which they interpreted to support early silicification. In addition, the preserved relict lath textures of many crystals and nodules in this study indicate they were originally made of anhydrite (Kinsman, 1970; Shearman, 1978). Geeslin and Chafetz (1982) recognized similar textures and interpreted them to indicate silicification during very early diagenesis while still in the vadose zone. This is because hydration of anhydrite to gypsum takes place readily in the presence of water (e.g. in a phreatic mixing zone; Shearman, 1978), and the silicified nodules lack any evidence of hydration of anhydrite to gypsum.

The presence of bent and broken crystals and disruption of anhydrite crystals by displacive growth is remarkably similar to those shown by the Shearman and Fuller (1969) for Holocene anhydrite laths in halite-cemented nodules from the supratidal sediments of the Trucial Coast. Some of the evaporites show chicken-wire fabric and occur with fenestral fabric which also supports the analogy (**fig. 9A**). Rare nodule fabrics with elongate crystal psuedomorphs of original evaporites occur (**fig. 8**). These are similar to fabrics shown by Orti and Rosell (2000) from the Miocene of Spain. They interpret these morphologies as distinctive of the anhydrite-to-gypsum hydration process, in which anhydrite originally formed interstitially in the sediment in a playa/sabkha setting replacing or displacing the matrix. Other evidence supporting replacement of original evaporites includes the presence of length-slow chalcedony (quartzine and lutecite), which has been interpreted to be associated with the replacement of evaporites (Folk and Pittman, 1971).

8) Some areas of silica-replaced evaporite pseudomorphs contain inclusions of dolomite crystals. This indicates a close temporal association of dolomite, evaporites, and silicification, all occurring early and perhaps simultaneously.

9) Post-DS2 subaerial exposure, burial compaction, and structural uplift resulted in brittle fracturing and brecciation that crosscuts all DS2 and DS1 facies and previous diagenetic events, including silicified evaporites. Several generations of crosscutting fractures are filled with a variety of material including silica cement, calcite cement, shale, subangular-to-rounded silt- to coarse-grained-size detrital quartz, chert, megaquartz, chalcedony grains, carbonate micrite, and non-skeletal and skeletal grains.

Schaben Field Area Depositional Environments

The following section interprets environments of deposition based on features observed in cores. This section briefly discusses DS1 and SB1, but focuses on DS2 because it is the sequence that contains abundant biosiliceous (sponge spicule) and heterozoan carbonate facies interpreted to have been deposited in shallow-water environments. Additional details on DS1 and SB1 can be found in Franseen (1996), Franseen et al. (1998) and Montgomery et al. (2000). The block diagram in fig, 11 is an interpretation of the general setting of depositional environments, especially during DS2 deposition.

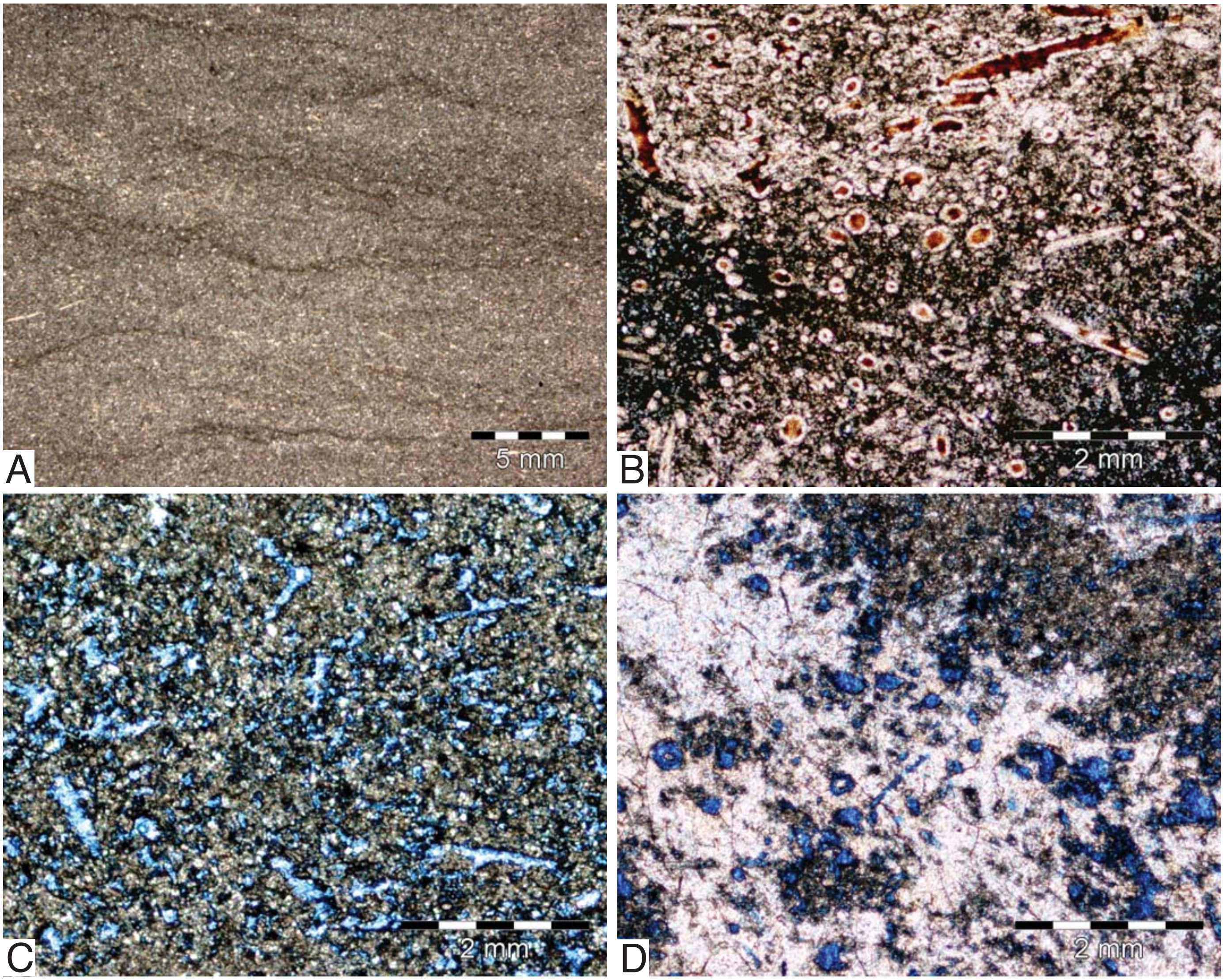

FIGURE 4—A) Mudstone/Wackestone (MW) Facies. Wispy lamination imparted by clay and horsetail stylolites. This facies is typically tight. B) Sponge Spicule-rich Wackestone/Packstone (SWP) Facies. In this sample the siliceous sponge spicules (note central axial canals) are preserved by microcrystalline quartz and chalcedony. Much of the matrix is silicified and only a minor amount of intercrystalline porosity is present. C) More typical preservation of SWP Facies with abundant sponge spicule molds (blue epoxy areas) and intercrystalline porosity in dolomite matrix. This is the main reservoir facies in Schaben field. D) Sponge spicules have been dissolved leaving molds (dark-blue round/oblong areas) and the surrounding matrix has been mostly replaced by silica (light areas). Much of the matrix in the upper right corner remains dolomitic.

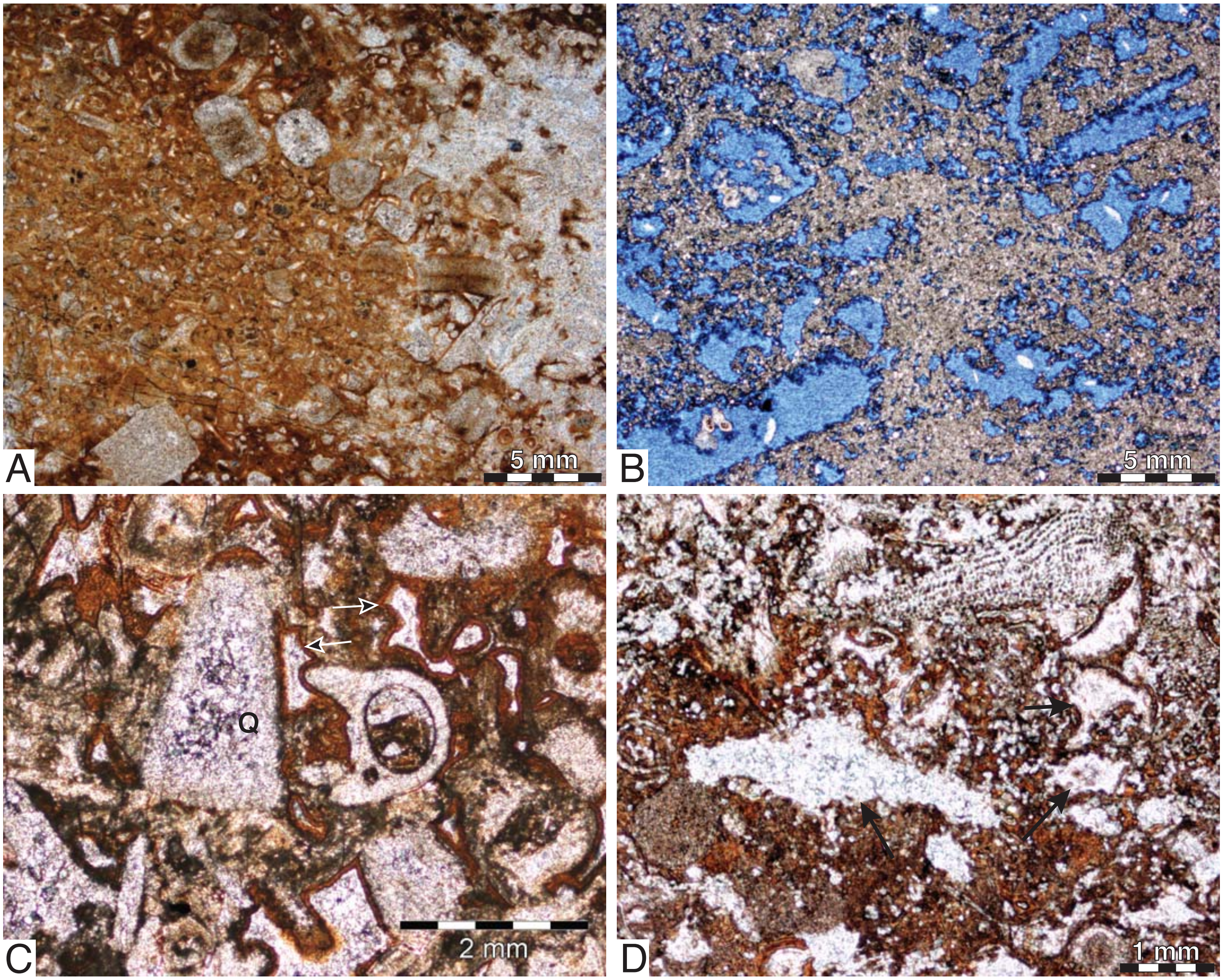

FIGURE 5—Echinoderm-rich Wackestone/Packstone/Grainstone (EWPG) Facies. A) Silicified EWPG Facies. Packstone-grainstone texture has largely been preserved. Echinoderm fragments with textures preserved or molds filled by silica cement predominate. Abundant fragments of other skeletal material occur, including sponge spicules, which also are replaced by silica or have molds filled with silica cement. B) EWPG Facies. Echinoderm fragments and other skeletal fragments, including sponge spicules, have been dissolved leaving abundant moldic porosity (blue areas) in relatively tight dolomitic matrix. C) Silicified EWPG Facies. Echinoderm fragments generally lack evidence of syntaxial overgrowths. Typically, primary pores are lined by brown isopachous chalcedony cement (arrows). Primary pores, or molds of echinoderms, are filled by later quartz cement (Q). D) Silicified EWPG Facies. This sample contains fenestral-type pores (arrows) filled by quartz cement.

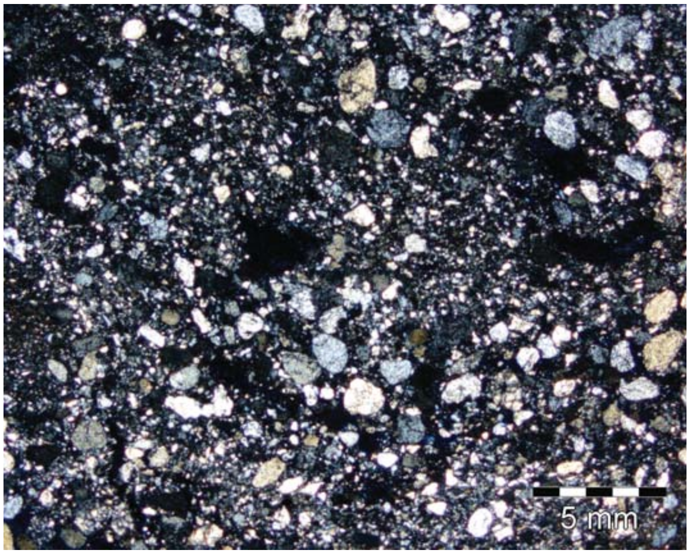

FIGURE 6—Shale/siltstone/sandstone layers are locally present, typically interbedded with SWP or MW facies. This facies occurs as interbedded layers associated with deposition during Osagean time and as post-depositional fill associated with SB1 and the pre-Pennsylvanian unconformity. This sample contains mostly subround to subangular detrital quartz grains with minor clay. Scale 1 mm. Crossed nicols.

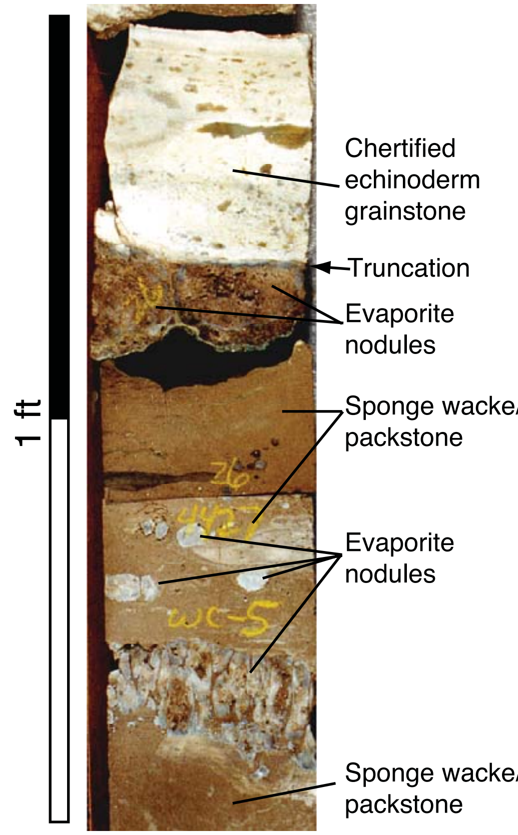

FIGURE 8—Core photo. Base of core consists of SWP Facies containing abundant silica-replaced evaporite nodules (white-gray to gray colored areas). Several evaporite nodule morphologies can be seen in this interval; vertically elongate crystals coalescing to form a layer (near base), individual round to oblong nodules, and coalesced nodules. Several coalesced nodules are truncated, with the truncation surface overlain by chertified echinoderm-rich grainstone containing silica cement-filled fenestral and vuggy pores.

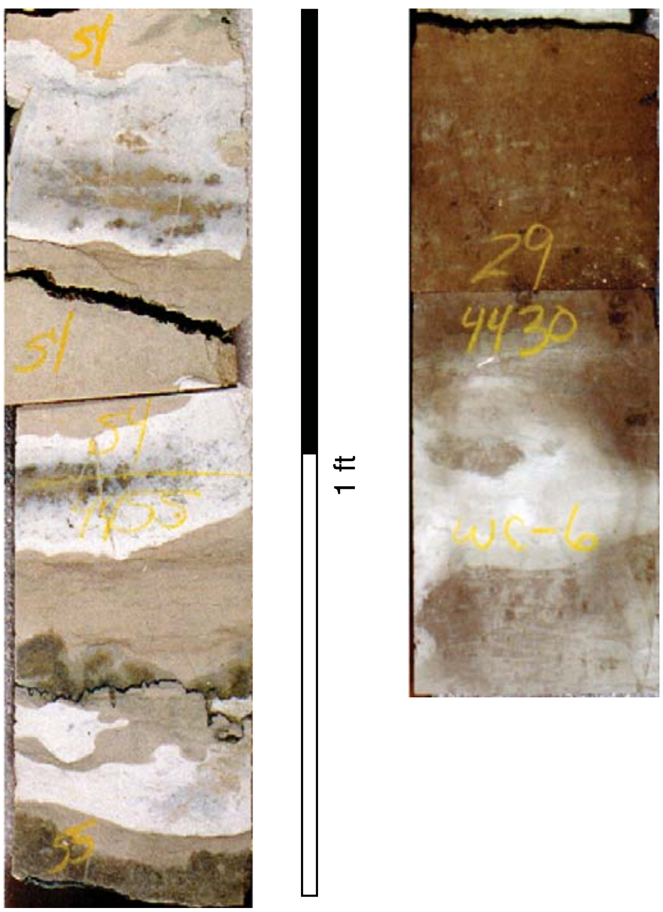

FIGURE 7—Different types of silica replacement. Core photo on the left is of EWPG Facies, which is characterized by convolute nodular, anastamozing bedded and bedded replacement chert (following terminology of Nolte and Benson, 1998). White and whitish-gray areas are chert and light-tan to light-gray areas are carbonate. Core photo on the right is of SWP Facies which is characterized by disseminated silica and“ragged” boundaries with unsilicified strata of the same facies. Whitish-gray areas are silica and darker-brown areas are dolomite.

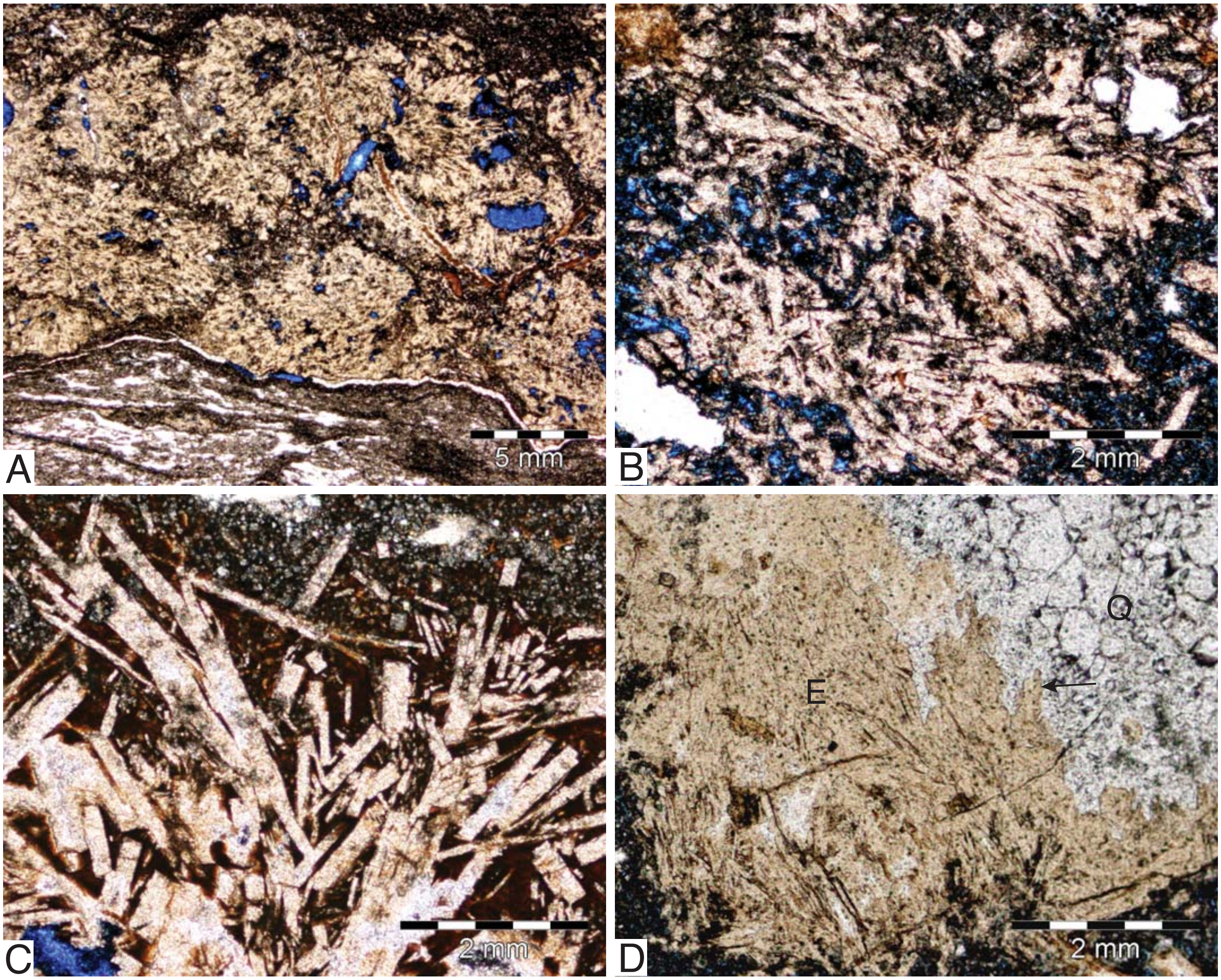

FIGURE 9—Silica-replaced evaporite textures. A) This sample contains evaporite nodules in dolomitic SWP Facies forming “chicken-wire texture”. The base of the sample contains elongate fenestral-type pores. B) Silica-replaced bladed and radiating bladed crystal pseudomorph textures of original evaporite (anhydrite, gypsum) minerals in SWP Facies. This sample exhibits displacive growth of crystals and formation of nodules in dolomitic sediment. Preservation of these fabrics suggests early replacement by silica prior to any significant compaction. C) Silica-replaced evaporite crystal pseudomorphs in SWP Facies. Laths become “bent” and sub-parallel to the periphery of the nodule at the contact with the host sediment. D) This sample shows original evaporite crystals replaced by clear to brown silica (E). This was followed by a dissolution/corrosion event (arrow). Remaining porosity was filled by clear megaquartz cement (Q).

FIGURE 10—#2 Lyle Schaben "P" core photo and description from ~ 4,418 ft to 4,431 ft. Note the SB1 surface at ~ 4,424 ft that separates DS1 (below) from DS2 (above). Strata below SB1 contain abundant evidence for subaerial exposure, including iron-stained (F) mottled areas. Petrographic examination indicates some of these altered areas are characterized by a central area filled with coarsely crystalline calcite cement surrounded by a halo rich in hematite and fenestral pores in dolomitic and replacive poikilotopic calcite matrix (see fig. 12C), which may indicate these are associated with land plant roots. Vanstone (1991) described identical feature in late Osagean-early Meramecian paleosols from southwest Britain. Strata below SB1 are also affected by a coarsely crystalline calcite poikilotopic replacement and cement (see also figs. 3 and 12A). Strata above SB1 consist of MW and SWP facies, containing abundant silica-replaced evaporites (e.g. ECN = coalesced evaporite nodules).

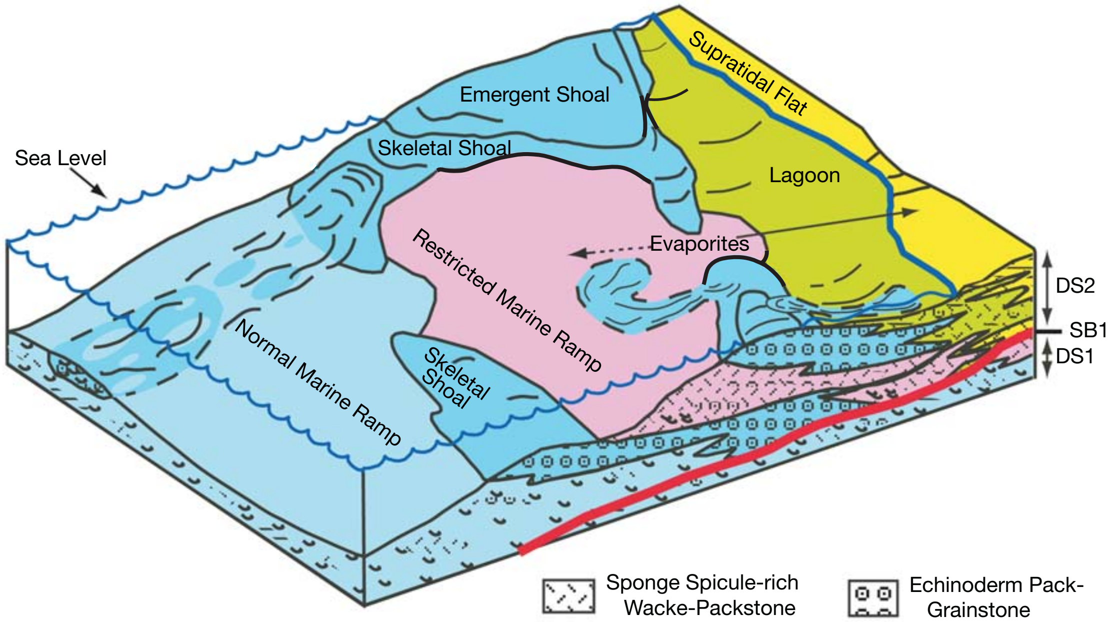

FIGURE 11—Block diagram of interpreted inner shelf/ramp depositional environments in the Schaben field study area, especially during deposition of DS2.

Depositional Sequence 1 (DS1)

The abundance of the echinoderm-dominated facies containing other diverse fauna, including bryozoans, sponge spicules, brachiopods, solitary coral fragments, gastropods, and evidence of extensive reworking by burrowing organisms suggest deposition in relatively shallow subtidal, normal-marine environments. Sedimentary structures are rare, likely due to bioturbation and reworking. Fluctuating energy conditions are indicated by the interbedding of mudstone-wackestone with packstone-grainstone, locally preserved crossbedding, grain breakage, and scoured contacts. Upward decrease in thickness of EWPG beds and local preservation of crossbedding in uppermost DS1 strata may reflect a shallowing of water and increase in energy upward. The increase in MWP and SWP facies containing local evidence of primary evaporites in uppermost DS1 strata (especially in the #4 Moore core) indicate increased restriction, likely due to shallowing of water leading up to the overlying SB1 subaerial exposure event. As shown on fig. 1B, the #4 Moore core is in a position nearer the CKU, which was likely a paleotopographically high feature during deposition.

The facies and sedimentary features in DS1 are similar to those described from other Mississippian examples. Johnson and Budd (1994) described dolomudstone, dolowackestone, dolopackstone/grainstone, and lime grainstone facies dominated by echinoderms and fenestrate bryozoan fragments in nearby shelfal Meramecian strata in Kansas (Bindley field), which they interpreted to represent deposition in a normal-marine, low- to high-energy shelf environment that was periodically winnowed by storms. They noted a gradual upward increase in spicule-rich dolomudstone facies (much like DS1 strata of this study) that they interpreted to reflect increasing restriction and stress on the normal marine fauna. Witzke et al. (1990) describe Keokuk Limestone crinoidal and spicular wackestone and mudstone in Iowa that they interpret to represent quiet-water subtidal environments below fair-weather wave base and interbedded crinoid-bryozoan packstone intervals that are interpreted to record episodic bottom agitation during storm events in the middle-shelf environments. Martindale and Boreen (1997) studied Early Mississippian carbonates in southern Alberta and described inner-ramp areas dominated by structureless echinoderm grainstone shoals, which they interpreted to be due to the variable nature of storm processes and biological mixing. They also noted evidence of abundant transport in crinoidal grainstones and autocyclic shifting of facies through bedform migration in areas of constricted flow and during large storms. The storms periodically transported crinoid grains downslope as tempestite flows.

The depositional setting for DS1 is envisioned as a mostly normal to slightly restricted marine-ramp setting that was a site of growth and accumulation of skeletal and spicule material as well as allochthonous deposition characterized by autocyclic shifting of facies through migration of bedforms (sandwaves, subtidal shoals) in areas of increased currents and during storms. Some beds may represent mass-flow transport of grains downslope during storms. Some of the echinoderm wackestone, sponge spicule dolowackestone-packstone, and bioclastic dolomudstone-wackestone facies are likely indicative of lower-energy subtidal setting compared to the echinoderm-rich packstone/grainstone facies in DS1 strata. The inner shelf during DS1 deposition became increasingly restricted prior to subaerial exposure and formation of a sharp contact (SB1) between DS1 and DS2 (fig. 3). Sequence Boundary 1 is regionally extensive and it, and the strata immediately below for several meters, show significant alteration and evidence for subaerial exposure (figs. 3, 10, 12) prior to deposition of DS2 (e.g. autobreccia, clay-rich crusts with

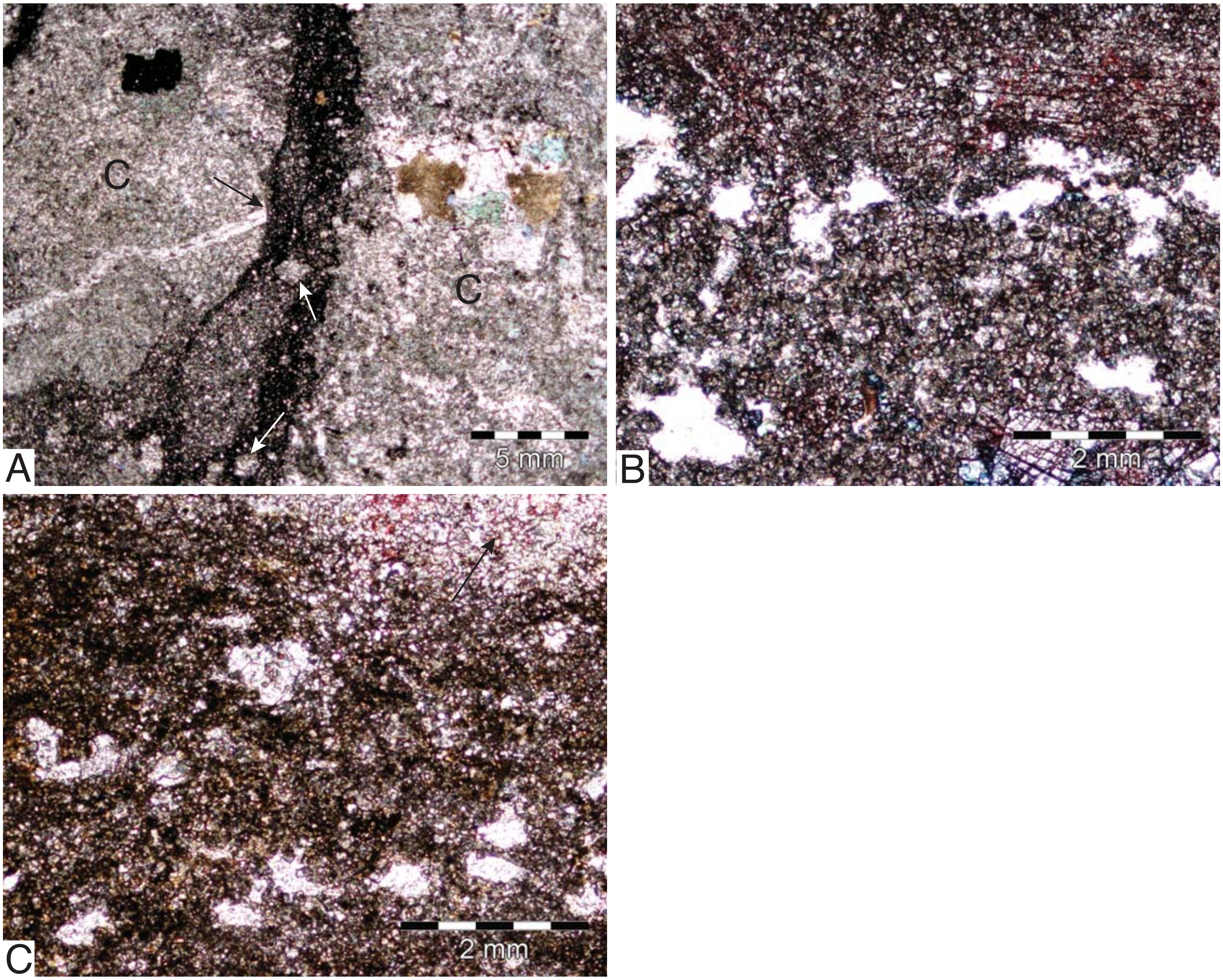

FIGURE 12—Features associated with SB1. A) Calcite-replaced facies (C) below SB1 that were subsequently fractured and filled with very finely crystalline dolomite that contains clasts of the poikilotopic calcite (white arrows). Note the truncated coarsely crystalline calcite cement-filled fracture in the poikilotopic calcite (black arrow). B) Abundant fenestral pores (white areas) developed in dolomitic matrix just below SB1 in the # 2 Lyle Schaben core. Note pore at bottom of photo (right of center) filled with coarsely crystalline calcite cement that is common below SB1. C) Altered facies below SB1. Some oblong and tubular altered areas (soil features?) are characterized by a central area filled with coarsely crystalline calcite cement (arrow) surrounded by a hematite halo (hypocoating?) and fenestral pores (white areas) in dolomitic and replacive poikilotopic calcite matrix.

abundant horizontal fenestrae interlaminated with fine- to coarse-grained detrital quartz, branching and tapering microfractures and iron-stained oblong features interpreted to be related to roots, poikilotopic calcite cement localized in strata just below the SB1 surface; see Franseen, 1996, for more details).

Depositional Sequence 2 (DS2)

After the SB1 subaerial exposure event, marine conditions returned but the depositional environment over the study area changed compared to that for much of DS1 deposition. DS2 shows a volumetric increase of sponge-spicule wackestone and packstone (SWP) with less diverse fauna, an abundance of original early evaporites (replaced by early silica; table 3), evidence for early dolomite (table 3) and evidence of shallowest water to possibly subaerially exposed conditions (mostly fenestral fabrics; e.g. fig.9A) throughout DS2. These features suggest deposition in more restricted environments (compared to DS1) that ranged from restricted inner shelf/protected embayment to evaporative lagoon (coastal salina?) and possibly supratidal flat. SWP and MW facies with an abundance of evaporites represent the most restricted conditions. Sponge dominance may reflect in-place accumulations where sponges thrived due to conditions inhibiting other biota (e.g. salinity, elevated silica and nutrients, cooler water temperatures) as well as shelfward transport from more open-marine environments. Local evidence of burrowing in DS2 indicates an influence of marine conditions sufficient to support some organisms that reworked the sediment during parts of DS2 deposition. Wispy and wavy horizontal lamination, alternating grain-rich and grain-poor layers, and local interbeds of grainstone in sponge-rich facies indicate transport and reworking of sediment by currents as well. Rare oncolitic coatings, wavy lamination, and micro-scale dark mottled areas may indicate some algal influence.

Thin interbeds of echinoderm-rich facies (EWPG) in DS2 are more open-marine deposits that could have resulted from several different processes. They could represent a cyclicity tied into relative sea-level changes, with the EWPG facies representing more normal-marine conditions during relative sea-level rises and highstands. Alternatively, these beds may be due to autochthonous processes such as migration of subtidal shoals or transport, including shelfward spillover deposition into a lagoon or supratidal environment, from tide or storm currents. Some of the relationships of EWPG and SWP/MW facies in DS2 (e.g., fig. 8) are similar to Holocene shallow-water saline lagoon carbonate and evaporite sediments described in the southwest Persian Gulf (Kendall and Skipwith, 1969). Shallowest water to locally subaerially exposed indicators (e.g. fenestral fabrics) that occur locally throughout DS2 could also result from several different processes, including local accumulations to sea level, evaporative drawdown, or relative sea-level falls. Distinguishing between the different possible controls for the formation of features and facies relationships within DS2 remains for future work.

One of the more significant characteristics in DS2 is the dominance of siliceous sponge-spicule facies and heterozoan carbonates that were deposited in shallow-water and restricted environments. Although it is common to think of such deposits as reflecting cold-water polar or deep basinal conditions (James, 1997), this study and others from numerous periods in the geologic record are indicating that shallow-marine, mid-latitude biosiliceous and heterozoan carbonates may be more common than previously thought (table 4). Especially interesting are the examples from Mississippian (Osagean-Meramecian) strata in North America that show similar facies associations with DS2 strata of this study (Ebanks et al., 1977; Johnson and Budd, 1994; Chowns and Elkins, 1974; Choquette et al., 1992; Lindsay, 1985).

Controls on Deposition of Early-Middle Mississippian Shallow-water Siliceous Sponge-spicule and Heterozoan Carbonate Facies

As indicated earlier, studies by others (Witzke, 1990; Golanka et al., 1994; Scotese, 1999) place the Kansas study area during Early-Middle Mississippian time in a tropical/subtropical location, at about 20° S latitude and drifting north during the Carboniferous. In this setting shallow-water carbonates dominated by photozoans might be expected. In addition Gammon et al. (2000) point out that siliceous spiculites do not occur on the inner portions of shelves in subtropical and tropical environments under typical conditions. Therefore, the dominance of shallow-water biosiliceous (sponge spicule) and heterozoan carbonates in this setting in Kansas and throughout similar settings in North America during the Early-Middle Mississippian (examples discussed above) requires elevated nutrient and dissolved silica supplies that prevented the development of photozoans and promoted the development of heterozoan and siliceous sponges (James, 1997).

Elevated nutrient and dissolved silica supplies could originate from terrestrial or oceanic sources. Some studies have emphasized fluvial and ground-water sources for elevated nutrients and dissolved silica with a link to humid climate for promoting biosiliceous and heterozoan carbonate facies development in mid-latitude, shallow water (inshore) environments (e.g. Gammon et al., 2000; James and Bone, 2000; Lane, 1981; Cavaroc and Ferm, 1968; Carlson, 1994). Upwelling is another mechanism that delivers nutrient- and silica-rich cool oceanic water to shelf margins. As discussed below, a number of studies interpret upwelling as an active process that was responsible for creating the widespread development of siliceous deposits during Early-Middle Mississippian time on margins of much of the North American carbonate shelf, including the current-day Kansas region.

Early-Middle Mississippian Regional Upwelling

Lowe (1975) noted the widespread development of siliceous deposits both within the Ouachita basin and on adjacent shelf areas, especially in Upper Devonian and Lower Mississippian strata that he suggested represented unusually high regional silica levels during at least part of the Paleozoic. Maliva and Sevier (1989) suggested that Paleozoic sea water might have contained more silica than modern sea water due to inefficiency of pre-diatom biogenic precipitation. Lowe (1975) additionally thought that silica for the Ouachita basin and adjacent shelf areas may have come from volcanic sources along the orogenic zone marking the North American-Gondwana convergent plate junction. The volcanic sources enriched westerly equatorial surface currents in silica, which produced an area of silica productivity associated with sites of dynamic upwelling off the west coasts of Gondwana and North America. Lowe (1975) postulated that during relative rises in sea level, waters from this upwelling area were able to spill eastward across the Paleozoic Mexican peninsula and into the Ouachita seas.

One model to transfer cold or cool, silica-rich water in the Ouachita basin to the adjacent shelf areas is the zonal coastal upwelling model of Parrish (1982), which shows upwelling occurs on north- or south-facing coastlines that are situated at the proper latitude relative to the major zonal wind systems (fig. 13). According to Parrish (1982), zonal coastlines were more common in periods of earth's history than they are now, and zonal coastal upwelling has the potential to be extensive because it is not limited in length by the Coriolis effect or confines of

TABLE 4—Shallow-water siliceous sponge associations.

Age & Location	Facies	Characteristics & Associated Features	Depositional Environments	References
Ordovician, New Mexico	Ribboned chert and dolomite	Abundant siliceous sponge spicules; associated with pellets, laminated textures, stromatolites, fenestral fabrics, replaced evaporite nodules	Sabkha, intertidal to shallow subtidal	Geeslin and Chafetz (1982)
Devonian Caballos Novaculite	Novaculite	Sponge spicules as the sole faunal remains; fenestral fabric; small evaporite nodules and laminae	Very shallow environment in semirestricted lagoons or bays; hypersaline, reducing tidal flat areas	Folk (1973)
Upper Devonian, Alberta, Canada	Siliceous sponge wackestone to fossil-rich pack-stone	Siliceous sponge spicules are the most abundant skeletal fragments in the wackestones	Basal portions of mud mounds (Miette) in 20-30 m water depth	Shiraki (1996)
Mississippian - uppermost Osagean, Kansas	Cherty dolomite	Abundant monaxon sponge spicules or their molds; chert replaced former evaporite minerals; interlaminated dolomite and shale, broken and curled dolomite laminae, scoured bedding surfaces	Supratidal, sabkha-like environment	Ebanks et al. (1977)
Mississippian - Meramecian, Kansas	Spicule-rich dolomud-stone	Low-diversity fauna; chalcedony/ quartz nodules after replaced evaporites	Low-energy, subtidal environment that ranged from restricted to evaporitic	Johnson and Budd (1994)
Mississippian-Osagean and Meramecian, Tennessee	Cherty dolomitic spiculites	Silica nodules after original evaporite minerals	Tidal-flat-lagoon-complex environments	Chowns and Elkins (1974)
Mississippian-Osagean, Illinois & Missouri	Siliceous dolostone	Abundant sponge spicules, burrows	Restricted conditions in protected inner-shelf environments	Choquette et al. (1992)
Mississippian-Meramecian, North Dakota	Spiculitic, dolomitized pelletal wacke/ packstones	Sparse anhydrite nodules, sponge spicules and their molds	Restricted marine to tidal-flat facies	Lindsay (1985)
Pennsylvanian-Desmoinsian, Indiana	Spiculite	Abundant monaxon spicules; occur with echinoderms, ostracodes, trilobite fragments, gastropods, byrozoans, and brachiopods	Sponge mats that formed in nearshore environments	Lane (1981)
Middle Pennsylvanian, Appalachian Plateau	Spiculite (flint); sponge-spicule-dominated flint beds	Dense mats of siliceous spicules; some brachiopods; ghosts of spicules common	Transgressive deposits formed in swampy shoreline areas removed from major sites of detrital influx	Cavorac and Ferm (1968)
			Still-stand deposits that formed in quiet, sediment-starved lagoons or bays that bordered the swampy portions of the resulting shore	Carlson (1994)
Upper Pennsylvanian, Austria, Italy	Bryozoan-spicule wackestone	Sponge spicules with brachiopods, bryozoans, small foraminifers, ostracodes, red algae, crinoids; silicification of biota is common	Shallow-water environments	Samankassou (2002)
Upper Carboniferous & Permian, Spitzbergen (Svalbard)	Hyalo-sponge association	Sponge-dominated siliceous carbonates	Intertidal to shallow subtidal	Huneke et al. (2001)
Late Permian, Sverdrup Basin, Canada	Fossiliferous spiculitic chert and light spicu-litic chert	Storm-dominated, distally steep-ened ramp environment	Inner ramp	Gates (2003)

TABLE 4 (continued)

Age & Location	Facies	Characteristics & Associated Features	Depositional Environments	References
Lower Eocene, Spanish Pyrenees	Laminated ostracod-rich facies with abundant sponge spicules	Laminated wackestone-packstone with monospecific ostracods and abundant sponge spicules; desiccation cracks abundant; chert occurs dominantly in this facies	Restricted, brackish-water conditions	Gimenez-Montsant et al. (1999)
Eocene, western Australia	Spiculite	N/A	Shallow marine	Maliva et al. (1989)
Late Eocene, south Australia	Spiculite	Sediment is a microbioclastic mudstone spiculite in texture; numerous peloids and a few large bryozoans, brachiopods, and echinoid spines	Shallow water (< 100 m) partially barred lagoon; warm-temperate and humid climate	James and Bone (2000)
Late Eocene, southwestern Australia	Siliceous spongolite and spiculite	Local trough crossbeds and rare wave ripples; abundant burrows; rare cal-careous fossils	Protected embayments and estuaries. Sponges colonized all available estuarine and embayment water depths (0-~40 m). Cimate was warm temperate (possibly warmer) and humid	Gammon and James (2000); Gammon et al. (2000); Gammon and James (2003)
Miocene, Alabama, Delaware	Diatomite-mudstone	Poorly lithified; mixtures of diatomite, spiculite, porcellanite, and terrigenous and authigenic clay; locally contains shallow-water carbonate debris	Highly productive shallow lagoons and bays in which terrigenous sediment was not sufficiently abundant to dilute the diatom frustules and siliceous sponge spicules	Maliva et al. (1989)

zonal climate patterns. The paleogeographic setting of Kansas and the surrounding regions at ~20° S latitude in the Osagean with a generally south-facing coastline, and the likely surface-wind patterns (fig. 13) are in favorable agreement with the zonal upwelling model of Parrish (1982).

Nobel (1993) notes the onset of tectonism in the Ouachita System in the Late Devonian to Early Mississippian, which resulted in compartmentalization in the Ouachita basin with microcontinental fragments and constriction of the transequatorial passageway connecting the Iapetus and Panthalassic seas during the collision of Laurasia and Gondwana. The stricture of passages resulted in increased bottom-current velocities in the Early Mississippian, and the microcontinental fragments served as intermittent barriers, which allowed for development of local anoxic conditions. Vogt (1989) showed that strongly anoxic waters form in restricted basins today, and that occasional upwelling occurs in some of them. The Early Mississippian eustatic sea-level rise may have been associated with an oceanic anoxic event (Jenkyns, 1980). These elements may have contributed to conditions that were conducive to upwelling of nutrient and silica-rich waters across the shelf adjacent to the Ouachita basin.

Parrish (1982) proposed that in the latest Devonian-earliest Mississippian the most vigorous upwelling would have been southwest of the eastern highlands (present orientation) over Texas, Kansas, and Oklahoma, although she showed Kansas sitting at a position nearer the equator during this time slice, as compared to the 20° S latitude position of more recent studies (Witzke, 1990; Golanka et al., 1994; Scotese, 1999) (fig. 13). Parrish (1982) indicated that areas near the highlands would have experienced less vigorous upwelling and that the degree of upwelling influence would also have decreased to the northwest, toward the Williston basin, as the shelf became shallower in that direction. Parrish (1982) placed the richest sources of upwelling in the southwest and midwest and pointed to those areas as the most likely site for chert.

Other studies of Early-Middle Mississippian strata have also called on upwelling. Gutschick and Sandburg (1983) interpreted upwelling to have been an important factor along the margins of much of the North American carbonate shelf during the latest Tournaisian (middle Osagean). Wright (1991) interpreted Early Mississippian deposits from within and outside of North America to have resulted from upwelling. Lumsden (1988) interpreted the proliferation of sponges in the Ft. Payne in Tennessee to be due to silica supplied from upwelling waters from the open ocean troughs to the west and southwest. More recently, Lasemi et al. (1998, 2003) interpreted upwelling of nutrient- and silica-rich cool oceanic water for Early Mississippian deposits in the Illinois basin, which sat at about 20° south of the equator, a position similar to that for Kansas during the same time interval.

Possible Controls on Study Area Inner-shelf Facies

The above studies indicate that upwelling likely was an active regional process during Osagean deposition in Kansas. The proliferation of siliceous sponges to form buildups in present-day Kansas and Oklahoma shelf margin areas (e.g. Rogers et al., 1995; Colleary et al., 1997; Montgomery et al., 1998; Watney et al., 2001) is compatible with upwelling of basinal waters to deliver nutrients and dissolved silica to those areas. In addition, the widespread abundance of glauconite in Osagean strata in Kansas (Goebel, 1968) is considered a characteristic

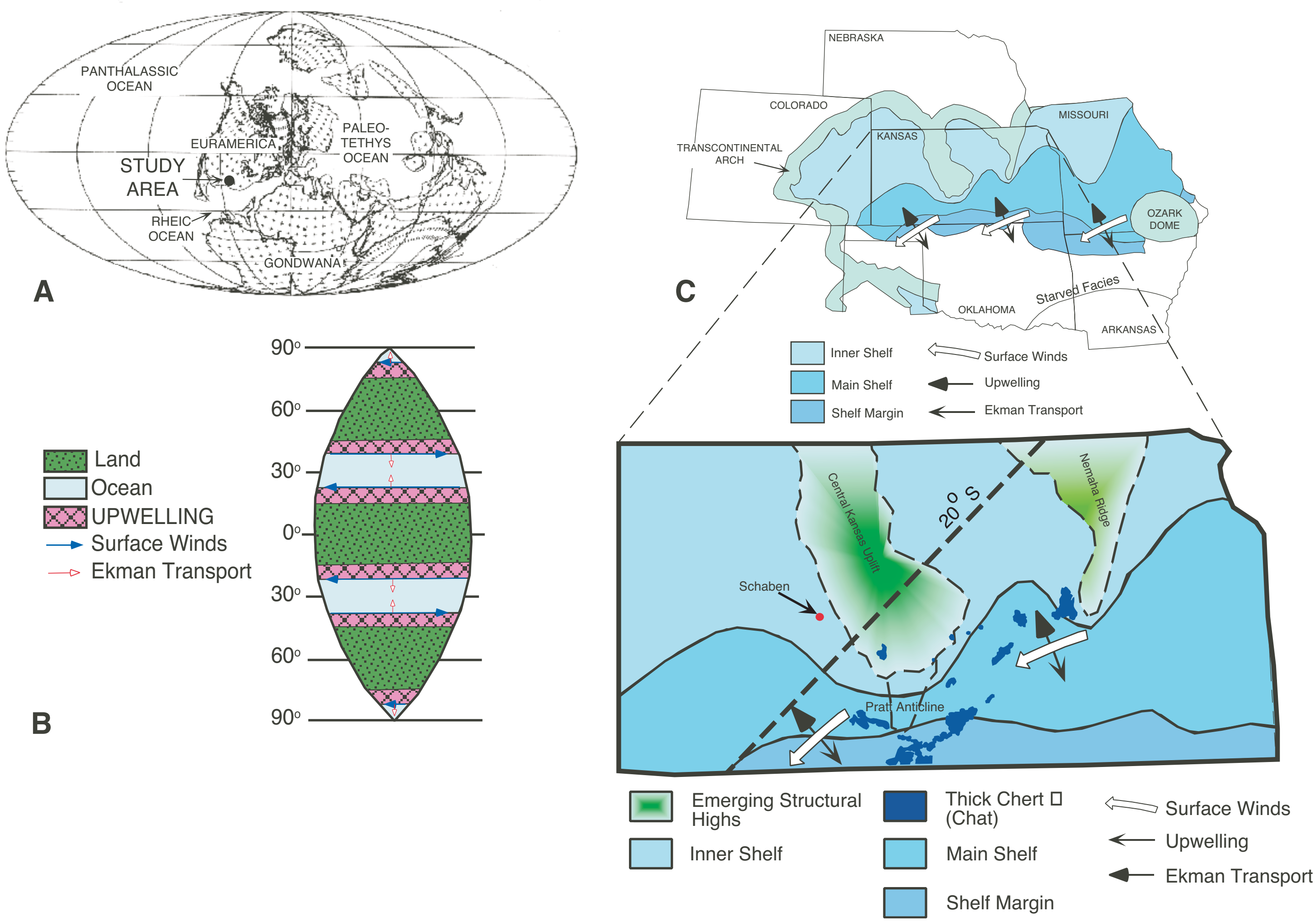

FIGURE 13—A) Paleogeographic setting during Kinderhookian, Osagean, Meramecian (Visean-Tournaisian) time. Note location of the study area, which was situated at ~ 20° S latitude. Modified from Scotese (1999). B) Zonal upwelling model of Parrish (1982). C) Details of the regional paleogeographic setting with interpreted depositional environments, predominant wind conditions and associated upwelling based on data from Lane and DeKeyser (1980), Parrish (1982), Gutschick and Sandberg (1983), Witzke (1990), Golanka et al. (1994), and Scotese (1999). The enlarged inset also shows location of Schaben field and areas of thick accumulations of chert ("chat") in shelf margin areas (chat areas from Montgomery et al., 1998).

of upwelling sediments (Parrish, 1982). However, it is still not fully understood whether upwelling alone could be the main factor affecting the innermost shelf areas of this study, or if other factors, including elevated nutrient and dissolved-silica supplies from land sources, were important in controlling facies associations. Some considerations of these various possibilities are discussed below.

It seems plausible that upwelling conditions could have at least contributed to, if not been a dominant factor for, the facies associations observed in the inner shelf areas. As nutrients are consumed, productivity decreases away from the site of upwelling, although upwelled water may remain on the surface for some distance (e.g. Ryther et al., 1971; Barber and Smith, 1981) and an upwelling zone may span hundreds of kilometers (Parrish, 1982). As noted in Parrish (1982), the actual depth required for upwelling over a shallow shelf depends on the thickness of the Ekman layers, which include the layer at the surface containing water set into motion by wind friction and a similar layer of retarded motion caused by friction with the sea bottom. Water at the surface constitutes the outward flow in an upwelling situation and water at the bottom constitutes the return flow. As long as the two Ekman layers are separated, upwelling is possible. The thickness of the Ekman layers vary. Transitory upwelling has been observed in water as shallow as 10 m (Parrish, 1982). Considering these factors, it is possible that upwelling waters affected the inner shelf portion of this study, which was located several hundred kilometers from the shelf margin.

Sea-level rise is an effective mechanism for allowing migration of upwelling zones over vast areas of cratons (Parrish, 1982). Sloss (1963) identified a major transgression across the craton in the latest Devonian and Early Mississippian (Kaskaskia) and Lowe (1975) suggested the associated spread of epicontinental seas during this time would have promoted the flow of silica-bearing ocean water onto the craton. Additional higher frequency relative sea-level fluctuations during the Early-Middle Mississippian (Ross and Ross, 1987) may have promoted repeated upwelling events that affected areas well onto the craton, including inner-shelf locations, such as the area described in this study.

Terrestrially sourced nutrients and dissolved silica also could have contributed to facies associations in inner-shelf areas. Evidence from SB1 (sequence boundary with evidence of subaerial exposure) and local evidence in DS2 indicate that the study area was at least locally subaerially exposed at times. This suggests that the adjacent topographically positive Central Kansas uplift (CKU) area was likely intermittently subaerially exposed as well, which is corroborated by Lane and Keyser (1980) who indicate that the Transcontinental arch, including the CKU, was near base level and intermittently subaerial exposed during Mississippian time. Goeble (1968) noted that red and dark-colored shale and red crinoidal limestone interbedded with cherty limestone in early Osagean sediments were evidence of a nearby shoreline reflecting concurrent uplift of the CKU. DS2 contains some interbedded detrital silt- and clay-size siliciclastics that are likely to have been sourced from the CKU during times of subaerial exposure. Therefore, it is possible that nutrients and dissolved silica from a terrestrial source could have contributed to facies associations in the inner-shelf study area. However, several factors combine to suggest that nutrients and dissolved silica from a terrestrial source would not have been the sole, or even dominant, control on inner-shelf facies. The relatively minor amounts of interbedded siliciclastic material in DS2 suggest that durations of subaerial exposure of the land source (CKU) were not long-lived and/or the amount of river runoff (perhaps linked with climate) was not high. The abundance of evaporites in DS2 of this study and in Osagean-Meramecian strata in other areas of North America indicate aridity (Cecil, 1990; Scotese, 1999). Gammon and James (2002) suggest that arid terrestrial environments may promote shallow shelf biosiliceous sedimentation. They note that ground waters from mid-latitude arid zones are high in salinity with enhanced silica solubility and concentrations and, importantly, suggest that these salt and silica-rich ground waters are flushed to nearshore environments with a change to humid climate. Gammons and James (2002) suggest that ancient shallow shelf biosiliceous deposits may be a record of terrestrial silica export associated with mid-latitude arid to humid climate fluctuations. Although this process cannot be completely ruled out for contributing to DS2 facies associations, no evidence has been observed to date to indicate arid to humid climate fluctuations. Instead, early silica replaced evaporites are consistently abundant throughout DS2 strata indicating overall aridity. Also, other workers have indicated a change to more arid climate at the end of Osagean deposition (e.g. Cecil, 1990; Smith and Dorobek, 1993).

Oolite deposits are relatively rare in Osagean strata (compared to earlier and later Mississippian units), but have been reported from several areas. For example the Short Creek oolite, which occurs in southeastern Kansas (Cherokee County), is an Osagean deposit (fig. 2). The local, sporadic development of oolite deposits during this time interval could indicate conditions, including either land-sourced or basin-sourced nutrients, that limited their development. Interestingly, Witzke and Bunker (1996) document Osagean oolite deposits in Iowa and show Early Osagean paleogeography with an inner-shelf environment that includes common oolite shoals occurring in close proximity to emergent land and siliciclastic facies belts. This relationship argues against land-sourced nutrients limiting oolite development. Finally, reconnaissance study of other Osagean core data in Kansas (Franseen, unpublished data) suggest a general decrease shelfward (northwest) in early silica replacement and cementation, which argues against land-sourced silica supplies dominating the system.

In summary, the predominance of Early-Middle Mississippian heterozoan carbonate and biosiliceous deposits, and lack of photozoan deposits, in the mid-latitude shallow-shelf setting in Kansas and surrounding areas was likely due to abundant nutrients and dissolved silica derived from basinal and/or terrestrial sources. Based on available evidence at this time, it appears that upwelling of basinal waters rich in nutrients and dissolved silica was a primary control on shelf margin and shelf facies. Upwelling even may have had a primary imprint on shallow-water, inner-shelf areas, especially during transgression(s). Although nutrients and dissolved silica from terrestrial sources cannot be ruled out entirely for contributing to the facies associations in shallowest water, inner-shelf areas, the available evidence from this and other studies suggests elevated nutrient and dissolved silica levels in shallow-water inner shelf areas were not predominantly sourced from terrestrial environments.

Further study is needed to better understand the relative roles of basinal and terrestrial sourced nutrients and dissolved silica, other paleoceanographic conditions (e.g. salinity), and paleogeography (e.g. identification of protected embayments that may have promoted biosiliceous deposits) in controlling the nature of Early-Middle Mississippian shallow water, inner-shelf heterozoan carbonate and biosiliceous deposits in Kansas and elsewhere in North America.

Reservoir Implications

Cumulative production from Mississippian reservoirs in Kansas exceeds 1 billion barrels (Adkins-Heljeson et al., 1999). In Lower-Middle Mississippian strata, production is from carbonates, cherty carbonates, and chert-dominated strata composed predominantly of heterozoan-dominated carbonate biota and biosiliceous material. Previous studies have focused on carbonate packstone-grainstones as reservoir facies in inner-shelf/ramp settings (e.g. Johnson and Budd, 1994), or, especially, the importance of chert-dominated (chat) sponge spiculitic-rich reservoir facies in deeper water shelf/ramp margin areas (Rogers et al., 1995; Colleary et al., 1997; Montgomery et al., 1998; Watney et al., 2001). As a complement to those previous studies, this study identifies another potentially important reservoir facies type for inner shelf/ramp settings. The shallow-water cherty dolomite DS2 strata of this study composed of abundant siliceous sponge spicule-rich facies (with silica replaced evaporites) and heterozoan carbonates, form reservoir facies in Schaben field (Franseen et al., 1998; Montgomery et al., 2000). Because a regional control, such as upwelling, is likely to have played a role in distribution of the shallow-water biosiliceous and heterozoan carbonate facies in DS2, the potential exists for these types of facies in Lower-Middle Mississippian strata to form reservoirs in other similar shelf settings in Kansas. This is demonstrated by recent study of time-equivalent strata in a core from Dickman field in Ness County, which indicates the reservoir interval is at least partially made up of similar shallow-marine sponge-spicule, heterozoan carbonate, and silica replaced evaporite facies (Franseen, unpublished data).

Similar facies with reservoir potential may exist outside of Kansas as well, based on the documented dominance of Early-Middle Mississippian heterozoan carbonate and biosiliceous deposits throughout North America, with several documented examples of shallow-water sponge spicule and evaporite facies that were deposited in inner-shelf/ramp settings.

Summary and Conclusions

Mixtures of heterozoan-dominated carbonate and biosiliceous deposits that formed in shallow-water middle-to low-latitude locations are increasingly being recognized in the rock record. Their formation in these locations requires special photic zone conditions, including elevated nutrient and dissolved silica levels, that promoted their development and prevented the development of photozoan carbonate deposits.

This study documents Osagean biosiliceous and heterozoan carbonate and original evaporite facies that were deposited in a mid-latitude (approximately 20° south latitude) shallow-water, inner shelf setting in Ness County, Kansas. Other studies document similar Early-Middle Mississippian facies elsewhere in North America.

Many of the studies documenting biosiliceous and heterozoan carbonate facies development in mid-latitude, shallow-water (inshore) environments have emphasized terrestrial sources (fluvial and ground water) and a link to humid climate for the elevated nutrients and dissolved silica necessary to form the deposits in these environments. Although a possible contributing factor in this study, the available evidence from this and other studies suggests elevated nutrient and dissolved silica levels in shallow-water inner-shelf areas were not predominantly sourced from terrestrial environments. Instead, this study and others indicate that upwelling of basinal waters rich in nutrients and dissolved silica was a primary control on shelf margin and shelf facies. Upwelling even may have had a primary imprint on shallow-water, inner-shelf areas, especially during transgression(s). Other factors that are currently poorly understood, such as variable paleogeography in shoreward areas (e.g. areas with protected embayments) and associated paleoceanographic conditions, may have promoted the formation of these deposits in the shallow-water, inner-shelf environments.

The recognition that shallow-water heterozoan carbonate and biosiliceous deposits can occur in mid-latitude locations, and the understanding of controls for their development in such an environment, has implications for petroleum reservoirs. The DS2 siliceous sponge spicule, heterozoan, and silica-replaced evaporite facies in this study form reservoirs in Schaben field. Because a regional control, such as upwelling, is likely to have played a role in distribution of the shallow-water biosiliceous and heterozoan carbonate facies in DS2, the potential exists for these types of facies to form reservoirs in similar Lower-Middle Mississippian inner shelf/ramp settings elsewhere in Kansas and North America.

The continued documentation and detailed study of ancient neritic heterozoan carbonate and biosiliceous deposits will increase the understanding of the paleoenvironmental controls on their deposition and improve predictive capabilities.

Acknowledgments

Research included in this paper has been partially supported by a U.S. Department of Energy Kansas Class 2 Project grant award (DE-FC22-93BC14987). Bob Goldstein, Alan Byrnes, and Lynn Watney reviewed early portions of the manuscript and made many useful comments. Current Research Bulletin reviewers Katherine Giles and Zakaria Lasemi are thanked for their constructive comments that helped clarify the paper. Marla Adkins-Heljeson is thanked for editorial assistance, and Jennifer Sims is thanked for graphic arts support.

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