Controls on Osagean-Meramecian (Mississippian) Ramp Development in Central Kansas: Implications for Paleogeography and Paleo-oceanography

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INTRODUCTION

Osagean-Meramecian (Mississippian) strata in several provinces in the United States, including the southern midcontinent, are composed predominantly of dolomite with local major components of chert (cherty dolomite). Some areas have been almost completely altered to chert (known as "chat"). Much attention has been given to the depositional and diagenetic history of these strata in regional studies and from surrounding areas (e.g. Indiana, Tennessee, Alabama, Illinois, Iowa, Kentucky). In contrast, partly because most of the Osagean-Meramecian strata occur in the subsurface in Kansas, relatively few sedimentologic and diagenetic studies have been done on these rocks. Also, because these strata form important petroleum reservoirs in Kansas, much of the focus in previous study of these strata in the subsurface has centered on reservoir characteristics and the post-Mississippian subaerial exposure that truncate these strata as the major control on reservoir character. Although focusing primarily on reservoir characteristics, some previous studies have documented depositional features and diagenetic complexities of these strata and noted, in part, the control of depositional facies and early diagenesis on reservoir character, including evidence for early silicification. (e.g. Ebanks *et al.*, 1977; McCoy, 1978; Ebanks, 1991; Johnson and Budd, 1994; Rogers *et al.*, 1995). Montgomery *et al.* (1998) provides a recent summary on current knowledge of these strata in Kansas, pointing out the poorly understood complexities.

In addition to understanding controls on reservoir character, the Osagean and Meramecian strata in central Kansas, consisting of a mixture of dolomite and chert, also provide an opportunity to add new insight into controls on depositional environments, including those related to paleogeography and paleo-oceanographic conditions. The results presented in this paper are part of a larger project addressing producibility problems in the numerous Kansas fields such as the Schaben field in Ness County (Fig. 1) that produce from Meramecian and Osagean dolomites beneath the sub-Pennsylvanian unconformity (e.g. Adkins-Heljeson *et al.*, 1999; Carr *et al.*, 1996). Reservoir characteristics of cores from the Schaben Field have been reported elsewhere (Franseen *et al.*, 1998; Byrnes, and Franseen, 2000; Montgomery *et al.*, in press).

This study is the first known that relates the importance of depositional setting in Kansas, including shallow-water environments dominated by brynoderm and sponge spicule facies, and early diagenetic processes to paleogeography, paleoceanography and climate. The results of this study suggest that ramp deposition and early diagenetic processes were variously controlled by: 1) cool, nutrient-rich water, most likely from upwelling under a tropical to subtropical climate; 2) a change to more arid conditions near the close of the Osagean; 3) early tectonic movements; and 3) relative sea-level changes. These results have broad implications for better understanding controlling factors on equivalent strata throughout the region.

GEOLOGIC SETTING

The Schaben Field study area 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, 1966; Thomas, 1982; Rogers *et al.*, 1995). Montgomery *et al.* (1998) and Watney *et al.* (in press) suggest that features associated with these early Mississippian events may have influenced depositional patterns, a theme important for this paper.

As shown on Figure 1A, Mississippian rocks are successively younger in a southwestward direction away from the CKU where all Mississippian rocks are absent. 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 ramp strata in the study area were differentially eroded at the post-Mississippian unconformity resulting in paleotopographic highs (buried hogbacks, Fig. 1B,C).

Paleogeographic studies place the study area at about 20 degrees S latitude, within the tropical to subtropical belt during Tournasian-Visean time (Parrish, 1982; Witzke, 1990: Scotese, 1999). Osagean-Meramecian deposition in the region was characterized by shallow shelf carbonates deposited on a gently sloping ramp to the south. The immediate study area of this paper is in the shelf facies 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 more minor amounts of chert (Selk, 1968; Lane and DeKeyser,

Figure 1: A) Mississippian subcrop map for the state of Kansas. Field and core locations used in this study are shown. B) Mississippian subcrop map of Schaben field area with Kinderhook and Osagian units (M0-M7) defined from log signatures. Note the locations of three cores that were studied in detail. Note also the location of the West to East (A-A') cross section shown in Figure 1C. C) A-A' cross section with Kinderhook and M0-M7 Osagian stratigraphic units identified based on log correlations throughout the entire Schaben field area. These units are overlain by the post-Mississippian unconformity and 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). Modified from Carr *et al.* (1996).

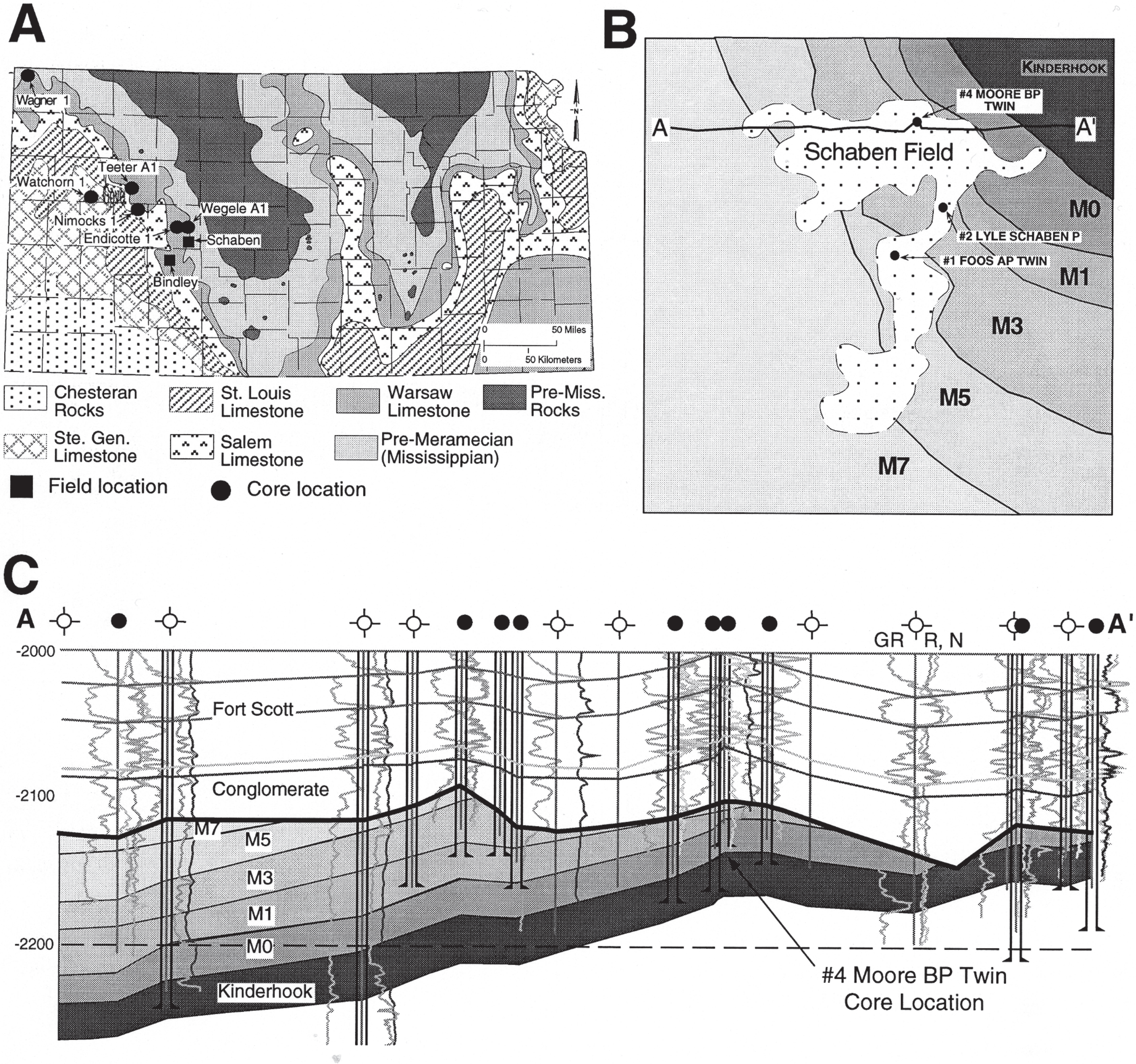

A
Wagner 1
Teeter A1
Watchorn 1
Nimocks 1
Wegele A1
Endicotte 1
Schaben
Bindley
50 Miles
50 Kilometers
Chesteran Rocks
St. Louis Limestone
Warsaw Limestone
Pre-Miss. Rocks
Ste. Gen. Limestone
Salem Limestone
Pre-Meramecian (Mississippian)
Field location
Core location
B
KINDERHOOK
#4 MOORE BP TWIN
A
A'
Schaben Field
M0
#2 LYLE SCHABEN P
#1 FOOS AP TWIN
M1
M3
M5
M7
C
A
A'
GR
R, N
-2000
Fort Scott
-2100
Conglomerate
M7
M5
M3
M1
-2200
M0
Kinderhook
#4 Moore BP Twin
Core Location

Figure 1

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 prefer to think of it as a facies boundary marking a unique depth or range of depths between "shallow" oxygenated waters and "deeper" less oxygen-rich waters (their quotes). According to Montgomery *et al.* (1998), fossiliferous burrowed lime wackestones and mudstones were deposited on the inner and middle shelf (Osagean limestone and equivalents), grading into finer grained carbonates and interbedded shales downdip (Cowley Formation). As shown in this study, inner shelf areas were also sites of accumulation of dolomitic sponge-rich wackestones-packstones, and carbonate skeletal wackestones, packstones and grainstones. Along the shelf margin, irregular or oval sponge bioherms, 15-48 m-thick, consisting mostly of sponge-spicule muds developed below wave base (Montgomery *et al.*, 1998). Interestingly, and of importance in considering depositional controls on Osagean strata in Kansas (discussed in a later section), there are few oolitic limestone beds in the Osagean rocks. Oolites are more abundant in overlying Meramecian rocks and underlying Kinderhookian strata (Goebel, 1968).

METHODS OF STUDY

The data for this study come predominantly from three recently cored wells from the Schaben field located in Ness County of west central Kansas (Fig. 1B). Detailed core and petrographic study, utilizing transmitted light, cold cathodoluminescence and UV fluorescence, was conducted on those three cores from Ness County, Kansas (Ritchie 4 Moore "B-P" Twin, Ritchie 1 Foos "A-P" Twin, Ritchie 2 Lyle Schaben "P"). Reconnaissance core and petrographic study was also conducted on seven other cores in the region in Kansas (Fig. 1A). Regional observations and interpretations include well log data. An extensive literature review also was conducted on other studies of Osagean-Meramecian strata in Kansas to add to the database for regional interpretations.

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). Based on conodont data, Osagean rocks west of the CKU, including those of this study, probably belong to the Keokuk Limestone (Goebel, 1968). The Schaben Field area has been further subdivided into subunits M0-M7 based on extensive

Figure 2: Mississippian stratigraphic units as defined for the state of Kansas. This study focuses on mostly Osagean (Keokuk Limestone) and some Meramecian (Warsaw Limestone) strata. From Maples (1994).

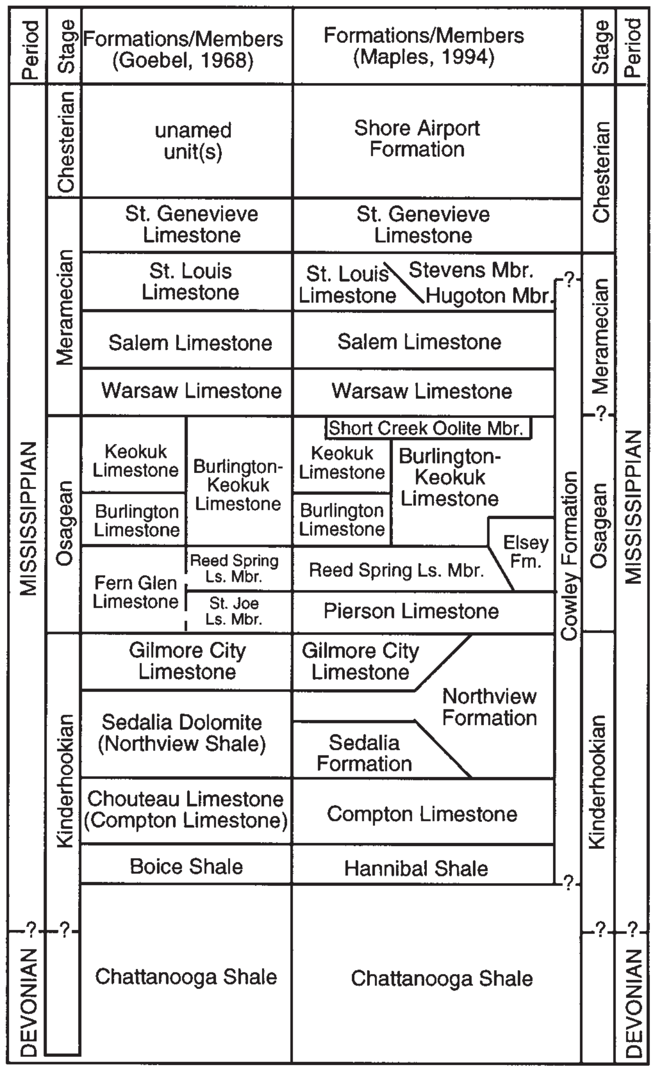

Period
Stage
Formations/Members (Goebel, 1968)
Formations/Members (Maples, 1994)
Stage
Period
MISSISSIPPIAN
Chesterian
unamed unit(s)
Shore Airport Formation
Meramecian
St. Genevieve Limestone
St. Genevieve Limestone
St. Louis Limestone
St. Louis Limestone
Stevens Mbr.
Hugoton Mbr.
Salem Limestone
Salem Limestone
Warsaw Limestone
Warsaw Limestone
Osagean
Short Creek Oolite Mbr.
Keokuk Limestone
Burlington-Keokuk Limestone
Keokuk Limestone
Burlington-Keokuk Limestone
Burlington Limestone
Burlington Limestone
Elsey Fm.
Fern Glen Limestone
Reed Spring Ls. Mbr.
St. Joe Ls. Mbr.
Reed Spring Ls. Mbr.
Pierson Limestone
Cowley Formation
Kinderhookian
Gilmore City Limestone
Gilmore City Limestone
Northview Formation
Sedalia Dolomite (Northview Shale)
Sedalia Formation
Chouteau Limestone (Compton Limestone)
Compton Limestone
Boice Shale
Hannibal Shale
?
DEVONIAN
Chattanooga Shale
Chattanooga Shale

Figure 2

correlation of well logs in the area (Carr *et al.*, 1996) (Fig. 1B,C). The cores from the Schaben field area, that form the basis of detailed study for this paper, are subdivided into two major units (M0 and M1 & Above) (Fig. 3). These two units are separated based on a regional surface of subaerial exposure (M1 surface) that can be traced between the cores. Although other subaerial exposure events are identified in the cores, correlations of these events between the cores remains uncertain at this stage. Therefore, the strata above the M1 surface are grouped together as M1 & Above, instead of subdividing into further M units, as was done for log correlations. Correlations of M units outside of the Schaben field remain uncertain at this time and other cores utilized in this study outside the area can only be characterized as Osagean or Meramecian.

SCHABEN FIELD AREA FACIES

Mudstone-Wackestone (MW)

This facies is typically light gray to olive green in color or dark gray to brown. Typically this facies is laminated, or wavy to wispy laminated. Locally it is massive. Laminations are imparted locally by interbedded green shale-siltstone and by horsetail stylolites (Fig 4A). Much of this facies has a mottled texture apparently imparted by burrowing organisms and locally microscopic fracturing. Local dark blebs and clotted areas likely are from organic matter and may indicate microbial structures. Other features include soft sediment deformation. Fenestral fabric occurs locally. Identifiable skeletal grains are rare; sponge spicules (mostly monaxon) and their molds are locally identifiable and appear to be the most common grain type with echinoderm and bryozoan, brachiopod, gastropods, peloids, and glauconite locally present. Pyrite occurs as an accessory mineral. The sponge spicules are locally concentrated in layers or in "pockets" presumably as a function of currents and reworking by burrowing organisms. Rare concentrations of very fine grained (~ 100 μm) detrital quartz grains also occur, likely from reworking by burrowing organisms. This facies is 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 are locally developed and more commonly identified in areas with intercrystalline porosity. This facies often contains silica that replaced evaporite crystals, nodules and coalesced nodules that form layers. Silica also locally replaces matrix and grains in this facies.

Figure 3: Core descriptions for the three cores from the Schaben field area showing depositional facies. Also shown are relative abundance of calcite and silica replacement and cements. The M1 surface 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 M0 strata (below) from M1 & Above strata (above).

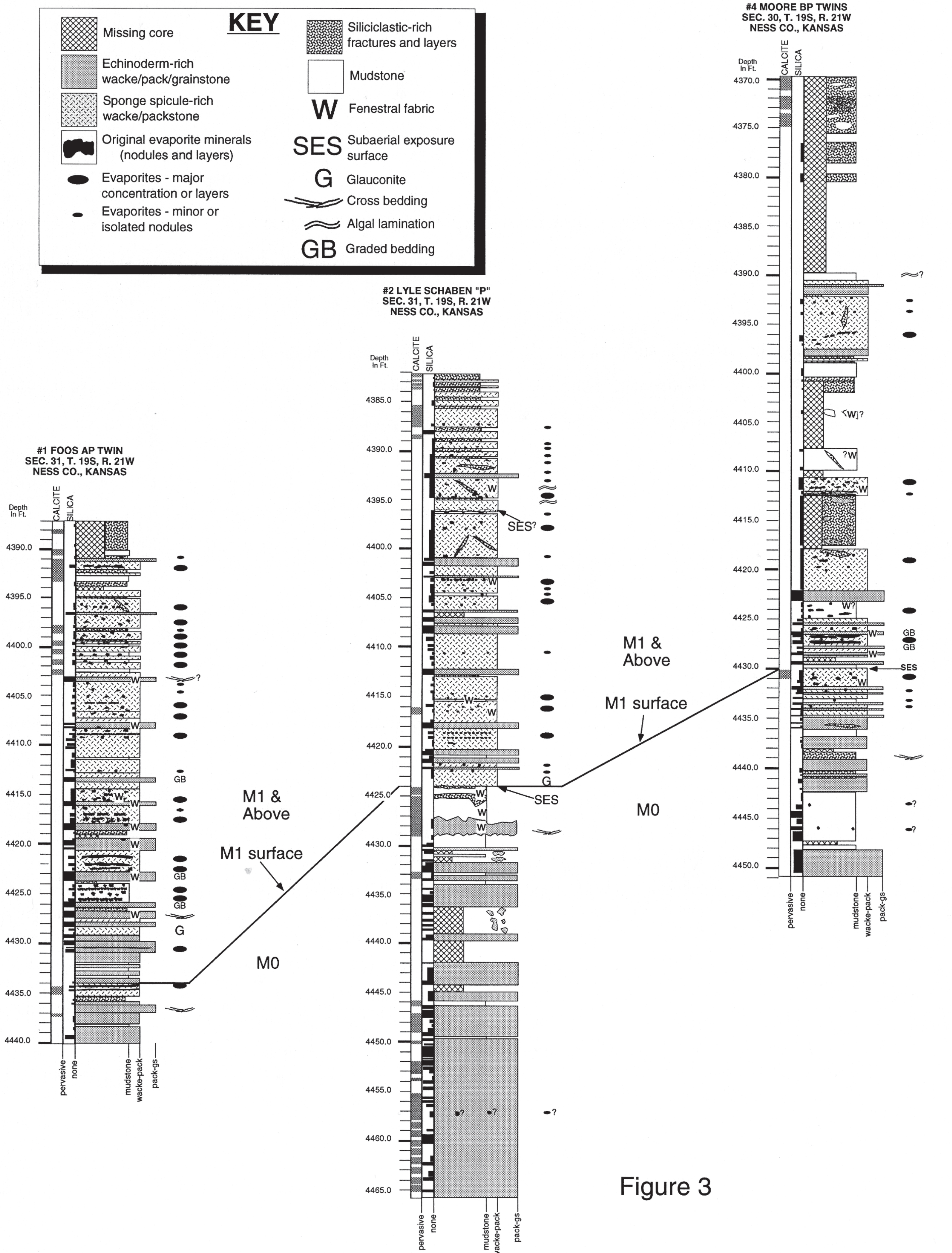

KEY
Missing core
Echinoderm-rich wacke/pack/grainstone
Sponge spicule-rich wacke/packstone
Original evaporite minerals (nodules and layers)
Evaporites - major concentration or layers
Evaporites - minor or isolated nodules
Siliciclastic-rich fractures and layers
Mudstone
W Fenestral fabric
SES Subaerial exposure surface
G Glauconite
Cross bedding
Algal lamination
GB Graded bedding
#1 FOOS AP TWIN
SEC. 31, T. 19S, R. 21W
NESS CO., KANSAS
#2 LYLE SCHABEN "P"
SEC. 31, T. 19S, R. 21W
NESS CO., KANSAS
#4 MOORE BP TWINS
SEC. 30, T. 19S, R. 21W
NESS CO., KANSAS
Depth In Ft.
CALCITE
SILICA
pervasive
none
mudstone
wacke-pack
pack-gs
M1 & Above
M1 surface
M0
SES
SES?

Figure 3

Sponge Spicule-rich Wackestone-Packstone (SWP)

This facies is abundant in all three Schaben field cores, especially in the upper portions of each core and is important as a reservoir facies (Fig. 3). This facies is dark to light gray, olive green, tan, or brown in color. Mottled, wispy horizontal laminated, and wavy horizontal laminated textures are common and sponge spicules are locally concentrated in layers as a function of depositional (current) processes. This facies also is characterized by mottling from burrowing organisms. This results in sponge spicules locally concentrated in "pockets" on a microscopic scale. Laminations are imparted locally by interbedded green-gray shale-siltstone and by horsetail stylolites. Local dark blebs and clotted areas likely are from organic matter and may indicate microbial structures. Sponge spicules (mostly monaxon) and their molds are the predominant grain type and commonly the exclusive grain type (Fig. 4B,C). The sponge spicules are originally thought to be from siliceous sponges because, where preserved, a centered axial canal can be identified (Fig. 4B) and there are some rare identifiable triaxon morphologies of some of the spicules (from Geeslin and Chafetz, 1982). Echinoderm, bryozoan, gastropod, peloids and glauconite grains occur more rarely. Pyrite is locally an abundant accessory mineral. Moldic (Fig. 4C), intercrystalline, and minor vuggy porosity ranges from 18-25% (Byrnes and Franseen, 2000). Fenestral fabric occurs locally. Some moldic porosity is solution enlarged forming vugs. The mottling texture and concentration of grains in layers 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; intercrystalline porosity is more common in areas where euhedral crystals are locally developed. This facies commonly contains chert after replacement of evaporite crystals, nodules and coalesced nodules that form layers (discussed later). Chert also replaces matrix and grains (Fig. 4B, D).

Echinoderm-Rich Wackestone-Packstone-Grainstone (EWPG)

This facies occurs in all three cores and is most abundant in the lower parts of the cores (Fig. 3). Packstone and grainstone fabrics are often difficult to separate out because of the difficulty in discriminating former interparticle mud in pervasively dolomitized grain-supported rocks. This facies is typically dominated by echinoderm fragments but also contains abundant sponge spicules, bryozoan fragments, brachiopods, solitary coral fragments, gastropods, ostracods, peloids, calcispheres, minor occurrences of complex grains and oncolites, and other unidentifiable skeletal debris. Skeletal fragments are

Figure 4: A) Mudstone/Wackestone (MW) Facies. Wispy lamination imparted by clay and horsetail stylolites. This facies is typically tight. Scale 1 mm. B) Sponge Spicule-rich Wackestone/Packstone (SWP) Facies. In this sample the sponge spicules are preserved by microcrystalline quartz and chalcedony (note central axial canals). Much of the matrix is silicified and only a minor amount of intercrystalline porosity is present. Scale 1 mm. C) More typical preservation of SWP Facies with abundant sponge spicule molds and intercrystalline porosity in dolomite matrix. Scale 1 mm. D) Sponge spicules have been dissolved leaving molds (dark round/oblong areas) and the surrounding matrix has been mostly replaced by silica (light areas). The upper right corner was not replaced by silica and is dolomitic. Scale 1 mm.

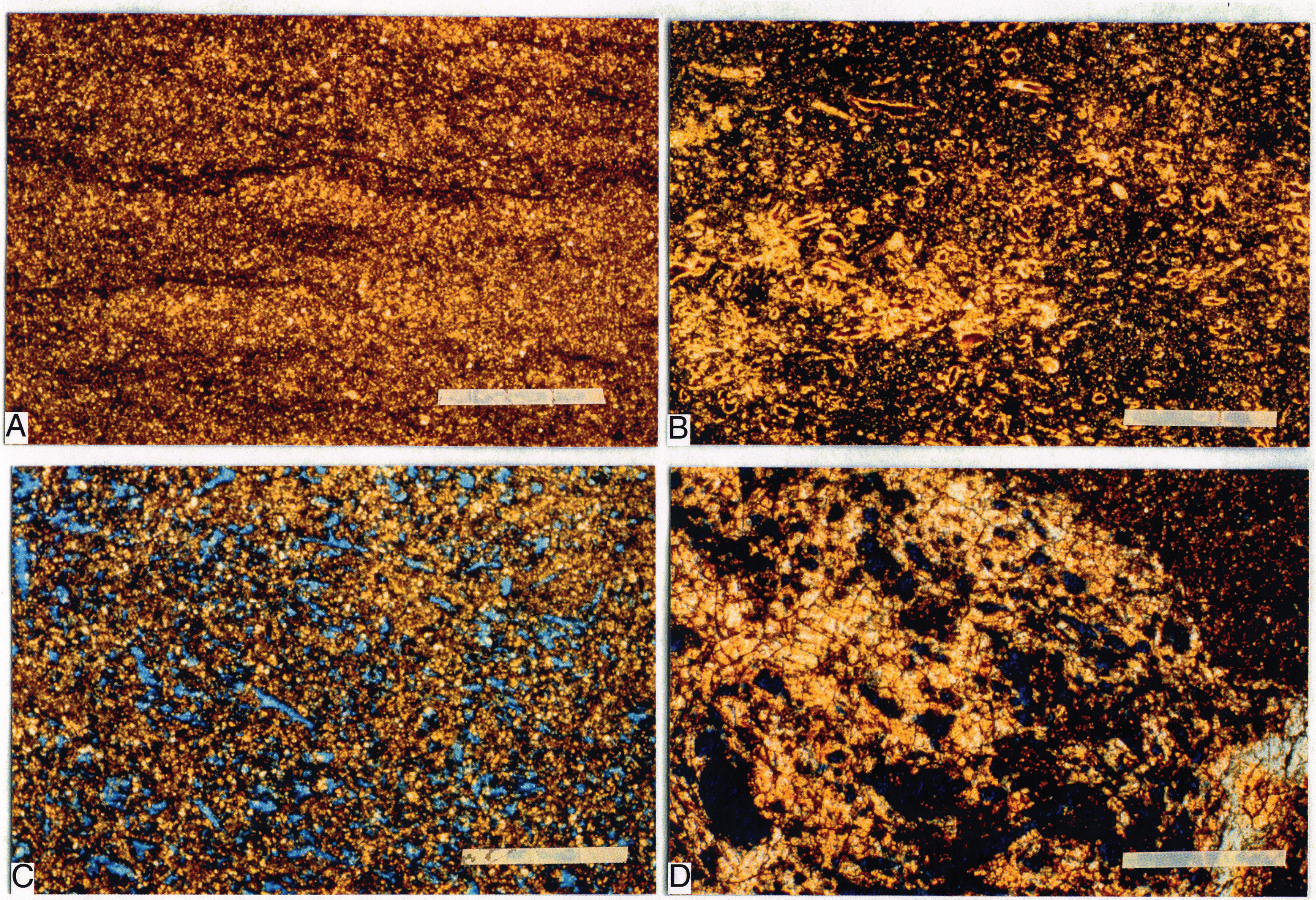


Figure 4

generally disarticulated but are 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 still dolomitic, skeletal grains are typically preserved as molds (Fig. 5B). Horizontal laminations and low-angle cross laminations are locally preserved. Some intervals show sorting of grains into fine-grained layers and coarser-grained layers. Other intervals show normal grading of grains. Locally, grains in this facies show compromise boundaries, overly close packing (Fig. 5C), grain breakage and flat, horizontal alignment of skeletal fragments, but typically there is not much over compaction or other evidence for much early compaction. Only minor occurrences of original calcite syntaxial overgrowths are evidenced in grainstones. Grainstones locally have an isopachous chalcedony cement (likely originally opal) that coats grains and lines primary pores (Fig. 5A, C). Some original molds, fenestrae, and vugs contain a floored (geopetal) internal sediment that was subsequently silicified and the remainder of the pore space filled with silica cement. This facies commonly has been partially or pervasively replaced with porcelaneous (tight) or, only locally, tripolitic (porous) chert/megaquartz. Abundant vuggy and microcrystalline porosity occur within tripolitic chert areas and both tripolitic and porcelaneous chert typically contains micro- and mega-fracture porosity. Only locally are vugs 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 moldic, fenestral or vuggy pores contain an initial silicified internal marine sediment and a later pore filling, or partially filling silica cement.

Where still dolomite, this facies is characteristically tan to dark brown in color and 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. Porosity in this facies can exceed 22% (Byrnes and Franseen, 2000). Common porosity types include moldic, moldic reduced, intercrystalline, and vugs. Oil staining occurs commonly in this facies where still mostly dolomitic. Dolomite is typically very finely crystalline (~50 μm or less) but locally exceeds 150 μm. Crystals are typically subhedral to euhedral. Some of the crystals are zoned with a clear to turbid (locally calcian) center and clear dolomite rim. Some dedolomite textures were identified. Locally, calcite cement and neomorphic spar occludes porosity and replaces original textures; some areas have dolomite rhombs, or silica "floating" in calcite.

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 with some identifiable sponge spicule molds filled with cement. Note chalcedony cement (brown) lines primary pores followed by later pore-filling clear megaquartz cement. Scale 1 mm. 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. Scale 1 mm. C) Silicified EWPG Facies. Overly-close packing of echinoderm fragments (CB=compromise boundary) that are preserved by mold-filling quartz cement (Q). Note also primary pores are lined by isopachous chalcedony cement (Ch). Scale 1 mm. D) Silicified EWPG Facies. This sample contains abundant fenestral pores (F) filled by quartz cement. Scale 1 mm.

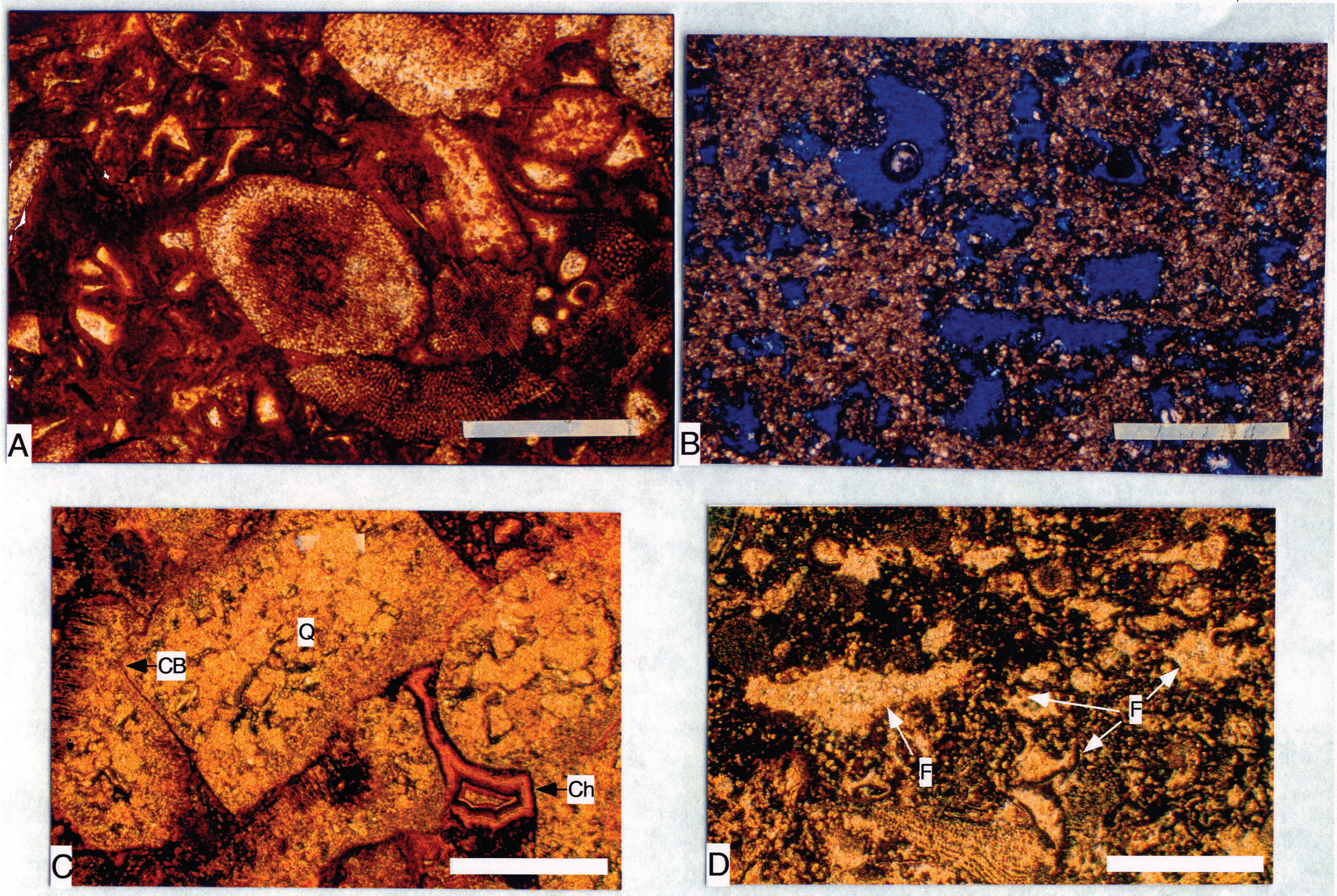


Figure 5

Dolomitic Siltstones & Shale

This facies is typically green to gray and locally red in color. It is wavy to wispy laminated and locally displays low-angle lamination. The shale locally occurs as wispy layers in dolomitic mudstone or wackestone facies. This facies is composed predominantly of very-fine grained sand (~100 μm) to silt-sized (<50 μm) quartz grains and clays (Fig. 6). This facies also occurs as fracture fill and breccia matrix containing clasts of carbonate facies and replacive silica (Fig. 3).

SILICA CEMENTATION AND REPLACEMENT

Replacement silica and silica cements are abundant throughout all three cores (Fig. 3). Convoluted nodular, anastamozing bedded, and bedded replacements (following terminology of Nolte and Benson, 1998) are characteristic in EWPG facies (Fig. 7A). Disseminated silica, characterized by "ragged" boundaries with unsilicified strata of the same facies, is most common in the MW and SWP facies (Fig. 7B). In addition, MW and SWP facies contain silica nodules, coalesced nodules, layers and vertically elongate nodule textures after evaporites (discussed below). Silica replacement occurs either as pervasive or partial replacement of original facies, textures or grains. The silica is typically white to light gray in hand sample and has a porcelaneous (tight) or more rarely a chalky porous (tripolitic) texture. Much of the chert replacement appears to follow original burrows or bedding planes. Chert areas commonly exhibit a fracture and brecciated texture. Variable micro-and macro-fracture porosity results from these processes.

Silica occurs as microquartz, megaquartz, chalcedony (both length-fast and length-slow), and zebraic chalcedony. Some microspherules (approximately 25-40 um diameter) occur and may represent original cristobalite lepispheres. Typically, several stages of 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). A void-filling silica fabric in other samples 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).

Figure 6: Shale and siltstone layers are locally present, typically interbedded with SWP or MW facies. This facies occurs as interbedded layers associated with deposition during Osagian time and as post-depositional fill associated with the post-Mississippian unconformity. This sample contains mostly angular-subround silt-very fine sand-size quartz grains with minor clay. Scale 1 mm. Crossed nicols.

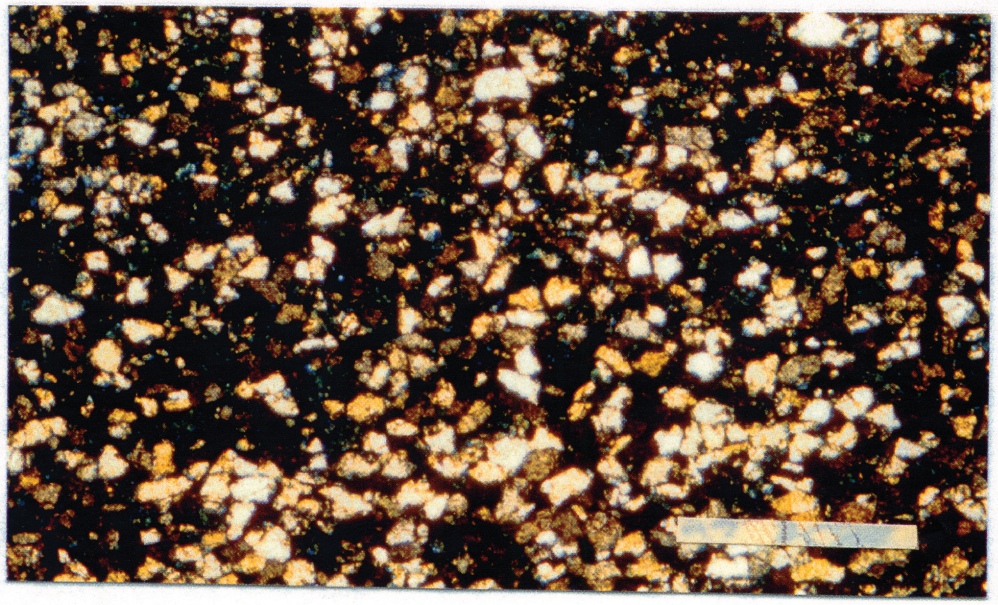


Figure 6

Figure 7: Different character of silica replacement. Core photo on the left is of EWPG facies which is characterized by convoluted nodular, anastamozing bedded (ABC) and bedded replacement (BC) 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, characterized by "ragged" boundaries with unsilicified strata of the same facies. Whitish-gray areas are silica and darker brown areas are dolomite.

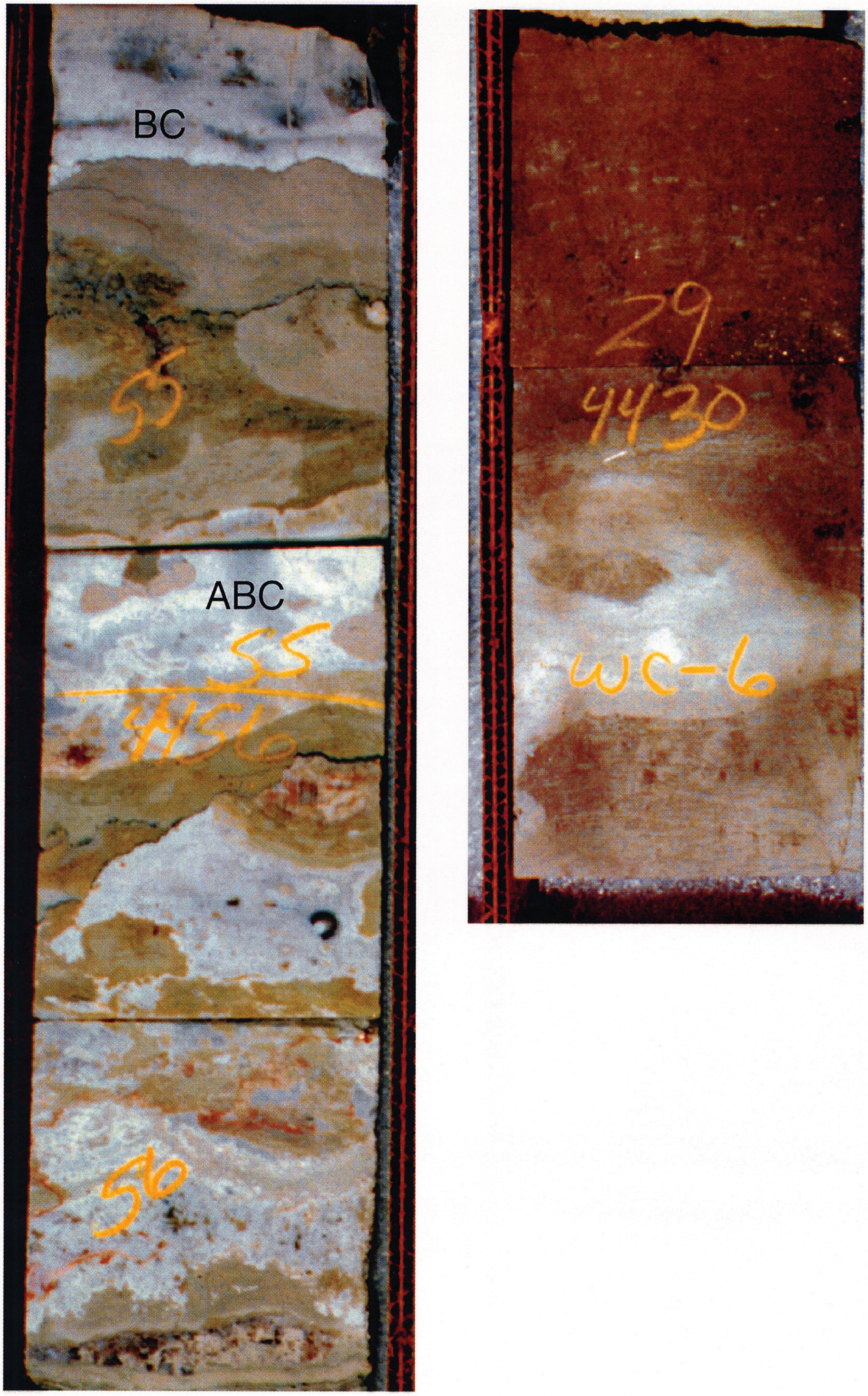


Figure 7

The silica replacement is typically tight and forms impermeable layers where replacement is pervasive. However, some of the pervasive chert replaced areas contain abundant microcrystalline, intergranular, and vuggy porosity (tripolitic texture).

Replacement of Evaporites

Silica also occurs as replacement of original evaporites. The evaporites preserve textures from initial nodule development through complete nodule development, from individual nodules, to laterally coalesced nodules forming horizontal layers, some of which are composed of coalesced vertically elongate nodules (Fig. 8). Some preserve 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 twined crystal morphology (Fig. 9B), indicating likely replacement of anhydrite or gypsum. Individual bladed crystals, 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 that replaced evaporites contain abundant inclusions of evaporite minerals (likely 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). The presence of bent and broken crystals and disruption of anhydrite crystals by displacive growth is surprisingly similar to those shown by the Shearman and Fuller (1969) for Recent anhydrite laths in halite cemented nodules from the supratidal sediments of the Trucial Coast. Some of the evaporites occur with fenestral fabric, which also supports the analogy (Fig. 9A).

Rare elongate crystal and nodule fabrics of original evaporites occur (Fig. 8). Some of these are similar to fabrics shown by Warren and Kendall (1985; their figure 5) for original subaqueous gypsum deposited as large upward-growing palmate to vertically aligned, gypsum crystals that were then converted to anhydrite with burial and are here preserved by silica replacement. If the textures in this study are analogous, then they imply bottom growth for at least some of the evaporites observed whereas the nodules and displacive crystals indicate growth below the water sediment interface.

The replaced evaporite textures are most prevalent in the upper portions of all cores (M1 & Above strata) where they form an important component of the SWP facies (Fig. 3). Silica replacement of evaporites typically has more associated vuggy porosity (Fig. 8).

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 (Ele), individual round to oblong nodules (En) and coalesced nodules (Enc). The coalesced nodules (Enc) are overlain by a truncation surface (TS) This surface is overlain by chertified echinoderm-rich grainstone (CEG) containing silica cement-filled fenestral (F) and vuggy pores. The evaporites and fenestral fabrics indicate deposition in very shallow water to vadose conditions, with at least local exposure.

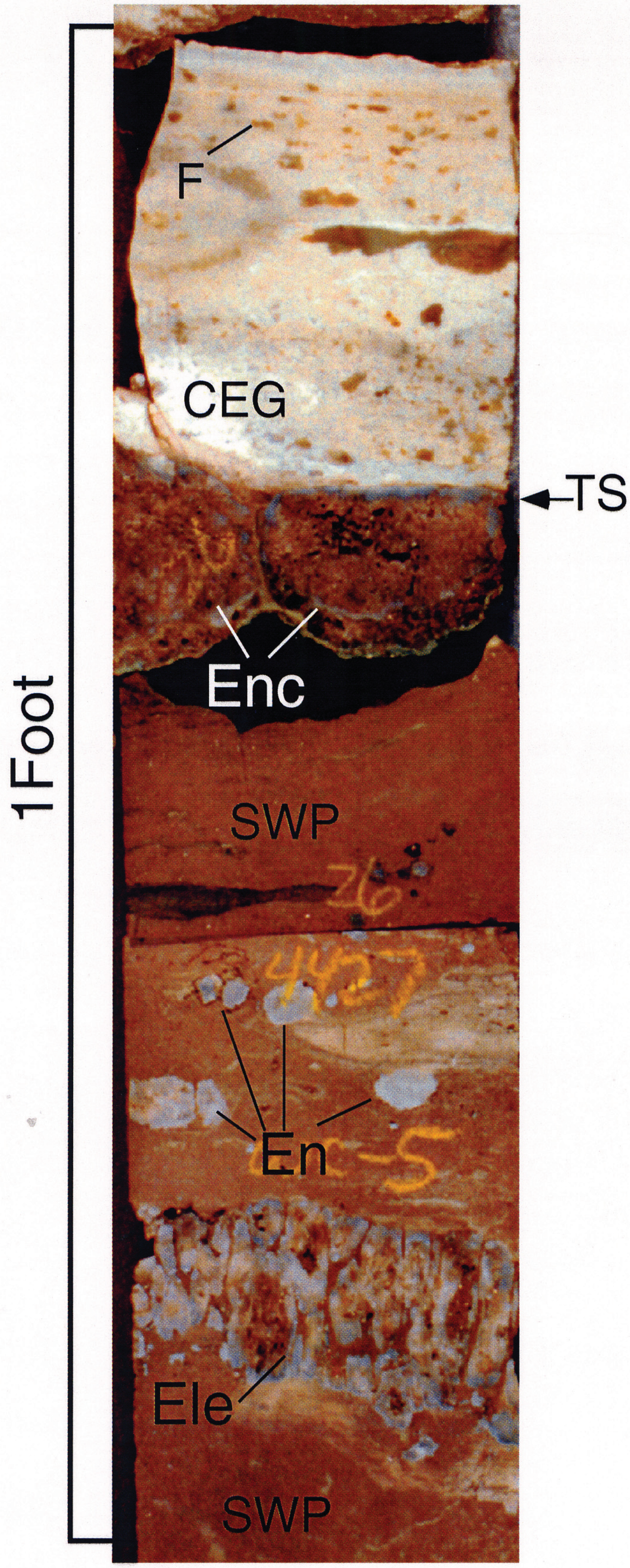


Figure 8

Figure 9: Silica-replaced evaporite textures. A) This sample contains evaporite nodules (E) in dolomitic SWP facies forming “chicken-wire texture”. The base of the sample contains elongate fenestral (F) pores indicating subaerial exposure. Scale 1 mm. B) Silica-replaced bladed and radiating bladed crystal 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. Scale 1 mm. 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. Scale 1 mm. D) This sample shows original evaporite crystals and nodule 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). Scale 1 mm.

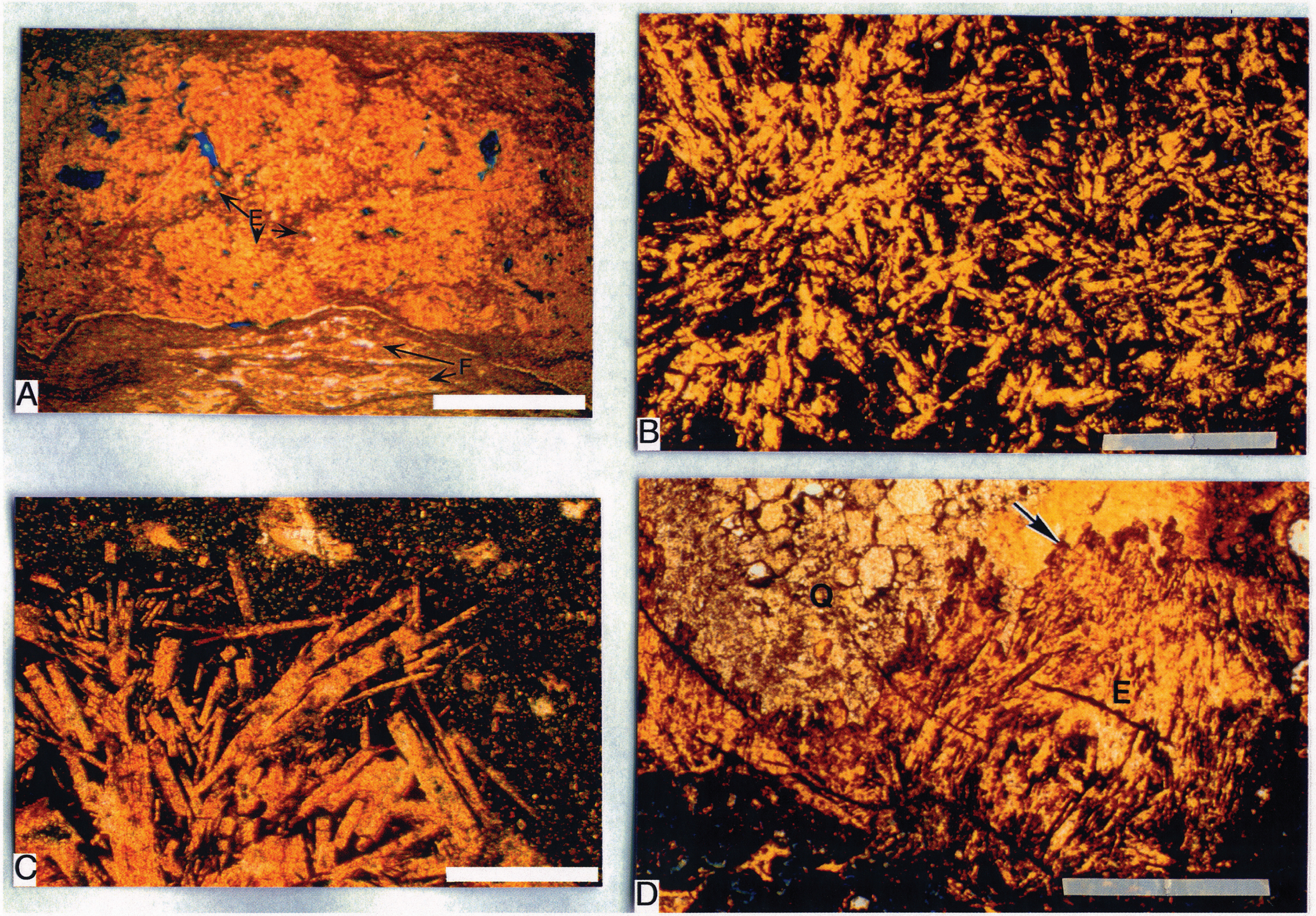


Figure 9

Evaporite crystal pseudomorphs are preserved by chalcedony or microquartz as individual crystals or groups of crystals within the sediment or within nodules, typically near the outer edges of nodules. Some of the crystals, especially in nodules show evidence of /corrosion/erosion forming an irregular surface that is overlain by megaquartz cement that filled in remaining pore space (Fig. 9D). 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). The most striking type of fibrous microquartz is zebraic chalcedony which has been associated by some with the original presence of sulfate minerals or other evaporites (e.g. McBride and Folk, 1977).

BRECCIATION/FRACTURING/CALCITE REPLACEMENT AND CEMENTATION

Macro- and micro-scale brecciation and fracturing are ubiquitous throughout the three cores (Fig. 10). Fracturing and brecciation results in fracture and mosaic breccias (textures ranging from little to no rotation on clasts indicating in-situ brecciation), 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, and depends on amount of fracturing and brecciation, "openness" of fractures, types and grain size of fracture fill, and types and grain size of breccia clasts and matrix. Interparticle, intercrystalline, vuggy and fracture porosity are common porosity types in breccia matrix.

Several different stages of calcite cementation and replacement occur in the cores (Franseen *et al.*, 1998). One event is associated with subaerial exposure at the M1 surface (Figs. 3, 10; discussed later) and results in replacement and cementation, locally extensive, of M0 strata. A later stage of calcite cementation and replacement is associated with the post-Mississippian subaerial exposure event (Fig. 3).

Figure 10: #2 Lyle Schaben ""P"" core description and core photo from ~ 4418' to 4431'. Note the M1 subaerial exposure surface at ~ 4424' that separates M0 strata (below) from M1 & Above strata (above). Strata below the M1 surface 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 coarse calcite cement surrounded by a halo rich in hematite and fenestral pores in dolomitic and replacive poikilotopic calcite matrix, which may indicate these are associated with land plant roots (see Figure 12B). Strata below the M1 surface are also affected by a coarse calcite poikilotopic replacement and cement (see also Figures 3, 12A). Strata above the M1 surface consist of MW and SWP facies, containing abundant silica-replaced evaporites (ECN-coalesced evaporite nodules).

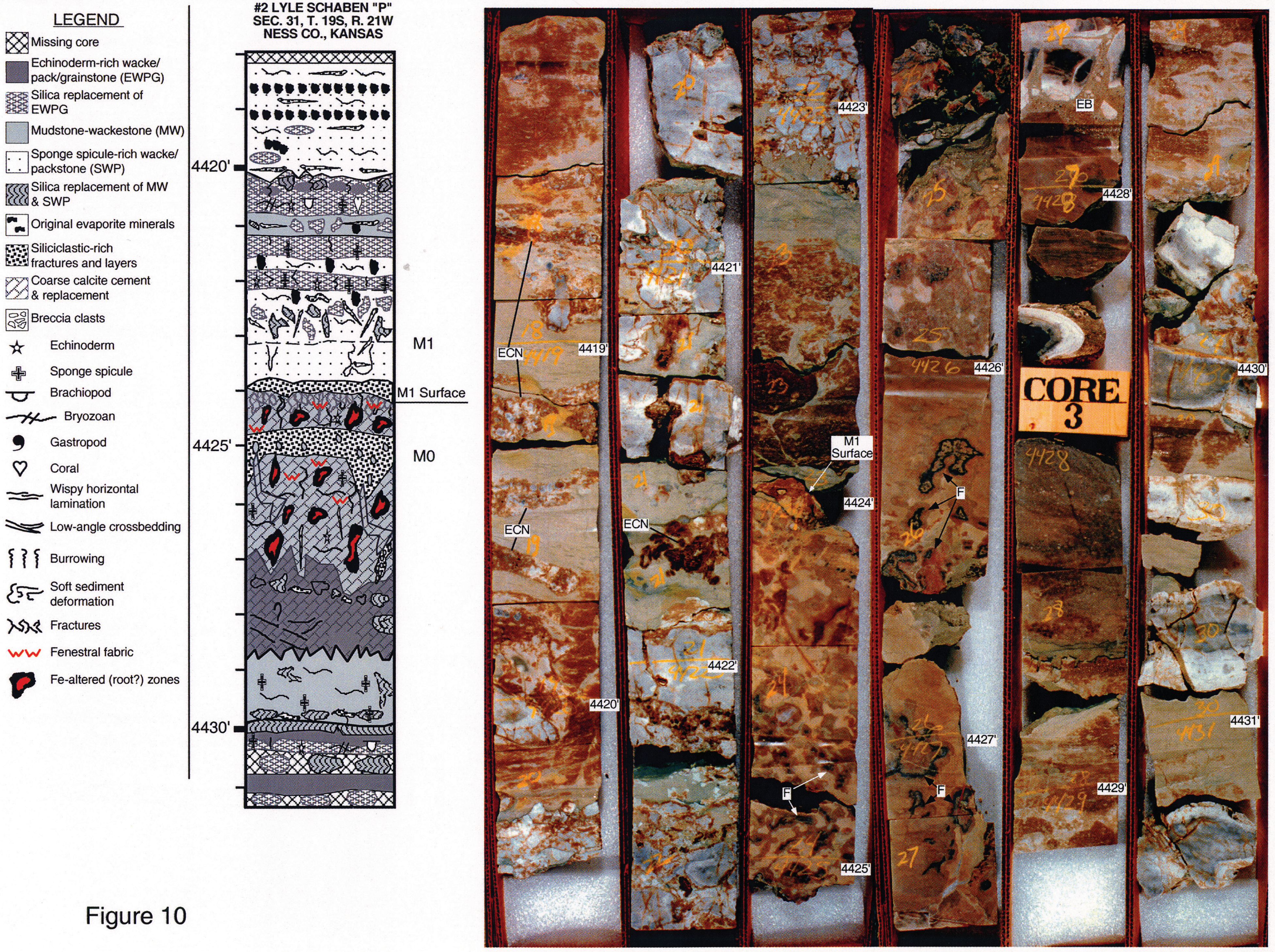

LEGEND
Missing core
Echinoderm-rich wacke/pack/grainstone (EWPG)
Silica replacement of EWPG
Mudstone-wackestone (MW)
Sponge spicule-rich wacke/packstone (SWP)
Silica replacement of MW & SWP
Original evaporite minerals
Siliciclastic-rich fractures and layers
Coarse calcite cement & replacement
Breccia clasts
Echinoderm
Sponge spicule
Brachiopod
Bryozoan
Gastropod
Coral
Wispy horizontal lamination
Low-angle crossbedding
Burrowing
Soft sediment deformation
Fractures
Fenestral fabric
Fe-altered (root?) zones
#2 LYLE SCHABEN "P"
SEC. 31, T. 19S, R. 21W
NESS CO., KANSAS
4420'
4425'
4430'
M1
M1 Surface
M0
ECN
4419'
4420'
4421'
4422'
4423'
M1 Surface
4424'
4425'
F
4426'
4427'
EB
4428'
CORE 3
4429'
4430'
4431'

Figure 10

DEPOSITIONAL ENVIRONMENTS

The block diagram in Figure 11 is a representation of general setting of depositional environments for M0 and M1 & Above strata. Similarity in facies and features observed in the cores studied in reconnaissance for this study indicate that depositional environments and block diagram, in general, applies for those areas as well. This diagram and resultant interpretations of strata observed in this study are further supported by analogs from the literature. The following discussion summarizes interpretations of strata in the Schaben field based on observations in the cores and then utilizes features in other cores and from the literature to further support the interpretations.

MO Strata

Echinoderm-rich facies predominates in the bases of the cores with lesser amounts of mudstone and sponge spicule-rich facies (Fig. 3). However sponge spicules are an important contributor to EWPG facies. Although other facies occur as well, importantly, evidence of evaporites is generally lacking. The abundance of the echinoderm facies with abundant other diverse fauna, abundance of burrowing organisms and only rare occurrence of evaporites in the basal portions of the cores suggest deposition in relatively normal shallow subtidal marine environments on the inner ramp. Beds range from < 15' thick to ~0.5' thick. Sedimentary structures are rare, likely to bioturbation and reworking. The relative reduction of the bryozoan content compared to areas more basinward (e.g. Montgomery *et al.*, 1998) is consistent with detrimental effects of warming of waters and dilution by increased crinoid production in an inner ramp environment (Martindale and Boreen, 1997). The presence and interbedding of mudstone-wackestone textures and packstone-grainstones with lamination, cross lamination, normal grading, close packing of grains, grain breakage, and scoured contacts indicate at least intermittent high energy. The setting can be envisioned to be 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. These processes periodically transported grainstones downslope as mass flow deposits. Some of the sponge spicule dolowackestone-packstone and dolomudstone-wackestone facies (beds mostly in the <0.25' – 0.5', locally up to ~5') are likely indicative of a lower energy compared to much of the echinoderm-rich facies in MO strata. In this environment sponges thrived and likely formed sponge "gardens" or "mounds" (Rogers *et al.*, 1995).

Figure 11: Block diagram of interpreted inner and main shelf depositional environments in the study area, based mainly on study of the cores from the Schaben Field area. These environments are also to generally apply to other Osagean and Meramecian cores studied in reconnaissance.

INTERPRETED INNER AND MAIN SHELF DEPOSITIONAL ENVIRONMENTS

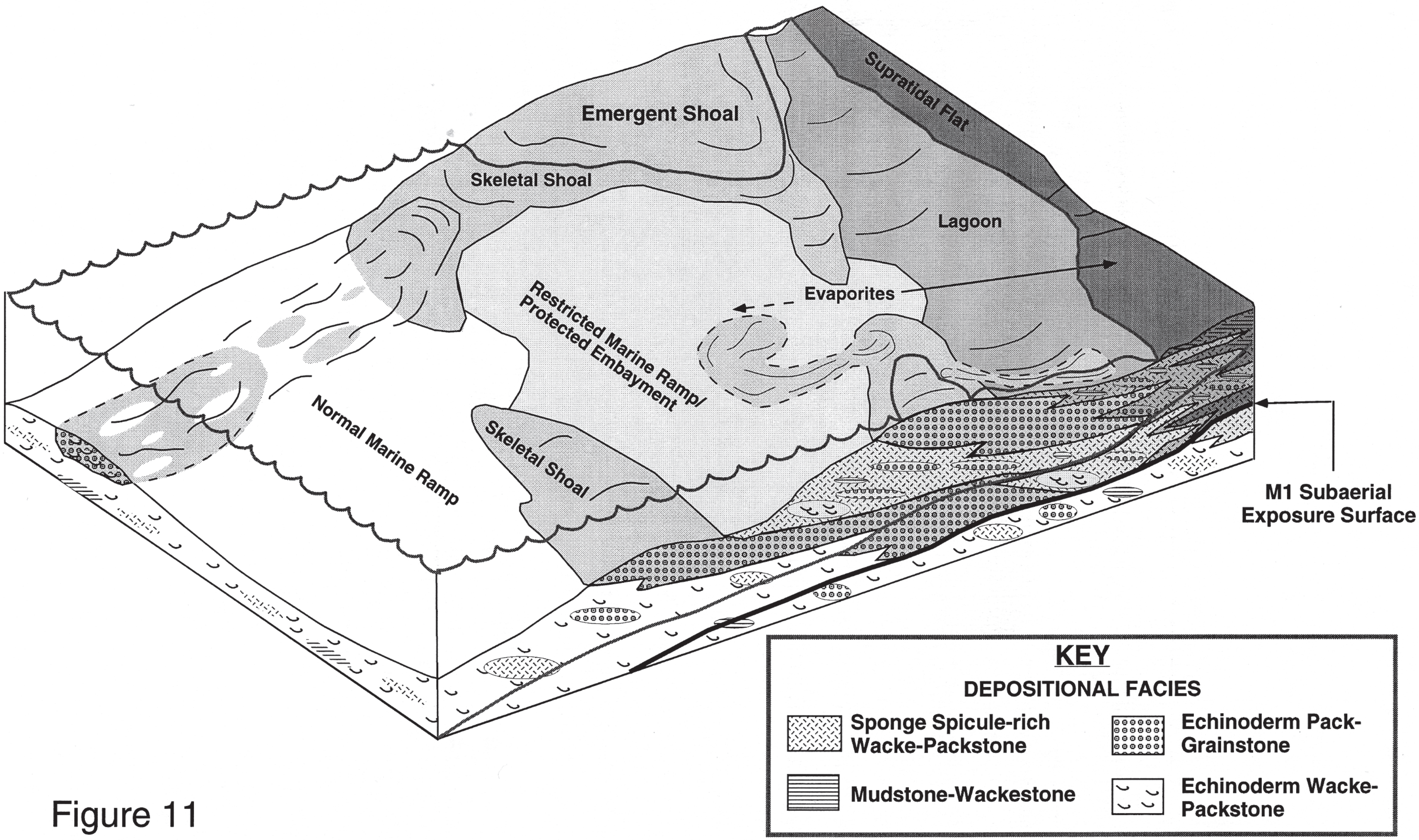


Figure 11

M1 Surface

The change between the normal to restricted marine ramp and the evaporitic ramp to lagoon in the Schaben cores is marked by a sharp contact termed the M1 surface (Fig. 3). This surface and the strata immediately below for several meters show significant alteration (Figs. 3, 10). A replacive poikilotopic calcite and coarse calcite cement (Fig. 12A) are associated with the M1 surface and occur pervasively below the surface for approximately 5 feet (Figs. 3, 10) and then more variably in strata below to the bottom of the core (Fig. 3). This calcite replacement and cement is very important for making these strata relatively tight compared to overlying strata which do not contain any of the replacive calcite or calcite cement (Figs. 3, 10). There is a similar calcite poikilotopic replacement and coarse calcite cement at the very top of the Schaben core (Fig. 3) but it only affects strata in the upper five feet of the core and is presumably related to the post-Mississippian subaerial exposure event.

In addition, the strata below the M1 surface contain local fenestral fabric (Fig. 12B), autobreccia, clay-rich "crusts" (most now chertified) with abundant horizontal fenestrae interlaminated with fine- to coarse-grained detrital quartz layers, locally abundant glauconite, pyrite, fractures and breccia with dolomite, clay, detrital quartz matrix locally cemented with coarse calcite cement, dolomite facies clasts, chalcedony, megaquartz and chert clasts, and, locally, poikilotopic calcite clasts. In addition, round or oblong to rounded elongate areas, altering original facies, occur for several meters below the surface (Fig. 10). These areas are characterized by a central area filled with poikilotopic calcite that is surrounded by a halo of iron staining and local fenestral fabric (Fig. 12C). These features are identical to spar-filled voids with well-developed hematitic hypocoatings described by Vanstone (1991) in late Osagean-early Meramecian paleosols from southwest Britain. Some of these areas in the Schaben core show associated microscopic horizontal and downward "bifurcating" of microfractures. These altered areas likely reflect the presence of land plant roots. The fenestral fabric, crusts, autobreccia, coarse calcite and poikilotopic cement, possibly associated with meteoric water, are consistent with subaerial exposure as well.

An early, intra-Mississippian exposure event at the M1 surface versus the alteration and features being related to the post-Mississippian exposure event is supported by several cross-cutting relationships. Below the M1 surface, original dolomitic facies and silica-replaced facies are fractured and brecciated and infilled with dolomite matrix, detrital quartz and replacive silica clasts. These facies and previously fractured and brecciated areas are crosscut by coarse calcite-filled fractures, replaced by poikilotopic calcite, and the

Figure 12: Features associated with the M1 surface. A) Calcite-replaced facies (alizarin red-stained areas) below the M1 surface that were subsequently fractured and filled with very finely crystalline dolomite that contains clasts of the poikilotopic calcite (white arrow). Note the truncated coarse calcite cement-filled fracture in the poikilotopic calcite (black arrow) Scale 1 mm. B) Abundant fenestral pores (white areas) developed in dolomitic matrix just below the M1 surface in the # 2 Lyle Schaben core. Note pore filled with coarse calcite cement (stained with alizarin red) that is common below the M1 surface. Scale 1 mm. C) Altered facies below the M1 surface. Some oblong and tubular altered areas (soil features?) are characterized by a central area filled with coarse calcite cement (arrow) surrounded by a hematite halo (hypocoating?) and fenestral pores (white areas) in dolomitic and replacive poikilotopic calcite matrix. Scale 1 mm.

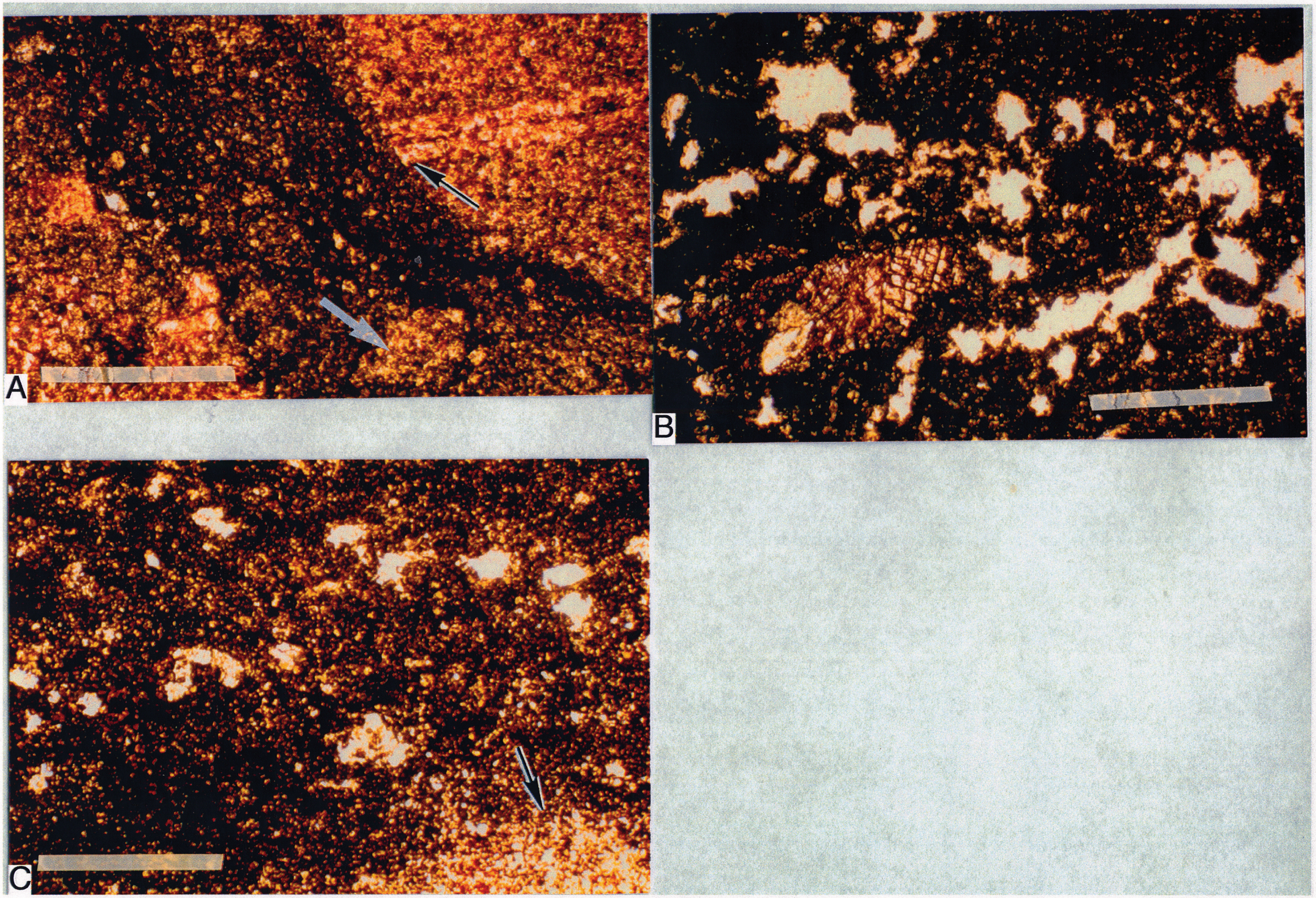


Figure 12

previously fractured and brecciated areas are locally cemented by coarse calcite. These fabrics, including the coarse calcite cement and poikilotopic calcite, are crosscut by fractures filled with dolomite (Fig. 12A) and locally, evaporite crystals and evaporite nodules from facies overlying the M1 surface. These dolomite-filled fractures contain clasts of poikilotopic cement and clasts of replacive silica. Importantly, none of these features are identified above the M1 surface, which strongly suggests a subaerial exposure event at this surface prior to deposition of overlying strata. All of these features are overprinted by fracturing, brecciation, and infilling sediment associated with the post-Mississippian subaerial exposure event and burial compaction processes.

M1 & Above Strata

The upper portions of all cores in the Schaben Field, above the M1 surface are dominated by the sponge spicule-rich and mudstone/wackestone facies (most beds in the 1' to ~6' thick range) and contain abundant evidence of original evaporite minerals (Fig. 3). Compared to MO strata, Echinoderm-rich facies are relatively less abundant, occur in thinner beds (< 0.25 ft to ~1.5 ft.), and many contain evidence of subaerial exposure (e.g. fenestral birdseye fabrics, Fig. 5D).

The abundance of evaporites and occurrence of at least local subaerial exposure throughout the entire length of M1 and Above strata suggest deposition in restricted ramp environments that likely include protected embayments, evaporative lagoons (coastal salina?) and supratidal flats. As discussed previously, the nodular, coalesced nodular morphology, preserved crystal fabrics within nodules and vertically aligned crystal habit of original evaporite minerals indicates formation in the vadose zone of a supratidal environment to a shallow subaqueous setting at or just below the sediment/water interface (Warren, 1989). However, the presence of burrow mottling in the facies indicates more normal marine conditions sufficient to support organisms that reworked the sediment. The echinoderm-rich facies in this part of the ramp may represent shelfward migration of a subtidal shoal (e.g. preservation of crossbedding) or shelfward spill-over deposition into a lagoon or supratidal environment from tide or storm currents (presence of graded beds). Alternatively, some of the occurrences of this facies may reflect a return to more normal marine conditions as a result of relative rises in sea level. The subaerial exposure features that occur locally in the echinoderm-rich facies could have formed as a result of accumulation to sea level, storm washover onto a supratidal flat, evaporative drawdown, or relative sea-level falls. The features in M1 strata are somewhat similar in setting to SW Persian Gulf (Abu Dabi) where Kendall and Skipwith (1969) described Holocene shallow-water carbonate and evaporite sediments forming in a saline lagoon. Most sediments there are bioclastic. Vertical sections in the supratidal zone show lagoonal sediments at the base capped by intertidal sediments and overlain by windblown and storm-washover sediments.

The abundance of sponge spicule dolowackestone-packstone and dolomudstone-wackestone in close association with evaporites and local subaerial exposure features represents a different environment of deposition than for these facies in MO strata. The sponge-spicule rich facies and mudstone/wackestone facies in M1 likely were deposited in low energy and slightly more restricted setting, such as a lagoon or protected embayment as compared to the co-eval echinoderm-rich facies deposited in more basinward normal marine conditions. In this environment sponges likely grew during times of more normal marine conditions. Alternatively, much of the sponge-rich facies could represent shelfward transport into the more protected environments. Wispy and wavy horizontal lamination, alternating grain-rich and grain-poor layers, some apparent normally graded beds and local interbeds of grainstone in sponge-rich facies indicate transport and reworking of sediment by storm or other currents.

OTHER CORES

Other cores studied in reconnaissance for this study (Fig. 1A) show similar facies and relationships as described above. Several general trends also seem to be apparent as well. In comparison to the Schaben Field area, there seems to be an increase in the abundance of bryozoans towards the basin and a decrease in chert going shelfward, to the northwest.

SUPPORT FOR DEPOSITIONAL ENVIRONMENTS FROM ANALOGS

Kansas

Probably the most extensively previously studied and interpreted Osagean-Meramecian strata in the central Kansas region, with regards to interpretations of facies and depositional environments, comes from several studies in the Bindley Field (Fig. 1A). Although most of the cores represent the Meramecian portion of the stratigraphic record, the similar facies identified and environments of deposition provide useful analogs for the Osagean strata of this study and also indicate that controls on deposition were similar in Osagean and Meramecian time in Kansas.

Ebanks *et al.* (1977) in their study of the Bindley Field described some Osagean strata, in addition to the Meramecian, that occurred in the basal-most portions of some cores. They noted that the Osagean strata represented supratidal or intertidal evaporitic environments and that Meramecian rocks reflected a slight deepening. Cores from the Bindley field only penetrate the uppermost Osagean, which is likely equivalent to the M1 & Above strata of this study. For latest Osagean-earliest Meramecian rocks Ebanks *et al.* (1977) described a cherty dolomite facies with abundant monaxon sponge spicules or their molds. They interpreted the chert in the rocks as a replacement of former evaporite minerals, probably anhydrite, and interpreted a supratidal, sabkha-like environment because of wavy interlamination of dolomite and shale, broken and curled dolomite laminae, scoured bedding surfaces, and the close resemblance of the silica nodules to nodular anhydrite in some modern supratidal sediments. The textures Ebanks *et al.* (1977) describe for replaced nodules and lines of evidence for former evaporite minerals are identical to this study. Ebanks also used the absence of regular lamination of any kind in this facies to downgrade the possibility that these rocks may have been deposited in an evaporitic basin.

Ebanks *et al.* (1977) also described a spicule dolomite facies (lower Meramecian portion of the cores) that, in addition to an abundance of sponge spicules and their molds, also contained an abundance of glauconite, fragments of fenestellid bryozoans present in some of the dolomite matrix, and pelmatozoan (crinoid and blastoid) columnals and plates. They interpreted this facies as transitional from supratidal to shallow marine. The environmental complex consisted of shallow-marine lagoons with poor tidal exchange and highly variable salinity into which occasional tongues of supratidal deposits prograded and infrequent strong currents delivered debris of fauna from nearby, more open-marine environments.

Johnson and Budd (1994) also studied cores from the Bindley field focusing on the middle part of the Meramecian portion. They described several facies that are directly comparable with characteristics and environmental interpretations of M1 & Above, and MO strata. They described a somewhat burrow mottled spicule-rich dolomudstone facies (their Lithotype 2) that contained chalcedony/quartz nodules and low diversity fauna which they interpreted to be replaced subaqueous evaporite structures. Their interpretation of the facies was that of a low-energy, subtidal environment that ranged from restricted to evaporitic. This facies and depositional environment interpretation is similar to the SWP in M1 & Above facies of this study.

Johnson and Budd (1994) also described an argillaceous dolomudstone-dolomitic shale (their Lithotype 5) that contained rare monaxon sponge spicules, bryozoans, thin, wavy laminae of shale-rich and shale-poor composition, amorphous organics, silica nodules; subangular quartz silt and burrows. They interpreted this facies as representing subtidal brackish to evaporitic, lagoonal environment. This facies and depositional environment is similar to that of the MW and siliciclasitic/shale facies, especially in the M1 & Above strata of this study.

Johnson and Budd (1994) described dolomudstone, dolowackestone, dolopackstone/grainstone and lime grainstone facies dominated by echinoderms and fenestrate bryozoan fragments (their Lithotype 4). They interpret these strata to represent deposition in a normal-marine, low- to high-energy shelf environment that was periodically winnowed by storms. This facies and depositional environment interpretation are similar to the EWPG facies of this study, especially for MO strata. They also noted that their echinoderm and bryozoan-rich strata (Lithotype 4) are gradational upward into spicule-rich dolomudstone facies (Lithotype 2), which probably represents an evolution of increasing restriction and stress on the normal marine fauna. They noted six depositional cycles (4-14' thick) of such types of upward facies transitions consisting of normal marine facies at the base and capped by a thin layer of evaporitic dolomudstone. Certainly the interbedding of these facies is similar to the relationship seen in the M1 & Above portion of this study (Fig. 3).

Other Areas

Some aspects of strata described in this study are curious and warrant further consideration. During Osagean-early Meramecian time, the setting was situated in the tropics-subtropics, approximately at 20 degrees S latitude. Yet, facies are dominated by an heterotrophic assemblage characteristic of temperate water conditions. Indicators of warmer and arid conditions are more local (e.g. evaporites, minor occurrence of phototrophic algae). Sponge spicule facies are typically thought of as deeper water facies, yet they occur in close association with evaporites and subaerial exposure indicators in M1 strata. Therefore, a comparison with examples from the Modern and ancient rock record, including other Mississippian examples from within and outside Kansas, is useful for understanding controls on deposition.

One of the more curious associations in the strata studied here, and that cited from the Bindley field, as noted above, are abundant sponge spicule facies with very shallow water indicators, especially in M1 & Above strata. Although sponge spiculitic rocks are often thought to indicate deeper water deposition, literature review indicates a number of examples that reflect shallow water. The review also indicates many workers that have cited the ease of postmortem transport of sponges and spicules, both basinward and shelfward, and suggest their accumulations may often reflect transport processes rather than reflecting the environment in which sponges actually lived. In addition, other studies of strata of differing ages, including other Mississippian examples, show many similarities with M0 and M1 and Above strata of this study. Therefore, the studies discussed below provide additional insight and serve as analogs, aiding in the interpretation for environments and processes important in deposition of strata in this study.

McKee *et al.* (1959) in a study of the Kapingamarangi Atoll show that sponge spicules are derived from the remains of sessile adults that inhabit a large range of depths and so may be deposited in-situ. Alternatively, in shallow water, the spicules may be carried by waves and surface currents and become redistributed over the lagoon surface, to be deposited with various kinds of sediment. Thus, because of their potential transport after death by water currents, sponge spicules may be either autochthonous or allochthonous. McKee *et al.* (1959) also show that sponge spicules accumulate only in large numbers in deeper, relatively quiet parts of the lagoon and that they do not accumulate much on the beach because of wave and current action that keeps them suspended within the water column.

Boreen *et al.* (1993) and Martindale and Boreen (1997), in studying the modern south Australian margin, show that redistribution of sponge spicules to deep quiet water after death is an extremely active process that leaves little *in situ* evidence of dense sponge communities growing across the shelf.

Maliva *et al.* (1989) document some Cenozoic shallow water cherts composed of lithified mixtures of diatomite, spiculite, porcellanite, and terrigenous and authigenic clay, locally with some shallow water carbonate debris. They appear to have accumulated in highly productive shallow lagoons and bays in which terrigenous sediment was not sufficiently abundant to dilute the diatom frustules and siliceous sponge spicules. They also note that the Eocene Pallinup Formation of the Bremer Basin, western Australia, is a widespread shallow marine spiculite. Gammon and James (1998) indicate that sheltered, shallow-water paleoembayments on the southern margin of Late Eocene Western Australia were sites of sponge-rich facies deposition in warm-temperate waters during an overall regression. Contemporaneous temperate-water bryozoan-rich limestones were deposited in open marine areas.

The Aleman (Ordovician) as described by Geeslin and Chafetz (1982) appears to be a direct analog for the strata of this study, especially for M1 & Above strata. Geeslin and Chafetz (1982) show a close association of dolomitic facies containing abundant spicules and their molds and silica-replaced evaporites that they interpreted as all early diagenetic features associated with mixing zone diagenesis.

Lane (1981) documented nearshore sponge spicule mats in Pennsylvanian limestones in west central Indiana and speculated that at least some basinal spiculites may have originated by accumulations of winnowed shelf or shelf-margin spicules. Cavorac and Ferm (1968) documented the occurrence of cherty spicule-bearing Pennsylvanian strata from the Appalachian Plateau, which formed in swampy coastal areas relatively free of detrital sediments where normal marine water approached the shoreline. In this case, Cavorac and Ferm (1968) interpret large sponge colonies to have formed near shorelines where silica-rich water from streams was delivered to the marine environment. Similarly, Carlson (1994) interpreted that Pennsylvanian sponge-spicule dominated flint beds of the northern Appalachian basin were shoreline indicators, having formed in detritus-starved lagoons or bays that bordered the swampy portions of the resulting shore.

In a study of the Devonian Caballos Novaculite (Folk and Mcbride, 1976; Mcbride and Folk, 1977; Folk, 1973), Folk suggested a very shallow environment for deposition. Deposition was in semirestricted lagoons or bays with sponge spicules being the sole faunal remains as a result of high salinity prohibiting other fauna. Restriction of bays, with limited interchange with open sea may have prevented influxes of pelagic, open-ocean Radiolaria. The presence of fenestral (birdseye) fabric indicated supratidal conditions and small evaporite nodules and laminae formed in hypersaline, reducing tidal flat areas. Deposition was in semirestricted lagoons where there was no influx of muddy river water. Evaporitic conditions were attained in very shallow peritidal flats, so that fenestral fabric was produced locally, and nodules and laminae of sulfate minerals formed. Subaerial exposure from relative sea-level fall resulted in dissolution and evaporative collapse. The characteristics are similar to those described for M1 strata.

Chowns and Elkins (1974) in a study of the Fort Payne and Warsaw formations in Tennessee described a succession of cherty dolomitic limestones consisting of interbeds of skeletal grain/packstone composed primarily of pelmatozoan and more minor bryozoan debris and dolomitic wacke/mudstone. Silica nodules (geodes) after original evaporite minerals are common and most abundant in the cherty dolomitic spiculites. These characteristics are identical to M1 & Above strata of this study. Chowns and Elkins (1974) interpret facies relationships to represent deposition in shallow, open marine to prograding tidal-flat-lagoon-complex environments. The lack of tidal flat sedimentary structures, such as algal laminations and flaser bedding, was attributed to bioturbation and dolomitization. The absence of cyclicity was due to lack of textural and mineralogical between peritidal and subtidal sediments to a low energy gradient across the shoreline and reflux of dolomitizing brines from peritidal to subtidal sediments. Such conditions could be envisaged where tidal flats prograded into quiet water lagoons, which accumulated large volumes of carbonate mud. Chowns and Elkins (1974) interpreted the sponges to have grown prolifically in the marine environment, marginal to the tidal-flat-lagoon environment. The abundance of sponge debris in beds with replaced evaporites was surprising to Chowns and Elkins (1974). To them it indicated that the organisms were prolific in marginal carbonate domains and, because of their size and low specific gravity, could have been transported by wind and water currents into peritidal zones and concentrated by wave swash. This would help explain the absence of heavier, less transportable skeletal debris. Chown and Elkins (1974) noted that the Keokuk, Borden, Harrodsburg, and Woodbury geodes, occurring at approximately the same stratigraphic position traditionally associated with the Osage-Meramec boundary, share a similar depositional environment and origin around the margins of the Illinois Embayment.

Witzke *et al.* (1990) describe Keokuk crinoidal and spicular wackestones and mudstones that likely represent quite-water subtidal environment 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. They also note that clay generally increases upward through the Keokuk sequence recording influx of distal terrigenous clastics during probable regression.

Choquette *et al.*(1992) in a study of the Burlington-Keokuk in Iowa, Illinois and Missouri described a siliceous dolostone with an abundance of spicules and burrows. The bioturbation but scarcity of biota suggested to them relatively restricted conditions and slow rates of sedimentation in protected inner-shelf environments.

Lindsay (1985) in a study of the Charles Formation (overlying the Mission Canyon Formation) in North Dakota identified a restricted marine to tidal flat facies with sparsely anhydritic, spiculitic (monaxon), dolomitized pelletal wacke/packstones with leaching of many of the spicules.

Other analogs reported in the literature that have many similarities to the Osagean-Meramecian strata of this study, include the Mississippian from Alabama (Nolte and Benson, 1998), Mississippian of Kentucky and Tennessee (Miliken, 1979), Mississippian Lake Valley from New Mexico (Meyers, 1977), Devonian Thirtyone Formation (Saller *et al*, 1994; Ruppel and Hovorka, 1995), and the Ordovician from Oklahoma (Gao and Land, 1991)

REGIONAL PALEOGEOGRAPHY, CLIMATE, PALEO-OCEANOGRAPHY

Although the above discussion aids in understanding environments of deposition for Osagean (and Meramecian) strata in inner shelf areas of Kansas, a further understanding is necessary for controlling factors on facies constituents, facies distribution and morphology of the Kansas Mississippian shelf (a ramp). As indicated by Brandley and Krause (1997), not all ancient carbonates can be fully aligned with either cool water or warm water models, as some contain characteristics of both. Nelson (1988) and James (1997) have suggested that many Paleozoic carbonates exhibit cool-water characteristics.

Recent studies (Witzke, 1990; Scotese, 1999) place the Kansas study area during Visean time in a subtropical location, at about 20 degrees S and drifting north during the Carboniferous where subtropical to tropical carbonates dominated by phototrophs might be expected. The presence of abundant evaporites in M1 & Above strata attest to an arid setting that fits with paleogeographic/climate reconstructions. However, a number of biotic and non-biotic associations from this study indicate the coexistence of lithofacies deposited in warm and colder water. As indicated from this study and from the literature discussed above, much of the inner to deep settings on the Kansas ramp during Osagean-Meramecian are dominated by echinoderms, siliceous sponges and bryozoans, heterotrophs whose growth and productivity is dependent on active circulation of nutrient-laden waters (Martindale and Boreen, 1997). Such widespread aphotic and heterotrophic feeding strategy is a fundamental characteristic of cool-water biotas (Boreen *et al.*, 1993). The general lack of phototrophs, ooids (especially in Osagean strata), and micritized grains in Osagean-Meramecian strata in Kansas is also supportive of a cool water setting and suggests much of the carbonate production occurred at considerable depths. Also, inner ramp sediments of this study consist of sequences of bioclastic packstones/grainstones, much of it evidencing transport (likely by storms), a characteristic very similar in aspect to Australian Tertiary cool-water limestones (Boreen and James, 1995).

James (1997) discusses characteristics of the cool-water carbonate depositional realm and provides examples of settings and models for cool water ramp development in warm water settings. Martindale and Boreen (1997) and Brandley and Krause (1997) studied Early Mississippian ramps in Canada that developed in a similar subtropical-tropical setting north of the equator and reflect cool-water conditions. Based on the subtropical-tropical setting of the study area presented here, and utilizing the examples and models provided by the above studies of James (1997), Martindale and Boreen (1997), and Brandley and Krause (1997), it appears the characteristics of the Mississippian ramp during Osagean and Meramecian in Kansas can best be explained by upwelling of cool, nutrient-rich waters that promoted growth of heterotrophic bryozoans and echinoderms over large areas of the Kansas Mississippian ramp. Before further discussion of the characteristics of those cool water ramps and comparison to features in this study, it is useful to discuss upwelling as a viable process for the study area during Osagean-Meramecian time.

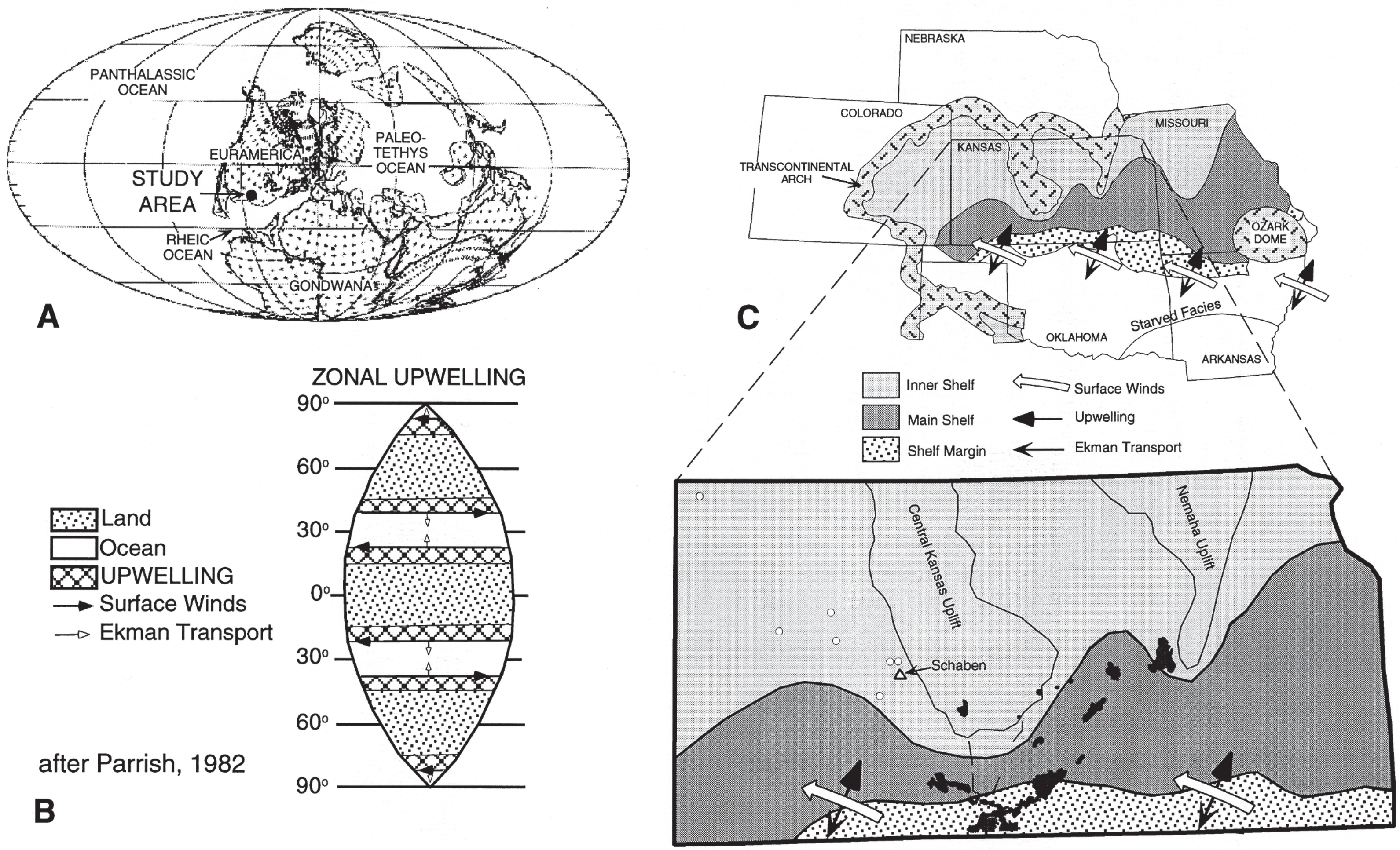
Regional Upwelling as a Dominant Process

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 degrees S position of more recent studies (Witzke, 1990; Scotese, 1999) (Fig. 13A). Parrish 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 those areas as the most likely site for chert.

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) suggest that Paleozoic sea water may 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 which enriched westerly equatorial surface currents in silica and an area of silica productivity associated with sites of dynamic upwelling off the west coasts of Gondwana and North America, when a more or less continuous western continental margin existed. 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.

A particular attractive 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) in which upwelling occurs on north- or south-facing coastlines that are situated at the proper latitude relative to the major zonal wind systems (Fig. 13B). 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

Figure 13: A) Paleogeographic setting during Visean-Tournasian time. Note location of the study area, which was situated at ~ 20 degrees S. 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), and Scotese (1999). The enlarged inset also shows location of Schaben Field and other data studied in reconnaissance for this study (white circles) and location of "chat" fields (dark areas) from Montgomery et al. (1998).



A
PANTHALASSIC OCEAN
EURAMERICA
PALEO-TETHYS OCEAN
STUDY AREA
RHEIC OCEAN
GONDWANA
B
ZONAL UPWELLING
90°
60°
30°
0°
30°
60°
90°
Land
Ocean
UPWELLING
Surface Winds
Ekman Transport
after Parrish, 1982
C
NEBRASKA
COLORADO
MISSOURI
KANSAS
TRANSCONTINENTAL ARCH
OZARK DOME
OKLAHOMA
Starved Facies
ARKANSAS
Inner Shelf
Main Shelf
Shelf Margin
Surface Winds
Upwelling
Ekman Transport
Central Kansas Uplift
Nemaha Uplift
Schaben

Figure 13

limited in length by the Coriolis effect or confines of zonal climate patterns. As compared to the zonal upwelling model of Parrish (1982) (Fig. 13B), the paleogeographic setting of the region at ~20 degrees S, a generally southerly facing coastline and likely surface wind patterns (Fig. 13A, C) are in favorable agreement. 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). The shoreward limit of the upwelling system is the bathymetric contour marking the depth where turbulence takes over from Ekman transport and a shallow shelf gradient, likely to have been the case for the shelf setting of this study, will result in a locus of upwelling that is removed from the geographic shoreline (Parrish, 1982).

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. Brunton and Dixon (1994) in a paleoecologic study of siliceous sponges through the Phanerozoic noted that sponges were dominated by heterotrophs whose local concentrations reflect environments characterized by short-lived periods of increased organic nutrients.

Nobel (1993) notes that the change from open-ocean circulation in the Late Devonian-earliest Mississippian to an increased restriction of marine circulation and compartmentalization in the Ouachita basin with microcontinental fragments serving as intermittent barriers which allowed for development of local anoxic conditions and increased velocity of bottom currents from stricture of passages. Vogt (1989) notes 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). Therefore, these elements (factors) may have also aided in conditions conducive to upwelling of nutrient and silica-rich waters across the shelf adjacent to the Ouachita basin.

Lasemi *et al.* (1998) similarly interpreted upwelling of nutrient- and silica-rich cool oceanic water for Ft. Payne and Ullin formation deposits in the Illinois Basin, which sat at about 20 degrees south of the equator as well. 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. Wright (1991) also attributes many characteristics of Early Mississippian deposits to result from upwelling

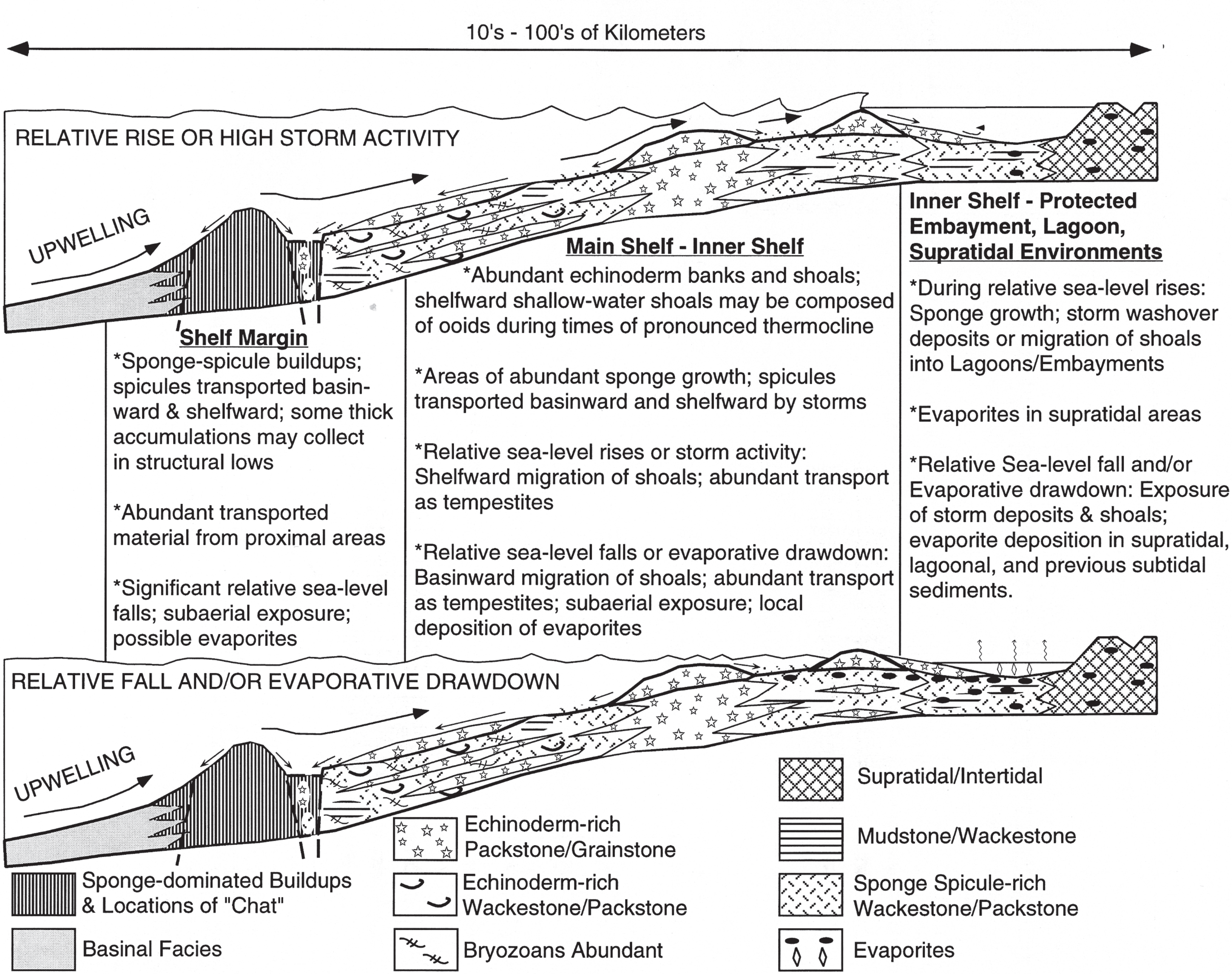
CONTROLS ON RAMP DEPOSITION

Upwelling of Cool, Nutrient-rich Water

Upwelling of cool, nutrient-rich water appears to have been a viable process that affected the ramp in Kansas during Osagean-Meramecian ramp deposition. The apparent decrease in chert towards the north observed in cores of this study is supportive of nutrient and silica-rich water from upwelling as opposed to a land (northward) source. Therefore, it is useful to consider features and models of cool water ramps described by James (1997), Martindale and Boreen (1997) and Brandley and Krause (1997). Figure 14 shows interpretations of depositional setting and controlling processes on facies characteristics during Osagean time in Kansas. This diagram combines information from the cores and incorporates data from the literature on Kansas Mississippian strata, comparisons to analogs discussed above and below, regional patterns, and consideration of paleogeographic, paleo-oceanographic and relative sea-level position.

Open shelves and ramps in cool-water settings shows most of the setting to be open subtidal with a complex array of shallow-water depositional environments clustered at or near the shoreline (James, 1997). As discussed by James (1977), in arid climates, strandline areas may consist of tidal flat areas with eolian dunes with interdune areas being sites of sea-marginal evaporites and lacustrine dolomite formation. Outer shelf and shelf edge environments are a zone of carbonate production and accumulation strongly affected by seasonal storms. Deeper regions are characterized by significant mud quantities composed of planktonic fallout, transported benthic skeletal fragments, clay and siliceous sponge spicules. These are the environments of the most extensive temperate carbonate sediments in the modern ocean (James, 1997). Bryozoans produce the most grains, especially in New Zealand, Australia and sectors of the NW European shelves (James, 1997). Interestingly, sponges appear to be particularly prolific but their remains account for little of the sediment. Sponges are especially important as sediment binders and for creating substrates for other biota. In some areas, such as the shelf off British Columbia,

Figure 14: Ramp model with controls on deposition for central portions of Kansas during Osagean-Meramecian time. The model is based on evidence from this study and from extensive literature review.



10's - 100's of Kilometers
RELATIVE RISE OR HIGH STORM ACTIVITY
UPWELLING
Shelf Margin
*Sponge-spicule buildups; spicules transported basinward & shelfward; some thick accumulations may collect in structural lows
*Abundant transported material from proximal areas
*Significant relative sea-level falls; subaerial exposure; possible evaporites
Main Shelf - Inner Shelf
*Abundant echinoderm banks and shoals; shelfward shallow-water shoals may be composed of ooids during times of pronounced thermocline
*Areas of abundant sponge growth; spicules transported basinward and shelfward by storms
*Relative sea-level rises or storm activity: Shelfward migration of shoals; abundant transport as tempestites
*Relative sea-level falls or evaporative drawdown: Basinward migration of shoals; abundant transport as tempestites; subaerial exposure; local deposition of evaporites
Inner Shelf - Protected Embayment, Lagoon, Supratidal Environments
*During relative sea-level rises: Sponge growth; storm washover deposits or migration of shoals into Lagoons/Embayments
*Evaporites in supratidal areas
*Relative Sea-level fall and/or Evaporative drawdown: Exposure of storm deposits & shoals; evaporite deposition in supratidal, lagoonal, and previous subtidal sediments.
RELATIVE FALL AND/OR EVAPORATIVE DRAWDOWN
UPWELLING
Sponge-dominated Buildups & Locations of "Chat"
Basinal Facies
Echinoderm-rich Packstone/Grainstone
Echinoderm-rich Wackestone/Packstone
Bryozoans Abundant
Supratidal/Intertidal
Mudstone/Wackestone
Sponge Spicule-rich Wackestone/Packstone
Evaporites

Figure 14

wide areas of the seafloor are covered with siliceous spicules produced by sponges (Conway *et al.*, 1991). Boreen *et al.* (1993) also noted that despite dense sponge communities growing across the modern south Australian shelf, the data suggest that redistribution of spicules to deep quiet water settings is an extremely active process which leaves little evidence of in situ growth environments.

James (1997) also noted that other temperate water areas where similar conditions prevail are the large ocean-facing gulfs of southern Australia, which extend so far into the continental interior with its warm and semi-arid climate that waters are warm and saline. The shallow, northern "head" of the gulfs are less than 20 m deep with extensive grass banks, intertidal mud flats and coastal lakes fed by saline continental groundwaters (Burne and Colwell, 1982; Gostin *et al.*, 1988). Sediments are Heterozoan with local prolific, yet monospecific, coral growth. Southward towards the open, cold Southern Ocean these sediments gradually change to completely Heterozoan and temperate in composition (Fuller *et al.*, 1994), but with local abundant corallines. Perhaps the setting in Kansas in early Mississippian time is similar to the large ocean-facing gulfs of southern Australia.

Brandley and Krause (1997) studied Tournasian and Visean strata in southwest Canada. They describe ramp facies similar to those found in equivalent-age strata of this study in Kansas, including an inner ramp peritidal to sabkha facies consisting of dolomudstone and anhydrite, and mid-ramp bank and shoal facies that include pelmatozoan packstones forming biologic and hydrodynamic banks. They suggested that chlorozforam facies characterized by ooids, peloids and ostracod-calcispheres represent deposition in an upper layer of solar heated water above a thermocline and that brynoderm and brynoderm-extended facies of mid and outer ramp environments represent cool and cold upwelling water below the thermocline.

Similarly Martindale and Boreen (1997) studied early Mississippian carbonates in southern Alberta. They note that warm water components (corals, phototrophs that include algae, ooids, micritized grains, peloids and evaporites) form relatively minor accumulations in narrow geographically restricted facies belts in a shoreward position, whereas the bulk of the sediments are dominated by fauna more typically of cool-water environments such as echinoderms and bryozoans.

The examples given above appear to reflect similar environments for the study of Kansas Osagean-Meramecian strata presented here. Figure 14 highlights interpreted environments and controlling processes across the Kansas Osagean-Meramecian ramp and calls upon evidence seen in the cores and information gleaned from analogs discussed previously. The discussion here focuses mostly on the inner parts of the ramp as represented by the cores of this study. Consideration of the more basinward portions, including the shelf-margin area, is given in the following sections on Tectonic Elements and Relative Sea Level Changes.

In the models shown in Figure 14, siliceous sponge-dominated buildups growing on the outer ramp were bathed in cold nutrient rich upwelling waters. Swell and storm waves caused winnowing and redistribution of bioclastic debris from the mound shelfward and basinward (noted also in Colleary *et al.*, 1997). The mid-ramp was dominated by echinoderm/bryozoan wackestones and graded grainstone/packstones derived from upslope shoals. Sponges appear to have been prevalent across much of the shelf, but because they are easily transported as has been documented earlier, their accumulations may be in large part a function of redeposition into areas of relative quite water both basinward and shelfward.

Martindale and Boreen (1997) note that deeper water areas of the inner ramp are dominated by echinoderm grainstone shoals promoted by high-energy, nutrient rich water circulation just below and a progressive shoreward reduction in bryozoan content which is consistent with the detrimental effects of warming of waters. An apparent decrease in bryozoans shelfward as indicated by data of this study seems to be similar to that recognized by Martindale and Boreen (1997) which they interpreted to indicate a change to warmer water shelfward. The widespread occurrence of echinoderm-rich packstones and grainstones across the mid and inner ramp suggests a broad environmental tolerance, high productivity and extensive transport. The presence of graded beds and some crossbedding in EWPG facies indicates transport from storms and migration of shoals, similar to megaripple fields and bioclastic sandwave deposits from modern open, temperate-water shelves (Martindale and Boreen, 1997). Much of the EWPG facies is structureless which may be due to the variable nature of storm processes and biological mixing as noted in the Cenozoic deposits of the Australian southern margin (Martindale and Boreen, 1997). They note evidence of abundant transport in crinoid grainstones and autocyclic shifting of facies through bedform migration in areas of constricted flow and during large storms which periodically transported downslope as tempestite flows.

In contrast to the examples from Martindale and Boreen (1997) and Brandley and Krause (1997), especially during the Osagean in Kansas, there are very few oolites as compared to strata above and below (Goebel, 1968) and very little evidence of phototrophs in general. Evaporites are the main remaining evidence that warm waters existed in the strata of this study. Although evidence of algae laminations may have been obscured by dolomitization (similar to that reported by Chowns and Elkins, 1974), this seems to indicate a very thin to absent thermocline over the Kansas ramp during the Osagean, possibly due to more vigorous upwelling. Perhaps areas of warm water were very limited aerially and where water was warm, such as lagoons or embayments, energy that could have formed ooids was already damped out. Where energy was high, water was still cool and would have resulted in crinoid shoals in very shallow water, in place of oolite shoals (Fig. 14). The lack of a pronounced thermocline may have also favored more widespread growth of sponges into shallow embayment and lagoon areas, as appears to have been the case for strata of this study. The strata underlying or overlying Osagean strata in Kansas that contain more abundant oolites, while still being dominated by bryonoderm facies, may indicate that oolite shoals developed in these shallow areas during times of a more prevalent thermocline and when high energy conditions occurred in warm water, similar to what is observed by Martindale and Boreen (1997), Brandley and Krause (1997). EWPG facies migrated and were transported through autocyclic shifting of bedforms, periods of high storm activity or during relative sea-level changes (discussed further below). In intertidal and subtidal areas these facies formed offshore barriers and shoals that protected embayments or lagoons. Periods of large storm activity or relative sea-level rises resulted in shelfward transport of EWPG facies by migration of bedforms or as storm deposits. Subsequent relative sea-level drops and/or evaporative drawdown resulted in subaerial exposure of some of EWPG shoals and storm deposits and formation of evaporites in lagoons and in supratidal to (previously) subtidal sediments (Fig. 14).

Tectonic Elements

In the earliest Mississippian, the southern margin of North America delineated the northern boundary of a transequitorial seaway connecting the Iapetus and Panthalassic seas. The convergence of Laurasia and Gondwana closed off the transequatorial seaway in the 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 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) indicated 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 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. Lee (1940; 1956) documented the wedgeout of Fern Glen rocks beneath Burlington rocks on the east side of the CKU and extension of only Burlington-Keokuk strata into the area of the CKU as evidence of early Osagean tectonic movement that raised the southern end of the CKU, created warpings, and resulted in southward tilting of Kansas. Goebel (1968) notes that conditions of deposition of early Osagean rocks in southwest Kansas are similar to those recorded in age-equivalent rocks in Missouri where Moore (1957) reported shaly and reddish limestones, thereby suggesting similar tectonic movement in that area due to regional processes.

More evidence for regional and local tectonism in Kansas during the Osagean-Meramecian may be indicated by some facies patterns and possibly some subaerial exposure features identified in the strata. Lasemi *et al.* (1998) cited the global increase in rate of subsidence during Devonian to the mid-Early Carboniferous time reported by Kominz and Bond (1991) to suggest tectonism may have played a role in the location of Fort Payne and Ullin formation buildups in faulted areas in the Illinois basin. However, more regional tectonism associated with early convergence of Gondwana and Laurassia may be a more likely factor. Montgomery *et al.* (1998) reported the possibility of some degree of local bathymetric control over thickness patterns of shelf margin Osagean sponge bioherms in Kansas related to low-level tectonism. Using isopach data for Osagean strata, including the chat Thomas (1982) and Rogers *et al.* (1995) suggested that development of CKU-Pratt Anticline structural features began in the Early Mississippian and therefore may have influenced depositional patterns. Similarly, Watney *et al.* (in press) note a close association of thickness change patterns of chat accumulations in Kansas (which coincide in location to the shelf margin sponge buildups) with basement lineaments. They used facies associations in these areas to suggest basement block movement during Osagean time.

Relative Sea-level Changes

Ross and Ross (1987) divided the Keokuk-Warsaw sequence into three major Transgressive-Regressive (T-R) cycles that they correlate globally, with an exposure surface separating the Keokuk and Warsaw formations.

Witzke *et al.* (1990) and Witzke and Bunker (1996) show an overall regressive sea level through the Keokuk and Warsaw (their cycle 6) with the Keokuk consisting of an interbedded sequence of spicule-bearing cherty dolomitized wackestones, storm-generated crinoidal packstones and grainstones and shales with shale generally increasing upward through the Warsaw marking siliciclastic progradation during the regressive phase and abundant quartz geodes after early diagenetic evaporites in the Warsaw sediments reflecting evaporative brines that formed as the seaway constricted during late regression. Although they recognized no obvious physical evidence for significant breaks in sedimentation within the Keokuk-Warsaw interval in southeast Iowa, they show more minor "subcycles" on their qualitative sea-level curve based on several glauconitic and bone-bed horizons within the upper Keokuk sequence. Although the boundary between the Osagean and Meramecian series has been variably drawn by different workers within, above or below the Warsaw formation, the top of the Warsaw marks a regional erosional boundary representing a major relative drop in sea level (Witzke *et al.*, 1990; Witzke and Bunker, 1996).

Read *et al.* (in press) recognize 6 to 8 Osagean-Meramecian depositional sequences in the Appalachian and Illinois basins.

The subaerial exposure surface separating MO and M1and Above strata is a regional feature and traceable between cores in the Schaben field. The surface marks a major change in overall pattern from mostly open marine subtidal conditions below to restricted, peritidal, evaporative environments above. The M1 surface is interpreted to mark a regional sequence boundary reflecting a relative drop in sea level. Whether this relative drop in sea-level is due to tectonism, eustacy, or a combination of both is not clear. Interestingly, the M1 surface is overlain in several of the cores by abundant glauconite (Fig. 3). Witzke *et al.* (1990) and Witzke and Bunker (1996) identify several glauconitic and bone-bed horizons within the upper Keokuk sequence to mark several "subcycle" boundaries within their upper Keokuk sequence. It may be that the M1 surface correlates to one of these horizons and reflects an extensive regional relative sea-level drop. The fact that the M1 surface contains extensive evidence of subaerial exposure may reflect a more localized tectonic overprint compared to the setting in Iowa. Interestingly, M1 and Above strata are similar (abundant silica nodules after evaporites, increase in siliciclastics) to Warsaw strata in Iowa (Witzke *et al.*, 1990; Witzke and Bunker, 1996) which may indicate that they are equivalent and reflect deposition during overall regression as indicated by Witzke *et al.* (1990) and Witzke and Bunker (1996) on their qualitative sea-level curve prior to regional erosion that marks the Osagean-Meramecian contact. Lumsden (1988) in a study of the Ft Payne in Tennessee noted that, overall, the water became more shallow as deposition progressed but was unsure if this was due to a fall in sea level, tectonic uplift of the ramp, buildup of the sea floor by sedimentation or a combination of factors. Certainly the recognition of similar, very shallow-water environments with evaporites in equivalent strata in the region and even outside (Virginia, West Virginia, Kentucky, Indiana, Illinois, Michigan and

Kansas, Williston Basin, reported in Chowns and Elkins, 1974) support at least a regional sea-level fall, perhaps coinciding with a change to a more arid climate (Cecil, 1990; Smith and Dorobek, 1993).

Watney *et al.* (in press) in their study of chat strata in shelf margin areas in Kansas interpreted these areas to be composed of sponge-microbe communities, possibly forming low-relief biostromes and bioherms surrounded by mudstone that resulted in accumulation of sponge spicule rich wacke-packstones. They noted a series of upward shallowing cycles with an ideal cycle, from base to top, consisting of sponge spicule-poor argillaceous mudstone to sponge spicule rich wacke-packstones which are overlain by bioclastic wacke-grainstone shelf deposits and terminated by submarine or subaerial exposure surfaces. They interpreted the cycles to represent transgressive-regressive (T-R) cycles. Interestingly, Johnson and Budd (1984) recognized a similar packaging of strata in Meramecian strata in the Bindley field and discussed cycles. However, in contrast, they placed bioclastic packstone-grainstone facies, representing more open marine conditions, at the base of the cycles and sponge spicule-rich wackestones-packstones (containing silica replaced evaporite nodules), reflecting more restricted conditions, at the tops of the cycle.

M1 and Above strata of this study consist of interbedded SWP, MW and EWPG facies. Some of the strata, especially EWPG facies contain evidence of subaerial exposure. Some of these strata could represent cycles formed by external forces similar to those recognized in farther basinward strata by Watney *et al.* (in press). However, at least some in the study presented here are likely to have formed from autocyclic processes as well. Even amongst the cores studied in detail in the Schaben area, there are different numbers of exposure events recognized (Fig. 3), some of the EWPG strata containing exposure evidence are thin (< 0.25' thick) and could represent exposure from local processes (e.g. storm washover into lagoon-tidal flat areas followed by evaporative drawdown and subaerial exposure) (Fig. 11). In addition, some of the SWP facies with evaporites contain subtle evidence of subaerial exposure which could relate to local subaerial exposure related to evaporative drawdown (Figs 9A, 14).

At least the M1 surface is likely to correlate with one of the cycle boundaries in the more basinward areas studied by Watney *et al.* (in press). Due to the regional, and global, recognition of sea level cycles and depositional sequences in Osagean strata (Witzke and Bunker, 1996; Ross and Ross, 1987), and because subaerial exposure of additional cycles in the more basinward area of Kansas would require subaerial exposure in the more shelfward areas of this study, it is apparent that at least some of the subaerial exposure events recognized in M1 and Above strata of this study reflect relative sea-level changes. The differences in numbers of cycles or depositional sequences, subtlety of some cycles (e.g. Iowa, Witzke and Bunker, 1996) versus more pronounced evidence of cycles or sequences and subaerial exposure (e.g. Kansas; Appalachians and Illinois, Read *et al.*, in press) may point to overprinting by more localized tectonic events.

Although the boundary between the Osagean and Meramecian series in Iowa has been variably drawn by different workers within, above or below the Warsaw formation, the top of the Warsaw marks a regional erosional boundary representing a major relative drop in sea level (Witzke *et al.*, 1990; Witzke and Bunker, 1996). Although Ebanks *et al.* (1977) describe the Osagean-Meramecian contact as gradational, McCoy (1978) provided evidence for major pre-Meramecian (pre-Warsaw in Kansas) erosion and significant channel incision in chat areas just southeast of the CKU. Channel incision appears to follow, at least in part, basement lineaments as shown in Watney *et al.* (in press). Thus, these characteristics, along with similarity to M1 and Above strata, may be supporting evidence that the Warsaw in Iowa is part of the Osagean.

More detailed work is necessary to further refine the chronostratigraphy and correlations to determine the relative effects of local, regional and global controls on stratigraphic packaging. Additional core, biostratigraphic and geochemical data and an increased understanding of the paragenetic sequence of events in Kansas are necessary to further refine our understanding of depositional and diagenetic controls, including those proposed in this study.

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REFERENCES

Adkins-Heljeson, D., Bhattacharya, S., Carr, T., Franseen, E.K., Gerlach, P., Guy, W., Hopkins, J., and Watney, W.L., 1999, Improved Oil Recovery in Mississippian Carbonate Reservoirs of Kansas - Near Term - Class 2: 1998 Annual Report : Kansas Geological Survey Open-file Report 99-22, 50 p.

Barber, R.T., and Smith, R.L., 1981, Coastal Upwelling Ecosystems: *in* Longhurst, A.R., ed., Analysis of Marine Ecosystems: New York, Academic Press, p. 31-68.

Brandley, R.T., and Krause, F.F., 1997, Upwelling, Thermoclines and Wave-Sweeping on an Equatorial Carbonate Ramp: Lower Carboniferous Strata of Western Canada: *in* James, N.P., and Clarke, J.A.D., eds., Cool-Water Carbonates, SEPM Special Publication No. 56, p. 365-390.

Brunton, F.R., and Dixon, O.A., 1994, Siliceous Sponge-microbe Biotic Associations and Their Recurrence Through the Phanerozoic as Reef Mound Constructors, Palaios, v. 9, p. 370-387.

Boreen, T.D., and James, N.P., 1995, Stratigraphic Sedimentology of Tertiary Cool-Water Limestones, SE Australia: Journal of Sedimentary Research, v. B65, p. 142-159.

Boreen, T.D., James, N.P., Wilson, C., and Heggie, D.T., 1993, Surficial Sediments of the Australian Otway Margin: A Cool-Water Carbonate Shelf: Marine Geology, v. 112, p. 35-56.

Burne, R.V. and Colwell, J.B., 1982, Temperate Carbonate Sediments of Northern Spencer Gulf, South Australia: A High Salinity Foramol Province: Sedimentology, v. 29, p. 223-238.

Byrnes, A.P. and Franseen, E.K., 2000, Lithofacies and Early Diagenetic Controls on Reservoir Properties in a Complexly Overprinted Carbonate Ramp System; Mississippian Schaben Field, Ness Co., Kansas: 2000 AAPG Annual Convention Official Program, New Orleans, LA, p. A21-22.

Carlson, E.H., 1994, Paleoshoreline Patterns in the Transgressive-Regressive Sequences of Pennsylvanian Rocks in the Northern Appalachian Basin, U.S.A.: Sedimentary Geology, v. 93, p. 209-222.

Carr, T. R., Adkins-Heljeson, D.M., Beaty, S.D., Bhattachary, S., Franseen, E.K., Gerlach, P.M., Guy, W.J. and Watney, W.L., 1996, Improved Oil Recovery in Mississippian Carbonate Reservoirs of Kansas-Near Term-Class 2: Annual Report: Kansas Geological Survey Open File Report 96- 7, 55 p.

Cavoroc, V.V., Jr., and Ferm, J.C., 1968, Siliceous Spiculites as Shoreline Indicators in Deltaic Sequences: Geological Society of America Bulletin, v. 79, p. 263-272.

Cecil, B.C., 1990, Paleoclimate Controls on Stratigraphic Repetition of Chemical and Siliciclastic Rocks: Geology, v. 18, p. 533-536.

Choquette, P.W., Cox, A., and Meyers, W.J., 1992, Characteristics, distribution and origin of porosity in shelf dolostones; Burlington-Keokuk Formation (Mississippian), U.S. Mid-Continent: Journal of Sedimentary Petrology, v. 62, p. 167-189.

Chowns, T.M., and Elkins, J.E., 1974, The origin of quartz geodes and cauliflower cherts through the silicification of anhydrite nodules: Journal of Sedimentary Petrology, v. 44, p. 885-903.

Colleary, W.M., Dolly, E.D., Longman, M.W., and Mullarkey, J.C., 1997, Hydrocarbon production from low resistivity chert and carbonate reservoirs in the Mississippian of Kansas: AAPG Rocky Mountain Section Meeting, Program Book and Expanded Abstracts Volume, p. 47-51.

Conway, K.W., Barrie, J.V., Austin, W.C., and Luternauer, J.L., 1991, Holocene Sponge Bioherms on the Western Canadian Continental Shelf: Continental Shelf Research, v. 11, p. 771-750.

Digital Petroleum Atlas: Kansas Geological Survey, URL=http://crude2.kgs.ukans.edu/DPA/County/ness.html.

Ebanks, W.J., Jr., Euwer, R.M., and Nodine-Zeller, 1977, Mississippian Combination Trap, Bindley Field, Hodgeman County, Kansas: American Association of Petroleum Geologists Bulletin, v. 61, p. 309-330.

Ebanks, W.J., Jr., 1991, Bindley field-U.S.A. Anadarko Basin, Kansas *in* Beaumont, E.A., and N.H. Foster, compilers, Stratigraphic Traps II: AAPG Treatise of Petroleum Geology Atlas of Oil and Gas Fields, p. 117-136.

Folk, R.L., 1973, Evidence for Peritidal Deposition of Devonian Caballos Novaculite, Marathon Basin, Texas: American Association of Petroleum Geologists Bulletin, v. 57, p. 702-725.

Folk, R.L., and Pittman, J.S., 1971, Length-slow Chalcedony a New Testament for Vanished Evaporites: Journal of Sedimentary Petrology, v. 41, p. 1045-1058.

Folk, R.L., and McBride, E.F., 1976, The Caballos Novaculite Revisited Part I: Origin of Novaculite Members: Journal of Sedimentary Petrology, v. 46, p. 659-669.

Franseen, E.K., Carr, T.R., Guy, W.J., and *Beaty, S.D., 1998, Significance of Depositional and Early Diagenetic Controls on Architecture of a Karstic-Overprinted Mississippian (Osagian) Reservoir, Schaben Field, Ness County, Kansas: Extended Abstracts, Vol. 1, 1998 AAPG Annual Convention, Salt Lake City, Utah. p. A210, 1-4.

Fuller, M.K., Bone, Y., Gostin, V.A., and Von Der Borch, C.C., 1994, Holocene Cool-Water Carbonate and Terrigenous sediments from Southern Spencer Gulf, South Australia: Australian Journal of Earth Sciences, v. 41, p. 353-363.

Gao, G., and Land, L.S., 1991, Nodular Chert from the Arbuckle Group, Slick Hills, SW Oklahoma: A combined Field, Petrographic and Isotopic Study: Sedimentology, v. 38, p. 857-870.

Gammon, P.R., and James, N.P., 1998, Shallow, Warm-Water Spiculites?: Geological Society of America Abstracts with Program, Annual Meeting, Toronto, Ontario, p. A-315.

Geeslin, J.H., and Chafetz, H.S., 1982, Ordovician Aleman Ribbon Cherts; An Example of Silicification Prior to Carbonate Lithification: Journal of Sedimentary Petrology, v. 52, p. 1283-1293.

Goebel, E.D., 1968, Mississippian rocks of western Kansas: American Association of Petroleum Geologists Bulletin, v. 52, p. 1732-1778.

Gostin, V.A., Belperio, A.P., and Cann, J.H., 1988, the Holocene Non-tropical Coastal and Shelf Carbonate Province of Southern Australia: Sedimentary Geology, v. 60, p. 51-70.

Gutschick, R.C., and Sandberg, C.A., 1983, Mississippian Continental Margins of the Conterminous United States: in Stanley, D.J., and Moore, G.T., The Shelfbreak Margin: Critical Interface on Continental Margins, SEPM Special Publication No. 33, p. 79-96.

James, N.P., 1997, The Cool-Water Carbonate Depositional Realm: *in* James, N.P., and Clarke, J.A.D., eds., Cool-Water Carbonates, SEPM Special Publication No. 56, p. 1-22.

Jenkyns, H.C., 1980, Cretaceous Anoxic Events: Continents to Oceans: Geological Society of London Journal, v. 137, p. 171-188.

Johnson, R. A., and Budd, D. A., 1994, The utility of continual reservoir description: An example from Bindley Field, Western Kansas: AAPG Bulletin, v. 78, p. 722-743.

Kendall, C.G.St.C., and Skipwith, P.A.D'E., 1969, Holocene Shallow-Water Carbonate and Evaporite Sediments of Khor al Bazam, Abu Dhabi, Southwest Persian Gulf: American Association of Petroleum Geologists Bulletin, v. 53, p. 841-869.

Kominz, M.A., and Bond, G.C., 1991, Unusually large subsidence and sea-level events during middle Paleozoic time; new evidence supporting mantle convection models for supercontinent assembly: Geology, v. 19, p. 56-60.

Lane, H.R., and DeKeyser, T.L., 1980, Paleogeography of the Late Early Mississippian (Tournaisian 3) in the Central and Southwestern United States: *in* Fouch, T.D., and Magathan, E.R., eds., Paleozoic Paleogeography of West-Central United States, Rocky Mountain Section, SEPM, p. 149-159.

Lane, N.G., 1981, A Nearshore Sponge-Spicule Mat from the Pennsylvanian of West-Central Indiana: Journal of Sedimentary Petrology, v. 51, p. 197-202.

Lasemi, Z., Norby, R.D., Treworgy, J.D., 1998, Depositional facies and sequence stratigraphy of a Lower Carboniferous bryozoan-crinoidal carbonate ramp in the Illinois Basin, Mid-Continent USA: *in* Wright, V.P., and Burchette, T.P., eds., Carbonate Ramps, Geological Society Special Publications No. 149, p. 369-395.

Lee, W., 1956, Stratigraphy and Structural Development of the Salina Basin Area: Kansas Geological Survey Bulletin 121, p. 1-167.

Lee, W., 1940, Subsurface Mississippian Rocks of Kansas: Kansas Geological Survey Bulletin 33, p. 1-114.

Lindsay, R.F., 1985, Rival, North and South Black Slough, Foothills and Lignite oil fields; their depositional facies, diagenesis and reservoir character, Burke County, North Dakota: *in* Longman, M.W., Shanley, K.W., Lindsay, R.F., Eby, D.E., eds., Rocky Mountain carbonate reservoirs; a core workshop, SEPM Core Workshop.7; Pages 217-263.

Lowe, D.R., 1975, Regional Controls on Silica Sedimentation in the Ouachita System: Geological Society of America Bulletin, v. 86, p. 1123-1127.

Lumsden, D.N., 1988, Origin of the Fort Payne Formation (Lower Mississippian), Tennessee: Southeastern Geology, v. 28, No. 3, p. 167-180.

Maliva, R.G., Knoll, A.H., and Siever, R., 1989, Secular Change in Chert Distribution: A Reflection of Evolving Biological Participation in the Silica Cycle: Palaios, v. 4, p. 519-532.

Maliva, R.G., and Siever, R., 1989, Nodular Chert Formation in Carbonate Rocks: Journal of Geology, v. 97, p. 421-433.

Maples, C.G., 1994, Revision of Mississippian Stratigraphic Nomenclature in Kansas: *in* Baars, D.L., compiler, Revision of Stratigraphic Nomenclature in Kansas, Kansas Geological Survey Bulletin 230, p. 67-74.

Martindale, W., and Boreen, T.D., 1997, Temperature-Stratified Mississippian Carbonates as Hydrocarbon Reservoirs - Examples from the Foothills of the Canadian Rockies: *in* James, N.P., and Clarke, J.A.D., eds., Cool-Water Carbonates, SEPM Special Publication No. 56, p. 391-410.

McBride, E.F., and Folk, R.L., 1977, The Caballos Novaculite Revisited: Part II: Chert and Shale Members and Synthesis, Journal of Sedimentary Petrology, v. 47, p. 1261-1286.

McCoy, J.R., 1978, Character of the Mississippian Formation in South-Central Kansas: Kansas Geological Survey, Open-File Report 78-9, 10 p.

McKee, E.D., Chronic, J., and Estella B.L., 1959, Sedimentary Belts in Lagoon of Kapingamarangi Atoll: American Association of Petroleum Geologists Bulletin, v. 43, p. 501-562.

Meyers, W.J., 1977, Chertification in the Mississippian Lake Valley Formation, Sacramento Mountains, New Mexico: Sedimentology, v. 24, p. 75-105.

Miliken, K.L., 1979, The Silicified Evaporite Syndrome - Two Aspects of Silicification History of Former Evaporite Nodules from Southern Kentucky and Northern Tennessee: Journal of Sedimentary Petrology, v. 49, p. 245-256.

Montgomery, S. L., Franseen, E.K., Bhattacharya, S., Gerlach, P., Guy, W., Byrnes, A.P., and Carr, T.R., in press, Schaben Field, Kansas: Improving Performance in a Mississippian Shallow-Shelf Carbonate: American Association of Petroleum Geologists Bulletin.

Montgomery, S.L., Mullarkey, J.C., Longman, M.W., Colleary, W.M., and Rogers, J.P., 1998, Mississippian "Chat" Reservoirs, South Kansas: Low-Resistivity Pay in a Complex Chert Reservoir: American Association of Petroleum Geologists Bulletin, v. 82, p. 187-205.

Moore, R.C., 1957, Mississippian Carbonate Deposits of the Ozark Region: SEPM Special Publication No. 5, p. 101-124.

Nelson, C.S., 1988, An Introductory Perspective on Non-tropical Shelf Carbonates: Sedimentary Geology, v. 60, p. 3-12.

Noble, P.J., 1993, Paleoceanographic and Tectonic Implications of a Regionally Extensive Early Mississippian Hiatus in the Ouachita System, Southern Mid-Continental United States: Geology, v. 21, p. 315-318.

Nolte, R.A., and Benson, D.J., 1998, Silica Diagenesis of Mississippian Carbonates of Northern Alabama: Gulf Coast Association of Geological Societies Transactions, v. XLVIII, p. 301-310.

Parrish, J.T., 1982, Upwelling and Petroleum Source Beds, with Reference to the Paleozoic: American Association of Petroleum Geologists Bulletin, v. 66, p. 750-774.

Read, J. F., Al-Tawil, A., Smith, L.B., Khetani, A.B., and Wynn, T.C., in press, High Resolution Sequence Stratigraphy of the Mississippian Carbonates of the Appalachian and Illinois Basins: SEPM/IAS Research Conference " Permo-Carboniferous Carbonate Platforms and Reefs", El Paso, Texas, May 14-16, 2000.

Rogers, J.P., Longman, M.W., and Lloyd, R.M., 1995, Spiculitic Chert reservoir in Glick Field, South-Central Kansas: The Mountain Geologist, v. 32, p. 1-22.

Ross, C.A., and Ross, J.R.P., 1987, Late Paleozoic Sea Levels and Depositional Sequences: Cushman Foundation for Foraminiferal Research, Special Publication 24, p. 137-149.

Rupple, S.C. and Hovorka, S.D., 1995, Controls on Reservoir Development in Devonian Chert: Permian Basin, Texas: American Association of Petroleum Geologists Bulletin, v. 79, p. 1757-1785.

Ryther, J.H., *et al.*, 1971, The Production and Utilization of Organic Matter in the Peru Coastal Upwelling Current: Investigaciones Pesqueras, v. 35, p. 43-59.

Saller, A.H., Van Horn, D., and Miller, J.A., 1991, Reservoir Geology of Devonian Carbonates and Chert - Implications for Tertiary Recovery, Dollarhide Field, Andrews County, Texas: American Association of Petroleum Geologists Bulletin, v. 75, p. 86-107.

Scotese, C.R., 1999, Paleomap Project: http://www.scotese.com/.

Selks, E.L., and Ciriacks, K.W., 1968, Mississippian Stratigraphy in Southern Kansas and Northern Oklahoma, Based on Conodont Fauna: Kansas Geological Survey Open-File Report 68-3, 5 p.

Shearman, D.J., and J.G. Fuller, Anhydrite Diagenesis, Calcitization and Organic Laminites, Winnipegosis Formation, Middle Devonian, Saskatchewan: Bulletin of Canadian Petroleum Geology, v. 17, p. 496-525.

Sloss, L.L., 1963, Sequences in the Cratonic Interior of North America: Geological Society of America Bulletin, v. 74, p. 93-113.

Smith, T.M., and Dorobek, S.L., 1993, Stable Isotopic Composition of Meteoric Calcites: Evidence for Early Mississippian Climate Change in the Mission Canyon Formation, Montana: Tectonophysics, v. 222, p. 317-331.

Thomas, M.A., 1982, Petrology and diagenesis of the Lower Mississippian, Osagean Series, Western Sedgwick Basin, Kansas: Kansas Geological Survey Open-file Report 82-24, 87 p.

Vanstone, S.D., 1991, Early Carboniferous (Mississippian) Paleosols from Southwest Britain: Influence of Climatic Change on Soil Development: Journal of Sedimentary Petrology, v. 61, p. 445-457.

Vogt, P.R., 1989, Volcanogenic Upwelling of Anoxic, Nutrient-rich Water: A Possible Factor in Carbonate-bank / Reef Demise and Benthic Faunal Extinctions?: Geological Society of America Bulletin, v. 101, p. 1225-1245.

Warren, J.K. 1989, Evaporite sedimentology: Englewood Cliffs, New Jersey, Prentice Hall, 285 p.

Warren, J.K., and Kendall, C.G.St.C., 1985, Comparison of Sequences Formed in Marine Sabkha (Subaerial) and Salina (Subaqueous) Settings - Modern and Ancient: American Association of Petroleum Geologists Bulletin, v. 69, p. 1013-1023.

Watney, W.L., Guy, W.J., and Byrnes, A.P., in press, Characterization of the Mississippian Osage Chat in South-Central Kansas: AAPG Memoir.

Witzke, B.J., and Bunker, B.J., 1996, Relative Sea-level Changes during Middle Ordovician through Mississippian Deposition in the Iowa Area, North American Craton: *in* Witzke, B.J., Ludvigson, G.A., and Day, J., eds., Paleozoic Sequence Stratigraphy: Views from the North American Craton: Geological Society of America, Special Paper 306, Boulder, CO, p. 307-330.

Witzke, B.J., 1990, Paleoclimatic Constraints for Paleozoic Paleolatitudes of Laurentia and Euramerica, *in* McKerrow, W.S., and Scotese, C.R., eds., Paleozoic Paleogeography and Biogeography: Geological Society of London, Memoir 12, p. 57-73.

Witzke, B.J., McKay, R.M., Bunker, B.J., and Woodson, F.J., 1990, Stratigraphy and Paleoenvironments of Mississippian Strata in Keokuk and Washington Counties, Southeast Iowa: Iowa Department of natural Resources, Geological Survey Bureau, Guidebook Series No. 10, 105 p.

Wright, V.P., 1991, Comment and Reply on "Probable Influence of Early Carboniferous (Tournaisian-Early Visean) Geography on the Development of Waulsortian and Waulsortian-like Mounds": Geology, v. 19, p. 413.