Paleoenvironmental Controls on Shallow-water Siliceous Sponge Spicule and Heterozoan Carbonate Facies: Mississippian Examples from Kansas and Implications for Regional Distribution of Potential Reservoir Facies

by

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INTRODUCTION

Interpretations of carbonate strata in the rock record are commonly driven by occurrences in modern ocean environments. For example, Heterozoan Association carbonates (an association of benthic carbonate particles produced by organisms that are light-independent plus or minus red calcareous algae; James, 1997), as opposed to Photozoan Association carbonates (an association of benthic carbonate particles including light-dependent organisms, and/or non skeletal particles such as ooids and peloids, plus or minus skeletons from the Heterozoan Association), are a characteristic component of cool-water carbonate shelves. In the modern, these occur where sea water temperatures are less than 20 degrees Celsius for prolonged periods and influx of terrigenous sediment is relatively low (Lees and Buller, 1972; Nelson, 1988; James, 1997; James and Bone, 2000). However, as pointed out by James (1997) Heterozoan carbonates do not always mean that the sediments reflect cool water settings. Heterozoans are an important component in most marine environments, and in addition to cool-water areas, can predominate even in low-latitude, warm water settings where environmental conditions limit the supply of siliciclastic and pelagic sediments, and where photic zone and nutrient conditions prevent the development of Photozoans (James, 1997).

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

Mixtures of biosiliceous (particularly those rich in sponge spicules) and Heterozoan-dominated carbonate deposits occur in the rock record. The occurrences in the modern of similar facies, as mentioned above, have led to these deposits usually being interpreted as recording cold-water polar or deep basinal conditions (James, 1997). However, there is a growing body of literature documenting biosiliceous and Heterozoan carbonate deposits, and specifically sponge-rich deposits, in the rock record that are interpreted to have been deposited in shallow-water middle-to low-latitude environments (e.g. Cavorac and Ferm, 1968; Folk, 1973; Chowns and Elkins, 1974; Geeslin and Chafetz, 1982; Maliva *et al.*, 1989; James and Bone, 2000; Gammon *et al.*, 2000). The increasing documentation of these deposits is aiding in understanding the paleoenvironmental attributes of these ancient neritic carbonate/spiculite accumulations. However, as pointed out by Gammon and James (2001), the depositional environments and sedimentology of such shallow-marine deposits are still poorly understood.

The Early-Middle Mississippian is one period characterized by extensive development of biosiliceous and carbonate accumulations in North America (Lowe, 1975; Gutschick and Sandberg, 1983). In the earliest Mississippian, the southern margin of North America delineated the northern boundary of a transequitorial seaway connecting the Iapetus and Panthalassic seas (Noble, 1993). During Early-Middle Mississippian time a shallow tropical sea covered most of the southern North American continent and was the site of a broad carbonate platform (Gutschick and Sandberg, 1983). Most of present-day Kansas was part of the platform area. Paleogeographic studies place that area at about 20 degrees S latitude, within the tropical to subtropical belt during Tournasian-Visean time (Parrish, 1982; Witzke, 1990; Scotese, 1999). Osagean deposition in the region was characterized by shallow shelf carbonates deposited on a gently sloping ramp to the south (Rogers *et al.*, 1995), with the shelf edge (bordering the Anadarko basin) located near the Kansas - Oklahoma border (Selk and Ciriaks, 1968; Lane and DeKeyser, 1980; Gutschick and Sandberg, 1983). Generally, shelf facies consist of limestones, dolomites, and cherts (Lane and DeKeyser, 1980; Gutschick and Sandberg, 1983). Previous detailed studies of Osagean strata in Kansas have focused on shelf-margin areas where thick accumulations of sponge-rich chert deposits occur (informally termed "chat") and form significant reservoirs (e.g. Rogers *et al.*, 1995; Colleary *et al.*, 1997; Montgomery *et al.*, 1998; Watney *et al.*, 2001). In comparison, relatively little detail is known about equivalent Osagean deposits in inner shelf (Lane and DeKeyser, 1980) locations in Kansas. The purpose of this paper is to: 1) document Osagean biosiliceous and Heterozoan carbonate and original evaporite facies that were deposited in a shallow-water, inner shelf area in Kansas; 2) provide examples in the rock record of similar biosiliceous and Heterozoan carbonate deposits to illustrate that these types of facies are more common in shallow-water, tropical/subtropical settings than previously thought; 3) show that shallow-water biosiliceous and Heterozoan carbonate deposits were widespread in North America during the Early-Middle Mississippian; and 4) use examples from this study and others in North America to interpret paleoenvironmental conditions that controlled deposition of biosiliceous and Heterozoan carbonate deposits in the Early-Middle Mississippian subtropical/tropical shallow-water settings. Recognition of these facies and understanding controls on their distribution has significance in that they form reservoirs in several areas of Kansas and could be important potential reservoir facies in other areas of Kansas and elsewhere in North America.

GEOLOGIC SETTING

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-Middle Mississippian tectonism is present in Kansas as well. Goebel (1968) indicated that the eastern flank of the Transcontinental Arch in western Kansas should be recognized as having been a positive area in early Mississippian time. Similarly, Lane and DeKeyser (1980) showed that the Transcontinental Arch was a subaerial physiographic element during much of the Paleozoic and that associated subaerial areas along the eastern margin included the Nemaha Ridge and Central Kansas Uplift (CKU). They also indicate that the Transcontinental Arch areas were near base level and intermittently subaerially exposed and submerged during Early-Middle Mississippian time.

The study focuses on Ness County, which is located on the upper shelf of the Hugoton Embayment of the Anadarko Basin, on the southwest flank of the Central Kansas Uplift (CKU), at the western edge of the Mississippian Osagean subcrop beneath the sub-Pennsylvanian unconformity (Fig. 1A). The CKU is the southeastward extension of the Transcontinental Arch (see Goebel, 1968; Lane and DeKeyser, 1980). Several authors indicate that the CKU started to become a structurally positive element before and during early Mississippian deposition but that the structural movements were minor compared with later tectonic events (e.g. Goebel, 1968; Thomas, 1982; Rogers *et al.*, 1995). Montgomery *et al.* (1998) and Watney *et al.* (2001) suggest that features associated with these early Mississippian events may have influenced depositional patterns.

Mississippian rocks are successively younger in a southwestward direction away from the CKU where all Mississippian rocks are absent (Fig. 1A). This pattern is due mainly to Late Mississippian - Early Pennsylvanian structural uplift related to the Ouachita orogenic event. This resulted in an extensive period of subaerial exposure and erosion of Mississippian strata forming a regionally significant unconformity that separates Mississippian from overlying Pennsylvanian rocks. The 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 (Lane and DeKeyser, 1980; Gutschick and Sandberg, 1983). Rogers *et al.* (1995) emphasized that it is most difficult to identify a shelf margin with significant topographic relief and instead characterize the margin as a facies boundary marking a transition from "shallow" oxygenated waters to "deeper" less oxygen-rich waters (their quotes). 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 shallow-water biosiliceous and Heterozoan carbonate (mostly dolomite) accumulations. Along the shelf margin, irregular or oval sponge bioherms, 15-48 m-thick, consisting mostly of sponge spicule-rich muds, developed below wave base (Montgomery *et al.*, 1998).

STUDY AREA STRATIGRAPHY

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

SCHABEN FIELD AREA DEPOSITIONAL ENVIRONMENTS

The following section discusses features observed in the cores and interprets environments of deposition. Facies and other features identified in the Schaben Field cores are shown in Tables 1 and 2, and Figures 4-10. This section briefly discusses DS1 and SB1, but focuses on DS2 because it is the sequence that contains abundant shallow-water biosiliceous and Heterozoan carbonate facies. Additional details on DS1 and SB1 can be found in Franseen *et al.* (1998) and Montgomery *et al.* (2000). The block diagram in Figure 11 is an interpretation of the general setting of depositional environments, especially during DS2 deposition.

Depositional Sequence 1 (DS1)

The abundance of the echinoderm facies with other diverse fauna, evidence of extensive reworking by burrowing organisms and only rare occurrence of evaporites suggest deposition in relatively normal shallow subtidal marine environments. The setting for DS1 is envisioned as a mostly normal to slightly restricted marine inner ramp setting that was a site of growth and accumulation of skeletal and spicule material as well as allochthonous deposition characterized by autocyclic shifting of facies through migration of bedforms (sandwaves, subtidal shoals) in areas of increased currents and during storms which periodically transported grainstones downslope as mass flow deposits. Some of the echinoderm wackestone, sponge spicule dolowackestone-packstone and bioclastic dolomudstone-wackestone facies are likely indicative of a lower energy compared to the echinoderm-rich packstone/grainstone facies in DS1 strata. The ramp during DS1 deposition became increasingly restricted prior to subaerial exposure (the SB1 surface).

The sharp contact between DS1 and DS2 is termed sequence boundary 1 (SB1) (Fig. 3). This surface is regionally extensive and it, and the strata immediately below for several meters, show significant alteration and evidence for subaerial exposure prior to deposition of DS2 (Figs. 3, 10, 12).

Depositional Sequence 2 (DS2)

After the SB1 subaerial exposure event, marine conditions returned but the depositional environment over the study area changed compared to that for much of DS1 deposition. The volumetric increase of sponge-spicule wackestone and packstone (SWP) with less diverse fauna and abundance of evaporites and subaerial exposure events throughout DS2 suggest deposition in more restricted environments that likely ranged from restricted ramp/protected embayment to evaporative lagoon (coastal salina?) and supratidal flat. Evidence of burrowing in much of DS2 strata indicates an influence of marine conditions sufficient to support organisms that reworked the sediment. The 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 currents as well. Elsewhere, rare oncolitic coatings and dark blebs likely indicate some influence of algae.

The interbedded echinoderm-rich layers (EWPG) in DS2 could have resulted from several different processes. The interbedding of this more normal marine facies with more restricted SWP and mudstone-wackestone (MW) facies could represent a cyclicity tied into relative sea-level changes, with the EWPG facies representing more normal marine conditions during relative sea-level rises and highstands. Alternatively, the interbedding may be due to autochthonous processes such as migration of subtidal shoals or transport, including shelfward spillover deposition into a lagoon or supratidal environment, from tide or storm currents (e.g. presence of graded beds). Similarly, the subaerial exposure features that occur locally in EWPG 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. Some of the relationships of EWPG, SWP, MW facies in DS2 (Fig. 8) are similar in setting to the southwest 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.

One of the more curious associations in DS2 is the dominance of sponge spicule facie and Heterozoan carbonates that were deposited in very shallow water. Although it is common to think of such deposits as reflecting cold-water polar or deep basinal conditions (James, 1997), this study and others from numerous periods in the geologic record are indicating that shallow-marine, mid-latitude biosiliceous and Heterozoan carbonates may be more common than previously thought (Table 3). Especially interesting are the examples that show similar facies associations with DS2 strata of this study. Most of those are from Mississippian (Osagean - Meramecian) strata from North America.

For example Ebanks *et al.* (1977) noted a relationship in the Bindley field of Kansas (lower Meramecian portion of the cores) of a skeletal facies (similar to EWPG facies of this study) with the sponge spicule/evaporite facies. They interpreted the relationship in the context of an environmental complex consisting 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. Also in a study on the Meramecian portion of the Bindley field in Kansas, Johnson and Budd (1994) described several facies that are directly comparable with characteristics and environmental interpretations of DS2 of this study. They described a somewhat burrow mottled spicule-rich dolomudstone facies 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. Johnson and Budd (1994) also described an argillaceous dolomudstone-dolomitic shale 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 siliciclastic/shale facie in DS2 of this study.

Chowns and Elkins (1974) in their 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. They interpret facies relationships to represent deposition in shallow, open marine to prograding tidal-flat-lagoon-complex environments. Chowns and Elkins (1974) cited other Osagian-Meramecian examples in Georgia, Tennessee, Kentucky, Indiana, Illinois and Missouri that showed similar facies associations which suggested to them the existence of similar shallow-water depositional settings (including sabkhas) around the margins of the mid-Mississippian-Illinois embayment. Similarly, 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. To those authors the bioturbation but scarcity of biota suggested relatively restricted conditions and slow rates of sedimentation in protected inner-shelf environments.

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

In summary, based on the features observed in DS2, and comparison to analogs, it appears that DS2 strata reflect a depositional environment that ranged from restricted ramp/protected embayment to evaporitic lagoon/supratidal flat (Fig. 11). SWP and MW facies with the abundance of evaporites represent the most restricted conditions. Sponge dominance may reflect in-place accumulations where sponges dominated due to increased salinity as well as shelfward transport from more open marine environments. EWPG facies are more open marine subtidal deposits that reflect relative sea-level rises, migration of subtidal shoals and transport from currents, including storms and possibly tides. Similarly, subaerial exposure surfaces that occur throughout DS2 may be due to relative sea-level falls or local processes such as accumulation to sea level, transport of subtidal deposits into lagoons or supratidal flats, and evaporative drawdown.

CONTROLS ON DEPOSITION OF EARLY-MIDDLE MISSISSIPPIAN SHALLOW-WATER SILICEOUS SPONGE SPICULE AND HETEROZOAN CARBONATE FACIES

As indicated earlier, studies (Witzke, 1990; Scotese, 1999) place the Kansas study area during Early-Middle Mississippian time in a tropical/subtropical location, at about 20 degrees S and drifting north during the Carboniferous. In this setting shallow water carbonates dominated by a Photozoan Association might be expected. In addition Gammon *et al.* (2000) point out that siliceous spiculites do not occur on the inner portions of shelves in subtropical and tropical environments. Therefore, the dominance of shallow-water biosiliceous (sponge spicule) and Heterozoan carbonates in this setting in Kansas and throughout similar settings in North America (as discussed above) during the Early-Middle Mississippian requires photic zone and elevated nutrient conditions that promoted their development and prevented the development of Photozoans (James, 1997).

Elevated nutrient and dissolved silica supplies could originate from fluvial or oceanic sources. Other studies have emphasized fluvial sources for elevated nutrients and dissolved silica with a link to a humid climate for promoting biosiliceous and Heterozoan carbonate facies development in mid-latitude, shallow water (inshore) environments (e.g. Gammon *et al.*, 2000; James and Bone, 2000; Lane, 1981; Cavaroc and Ferm, 1968; Carlson, 1994). However, several lines of local and regional evidence suggest that land-sourced nutrients and dissolved silica were not primary factors in development of Early-Middle Mississippian shallow-water biosiliceous and Heterozoan carbonate deposits in Kansas and surrounding regions, and instead suggest an oceanic basinal source.

The abundance of evaporites in DS2 of this study and in Osagean-Meramecian strata in other areas of North America indicate aridity (Cecil, 1990), which argues against large volumes of nutrients and dissolved silica coming from fluvial sources. Oolites are relatively rare in Osagean strata, but have been reported from several areas. For example the Short Creek oolite, which occurs in southeastern Kansas (Cherokee County), is interpreted to be an Osagean deposit. Witzke and Bunker (1996) also document Osagean oolite deposits in Iowa and show Early Osagean paleogeography with an inner shelf environment that includes common oolite shoals. Interestingly, this facies belt occurs in close proximity to emergent land and sandy siliciclastic facies belts. The local, sporadic development of oolite deposits could be characteristic of either land-sourced or basin-sourced nutrients that limited their development. However, the occurrence of oolite facies close to emergent land and land-derived siliciclastics (Witzke and Bunker, 1996) argues against excessive nutrients and dissolved silica coming from land-sourced runoff. Instead, the widespread distribution of biosiliceous and Heterozoan carbonate deposits across the shelf, including the proliferation of siliceous sponges to form buildups in shelf margin areas, is suggestive of an elevated nutrient and dissolved silica supply coming from basinal sources.

<u>Regional Upwelling as a Dominant Process</u>

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 (1982) indicated that areas near the highlands would have experienced less vigorous upwelling and that the degree of upwelling influence would also have decreased to the northwest, toward the Williston basin, as the shelf became shallower in that direction. Parrish (1982) placed the richest sources of upwelling in the southwest and midwest and pointed to those areas as the most likely site for chert.

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) also suggested that Paleozoic sea water might have contained more silica than modern sea water due to inefficiency of pre-diatom biogenic precipitation. Lowe (1975) additionally thought that silica for the Ouachita basin and adjacent shelf areas may have come from volcanic sources along the orogenic zone marking the North American-Gondwana convergent plate junction. The volcanic sources enriched westerly equatorial surface currents in silica, which produced an area of silica productivity associated with sites of dynamic upwelling off the west coasts of Gondwana and North America. Lowe (1975) postulated that during relative rises in sea level, waters from this upwelling area were able to spill eastward across the Paleozoic Mexican peninsula and into the Ouachita seas.

A particularly 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), which shows upwelling occurs on north- or south-facing coastlines that are situated at the proper latitude relative to the major zonal wind systems (Fig. 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 limited in length by the Coriolis effect or confines of zonal climate patterns. The paleogeographic setting of Kansas and the surrounding regions at ~20 degrees S in the Osagean with a generally southerly facing coastline, and the likely surface wind patterns (Fig. 13A, C) are in favorable agreement with the zonal upwelling model of Parrish (1982).

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).

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

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

Other studies of Early-Middle Mississippian strata have also called on upwelling. Gutschick and Sandburg (1983) interpreted upwelling to have been an important factor along the margins of much of the North American carbonate shelf during the latest Tournaisian (middle Osagean). Wright (1991) also attributes many characteristics of Early Mississippian deposits from within and outside of North America to result from upwelling. Lumsden (1988) interpreted the proliferation of sponges in the Ft. Payne in Tennessee to be due to silica supplied from upwelling waters from the open ocean troughs to the west and southwest. More recently, Lasemi *et al.* (1998) 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, a position similar to this study.

Therefore, upwelling of nutrient-rich water appears to be the best mechanism to explain the extensive development of Early-Middle Mississippian shallow-water, mid-latitude biosiliceous and Heterozoan carbonate accumulations in North America, including Kansas.

SUMMARY AND CONCLUSIONS

Mixtures of biosiliceous (particularly those rich in sponge spicules) and Heterozoan-dominated carbonate deposits are usually interpreted as recording cold-water polar or deep basinal conditions. However, there is increasing documentation in the rock record that indicate these deposits can also occur in shallow-water middle-to low-latitude environments under photic zone and elevated nutrient conditions that promoted their development and prevented the development of Photozoans.

This study documents Osagean biosiliceous and Heterozoan carbonate and original evaporite facies that were deposited in a mid-latitude (20 degrees south) shallow-water, inner shelf setting in Ness County, Kansas. Literature review indicates widespread distribution of similar Early-Middle Mississippian facies in shallow-water settings in North America, which indicates a regional control on their distribution.

Other studies have emphasized fluvial sources for elevated nutrients and dissolved silica with a link to a humid climate for promoting biosiliceous and Heterozoan carbonate facies development in mid-latitude, shallow water (inshore) environments. However, evidence from this study (and from literature review of time-equivalent deposits) indicates that the occurrence of shallow water, mid-latitude biosiliceous and Heterozoan carbonate facies are not necessarily dependent on a humid climate, but in fact may also occur in arid climates, as appears to have been the case for such Early-Middle Mississippian deposits in Kansas and other locations in North America. In such instances, upwelling of basinal oceanic water may be the most important source of excess nutrients and dissolved silica across the shelf.

The recognition that such shallow water biosiliceous and Heterozoan carbonate deposits can occur in mid-latitude locations, and understanding the controls for their development in such an environment, has implications for petroleum reservoirs. The DS2 sponge spicule, Heterozoan carbonate, and replaced evaporite facies in this study form reservoirs in Schaben field (Franseen *et al.*, 1998; Montgomery *et al.*, 2000). Recent study of roughly time-equivalent strata in a core from Dickman Field in Ness County (Fig. 14) indicates the reservoir interval there is at least partially made up of similar shallow-marine sponge spicule, Heterozoan carbonate, and replaced evaporite facies. Therefore, these types of facies may form important reservoirs in strata that were deposited in inner shelf environments elsewhere in Kansas and North America during the Early-Middle Mississippian.

Predictive capabilities of the controls on deposition, facies distribution patterns, stratal geometries, and diagenesis in mid-latitude biosiliceous and Heterozoan carbonate deposits can be improved by incorporating aspects of cool-water carbonate models (e.g. see papers in James and Clarke, 1997) rather than the more typical tropical carbonate models.

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Figure Captions

Figure 1: A) Mississippian subcrop map for the state of Kansas. Note location of Schaben Field B) Mississippian subcrop map of Schaben field area with Kinderhook and Osagean units defined in cores (DS1, DS2) and units defined on electric logs (M0-M7). 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 Osagean stratigraphic units defined in cores and electric logs. These units are unconformably overlain by Pennsylvanian strata. Post-depositional regional uplift, subaerial exposure, and differential erosion of the ramp strata at the post-Mississippian unconformity resulted in paleotopographic highs (buried hills). Logs consist of gamma ray (GR) and suites of resistivity and neutron logs (R, N).

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).

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. SB1 is identified in all cores based on evidence of subaerial exposure and associated calcite replacement and cementation fabrics. This surface is used for correlation and separates DS1 (below) from DS2 (above).

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 siliceous sponge spicules (note central axial canals) are preserved by microcrystalline quartz and chalcedony. Much of the matrix is silicified and only a minor amount of intercrystalline porosity is present. 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 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. Sutured contacts between 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 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 Osagean 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 7: Different types 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 and"ragged" boundaries with unsilicified strata of the same facies. Whitish-gray areas are silica and darker brown areas are dolomite.

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 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. 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 10: #2 Lyle Schaben ""P"" core photo and description from ~ 4418' to 4431'. Note the SB1 surface at ~ 4424' that separates DS1 (below) from DS2 (above). Strata below SB1 contain abundant evidence for subaerial exposure, including iron-stained (F) mottled areas. Petrographic examination indicates some of these altered areas are characterized by a central area filled with 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 SB1 are also affected by a coarse calcite poikilotopic replacement and cement (see also Figures 3, 12A). Strata above SB1 consist of MW and SWP facies, containing abundant silica-replaced evaporites (e.g. ECN = coalesced evaporite nodules).

Figure 11: Block diagram of interpreted inner and main shelf depositional environments in the Schaben Field study area during deposition of DS2.

Figure 12: Features associated with SB1. A) Calcite-replaced facies (alizarin red-stained areas) below SB1 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 SB1 in the # 2 Lyle Schaben core. Note pore filled with coarse calcite cement (stained with alizarin red) that is common below SB1. Scale 1 mm. C) Altered facies below SB1. 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 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).

Figure 14: Preliminary description of the Tilley #2 core from Dickman Field, Ness County, Kansas. Note map for location of Dickman Field with respect to Schaben Field.

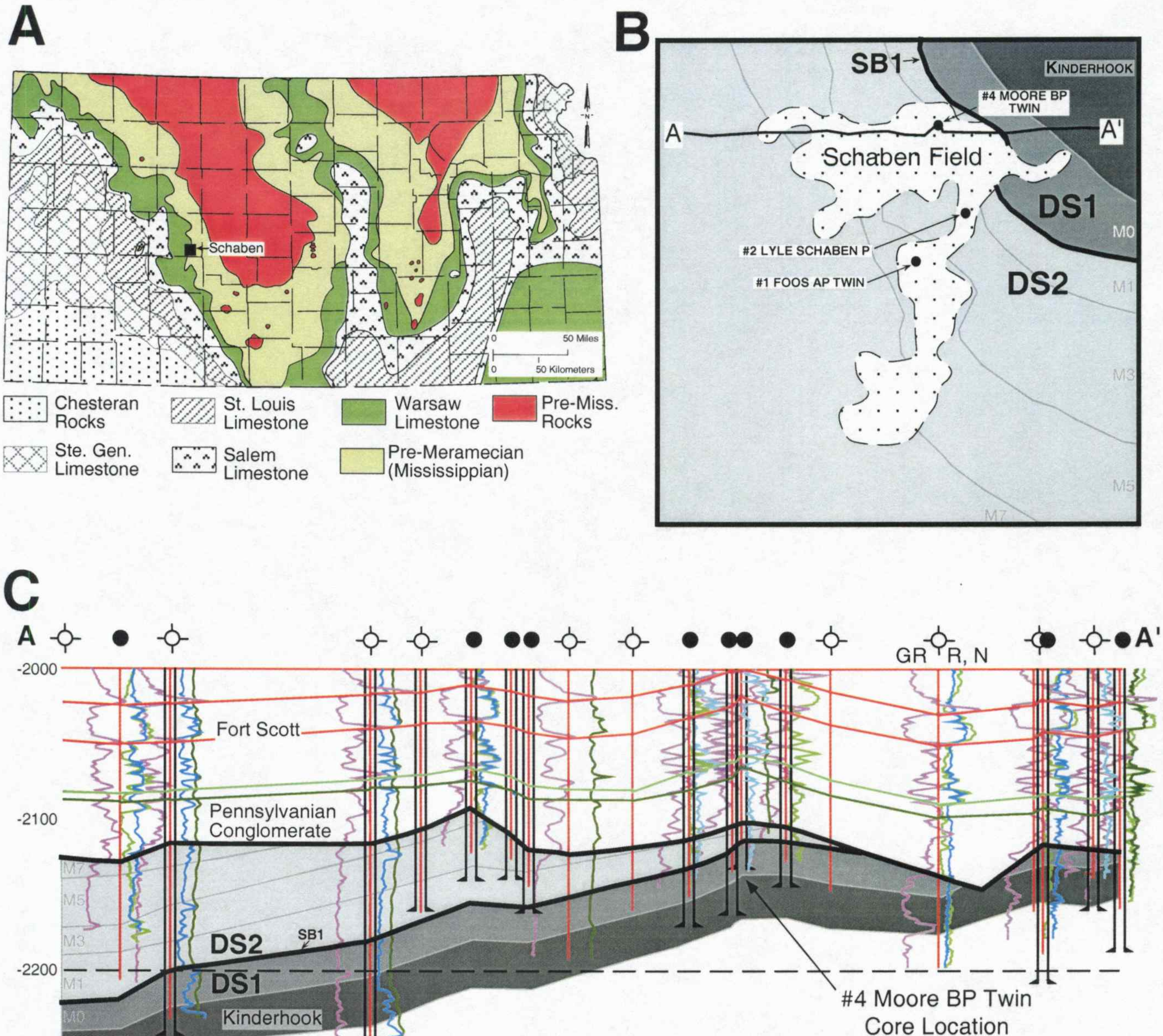

A
Schaben
0 50 Miles
0 50 Kilometers
Chesteran Rocks
St. Louis Limestone
Warsaw Limestone
Pre-Miss. Rocks
Ste. Gen. Limestone
Salem Limestone
Pre-Meramecian (Mississippian)
B
SB1
KINDERHOOK
#4 MOORE BP TWIN
A
A'
Schaben Field
DS1
M0
#2 LYLE SCHABEN P
#1 FOOS AP TWIN
DS2
M1
M3
M5
M7
C
A
A'
GR
R, N
-2000
Fort Scott
-2100
Pennsylvanian Conglomerate
M7
M5
M3
DS2
SB1
-2200
M1
DS1
M0
Kinderhook
#4 Moore BP Twin Core Location

Figure 1

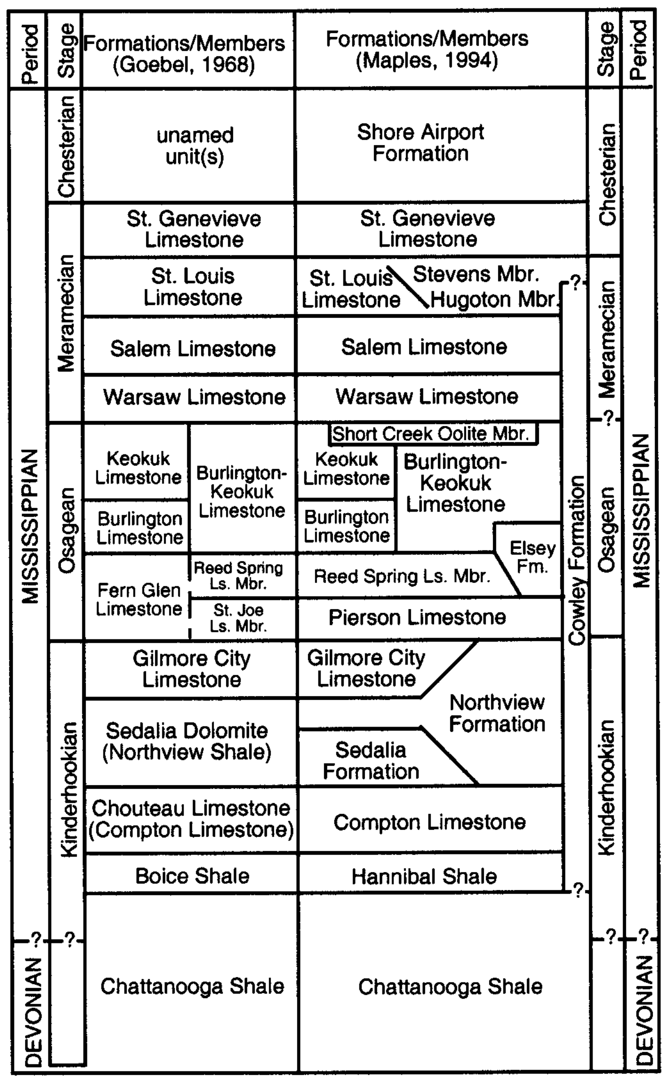

Period
Stage
Formations/Members (Goebel, 1968)
Formations/Members (Maples, 1994)
Stage
Period
MISSISSIPPIAN
DEVONIAN
Chesterian
Meramecian
Osagean
Kinderhookian
unamed unit(s)
Shore Airport Formation
St. Genevieve Limestone
St. Genevieve Limestone
St. Louis Limestone
St. Louis Limestone
Stevens Mbr.
Hugoton Mbr.
Salem Limestone
Salem Limestone
Warsaw Limestone
Warsaw Limestone
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
Gilmore City Limestone
Gilmore City Limestone
Northview Formation
Sedalia Dolomite (Northview Shale)
Sedalia Formation
Chouteau Limestone (Compton Limestone)
Compton Limestone
Boice Shale
Hannibal Shale
Chattanooga Shale
Chattanooga Shale
?

Figure 2

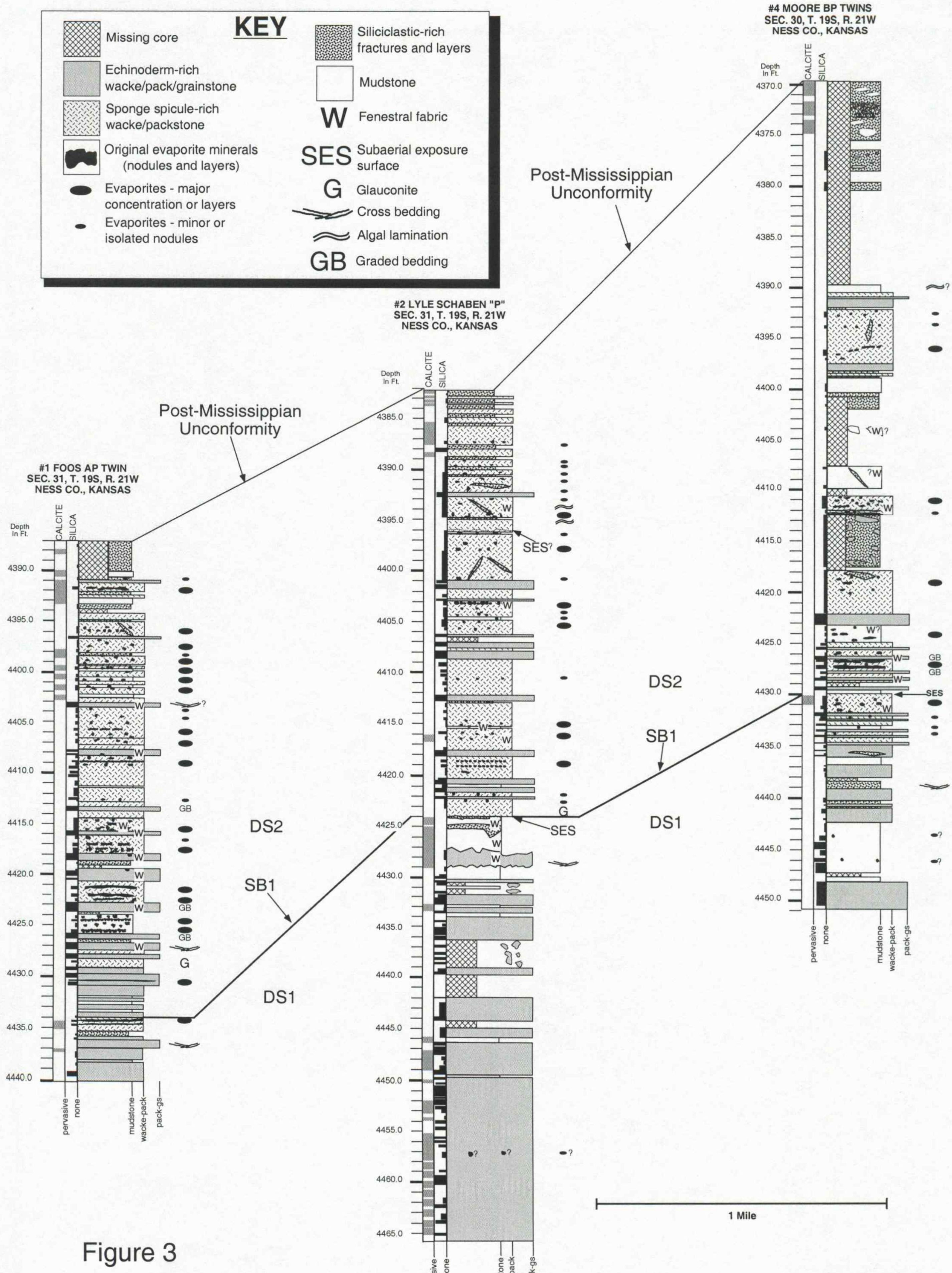

KEY
Missing core
Echinoderm-rich wacke/pack/grainstone
Sponge spicule-rich wacke/packstone
Original evaporite minerals (nodules and layers)
Evaporites - major concentration or layers
Evaporites - minor or isolated nodules
Siliciclastic-rich fractures and layers
Mudstone
W Fenestral fabric
SES Subaerial 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
Post-Mississippian Unconformity
Depth In Ft.
CALCITE
SILICA
pervasive
none
mudstone
wacke-pack
pack-gs
DS2
SB1
DS1
SES?
SES
1 Mile

Figure 3

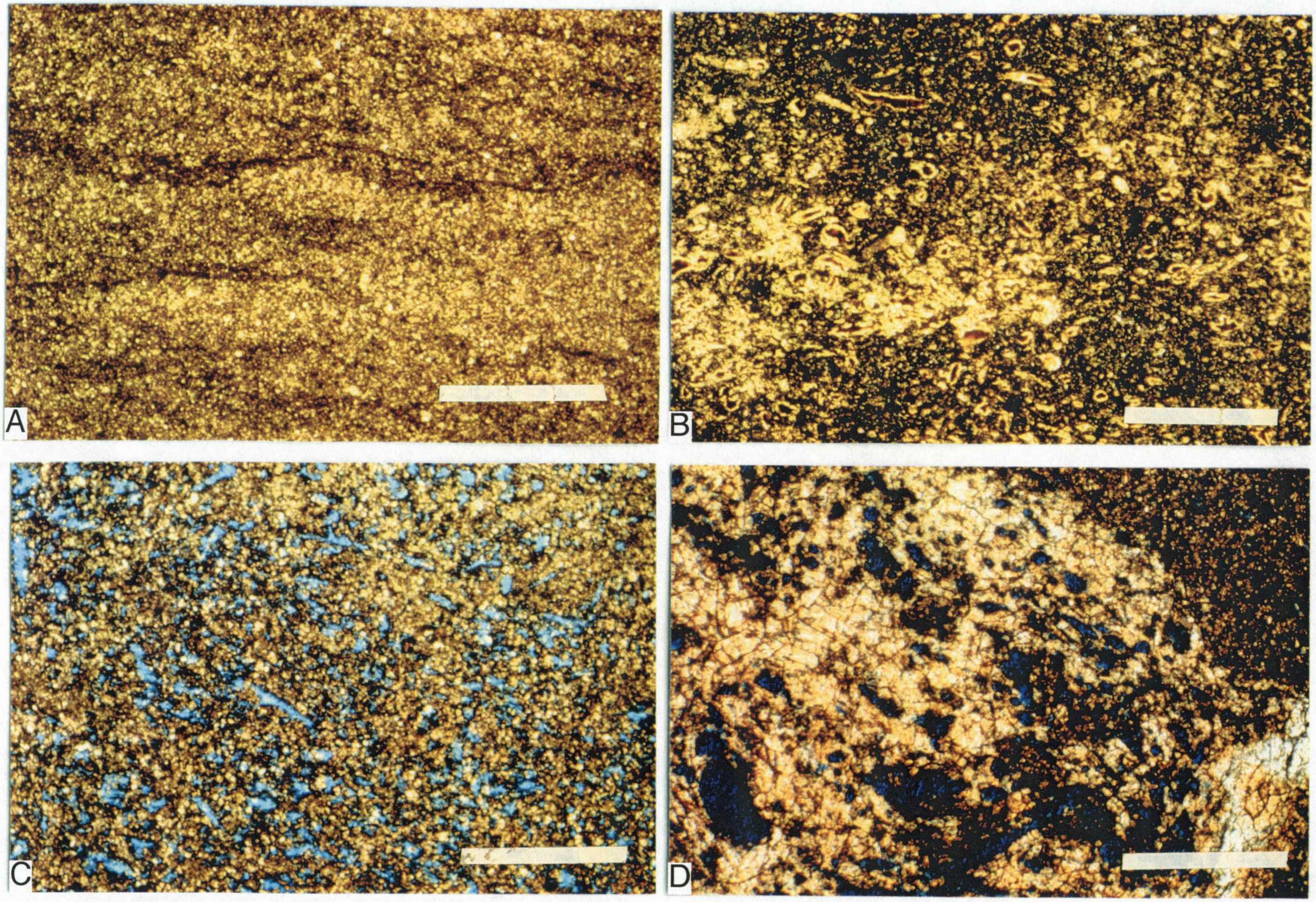


Figure 4

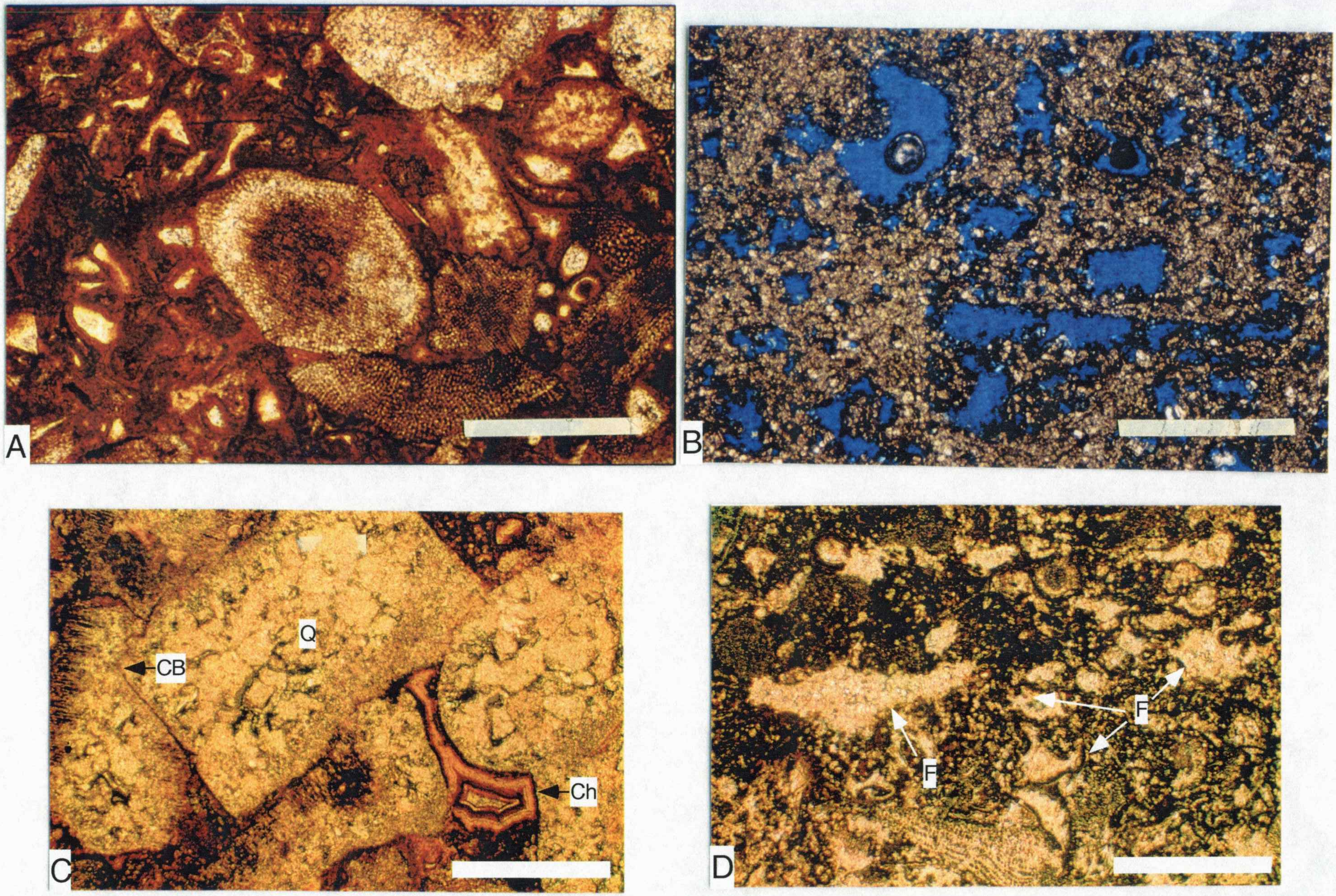


Figure 5

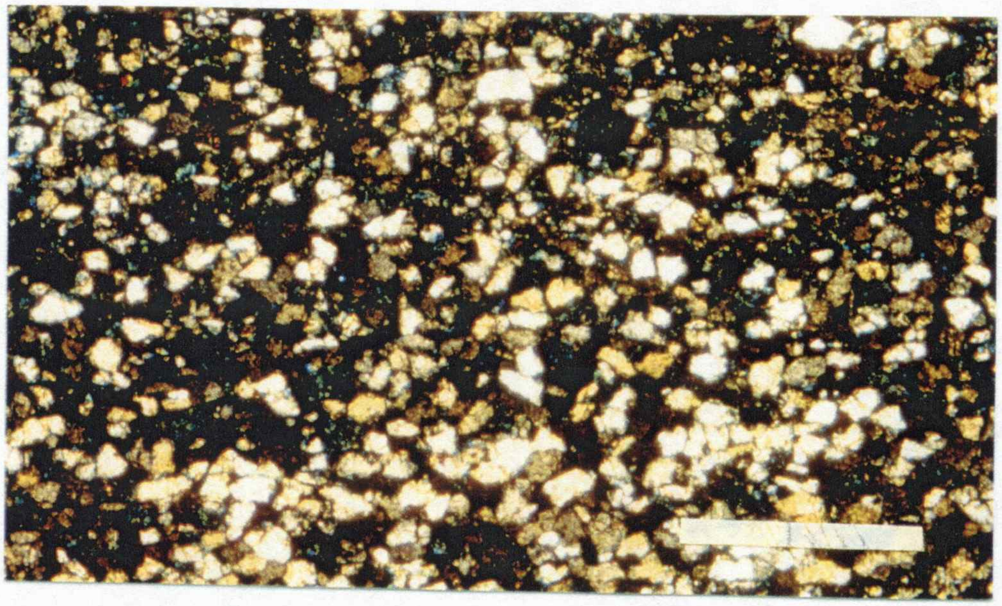


Figure 6

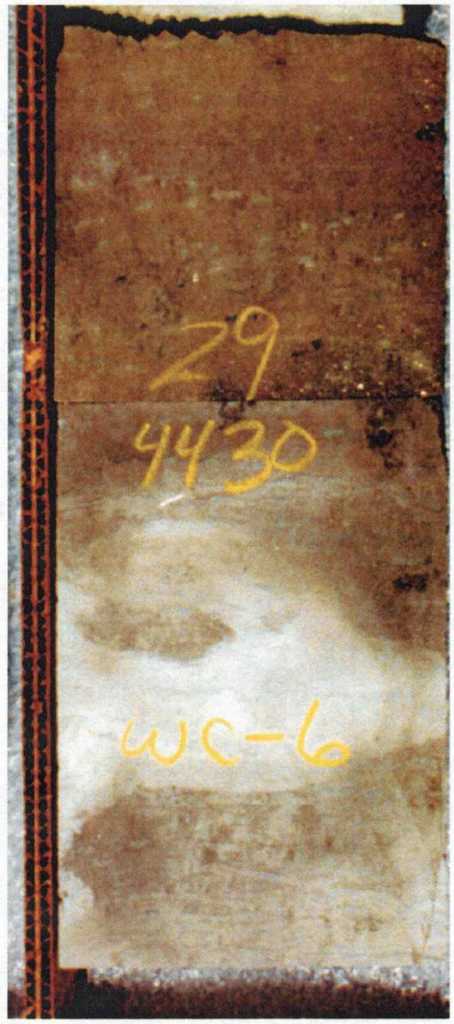


Figure 7

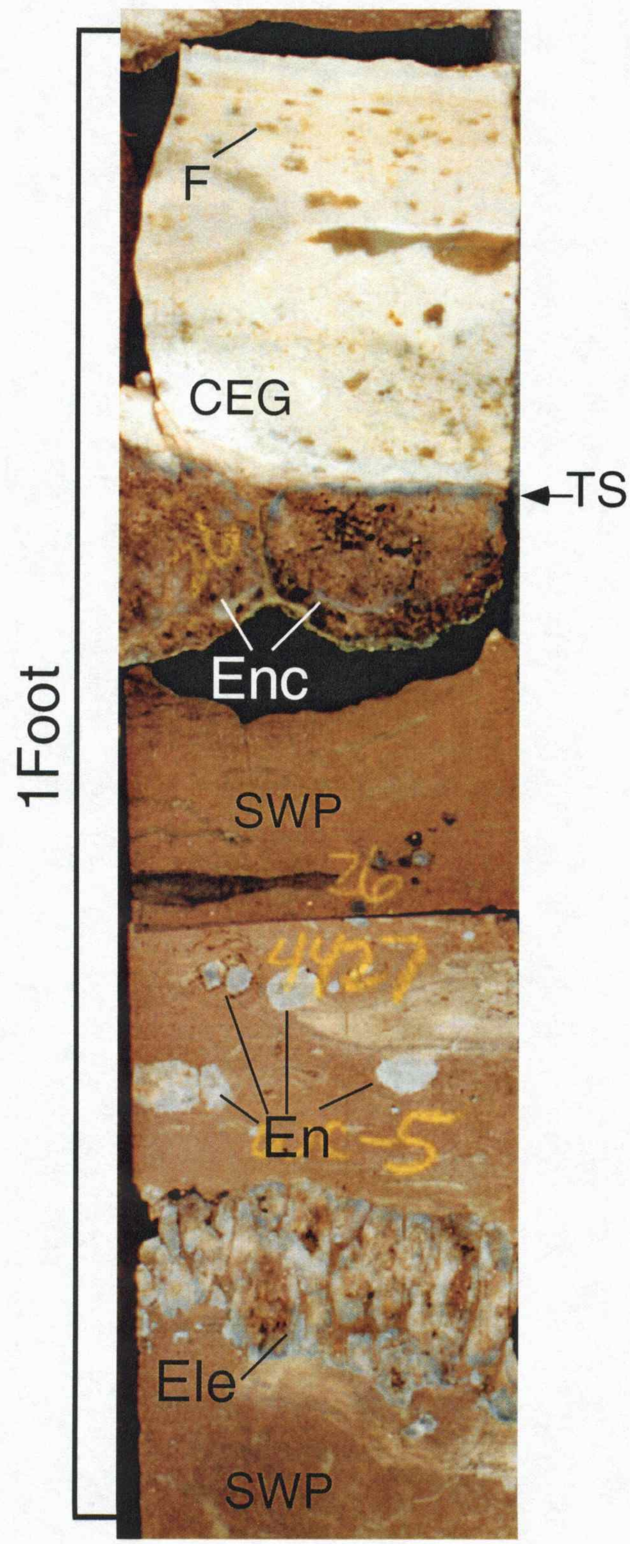


Figure 8

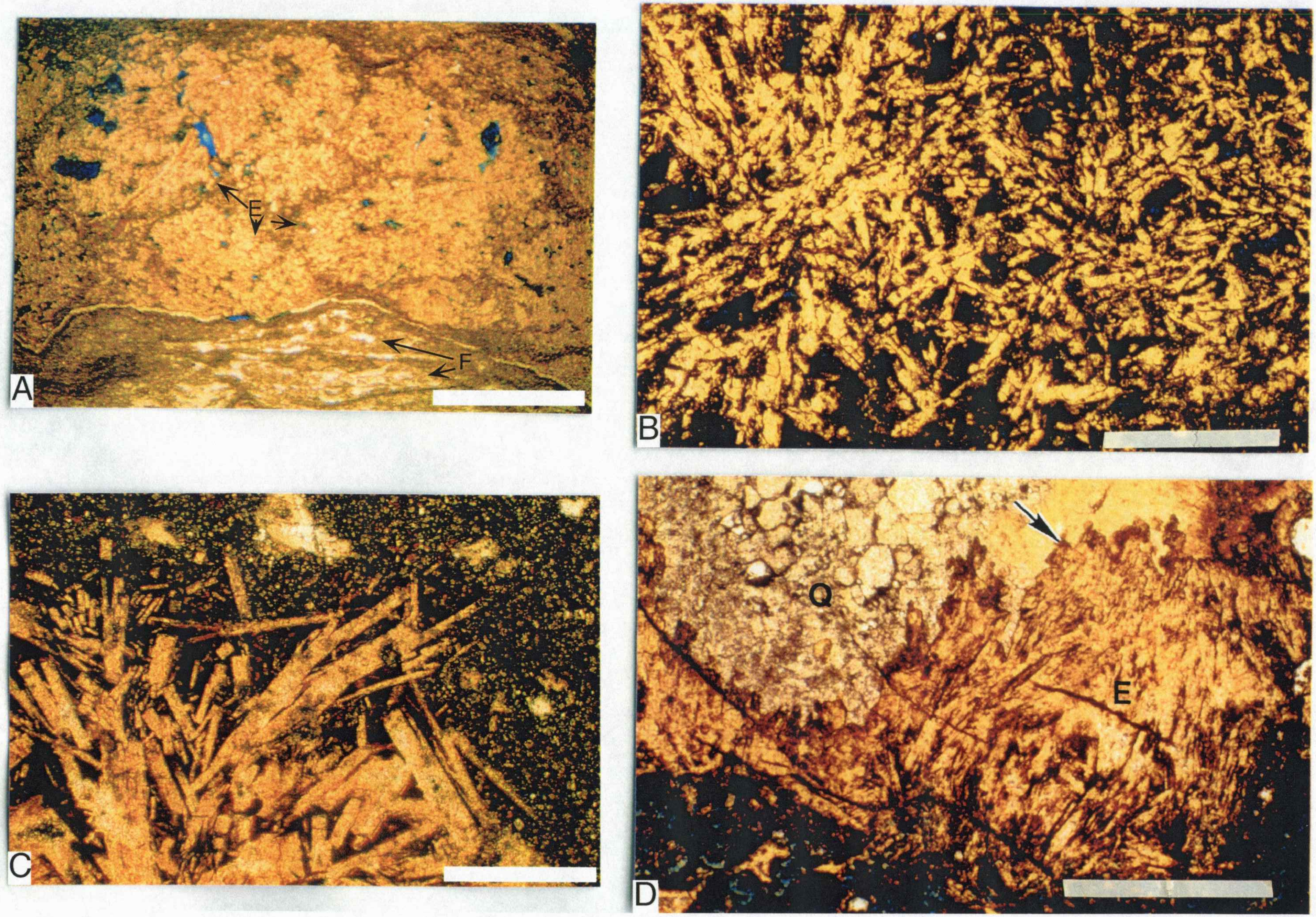


Figure 9

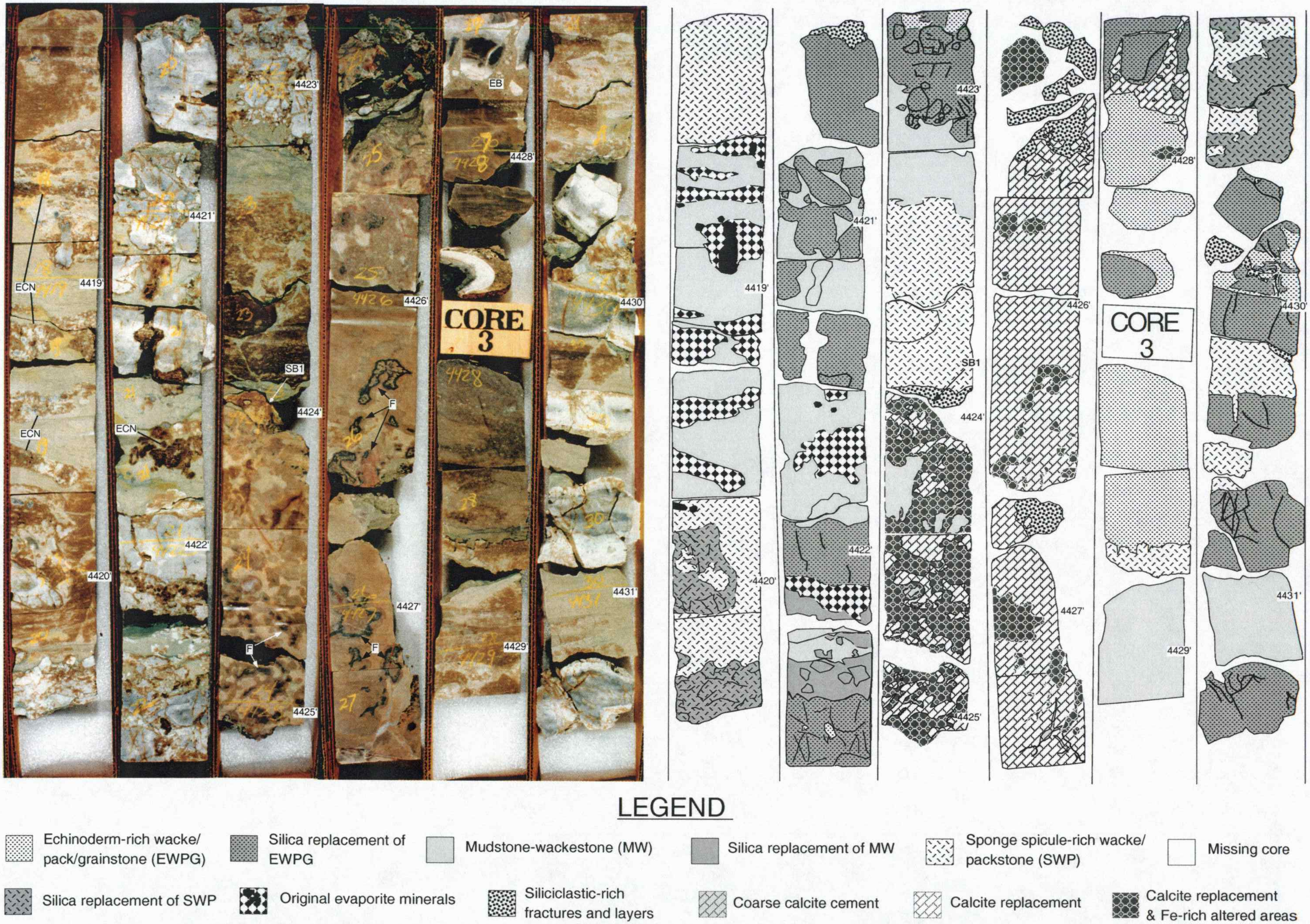

4419'
4420'
4421'
4422'
4423'
4424'
4425'
4426'
4427'
4428'
4429'
4430'
4431'
ECN
ECN
ECN
SB1
F
F
F
EB
CORE 3
4419'
4420'
4421'
4422'
4423'
4424'
4425'
4426'
4427'
4428'
4429'
4430'
4431'
SB1
CORE 3
LEGEND
Echinoderm-rich wacke/pack/grainstone (EWPG)
Silica replacement of EWPG
Mudstone-wackestone (MW)
Silica replacement of MW
Sponge spicule-rich wacke/packstone (SWP)
Missing core
Silica replacement of SWP
Original evaporite minerals
Siliciclastic-rich fractures and layers
Coarse calcite cement
Calcite replacement
Calcite replacement & Fe-rich altered areas

Figure 10

INTERPRETED INNER AND MAIN SHELF DEPOSITIONAL ENVIRONMENTS

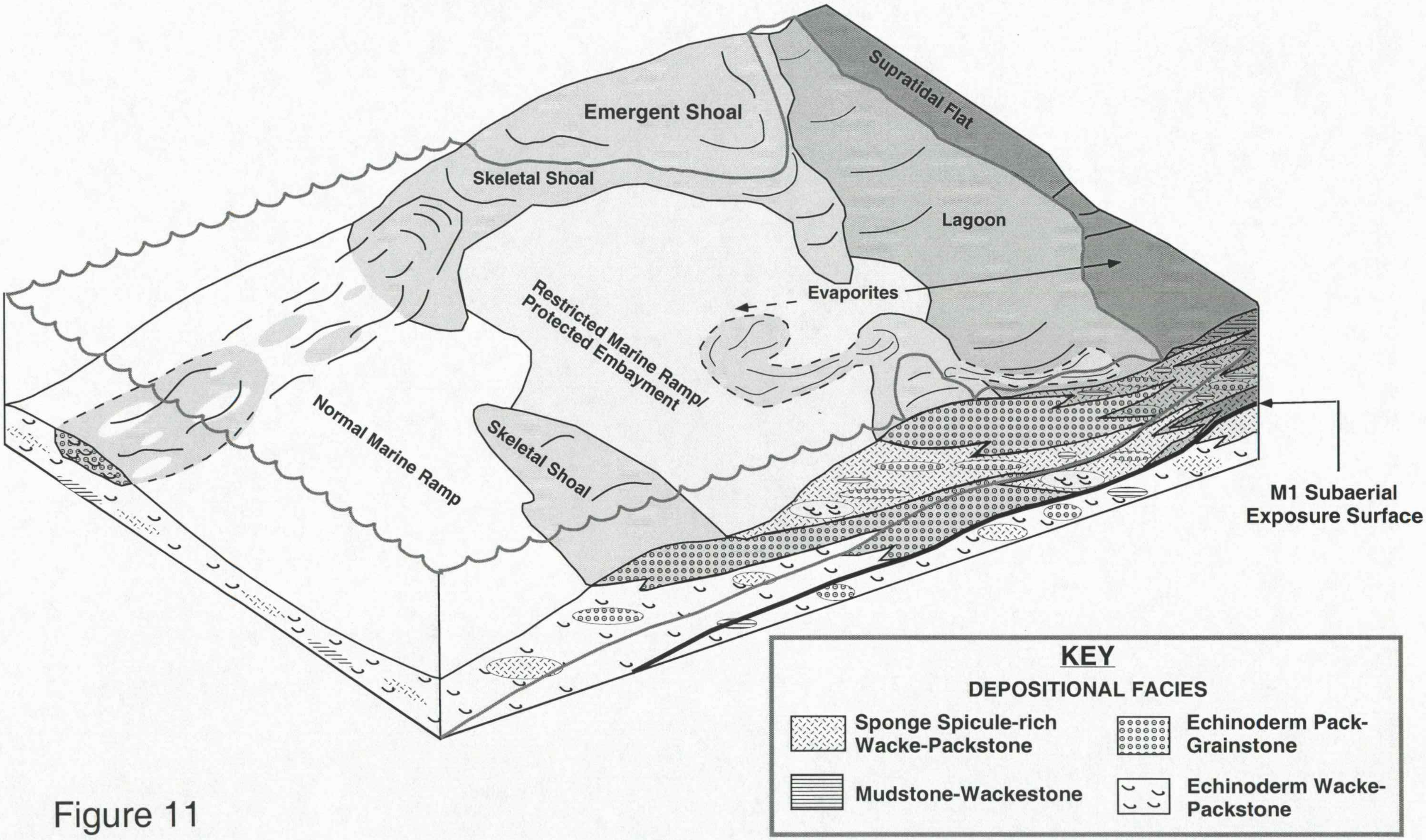


Figure 11

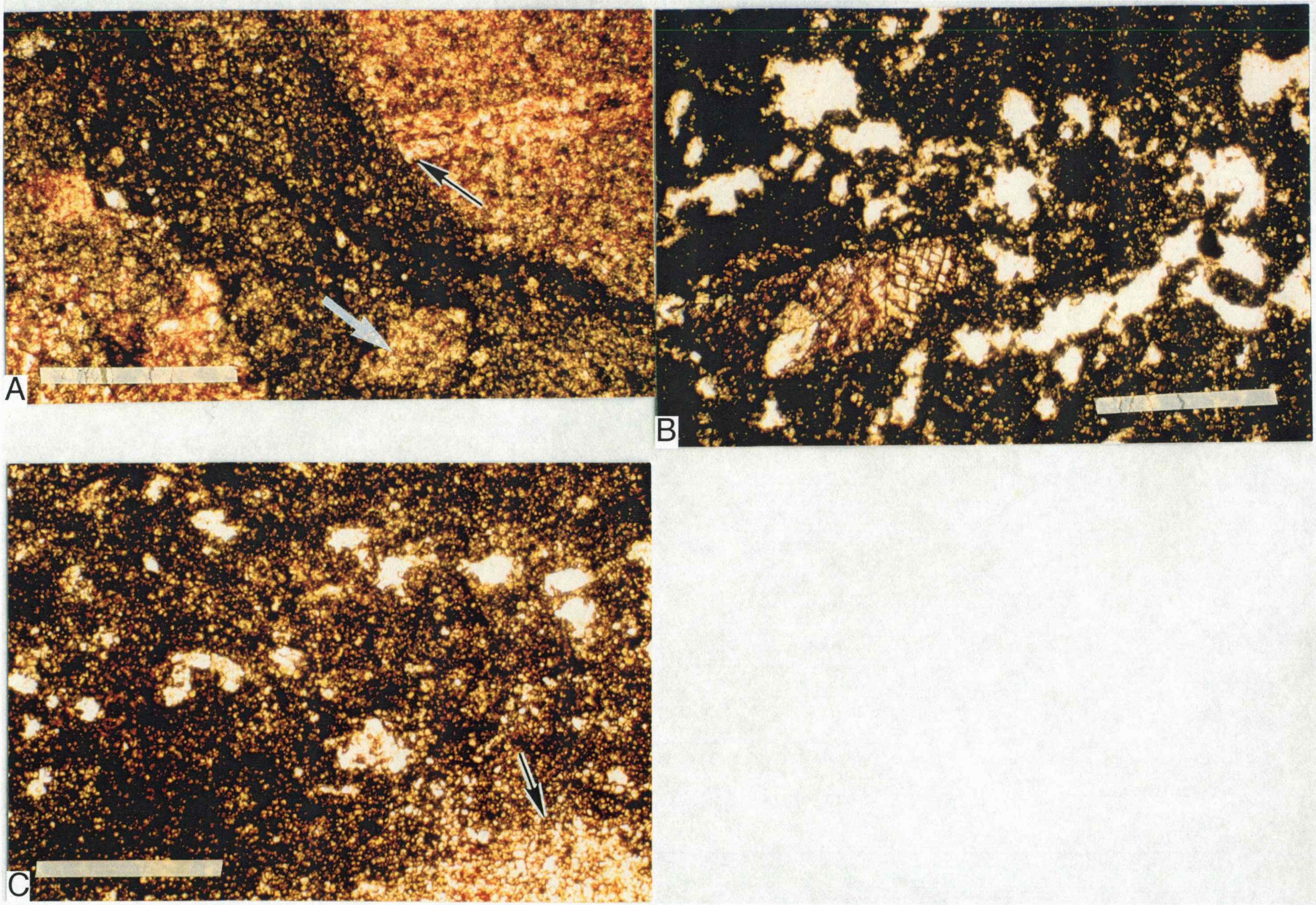


Figure 12

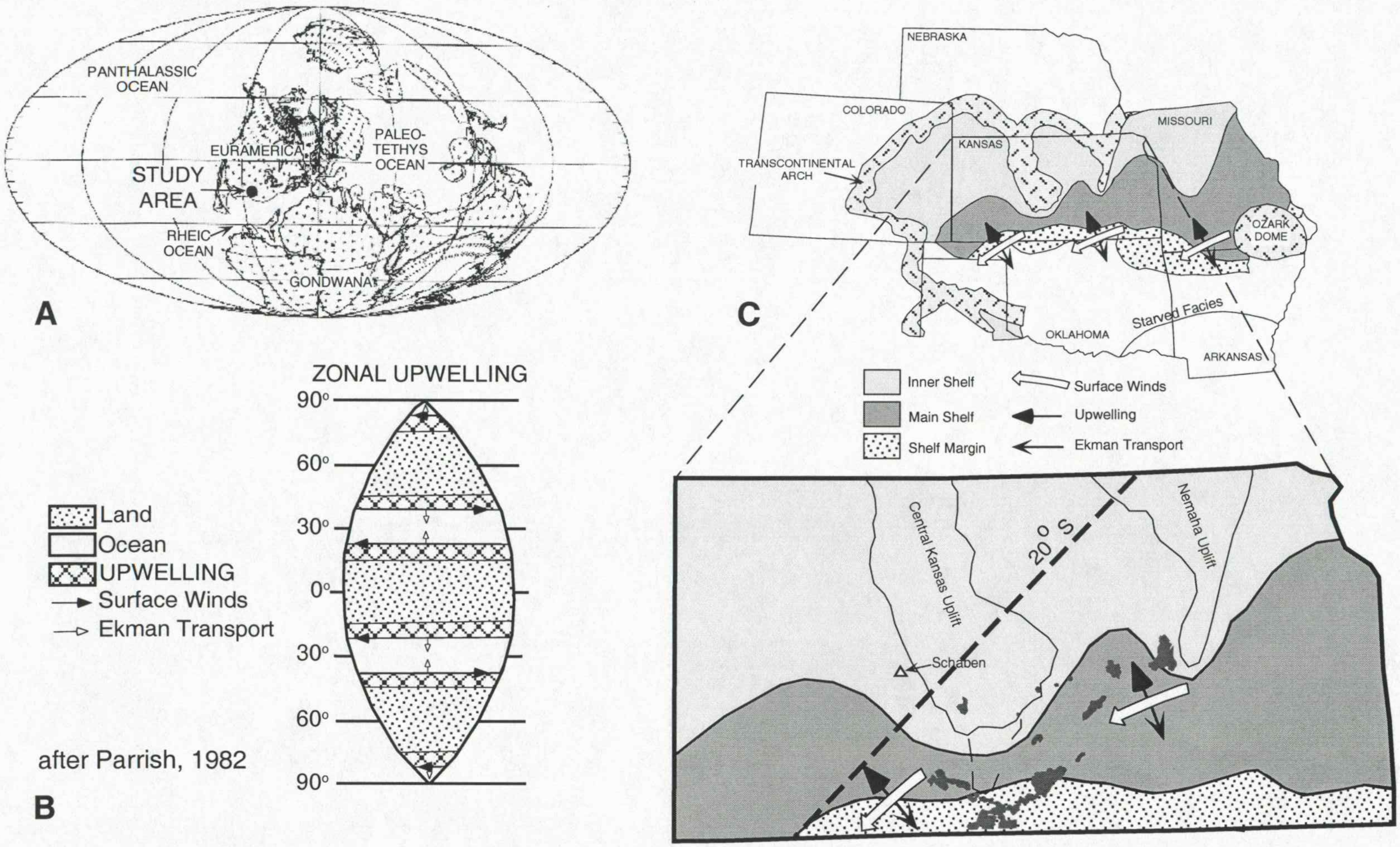
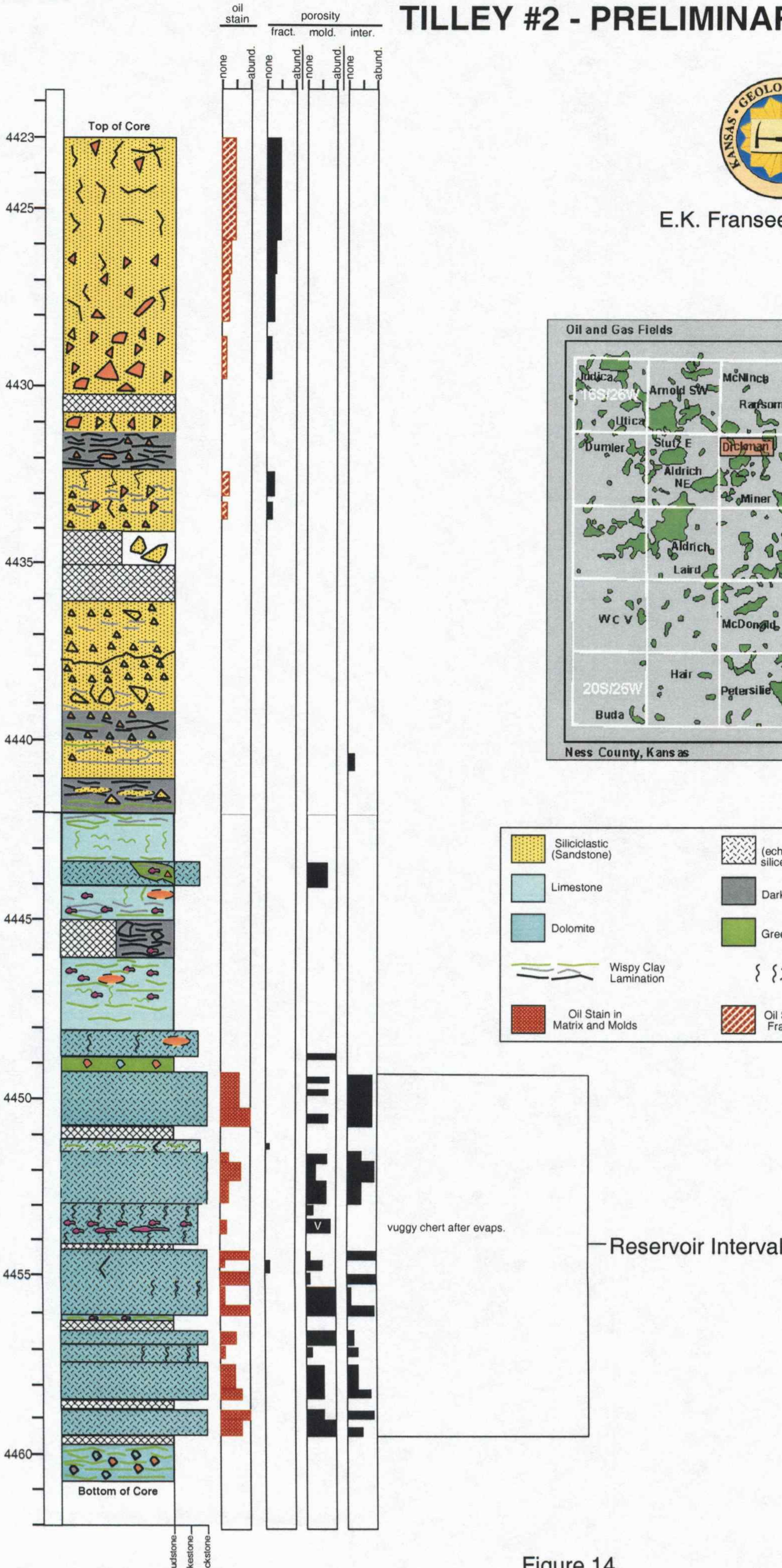
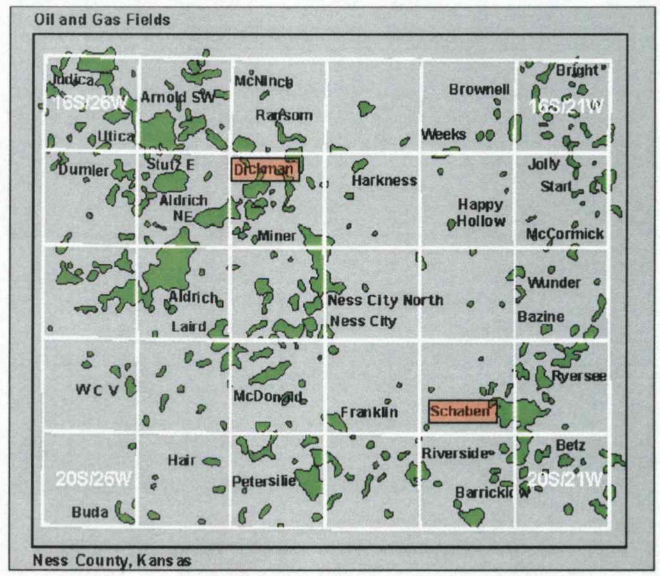

PANTHALASSIC OCEAN
EURAMERICA
PALEO-TETHYS OCEAN
STUDY AREA
RHEIC OCEAN
GONDWANA
A
ZONAL UPWELLING
90°
60°
30°
0°
30°
60°
90°
Land
Ocean
UPWELLING
Surface Winds
Ekman Transport
after Parrish, 1982
B
NEBRASKA
COLORADO
KANSAS
MISSOURI
TRANSCONTINENTAL ARCH
OZARK DOME
OKLAHOMA
Starved Facies
ARKANSAS
C
Inner Shelf
Main Shelf
Shelf Margin
Surface Winds
Upwelling
Ekman Transport
Central Kansas Uplift
20° S
Nemaha Uplift
Schaben

Figure 13

TILLEY #2 - PRELIMINARY CORE DESCRIPTION

E.K. Franseen - 10/2003





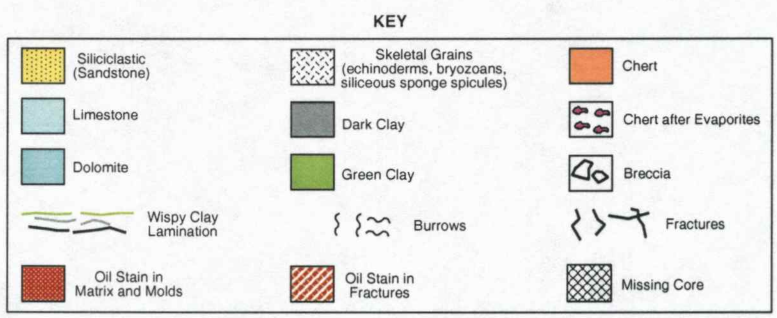


Figure 14

TABLE 1 – Depositional Facies

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

TABLE 2 - Other Core Features

Core Feature	Characteristics
Silica Cementation & Replacement	Replacement silica and silica cements abundant throughout all three cores (**Fig. 3**). Convoluted nodular, anastamozing bedded and bedded replacements (terminology of Nolte and Benson, 1998) are characteristic in EWPG facies (**Fig. 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**). Silica replacement occurs either as pervasive or partial replacement of original facies, textures or grains. Silica typically white to light gray in hand sample with a porcelaneous (tight) or more rarely a chalky porous texture. Much of the chert replacement appears to follow original burrows or bedding planes. Silicified areas commonly exhibit a fracture and brecciated texture with variable micro-and macro-fracture porosity. Silica occurs as microquartz, megaquartz, chalcedony (both length-fast and length-slow), and zebraic chalcedony. Some microspherules (approximately 25-40 um diameter) occur and may represent original cristobalite lepispheres. Silica replacement and cementation appear to have occurred in stages with early microquartz and chalcedony replacement of facies and grains, isopachous brown chalcedony cement lining pores and megaquartz as a later stage replacement or pore-filling cement (**Fig. 5A, C**). Ghosts of micron-sized microstructural features in some silicified grains that were originally carbonate, such as echinoderms, indicate that silica precipitation and carbonate dissolution occurred simultaneously along thin solution films (**Fig. 5A**) (Maliva and Siever, 1989). Void-filling silica indicates a more rapid volumetric calcite dissolution rate than the volumetric silica precipitation rate (**Fig. 5C**). Silica in the form of microquartz or chalcedony locally preferentially replaces spicules (**Fig. 4B**) or replaces the matrix surrounding the spicules and leaves the spicules as molds (**Fig. 4D**).
Replaced Evaporites	Silica-replaced evaporites textures include individual crystals, initial nodule development,complete nodule development, laterally coalesced nodules forming horizontal layers, some of which are composed of coalesced vertically elongate nodules (**Fig. 8**), and local chicken-wire structure (**Fig. 9A**). Individual nodules are generally <0.5 to 5 cm in size. Nodules and crystals preserve a bladed, radiating bladed, and twined crystal morphology (**Fig. 9B**), indicating replacement of anhydrite or gypsum. Individual bladed crystals, many with blunt ends, are typically between 100 μm-300 μm in length (20-60 μm width) with some blades over 500 μm in length (**Fig. 9B, C**). Some megaquartz crystals in replaced evaporites contain abundant inclusions of evaporite minerals (anhydrite). Some preserved fabrics of pseudomorphed evaporites show crystal fabric evolution characteristic of different modes of nodular anhydrite growth as depicted by Shearman and Fuller (1969). Crystals show a d-decussate and sub-parallel arrangement of laths within the more central portion of the nodules and the laths become "bent" and sub-parallel to the periphery of the nodule at the contact with the host sediment (**Fig. 9C**). The presence of bent and broken crystals and disruption of anhydrite crystals by displacive growth is remarkably similar to those shown by the Shearman and Fuller (1969) for 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 nodule fabrics with elongate crystal psuedomorphs of original evaporites occur (Fig. 8). These are similar to fabrics shown by Orti and Rosell (2000, figure 3G) from the Miocene of Spain. They interpret these morphologies as distinctive of the anhydrite-to-gypsum hydration process, in which anhydrite originally formed interstitially in the sediment in a playa/sabkha setting replacing or displacing the matrix. Other evidence supporting replacement of original evaporites includes the presence of length-slow chalcedony (quartzine and lutecite) which has been interpreted to be associated with the replacement of evaporites (Folk and Pittman, 1971).
Brecciation & Fracturing	Macro- and micro-scale brecciation and fracturing are ubiquitous throughout the three cores (**Fig. 10**) resulting in fracture and mosaic breccias. Textures range from little to no rotation on clasts to matrix-supported and clast-supported chaotic breccias that represent mixtures of autochthonous and allochthonous materials resedimented by gravitationally driven processes. Fracture fill and breccia matrix includes shale, subangular to rounded, silt- to coarse-grained size detrital quartz, chert, megaquartz, chalcedony grains, carbonate micrite, carbonate grains, and skeletal grains. Clasts (ranging from rounded to angular) include chert/chalcedony/megaquartz fragments, clasts of original carbonate facies, replacive poikilotopic calcite clasts, coarse calcite cement fragments, and rubble of red and greenish limy clay. Porosity associated with fracturing and brecciation is quite variable, ranging from tight to very porous. Interparticle, intercrystalline, vuggy and fracture porosity are common porosity types in breccia matrix.
Calcite Cementation & Replacemnt	Several different stages of calcite cementation and replacement occur. One event is associated with subaerial exposure at the M1 surface (**Figs. 3, 10**) and results in locally extensive replacement and cementation of M0 strata. A later stage of calcite cementation and replacement is associated with the post-Mississippian subaerial exposure event that effects facies in the upper portions of cores (**Fig. 3**).

Table 3 - Shallow-Water Siliceous Sponge Associations

Age & Location	Facies	Characteristics & Associated Features	Depositional Environments	References
Ordovician, New Mexico	Ribboned chert and dolomite	Abundant siliceous sponge spicules; associated with pellets, laminated textures, stromatolites, fenestral fabrics, replaced evaporite nodules	Sabkha, intertidal to shallow subtidal	Geeslin and Chafetz (1982)
Devonian Caballos Novaculite	Novaculite	sponge spicules as the sole faunal remains; fenestral fabric; small evaporite nodules and laminae	very shallow environment in semirestricted lagoons or bays; hypersaline, reducing tidal flat areas	Folk (1973)
Mississippian - uppermost Osagean, Kansas	cherty dolomite	abundant monaxon sponge spicules or their molds; chert replaced former evaporite minerals; interlaminated dolomite and shale, broken and curled dolomite laminae, scoured bedding surfaces	supratidal, sabkha-like environment	Ebanks et al. (1977)
Mississippian - Meramecian, Kansas	spicule-rich dolomudsto-ne	low diversity fauna; chalcedony/quartz nodules after replaced evaporites;	low-energy, subtidal environment that ranged from restricted to evaporitic	Johnson and Budd (1994)
Mississippian-Osagean and Meramecian, Tennessee	cherty dolomitic spiculites	silica nodules after original evaporite minerals	tidal-flat-lagoon-complex environments	Chowns and Elkins (1974)
Mississippian-Osagean, Illinois & Missouri	siliceous dolostone	Abundant sponge spicules, burrows	restricted conditions in protected inner-shelf environments	Choquette et al. (1992)
Mississippian - Meramecian, North Dakota	spiculitic, dolomitized pelletal wacke/packs tones	sparse anhydrite nodules, sponge spicules and their molds	restricted marine to tidal flat facies	Lindsay (1985)

Table 3 (continued) - Shallow-Water Siliceous Sponge Associations

Pennsylvanian-Desmoinian, Indiana	spiculite	Abundant monaxon spicules; occur with echinoderms, ostracodes, trilobite fragments, gastropods, byrozoans, and brachipods	Sponge mats that formed in nearshore environments	Lane (1981)
middle Pennsylvanian, Appalachian Plateau	Spiculite (flint); sponge-spicule dominated flint beds	Dense mats of silicious spicules; some brachiopods; ghosts of spicules common	Transgressive deposits formed in swampy shoreline areas removed from major sites of detrital influx; Still stand deposits that formed in quiet, sediment-starved lagoons or bays that bordered the swampy portions of the resulting shore	Cavorac and Ferm (1968) Carlson (1994)
Upper Pennsylvanian, Austria, Italy	Bryozoan-spicule wackestone	Sponge spicules with brachiopods, bryozoans, small foraminifers, ostracodes, red algae, crinoids; silicification of biota is common.	Shallow-water environments	Samankassou (2002)
Upper Carboniferous & Permian, Spitzbergen (Svalbard)	Hyalo-sponge Association	Sponge-dominated siliceous carbonates	Intertidal to shallow subtidal	Huneke et al. (2001)
Miocene, Alabama, Delaware	Diatomite-mudstone	Poorly lithified; mixtures of diatomite, spiculite, porcellanite, and terrigenous and authigenic clay; locally contains shallow water carbonate debris	Highly productive shallow lagoons and bays in which terrigenous sediment was not sufficiently abundant to dilute the diatom frustules and siliceous sponge spicules	Maliva et al. (1989)
Eocene, w. Australia	spiculite	N/A	Shallow marine	Maliva et al. (1989)
Late Eocene, south Australia	spiculite	Sediment is a microbioclastic mudstone spiculite in texture; numerous peloids and a few large bryozoans, brachiopods, and echinoid spines.	Shallow water (< 100 m) partially barred lagoon; warm-temperate and humid climate	James and Bone (2000)

Table 3 (continued) - Shallow-Water Siliceous Sponge Associations

Eocene, southwestern Australia	Siliceous spongolite and spiculite	Local trough cross beds and rare wave ripples; abundant burrows; rare calcareous fossils	Protected embayments. Sponges colonized all available embayment water depths (0-~40 m). Cimate was warm temperate (possibly warmer) and humid	Gammon et al. (2000)