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DEPOSITIONAL FACIES AND DIAGENETIC CHARACTERISTICS OF MISSISSIPPIAN (OSAGIAN) STRATA FROM THE SCHABEN FIELD, NESS COUNTY, KANSAS

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INTRODUCTION

This paper contains the initial reporting of lithologies and facies from three cores taken at the Schaben demonstration site within the Schaben field as part of a DOE funded project entitled Improved Oil Recovery in Mississippian Carbonate Reservoirs of Kansas-Near Term-Class Two (see Carr et al., 1996). The three cored intervals (#4 Moore BP Twins, #1 Foos AP Twin, and #2 Lyle Schaben "P") are located in Township 19 South-Range 21 West, Township 20 South--Range 21 West, and Township 19 South--Range 22 West, Ness County, Kansas (Figs. 1, 2). This area is located on the upper shelf of the Hugoton Embayment of the Anadarko Basin and produces oil from Mississippian (lower Meramecian Warsaw Limestone and Osagian Keokuk Limestone) dolomites and limestones (Fig. 1). The three cores in this report are apparently from the Osagian interval; the #4 Moore BP Twins core extends from approximately 4370' to 4451', the #1 Foos AP Twin core extends from approximately 4387' to 4440', and the #2 Lyle Schaben "P" core extends from approximately 4382' to 4466' (Fig. 3). Core photographs from selected intervals of each of the three cores are at the end of this report (Moore core photographs = Figs. M.1-M.2; Schaben core photographs = Figs. S.1-S.5; Foos core photographs = Figs. F.1-F.2). The full suite of core photographs for each of the three cores can be found in the Kansas Geological Survey Digital Petroleum Atlas on the World Wide Web at the following URL: http:///www.kgs.ukans.edu/DPA/Schaben/core scans/core.html. Graphic core descriptions are illustrated in Plate 1 at the end of this report. The body of this report contains depositional facies descriptions, general diagenetic features, photomicrographs, interpretations of depositional environments, and implications for reservoir characteristics.

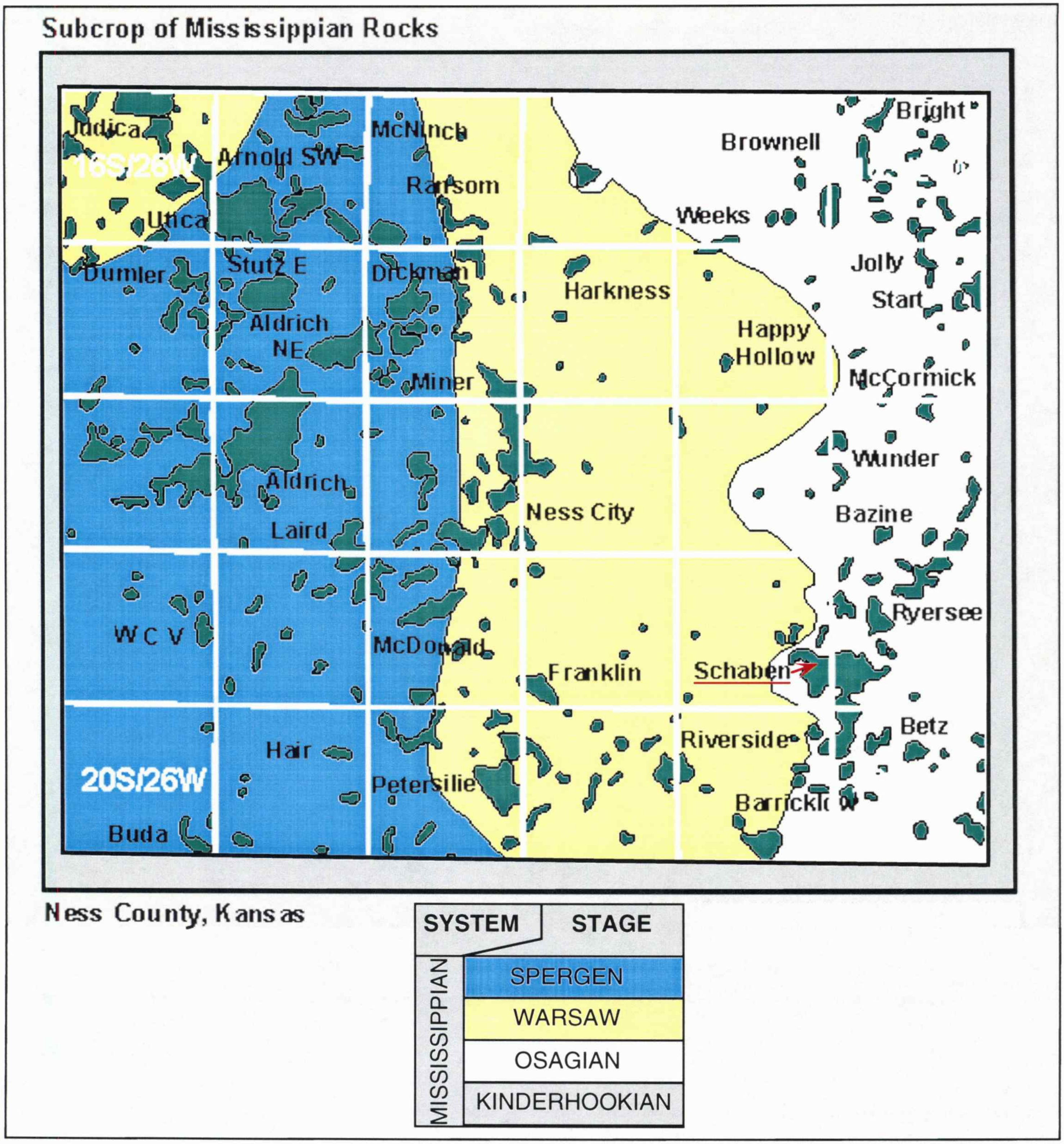

Figure 1: Subcrop map of Mississippian strata in Ness County. Note that the Schaben Field (arrow) is located in the Osagian part of the section (light gray), close to the contact with Warsaw strata (yellow). Modified from Kansas Geological Survey, Digital Petroleum Atlas, URL=http://crude2.kgs.ukans.edu/DPA/County/ness.html (Updated February 7, 1996). Geologic information originally from Goebel (1968).

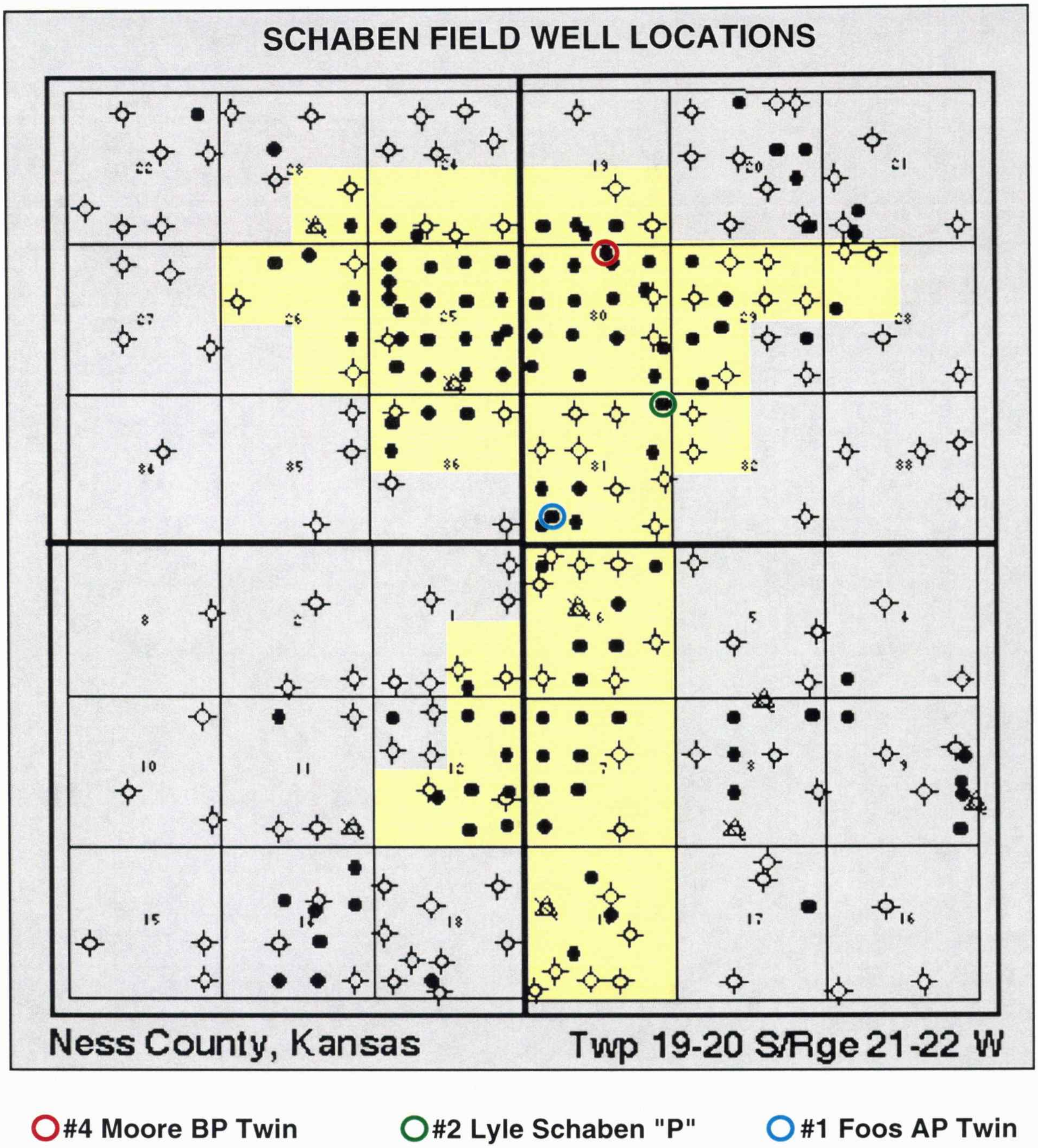

Figure 2: Well locations in Schaben field. Locations of the cored intervals described in this report are indicated by the blue, green, and red circles. Modified from Kansas Geological Survey, Digital Petroleum Atlas, URL=http://crude2.kgs.ukans.edu/DPA/Schaben/Wells/schaben Well1.html (Updated April 12, 1996).

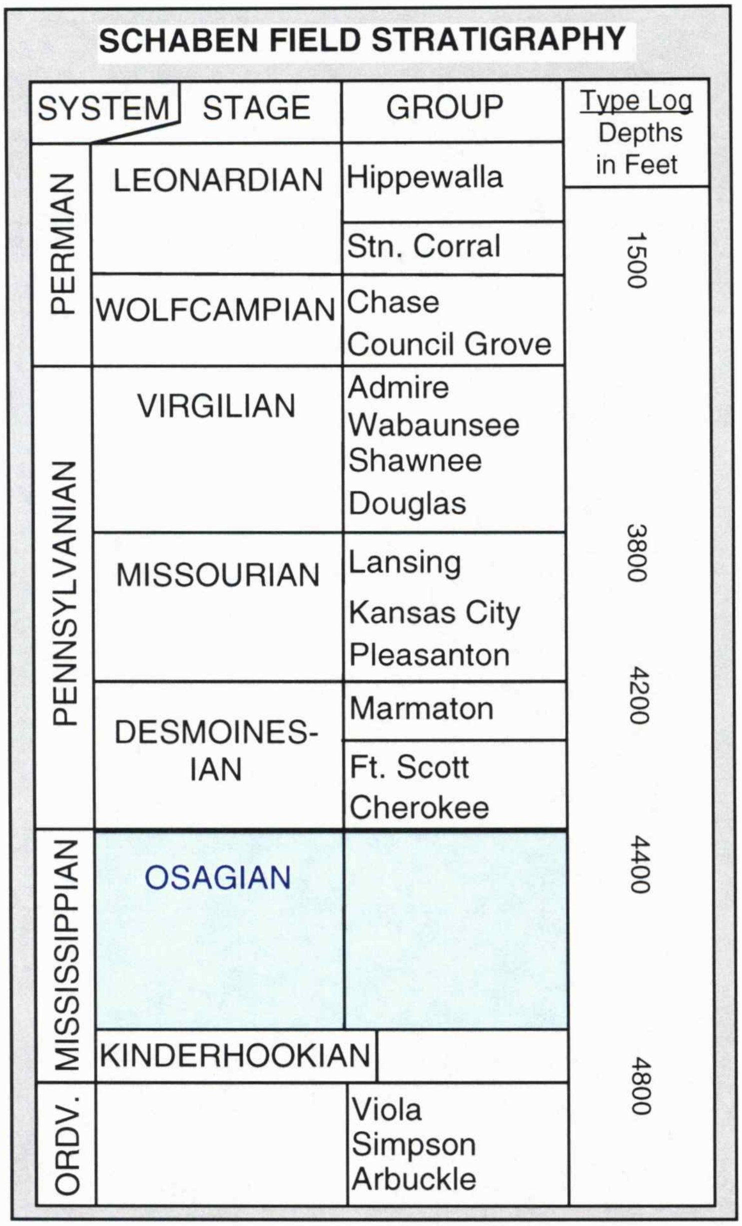

Figure 3: Schaben Field Stratigraphy. The cored intervals described in this report come from the Osagian part of the section (blue). Depths from the type log give an idea of the general depths of different intervals in the field area. Modified from Kansas Geological Survey, Digital Petroleum Atlas, URL=http://crude2.kgs.ukans.edu/DPA/County/ness7.html (Updated February 7, 1996).

This study is part of an overall project designed to demonstrate and provide useful technologies for improved reservoir development and to provide detailed reservoir characterization utilizing modern data from the three drilled wells. The core data thus far indicate that original depositional facies and relatively early diagenetic events are important in present reservoir characteristics and that later fracturing and dissolution from karst and or structural influences are locally important but may not always be the primary control on favorable reservoir conditions.

Other studies and reports are being prepared that describe in detail the paragenetic sequence and integrate other subsurface information for construction of maps and cross sections allowing a detailed understanding of reservoir characteristics of Schaben field.

Depositional Facies

Dolomite or Lime 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 (Figs. 4A, F.2). Much of this facies has a mottled texture apparently imparted by burrowing organisms and locally microscopic fracturing. Other features include soft sediment deformation. Fenestral fabric, indicating early subaerial exposure, 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, peloid, and glauconite locally present. The sponge spicules are locally concentrated in layers or in "pockets" presumably as a function of currents and reworking by burrowing

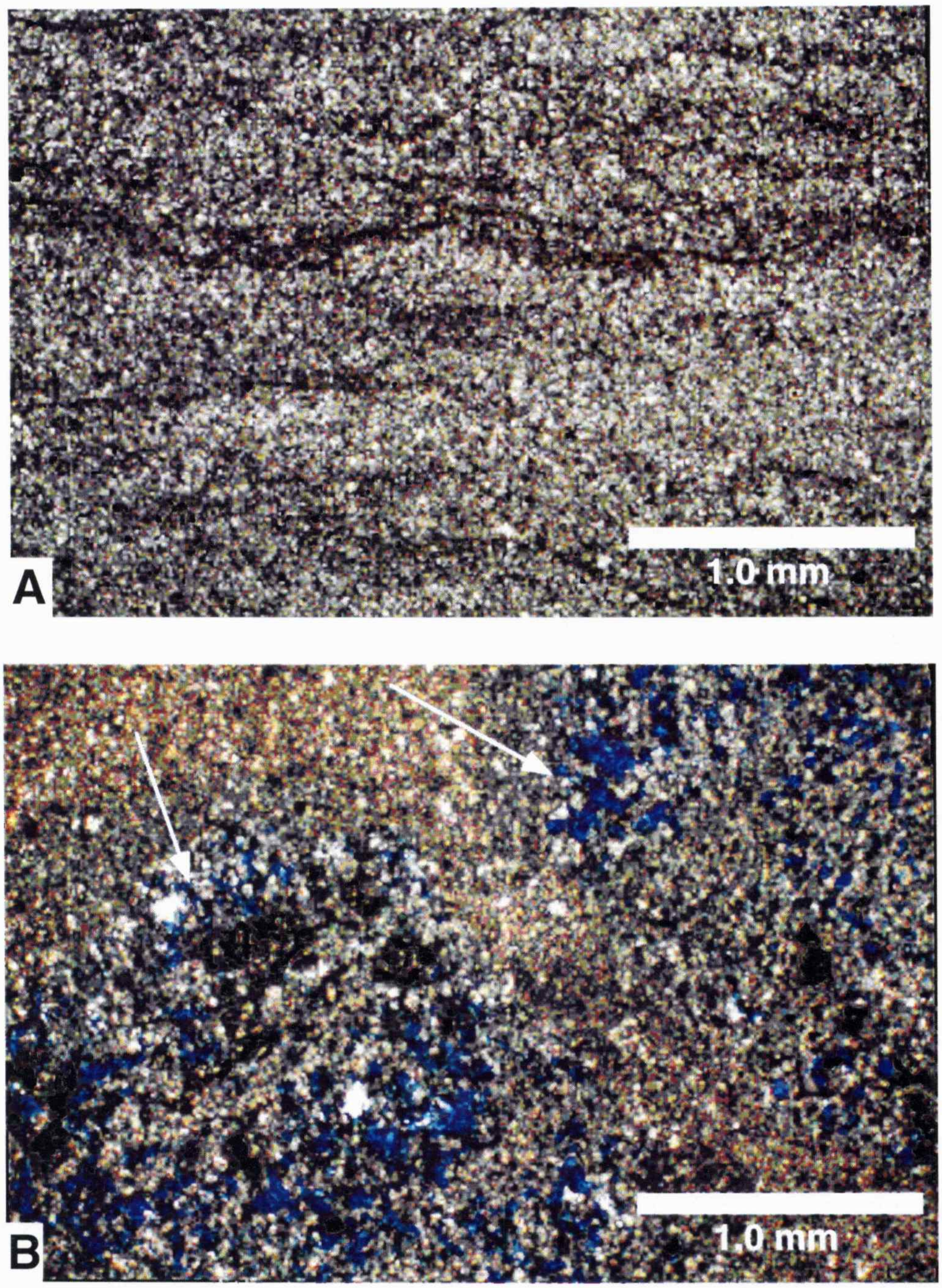

Figure 4: A) Dolomite Mudstone-Wackestone facies. Wispy lamination imparted by clay and horsetail stylolites. This facies is typically tight. Plane polarized light. B) Sponge Spicule-rich Dolomite Wackestone-Packstone facies. Burrow mottling has created variously separate tight and porous (arrows) areas with abundant moldic and intercrystalline porosity. Plane polarized light.

organisms. Rare concentrations of very fine grained (~ 100 μm) detrital quartz grains also likely occur from reworking by burrowing organisms. This facies is typically tight or has moldic, intercrystalline, and vuggy porosity (up to ~25%, visual estimate) locally developed; 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.

Sponge Spicule-Rich Dolomitic or Lime Wackestone-Packstone (SWP)

This facies is defined because of its abundance in all three cores, especially in the upper portions of each core and because of its importance as a reservoir facies. 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 (Fig. F.1). This facies is typically characterized by mottling from burrowing organisms. This results in sponge spicules locally concentrated in "pockets" on a microscopic scale (Fig. 4B). Laminations are imparted locally by interbedded green-gray shale-siltstone and by horsetail stylolites. Sponge spicules (mostly monaxon) and their are the predominant grain type and commonly the exclusive grain type (Fig. 5). Echinoderm, bryozoan, gastropod, and peloid grains occur more rarely. Moldic, intercrystalline, and vuggy porosity is locally abundant (up to ~65%, visual estimate). Fenestral fabric occurs locally. Some primary porosity is solution enlarged forming vugs. The mottling texture and concentration of grains in

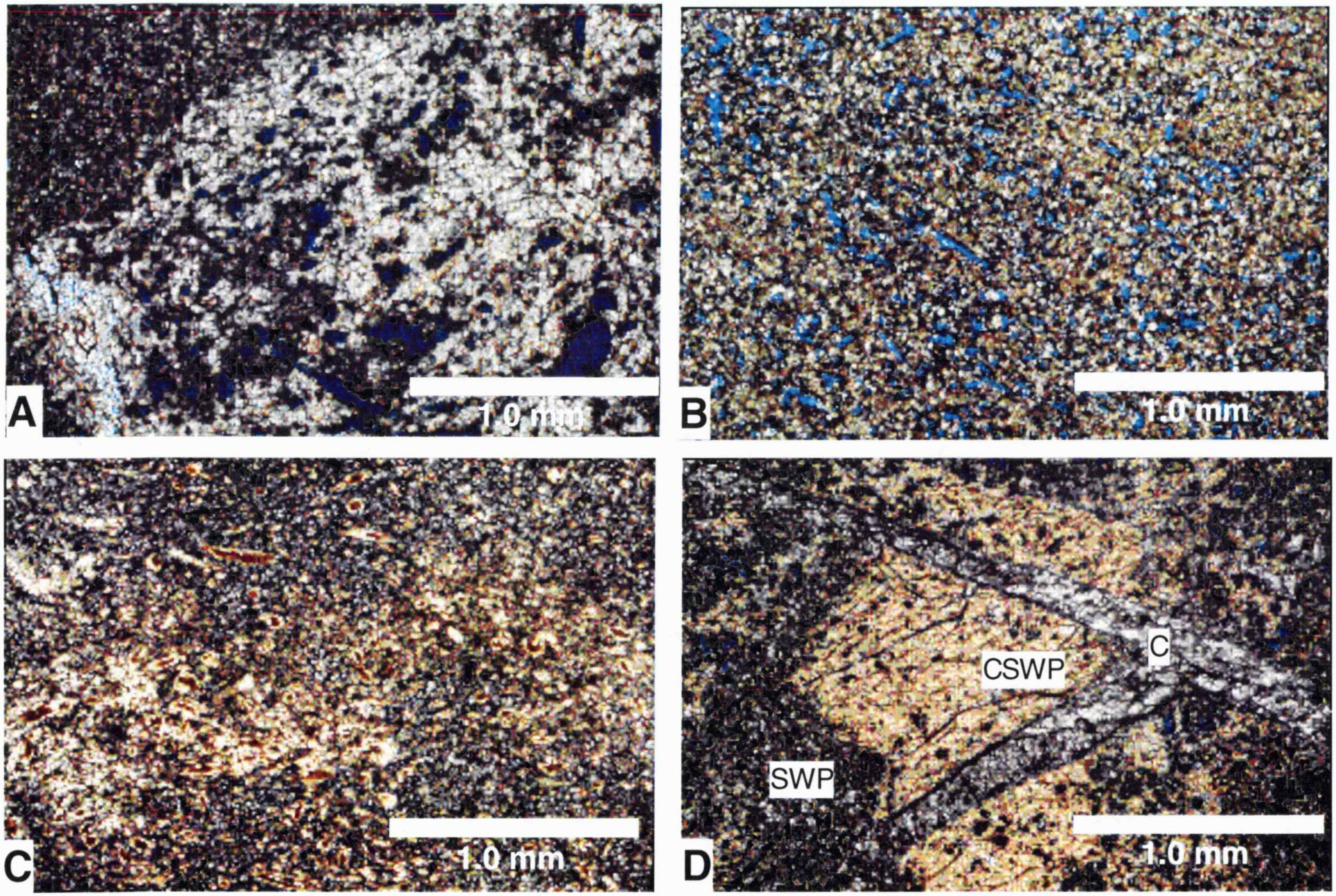

Figure 5: Sponge Spicule-rich Dolomite Wackestone-Packstone facies.
A) In this sample sponge spicules have been dissolved leaving molds (blue areas) and the surrounding matrix has been replaced by chert. Note the upper left corner of this photomicrograph has not been replaced by chert and is dolomitic. Plane polarized light. B) Abundant sponge spicule moldic and intercrystalline porosity which tend to form favorable reservoir facies. Plane polarized light. C) In this sample the sponge spicules are siliceous and only a minor amount of intercrystalline porosity is present. Plane polarized light. D) Dolomitic sponge wackestone packstone (SWP) with some intercrystalline and moldic porosity variably replaced by chert preserving sponge molds (CSWP). Later fracturing filled with coarse calcite cement cuts through both the dolomite and chert imparting a breccia texture.

layers locally results in variable tight and porous areas at a thin section scale (e.g. Fig. 4B). 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 common in areas with intercrystalline porosity. This facies commonly contains chert after replacement of evaporite crystals, nodules and coalesced nodules that form layers (Figs. M.2, S.3, F.1). Chert also replaces matrix and grains (Figs. 5A, 5D, M.2, F.1). A breccia fabric is common from dissolution and collapse of evaporites and due to early differential compaction between brittle chert and soft dolomitic matrix (Figs. M.2, S.2). This facies is the most common to contain oil staining.

Echinoderm-Rich Dolomitic or Lime Wackestone-Packstone-Grainstone (EWPG)

This facies occurs in all three cores and is most abundant in the lower parts of the cores. This facies is typically dominated by echinoderm fragments but also contains abundant sponge spicules, bryozoan fragments, brachiopods, coral fragments, gastropods, ostracods, ooids, peloids, grapestone, calcispheres, oncolites, and other unidentifiable skeletal debris. 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. 6A). Grainstones locally have an isopachous chalcedony cement that coats grains and lines primary pores. Where still dolomitic, the grains are typically preserved as molds (Fig. 6B). 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, grain breakage and flat, horizontal alignment of skeletal

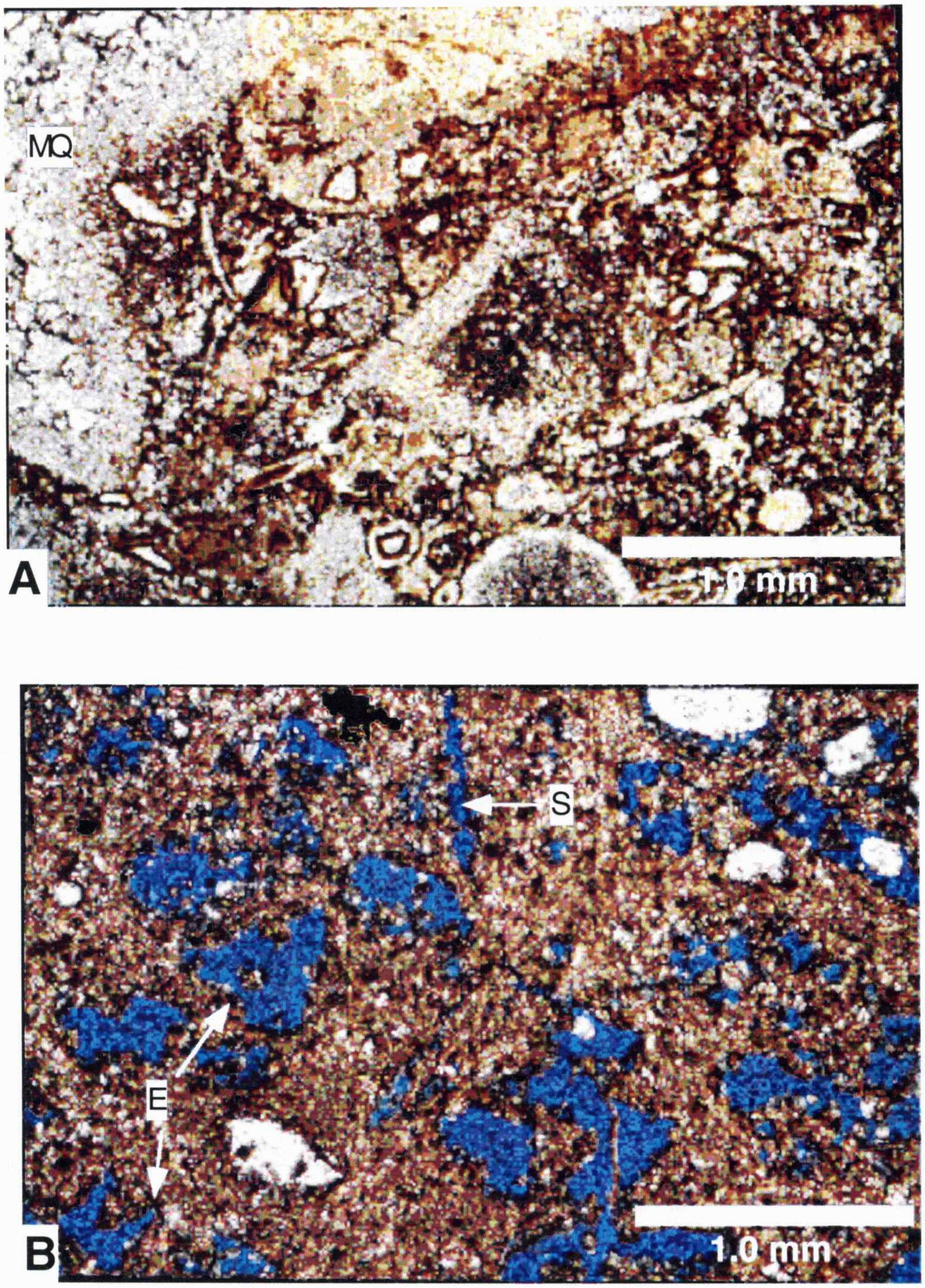

Figure 6: Echinoderm-rich Wackestone-Packstone-Grainstone facies.
A) Echinoderm, brachiopod, sponge spicule and other skeletal fragments in this sample have been entirely replaced by chert. Pores are filled with clear megaquartz cement (MQ). B) Echinoderm fragments (E) and other skeletal fragments, including sponge spicules (S), have been dissolved leaving abundant moldic porosity (blue areas) in relatively tight dolomitic matrix. Plane polarized light.

fragments, but typically there is not much over compaction or other evidence for much early compaction.

Where still dolomite, this facies is characteristically tan to dark brown in color and typically has a wispy laminated or mottled texture (Fig. S.5); 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 (Fig. F.2). Porosity in this facies can exceed 35% (visual estimate). 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 occlude porosity and replace original textures; some areas have dolomite rhombs, or silica "floating" in calcite.

This facies commonly has been partially or pervasively replaced with porcelaneous (tight) or tripolitic (porous) chert/megaquartz (Figs. 7A, 7B). 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. M.2A).

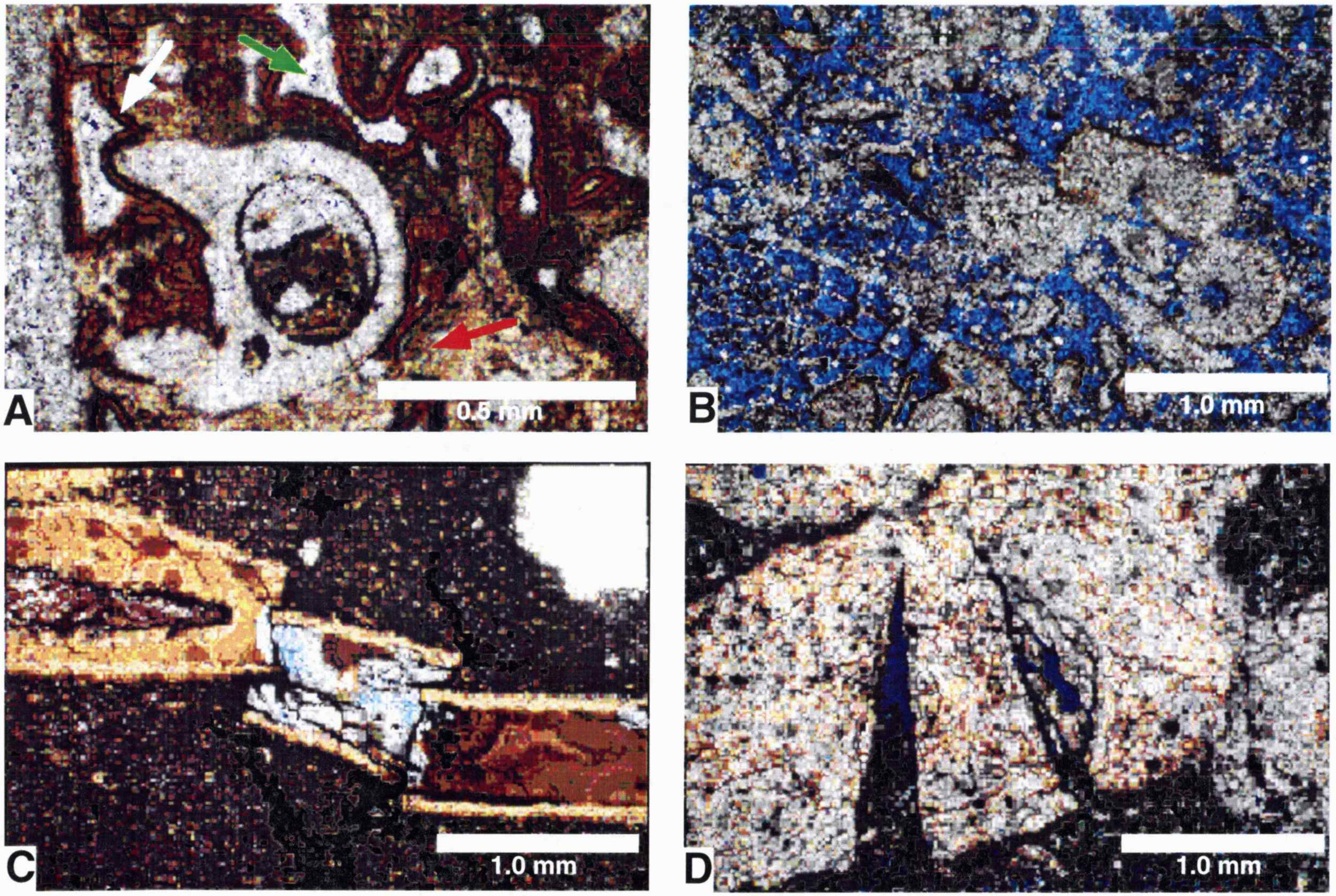

Figure 7: A) Echinoderm grainstone in which echinoderms, brachiopods, and other skeletal fragments have been entirely replaced and cemented by silica. Red arrow points to initial chert replacement, white arrow points to brown isopachous chalcedony cement that lines primary pores, and the green arrow points to clear pore-filling micro-megaquartz cement. Plane polarized light. B) Echinoderm grainstone in which the grains have been preserved by chert replacement and surrounding matrix has been dissolved leaving abundant interparticle, vuggy, and some intercrystalline porosity (tripolitic texture). Plane polarized light. C) Chert and chalcedony filled fracture in dolomitic mudstone-wackestone facies. Note the fracture was subsequently fractured and the surrounding dolomitic matrix fills in around fractured areas without brittle fracture. Plane polarized light. D) Partial chert replacement of Sponge spicule-rich Dolomite Wackestone-Packstone facies. Some sponge spicule molds (blue areas) can be identified in chert areas. Note brittle fracturing of chert and infill by surrounding dolomitic matrix indicating early chert replacement and differential compaction. Plane polarized light.

Other Lithologies and Features

Chert/Chalcedony/Megaquartz Replacement and Cementation

Silica replacement of original lithologies is abundant throughout all three cores and replaces all facies types described above. Silica cementation occurs in the form of chalcedony and megaquartz. 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 or tripolitic texture. Typically, several stages of silica replacement and cementation can be identified microscopically. A typical sequence shows a first stage of brown/black chert replacing facies and grains, a second stage of isopachous brown chalcedony cement, and a third stage of megaquartz replacement or cementation (Figs. 7A, 7C) .

The abundance of silica replacement is likely at least partially due to the abundance of sponge spicules. Silica locally preferentially replaces spicules imparting a wispy laminated texture (Fig. F.1A) or replaces the matrix surrounding the spicules and leaves the spicules as molds. Much of the chert replacement appears to follow original burrow mottling and networks. The silica replacement is typically tight and forms impermeable layers where replacement is pervasive (Figs. M.3, S.5, F.1). However, some of the pervasive chert replaced areas contain abundant microcrystalline, intergranular, and vuggy porosity (tripolitic texture). Chert areas commonly exhibit a fracture and brecciated texture due to early differential compaction between brittle chert areas and surrounding matrix areas that were still soft (Figs. 7C, 7D, S.4A), and from later fracturing related to subaerial exposure and later burial compaction (Fig. 5D). Variable micro-and macro-fracture porosity results from these processes.

Silica also occurs as replacement of original evaporite crystals, isolated nodules, horizontal layers of isolated or laterally coalescing nodules, or as horizontal layers of vertically elongate nodules (Figs. 8, M.3, S.3, F.1). This silica replacement is typically dark gray in color and has more associated vuggy porosity (Figs. 8B, M.2, S.3). Some of these nodules preserve a bladed, radiating bladed, and twined crystal morphology when viewed with a petrographic microscope (Fig. 8), indicating likely replacement of an original evaporite mineral (anhydrite or gypsum). Typically, the original evaporite crystals and nodules display replacement by clear to dark brown chert followed by a dissolution/corrosion/erosion event forming an irregular surface which is overlain by megaquartz cement that filled in remaining pore space (Fig. 8C).

Sandstone/Siltstone/shale

This facies is typically green to gray and locally red in color (Figs. S.1, F.1). It is wavy to wispy laminated and locally displays low-angle lamination. This facies is composed predominantly of very-fine grained sand (~100 μm) to silt-sized (<50 μm) quartz grains and clays (Fig. 9). Intergranular porosity is locally developed (> 20% locally, visual estimate). This facies occurs as fracture fill and breccia matrix containing clasts of carbonate facies and replacive silica (Fig. 9B). The shale locally occurs as wispy layers in dolomitic mudstone or wackestone facies (Fig. 9C).

Breccia and Fracturing

Macro- and micro-scale brecciation and fracturing are ubiquitous throughout the three cores (Figs. 9, 10, 11; see also core photographs). Fracturing and brecciation results in fracture and mosaic breccias (textures ranging from little to no rotation on clasts indicating in-situ brecciation; Fig. 11A),

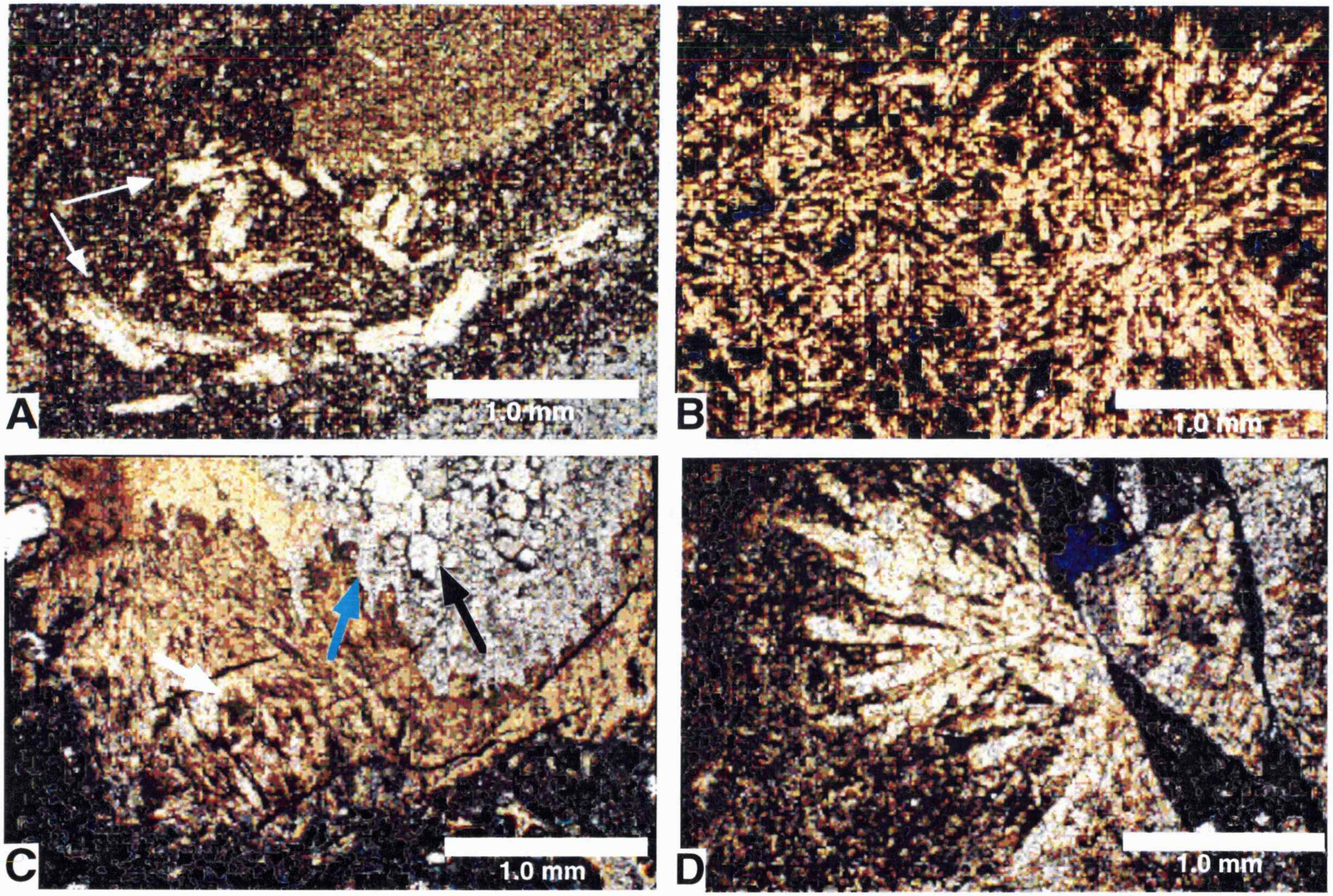

Figure 8: Silica-replaced bladed and radiating bladed crystal textures of original evaporite (anhydrite/gypsum) minerals. A) Individual replaced evaporite crystals in sponge-rich wackestone-packstone facies. Plane polarized light.
B) This sample exhibits displacive growth of crystals and formation of nodules in dolomitic sediment. Preservation of the radiating crystal and coalescing nodule texture suggests early replacement by silica prior to any significant compaction. Plane polarized light. C) Replacement of original evaporite crystals and nodule by clear to brown chert (white arrow). This was followed by a dissolution/corrosion/erosion event (blue arrow). Remaining porosity was filled by clear megaquartz cement (black arrow). Plane polarized light. D) Silica replaced evaporite mineral blades and nodule cut by later fracture that is partially filled with very finely crystalline dolomite and evaporite crystal matrix containing evaporite nodule clasts. Plane polarized light.

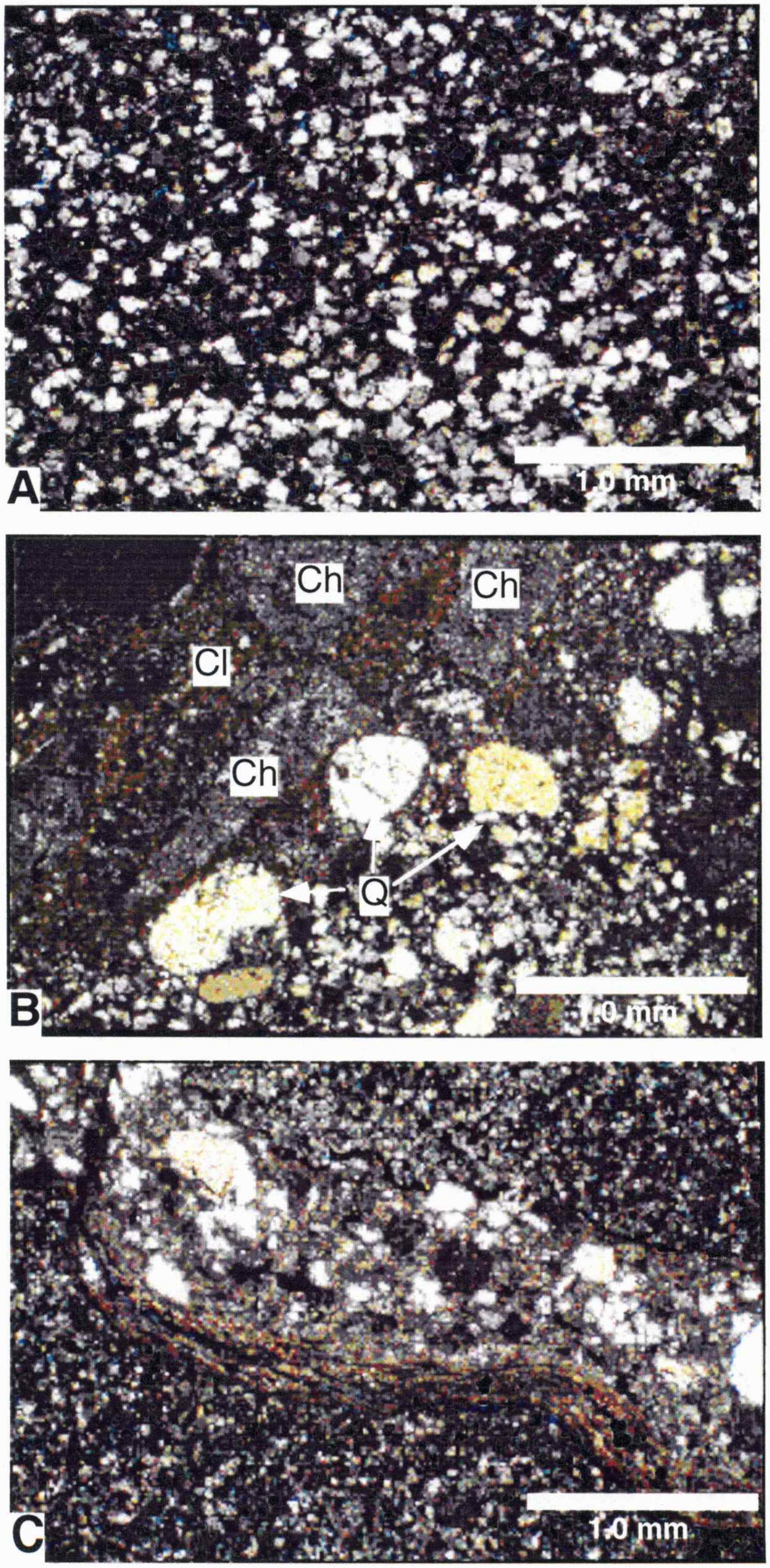

Figure 9: A) Fracture fill containing mostly subangular to subround silt- to very fine sand-size detrital quartz grains with minor clay. Crossed nicols. B) Fracture fill with angular chert fragments (Ch), subangular to round, silt- to coarse-grained detrital quartz (Q) and clay (Cl). Crossed nicols. C) Dolomitic matrix cut by a fracture filled with chert and detrital quartz. Plane polarized light.

to matrix-supported and clast-supported chaotic breccias that represent mixtures of autochthonous and allochthonous materials resedimented by gravitationally driven processes (Figs. 9B, 11B, M.1).

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.

Brecciation and fracturing were caused by a variety of processes interacting at different times. Some areas reveal several generations of fracturing, brecciation, cementation and sediment fills (e.g. Figs. 10B, 10E, 10F, S. 4A). The overprinting of these different events results in complex fabrics. Relatively early silica replacement resulted in layers and areas that were cemented versus surrounding original matrix that was still soft. Early compaction resulted in differential brittle and soft deformation between the chert and surrounding matrix which imparted a fractured and brecciated fabric (e.g. Figs. 7C, 7D, M.3A, S.2, S.4A, S.5). Displacive growth of chert nodules in soft dolomitic sediment resulted in soft sediment deformation textures and some brecciation (e.g. S.2). Some breccia was locally caused by depositional processes (e.g. current rip-up). Other brecciation and fracturing were caused by early (intra-Mississippian) subaerial exposure, dissolution and collapse of

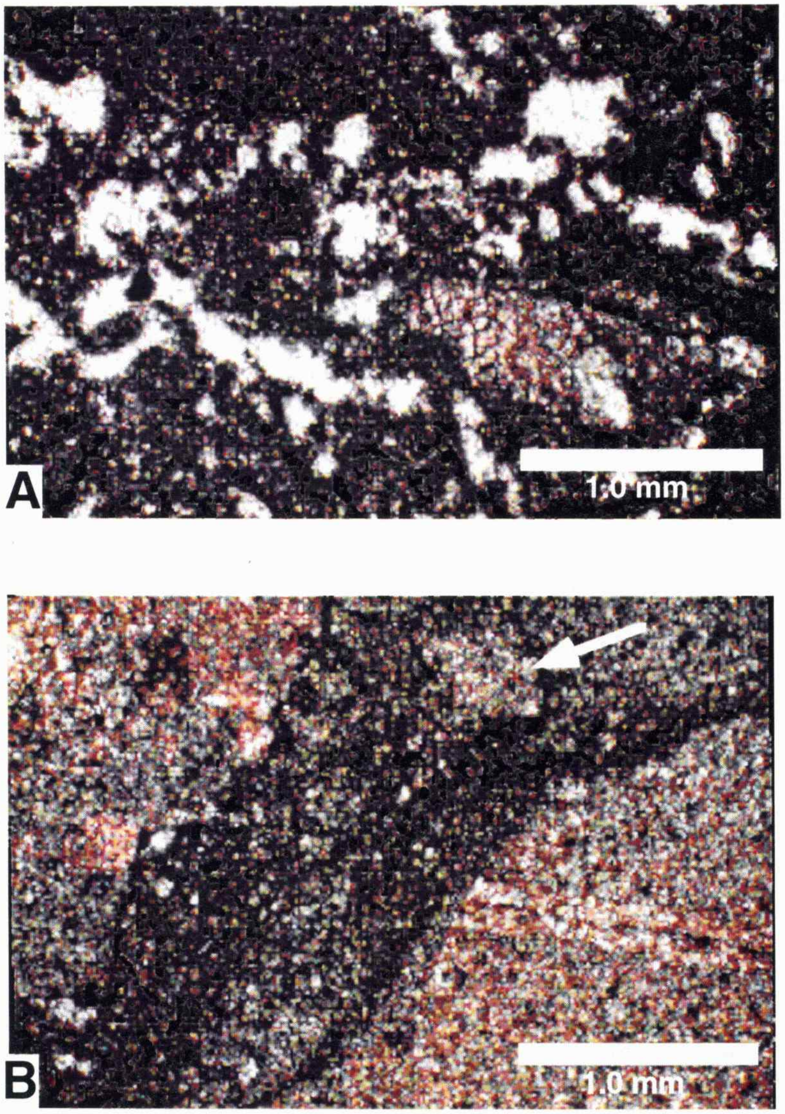

Figure 10: A) Abundant fenestral pores (white areas) developed in dolomitic matrix just below the 4424' surface in the # 2 Lyle Schaben core. Note pore filled with coarse calcite cement (stained with Alizarin red) that is common below the 4424'. Plane polarized light. B) Poikilotopic calcite replaced facies (red-stained areas) below the 4424' surface that were subsequently fractured. The fracture is filled with very finely crystalline dolomite from above the 4424' surface and locally contains clasts of poikilotopic calcite (white arrow). Note the truncated coarse calcite cement-filled fracture in the poikilotopic calcite in the bottom right portion of the photomicrograph. Plane polarized light.

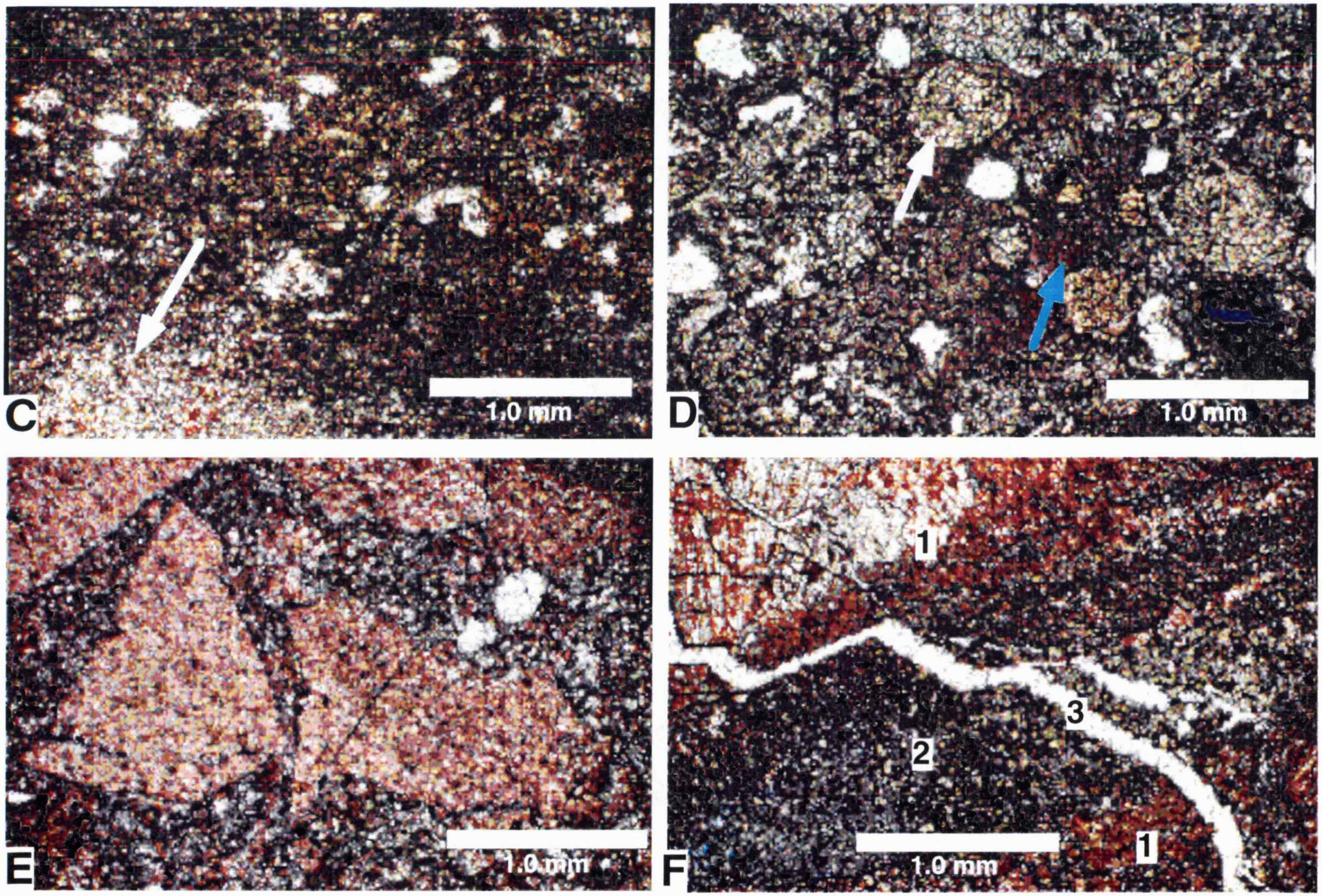

Figure 10: C) Altered facies below the 4424' surface. Some altered areas are characterized by a central area filled with coarse calcite cement (white arrow) surrounded by a halo rich in iron and fenestral pores (white areas) in dolomitic and replacive poikilotopic calcite matrix. Plane polarized light. D) Fracture below the 4424' surface filled with dolomite, clay, detrital quartz (white arrow) clasts and matrix that is cemented by coarse calcite cement (blue arrow). Plane polarized light. E) Fracture below the 4424' surface that contains angular poikilotopic calcite clasts (red-stained) and detrital quartz in very finely crystalline dolomitic matrix. Plane polarized light. F) Coarse calcite cement and poikilotopic calcite areas (1) cut by fracture filled with Fe-rich dolomite (2). Later open fractures (3) cut across all previous facies and events. Plane polarized light.

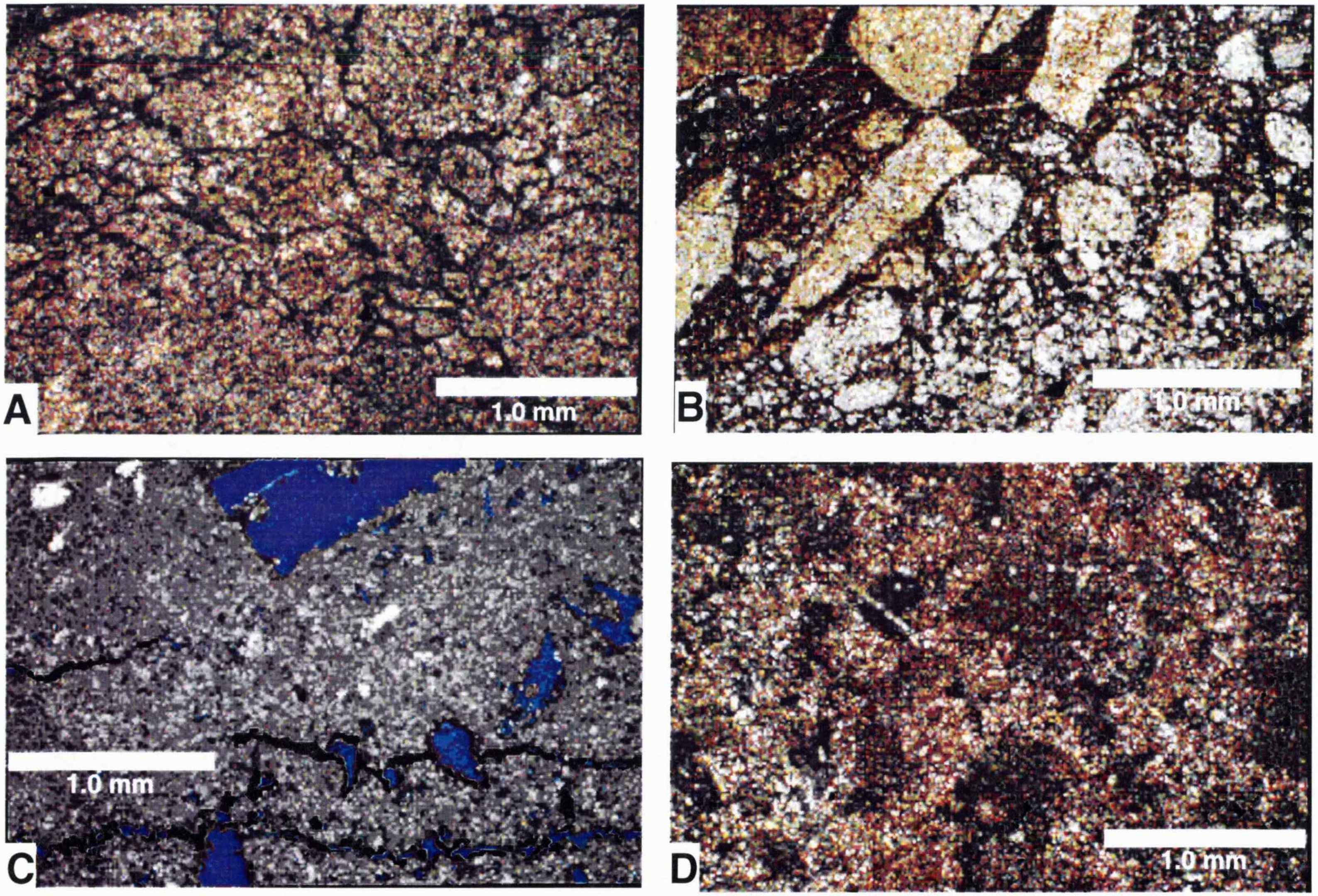

Figure 11: A) Autobreccia fabric indicative of in-place brecciation. Plane polarized light. B) Chaotic breccia fabric with subround to round detrital quartz and megaquartz cement grains and angular to subangular chert fragments in dolomitic and chert matrix. Plane polarized light. C) Echinoderm-rich wackestone-packstone. Note that grain molds (blue areas) are lined with oil and connected by open fractures lined with oil. Plane polarized light. D) Poikilotopic replacive calcite just below the post-Mississippian unconformity. Here the calcite replaces sponge spicule-rich facies. The dark areas are extinction patterns of the poikilotopic calcite. Crossed nicols.

evaporites, post-Mississippian subaerial exposure, and late burial compaction that resulted in brittle deformation of all lithologies.

Depositional Environment

A general upward facies change is discernible in all three cores (Plate 1). Echinoderm facies predominates in the bases of all the cores (up to 4435' in Moore, up to 4428' in Schaben and up to 4436' in Foos). Although other facies occur as well, importantly, evidence of evaporites is generally lacking. The upper portions of all cores (above 4435' in Moore, above 4428' in Schaben and above 4436' are dominated by the sponge spicule-rich and mudstone/wackestone facies and contain abundant evidence of evaporites. 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 to somewhat restricted marine environments. In contrast, the abundance of mudstone, wackestone and spicule-rich facies, relative rarity of echinoderm-rich facies, and abundance of evaporites in upper portions of the cores suggest deposition in restricted, evaporitive ramp or lagoon environments. However, the abundance of burrow mottling indicates conditions sufficient to support organisms that reworked the sediment. The morphology and alignment of the evaporite crystals, nodules, and layers likely indicates formation in a supratidal to shallow subaqueous setting at or just below the sediment/water interface (Warren, 1989). Local fenestral fabric indicates at least intermittent subaerial exposure.

Overall, each core shows an upward shoaling trend leading up to the post-Mississippian subaerial exposure event. The echinoderm-rich facies are mostly characteristic of a shallow subtidal shelf setting. The lamination, cross lamination, normal grading, packing of grains, grain breakage, and scoured contacts evidence at least intermittent high energy. In the normal to restricted portion of the ramp, this facies likely represents deposition from storm and turbidity currents or from migration of subtidal shoals or banks. Local fenestral fabrics in the echinoderm facies, especially in the evaporite ramp or lagoon portion of the section, indicate at least local subaerial exposure in a supratidal setting. The echinoderm-rich facies in this part of the ramp may represent shelfward migration of a subtidal shoal or shelfward deposition from tide or storm currents. The sponge spicule dolowackestone-packstone and dolomudstone-wackestone facies are likely indicative of a low energy and slightly more restricted setting as compared to the echinoderm-rich facies. In this environment sponges thrived and likely formed sponge "gardens" or "mounds" (Rogers et al., 1995). Wispy and wavy horizontal lamination, alternating grain-rich and grain-poor layers, some apparent normally graded beds and local interbeds of grainstone in mudstone to packstone indicate transport and reworking of sediment by currents likely generated from tides or storms.

The change between the normal to restricted marine ramp and the evaporitic ramp to lagoon in the Schaben core is marked by a sharp contact at 4424' (Plate 1; Fig. S.3). This surface and the strata immediately below for several meters show significant alteration (Figs. S.3, S.4). A replacive poikilotopic calcite and coarse calcite cement (Fig. 10) are associated with the 4424' surface and occur pervasively below the surface to a depth of approximately 4428.5' (Figs. S.3, S.4) and then more variably in strata below to the bottom of the core (Fig. S.5A). 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 (S.3B; S.4B).

There is a similar calcite poikilotopic replacement and coarse calcite cement at the very top of the Schaben core (Fig. 11D) but it only affects strata in the upper five feet of the core and is presumably related to the post-Mississippian subaerial exposure event. Strata from about 4390' to 4424' do not contain any coarse poikilotopic calcite or coarse calcite cement. In addition, the strata below the 4424' surface contain local fenestral fabric (Fig. 10A), 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 (Fig. 10D), dolomite facies clasts, chalcedony, megaquartz and chert clasts, and, locally, poikilotopic calcite clasts (Figs. 10B, 10E). In addition, round or oblong to rounded elongate areas altering original facies occur for several meters below the surface (Fig. S.4A). 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. 10C). Some of these areas show associated microscopic horizontal and downward "branching" of microfractures. These altered areas may 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 4424' surface versus the alteration and features being related to the post-Mississippian exposure event is supported by several cross-cutting relationships. Below the 4424' surface, original dolomitic facies and silica replaced facies are fractured and brecciated and infilled with dolomite matrix, detrital quartz and replacive silica clasts (Fig. 10D). These facies and previously fractured and brecciated areas are crosscut by coarse calcite-filled fractures, replaced by poikilotopic calcite, and the previously fractured and brecciated areas are locally cemented by coarse calcite (Fig. 10D). These fabrics, including the coarse calcite cement and poikilotopic calcite, are crosscut by fractures filled with dolomite (Figs. 10B, 10F) and locally, evaporite crystals and evaporite nodules from facies overlying the 4424' surface. These dolomite-filled fractures contain clasts of poikilotopic cement (Figs. 10B, 10E) and clasts of replacive silica. Importantly, none of these features are identified above the 4424' 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 (Figs. 10F; S. 4A).

Discussion

Although reservoir characteristics in strata underlying major subaerial exposure unconformities, such as the Schaben field, are thought to be controlled by processes associated with subaerial exposure, the value of sorting out the different depositional and diagenetic events in these types of fields as discussed above is demonstrated by comparing locations of oil stains in relationship to core data. An original depositional facies control for favorable reservoir strata is shown by most of the oil shows occurring in spicule-rich facies that originally had abundant evaporites present and, less commonly, echinoderm-rich wackestones/packstone facies (see Plate 1 and core photographs). Burrow mottling was very important in creating and locating fluid flow networks for early diagenetic fluids that resulted in variable porous and non-porous areas on macroscopic and microscopic scales. Early diagenetic events such as dolomitization, dissolution, silica cementation and replacement, associated fracturing and brecciation, poikilotopic calcite replacement and calcite cementation were important for reservoir architecture. Dissolution of grains and dolomitization created the moldic, intercrystalline and vuggy porosity important for favorable reservoir facies. Early silica cementation and replacement was important in creating the vertical heterogeneity illustrated by oil staining patterns. Whereas silica replacement and cementation tend to result in relatively tight and pervasive replacement in echinoderm-rich facies, the silica replacement and cementation in spicule-rich facies tends to be more variable, especially where evaporites were replaced by silica, and tend to contain more moldic and vuggy porosity. The poikilotopic calcite replacement and coarse calcite cement associated with the 4424' subaerial exposure event was extremely important in occluding porosity in underlying strata in the Schaben field as reflected by the relative lack of oil staining. Both early and late fracturing and brecciation variously enhanced or destroyed reservoir characteristics as indicated by variable oil stain patterns associated with such features. Certainly the late fracture and breccia matrix porosity that remained open are important for creating effective porosity when intersecting favorable reservoir facies.

In summary, topographic highs just underlying the post-Mississippian unconformity are typically viewed as the most favorable locations for petroleum exploration and production. The dipping Mississippian ramp were differentially eroded at the post-Mississippian unconformity resulting in paleotopographic highs (buried hogbacks, Carr et al., 1996). The features reported in this study and from an ongoing diagenetic and paragenetic study indicate that the most favorable areas for successful production may be where spiculitic-rich facies originally containing abundant evaporites intersect open fractures associated with the post-Mississippian unconformity and burial processes, and form the topographic highs. In contrast, areas in which mudstone-wackestone facies or echinoderm-rich facies intersect fractures associated with the unconformity and form topographic highs may not always be as favorable reservoirs. This is especially true for pre-4424' surface strata that are relatively tighter due to calcite replacement and cementation, and more pervasive chert replacement.

Ongoing studies are evaluating and confirming the details of paragenesis to determine more fully the relationship of the different depositional and diagenetic events to reservoir architecture. This detailed understanding not only has important implications for Schaben field, but for other Mississippian reservoirs in Kansas that contain similar facies and directly underly the post-Mississippian unconformity such as Glick field (Osagian, Rogers et al., 1995), Western Sedgwick basin (Osagian; Thomas, 1982), Bindley field (Warsaw, Ebanks, 1991; Johnson and Budd, 1994) and other similar Mississippian strata outside of Kansas such as Madison Group strata from the Williston Basin of Southeast Saskatchewan (P. Gerlach personal communication, 1996).

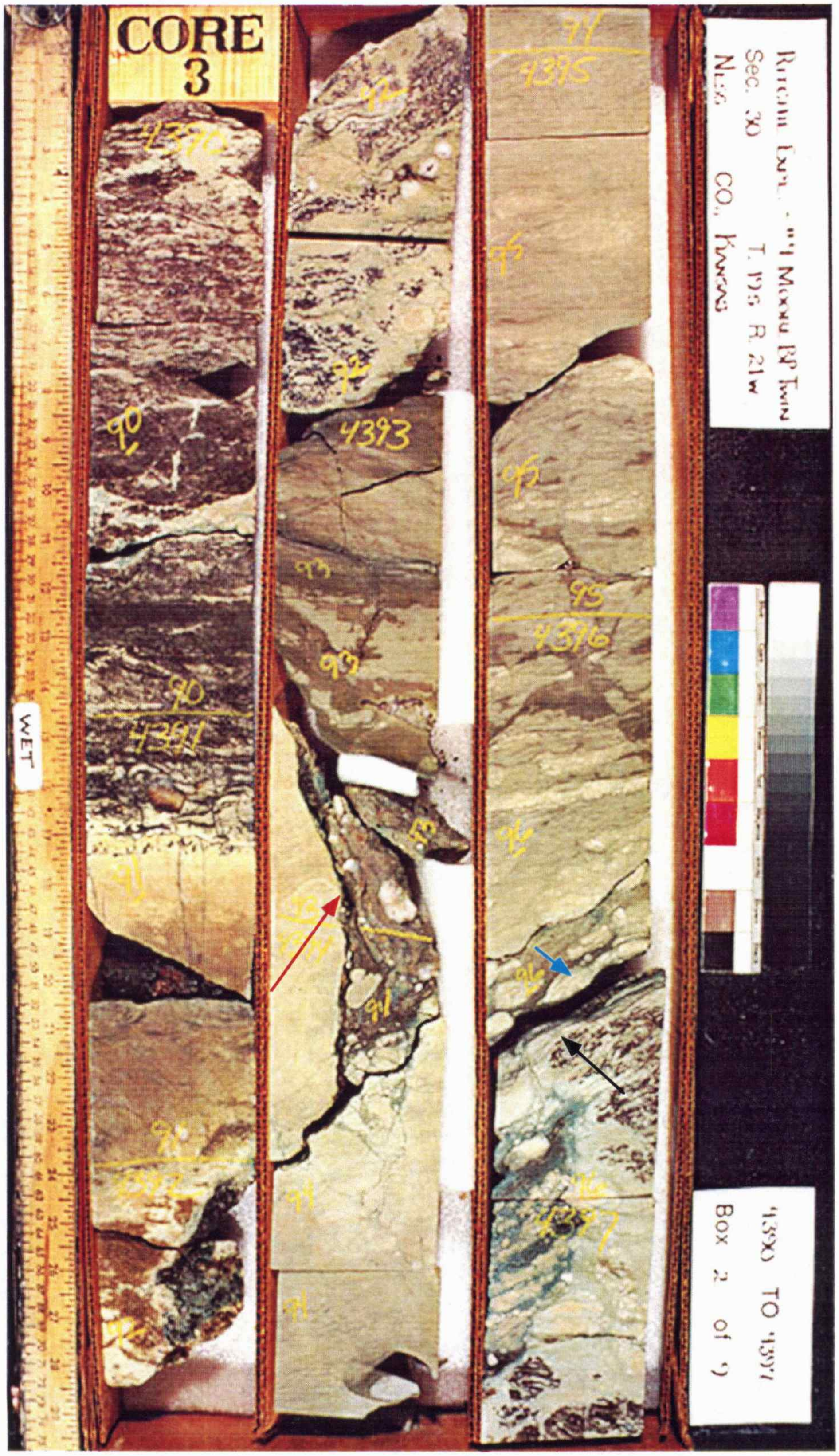

Figure M.1A: Core photo of #1 Moore BP Twin (4390' to 4397'). Red arrow points to fracture cutting through sponge spicule-rich wackestone-packstone facies and filled with clasts of sponge-rich facies in siliciclastic matrix forming chaotic breccia texture. Black arrow points to tilted sponge-rich facies cut by fracture and filled with clasts of sponge-rich facies, siliciclastic matrix and clasts of silica replaced evaporite nodules (blue arrow) from overlying beds (chaotic breccia fabric). Note the beds above the blue arrow (near the 4395-4396' contact) are fractured and disrupted with little displacement forming a fracture breccia. Fracturing and siliciclastic fill are likely related to the post-Mississippian subaerial unconformity.

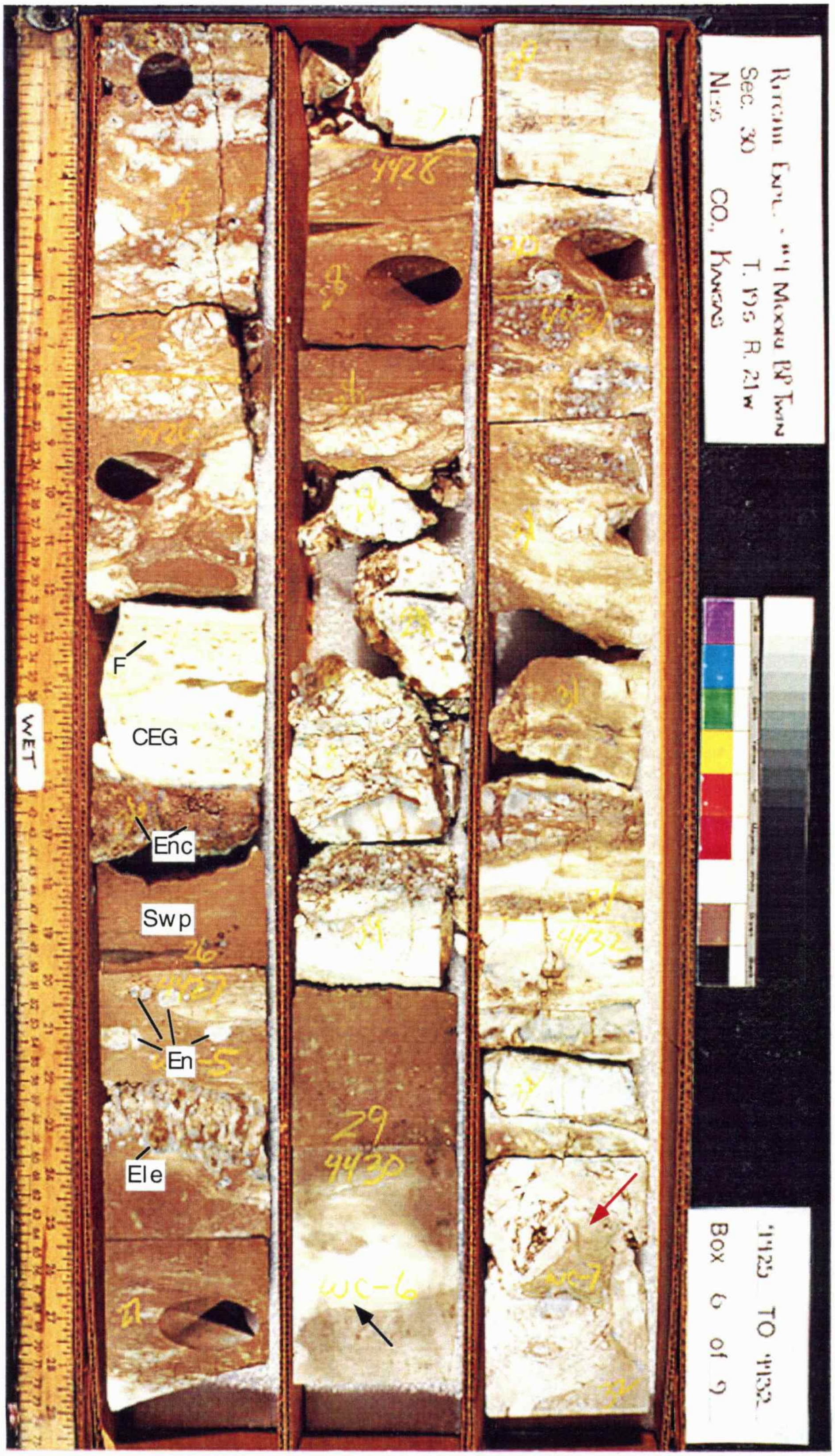

Figure M.2A: Core photo of #1 Moore BP Twin (4425' to 4432'). The predominant original depositional facies throughout this interval is sponge spicule-rich wackestone-packstone (brown colored areas; Swp). White areas typically reflect chert replacement of original facies (e.g. areas indicated by black and red arrows). The red arrow points to an area where differential compaction between chert and soft dolomitic facies caused brittle fracture of the chert and soft sediment deformation of the dolomitic facies. The black arrow indicates an area of diffuse chert replacement that is also typical in the sponge-rich facies. White-gray to gray colored areas typically reflect silica replacement of evaporite nodules (e.g. Ele, En, Enc). Several evaporite nodule morphologies can be seen in this interval; vertically elongate crystals coalescing to form a layer (Ele), individual round to oblong evaporite nodules (En) and coalesced evaporite nodules. Note just above the 4427-4426' contact that sponge-rich facies (Swp) are overlain by evaporite nodules (Enc) which are overlain by chertified echinoderm-rich grainstone (CEG) containing fenestral fabric (F) indicating deposition in very shallow marine conditions for these facies that experienced at least local exposure. The echinoderm-rich grainstone is pervasively replaced by fabric preserving chert. This type of replacement is common in the echinoderm-rich facies and typically forms a tightly cemented interval.

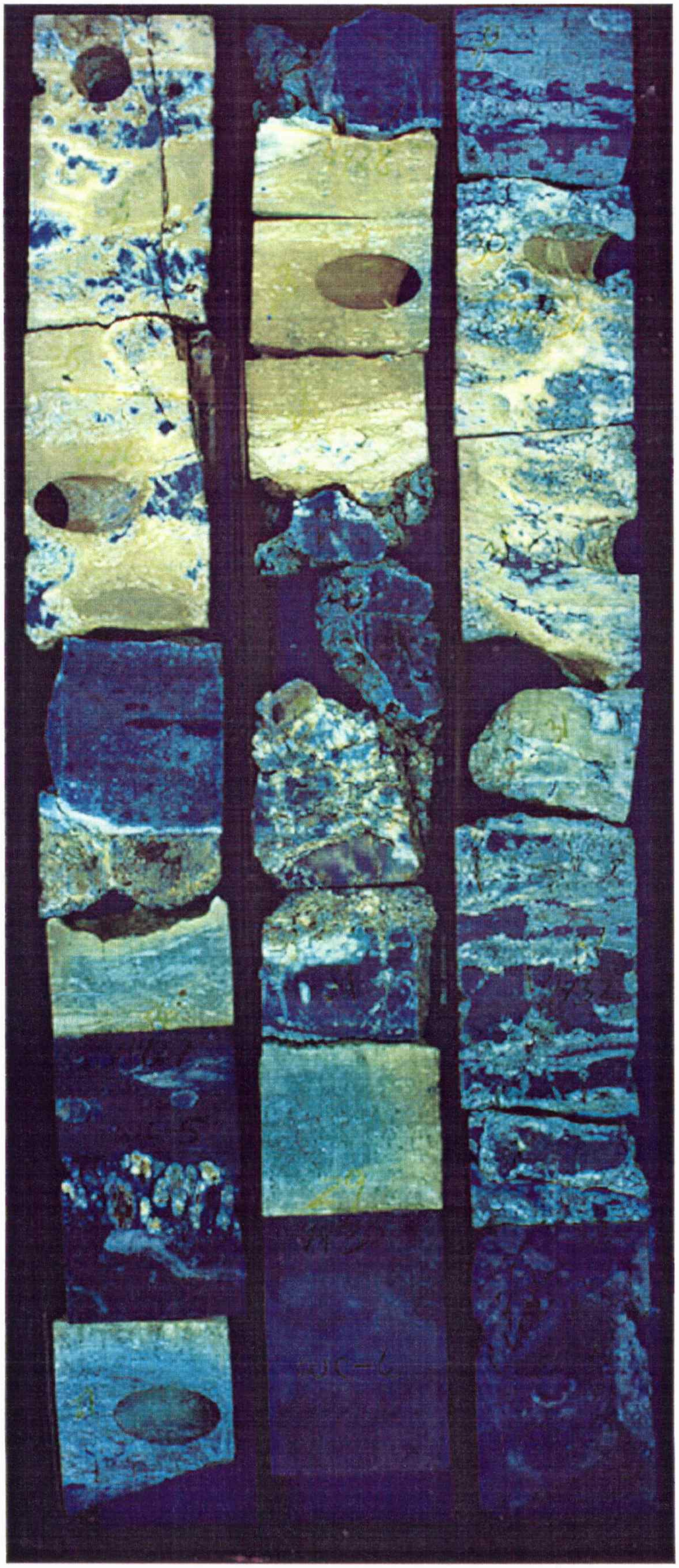

Figure M.2B: Core photo of #1 Moore BP Twin (4425' to 4432'). Same interval as Figure M.2A but taken under ultraviolet light (UV). Bright fluorescent areas indicate staining with oil. Dark areas are tight and contain no oil. Note the sponge spicule-rich facies, and some of the replaced evaporites contain some oil staining whereas the other chert areas are typically tight.

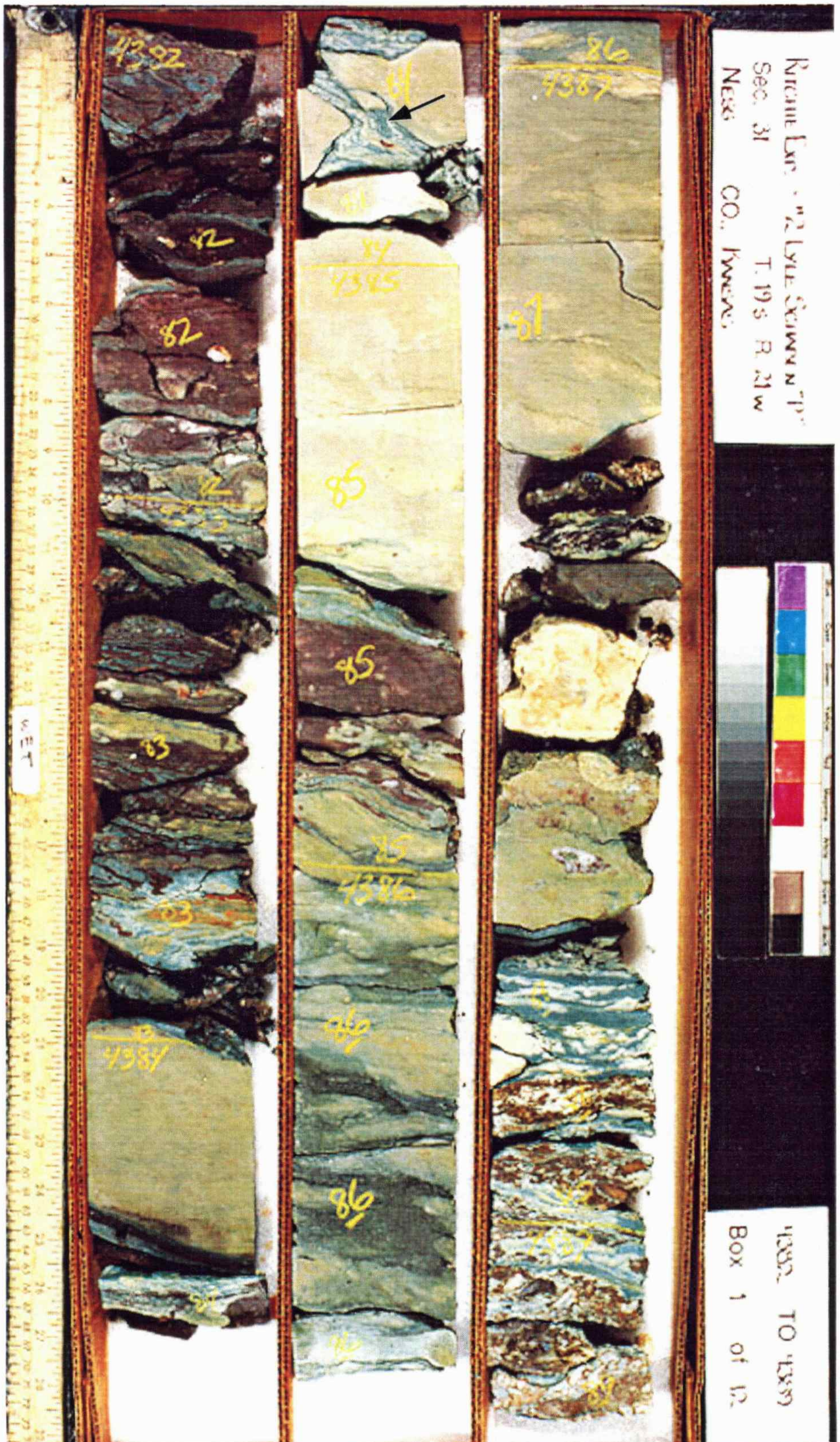

Figure S.1: Core photo of #2 Lyle Schaben "P" (4382' to 4389'). This interval reveals abundant red and green clay likely associated with the post-Mississippian subaerial exposure event filling in fractures within sponge spicule-rich strata, locally containing replaced evaporite nodules, that underlie the post-Mississippian unconformity.

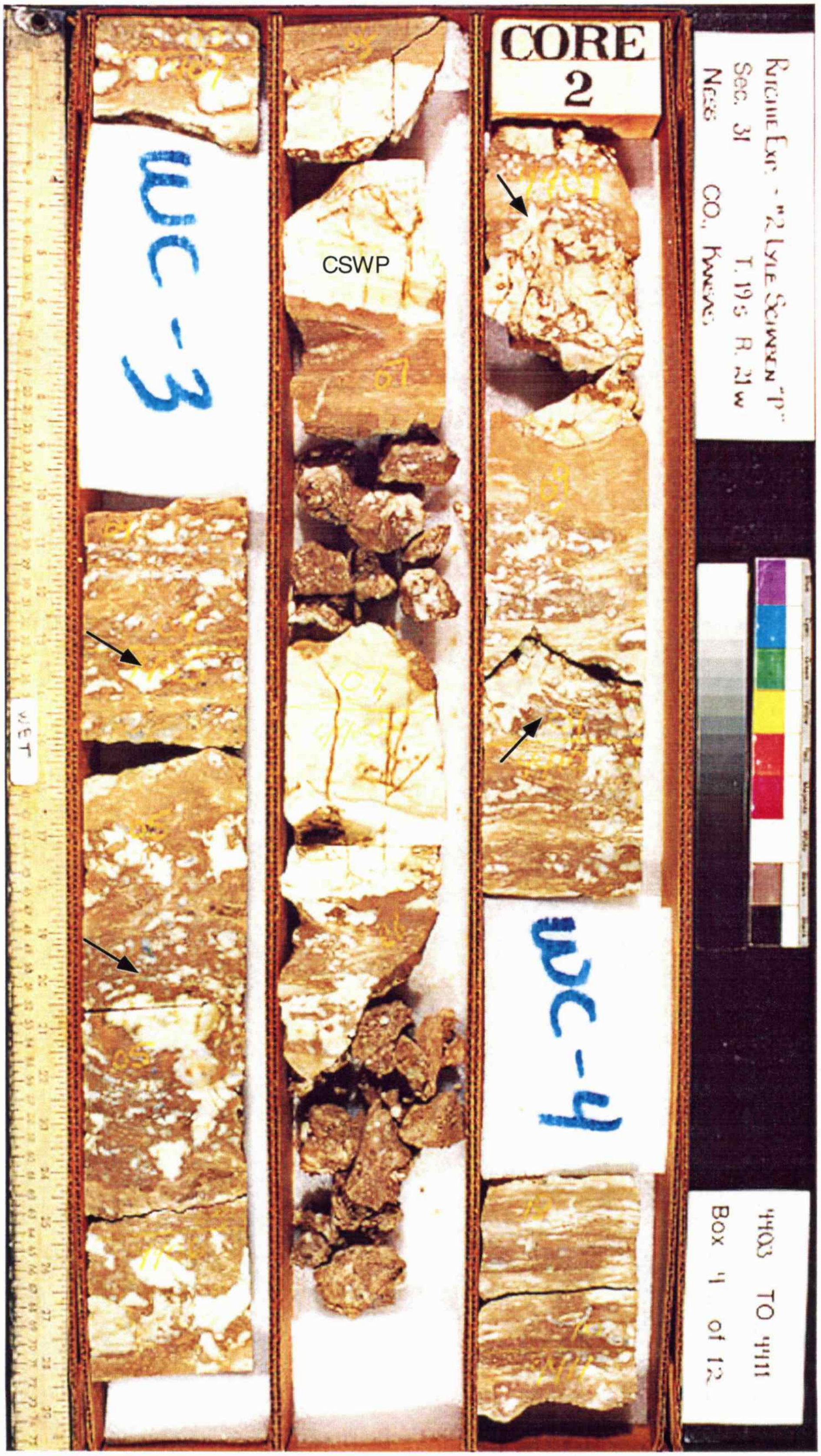

Figure S.2A: Core photo of #2 Lyle Schaben "P" (4403' to 4411'). Sponge spicule-rich facies (brown) with abundant chert (white) that replaced facies and original evaporite minerals. Black arrows indicate areas of irregular growth boundaries of chert, incipient chert nodule formation, and differential compaction between cemented chert and soft dolomite facies which impart a brecciated texture to these rocks. Note near the bottom of this interval, chert replacement appears to follow original bedding and possibly burrow structures.

Figure S.2B: Core photo of #2 Lyle Schaben "P" (4403' to 4411'). Same interval as Figure S.2A but taken under UV light. Note that the sponge spicule-rich facies contains abundant oil stains (bright areas) whereas the chert areas are relative tight (dark areas). This photo nicely shows oil stained fractures that cut across some of the chert areas (black arrows).

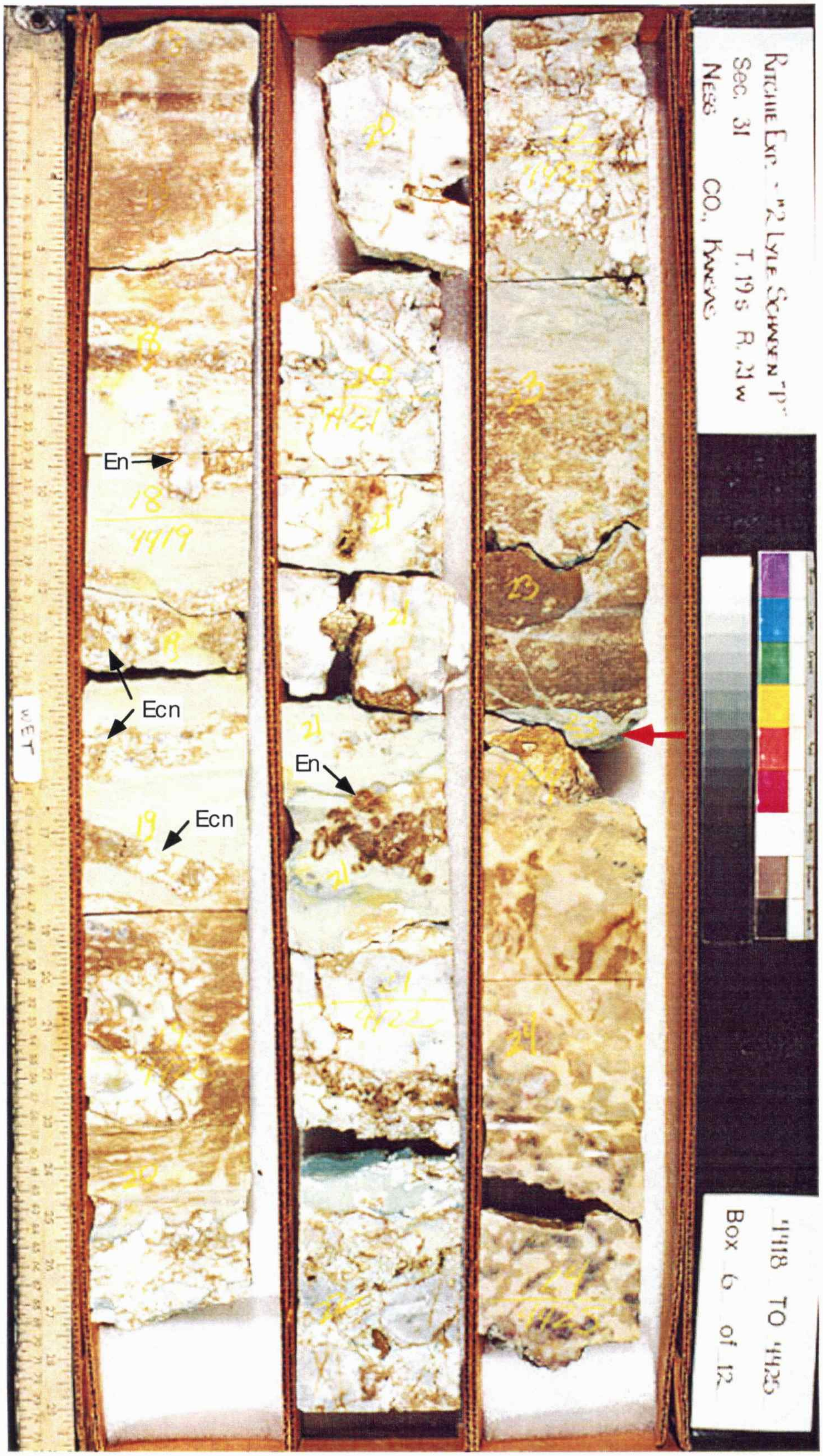

Figure S.3A: Core photo of #2 Lyle Schaben "P" (4418' to 4425'). Predominantly sponge-rich facies (with some minor interbedded echinoderm-rich grainstone beds) containing abundant chert, mostly after evaporite nodules (En), some of which are coalesced to form incipient layers (Ecn). The red arrow points to the surface at 4424'. Note the strata below this surface are altered and have a mottled texture. Petrographic evidence suggests subaerial exposure at this surface.

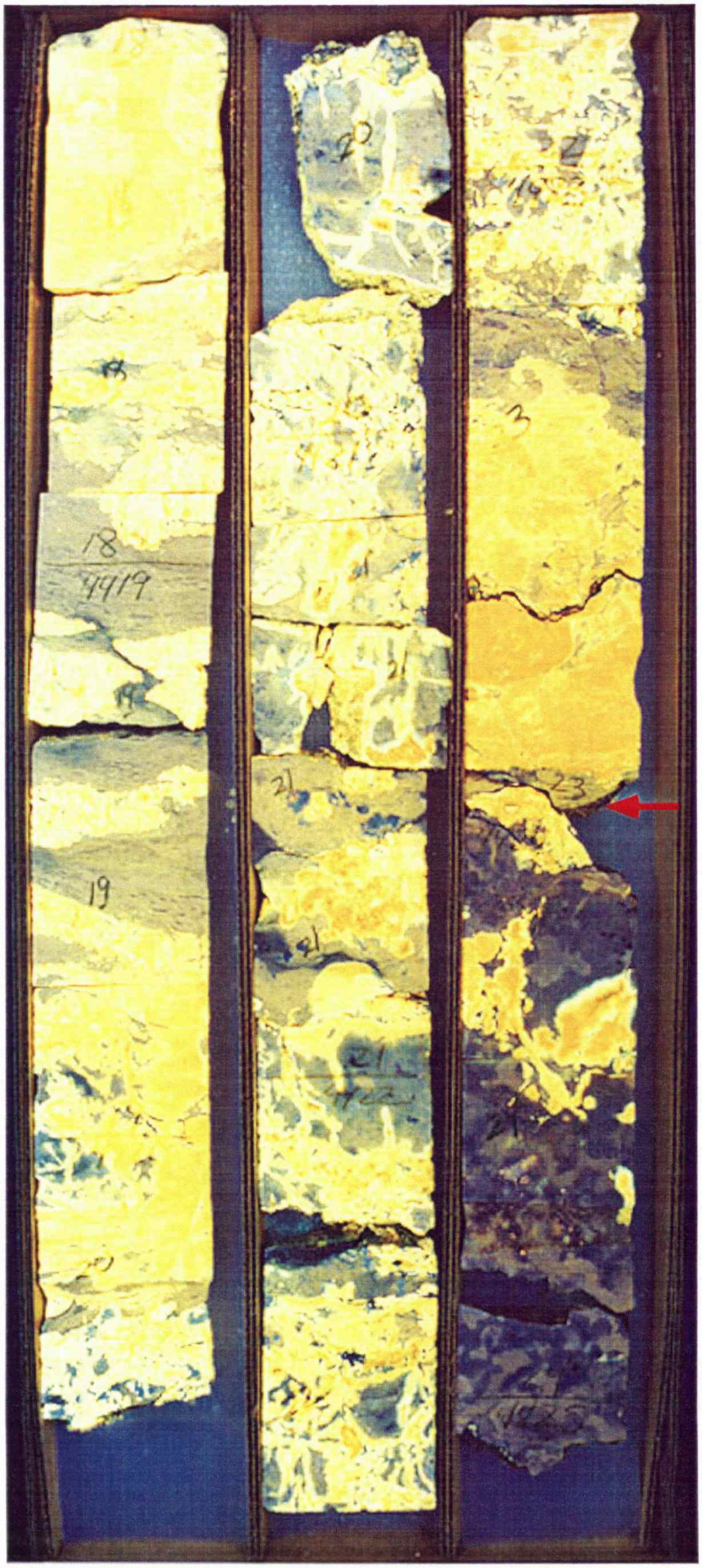

Figure S.3B: Core photo of #2 Lyle Schaben "P" (4418' to 4425').). Same interval as Figure S.3A but taken under UV light. Note the strata below the 4424' surface (red arrow) are relatively tight due to pervasive coarse poikilotopic calcite replacement and cementation.

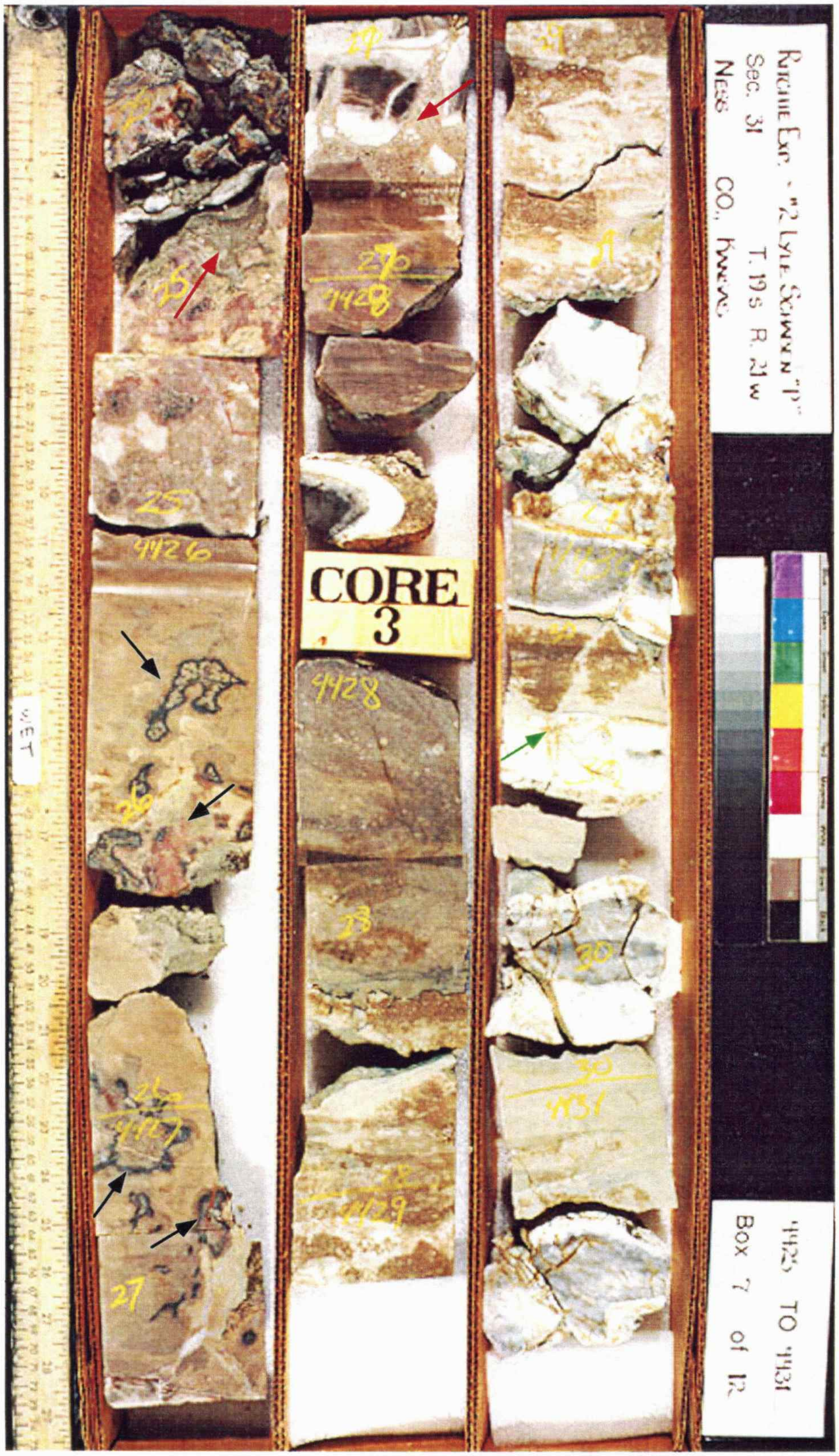

Figure S.4A: Core photo of #2 Lyle Schaben "P" (4425' to 4431'). Black arrows point to iron-stained mottled areas. Petrographic examination indicates some of these altered areas are characterized by a central area filled with coarse calcite cement surrounded by a halo rich in iron and fenestral pores in dolomitic and replacive poikilotopic calcite matrix, which may indicate these are associated with land plant roots (see Figure 10c). The red arrows point to fracturing and brecciation likely associated with the 4424' surface subaerial exposure event. These fractures cut across original dolomite facies, poikilotopic cement replaced facies coarse calcite cement and chert replaced facies (see Figures 10B, D, E, F for petrographic characteristics of these fractured and brecciated areas. Note that the fractured area indicated by the red arrow near the top of the arrow (~4425.5') was in turn crosscut by a later fracture filled with abundant green clay, possibly associated with the post-Mississippian subaerial exposure event. The green arrow near 4430' points to a fracture in chert that is filled with dolomite matrix from immediately overlying facies. This indicates early chert replacement and fracturing.

Figure S.4B: Core photo of #2 Lyle Schaben "P" (4425' to 4431'). Same interval as Figure S.4A but taken under UV light. Notice that the strata are extremely tight down to a level of ~4428.5' due to pervasive coarse poikilotopic calcite replacement and cementation. Strata below this level are variably stained with oil.

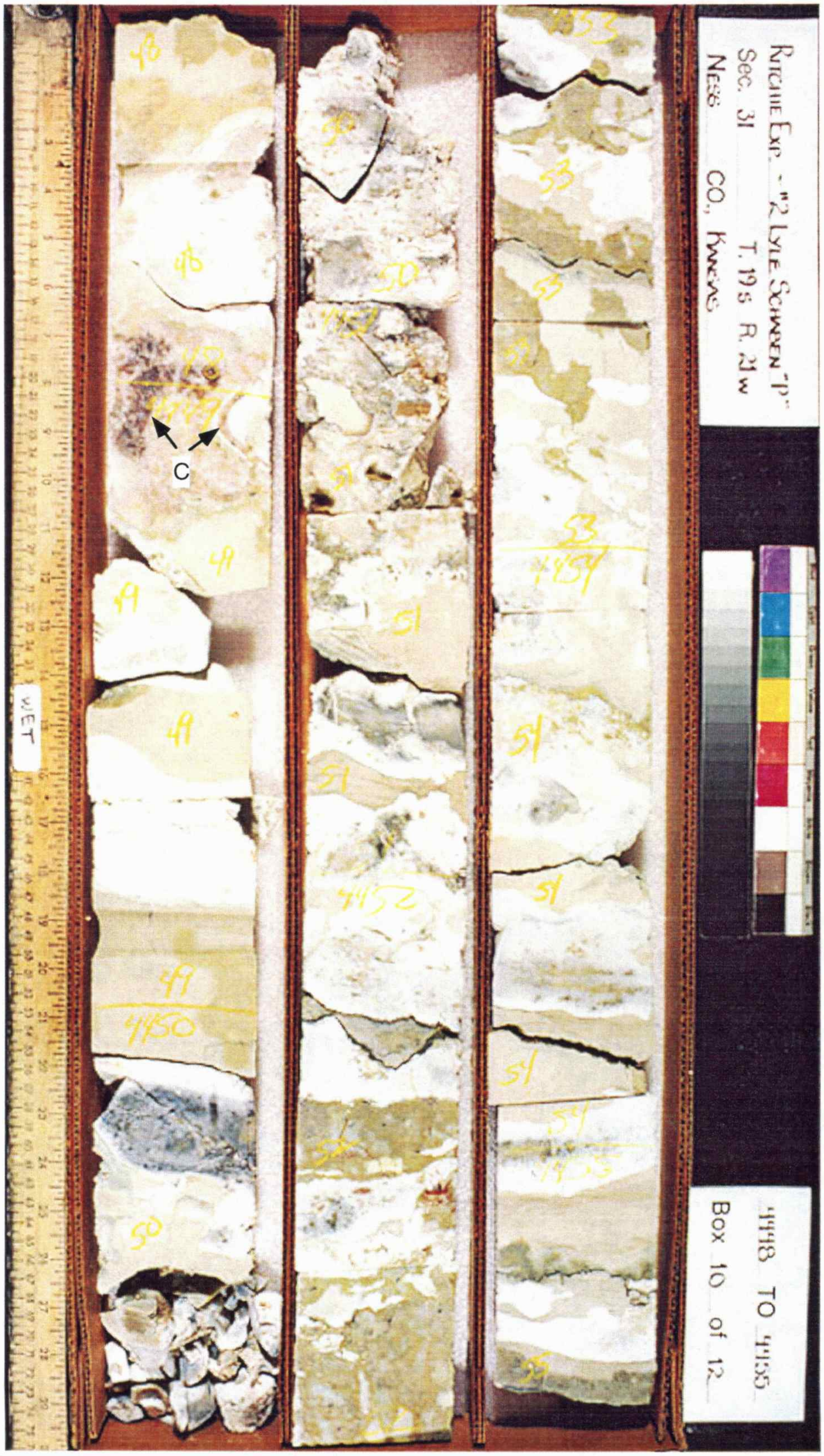

Figure S.5A: Core photo of #2 Lyle Schaben "P" (4448' to 4455'). This interval is composed predominantly of echinoderm-rich wackestone-packstone-grainstone facies (EWPG), with abundant chert replacement of original facies (white areas). Chert replacement of EWPG facies is typically more pervasive than in the sponge spicule-rich facies as exemplified in this photo. Chert replacement here follows depositional bedding and burrow networks. Coarse poikilotopic calcite replacement and cementation from the 4424' surface subaerial exposure event is more variable at lower levels but extends to the bottom of the core. In this photo coarse calcite cement (C) indicated by the black arrows fills fractures that cut across both dolomite facies and facies replacive chert.

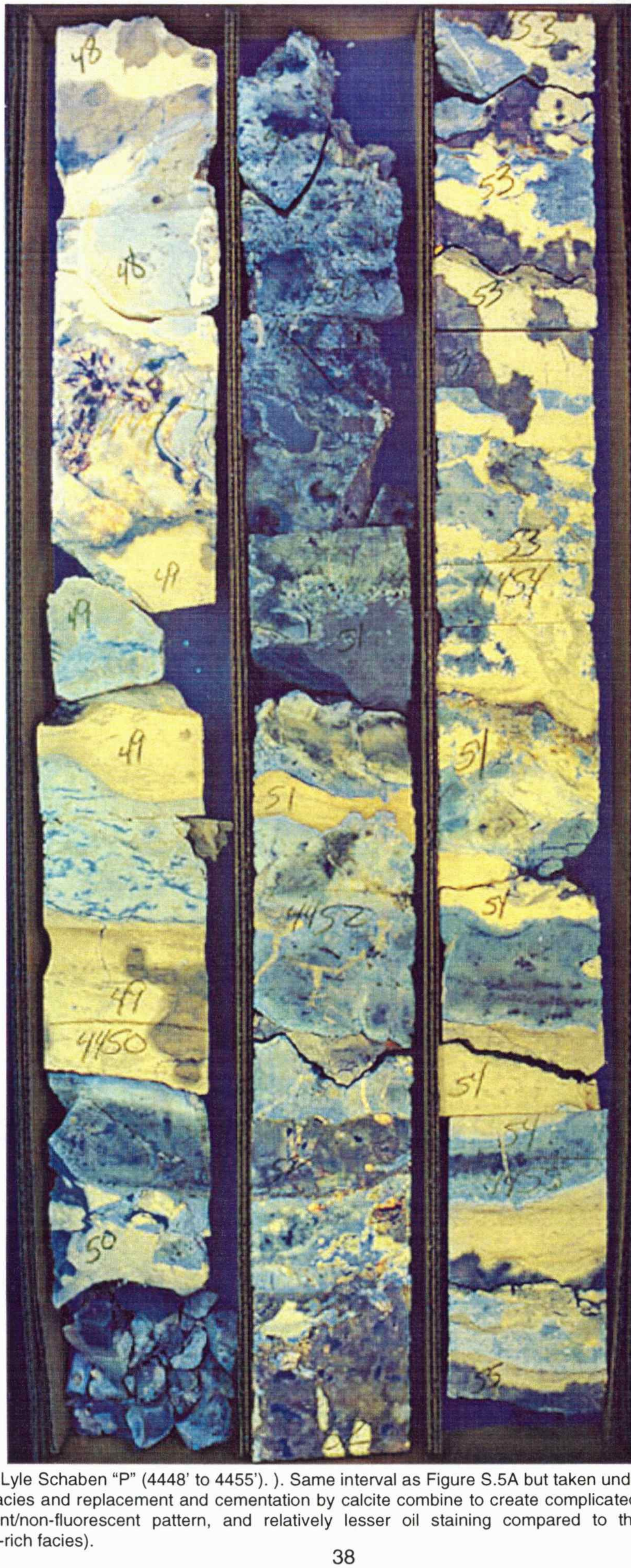

Figure S.5B: Core photo of #2 Lyle Schaben "P" (4448' to 4455').). Same interval as Figure S.5A but taken under UV light. Abundant and pervasive chert replacement of EWPG facies and replacement and cementation by calcite combine to create complicated vertical heterogeneity, indicated by the complex bright fluorescent/non-fluorescent pattern, and relatively lesser oil staining compared to the facies above the 4424' surface (predominantly sponge spicule-rich facies).

Figure F.1A: Core photo of #1 Foos AP Twin (4396'-4404'). This interval consists of interbedded sponge spicule-rich facies, mudstone-wackestone facies and green siliciclastic layers with one pervasively chertified echinoderm grainstone bed (CEG). The black arrows point to chert replaced evaporite nodules and the red arrows point to areas where chert has replaced sponge spicule-rich or mudstone-wackestone facies. Note the facies replacing chert appears to follow horizontal to wavy horizontal bedding and/or burrow networks.

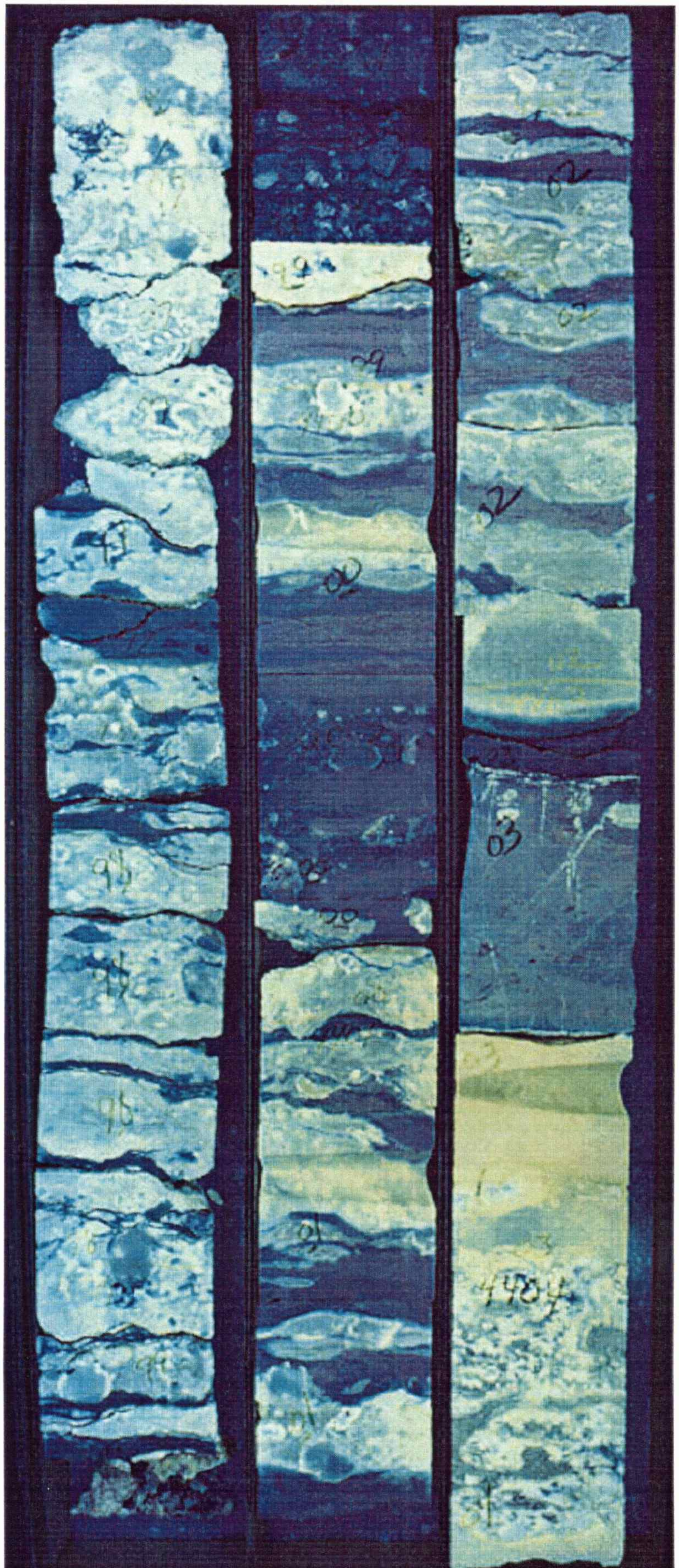

Figure F.1B: Core photo of #1 Foos AP Twin (4396'-4404'). Same interval as Figure F.1A but taken under UV light. The sponge spicule-rich facies has some oil staining but the abundance of chert layers and shale results in complex vertical heterogeneity.

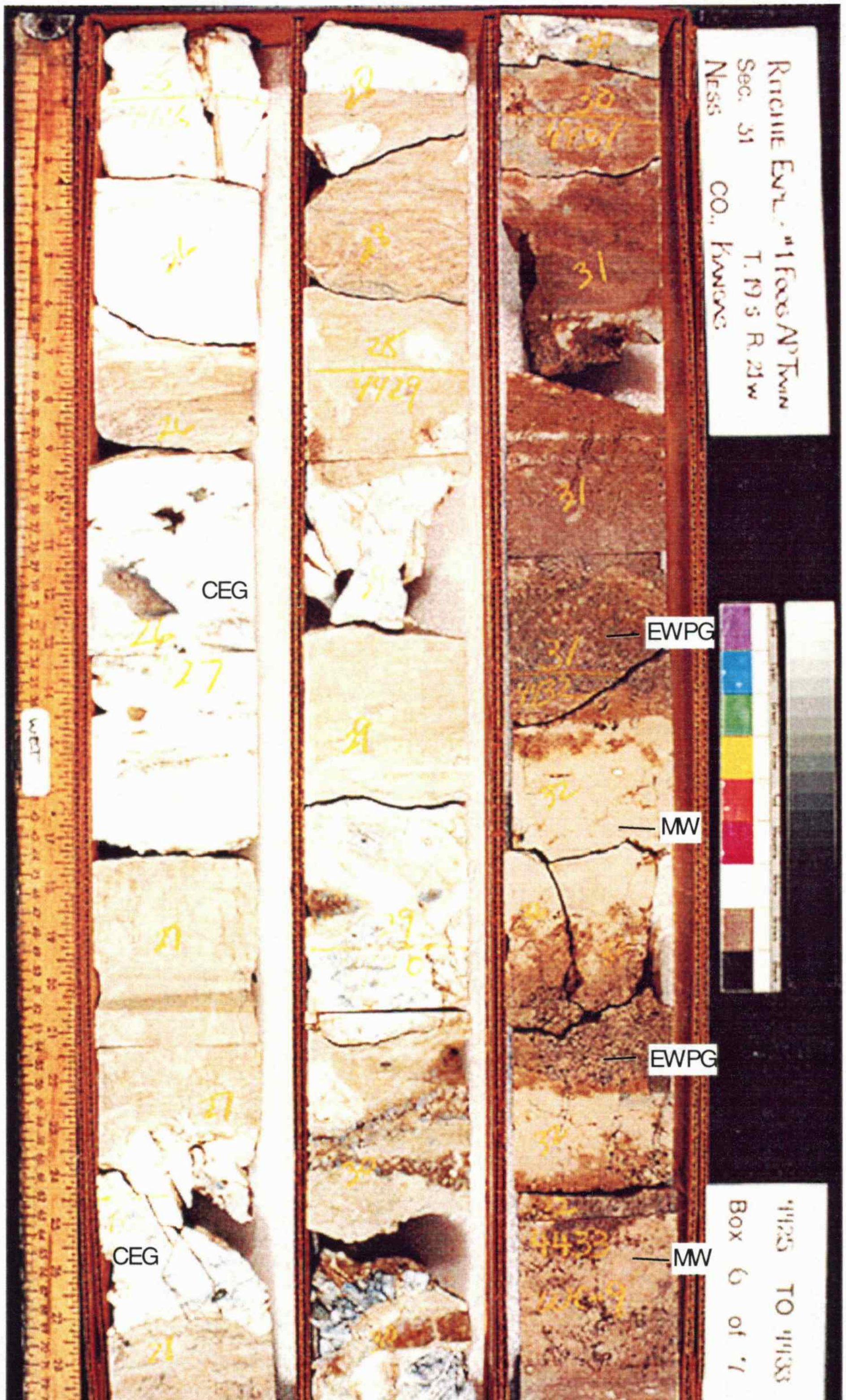

Figure F.2A: Core photo of #1 Foos AP Twin (4425'-4433'). This interval consists of interbedded sponge spicule-rich facies (light gray layers), echinoderm-rich wackestone-packstone-grainstone layers (EWPG), some of which are pervasively replaced by chert (CEG), and mudstone-wackestone facies (MW).

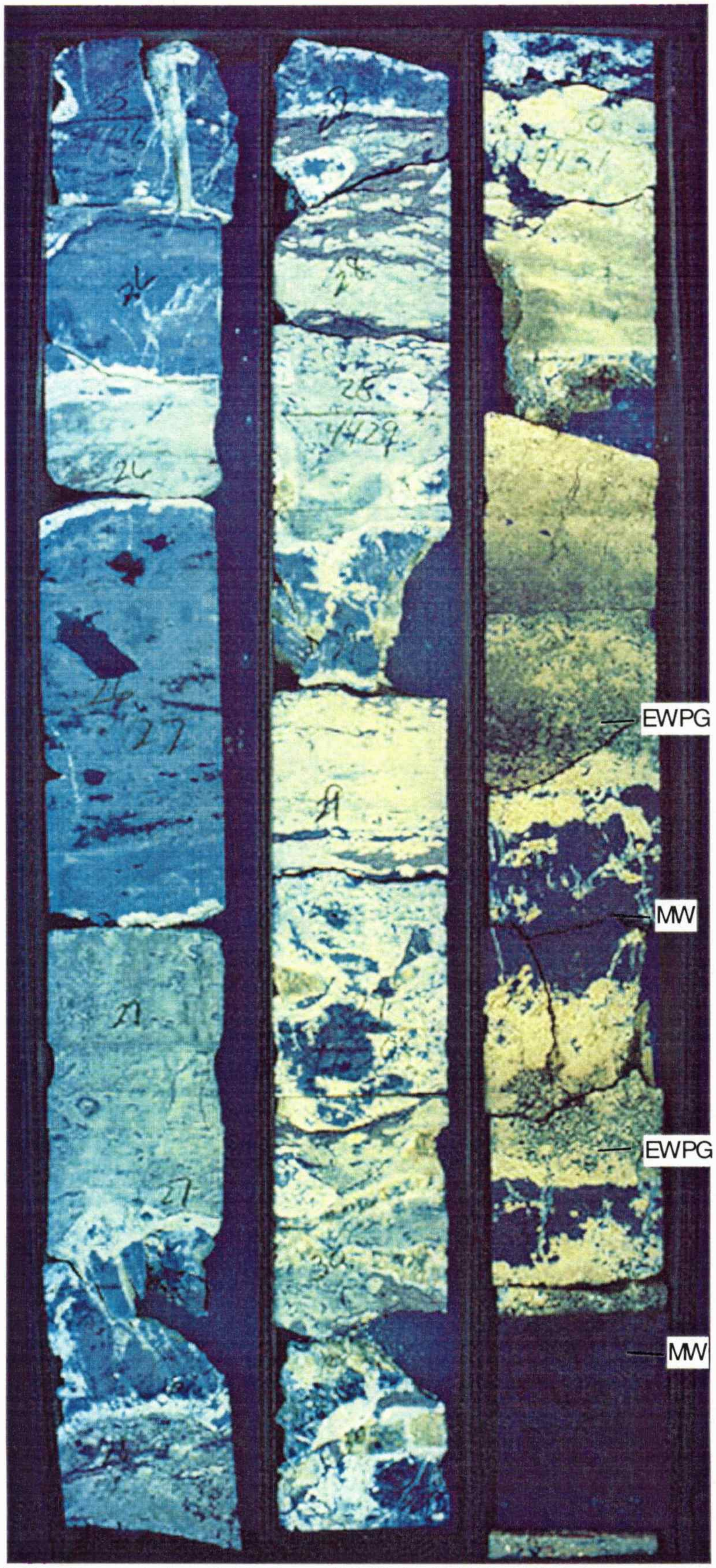

Figure F.2B: Core photo of #1 Foos AP Twin (4425'-4433').). Same interval as Figure F.1A but taken under UV light. The sponge-rich facies and EWPG facies (where not replaced by chert) show oil staining but the interbedded tightly cemented MW facies and chert horizons result in complex vertical heterogeneity.

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