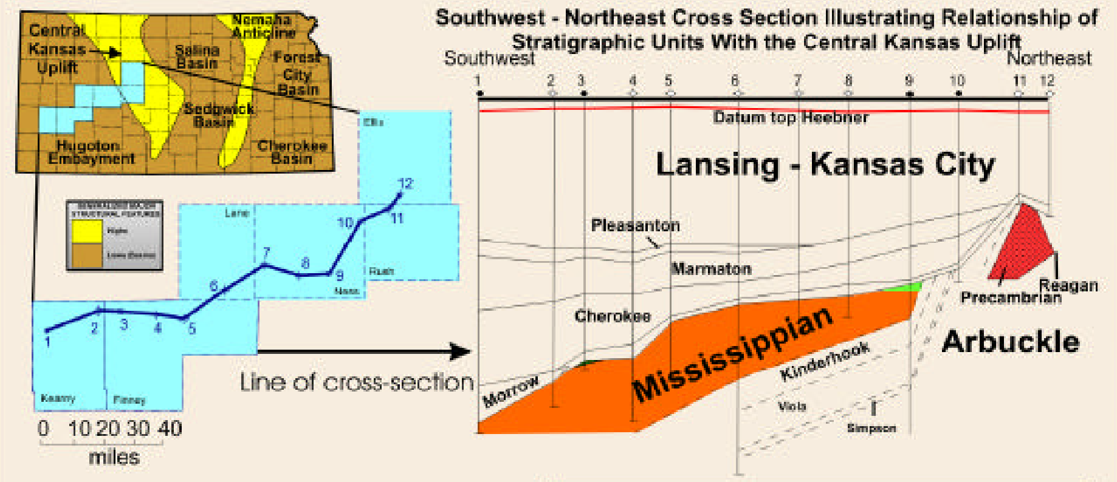
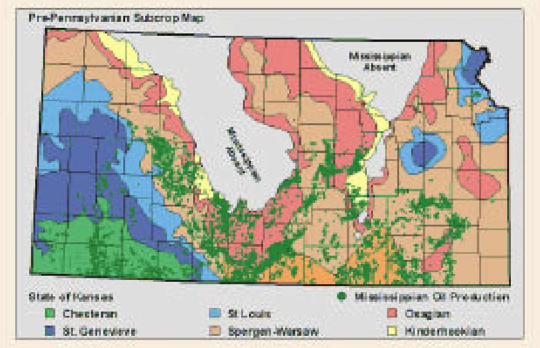
Mississippian Limestones, Dolomites, and Cherts

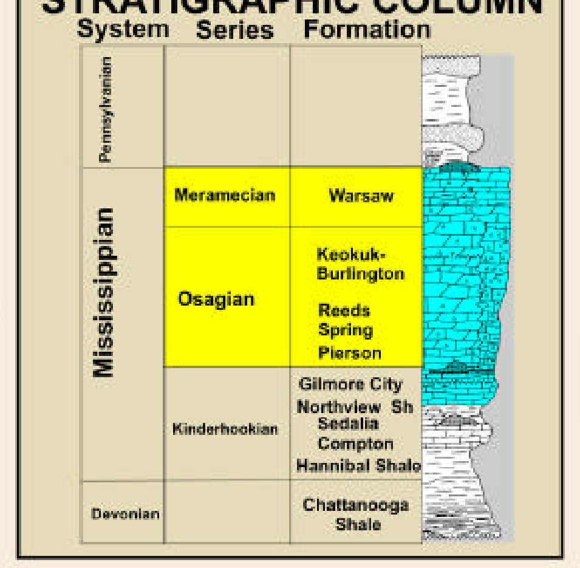
Geologic Setting

The fields used in the study lie in Ness and Hodgeman Counties, Kansas which are located on the upper shelf of the Hugoton Embayment of the Anadarko Basin. The fields are situated on the southwest flank of the Central Kansas Uplift, a structural high during Mississippian time that was accentuated in post-Mississippian time. Mississippian units get progressively older as strata are traced onto the Central Kansas Uplift. The Schaben Field sits on the western edge of the Osagian subcrop and the Ness City and Bindley Fields are located in the center of the Warsaw subrop beneath the sub-Pennsylvanian unconformity. Strata in the fields represent shelf carbonates deposited on a gentle south-southwest sloping ramp. The transition from shelf carbonates to basin facies in Osage strata occurred some 15-20 km to the south of the Schaben Field area as mapped by Selk (1968). Post-depositional regional uplift, subaerial exposure and differential erosion of the ramp strata at the pre-Pennsylvanian unconformity resulted in paleotopographic highs (buried hills). These structural highs have been the targets of exploration and production efforts. The majority of Mississippian production in Kansas occurs at or near the top of the Mississippian section just below the sub-Pennsylvanian unconformity. Field locations can also be correlated in some areas with basement lineaments.





STRATIGRAPHIC COLUMN

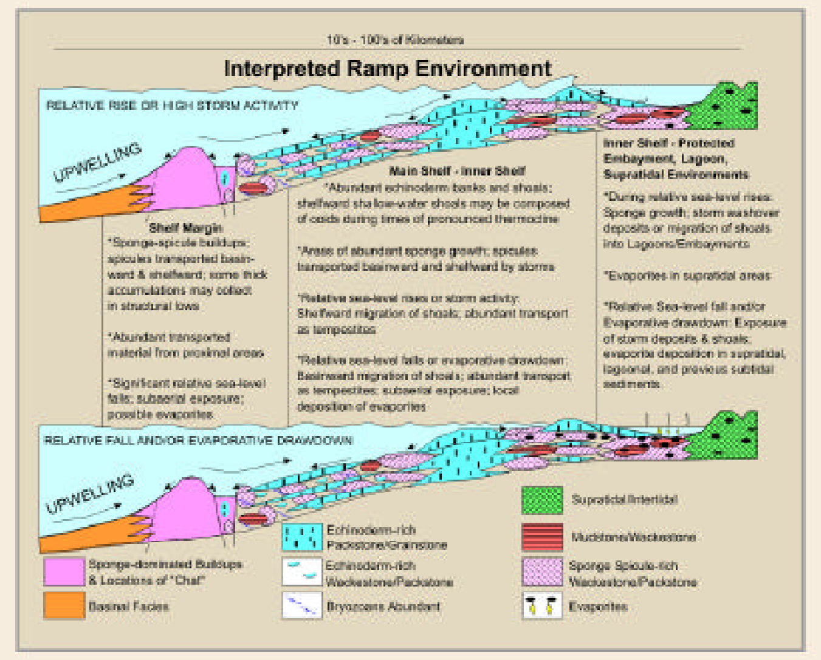


Interpreted Regional Depositional Setting and Controls

Recent studies place the Kansas study area during Osagean-Meramecian time in a subtropical-tropical location, at about 20 degrees S.

A number of biotic and non-biotic associations indicate co-existence of warm and colder water. Presence of evaporites indicates arid conditions. However, the dominance of a heterozoan association (light-independent organisms such as echinoderms, siliceous sponge spicules, bryozoans) and the lack of a photozoan association (few light dependent organisms/skeletons, rare ooids and peloids) points to nutrient-rich cool water conditions.

Based on the subtropical-tropical setting and regional paleogeography, ramp characteristics during Osagean-Meramecian deposition are interpreted to result from upwelling of nutrient-rich colder waters from the Ouachita basin up onto the shelf.



Depositional Facies

FACIES DESCRIPTIONS

Sponge Spicule-rich Wacke-Packstone (SWP):

*Dark to light gray, olive green, tan, or brown
*Mottled from burrowing, wispy to wavy horizontal laminated
*Sponge spicules (mostly monaxon) and their molds are the dominant, and commonly exclusive, grain type
*Rare echinoderm, bryozoan, gastropod, and peloid grains
*Moldic, intercrystalline, and vuggy porosity is common
*Extensively dolomitized (v.f. crystalline or finer; 20 μm - <100 μm)
*Commonly contains silica replaced evaporite crystals, nodules or coalesced nodules that form layers
*Silica variably replaces matrix and grains and locally contains matrix, moldic, and vuggy porosity

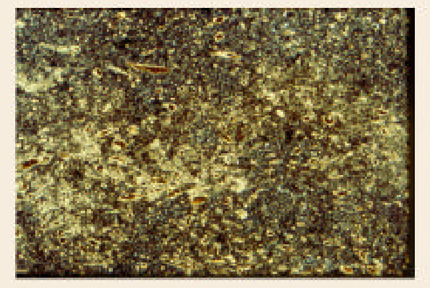
Mudstone-Wackestone (MW):

*Similar to SWP facies except identifiable skeletal grains or molds are rare
*Typically tight; local moldic, intercrystalline, and vuggy porosity

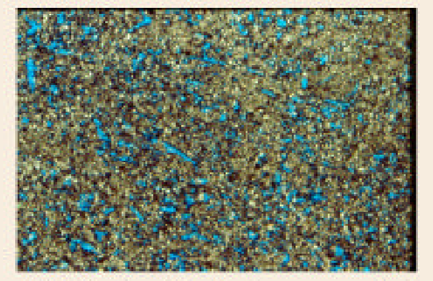
Echinoderm Wacke-Pack-Grainstone (EWPG):

*Tan to dark brown
*Typically wispy laminated or mottled texture
*Horizontal laminations and low-angle cross laminations locally
*Local fine-grained/coarser-grained layer interbedding and normal grading
*Echinoderm fragments typically dominant; locally abundant sponge spicules, bryozoan fragments, brachiopods, coral fragments, gastropods, ostracods, ooids, peloids, grapestone, calcispheres, oncolites, and unidentifiable skeletals
*Extensively dolomitized. Mostly very finely crystalline (< ~50 μm; locally > 150 μm)
*Where dolomitic, grains are typically preserved as molds
*Moldic, intercrystalline and vuggy porosity
*Common partial or pervasive replacement and cementation by chert, megaquartz and chalcedony; typically tight in these areas
*Where silicified, grains have either been replaced with textures preserved or their molds are filled with silica cement; an isopachous chalcedony cement locally lines primary pores
*Abundant matrix porosity occurs within tripolitic chert areas

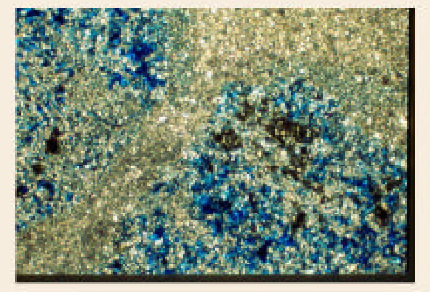
SPONGE SPICULE-RICH WACKESTONE-PACKSTONE (SWP) and MUDSTONE-WACKESTONE (MW) FACIES



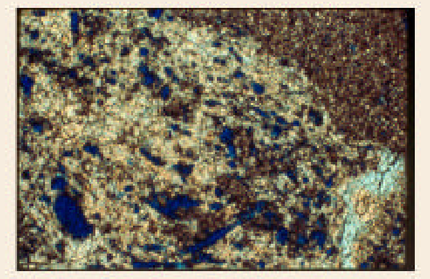
SWP Facies. In this sample the sponge spicules are preserved, much of the matrix is silicified and only a minor amount of intercrystalline porosity is present. Width 5 mm.



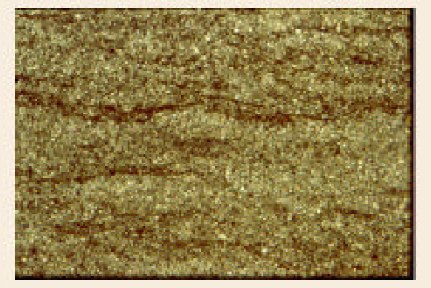
SWP Facies. Abundant sponge spicule moldic and intercrystalline porosity in dolomite matrix which tend to form the most favorable reservoir facies. Width 5 mm.



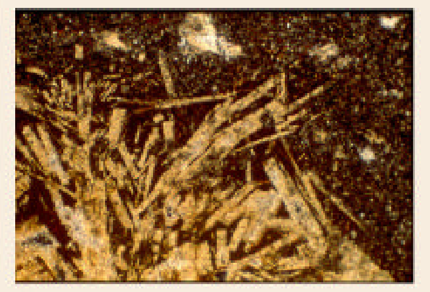
SWP Facies. Burrow mottling created variably tight and porous (blue) areas with abundant moldic and intercrystalline porosity. Width 5 mm.



SWP facies. Sponge spicules have been dissolved leaving molds (dark blue areas) and the surrounding matrix has been mostly replaced by chert. The upper right corner was not replaced by silica and is dolomitic. Width 5 mm.

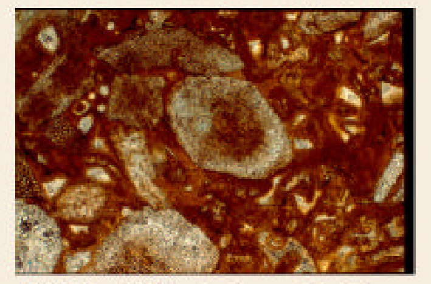


MW Facies. Wispy lamination imparted by clay and horsetail stylolites. This facies is typically tight. Width 5 mm.

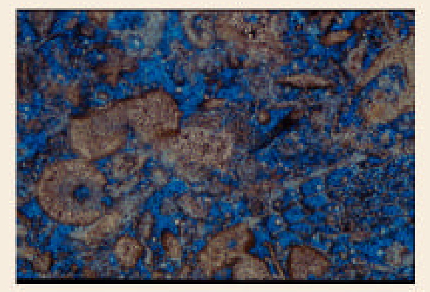


Silica-replaced bladed and radiating bladed crystal textures of original evaporite (anhydrite/gypsum) minerals in SWP facies. This sample exhibits displacive growth of crystals and formation of nodules in dolomitic sediment. Preservation of these fabrics suggests early replacement by silica prior to any significant compaction. Width 5 mm.

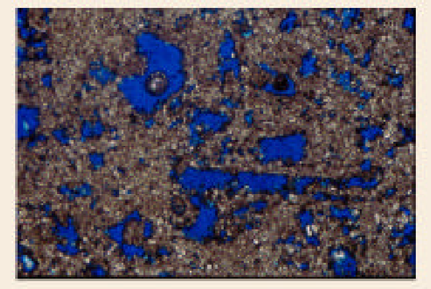
ECHINODERM WACKE-PACK-GRAINSTONE (EWPG) FACIES



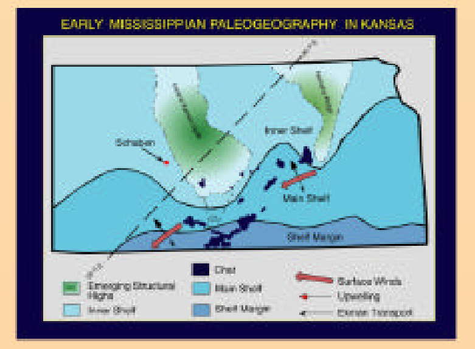
Silicified EWPG Facies. Packstone-grainstone texture has largely been preserved. Echinoderm fragments with textures preserved or molds filled by cement predominate with some identifiable sponge spicule molds filled with cement. Note chalcedony cement (brown) lines primary pores followed by later pore-filling clear megaquartz cement. Width 5 mm.



Silicified EWPG Facies. Skeletal grains, inluding echinoderm, bryozoan, and other unidentifiable grains, have been preserved by silica replacement whereas surrounding matrix has been dissolved leaving abundant interparticle, vuggy, and some intercrystalline porosity (tripolitic texture). Width 5 mm.

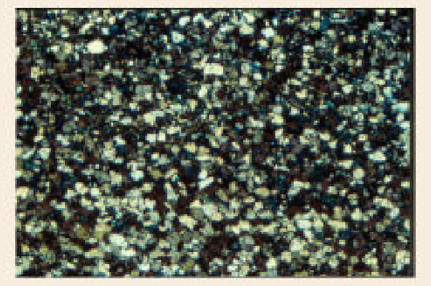


EWPG Facies. Echinoderm fragments and other skeletal fragments, including sponge spicules, have been dissolved leaving abundant moldic porosity (blue areas) in relatively tight dolomitic matrix. Width 5 mm.

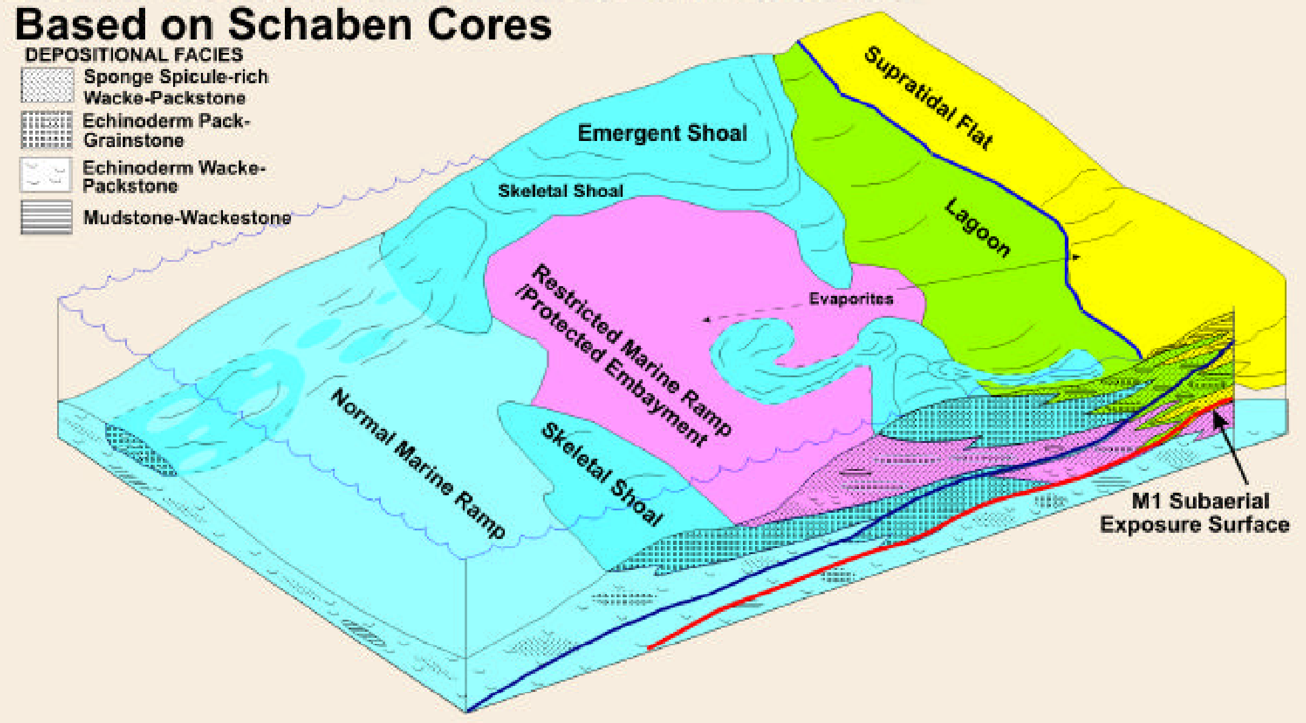


SHALE and SILTSTONE FACIES

Shale and siltstone layers are locally present, typically interbedded with SWP or MW facies. Much of this material is likely related to post-depositional fill, but some layers appear to be associated with deposition during Osagian time. This sample contains mostly angular-subround silt-very fine sand-size quartz grains with minor clay. Width 5 mm. Crossed nicols.



Interpreted Main-Inner Shelf Environments Based on Schaben Cores



Schaben Deposition

The abundance of EWPG facies with other diverse fauna, abundance of burrowing organisms and only rare occurrence of evaporites in the M0 unit suggest deposition in relatively normal to somewhat restricted marine environments.

The abundance of SWP and MW facies, relative rarity of EWPG, and abundance of evaporites in M1 and units above suggest deposition in restricted, evaporitive ramp, lagoon or supratidal environments. Burrow mottling indicates conditions sufficient to support organisms that reworked the sediments. Evaporite characteristics (radiating blades, isolated coalesced nodules, and coalesced vertically elongate nodule layers) indicate formation in a supratidal to shallow subaqueous setting at or just below the sediment water interface. Local fenestral fabric indicates at least intermittent subaerial exposure.

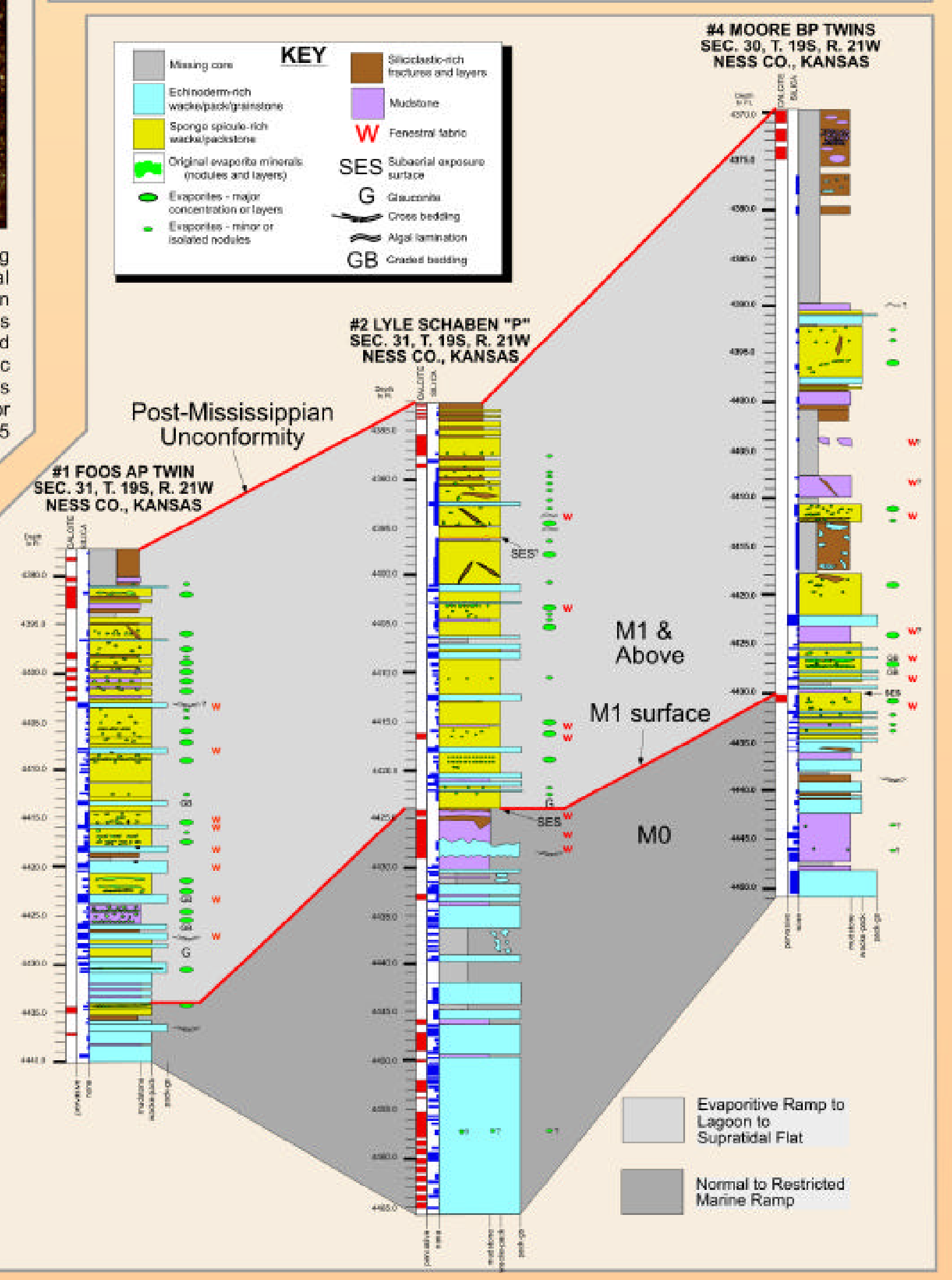
The change between the M0 unit and the M1 unit is marked by a subaerial exposure surface. This surface and the strata immediately below for several meters show significant alteration. A coarse calcite cement and replacive poikilotopic calcite is associated with the M1 surface and occurs variably throughout strata below this surface to the bottom of the cores. A similar calcite cement and calcite replacement in the upper five feet of the cores is presumably a separate event related to post-Mississippian subaerial exposure.

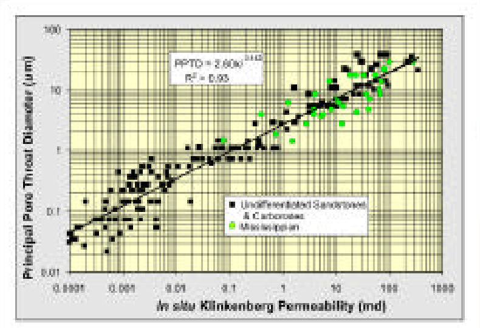
Moldic Porosity and Petrophysics

- Early dissolution of grains and dolomitization created moldic, intercrystalline and vuggy porosity important for favorable reservoir conditions.
- Very finely crystalline (<10-50 μm) dolomite is characteristic of early reflux or mixing zone dolomitization. The predominance of original evaporites in M1 strata is supportive of a reflux mechanism.
- Lithofacies and early diagenesis are the major controls on the nature and distribution of reservoir properties despite overprinting by sub-Pennsylvanian subaerial exposure and burial processes.
- Despite complex diagenetic overprinting, core plug petrophysical data (porosity-ϕ; permeability-k; pore size; capillary pressure properties, including "irreducible" water saturation-Swi) in the different fields show similar, unique trends that are directly linked to depositional lithofacies.
- Increasing moldic content, and associated increasing ϕ, increase k at a lower rate than overall k-ϕ trend indicating matrix properties dominate control of flow in these rocks.
- High sponge-spicule mold content in Chat rocks is associated with proximity to exposure surface, similar to L-KC.
- High spong-spicule mold content in Chat is associated with very high Archie cementation exponents consistent with high micro-vug content but electical current flow dominated by matrix pores. Knowing these values is critical to quantitative wireline log interpretation.

Events Important to Reservoir Properties in the Schaben Field

- Burrow mottling created networks for diagenetic fluids rich in silica _ resulted in variable porous and tight areas
- Early dolomitization and dissolution of grains created moldic, intercrystalline and vuggy porosity
- Early silica replacement and cementation tends to result in relatively tight and impermeable layers in echinoderm_rich facies
- Some silicified areas contain abundant microcrystalline porosity (tripolitic chert)
- Silica replacement and cementation in mudstones and sponge_rich facies is variable; more moldic and vuggy porosity is present, especially where evaporites were dissolved or replaced
- Silica replacement partially or totally replaces matrix and grains, or replaces the dolomite matrix and leaves spicules as molds
- Several generations of fracturing, brecciation, cementation and sediment fills create complex fabrics that variably enhanced or destroyed reservoir characteristics
- Early differential compaction resulted in brittle fracturing of silicified areas and soft_sediment deformation of surrounding matrix imparting a fracture and breccia fabric
- Internal subaerial exposure event resulted in coarse calcite replacement and cementation of strata in lower portions of cores (MO strata) _ important in occluding porosity in much of the echinoderm_rich facies
- Post_Mississippian subaerial exposure, burial compaction and structural uplift resulted in brittle fracturing and brecciation of all facies and previous diagenetic

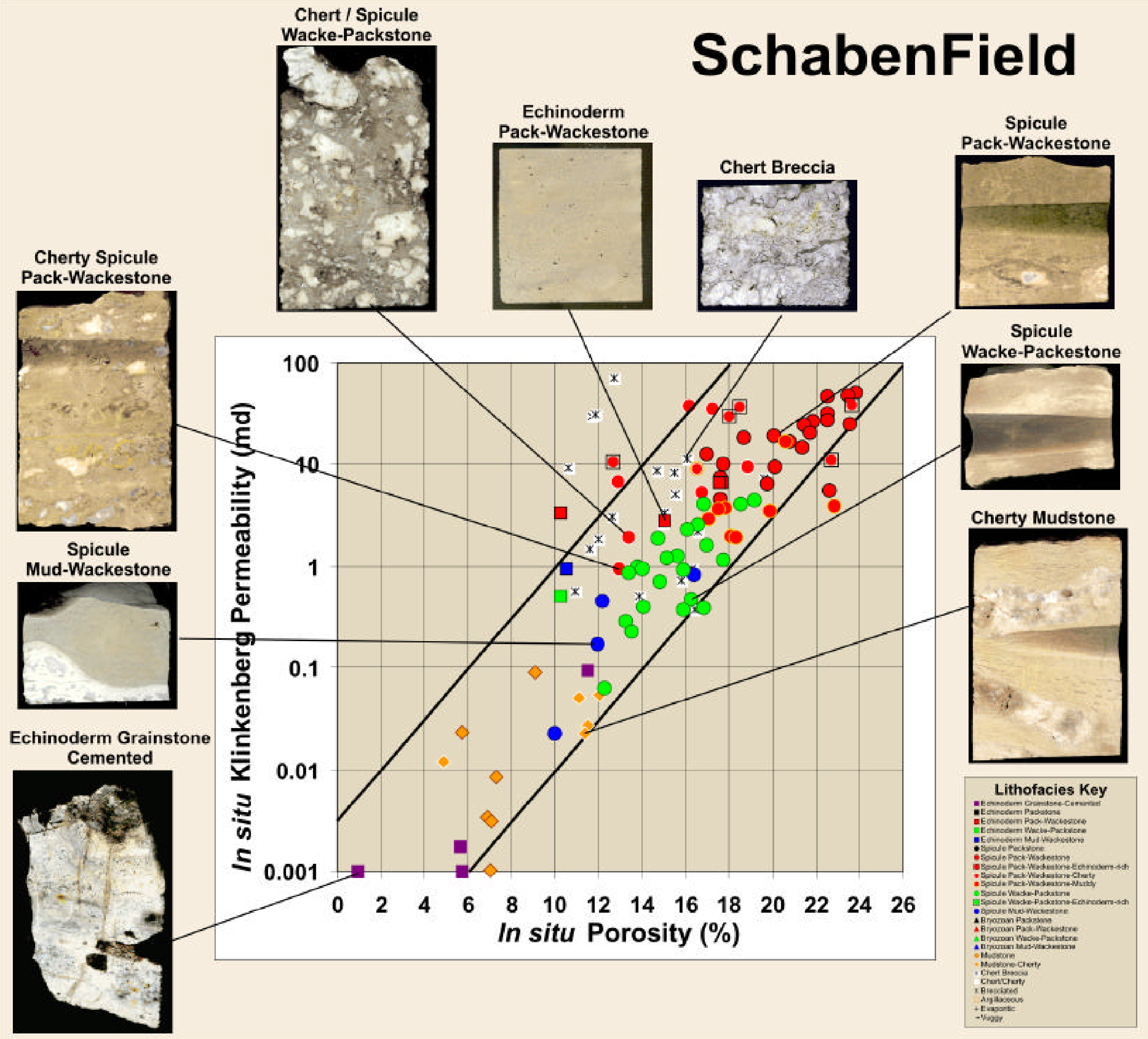




Permeability and Pore Throats

Though permeability is shown correlated with porosity, variables that control permeability in Mississippian rocks include pore throat size and distribution, grain size distribution, moldic pore size and packing, and moldic pore connectivity. Porosity is only one of the variables controlling permeability and bivariate correlation therefore relies on the correlation between porosity and the other controlling variables. A crossplot of permeability and principal pore throat diameter (PPTD) illustrates the control PPTD exerts on permeability.

SchabenField



Lithofacies, Permeability, Porosity

Lithofacies and early diagenesis are major controls on permeability (*k*) and porosity (ϕ) despite complex diagenetic overprinting by sub-Pennsylvanian subaerial exposure and burial processes.

- *k* and ϕ decrease significantly and continuously with decreasing grain/mold size from packstone to mudstone (a trend exhibited by many other carbonates) and from echinoderm-rich to spicule-rich facies
- An exception is the echinoderm grainstone facies which is silica cemented and exhibits very low *k* and ϕ

The permeability-porosity trend for all lithofacies are approximately bounded within two orders of magnitude by trendlines defined by:

$$\log k_{in\ situ} = 0.25\ \phi_{in\ situ} - 2.5$$

$$\log k_{in\ situ} = 0.25\ \phi_{in\ situ} - 4.5$$

- Between these bounding trends each lithofacies exhibits a generally unique range of *k* and ϕ which together define a continuous trend, with *k* decreasing with decreasing grain/mold size for any given porosity. Each individual lithofacies exhibits a unique sub-parallel trend to the general trend. Statistically the general trend is dominated by the large number of spicule-rich samples and is strongly influenced by mudstone and cemented echinoderm grainstone properties:

$$\log k_{in\ situ}\ (md) = 0.24\ \phi_{in\ situ}(\%) - 3.78$$

Subtrends for clusters of facies or individual facies may also be defined and are significantly more accurate with standard error of prediction of permeability decreasing with increasing selectivity of lithofacies characteristics. Standard error for a specific lithofacies is generally less than a factor of 3. Linear regression trends for spicule- and echinoderm-rich facies are:

$\log k_{in\ situ}\ (md) = 0.19\ \phi_{in\ situ}(\%) - 2.88$ [Spicule-rich]

$\log k_{in\ situ}\ (md) = 0.12\ \phi_{in\ situ}(\%) - 1.04$ [Echinoderm-rich]

Other Mississippian fields', including Bindley and Ness City field, permeability (*k*)-porosity (ϕ) trends are similar to those of the Schaben for similar lithofacies. One significant difference is that calcite cementation of spicule-rich pack-wackestones significantly occludes porosity and reduces permeability. The bounding trends can be considered to define the range of porosity for a given lithofacies trend. The low k-ϕ slopes of individual lithofacies trends indicate that increasing porosity does not significantly increase permeability compared with the influence of grain size. This is consistent with porosity development through dissolution of pores surrounded by permeability-controlling matrix.

Trends for echinoderm-rich and spicule-rich facies are significantly different:

$\log k_{in\ situ}\ (md) = 0.157\ \phi_{in\ situ}(\%) - 1.87$ [Echinoderm-Bindley Field]

$\log k_{in\ situ}\ (md) = 0.147\ \phi_{in\ situ}(\%) - 1.50$ [Echinoderm-Ness City Field]

$\log k_{in\ situ}\ (md) = 0.230\ \phi_{in\ situ}(\%) - 4.04$ [Spicule-Bindley Field]

$\log k_{in\ situ}\ (md) = 0.170\ \phi_{in\ situ}(\%) - 2.76$ [Spicule-Ness City Field]

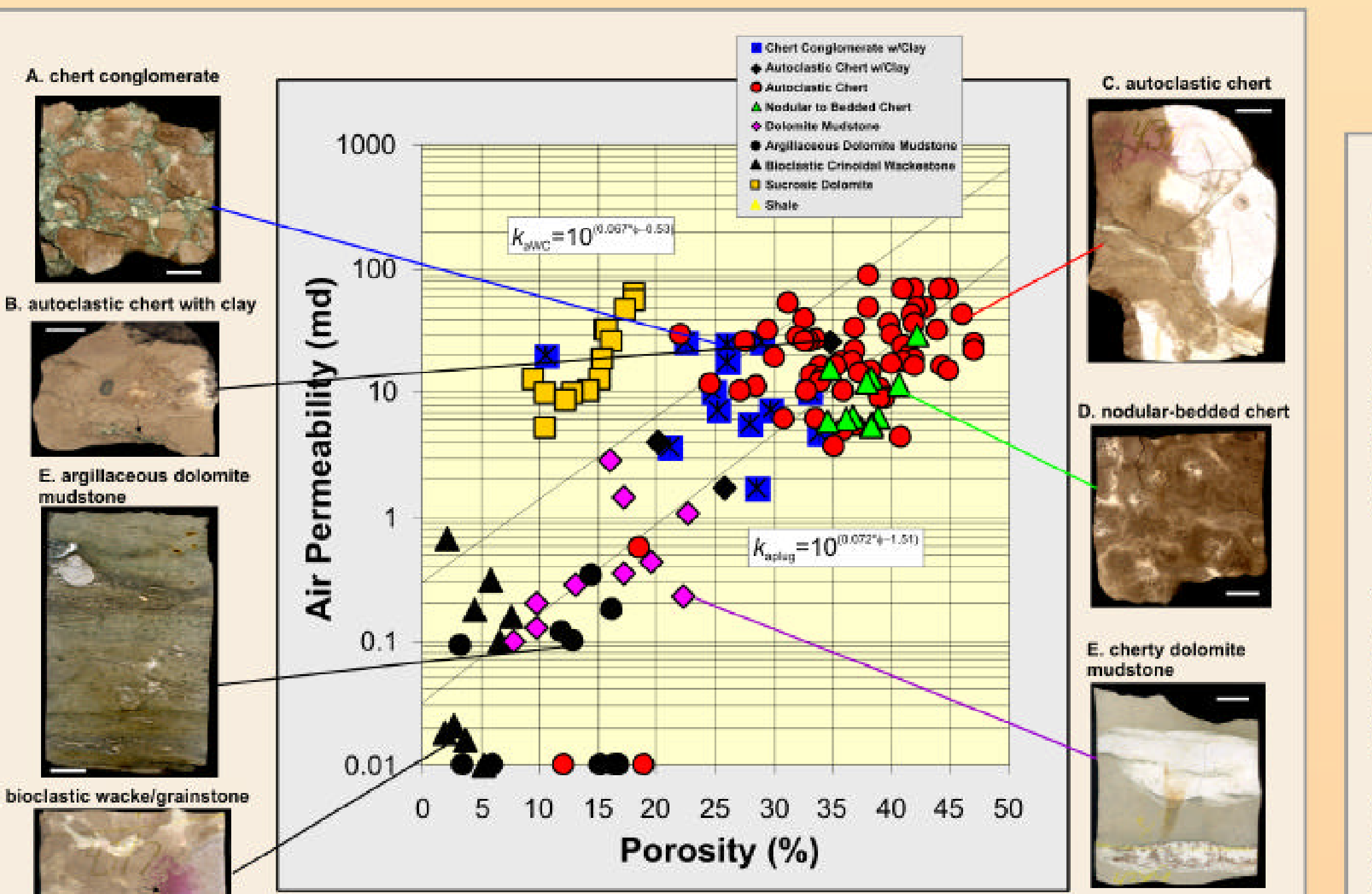
Standard error of prediction of k ranges from a factor of 2 to 4.8. For all fields the lowest k-ϕ slope and highest predictive accuracy is obtained for a single lithofacies. With successive addition of more lithofacies into a statistical analysis the resulting trend-line slope approaches that of the bounding trends. The intercept varies as a function of the nature of the population grain/mold size.

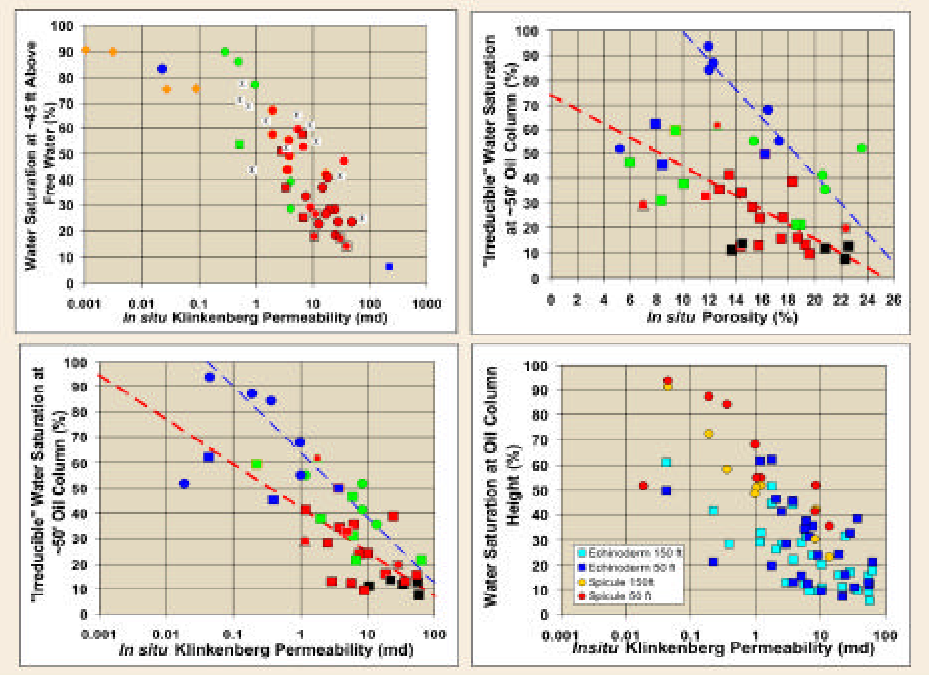
Mississippi "Chat" Porosity and Permeability

Figure illustrates the log-linear relationship between routine air permeability (k_a) and routine porosity (ϕ_a). Each of the Chat lithofacies generally occupy a unique porosity-permeability region. Porosity in the Chat matrix is approximately 15±5%. Porosities grater than ~20% are largely due to sponge spicule mold content. Note that with almost a doubling of porosity (e.g. 20 to 40%) permeability increases are less than a factor of ~5.

Autoclastic cherts exhibit the maximum porosity and permeability with porosities ranging from 25-50% and permeabilities >5 md. Permeability variance within this lithofacies at any given porosity can be attributed primarily to: 1) sponge-spicule mold content, 2) small vug content, believed to result from both sponge-spicule dissolution and dissolution of microporous chert, 3) enhanced porosity development at clast boundaries, and 4) circum- and intraclast microfracturing.

At any given porosity the nodular to bedded chert facies exhibits permeabilities approximately a factor of 2 less than the autoclastic chert facies. The lower permeability of this facies appears to be related to lower vug content, less porosity development at clast boundaries, and an absence of circum-clast microfracturing. The cherty dolomite mudstones, and argillaceous dolomite mudstones can exhibit porosities up to 22% but due to the small grain and pore size, display routine air permeabilities of less than 1md. The development of sucrosic dolomites at Bates Field does not result in a significant increase in porosity above that found in dolomite mudstones, but results in permeabilities that are two orders of magnitude greater.





Capillary Pressure

Capillary pressure properties of Mississippian carbonates differ between lithofacies. Structural closure in many Mississippian Kansas fields is less than 60 feet limiting oil column heights thereby necessitating an understanding of the exact capillary pressure relationships.

Air-brine capillary pressure measurements indicate that water saturations at 45-50 ft (Sw45,Sw50) above free water increase with decreasing porosity and permeability (Figures). Because of the close correlation between lithofacies and permeability-porosity, Sw also increase with decreasing grain/mold size from packstone to mudstone. Sw45 in Schaben can be predicted within ± 14% (saturation %) using: Sw45(%) = -20*log *kinsitu* + 61.

The echinoderm-rich facies in Ness Field, S_{w50} is correlated with ϕ and ***k*** but exhibits very different relations between the spicule-rich and the echinoderm-rich facies:

Sw50(%) = -3.21 ϕ*insitu* + 87.6	All (SE=19%)
Sw50(%) = -2.95 ϕ*insitu* + 74.5	Echinoderm (SE=9.3)
Sw50(%) = -5.76 ϕ*insitu* + 156.4	Spicule (SE=6.7)
Sw50(%) = -17.5 $\log_{10}$ *kinsitu* + 42.1	Echinoderm (SE=8.7)
Sw50(%) = -25.5 $\log_{10}$ *kinsitu* + 63.8	Spicule (SE=6.6)

Sw-ϕ and Sw-*k* crossplots reveal how subtle changes in lithology can affect saturations. Increase in mud and spicule content elevates *Sw* in the echinoderm pack-wackestones. Increase in dense chert content decreases porosity without changing *Sw*. Changes in *Sw* between 50 and 150 feet in oil column height are small for spicule-rich facies indicating they are at "irreducible" *Sw* at 50 feet. Echinoderm-rich facies have low saturations, additional capillary pressure continues to decrease *Sw*.

Archie Cementation Exponents

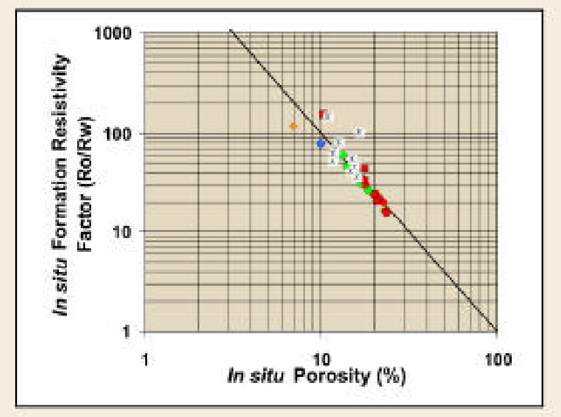
Dolomites- Traditional wireline log calculation of saturations use the Archie equation and cementation (m) and saturation exponent (n) values of 2. Formation resistivity factors (Ro/Rw) measured at Rw=0.045 ohm-m (Figure) indicate that the Archie cementation exponent (assuming an Archie intercept of 1.0) averages m=1.97+0.09 for all facies. Echinoderm-rich facies can exhibit cementation exponents between 2.0 and 2.1. Vuggy cherts can exhibit cementation exponents between 2.1 and 2.2.

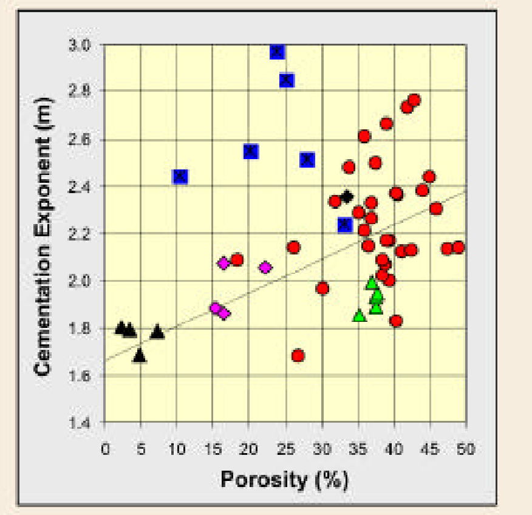
Chat - Chert conglomerates exhibit very high cementation exponent values with m_{avg}=2.59±0.27. This is consistent with the high moldic and vuggy porosity in the clasts of this lithofacies. Autoclastic cherts exhibit a range in cementation exponent from m=1.68 to 2.76. Nodular to bedded cherts exhibit low cementation exponents ranging from m=1.86 to 1.99 with. Similarly, the dolomite mudstones and bioclastic wacke/ grainstones exhibit m_{avg} = 1.97±0.11 and m_{avg} = 1.77±0.05, respectively.

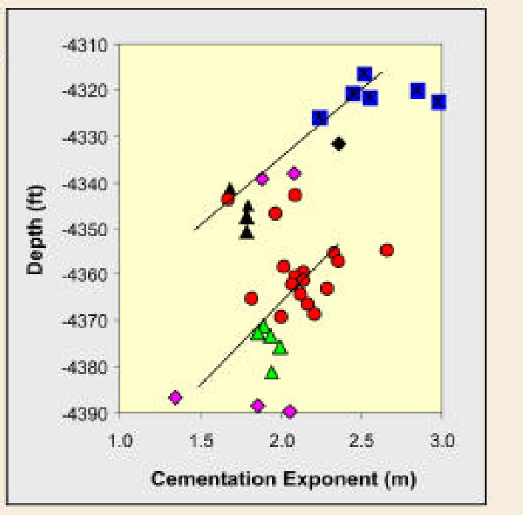
Variance in the cementation exponent of the autoclastic cherts can be explained partially by sponge-spicule mold content and vugginess at the plug scale but these are in turn related to position within the depositional cycle and/or position relative to the exposure surface or a perched water table.

Figure illustrates the relationship of cementation exponent with depth and lithofacies in the Tjaden 1-A WIW. The pattern in cementation exponent shown in Figure can be related to both deposition and exposure. Cementation exponents increase with increasing sponge-spicule mold content and vugginess. The basal interval exhibits a slight increase in sponge-spicule mold content upward in the section, terminating at the base of the overlying bioclastic wacke/grainstone. Autoclastic cherts interbedded with the bioclastic wacke/grainstones exhibit lower sponge-spicule mold content. As such, the cementation exponent-depth pattern may be related to deposition and sponge-spicule content.

Assuming the encrinite beds were lithified at the surface, they could be anticipated to act as aquitards and would be capable of forming the base of a perched water table. Within and immediately above a perched water table dissolution could be anticipated to be less than in the overlying vadose. With decreased vugginess in this wet interval, cementation exponents would be lower and would increase with proximity to the surface. Below the perched water table a saturation profile would also be established and the degree of vugginess and brecciation would decrease with increasing depth along with cementation exponents.







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