The Role of Moldic Porosity in Paleozoic Kansas Reservoirs and the Association of Original Depositional Facies and Early Diagenesis With Reservoir Properties

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http://www.kgs.ku.edu/PRS/publication/2003/ofr2003-32/index.html

Purpose

The multiple goals of this work include:

- To better understand the nature and distribution of moldic porosity in the shallow shelf carbonate systems.
- To understand the role of original depositional facies and early diagenesis on subsequent rock geologic and petrophysical properties.
- To enhance modeling relating moldic porosity, and more broadly pore architecture, to petrophysical properties.
- To compare and contrast the effects of different kinds of moldic porosity.
- To improve prediction of reservoir quality in these systems (or better define the limits of prediction).
- To improve reservoir properties models for reservoir evaluation, characterization, and simulation.

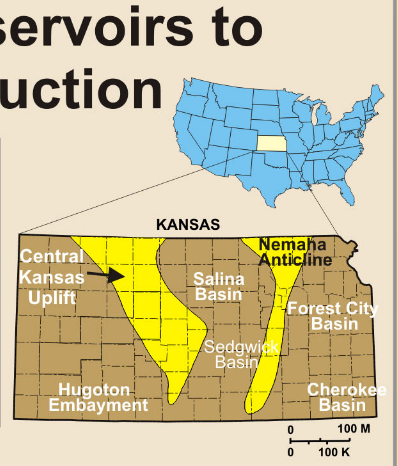
Results and Implications

- Core examples from Upper Cambrian- Lower Ordovician Arbuckle, Mississippian & Pennsylvanian shallow-shelf carbonates in Kansas indicate that moldic porosity is abundant in each system, & reservoir properties, including porosity/permeability, are strongly correlated with original depositional facies.
- Despite the nature of the molds varying through time, reflecting changes in primary carbonate grains, reservoir quality is similar in each system & increases from mudstone through grainstone.
- Despite significant diagenetic overprinting in many of the rocks, & even some complete reversal of original solid & pore space, final moldic textures exhibit petrophysical-lithofacies trends that parallel those of original primary porosity carbonates.
- Correlation of permeability and pore throat size in moldic-porosity rocks is similar to that of intergranular- porosity rocks. This can be interpreted to indicate that despite,in some rocks, very high moldic porosity, permeability is primarily controlled by matrix properties.
- Moldic rocks play an enormous role in Kansas oil and gas production. The diverse nature of the matrix, molds and mold content with continued study is providing better understanding of the role of moldic porosity and of pore architecture to fluid flow in porous media.

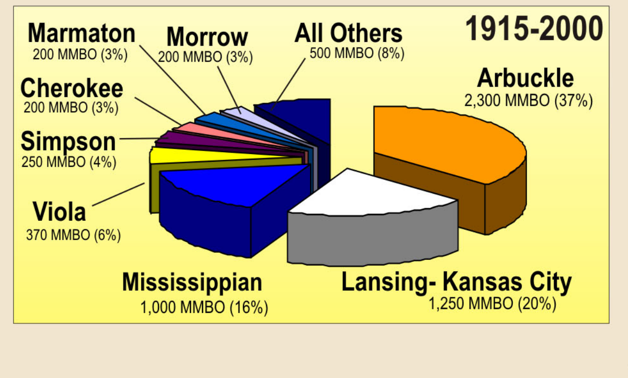
Panel 1

Presented at American Association of Petroleum Geologists Annual Meeting, May 11-14, Salt Lake City, Utah.

Importance of Moldic Reservoirs to Kansas Oil and Gas Production



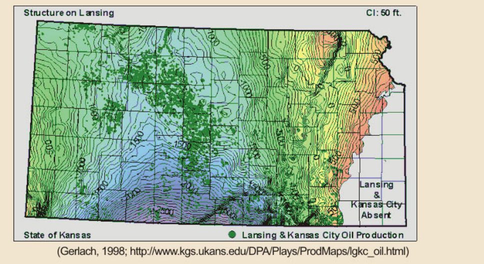
Kansas reservoirs have produced nearly 6.3 billion barrels of oil (BBO) to date, with a significant majority of the past production coming from reservoirs in proximity to the Central Kansas Uplift (CKU). Of the 6.3 BBO, 73% (4.5 BBO) has been produced from Arbuckle Gp, Mississippian, and Lansing-Kansas City Gp reservoirs that are predominantly moldic porosity systems.



Arbuckle Gp reservoirs account for 37% of all production (2.4 BBO) but are declining in production and presently represent 20% of annual production. With declining Arbuckle Group production, Mississippian reservoirs account for 33% of the total state production over the last decade and are increasing in importance. Lansing-Kansas City reservoirs represent 16% of current production.

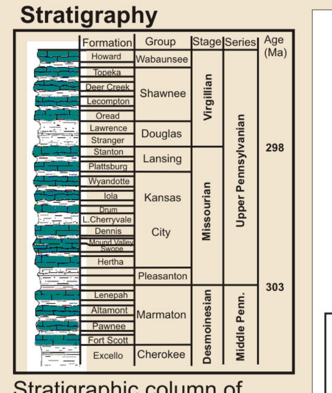
General Lansing-Kansas City Geologic Setting

Oolitic packstones and grainstones are the most prolific reservoir lithofacies for the Pennsylvanian Lansing-Kansas City. Oolite shoal facies owe their wide distribution geographically within Kansas and stratigraphically within the Upper Pennsylvanian to bathymetry (very low-angle ramp) and episodic sea level changes. The broad Kansas shallow shelf and oscillating sea level resulted in lateral migration of oolite shoal conducive environments and successive creation of stacked oolite cyclothems (figure).

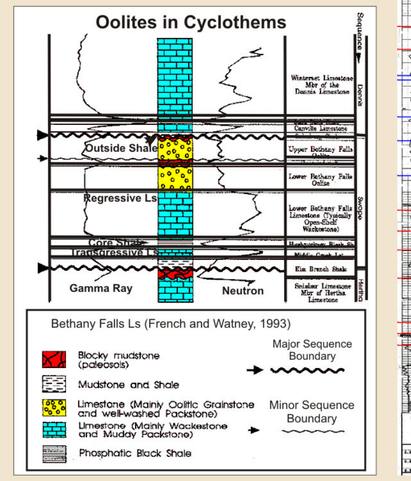


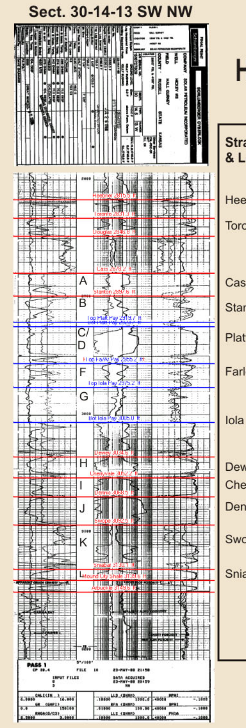
(Gerlach, 1998; http://www.kgs.ukans.edu/DPA/Plays/ProdMaps/lgkc_oil.html)

Stratigraphy



Stratigraphic column of Upper Middle Desmoinesian and Upper Missourian Strata.

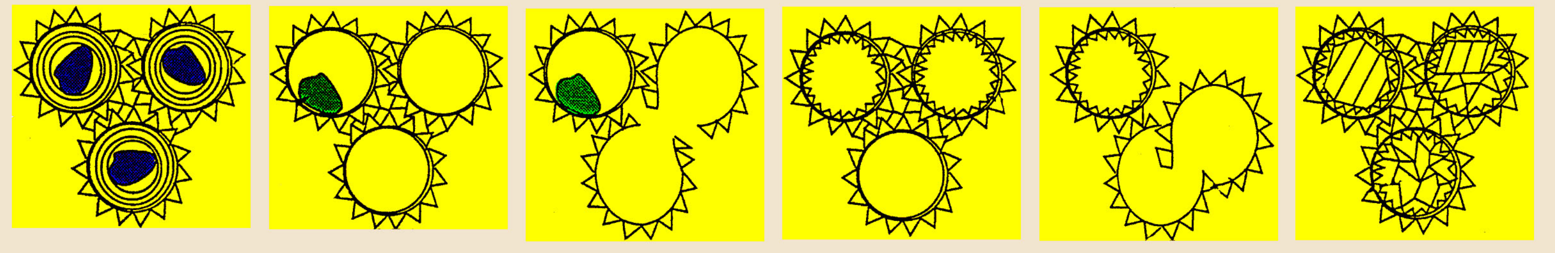




Type Log Hall-Gurney Field

Stratigraphic Formation & Letter Nomenclature

Heebner Shale
Toronto Limestone
Cass Limestone (A)
Stanton Limestone (B)
Plattsburg Limestone (C/D)
Farley/Argentine Ls (F)
Iola Limestone (G)
Dewey Limestone (H)
Cherryvale Formation (I)
Dennis Limestone (J)
Swope Limestone (K)
Sniabar Limestone (L)



Growth of equant calcite spar in isopachous rims on ooid grains - occlusion of porosity | Dissolution of ooids- creation of isolated oomoldic porosity | Continued dissolution of grains and early calcite cement - creation of connected porosity | Growth of equant calcite spar on inner walls of oomolds - decreases connectivity | Slight crushing of some ooids to form connections between pores | Continued growth of carbonate cement, ferroan calcite, and baroque dolomite during burial. Possible complete occlusion of porosity

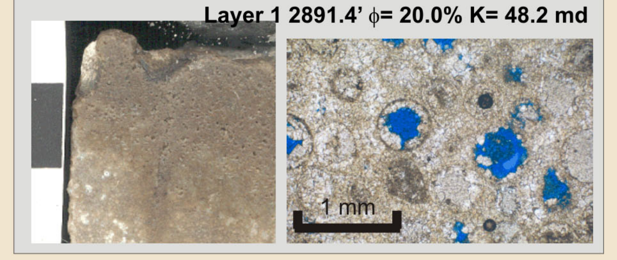
Generalized Paragenetic Sequence →

(after LeBeau, 1997)

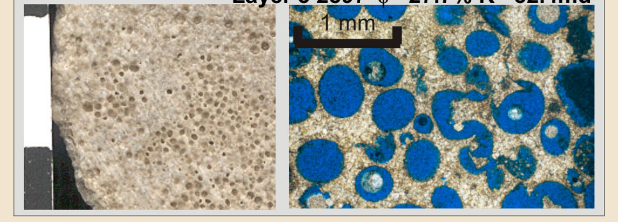
Murfin Drilling #CO2 I-1: 2985-2914 ft

Layer 2 - 2894.2 ϕ=34.1% K =113.9md

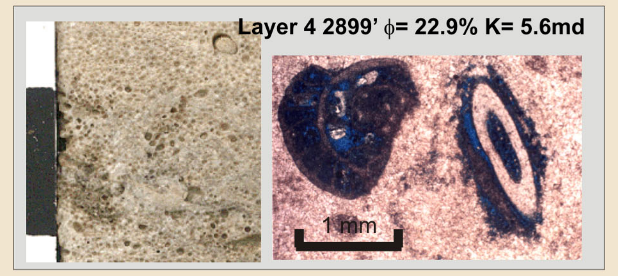
Layer 1 2891.4' ϕ= 20.0% K= 48.2 md



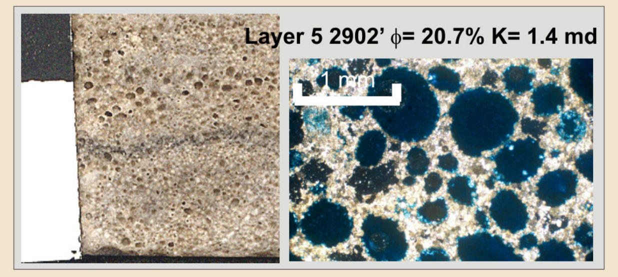
Layer 3 2897' ϕ= 27.7% K= 32.4md



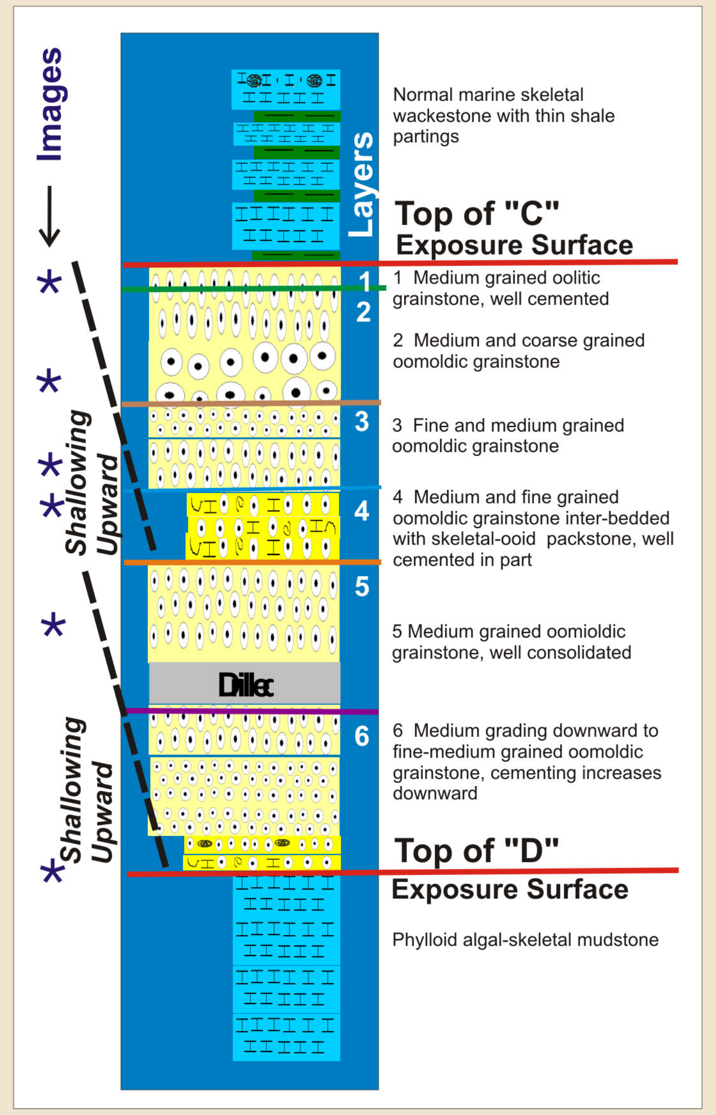
Layer 4 2899' ϕ= 22.9% K= 5.6md



Layer 5 2902' ϕ= 20.7% K= 1.4 md



Layer 6 2903



Normal marine skeletal wackestone with thin shale partings

Top of "C" Exposure Surface

1 Medium grained oolitic grainstone, well cemented

2 Medium and coarse grained oomoldic grainstone

3 Fine and medium grained oomoldic grainstone

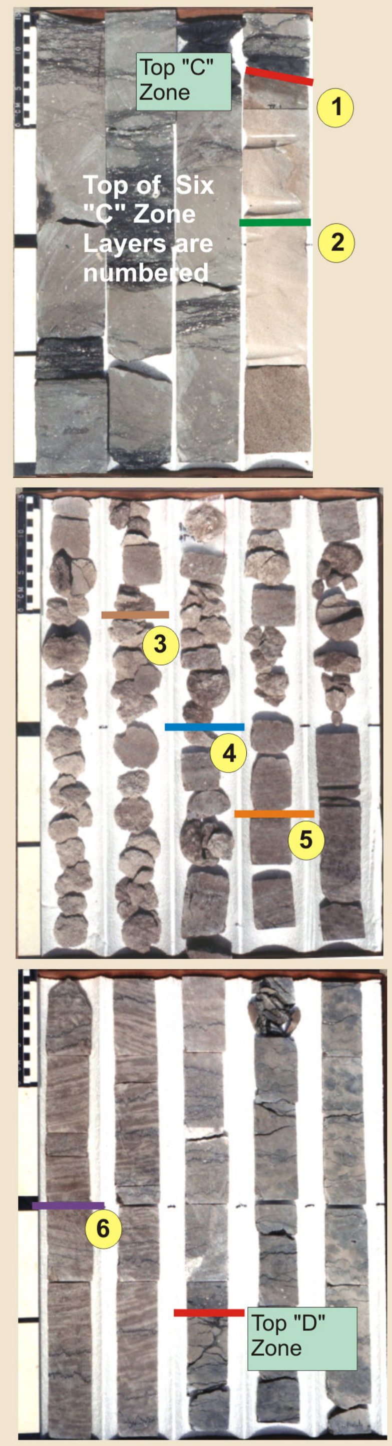
4 Medium and fine grained oomoldic grainstone inter-bedded with skeletal-ooid packstone, well cemented in part

5 Medium grained oomioldic grainstone, well consolidated

6 Medium grading downward to fine-medium grained oomoldic grainstone, cementing increases downward

Top of "D" Exposure Surface

Phylloid algal-skeletal mudstone



Upper Pennsylvanian Lansing-Kansas City Gp

Geology and Architecture

Lansing-Kansas City oolitic reservoirs exhibit geometries and architectures similar to modern oolites. Reservoirs usually contain multiple stacked, or *en echelon* shoals that formed in response to sea level fluctuations. It appears that two such lobes are stacked in the Plattsburg Limestone at the planned CO2 miscible flood site represented by the core. Oomoldic reservoirs formed across the entire Kansas Pennsylvanian ramp, however, thicker, porous and permeable oolite deposits are commonly associated with the flanks or crests of paleostructural highs. These highs, such as that underlying the Hall-Gurney Field, may have influenced the intensity of early diagenesis and may have been responsible for development of good reservoir properties. Grain size variation, location on oolite buildups and interbedded carbonate mud (aquitards) influenced the nature and extent of diagenetic overprinting.

Subaerial exposure and meteoric water percolation led to cementation around the aragonite ooids and often dissolution of the ooids and variable development of matrix and vuggy porosity. Resulting oomoldic grainstones, the principal reservoir lithofacies, underwent variable degrees of early or later fracturing and crushing, providing connection between otherwise isolated oomolds.

Petrophysics and Reservoir Properties

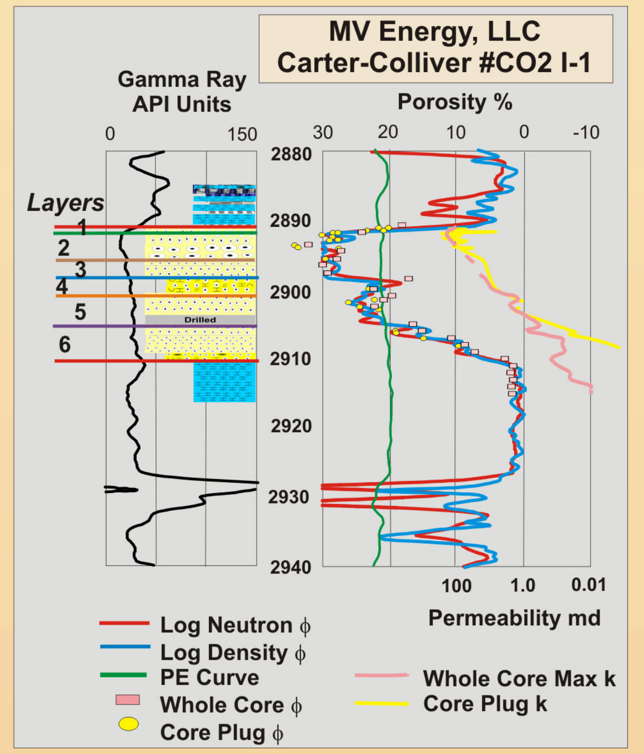
Porosities in these oomoldic limestones range up to 35% and permeabilities range from 0.001-400 md. Permeability is principally controlled by porosity, oomold connectivity, and connection created by matrix crushing and fracturing. Permeability is also influenced by oomold diameter, oomold packing, and matrix properties. Increasing bioclastic constituents within and bounding oolite beds are often associated with increasing mud matrix and decreasing porosity and permeability. Individual wells exhibit porosity-permeability trends with less variance than the overall trend exhibited by L-KC oomoldic limestones.

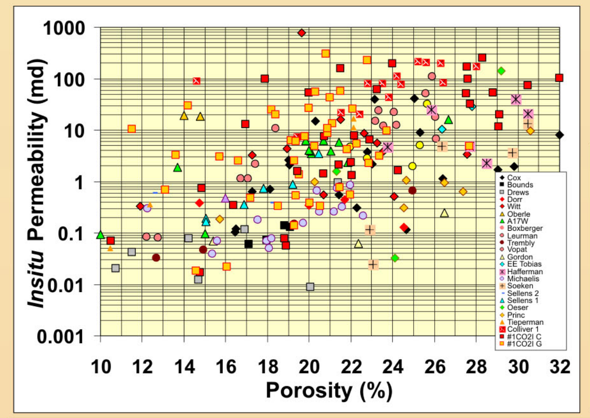
Within the L-KC 'C' zone in the Hall-Gurney field and the CO2 demonstration site, permeability decreases from the top of the bottom of the LKC 'C' interval. Lower permeability with increasing depth in the reservoir interval is attributed to increased dense bioclastic limestone content and decreasing moldic porosity.

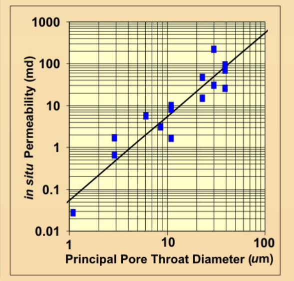
Correlations of “irreducible” water saturations (measured at pressures equivalent to 60-120 feet above free water level) indicate that Swi increases with decreasing permeability following the trend:
logSw50 (%) = 0.22 log k(md)) - 0.43

Lansing-Kansas City oomoldic limestones exhibit a near log-linear trend between wetting phase saturation and oil-brine height above free water level with capillary pressures decreasing with increasing permeability at any given saturation and can be modeled using the relation: $Pc = 10^{(A\ Sw\ +\ B)}$ (ρwater-ρoil).

Residual oil saturation to waterflood (Sorw) is a critical variable for both waterflooding and carbon dioxide miscible flooding since this represents the target resource. Most L-KC waterfloods in Kansas have only involved 1-5 pore volumes (PV) throughput before reaching their economic limit. At 5 pore volumes throughput Sorw averages near 30%. Though sampling is limited, Sorw may increase then decrease with increasing permeability (k).







Permeability and Porosity

Porosity in L-KC oomoldic limestones ranges from 0-35%. Generally rock below 15% porosity are non-reservoir. Permeability (<0.001-400 md) is principally controlled by : **Porosity and Oomold connectivity.**

Other variables that exert influence but are colinear with the above variables include: **Oomold diameter, Oomold packing, Matrix properties, Matrix fracturing.** Although permeability is controlled by and correlates with several of these variables (figure below), multivariate linear regression methods only improve prediction from a factor of 6.9X to 5.4X by inclusion of information concerning connectivity index, as measured on rock pieces.

log k = 0.112 ϕ - 2.48 SE = 7X

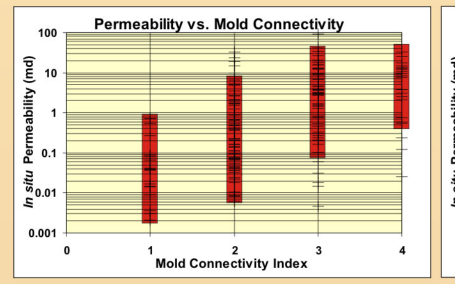
log k = 0.090 ϕ + 0.47 Connectivity Index - 3.21SE=5.5X

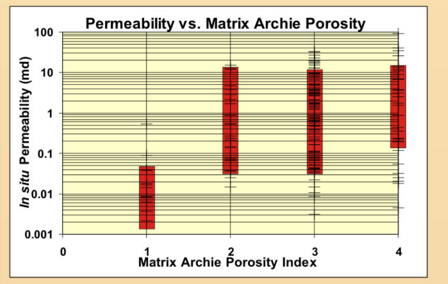
Individual wells generally exhibit k-ϕ trends with less variance than the overall trend.

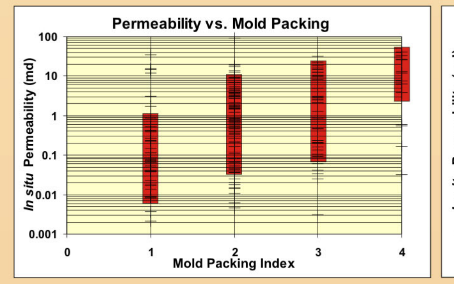
Correlation of Textural Properties with Permeability

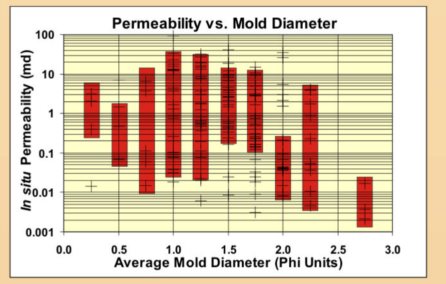
Previous investigation showed the relationship between permeability and rock textural parameters including:

- ***Connectivity Index*** - An index ranging from 1 to 4 representing the degree of connection between oomolds as observed at 10X-20X:
- ***Packing Index*** - An index from 1 to 4 representing the packing density of oomolds:
- ***Size*** - An estimate of the average oomold diameter in phi units
- ***Archie Matrix Porosity Index*** - base on Archie's (1952) second parameter for describing matrix porosity.

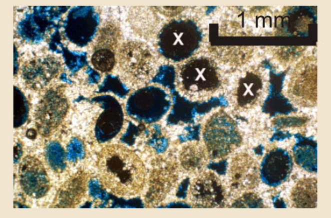




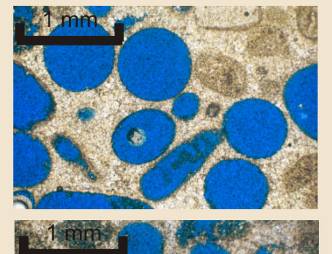




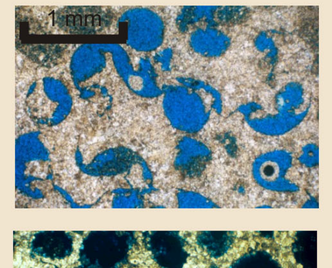
Important Microscopic Textures



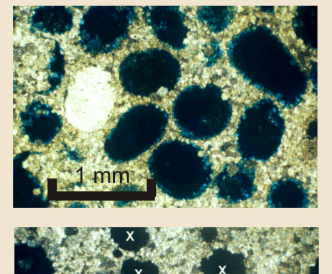
Carter-Colliver #CO2 I-1 2892.8 **ϕ = 28.3% k = 219.6md**
Coarse grained oolitic grainstone with moldic and primary intergranular porosity. Early isopachous rim and miniscus calcite cements with little cement growth into oomolds. Micritized ooid cortices and oolite grains preserved. Isolated oomolds not filled with blue epoxy (X) suggest these pores are not connected. Thin section photomicrograph with crossed polarizers. *(Layer 2)*



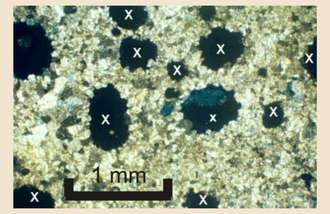
Carter-Colliver #CO2 I-1 2894a **ϕ = 32.0% k = 101.0md**
Coarse grained oolitic grainstone with moldic porosity. Early rim cement followed by pore filling calcite cement that occluded intergranular pores. Notable absence of cement within oomolds. No crushing evident in this view but pore connections are visible in few cases and are likely outside the plane of section. Thin section photomicrograph with plane polarized light. *(Layer 2)*



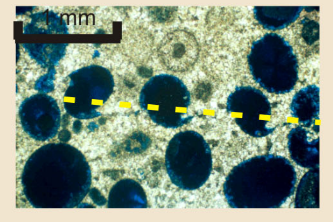
Carter-Colliver #CO2 I-1 2894b **ϕ= 32.0% k = 101.0md**
Coarse grained oolitic grainstone from same interval as above is very similar except extensive crushing and collapse has created well connected pore system. Fine cement shards appear to form geopedal fabric. Thin section photomicrograph with plane polarized light. *(Layer 2)*



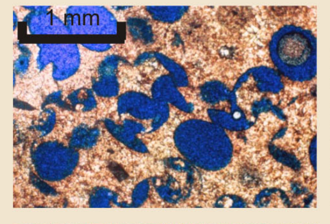
Carter-Colliver #CO2 I-1 2900b **ϕ = 22.9% k = 5.6 md**
Medium-coarse grained oolitic grainstone with moldic porosity. Single crinoid grain. Neomorphosed early rim and pore filling calcite cement that occluded intergranular pores. Some cement growth into oomolds. Oomolds do not appear to be in contact, nor is communication through crushing evident. Thin section photomicrograph with crossed polarizers. *(Layer 4)*



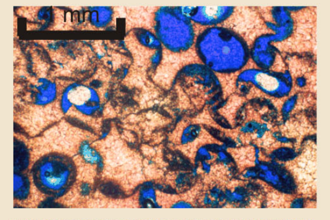
Carter-Colliver #CO2 I-1 2902.5 **ϕ = 20.7% k= 1.4 md**
Medium grained oolitic grainstone with moldic porosity. Heavily neomorphosed early rim and intergranular pore filling calcite cement. Significant cement growth into oomolds reduced moldic porosity. No crushing of oomolds evident. Lack of epoxy impregnation in nearly all oomolds (X) suggests these pores are not connected. Thin section photomicrograph with Nichols crossed. *(Layer 5)*



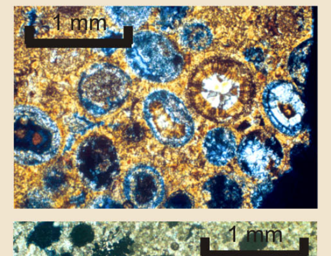
Colliver #2 2892 **ϕ = 29.1% k = 46.7md**
Coarse grained oolitic grainstone with moldic porosity. Early rim cement followed by pore filling calcite cement that occluded intergranular pores. Notable absence of cement within oomolds. Minor crushing of oomolds and slight offset is related to microfracture. Thin section photomicrograph with crossed polarizers. *(Layer2)*



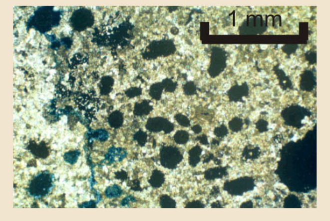
Carter-Colliver #CO2 I-1 2894b **ϕ = 32.0% k = 101.0md**
Coarse grained oolitic grainstone. Extensive crushing of oomolds and collapse of matrix framework resulted in added permeabiltiy. No cement evident after collapse. Thin section photomicrograph with plane polarized light. Alizarin red stain. *(Layer 2)*



Colliver #2 2892 **ϕ = 29.1% k= 46.7md**
Coarse grained oolitic grainstone. Extensive crushing of oomolds and collapse of matrix framework resulted in slightly reduced porosity. No cement after collapse is evident. Thin section photomicrograph with plane polarized light. Alizarin red stain.



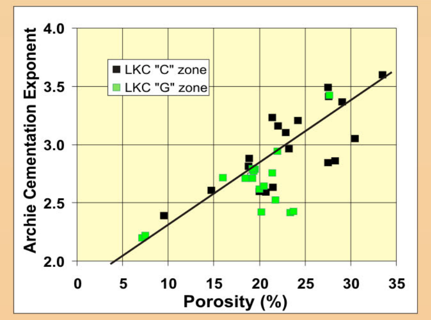
Carter #3 2854-57 **NA well cutting**
Medium-coarse grained oolitic grainstone with early silica replacement. Fabric prior to silicification, early rim and pore filling calcite cement, is well preserved. Thin section photomicrograph with crossed polarizers.

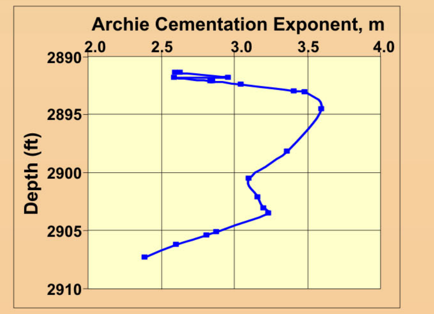


Carter-Colliver #CO2 I-1 2902.5 **ϕ = 20.7% k = 1.4 md**
Fine grained oolitic grainstone with moldic porosity. Heavily neomorphosed early rim. and intergranular pore filling calcite cement. Lack of epoxy impregnation of any pores suggests that very few are connected. No crushing of oomolds evident. Thin section photomicrograph with crossed polarizers. (*Layer 5)*

Archie Cementation Exponent

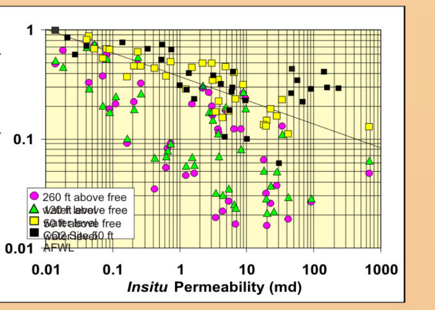
Oomoldic limestones from Kansas and globally exhibit extremely high Archie cementation exponents. This is consistent with the interpretation that the oomoldic pores are similar to micro-vugs. Modified Archie parameters for the Carter-Colliver Lease rocks are: **m=1.36, a=9.59.** Conversely, if m is considered to change with porosity then m can be predicted for the higher porosity rocks using: **m = 0.05****Porosity(%)*** **+ 1.9.** Cementation exponents are near 2.0 in the bioclastic wackestone overlying the ‘C’ zone. Cementation exponents increase into the top of the ‘C’ and then decrease with increasing depth to the base. This is associated with the higher porosity at the top of the ‘C’ zone but is also influenced by pore structure changes associated with the unconformity surface.

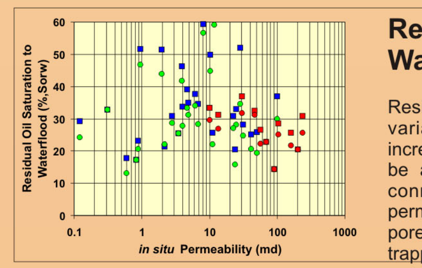




“Irreducible” Water Saturation

With finer pores in the matrix surrounding large oomolds it is important to understand capillary pressure relationships since high porosity may not be directly associated with effective oil porosity. Correlations of “Irreducible” water saturations indicate that *Swi* increases with decreasing permeability as exhibited by many rocks. Saturation increases with decreasing permeability following the relation:**log S_{w50} *(%)* = 0.22 log *k(md)*) - 0.43**





Residual Oil Saturation to Waterflood

Residual oil saturation to waterflood (*Sorw*) is a critical variable. *Sorw* increases then decrease with increasing permeability (*k*). At lower *k*, higher *Swi* must be associated with lower *Sorw*. At high *k* good connectivity promotes low *Sorw*. Intermediate permeability rock have large pore bodies and smaller pore throats which supports oil-globule snap-off and trapping.