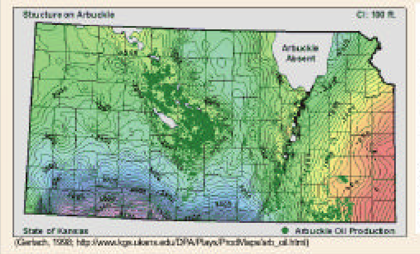
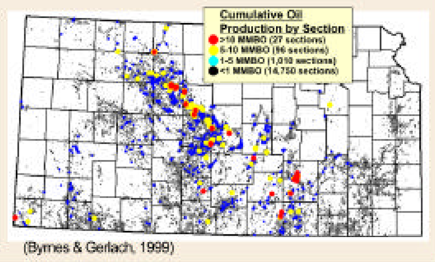
Cambro-Ordovician Arbuckle Group

Arbuckle Production

Arbuckle Group reservoirs have produced over 2.3 BBO with most production occurring on the Central Kansas Uplift (figure) and over 85% produced by 21 major fields.



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

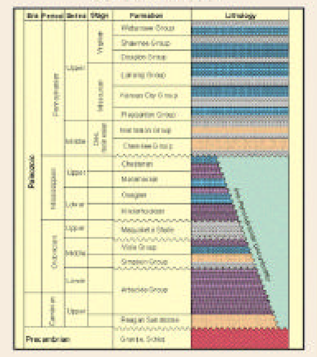


(Byrnes & Gerlach, 1999)

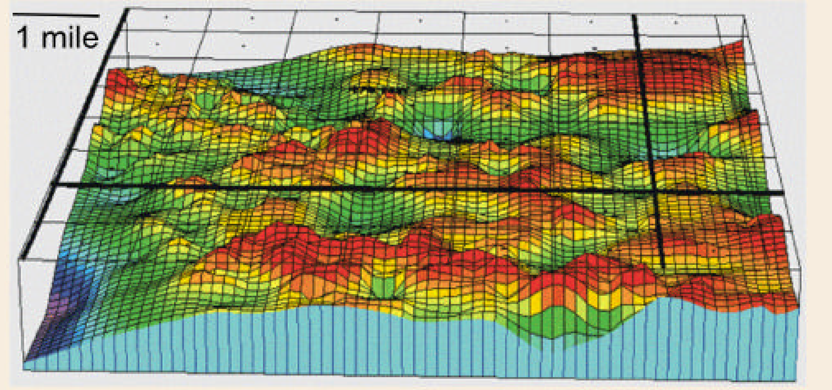
Geologic Setting

Arbuckle strata in Kansas are interpreted to have been deposited on a broad shallow shelf in shallow subtidal to peritidal environments, similar to what is recognized in Arbuckle equivalent strata elsewhere in the Midcontinent. The stratigraphic section consists of up to hundreds of feet of largely dolomitized subtidal to peritidal cyclic carbonates ranging in thickness from one to several tens of feet with karst overprinting in the upper portion as a result of prolonged exposure related to the overlying post-Arbuckle (Sauk-Tippecanoe) unconformity.

Lower Paleozoic Stratigraphy Central Kansas



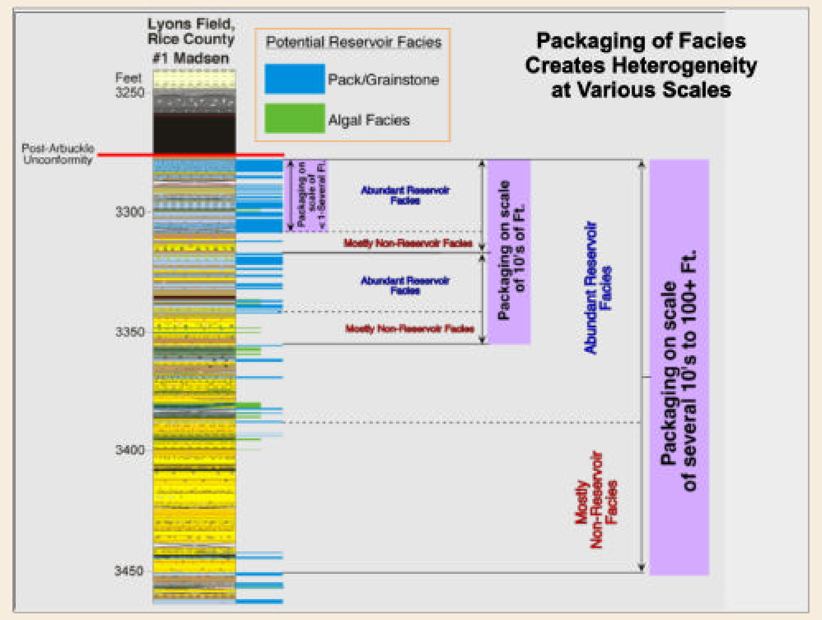
Karst and Porosity



Top of Arbuckle showing Cockpit karst structure (Cansler & Carr, 2001).

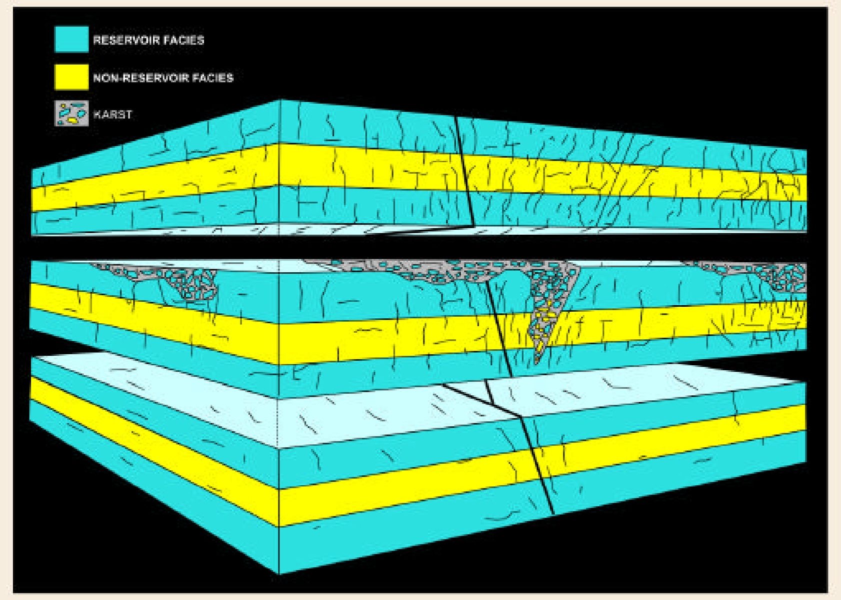
Arbuckle and equivalent Midcontinent reservoirs are generally considered to have favorable reservoir qualities directly related to structural highs that resulted from regional uplifts and prolonged subaerial exposure and development of karstic features in the upper 30 to 50 feet of the Arbuckle. Examination of core indicates that karstic processes variously destroyed or enhanced porosity. In some areas karstification significantly enhanced porosity and permeability in a pattern similar to modern karst systems (Figure above) where dissolution follows fracture systems.

Arbuckle Architecture

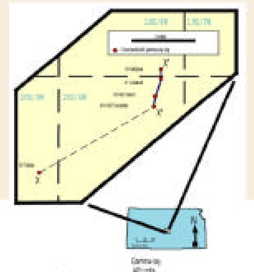


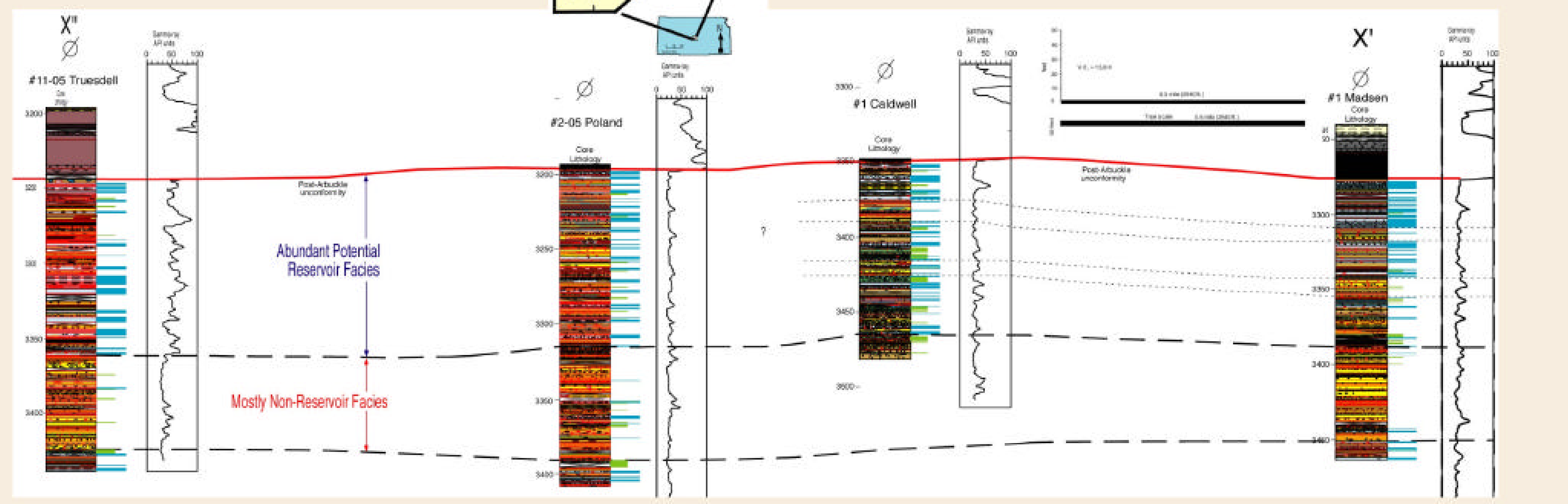
Lithologies are stacked into cycles and cycle bundles that affect vertical and lateral heterogeneity and variable connectivity to the underlying Arbuckle aquifer.

Possible End-member Reservoir Architectures



The architecture of the Arbuckle can be character as representing three basic end-members: 1) Fracture-dominated, facies control ϕ and layer permeability but fractures dominate reservoir permeability and vertical water flow; 2) Karst-dominated; complex ϕ and permeability reflecting the interaction of karst processes and early lithofacies petrophysical properties; and 3) Facies-dominated; facies and dolomitization control ϕ and ***k***. Even within fields Arbuckle architectures vary between these end-members. Controls for why an end-member forms in any given location are a function of the combined influence of stratigraphic, structural, facies, and karst influences.





Arbuckle Core Characteristics

- Relative lack of karst associated fracture, breccia, and dissolution porosity in most cores - especially surprising considering that the cores came from flanks or tops of structural highs where karst processes would likely have been most extensive
- Dominance of matrix porosity (intercrystalline, moldic, fenestral, vuggy) related to depositional facies, early diagenesis, and dolomitization

Lithofacies

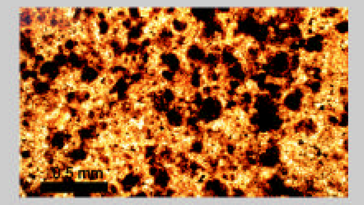
Major facies include: (1) Clotted algal boundstone, (2a) laminated muddy algal boundstone, (2b) laminated grainy algal boundstone, (3) peloidal packstone-grainstone, (4) packstone-grainstone, (5) ooid packstone-grainstone, (6) mudstone, (7) wackestone, (8) intraclastic conglomerate and breccia, (9) cave fill shale and depositional shale, and (10) chert. In the cores studied the first seven lithologies account for more than 85% of the cored intervals.

Summary of Petrophysical Trends

Petrophysics of lithofacies at the core-plug scale, and for many lithologies at the whole-core scale, are dominantly controlled by grain size. Each lithology exhibits a generally unique range of petrophysical properties modified by the presence of fractures, vuggy porosity, and grain size variation within the lithologic class. Facies comprising multiple lithologies of differing grain size exhibit bulk properties that are scale-dependent and are a function of the architecture of the constituent facies.

Variance in permeability at any given porosity is approximately two orders of magnitude and may be primarily attributed to the influence of such lithologic variables as the ratio and distribution of matrix and fenestral/vuggy porosity, grain size variations, and subtle mixing or interlamination of lithologies. Fracturing enhances permeability but does not add significantly to porosity. Vuggy porosity is largely isolated in mudstones, even up to vuggy porosities as high as 8%, but is better connected in wackestones. Vuggy pores can be well

- **Peloidal Packstone-Grainstone:** Cementation of matrix has resulted in nearly total occlusion of porosity and destruction of reservoir properties. In the absence of cross-cutting vugs or fractures these beds may act as **seals**. Fenestrae within this facies may range up to several centimeters in length and may enhance porosity by several percent but are not interconnected but are isolated by low permeability matrix.
- **Mudstones:** Without fractures or fenestrae these exhibit porosities ranging from zero to 10% and absolute permeabilities ranging from <0.0001md to 0.1md. Where fenestrae are present, porosity may be enhanced up to values as high as 17%, however, the fenestrae are primarily isolated and permeabilities are not increased significantly. Threshold capillary entry pressures for this lithology are sufficiently high that these can act as **seals** in the absence of fractures.
- **Wackestones:** Without vugs these exhibit porosities ranging from 2% to 11% and permeabilities ranging from 0.01md to 1md. Where vugs are present, porosities can range from 9% to 17% and permeabilities can range from 1md to 1,000 md.
- **Ooid Packstone-Grainstone:** Generally contain little to no vuggy porosity but exhibit intercrystalline and moldic porosities ranging from 11% to 30%, associated permeabilities range from 10md to 1,500md. The highest porosity and permeability values are exhibited by clean, homogeneous, medium-grained moldic packstones.
- **Algal boundstones:** Exhibit both reservoir and non-reservoir properties. Laminated muddy algal boundstones exhibit porosities generally less than 6% and permeabilities below 0.1md. Where fenestral or vuggy porosity is developed these may exhibit high permeability at the core-scale but it is unlikely that these permeabilities represent higher scales. Laminated grainy algal boundstones represent some of the best reservoir rock ranging in porosity up to 32% and permeability up to 1,500md. This lithology may extend laterally to the inter-well scale.



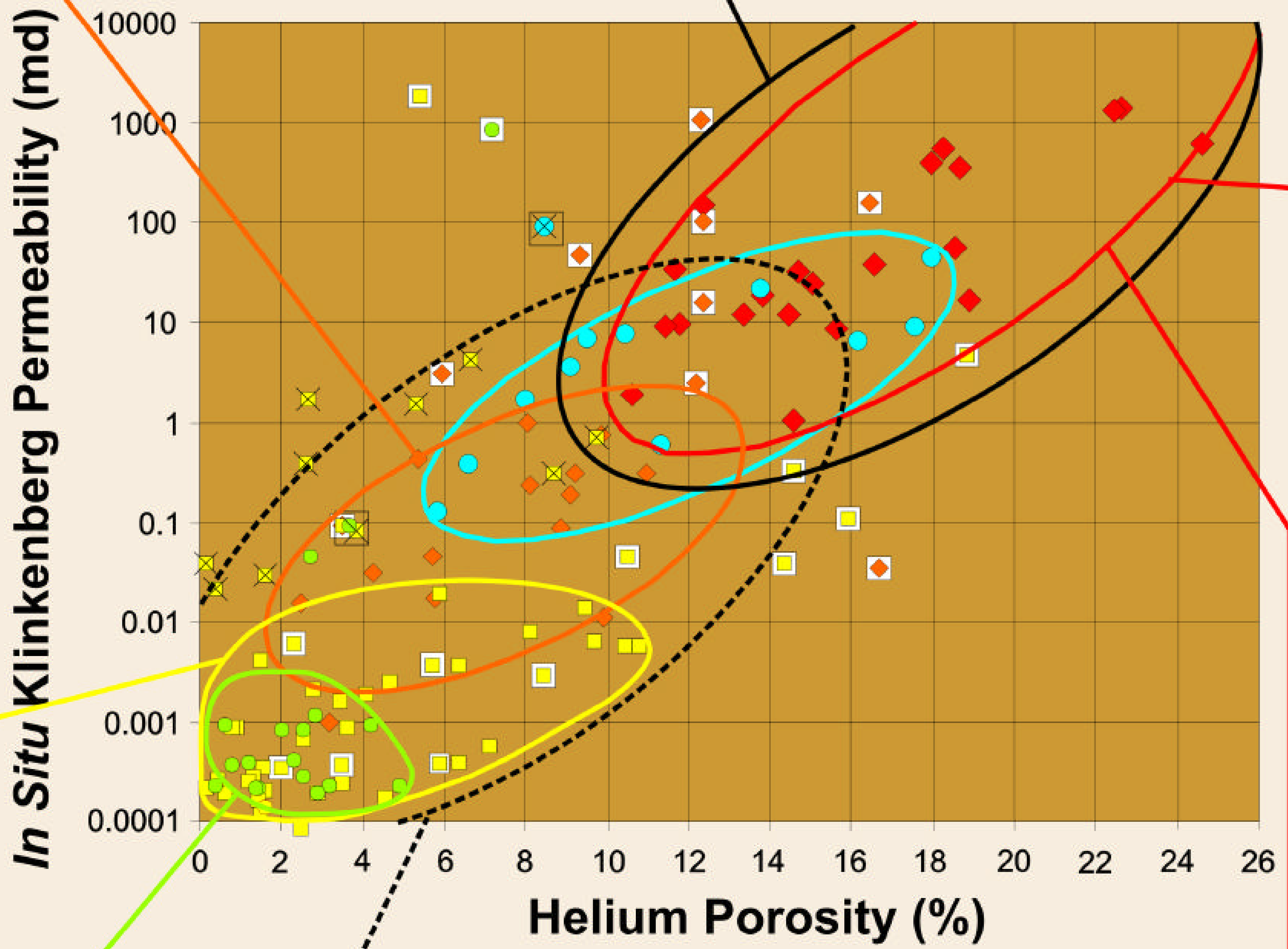
Peloidal wackestone / packstone with clotted fabric, #2 Matoush 3345', plane polarized light.

#23 Batman 2375' 1cm

Facies (7) Wackestone (Non-reservoir): Typically massive to horizontally laminated with burrow mottling also common. Matrix is composed of euhedral dolomite (< 0.05 mm) with little or no porosity. Replacement of evaporite nodules with chert is observed in some intervals. This facies is interpreted as being deposited in shallow-water, low energy restricted environments or in deeper water away from the Central Kansas Uplift. Vuggy porosity up to 8% is locally present near the unconformity but is often isolated or separated by low permeability matrix.

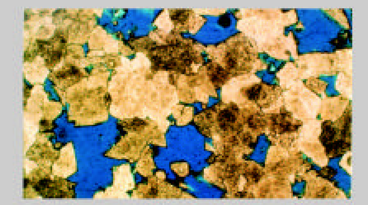
Key

- Fractured rock
- Vuggy rocks
- Moldic packstone and grainstone (excluding peloidal rocks, including oomoldic packstone)
- Packstone (excluding peloidal rocks, including oomoldic packstone)
- Wackestone (excluding peloidal packstone)
- Mudstone
- Peloidal rocks (wackestone, packstone, and algal boundstone)



#23 Batman 2465.7' 1cm

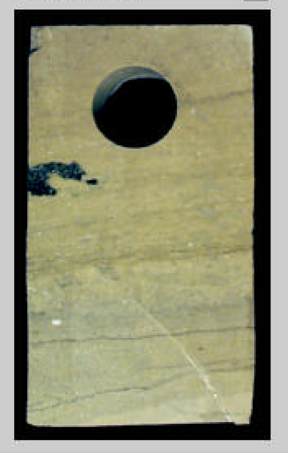
Facies (2) Laminated Grainy Algal Boundstone and Stromatolites: Current-modified (ripple) lamination occurs locally. Where stromatolites trapped grains, intercrystalline porosity is present and fenestral, keystone vug, and solution enlarged porosity that closely follows laminations may occur. This facies likely represents subtidal to peritidal (where fenestrae are present) environments. This facies is locally oil stained and can exhibit some of the highest matrix permeabilities in the Arbuckle.



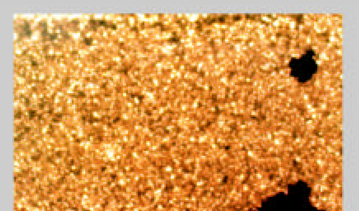
Packstone, intrercrystalline porosity, #2 Tobias 3329', plane polarized light, blue epoxy.

Tobias #2 3329.4' 1cm

Ord #1 1424' 1cm

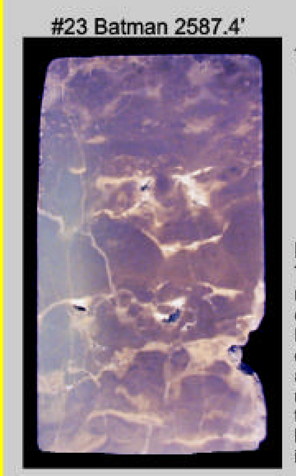


Facies (4) Packstone-grainstone (Reservoir): Typically massive, horizontally bedded or crossbedded and typically interbedded with ooid packstone-grainstone and wackestone-packstone facies. Grains include intraclasts, skeletal and algal fragments, ooids, peloids, and lumps. This facies indicates higher energy deposition in subtidal to pertidal settings (fenestrae and keystone vugs). Locally packstone-grainstone is tightly cemented by euhedral dolomite (< to 0.5 mm). However, this facies typically has good intercrystalline porosity. In some rocks the original cement between grains has been leached creating interparticle porosity that is open or filled with chert. This chert has a "chalky" appearance and is porous but exhibits low permeability. This facies typically has good intercrystalline porosity and high permeability.



Mudstone (pyrite lower and upper left), #23 Batman 2435', plane polarized light.

#23 Batman 2587.4' 1cm

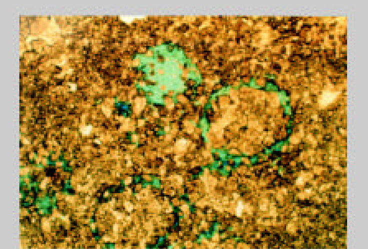


Augusta #6-56 2558.4' 1cm

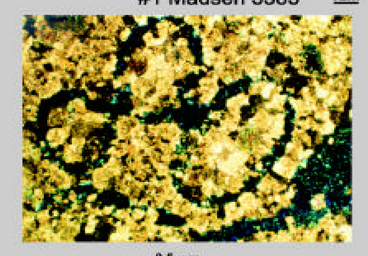
Facies (6) Mudstone (Non-reservoir): Typically massive to horizontally laminated with burrow mottling also common. Matrix is composed of euhedral dolomite (< 0.05 mm) with little or no porosity. Replacement of evaporite nodules with chert is observed in some intervals. This facies is interpreted as being deposited in shallow-water, low energy restricted environments or in deeper water away from the Central Kansas Uplift. Vuggy porosity up to 8% is locally present near the unconformity but is commonly isolated or separated by low permeability matrix.

Facies (5) Ooid packstone-grainstone (Reservoir): Typically massive, horizontally bedded or crossbedded and typically interbedded with undifferentiated packstone-grainstone and wackestone-packstone facies. Ooids compose more than 80% of the grains but other coated grains, peloids, and lumps are also present. This facies indicates higher energy deposition in subtidal to pertidal settings. This facies typically has good oomoldic and intercrystalline porosity and variable moderate to high permeability.

#1 Madsen 3383' 1cm

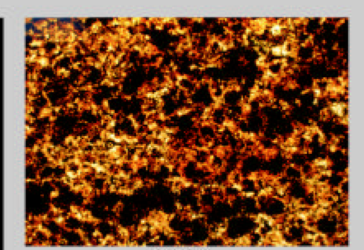


Oomoldic packstone, #23 Batman 2472', plane polarized light, blue epoxy.



Oomoldic packstone, #2-05 Poland 3315', crossed polarized light, blue epoxy.

#11-05 Truesdell 3246.3' 1cm



Peloidal packstone with clotted fabric, #1 Madsen 3354', plane polarized light.

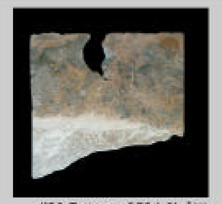
Facies (3) Peloidal packstone-grainstone (Non-reservoir): Typically massive, horizontally laminated or bedded and commonly interbedded with coarser-grained lithologies. Locally, it contains wispy lenses of shale and interbedded shale layers. Burrow traces and mottling are common. Peloids are abundant and rare interclasts, lumps, and skeletal grains (gastropods) are present. Soft sediment deformation, dewatering or teepee-like structures, mudcracks, and rip-up clasts are locally associated with this facies. The mud-rich peloidal packstone/grainstone facies represents deposition in relatively lower-energy subtidal and peritidal environment. This rock is tightly bound consisting of anhedral, euhedral, and polyhedral dolomite (< 0.5 mm) and peloidal cement.

#1 Madsen 3386.3' 1cm

(2) Laminated Muddy Algal Boundstone and Stromatolites (Non-reservoir): Brecciated stromatolite facies typically grades upwards to non-brecciated, in-place stromatolites. Locally or near unconformity may contain isolated vugs which can result in high core-scale permeability that are not representative of scales larger than whole-core.

#23 Batman 2515.5' 1cm

Facies (1) Clotted Algal Boundstone (Non-reservoir): muddy, peloid-rich mottled (thrombolitic) to wavy laminated clotted algal lithology. Other clotted forms (Renalcis?) are also present. Thrombolite-leopard rock texture is typically muddy with some grains. Matrix is tightly bound anhedral, euhedral, and polyhedral dolomite (< 0.5 mm) with peloidal cement. Commonly contains sheet-like vuggy and fenestral porosity and poor intercrystalline porosity. Most thrombolitic boundstones were probably deposited in subtidal environments; fenestral porosity indicates at least local subaerial exposure. Fenestral pores are typically separated by tight matrix resulting in poor permeability.



#23 Batman 2504.8' 1cm

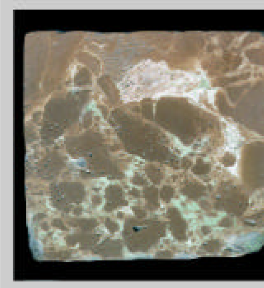
Facies (10) Chert (Non-reservoir): Chert commonly occurs as a replacement of carbonate facies (typically preserving original textures) and, locally, original evaporite minerals. Chert replacement commonly results in tight and impermeable areas. Locally, where only partial replacement occurs, some vuggy and intercrystalline porosity is developed.

#1 Caldwell 3476' 1cm
Autobreccia within Arbuckle

Facies (8) Conglomerate and Breccia (Non-reservoir): Many conglomerates or breccias consist of rip-up clasts derived from underlying lithologies. Textures range from clast- to matrix supported. Conglomerates and breccias are commonly associated with desiccation and mud cracks, dewatering structures and teepees. Local autoclastic breccia textures indicate intra-Arbuckle subaerial exposure events. Some collapse breccia may have resulted from the dissolution of evaporites. These conglomerates indicate intra-Arbuckle high energy erosional and subaerial exposure events in subtidal to peritidal settings. The conglomerate and breccia facies typically has variable porosities and permeabilities that are primarily a function of the lithologies that were brecciated.

Facies (9) Intra-Arbuckle Shale (Non-reservoir): Some shales are interbedded with carbonate rocks suggesting they were deposited during Arbuckle deposition. In addition, horizons with wavy horizontal to horizontally interbedded shale and carbonate mudstone-wackestone are present. Several shale layers contain silicified nodules and lenses that may have replaced evaporites. These shale layers likely represent relatively low energy subtidal to peritidal conditions. Supratidal conditions may be indicated for some horizons where silicified nodules apparently represent replacement of original evaporite minerals.

Augusta #6-56 2576' 1cm



Facies (9) Fracture-fill Shale (Non-reservoir): Much of the shale in the uppermost section of the Arbuckle is green and clearly represents fracture or cave fill, with sediment originating from above the unconformity. Locally, fracture fills contain fragments of dolomite rhombs and subangular to rounded silt-size to coarse-grained detrital quartz grains.

#11-05 Truesdell 3386.3'
Breccia with green shale matrix
1cm

Discussion & Conclusions - All Systems

- Multi-scale carbonate-dominated sequences were deposited in subtidal to supratidal environments on the broad shallow Kansas shelf throughout the Paleozoic.
- A repeating association of original depositional facies and early diagenesis for these rocks produced lithofacies ranging from mudstones to grainstones with abundant moldic porosity. The nature of the molds varied through time reflecting the change in primary carbonate grain constituents:
- U. Cambrian-L. Ordovician Arbuckle peloid and ooid molds
- Mississippian carbonate/siliceous sponge spicule and echinoderm/ brachipod molds
- Pennsylvanian ooid and bioclast molds

Primary Factors Controlling Reservoir Properties

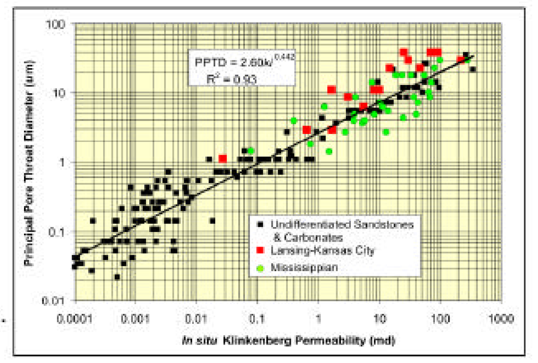
- Depositional Facies - grainstones/boundstones exhibit best properties, properties improve from mudstone to grainstone/boundstones.
- For the systems investigated, depositional facies are dominant control even with: 1) extensive and various, early and late diagenesis; 2) biotic constituent differences; 3) warm-cool water environments; 3) karst overprinting; 4) burial overprinting.
- Reservoir properties for each system, including porosity and permeability, are strongly correlated with original depositional facies despite significant fabric transformation, and in some cases even complete reversal of solid and pore space, with reservoir quality increasing from mudstone through grainstone.
- The final moldic rocks exhibit petrophysical-lithofacies trends that parallel those of original primary porosity carbonates.
- Understanding facies locations is important for both stratigraphic and structural plays.

Secondary Factors Favoring Reservoir Properties

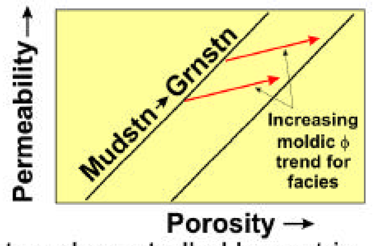
- Stratigraphy - e.g., shallowing upward high frequency cycles
- Diagenesis - e.g., dissolution of carbonate grains to form molds, extensive dissolution to establish direct mold-mold connections
- Paleotopography - e.g., local relief that accentuates diagenetic processes
- Structure/Burial - e.g., fracturing, crushing to establish direct mold connectivity

Synthesizing Lithofacies-Petrophysical Properties for All Systems - A Pore Understanding

- 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 some rocks having very high moldic porosity, permeability is primarily controlled by matrix properties. However, the strong association of increasing permeability with increasing grain size and packing (i.e. mudstone to grainstone) indicates that matrix pores must also be increasing in size.
- Enhanced mold connectivity resulting from extensive dissolution, crushing, or fracturing creates high permeability parallel flow systems.



- Dominant control of matrix properties in rocks with high moldic porosity is consistent with a pore-scale series-flow model of low permeability matrix and high permeability moldic pore bodies. The strong correlation of permeability with connectivity may result from the establishment of increasing pore-scale parallel flow, effectively "short-circuiting" the series-flow dominated system.
- Lithofacies progression from mudstone through grainstone results in a greater change in permeability than increasing porosity. For a given facies, increasing mold content and porosity results in a k increase that is subparallel and at a lower slope to the general k-ϕ trend. This is consistent with matrix properties being the dominant control on flow.



- Although permeability in moldic porosity-dominated rocks is strongly controlled by matrix properties, and is correlated with porosity, permeability is also controlled by other rock textural parameters including:
  Connectivity Index - A 1-4 index for the degree of connection between molds
  Packing Index - An index from 1 to 4 for the packing density of molds
  Size - An estimate of the average mold diameter in phi units
  Archie Matrix Porosity Index - Archie's 2nd parameter for matrix porosity
- High sponge-spicule mold content in Chat and oomold content in the L-KC is associated with Archie cementation exponents ranging up to 3 for the Chat and 3.6 for the L-KC. These values are consistent with high micro-vug content with electrical current flow dominated by matrix pores. Knowing these values is critical to quantitative wireline log water saturation interpretation.
- 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.

Portions of this research were derived from programs funded in part by the U.S. Department of Energy - National Petroleum Technology Office. We are grateful for their support