The Hoxbar Project

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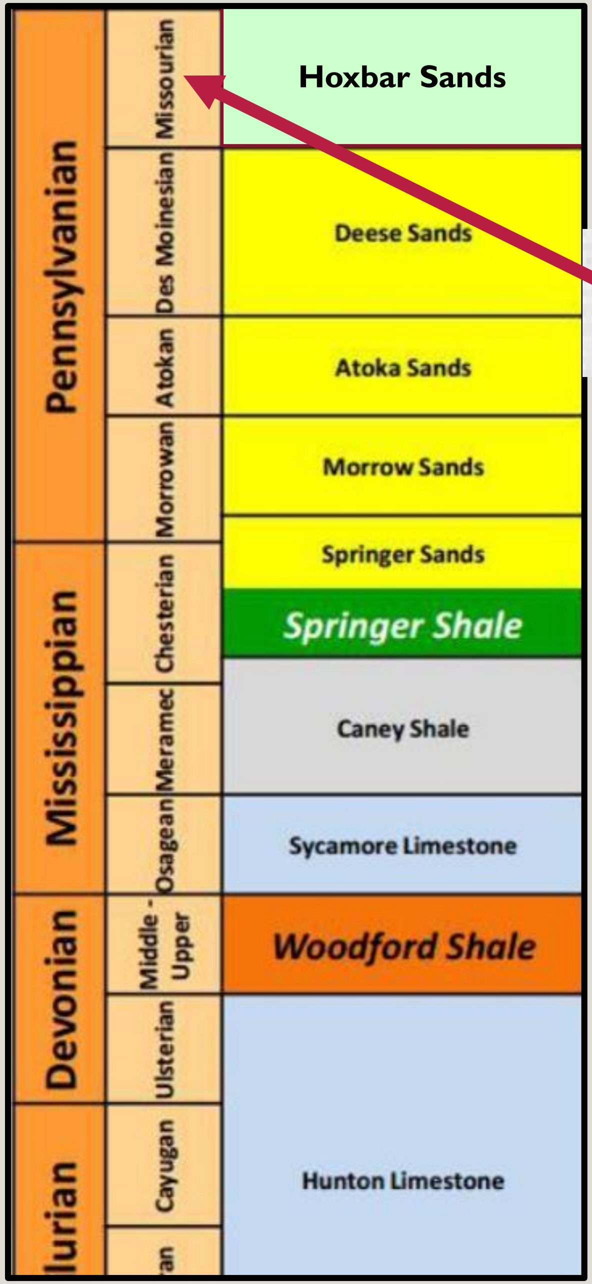
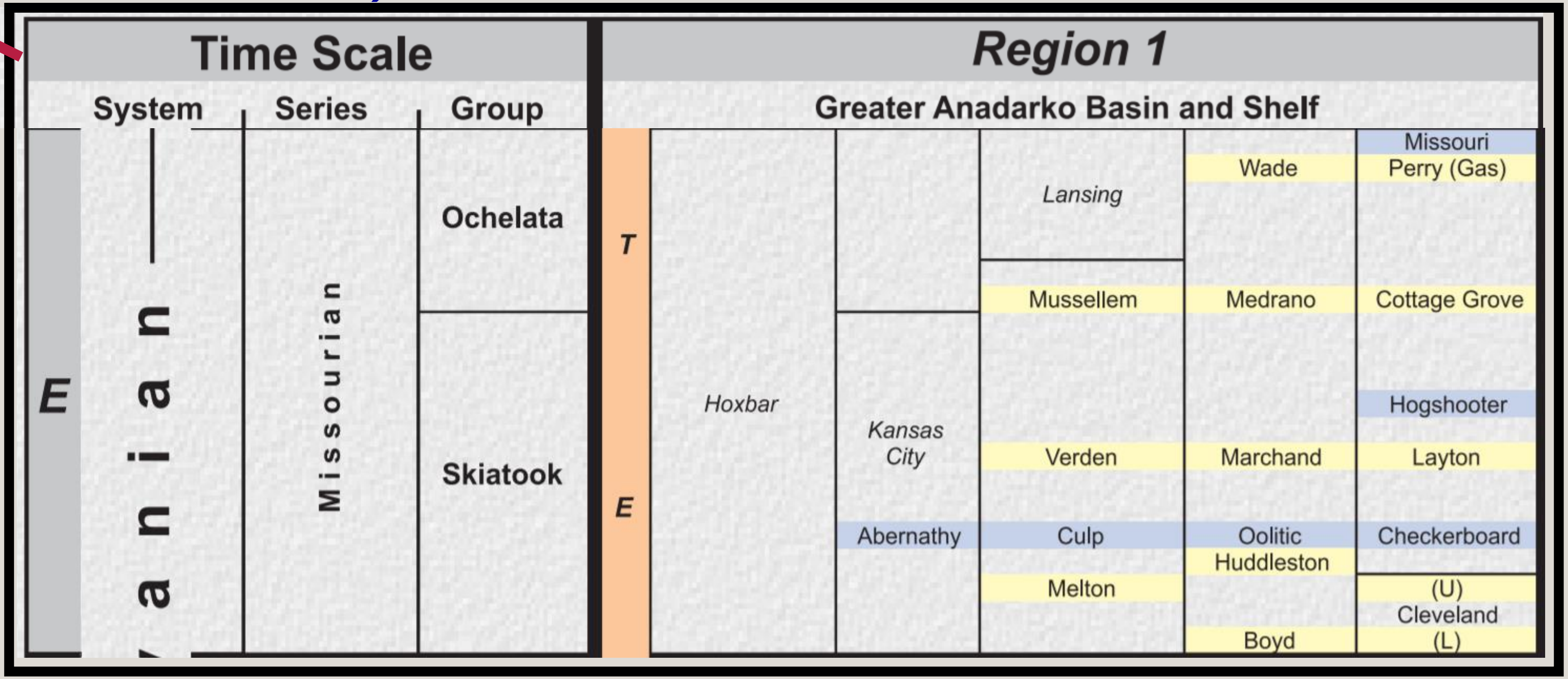
Importance

- The Pennsylvanian *Hoxbar* Group is economically important for the OK petroleum industry
  - Named for the town of Hoxbar in Carter County, Ardmore Basin, Southern Oklahoma folded belt province
- Caddo and Grady Counties (2448 square miles) have been the sites for exploration for oil and gas since the 1920's
  - A great deal of information has remained the private property of petroleum companies
- Not much work on the Hoxbar has been recently performed by OGS geoscientists
- Complex geological structures of the Oklahoma Basins make it challenging for sedimentologists
- Horizontal drilling in the southern part of Oklahoma is commonplace
- This is a tight sandstone with some interbedded shales and a few limestones
- Possible contribution of the Hoxbar Group shales to the sources of oil
- Reservoir heterogeneity/mineralogy (petrophysics) are important components of the characterization of this play
- Excellent opportunity for Enhanced Oil Recovery (EOR) processes
- The results of this project can be applied to other tight sandstones worldwide as an analog

Hoxbar Stratigraphy

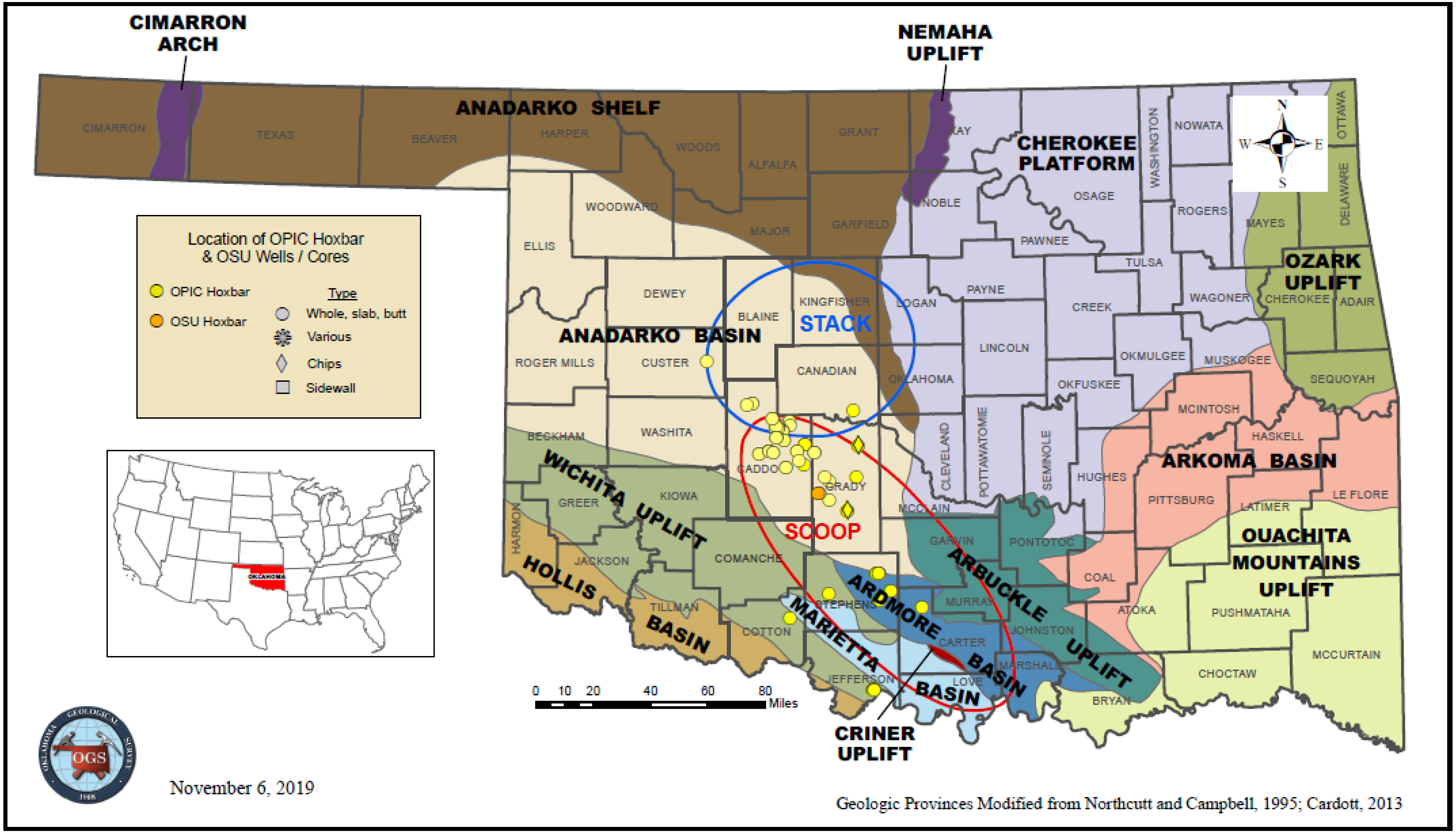
Members of the Hoxbar Group includes the Wade, Medrano, Marchand (Verden) and Culp (Oolitic Huddleston)



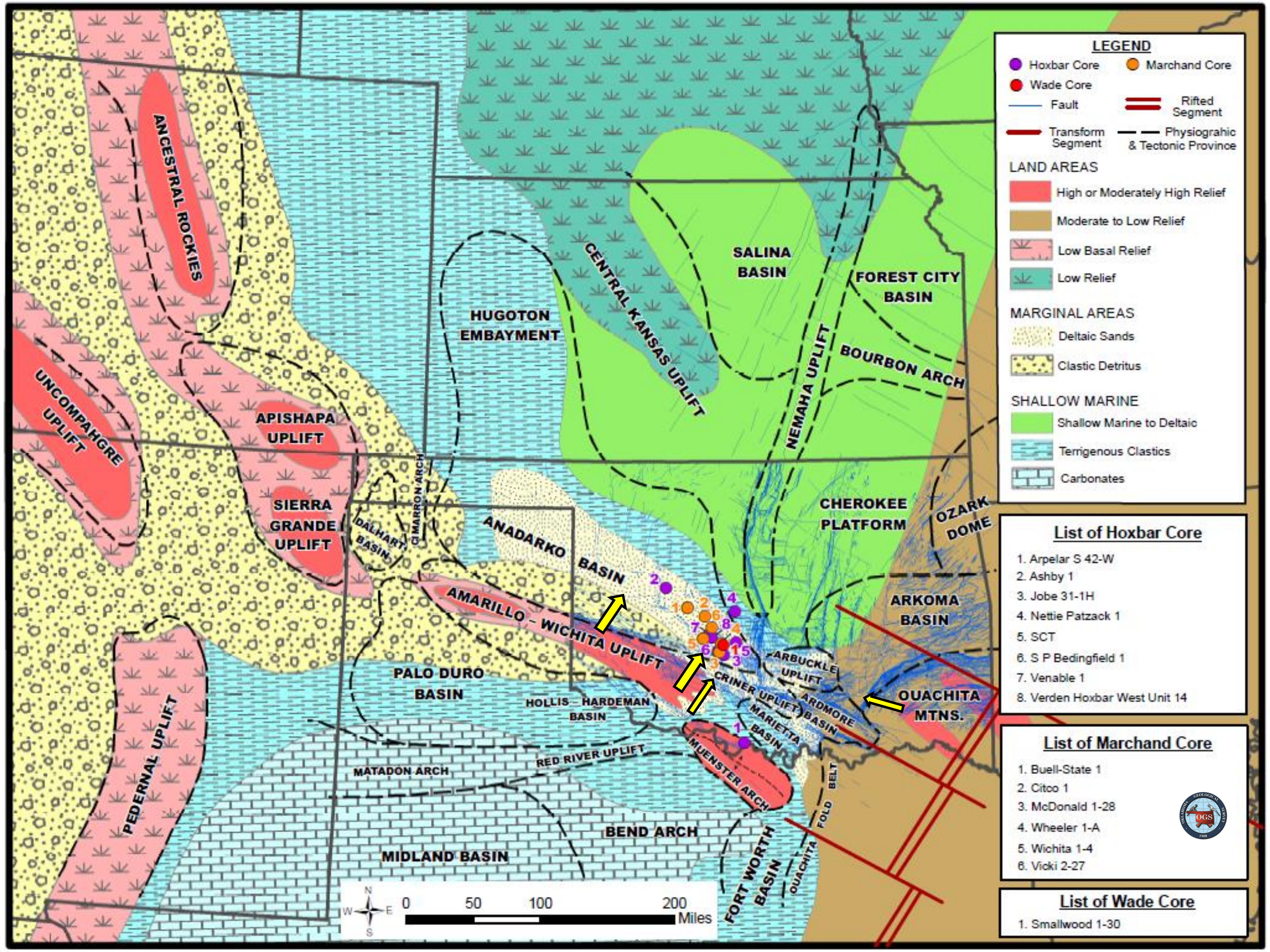


Lithologic Constituents **Major Shale, Silty Mudstone, SS and LS Beds**

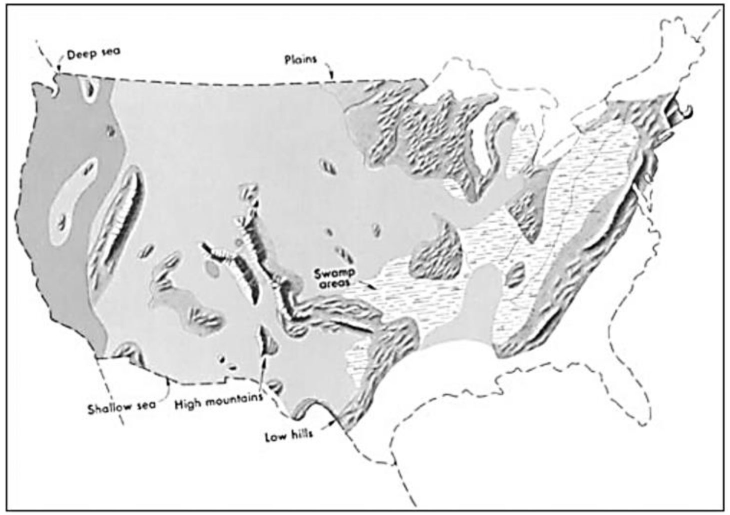
Geographic Area & Available OPIC Cores & Rocks



Regional Hoxbar Paleogeography with Location of Studied Cores



Hinterland rocks: shallow plutonic bodies, alkali-granitic rocks (felsic), metamorphic rocks, chert

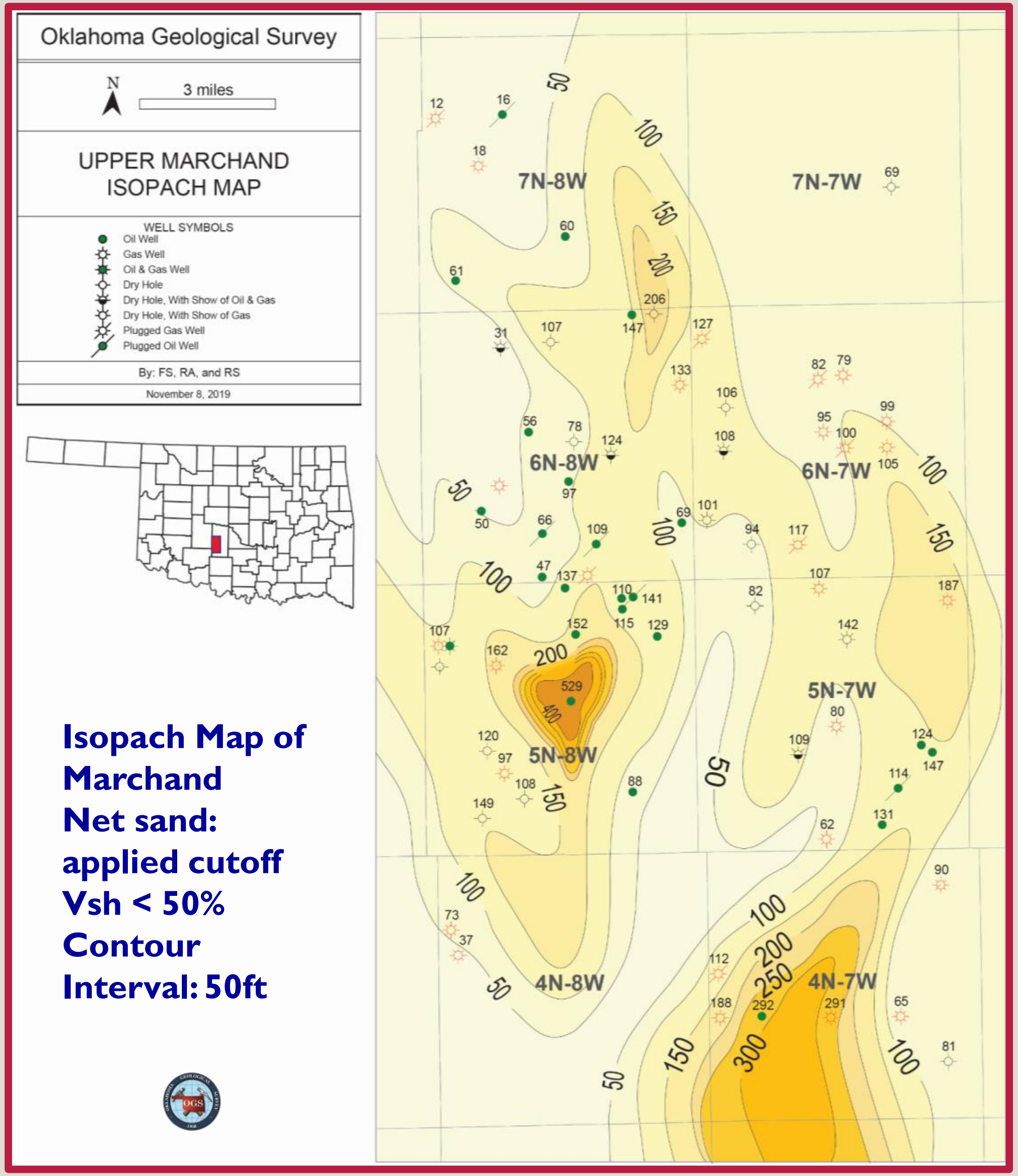


Generalized geographic map of the United States in middle Pennsylvanian time.

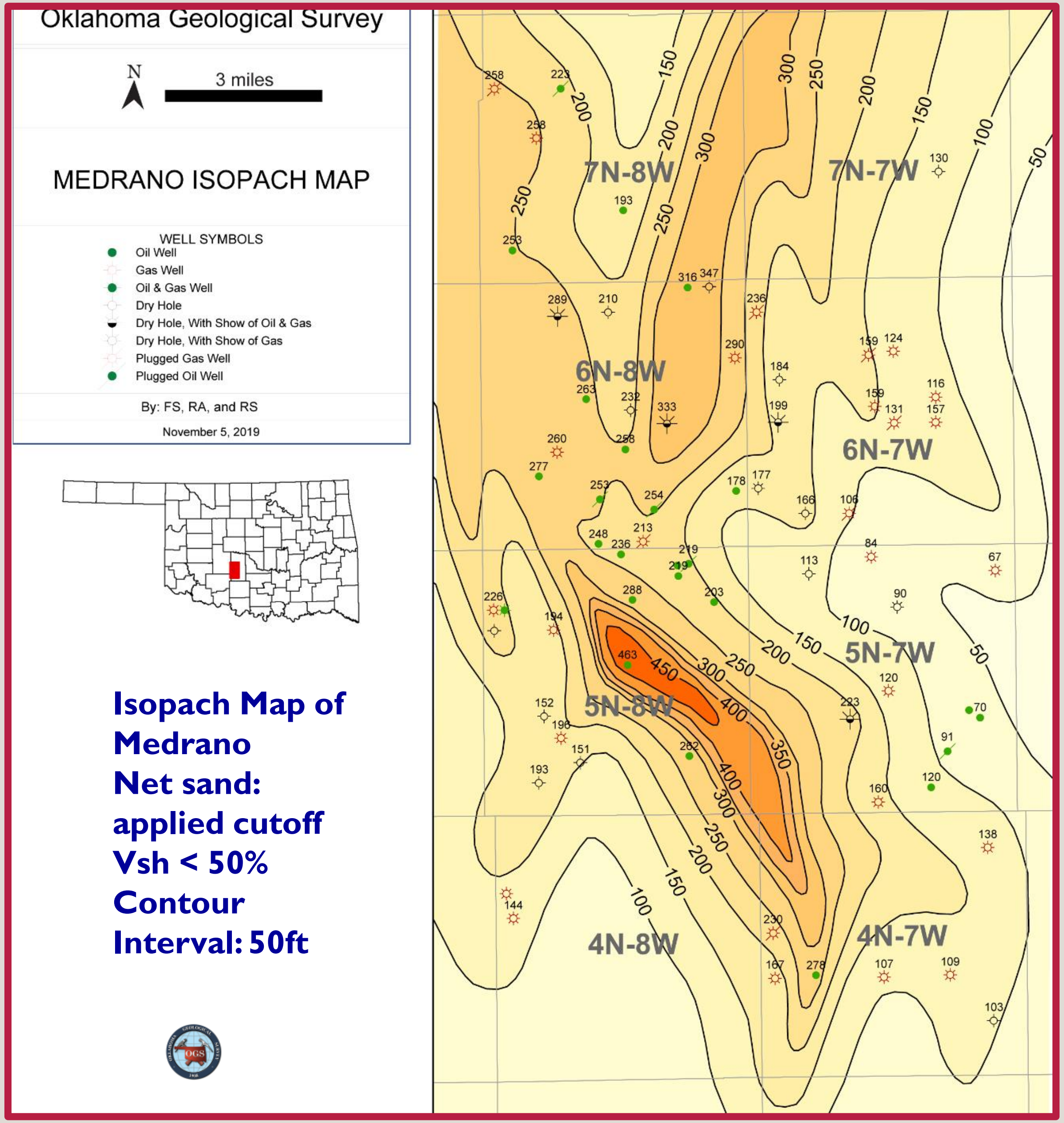
http://pubs.usgs.gov/gip/continents/pennmap.jpg

Yellow arrows point to the direction of sand fairways

Partial Marchand & Medrano Isopach Maps – Grady County



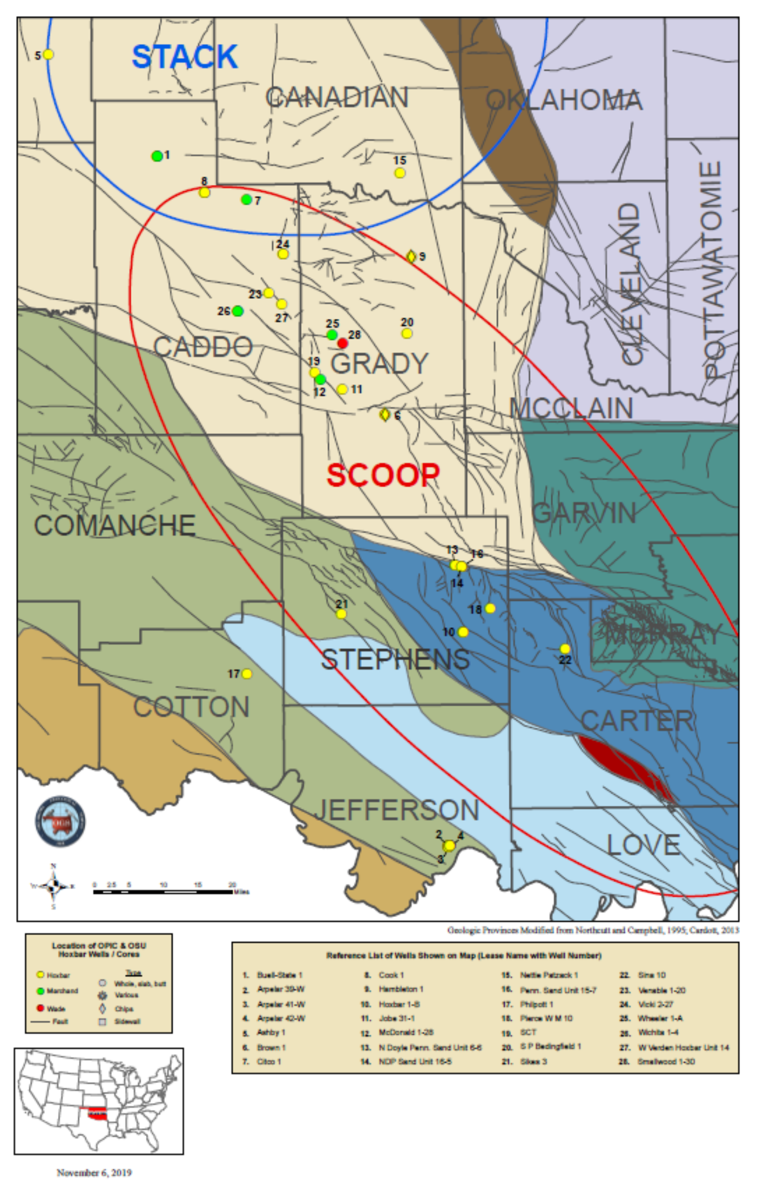
Isopach Map of Marchand Net sand: applied cutoff Vsh < 50% Contour Interval: 50ft



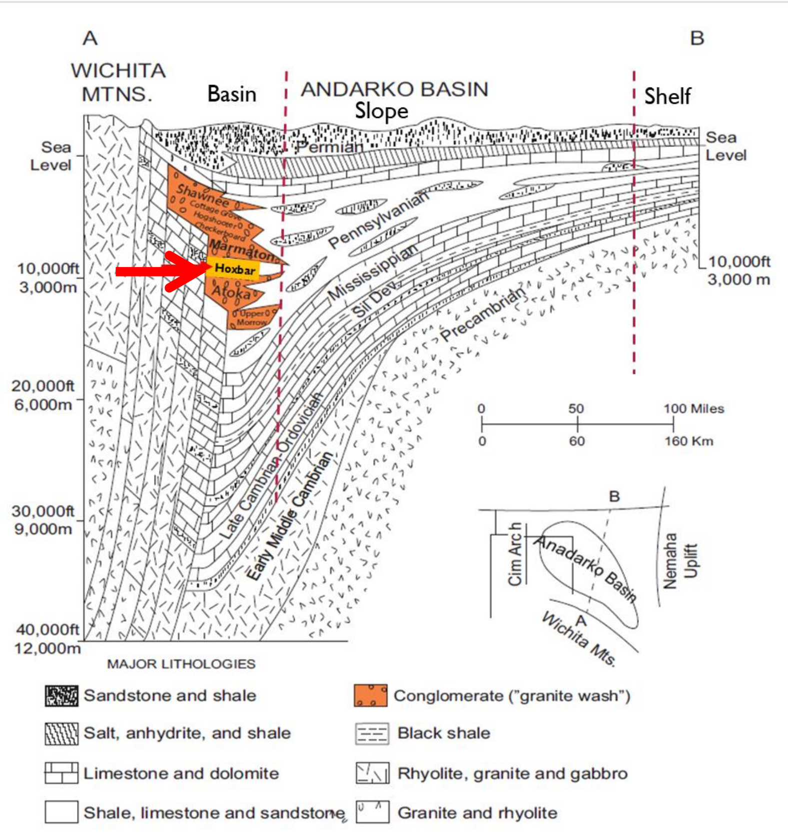
Isopach Map of Medrano Net sand: applied cutoff Vsh < 50% Contour Interval: 50ft

Looks fault controlled!

Generalized Structural Setting

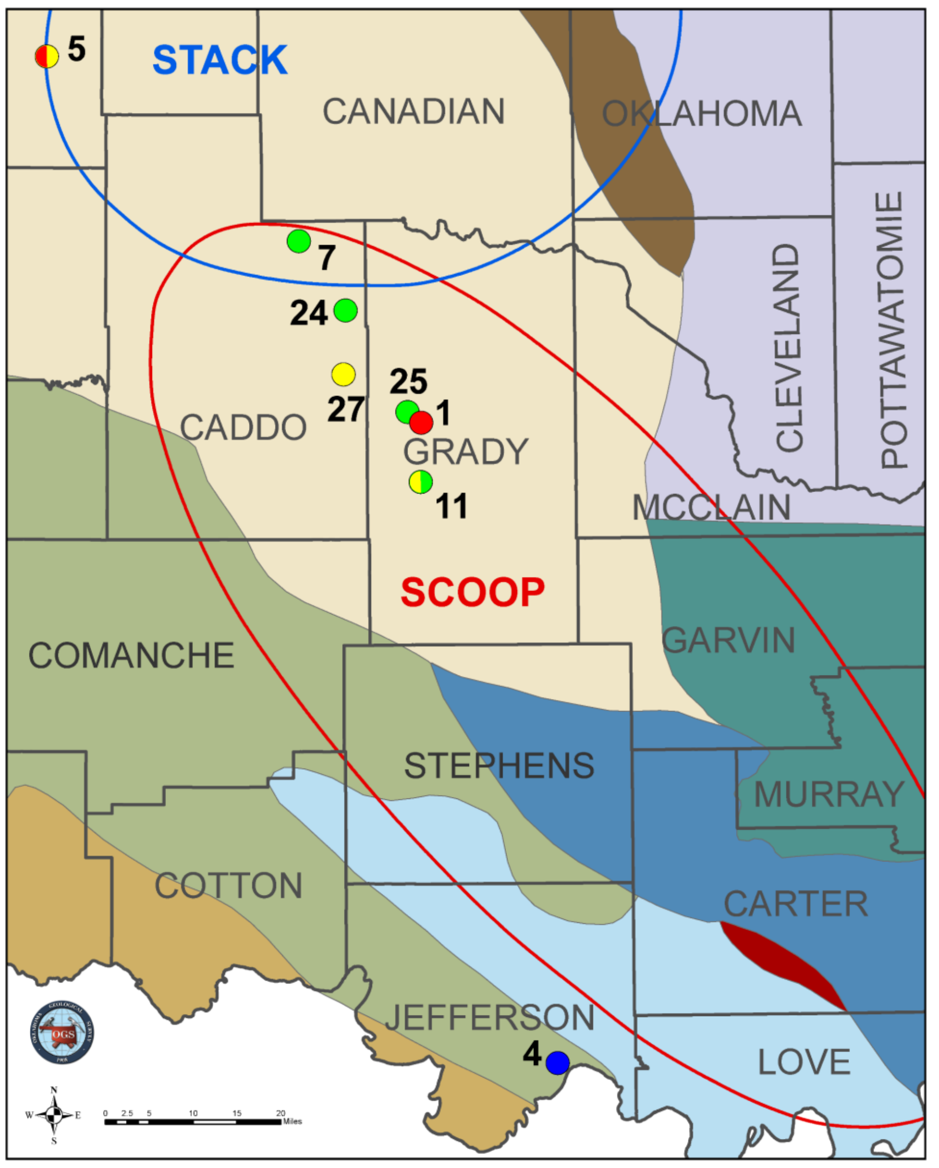


The structural history of the area of study before the deposition of the Hoxbar Series is complex (Ghosh, 2017). During the time of deposition, the uplifting Wichita Mountains and sinking Anadarko basin were transected by a series of WNW trending reverse faults and strike-slip movements related to the larger tectonic movements of the continents (Evans, 1979; Axtmann, 1985; Johnson, 1989; Ghosh, 2017, to name a few).



Cross section of present-day Anadarko Basin with relative location of the Hoxbar Group (red arrow). Note the complex vertical structure. Modified from Karis and Pranter, 2015

Cores for Workshop



The cores were chosen using the following criteria:

- **Availability**
- **Representative of the different Hoxbar sandstones as practical**
- **Reflect potential geographic variability**
- **Reflect potential reservoir types (shallow vs. deep)**

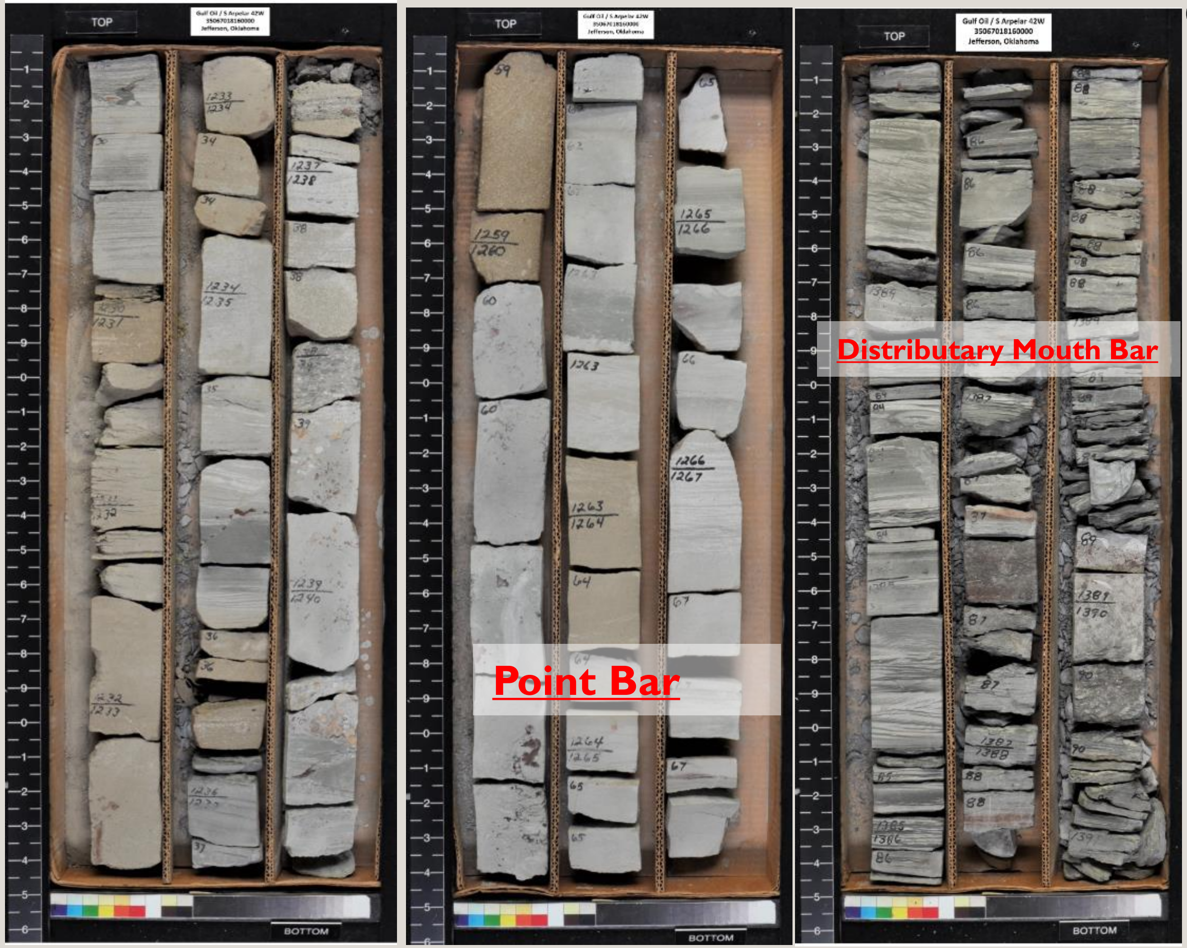
Location of Hoxbar Wells / Cores

Marchand Medrano Wade
Hoxbar Medrano & Marchand
Wade & Medrano

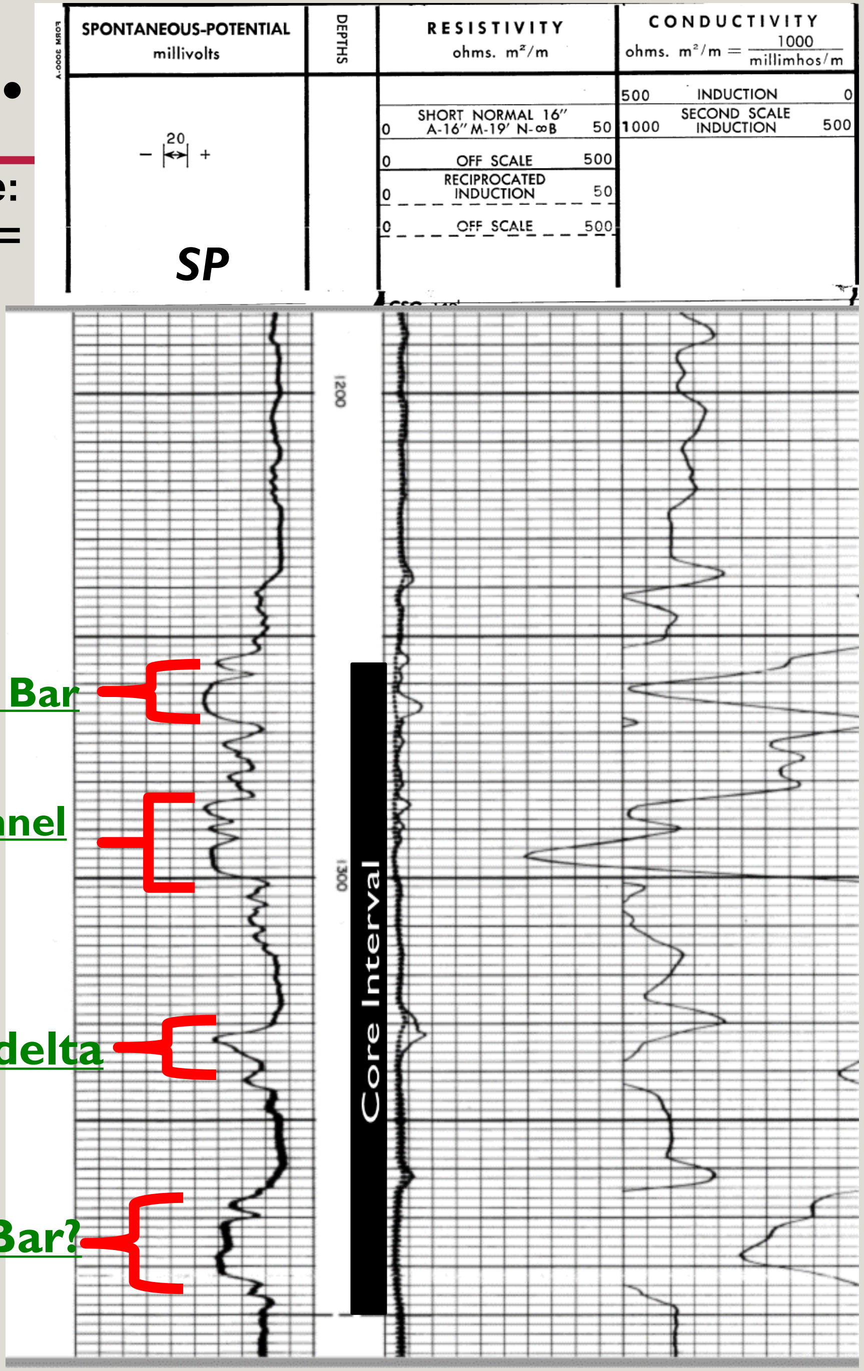
Reference List of Wells Shown on Map (Lease Name with Well Number)

1. Smallwood 1-30	5. Ashby 1	11. Jobe 31-1	24. Vicki 2-27
4. Arpelar 42-W	7. Citco 1	25. Wheeler 1-A	27. W Verden Hoxbar Unit 14

Gulf S Arpelar 42W, Jefferson Co.



Core Coverage: 1230 to 1391ft = 161ft



Fluvial Point Bar

Marine Channel Fill?

Prodelta

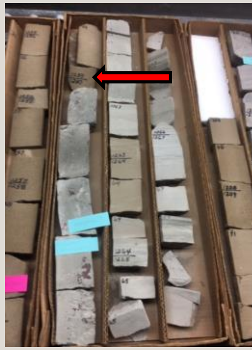
Distributary Mouth Bar?

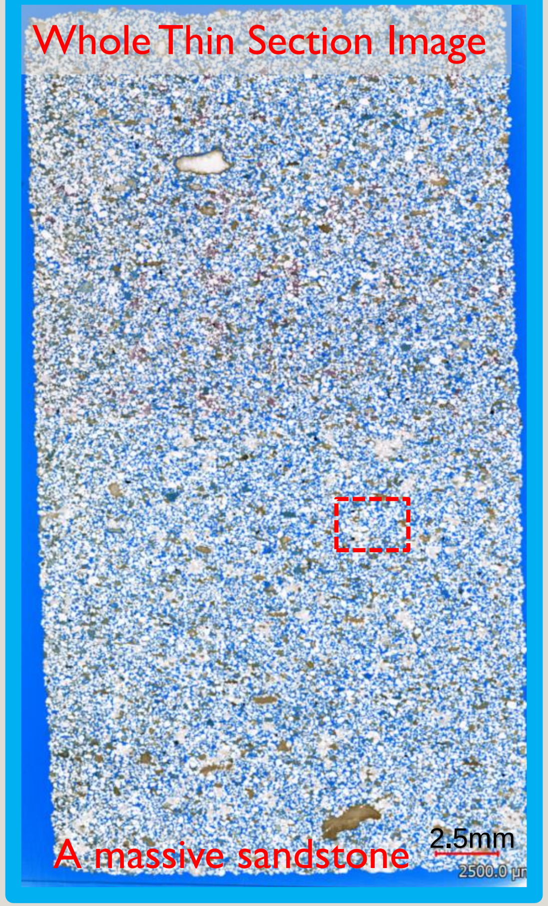
Overview of the Arpelar well and log characteristics. Note the shallow depth and localized facies changes which can affect reservoir quality.

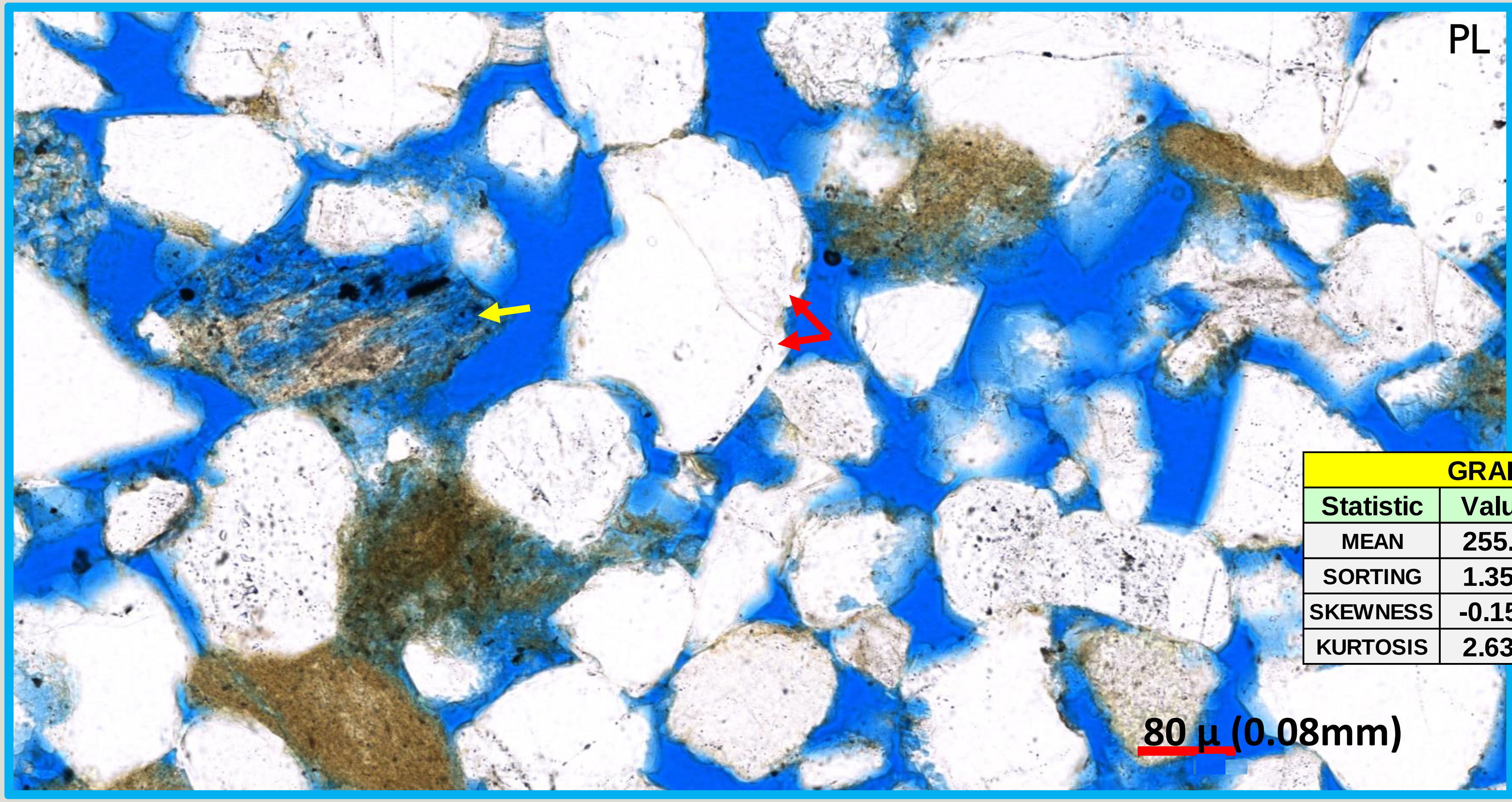
Hoxbar Arpelar Core 1260 ft – Thin Section Image

Sample ID	Grain Density	Gas filled porosity	Liquid filled porosity	Total Porosity (%)	Sw	So
	g/cc	P.U	P.U	P.U	%	%
GWG-ARP.42W-1260	2.54	20.4	3.5	23.9	2	13

Point Bar



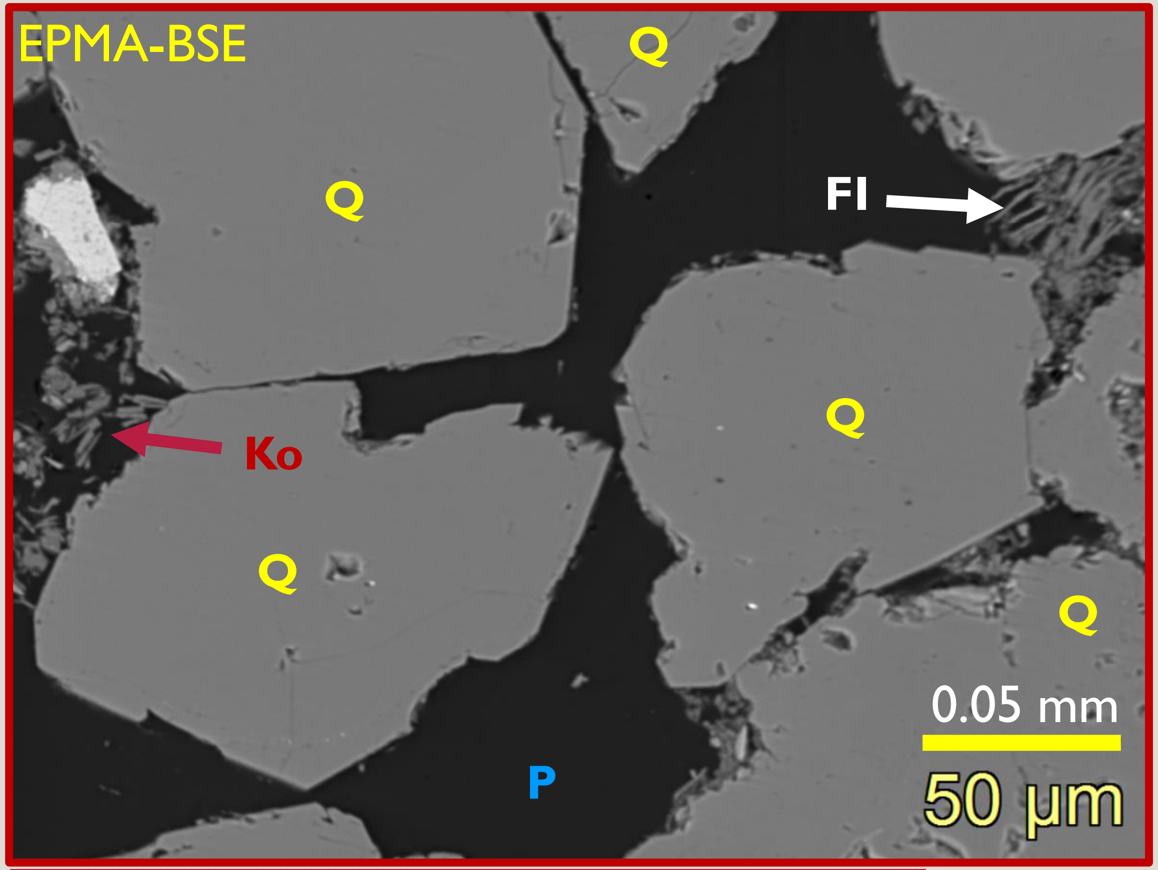


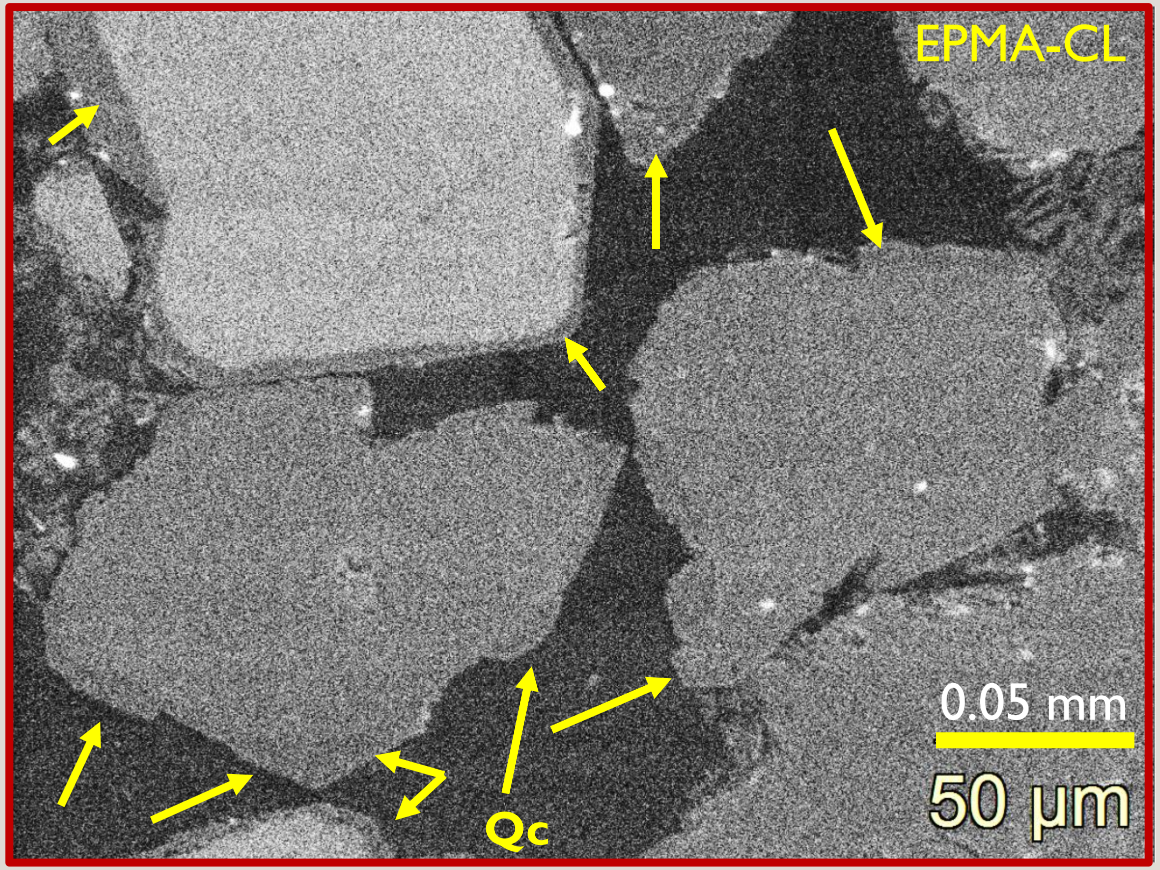


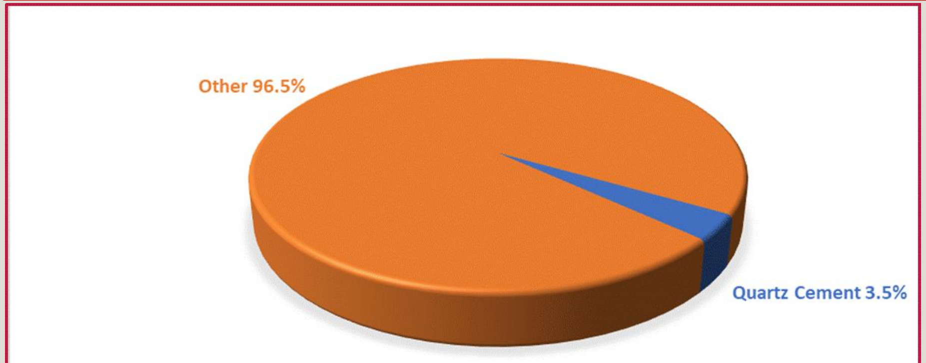
GRAIN SIZE		
Statistic	Value	Description
MEAN	255.1	Medium Sand
SORTING	1.354	Well Sorted
SKEWNESS	-0.151	Symmetrical
KURTOSIS	2.632	Mesokurtic

Typical high porosity thin section images: the image on the left is the whole thin section with the red dashed outline showing the location of the image shown on the right. In the right image, the yellow arrow points out a partially dissolved grain while the red arrows show quartz overgrowth on quartz grains. Both of these are likely post-depositional.

Hoxbar Arpelar Core 1260ft: EPMA-BSE/CL Images



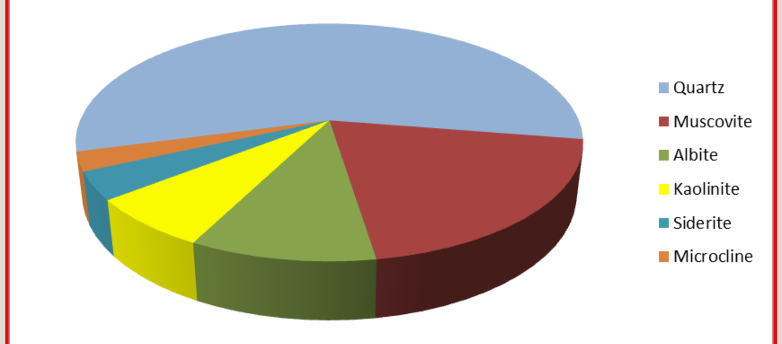




EPMA-CL Quantitative Point Count Analysis (250 Counts)

Q = Quartz
Qc = Quartz cement
FI = Fe-bearing illite
Ko = Kaolinite
P = Pore

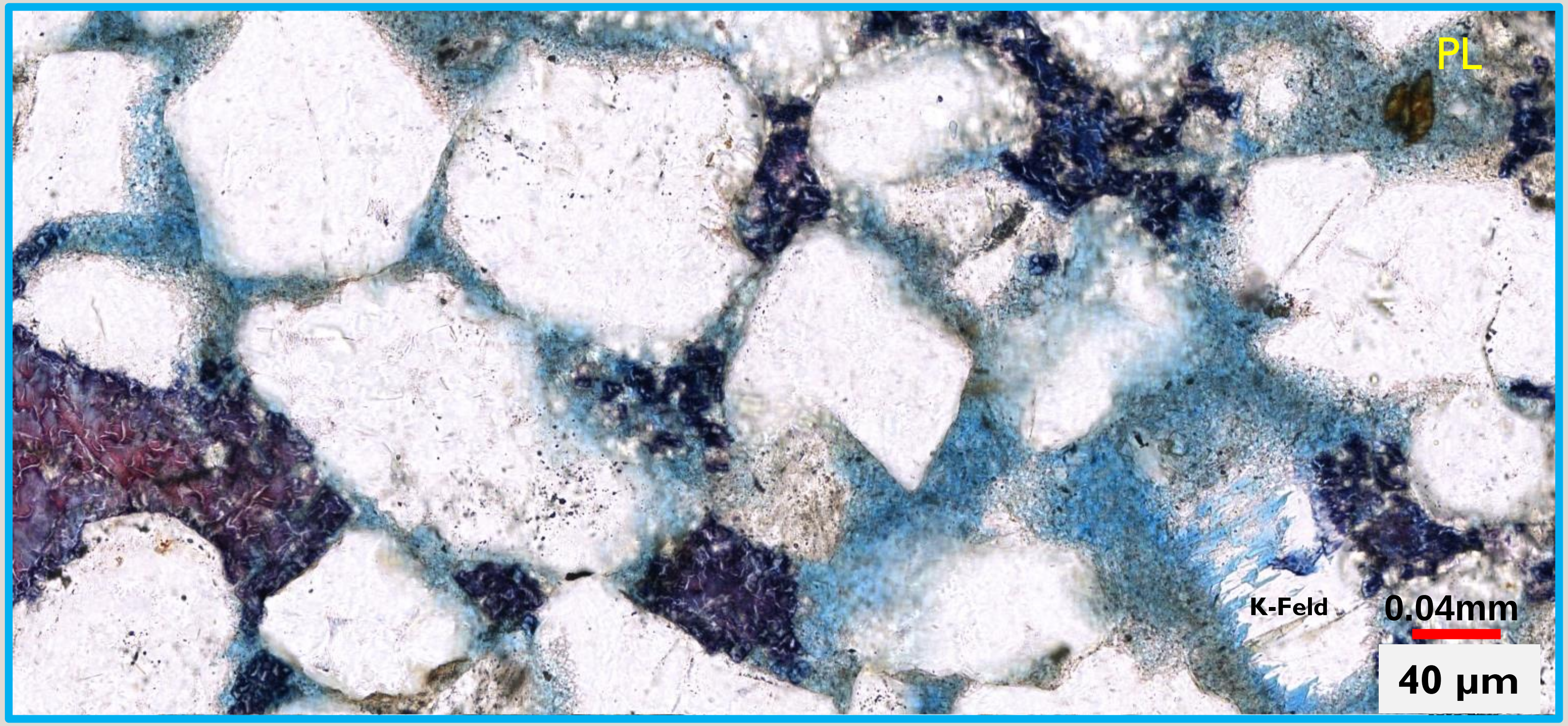
XRD Data



Hoxbar Arpelar Core 1386.5 ft – Thin Section Image

Sample ID	Grain Density	Gas filled porosity	Liquid filled porosity	Total Porosity (%)	Sw	So
	g/cc	P.U	P.U	P.U	%	%
GWG-ARP.42W-1386.5	2.62	10.8	4.8	15.6	29	2

Distributary Mouth Bar?

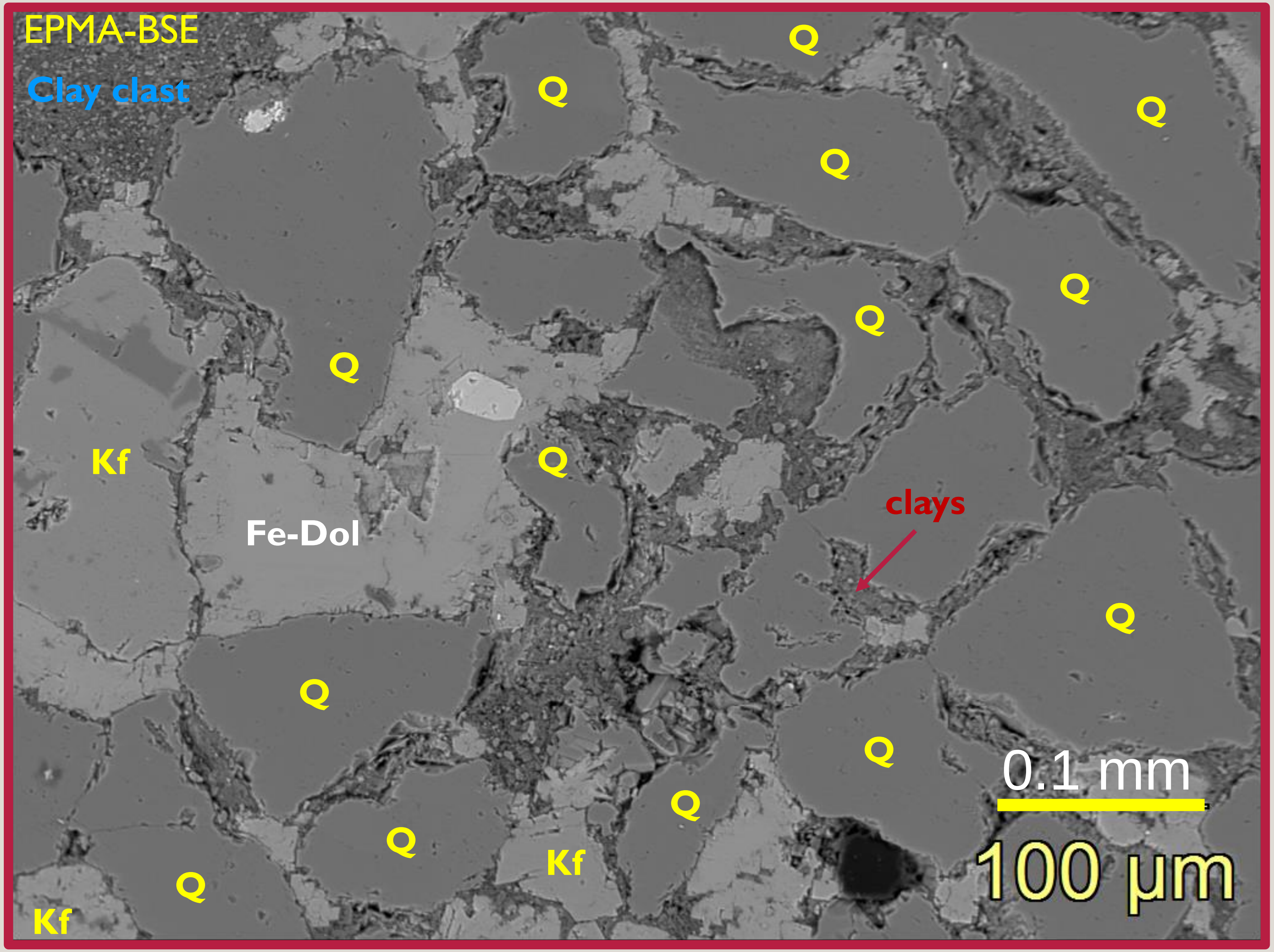


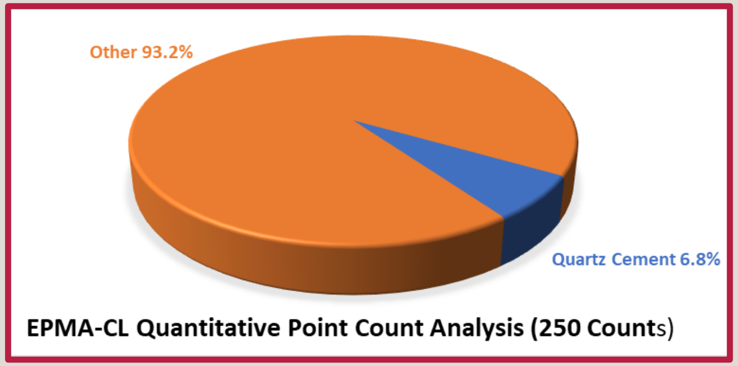
GRAIN SIZE		
Statistic	Value	Description
MEAN	197	Fine Sand
SORTING	1.346	Well Sorted
SKEWNESS	-0.338	Symmetrical
KURTOSIS	2.759	Mesokurtic

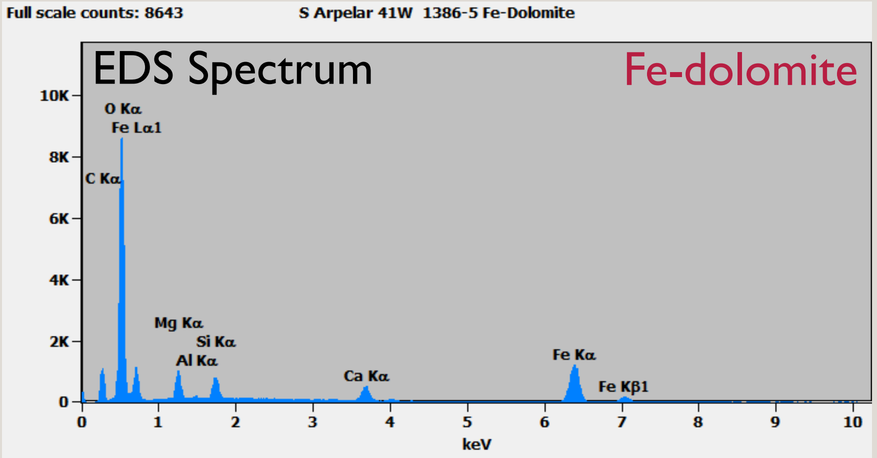
Whole Thin Section Image: framework grains: dominantly quartz, minor feldspars, sedimentary rock fragments, minor detrital carbonate fragments, zircon, rutile and pore filling calcite and clays.

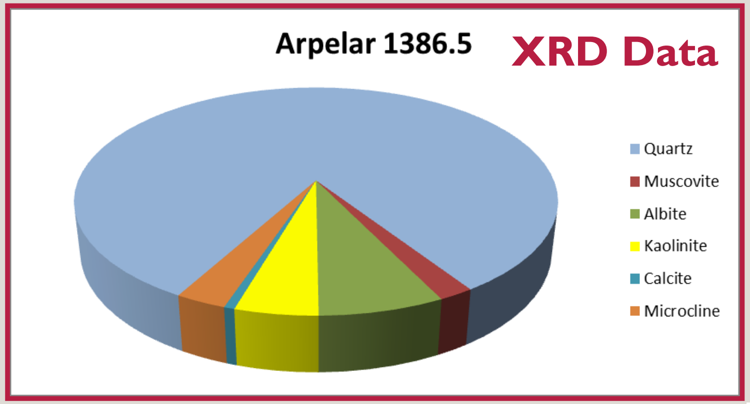
Where is the porosity? Must be either tied up in clays or micro/nano? porosity!

Hoxbar Arpelar Core 1386.5 ft – BSE Image



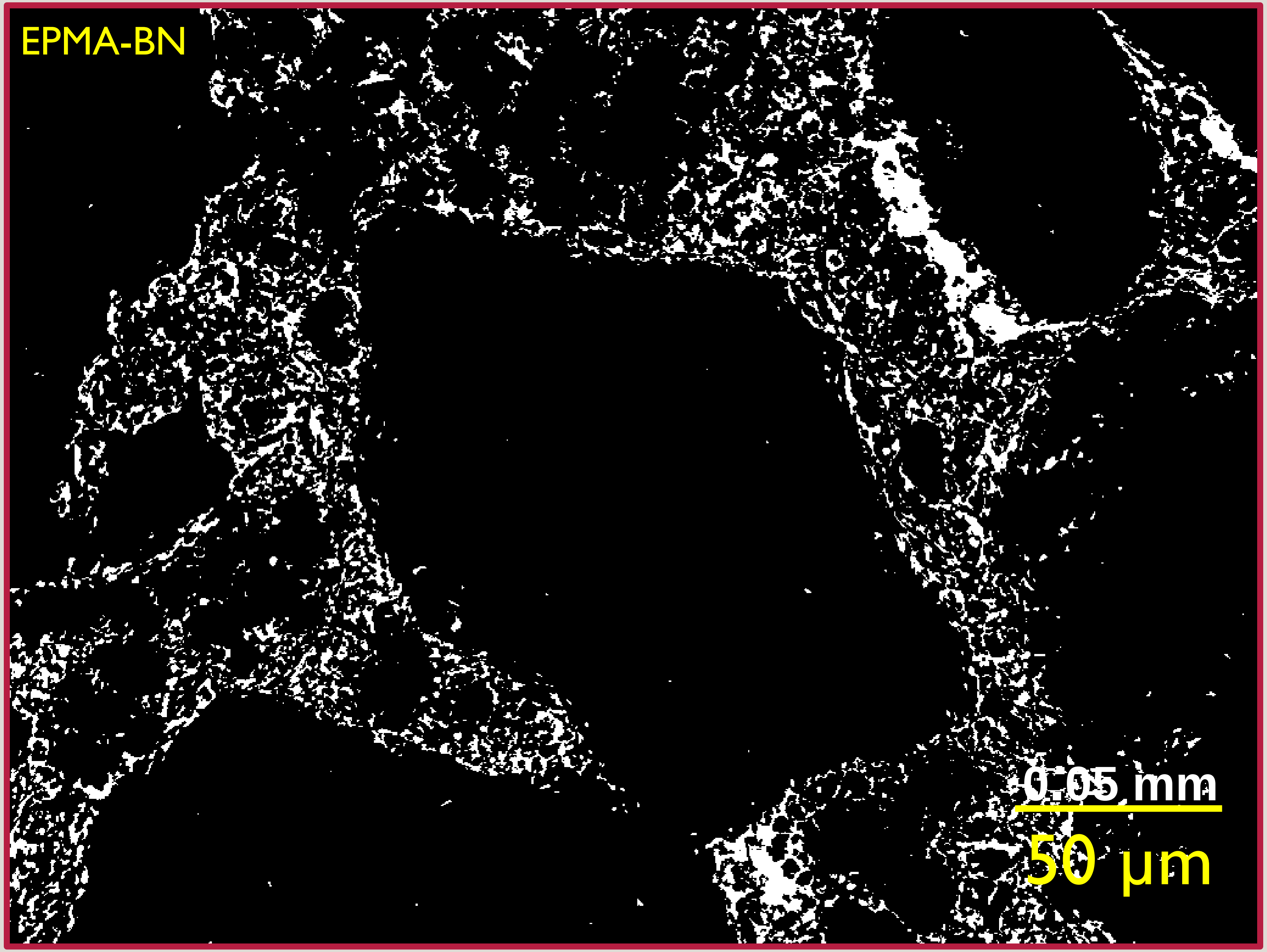






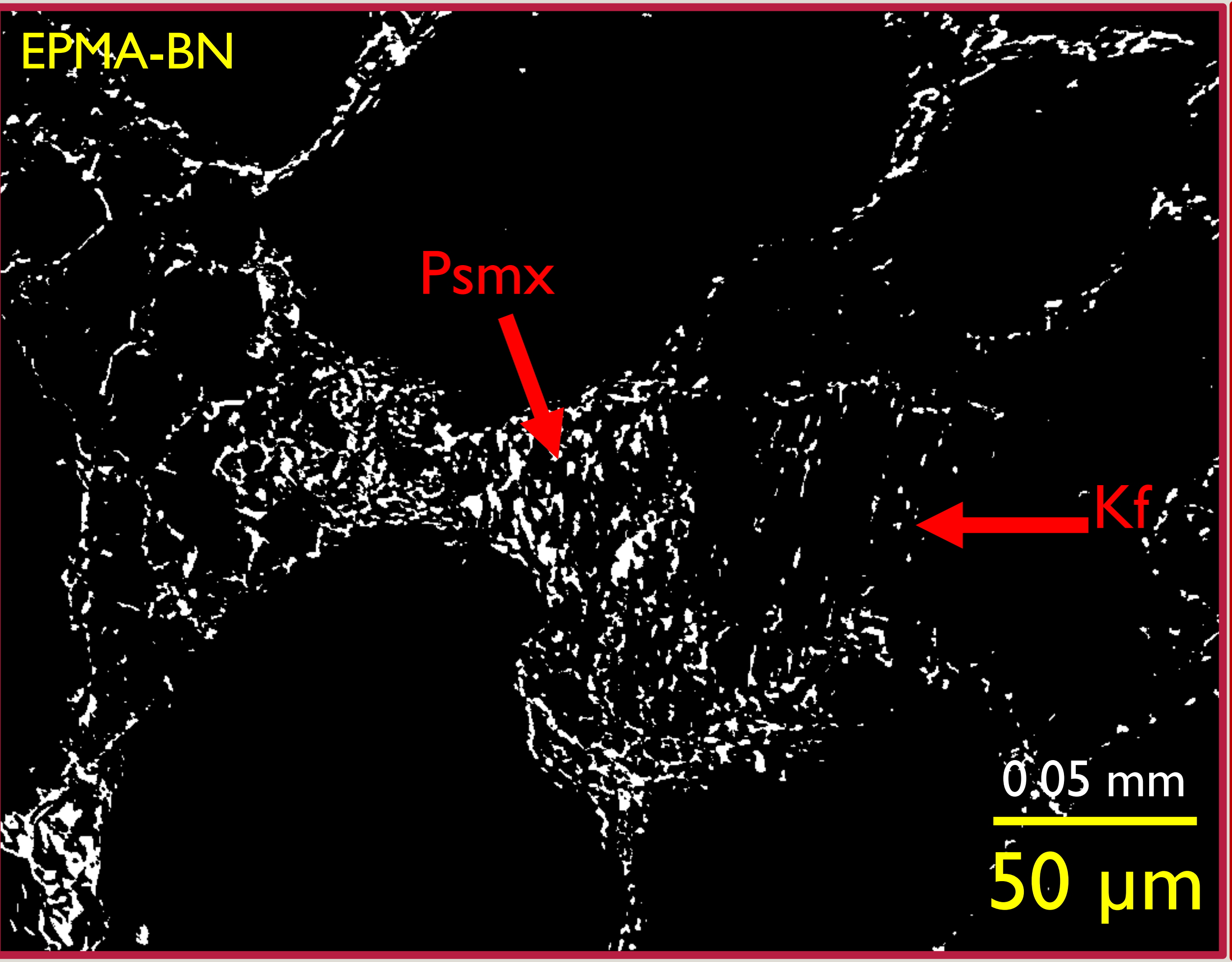
Hoxbar Arpelar Core 1386.5 ft – SEM-BN Image

Using the SEM-BSE image holes in the rock (white portions in the binary image) can be defined which are used to quantify pore geometries and make prediction of reservoir parameters. These images are also used to create secondary recovery schemas.

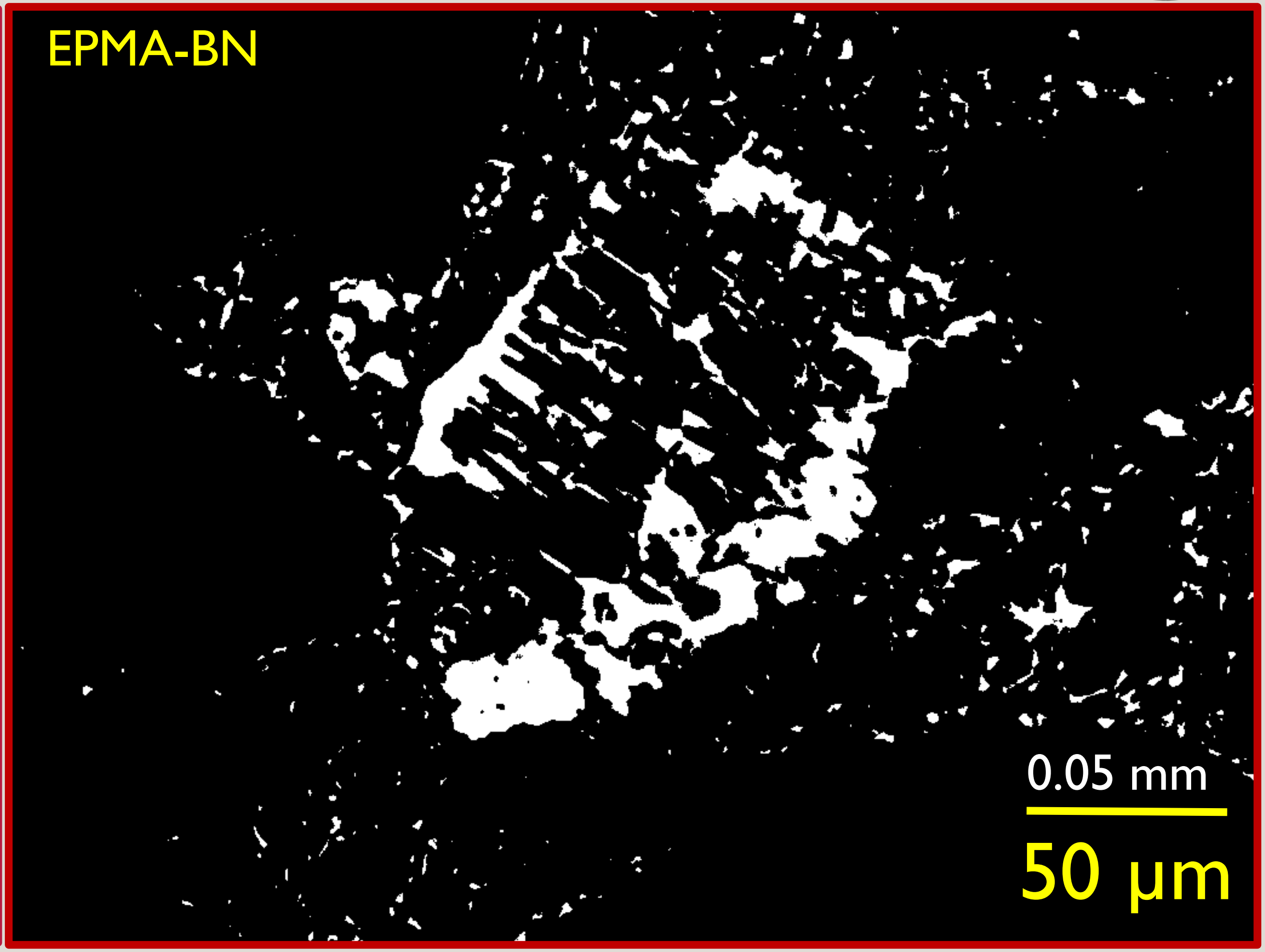


Note the larger pores are connected via narrow pore throats – something that directly affects recoverability and EOR.

Hoxbar Arpelar Core 1386.5 ft – BSE-BN Images



A partially dissolved K-Feldspar (Kf) with a locally formed Pseudomatrix (Psmx)



A partially dissolved Plagioclase which is also albitized

Hoxbar Sandstone Compositional Plot

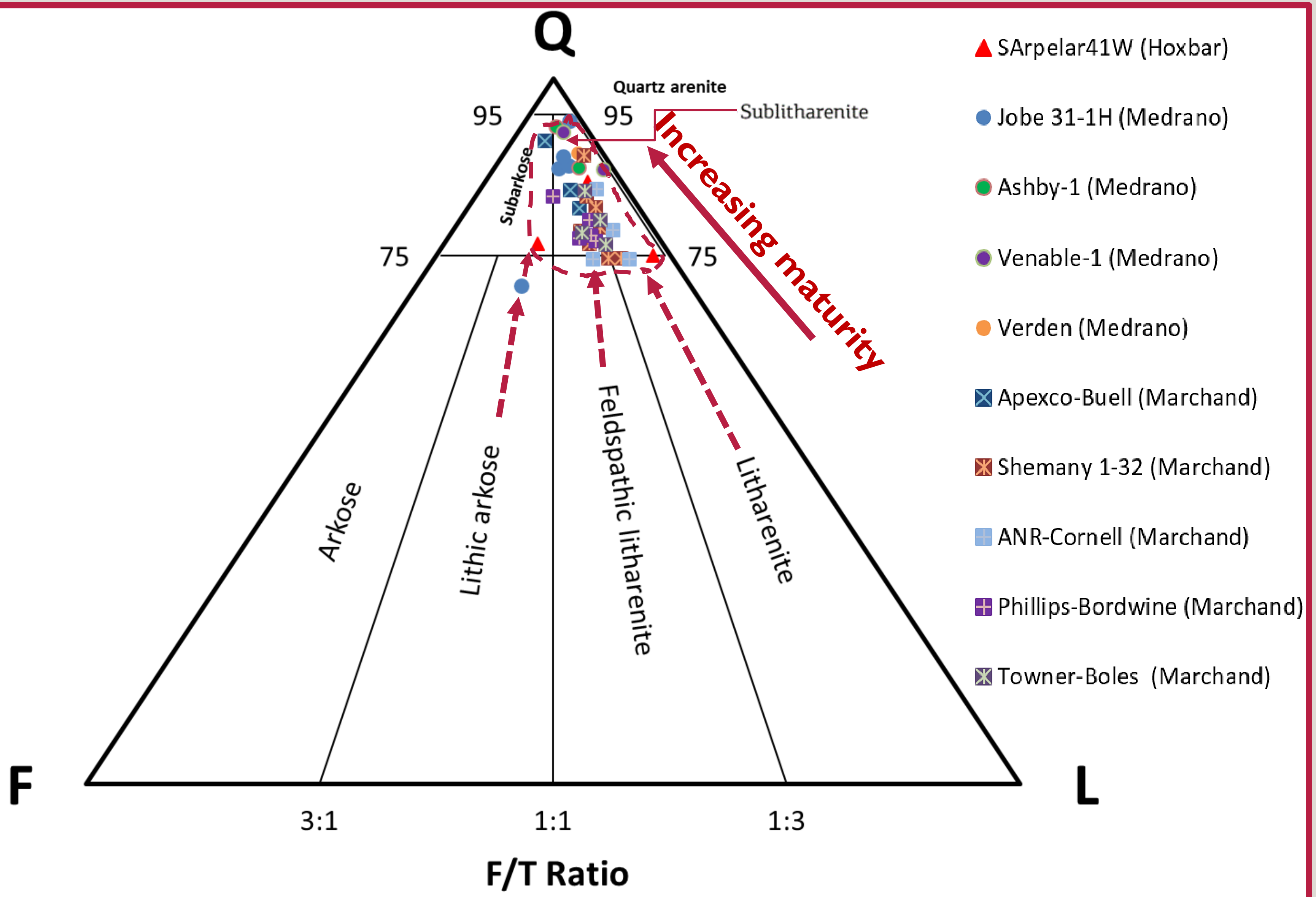
Q = monocrystalline and polycrystalline quartz (excluding chert)

F = monocrystalline feldspar

L = rock fragments (igneous, metamorphic, and sedimentary, including chert)

Plot based on Folk's (1968) sandstone compositional diagram

The dominant sand composition of the Hoxbar Group is Sublitharenite



Analysis based on 250-point counts per thin section

Hoxbar Feldspar Compositional Plot

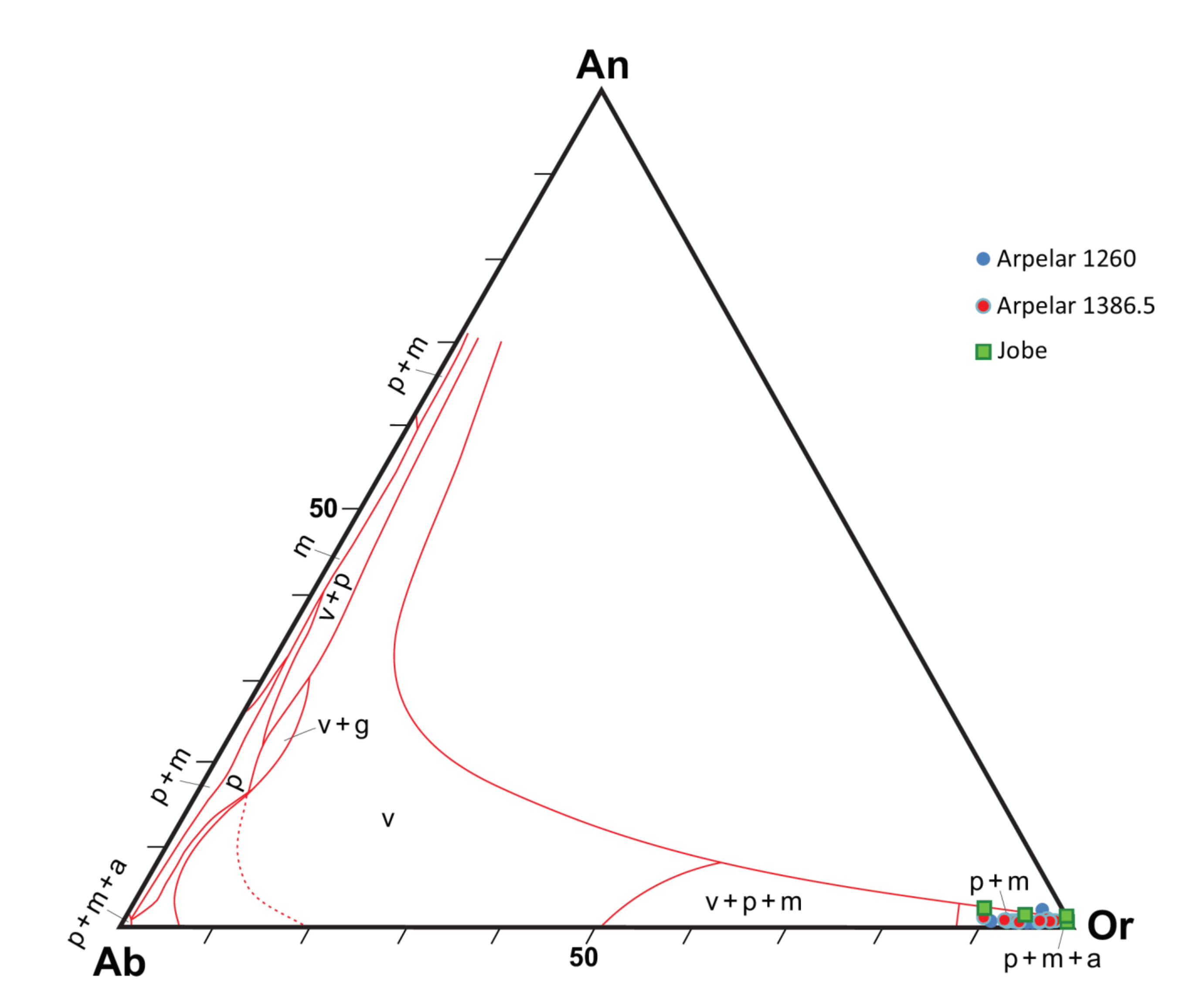
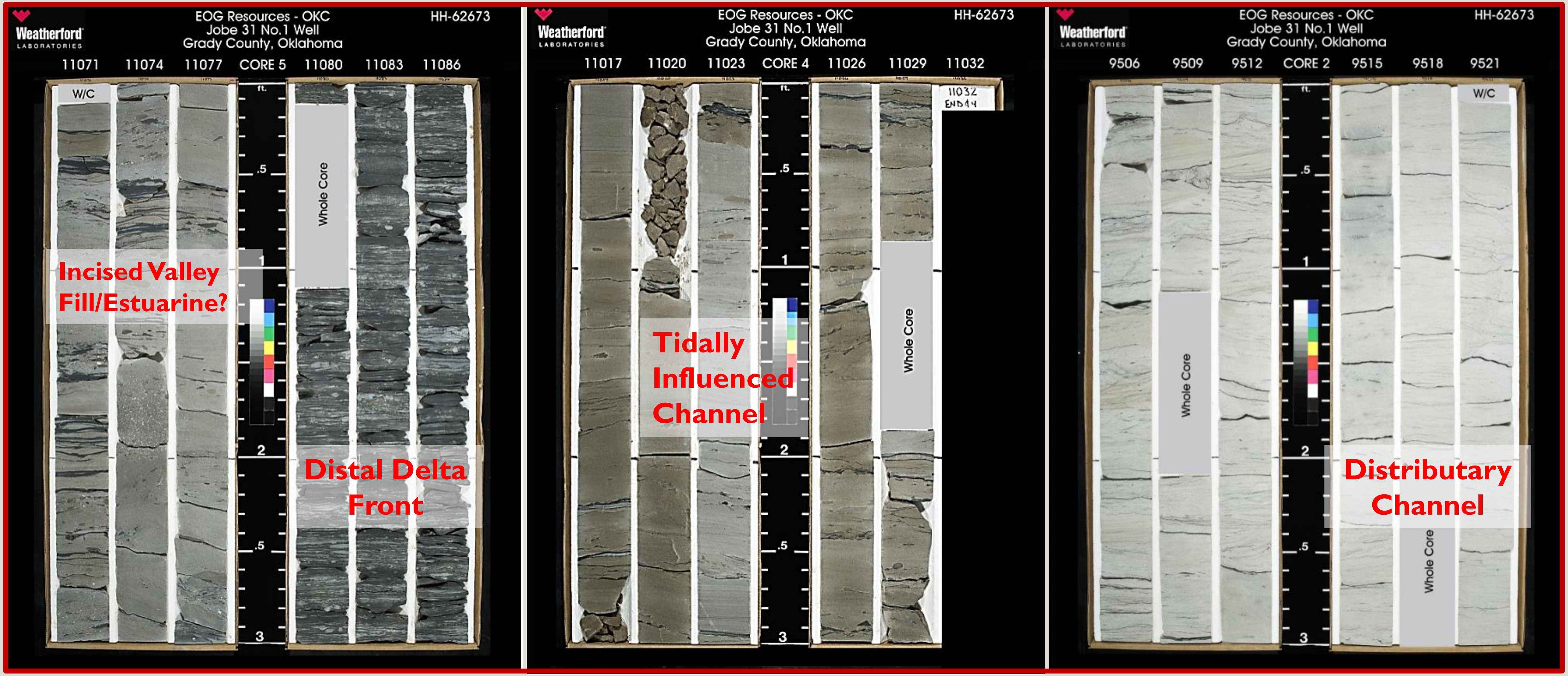


Diagram showing compositional range of eight provenance groups of feldspar: v = volcanic; p = plutonic; m = metamorphic; v+g =volcanic or granophyre, v+p = volcanic or plutonic; p+m = plutonic or metamorphic; v+p+m = volcanic, plutonic or metamorphic; p+m+a = plutonic, metamorphic, or authigenic. Analyses to the left of the dashed line in the volcanic (v) field and from uncommon low-temperature rhyolites of extreme composition (Turley and Nash, 1980; Evans, 1978).

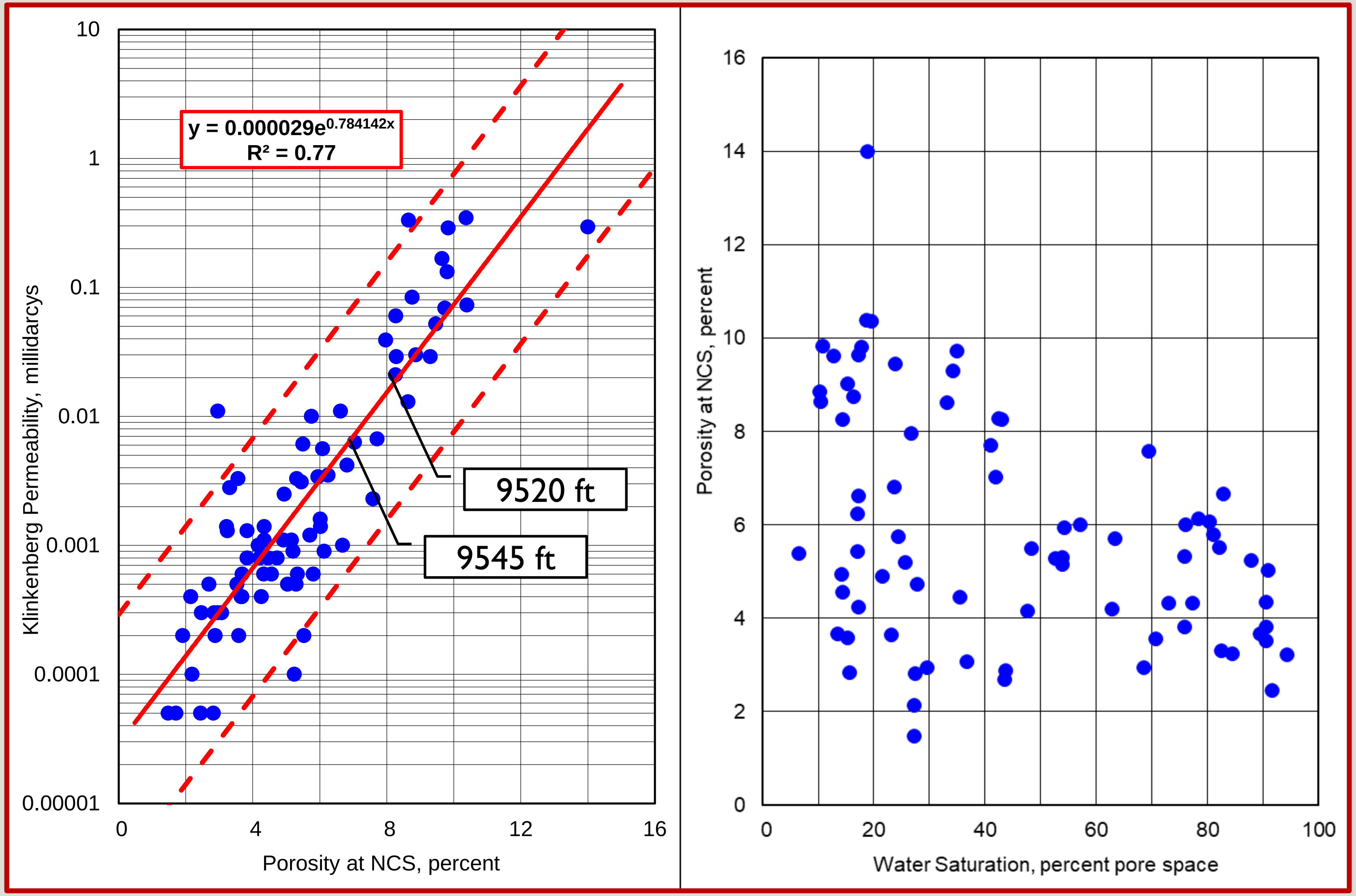
Perthite inclusions commonly <100 microns commonly occur only in small plutons (Boggs, Jr., 1992)

Jobe 31-1H Medrano Sandstone- Core Photos



From 10, 947' section, there is a well-expressed Zoophycos, placing this section of the core further offshore from prodelta or offshore transition, but not necessarily in "deep water"

Jobe 31-1H Medrano Sandstone - Porosity vs. Perm & Porosity vs. Fluid Saturation

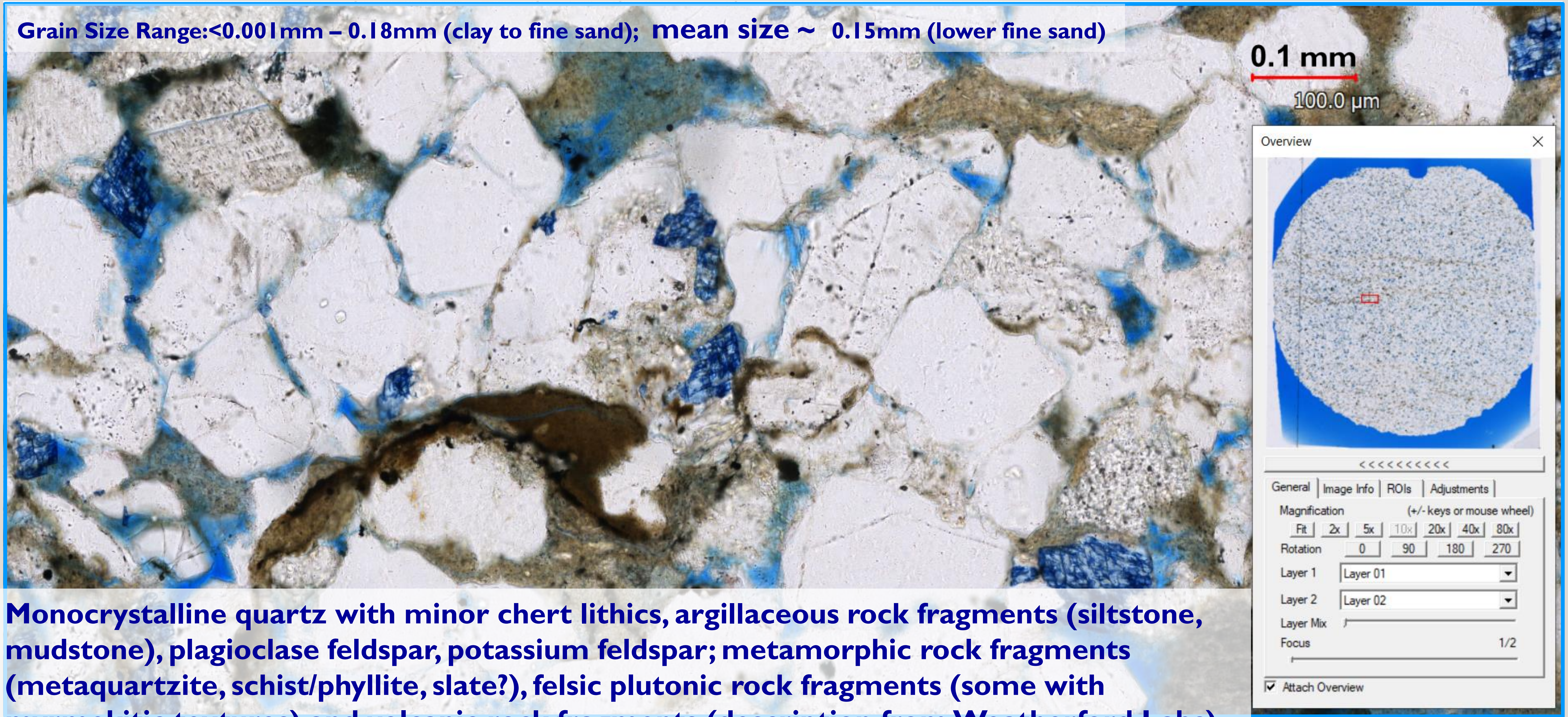


Plot of the porosity versus Klinkenberg Permeability (800 psi confining pressure) on left and plot of porosity versus water saturation on the right. The plot on the left is typical for rocks of complex pore geometry where the original properties normally controlled by grain size and sorting are significantly altered by mechanical and chemical diagenesis. This detail is recognized by the potential range of permeability being approximately two orders of magnitude (shown by dashed lines) or more for a given porosity (Comisky et al., 2007: SPE 110050).

These reservoirs can be considered as unconventional!

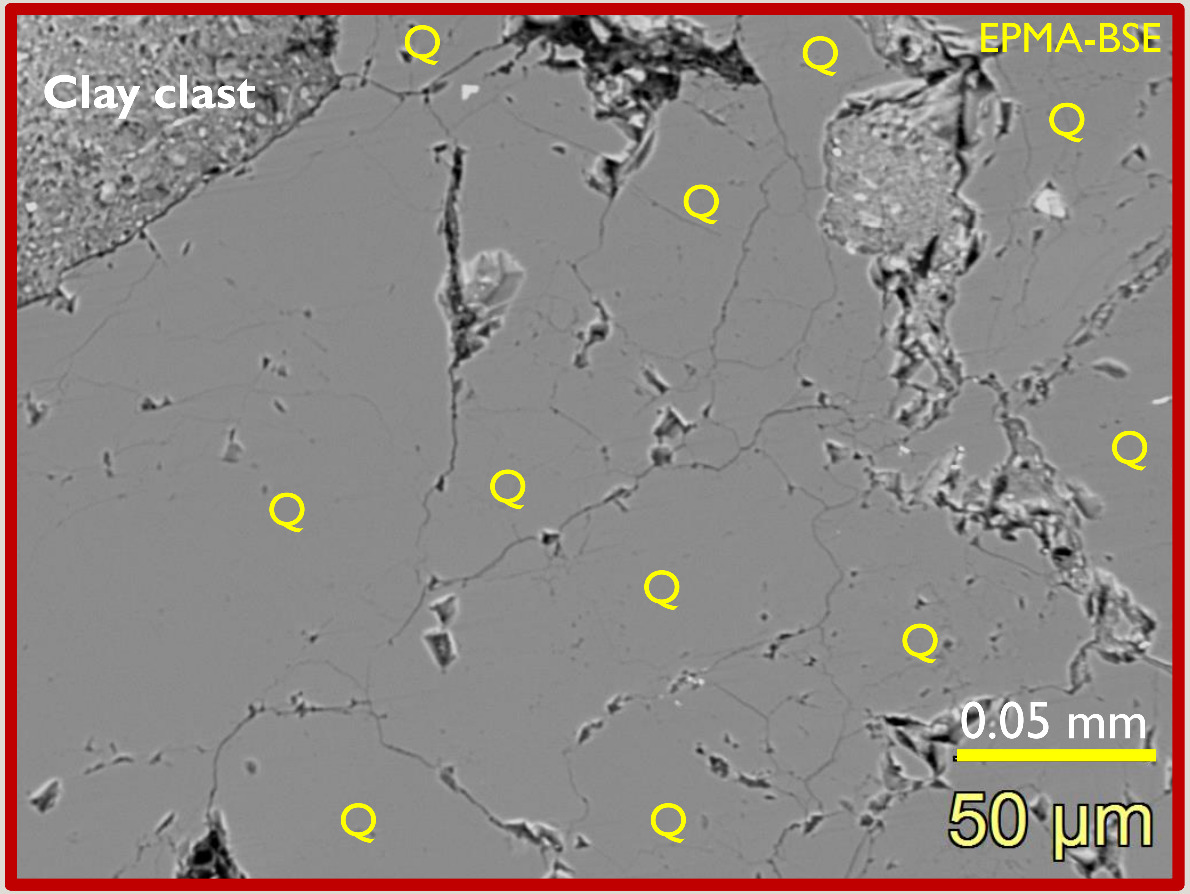
Jobe 31-1H Medrano Sandstone 9520ft

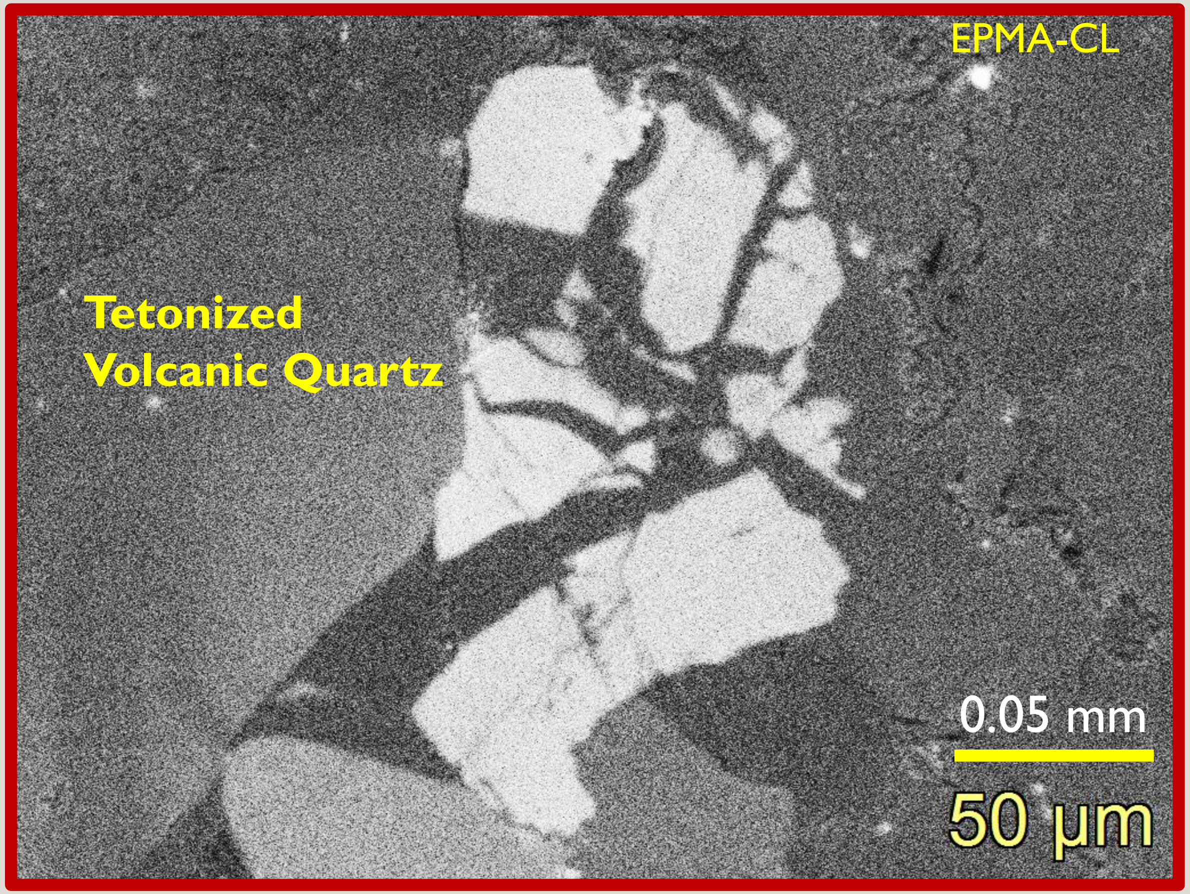
Grain Size Range:<0.001mm – 0.18mm (clay to fine sand); mean size ~ 0.15mm (lower fine sand)

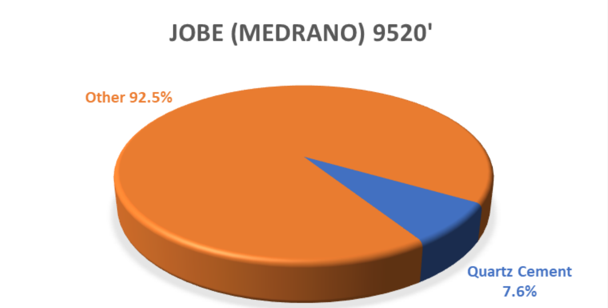


Monocrystalline quartz with minor chert lithics, argillaceous rock fragments (siltstone, mudstone), plagioclase feldspar, potassium feldspar; metamorphic rock fragments (metaquartzite, schist/phyllite, slate?), felsic plutonic rock fragments (some with myrmekitic textures) and volcanic rock fragments (description from Weatherford Labs)

Jobe 31-1H Medrano Sandstone 9520ft

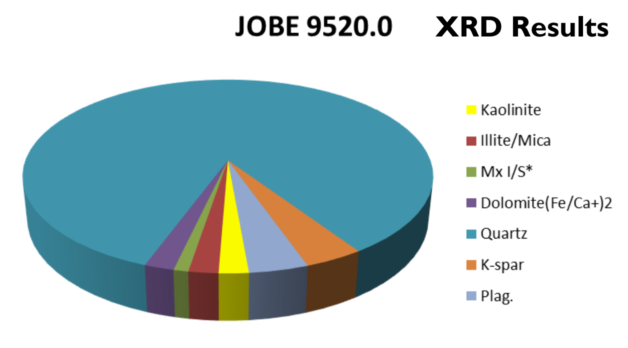




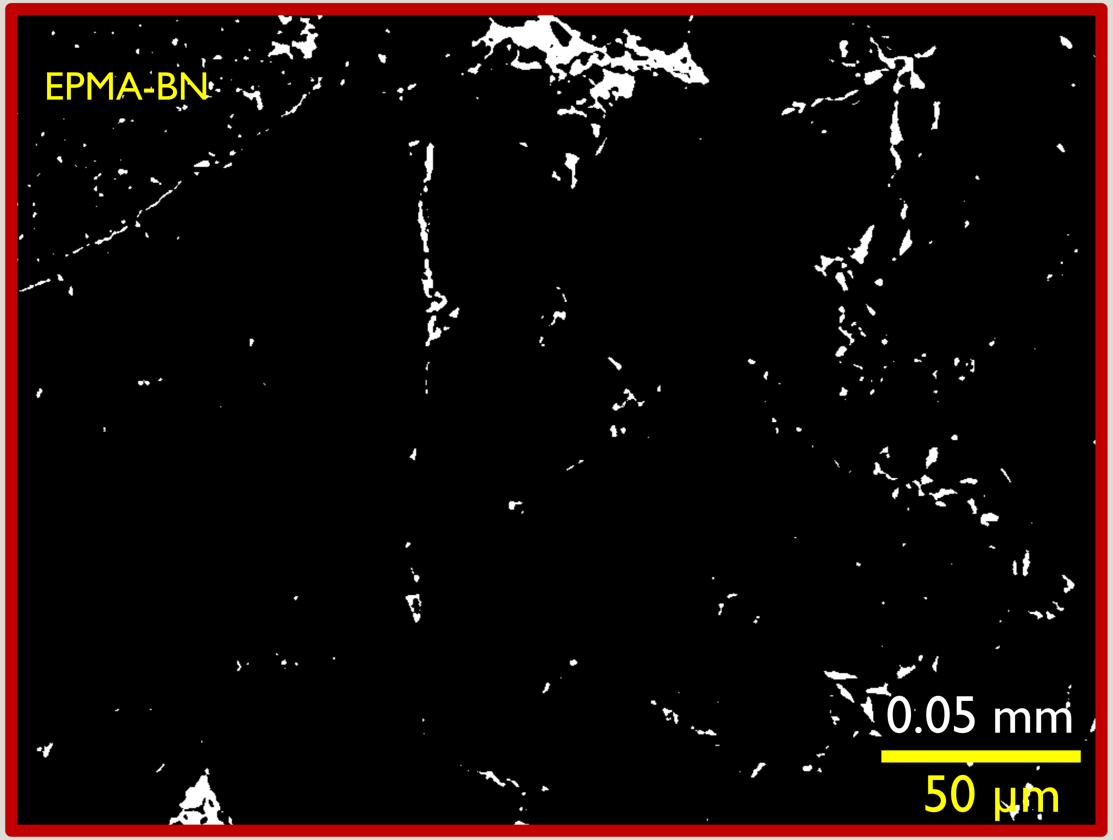


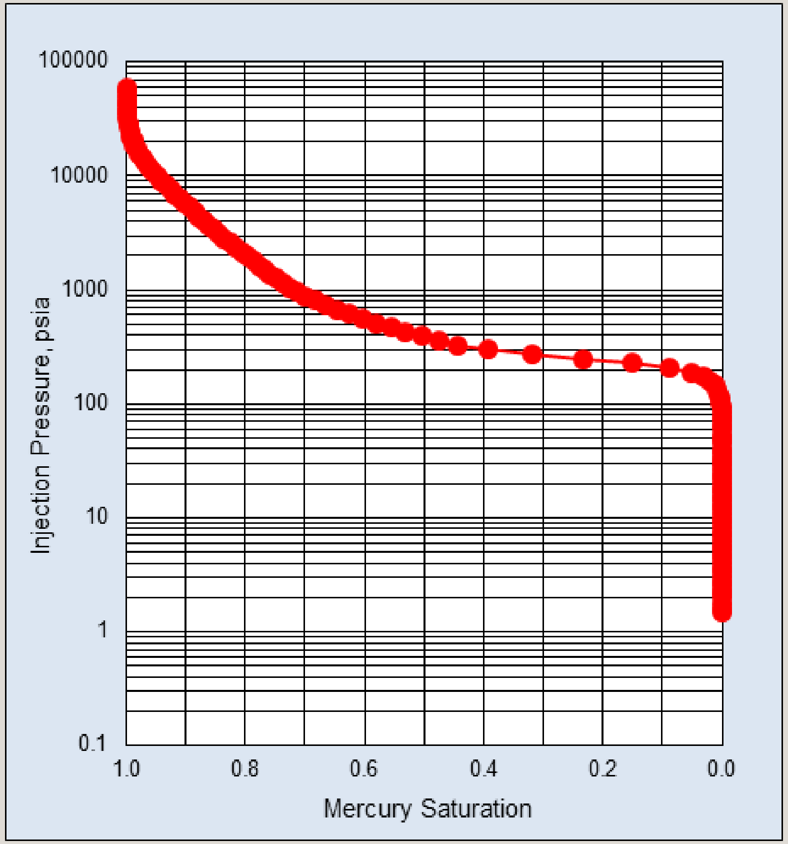
EPMA-CL Quantitative Point Count Analysis (250 Counts)

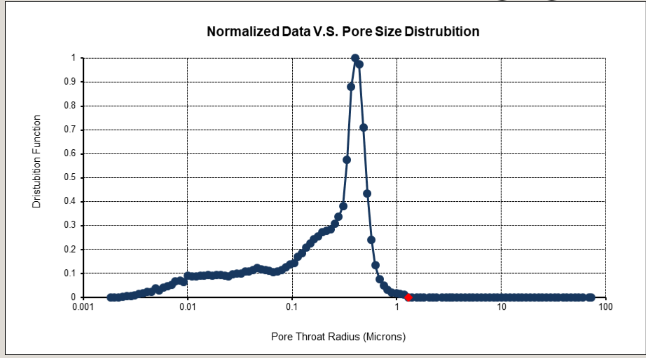
Q=Quartz



Jobe 31-1H Medrano Sandstone 9520ft (MICP)





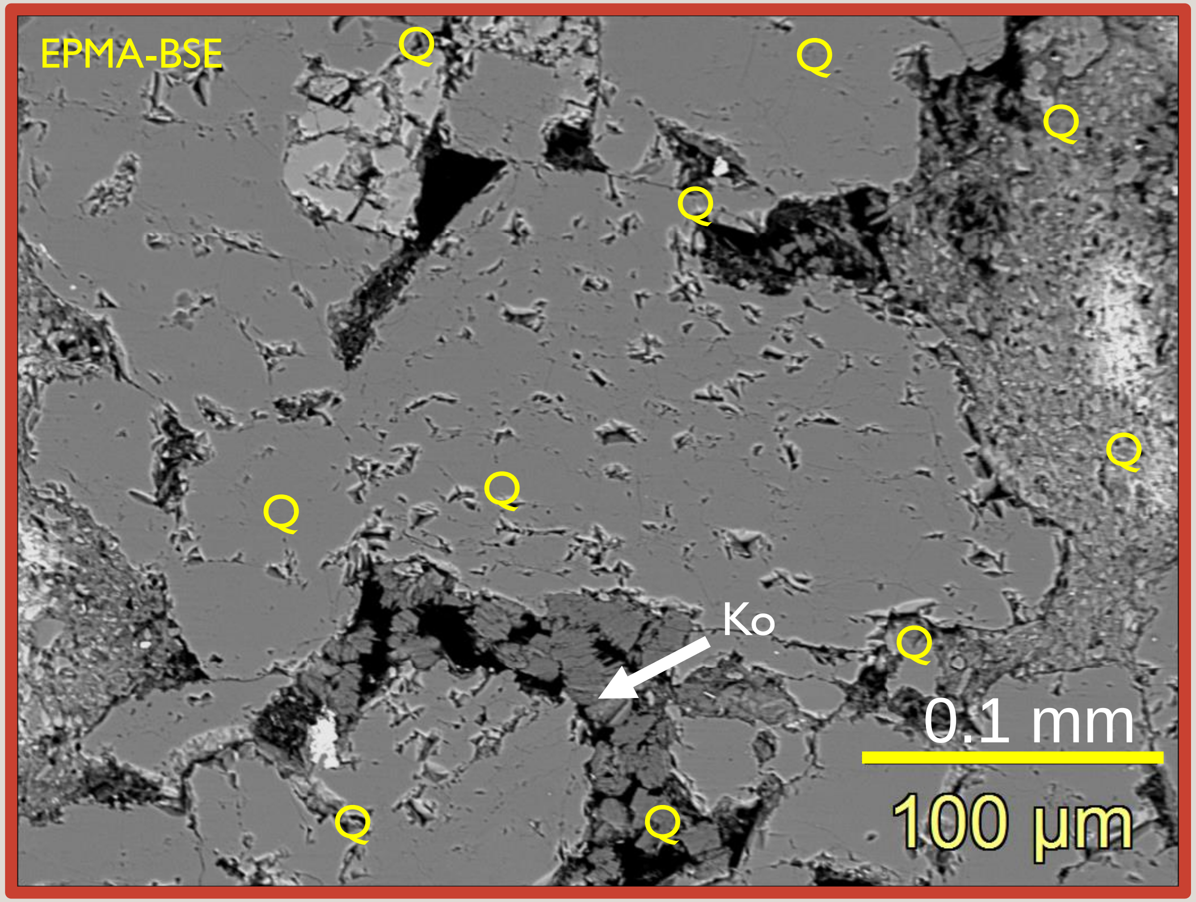


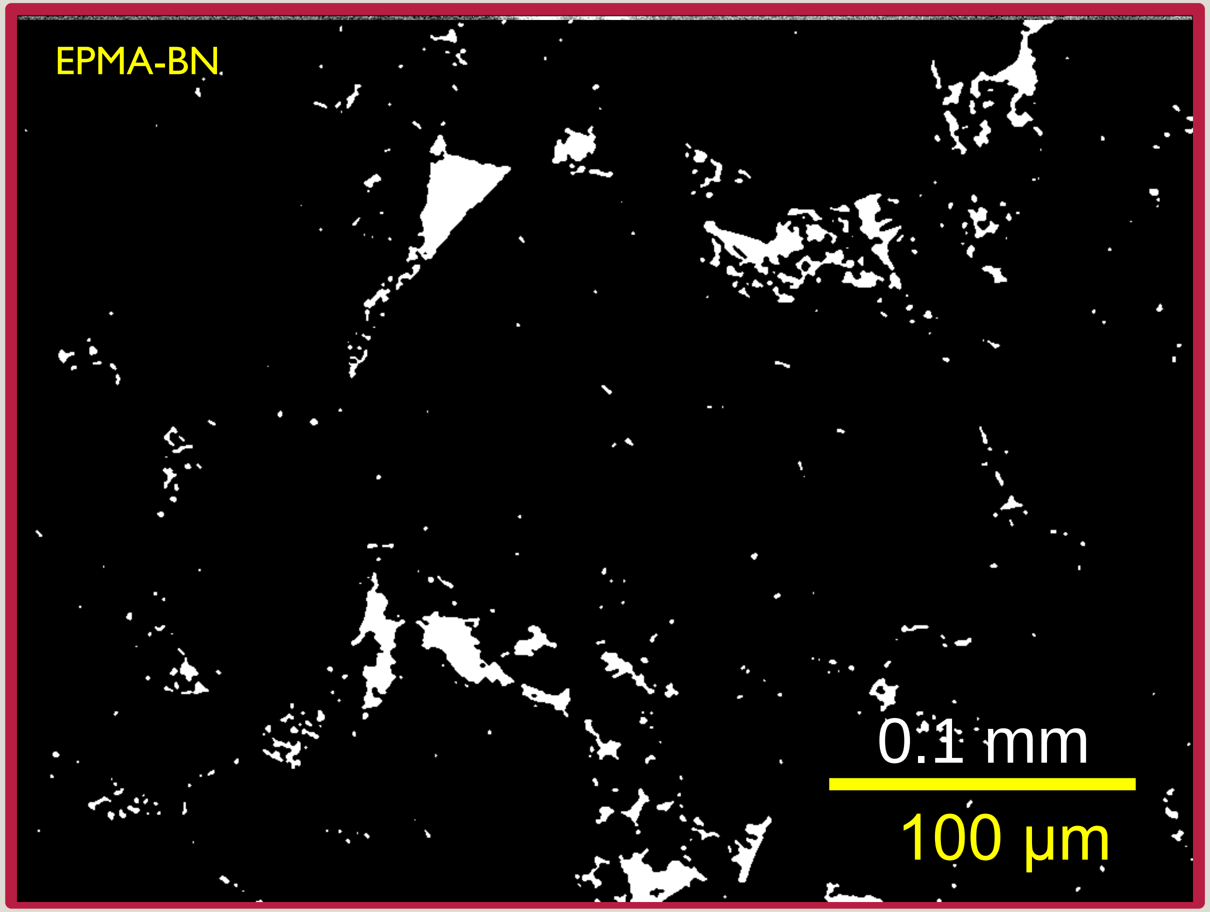
Note: the combination of the MICP and binary image indicates that this sample can be classified as an unconventional reservoir.

Mercury Injection					
Pore Volume, cc	Bulk Volume, cc	Grain Volume, cc	Porosity, fraction	Grain Density, grams/cc	Sample Weight, grams
0.95	11.72	10.76	0.081	2.65	28.52

The MICP plot shows relatively high displacement pressure and steeper curve, indicating relatively poor rock quality. The PSD plot show predominantly nanoporosity (<1 micron). These pores are potentially connected as indicated by the MICP plot.

Jobe 31-1H Medrano Sandstone 9520ft

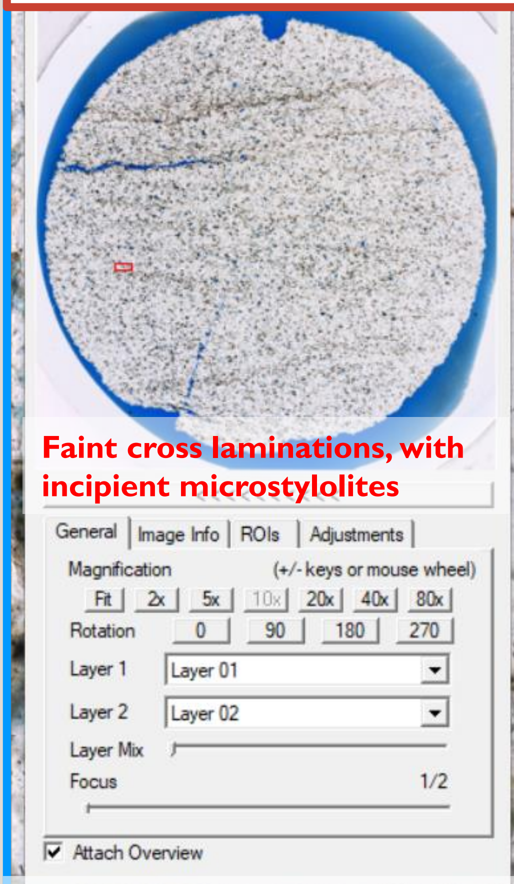




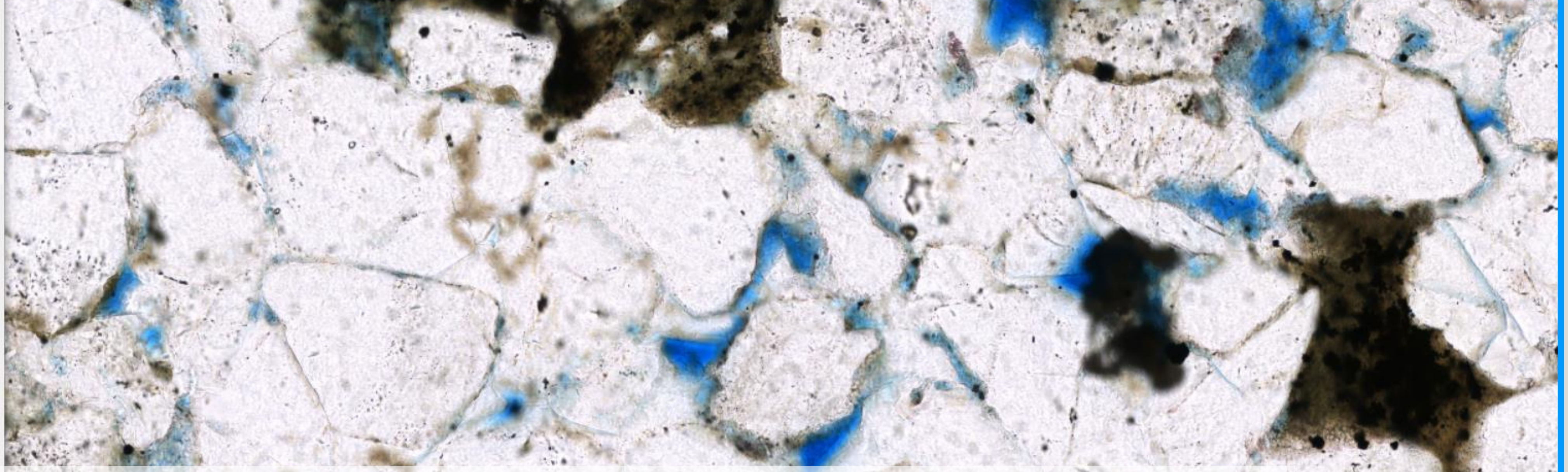
Minor secondary intragranular pores and moldic pores associated with partially dissolved grains; trace to minor primary intergranular pores; micropores are associated with partially leached grains and authigenic clay.

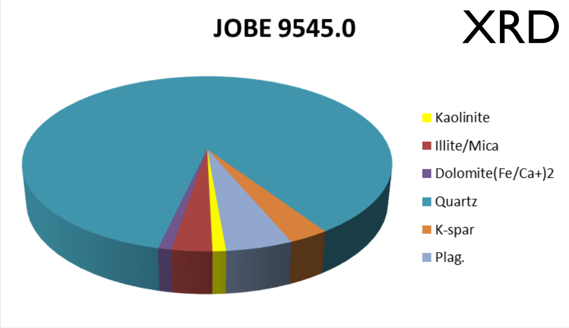
Jobe 31-1H Medrano Sandstone 9545ft

Grain Size Range < 0.001mm – 0.25mm (clay to upper fine sand): $\bar{x}$ = 0.17mm (lower fine sand)



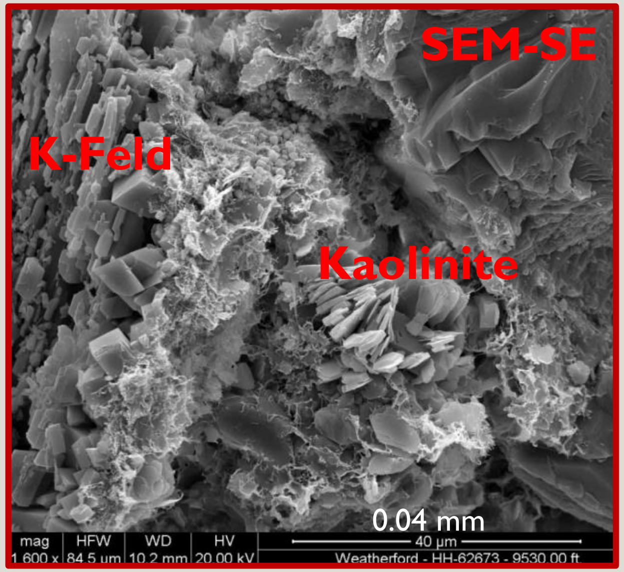
Faint cross laminations, with incipient microstylolites

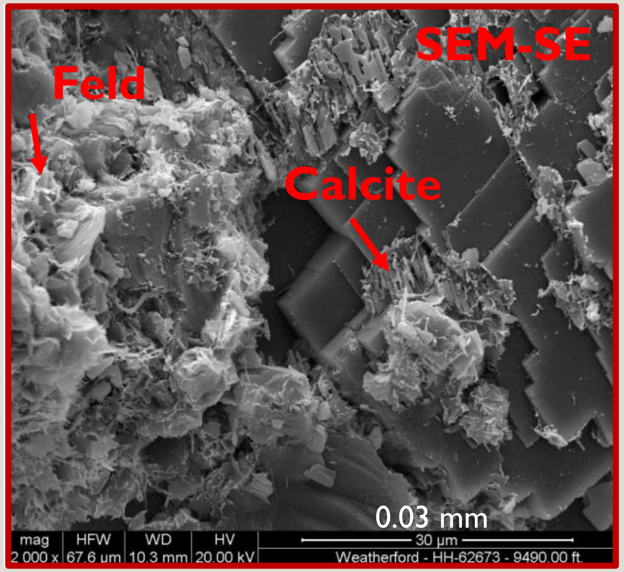


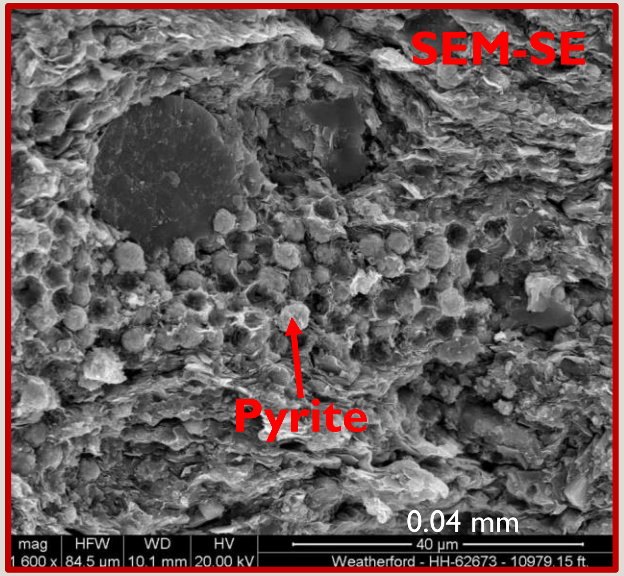


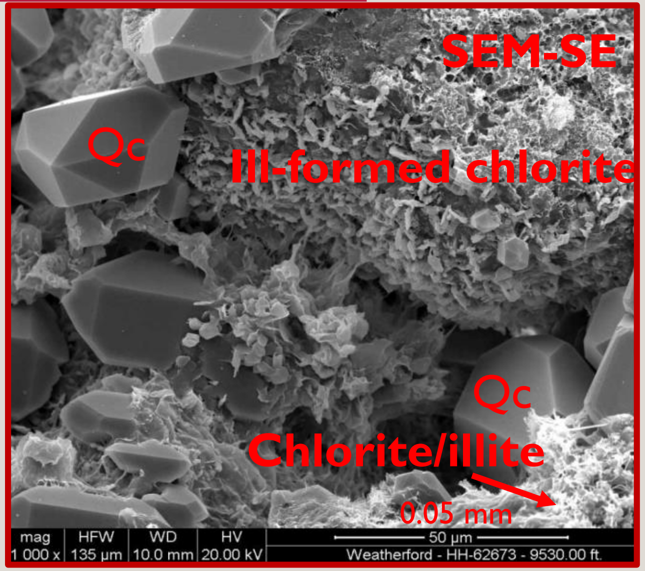
Monocrystalline quartz: Minor: Chert lithics; argillaceous rock fragments (siltstone, mudstone); plagioclase feldspar; potassium feldspar; metamorphic rock fragments (metaquartzite, schist/phyllite, slate?); felsic plutonic rock fragments (some with myrmekitic textures); volcanic rock fragments. Accessory: Heavy minerals; muscovite; clay-coated grains (chamosite ooids?); organic material associated with microstylolites

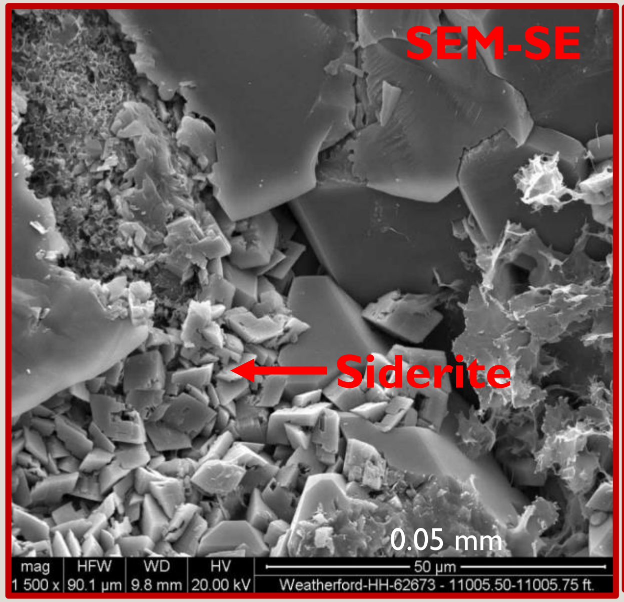
Jobe 31-1H Medrano Sandstone - SEM Analysis

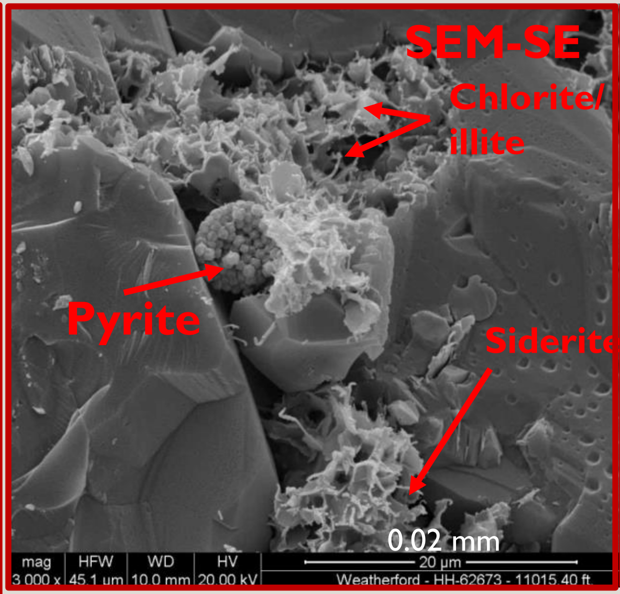


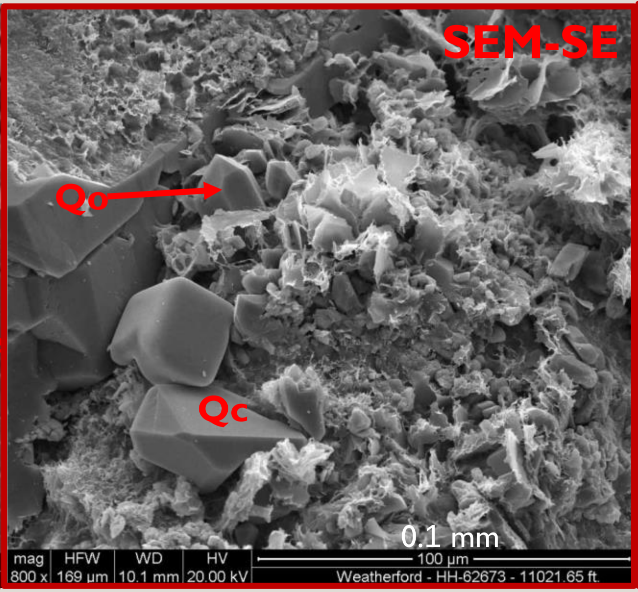


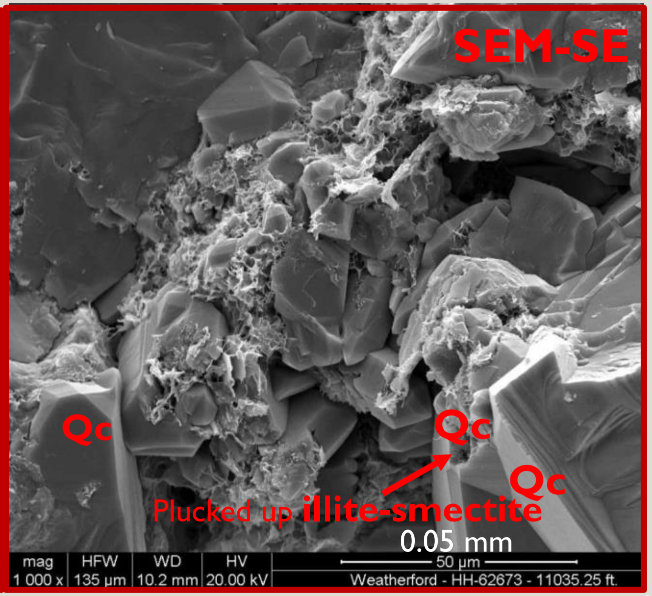




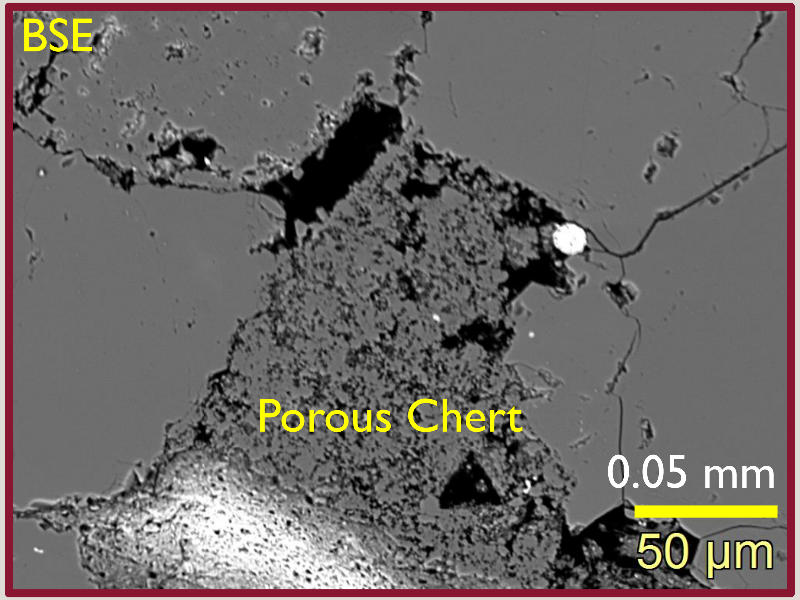


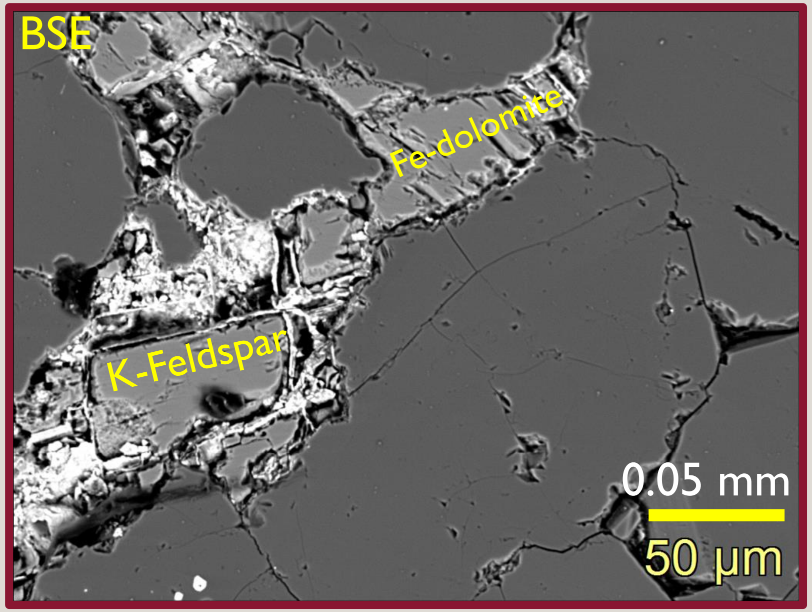


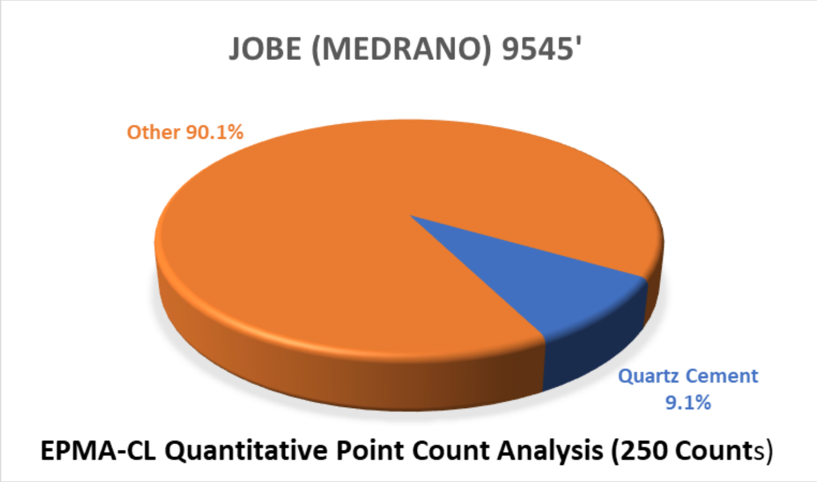


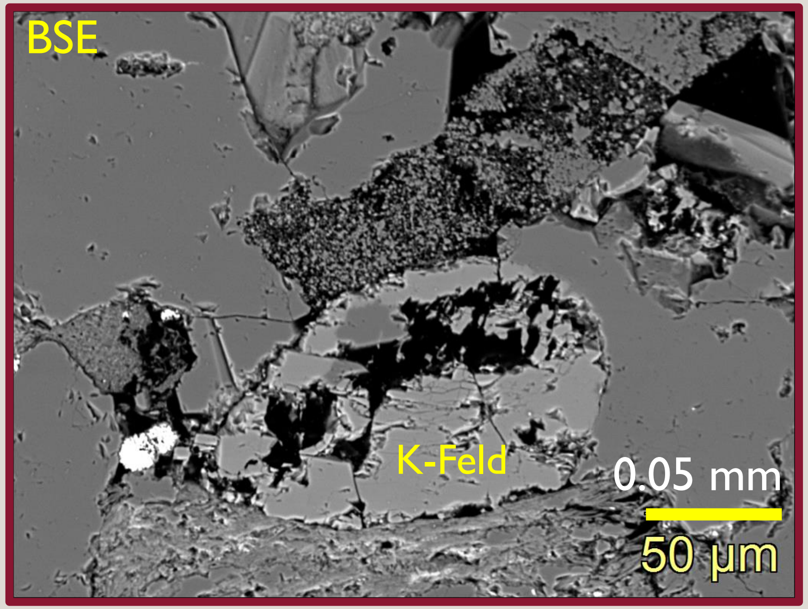


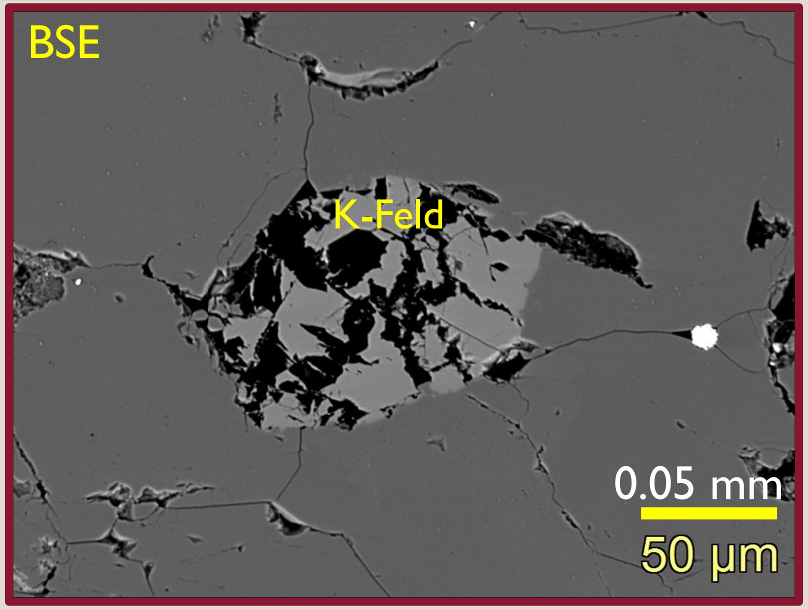
Jobe 31-1H Medrano Sandstone, 9545ft – EPMA Analysis





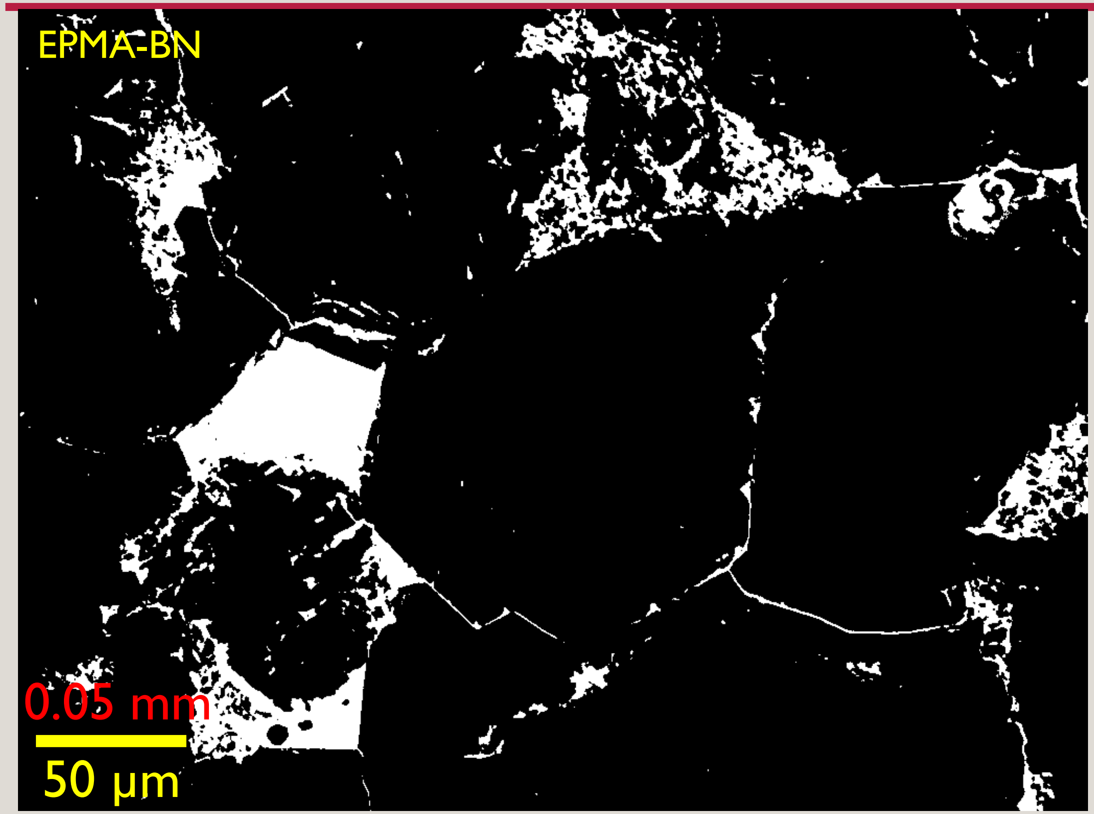


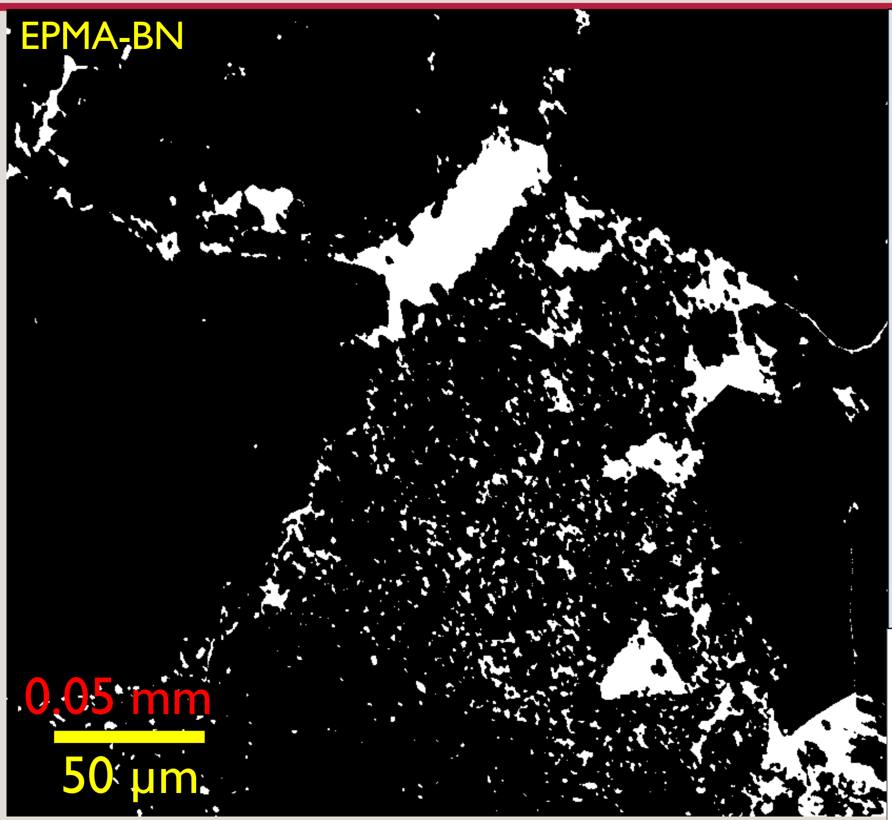


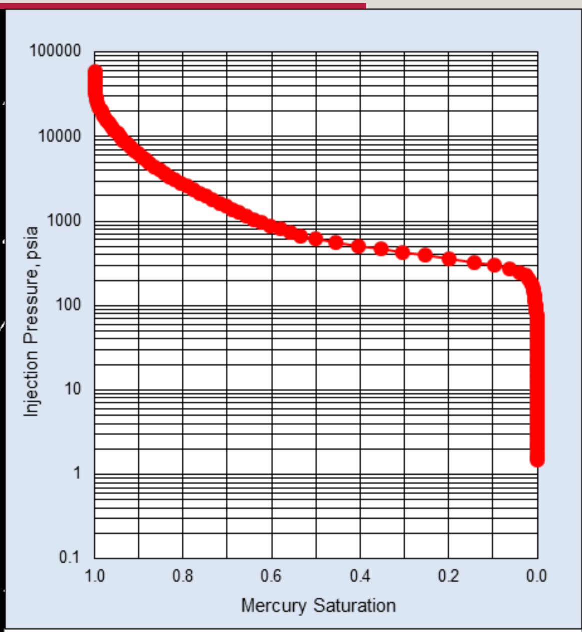


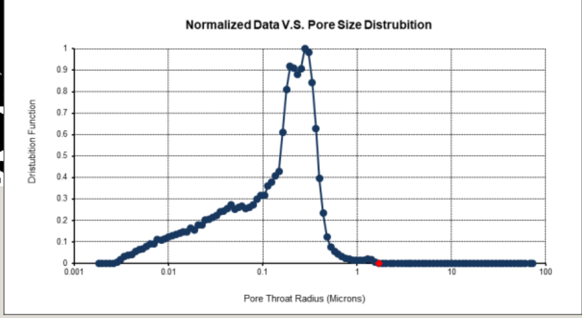
Note the feldspars being dissolved as well as the porous chert being altered in situ. Both of these can easily supply the silica needed for the increase in quartz cement observed in this sample (pie chart above).

Jobe 31-1H Medrano Sandstone, 9545ft – MICP Analysis









Mercury Injection					
Pore Volume, cc	Bulk Volume, cc	Grain Volume, cc	Porosity, fraction	Grain Density, grams/cc	Sample Weight, grams
0.68	11.97	11.29	0.057	2.65	29.96

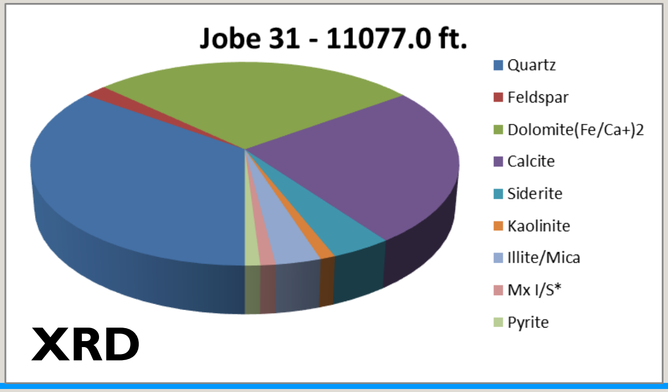
(Note the overall low porosity – red arrow) similar to the previous result. Outlines of grains can be observed in this image. The MICP plot suggests these nanopores are connected to the overall flow system by much smaller pore throats.

Jobe 31-1H Marchand Sandstone 11077ft

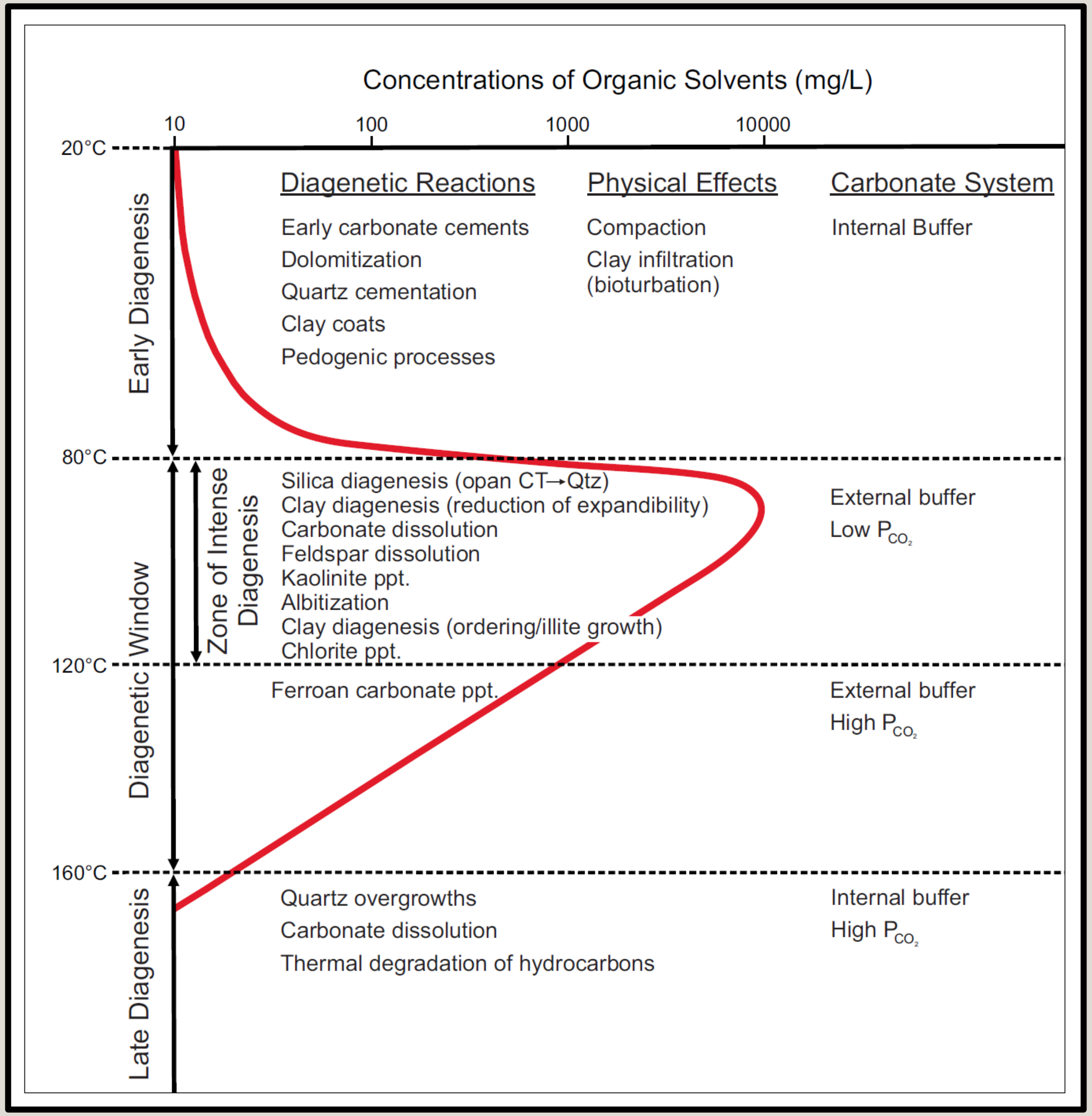
Lithology: Calcareous to dolomitic sandstone
Sedimentary Fabric: Faint disturbed cross laminations; possible siltstone clast or silt-filled burrow?
Visual Sorting: Moderate
Grain Size Range: <0.001mm – 0.60mm (clay to medium sand)
Average Grain Size: 0.30mm (medium sand)
Compaction: Moderate

Detrital grains consist predominantly of quartz, with minor chert fragments . Brachiopod fragments, echinoderm fragments, and bryozoan fragments (are replaced/recrystallized by calcite and dolomite. Ferroan dolomite occurs as replacement and cement. Calcite cement occludes intergranular pores.
The clay coating associated with a possible chamosite ooid is replaced by calcite and ferroan dolomite. Ferroan dolomite replaces calcite cement (description from Weatherford Labs).

A general view of this calcareous sandstone is shown in this low magnification photomicrograph. The left half of the sample is stained for carbonate minerals.



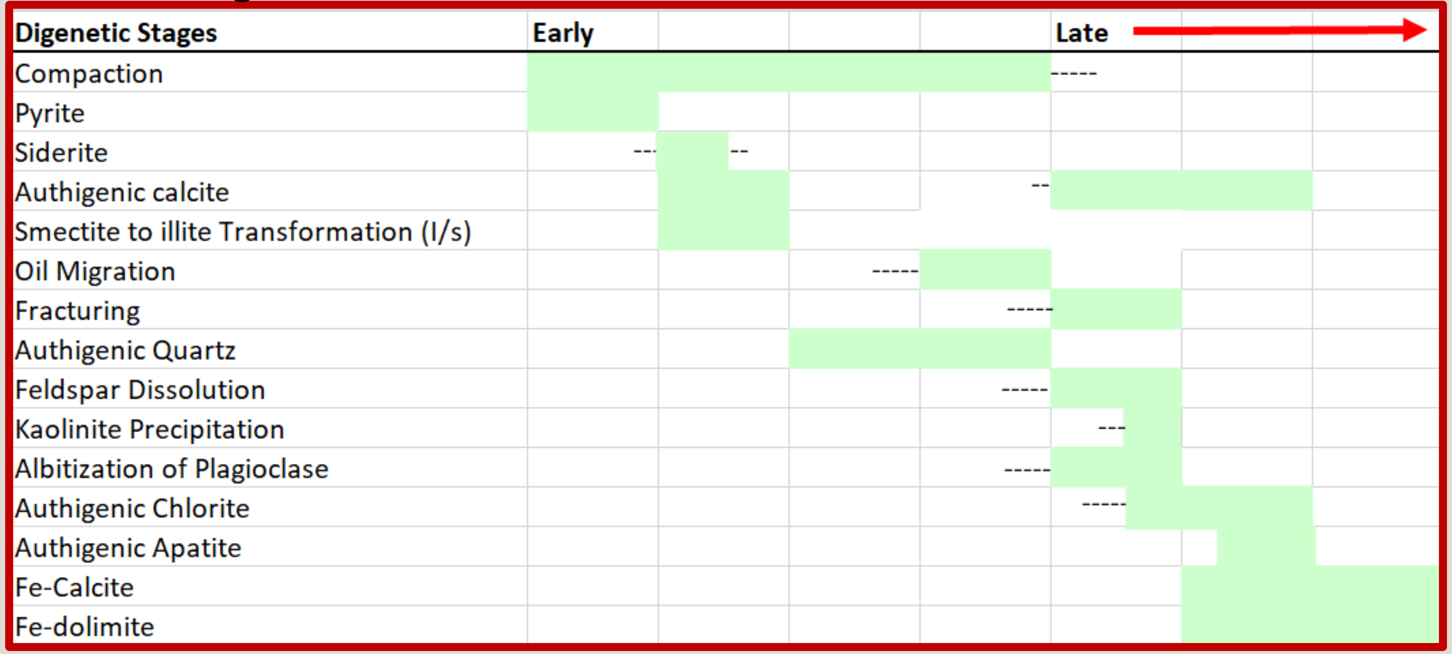
Preliminary Diagenesis Schema – Medrano, Hoxbar & Marchand



"Commonly observed diagenetic reactions superimposed on concentration vs. temperature curve for organic acids in oil-field waters." Modified from Crossey 1985; Surdam et al., 1990

The type, expectation and relative timing of the diagenetic processes have been identified for the overall Hoxbar group of rocks (see below). Typical diagenetic pathways related to temperature are shown on the left diagram. Overall, the Hoxbar Group appear to have undergone multiple periods of diagenesis.

Hoxbar Paragenesis Schema Medrano Sandstone Anadarko Basin

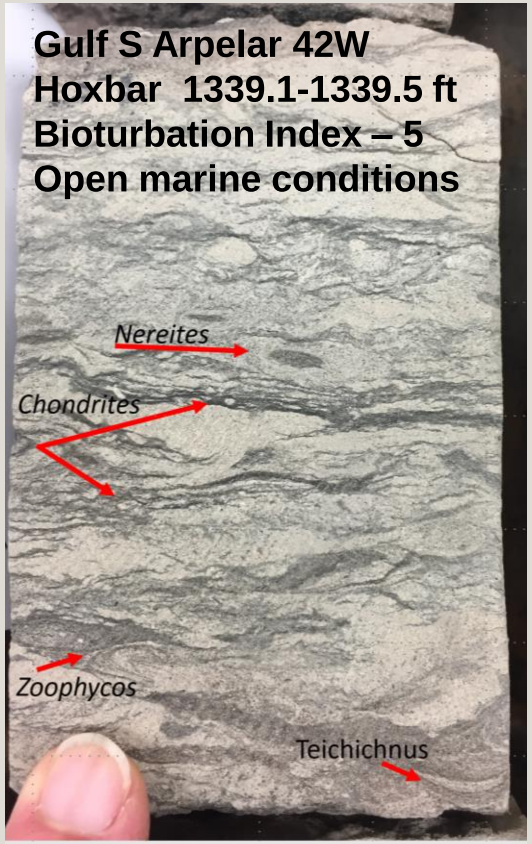


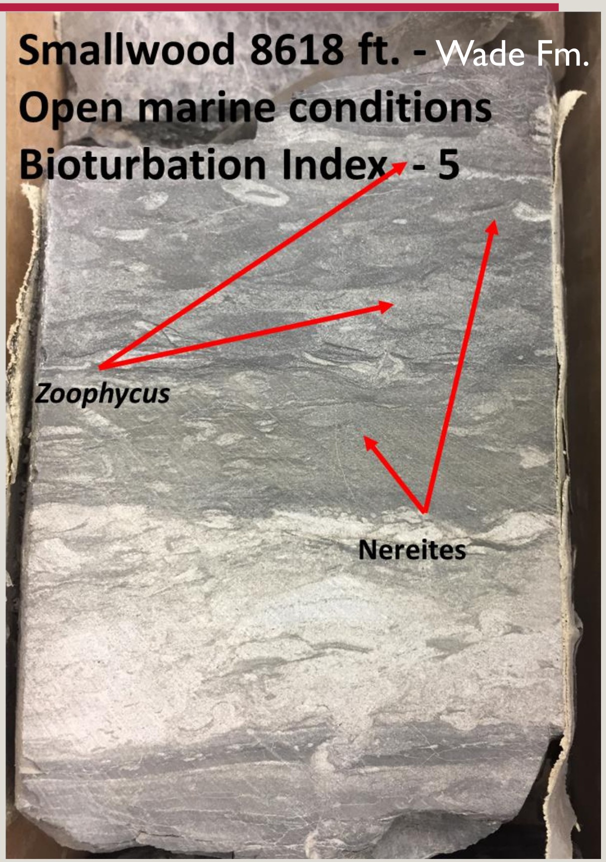
Ichnological Summary

EOG Resources Jobe #31-1
Marchand Fm.
Ichnofacies indicate both “stressed” suites (prodelta) and more open marine conditions

11081.8 ft – sparsely burrowed (BI-2) by *Teichichnus* and *Planolites*)

Typical observations – these observations are used as controls to the definition of potential depositional environments and for the identification of modern analogs (next slide).

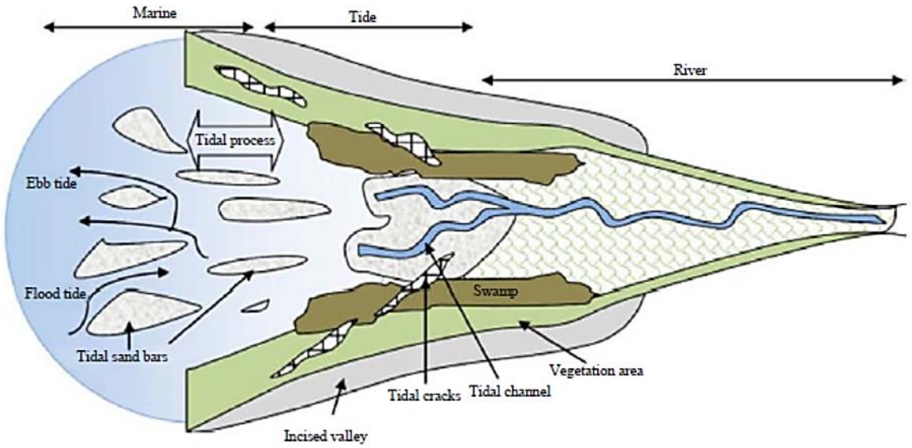




- Ichnology from the displayed cores suggests that conditions alternated between fairly diverse, open marine conditions to less diverse, more stressed pro-delta environments. Ichnology also suggests the presence of estuarine and valley fill deposits during the deposition of the Wade, Medrano and Upper Marchand Formations.
- Ichnology and sedimentary structures from the Lower Marchand core displayed today indicate a strong tidal influence, perhaps representing a tidal sand ridge or other tidal sand body.

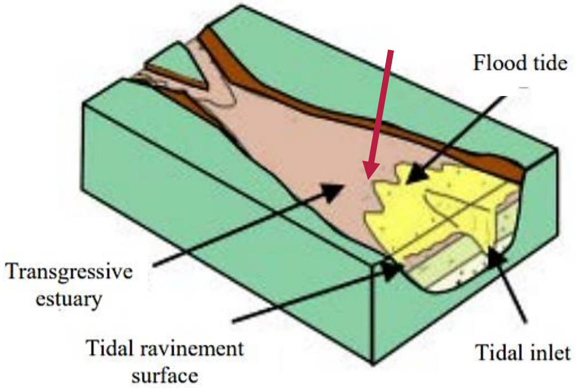
Delta & Fluvial System &Tidal Current Ridges/Bars & Estuary: Analogs

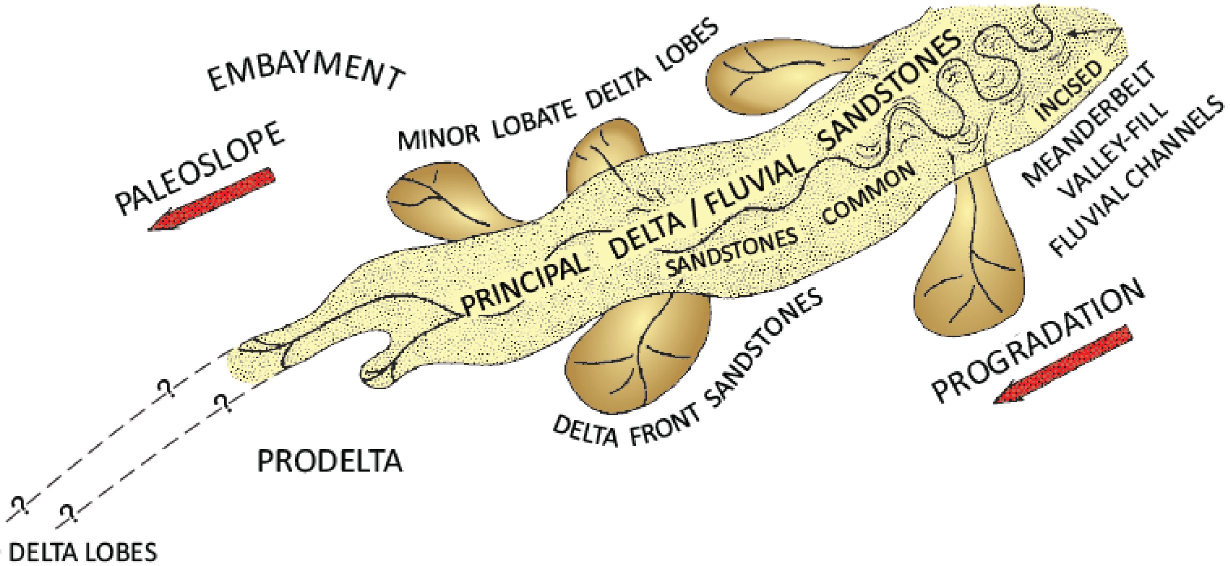
Tide-Dominated Estuary



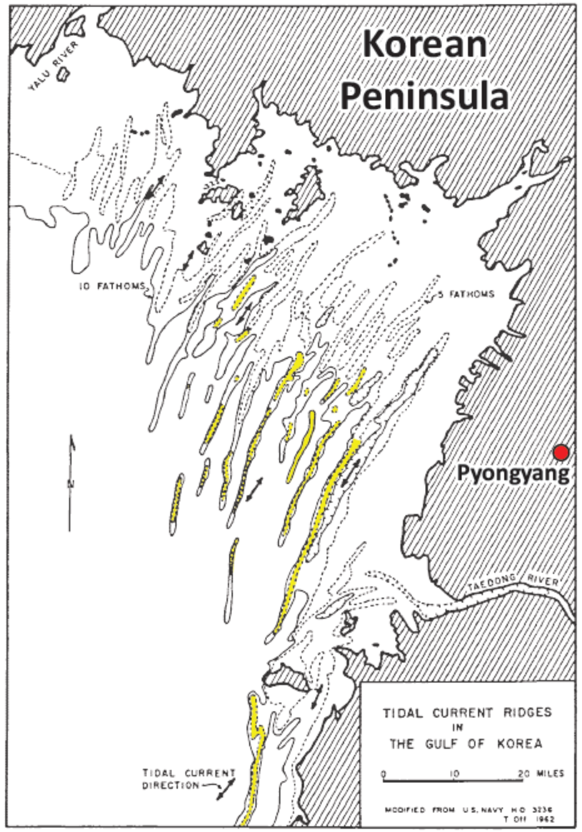
Gironde estuary, southwest France

Incised Valley Fill





Modified from Hyne,1979; Siddiqui et al., 2017

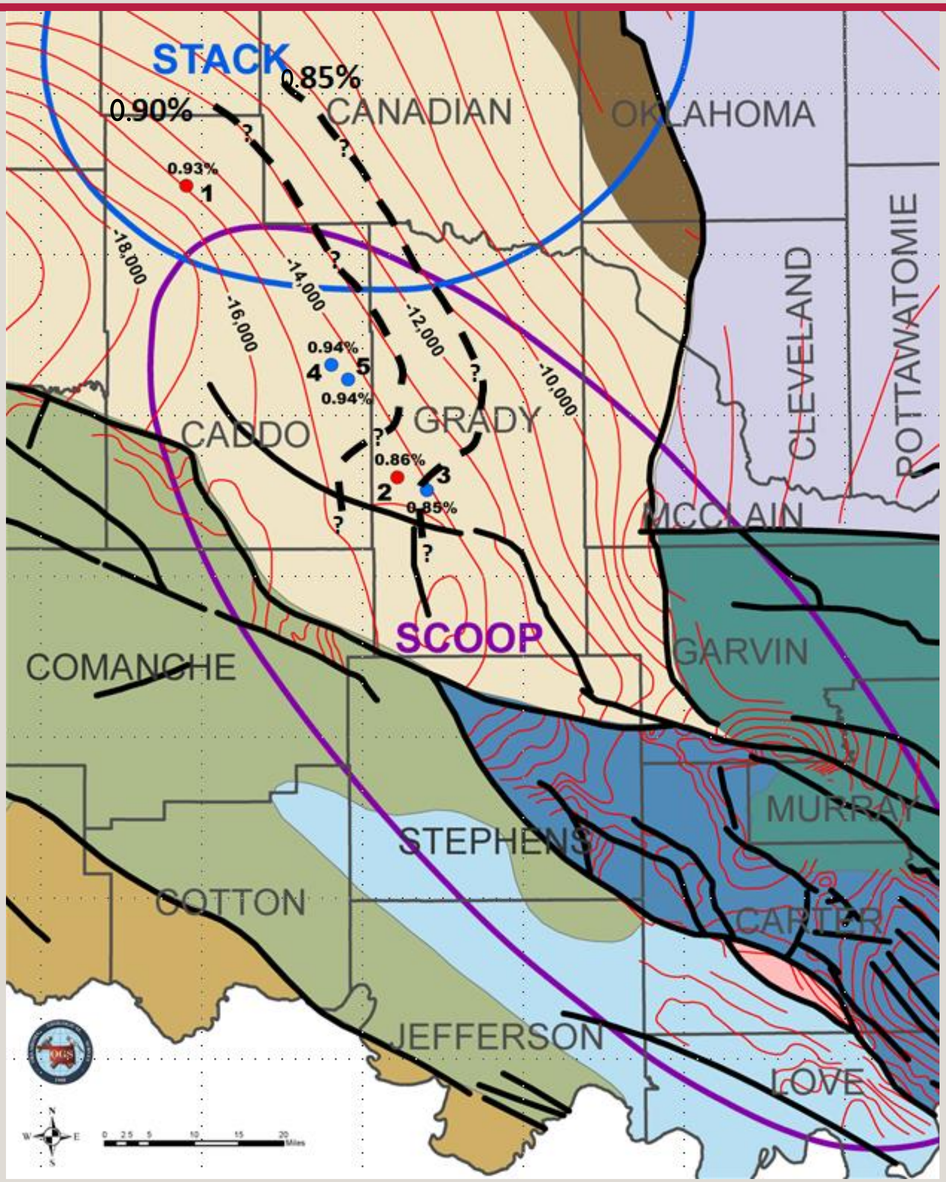


Tidal current ridges from Gulf of Korea. Note the closed depressions associated with ridges (Modified from Off, 1963).

Summary of Depositional Environment Interpretation

- The Medrano sandstone and the associated mudstone appear to be part of the deltaic/shallow marine system
- There is a possibility of incised valley-fill deposits that may include estuarine sediments
- The Upper(?) Marchand sandstone is part of a channelized clastic tidally dominated system (tidal bar and ridges) and displays coarsening upward
  - Although distributary channel delta deposits are common depending on the location
  - Distinctive herringbone cross-stratifications in various scales are commonly present in the cores from Caddo County indicating tidal influence
  - The Lower Marchant appears to be more distal than the upper zone with increasing mud content/fining upward and less pronounced herringbone cross-stratifications in some locations (discussed at *Core Workshop*).
- Both the Medrano and Marchand sandstones and particularly the associated mudstones appear to bioturbated with a different intensity, however with a low diversity (e.g., distal *Cruziana* ichnofacies)
- The Wade Formation consists of conglomerate, sandstone and silty mudstone
  - Depositional environment is a very distal pro-delta in some locations (discussed at core workshop). There are an abundance of Nereites as well as a few Zoophycos, indicating distal shelf or pro-delta; below fair-weather wave base
  - The conglomerates may represent transgressive incised valley deposits
- Ichnofossil study aids in differentiating fluvial-deltaic deposits from tidally influenced marine sediments

Organic Maturity: Hoxbar Shales



Geologic Provinces Modified from Northcutt and Campbell, 1995; Cardott, 2013
Woodford Structure Contours and Faults from Evans and Others, 2018

Reference List of Wells Shown on Map (Operator, Lease, Well Number, API)

1. Apexco-Buell State 1, 35015204200000
2. Cleary McDonald 1-28, 35051203810000
3. EOG Jobe 31-1H, 35051236640000
4. EOG Venable 1, 35015223110000
5. EOG-Verden Hoxbar W Unit 14, 35015224090000

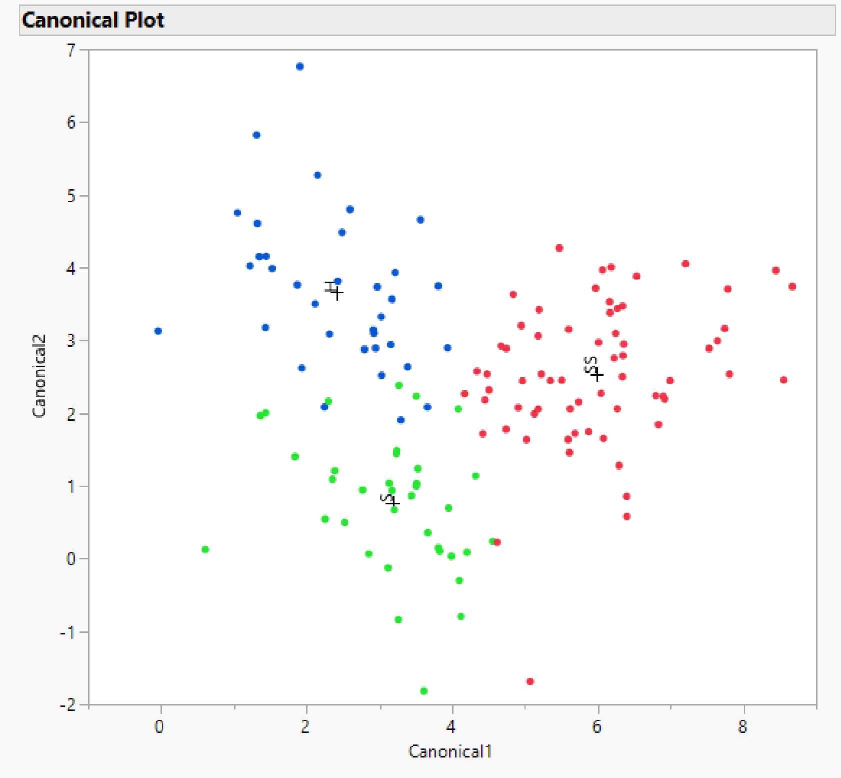
Location of OPIC Wells / Cores with Shale Samples

- Marchand
- Medrano
- 0.86 Vitrinite reflectance (R_o)
- Fault
- Woodford Structure Contour

Well #	Depth	Maturity
3	9,799-9,801	0.86% Ro (22 values, 0.67-1.03% Ro, S.D. = 0.11)
2	10,919-10,932 ft	0.85% Ro (33 values, 0.64-1.02% Ro; S.D. = 0.11)
5	9,430-11,121 ft	0.94% Ro (28 values, 0.78-1.08% Ro, S.D. = 0.09)
4	9,833 ft	0.94% Ro (23 values, 0.81-1.04% Ro, S.D. = 0.06)
1	9,732 ft	0.93% Ro (29 values, 0.81-1.05% Ro, S.D. = 0.07)

The thermal maturity of samples of Hoxbar shales from 5 wells (above) were determined (above table) and plotted on the Woodford structure contour map (diagram on the left). While the maturity contour lines are conjecture, it does appear that the area around the two southern samples (2 and 3) have undergone a more complex thermal history likely due to the increased basement depth and nature of the fault system. Based on the measurements from the Hoxbar Shales (VRo=0.85-0.93%) and using the calculated temperature table from Barker and Pawlewicz (1994), the Max burial Temp is ~125-130ºC.

Initial XRF Analyses – Some surprises!

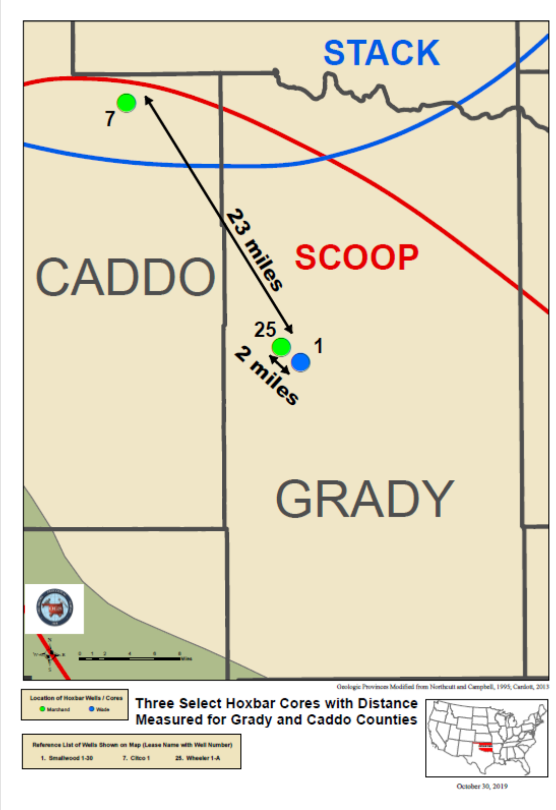


Color Codes
C = Citco 3
S = SmallWood 1-30
W = Wheller 1-A

Key Elements
Mn
Ca
Ba
Sr
Mg
K

Actual	Predicted Count		
	C	S	W
C	35	0	0
S	0	37	0
W	0	0	66

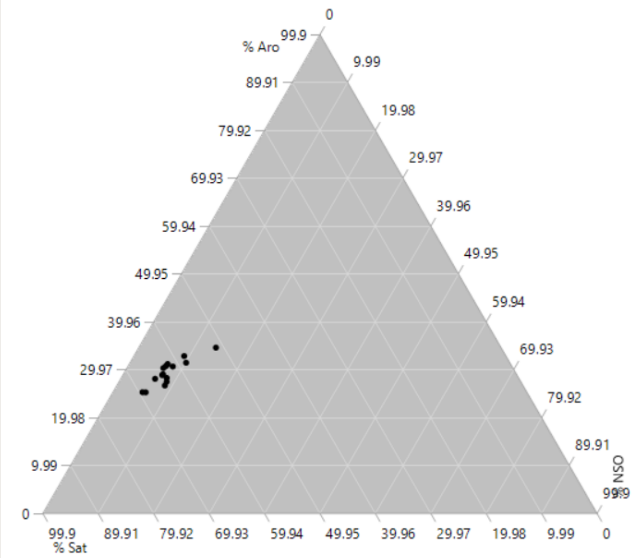
Do we have a way to quantify geologic variability for the Hoxbar Group of rocks?

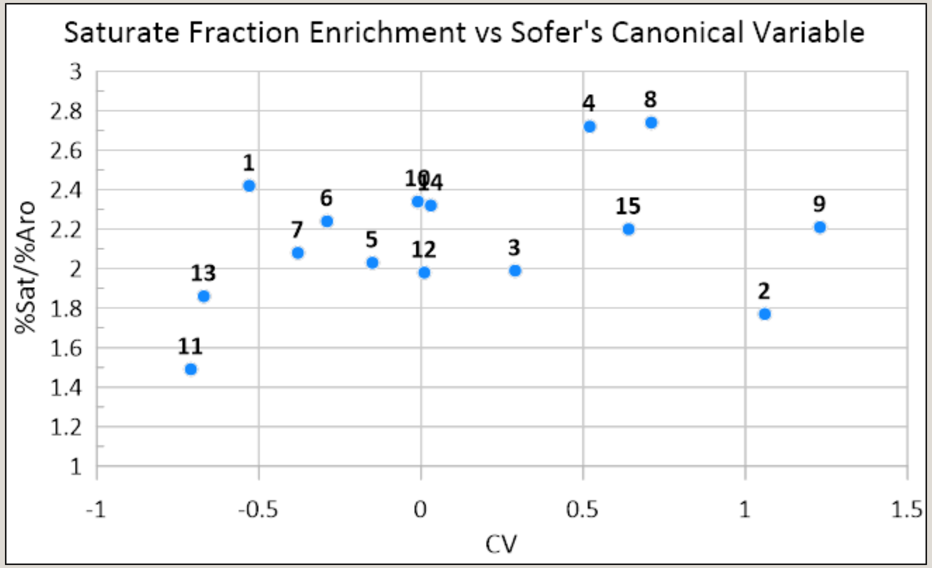


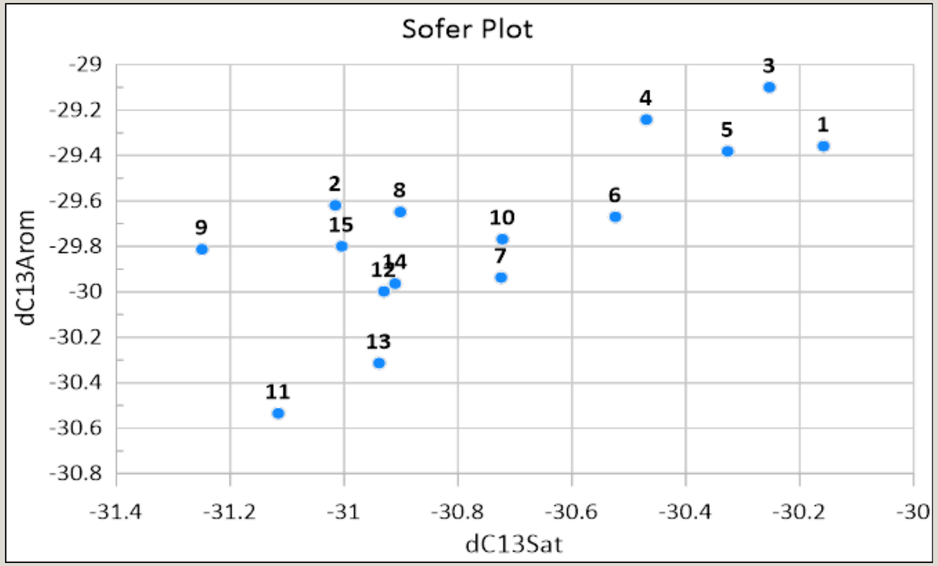
XRF data was generated on 3 sections of core: 2 Marchand sands and a Wade sand section. Statistical analysis consisted of performing a typical Principle Component Analysis (PCA) – both R and Q mode - and multiple elemental cross plots which are not shown in this presentation. A Linear Discriminant Analysis (LDA) was also performed (stepwise) in order to evaluate the differences and similarities. To our surprise, the approach was able to be 100% accurate in separating a given sand from another (center above). The discriminating canonical plot is shown on the left (color coded by well) while the relative location of the wells are shown on the right. While it is difficult to believe generalities based on three sample zones, it is intriguing that individual zones can be ID'd by XRF data as well as having a new way to decipher regional variability. The final solution used 15 elements with the 6 key elements listed above. It would appear that XRF offers a different way to quantify geologic variability in the Hoxbar Group of rocks. More data are needed to test the efficacy of these results.

Hoxbar Bulk Oil Data – Preliminary Analysis

Oil samples curtesy of Unit Petroleum (2019), analyses courtesy of the GeoMark Research (2019). The extracted rocks will next undergo SARA analyses on the way to isotopes and biomarkers.







15 oil samples have been subjected to traditional organic analysis. In the triangular diagram (left), the plot of the %Sat-%Aro-%NSO show a distinctive trend; the %Sat/%Aro ratio versus Sofer's Canonical Variable (CV) plot (center) displays the interesting scatter and the Sofer plot of the carbon isotope value of the saturates and aromatics (right) shows scatter (using analyses described in Wang 1993 and Hana, et al., 2018). While the samples are from a relatively limited region, the data cannot rule out one or more sources of oil outside of the Woodford. Vapor fractionation of crude oil produced from the same source rock (e.g., Woodford) is not likely as the trends in the center and right plot do not closely match. The initial conclusion is that there is probably more than one source for the oil present in this area of the Hoxbar Group.

Key Findings & Recommendations

- The Wade Formation is commonly present as a distal pro-delta
- The Medrano sandstone and the associated mudstone appears to be part of the deltaic/shallow marine system
- The Marchand sandstone is likely part of a channelized clastic tidally dominated system (tidal bar and ridges), although distributary channel delta deposits are common depending on the location
- Ichnofossil study aids in differentiating fluvial-deltaic deposits from tidally influenced marine sediments
- The reservoir quality of Hoxbar sandstones throughout much of the deeper Anadarko Basin is locally diminished due to compaction and cementation, the latter of which includes calcite, Fe-calcite, Fe-dolomite, siderite, Fe-bearing illite, quartz cementation and K-feldspar overgrowths
- Most Hoxbar shales studied are in the peak of the oil generation window depending on the location
- Compartmentalization is possible - what cause it? Depositional (stratigraphy), tectonic (faults), diagenesis?
- The hinterland is dominantly from the Wichita Mountains with some components from the Ouachita Mountains

What would be nice to also add to the mix of data:

- If quality seismic data can be acquired, seismic stratigraphy/geomorphology would be very useful
- More organic petrography to delineate maturity
- Evaluation of shallow Bouguer gravity, and magnetic data to understand basement and faults

Join the OGS Consortium!!!

Contribute & Help to Provide Knowledge & Promote the Vast Oklahoma Resources!!!