Integrated Petrophysical and High-Resolution Sequence Stratigraphic Characterization of an Unconventional Carbonate Mudrock Reservoir*

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Abstract

The Mid-Continent Mississippian age limestone is a valuable unconventional carbonate reservoir in Oklahoma and Kansas. Although over 14,000 vertical wells have been producing oil and gas from Mississippian age reservoirs for over 50 years, recent horizontal activity has illustrated how crucial it is to understand the petrophysical and depositional characteristics associated with producing intervals. Petrophysical analysis has been integrated with high resolution sequence stratigraphic analyses of core from North-Central Oklahoma to better understand the distribution of reservoir facies in this unconventional carbonate reservoir. Horizontal porosity in the data set, ranges from 0.5–7%, although porosity values may be as high as 20% locally. Correlative permeability ranges from 0.001 md to just over 1.0 md. SEM analysis shows the pores are mostly oblong to oval, intercrystalline to vuggy, meso- (4 mm - 62.5 μm) to nanopore (1 μm – 1 nm) size, while pore throat measurements are consistently in the nanopore range. Acoustic response data show the inverse relationship with porosity in unconventional carbonate mudrocks is consistent with previous work using Mesozoic to Cenozoic age conventional carbonates. However, the carbonate mudrock data from the Mississippian show a significant shift in the median value that appears to be consistent with analysis from Neogene carbonate mud samples. Detailed facies analysis from three cores in North-Central Oklahoma suggests deposition occurred on a regionally pervasive, distally steepened carbonate ramp. The facies stack into shoaling upward packages of weakly calcareous mudstones to wackestones at the base, overlain by progressively higher energy skeletal packstone to grainstone facies. A sequence stratigraphic hierarchy of shoaling upward packages is observed in core and wireline logs at the third, fourth, and fifth order scales. Tying the correlation between the wireline log signature and facies stacking patterns into the sequence stratigraphic framework provides a means for increasing the predictability of reservoir quality units in the subsurface. Augmenting this data with the acoustic response, and characterization of the macro- to nanoscale pore architecture, provides an example of how integrated studies can enhance predictability of key reservoir facies and producing intervals within unconventional carbonate reservoirs.

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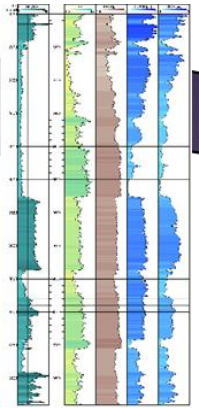
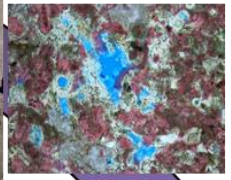
Integrated Reservoir Characterization

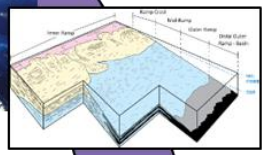


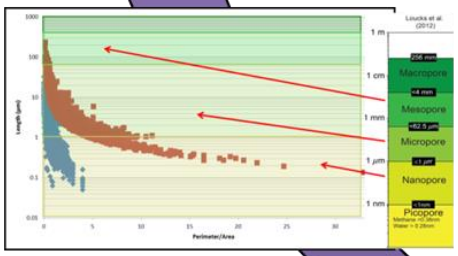
Wireline Logs

Core and
Thin Sections

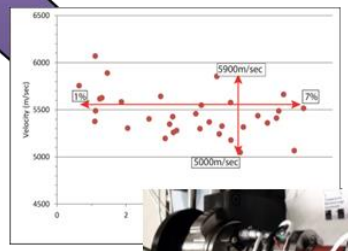


Depositional
Analogs
And Models

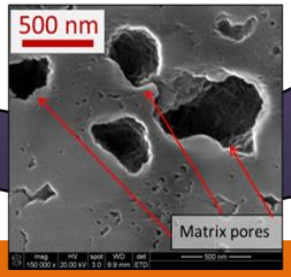




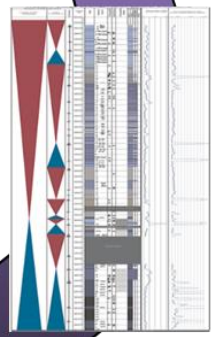
Digital Image
Analysis



Sonic Velocity/K



Pore
Architecture



Sequence
Stratigraphy

Mid-Continent "Mississippi Limestone" Oil and Gas Production History

- Production began in the early 1900's
- Reservoir intervals vary from limestone, or dolomite-rich intervals to tripolitic, nodular and bedded chert intervals
- Horizontal drilling has revitalized production, but highlighted the need to better understand the reservoir architecture

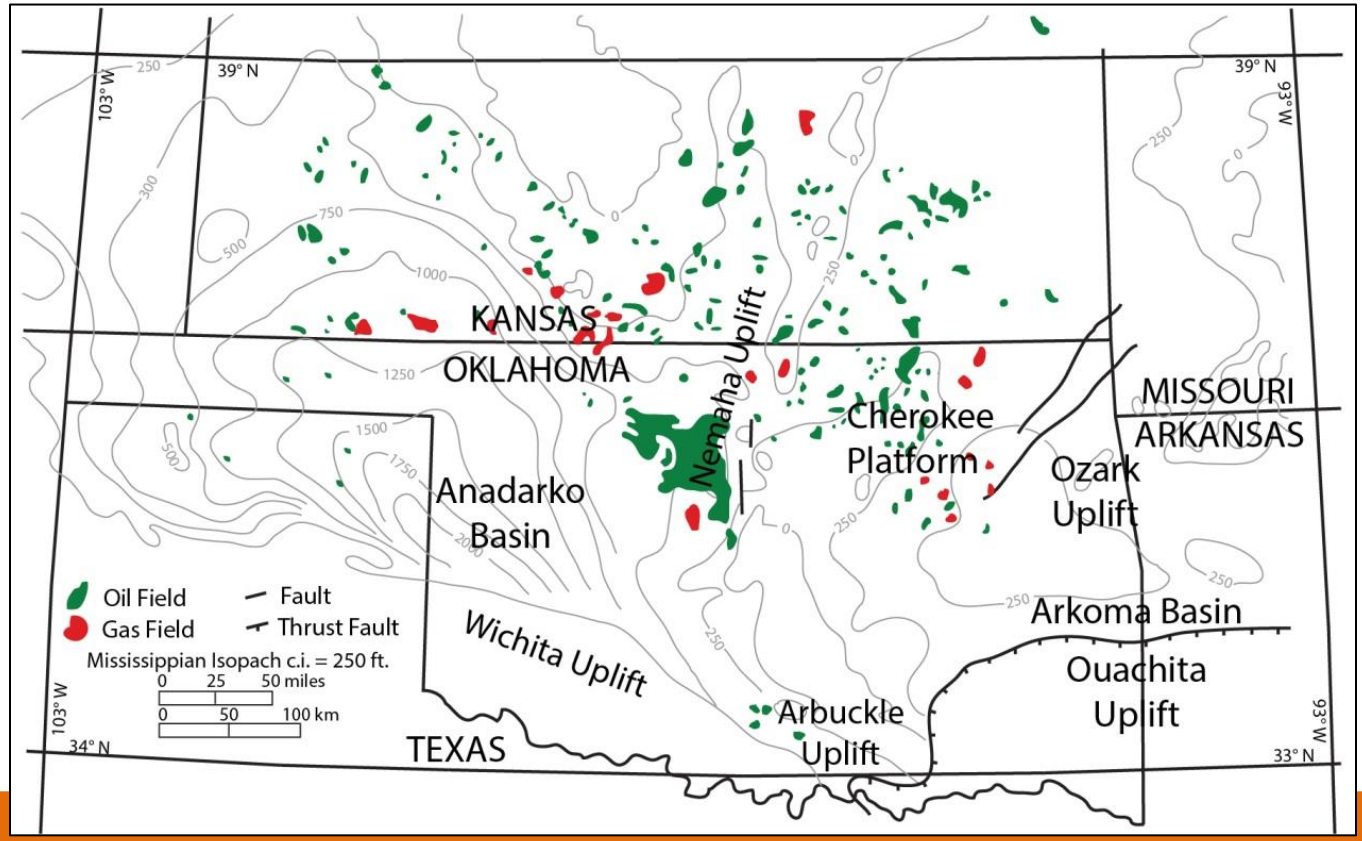
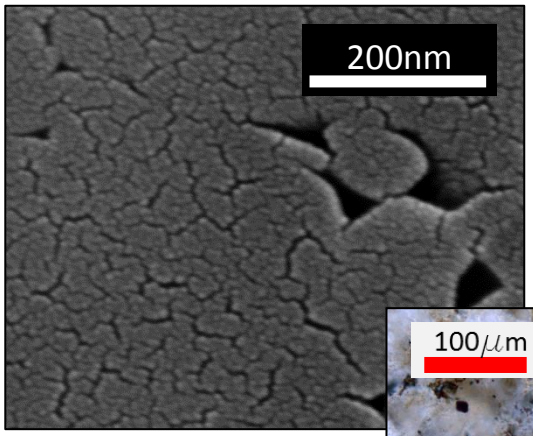
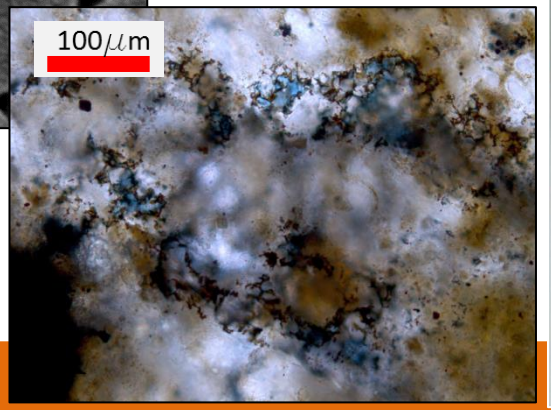


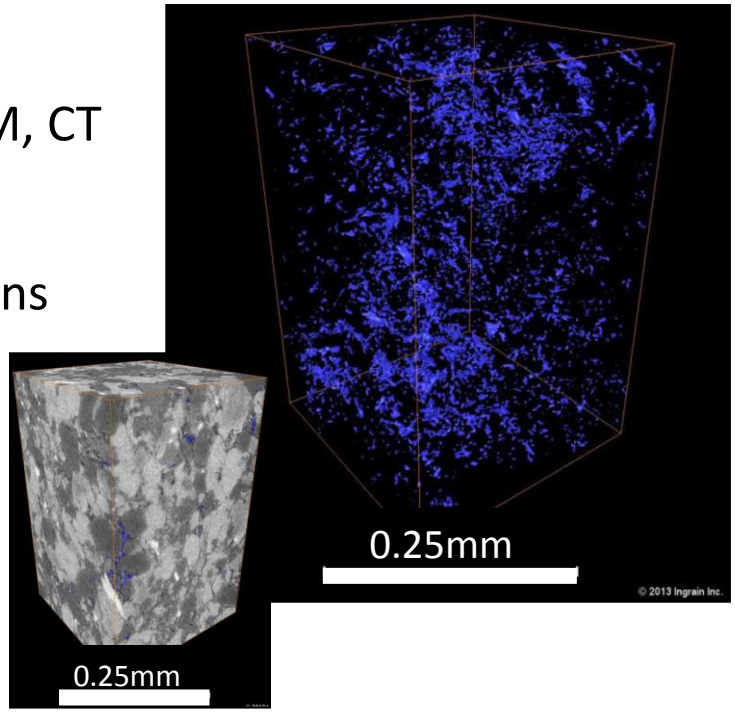
Figure modified from Harris (1975)

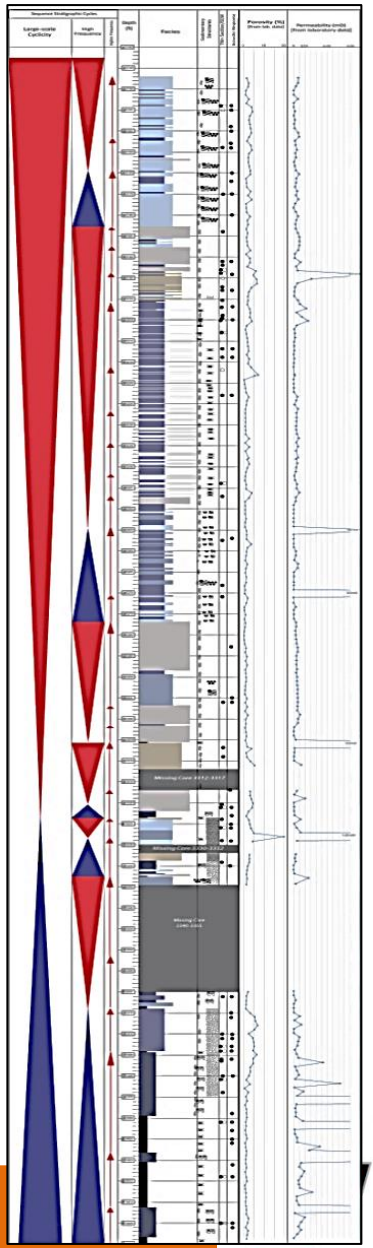
Predicting permeability

1. Pore architecture
   - Thin section, SEM, FIB-SEM, CT
2. Sequence Stratigraphy
   - facies, diagenetic alterations
3. Acoustic Response



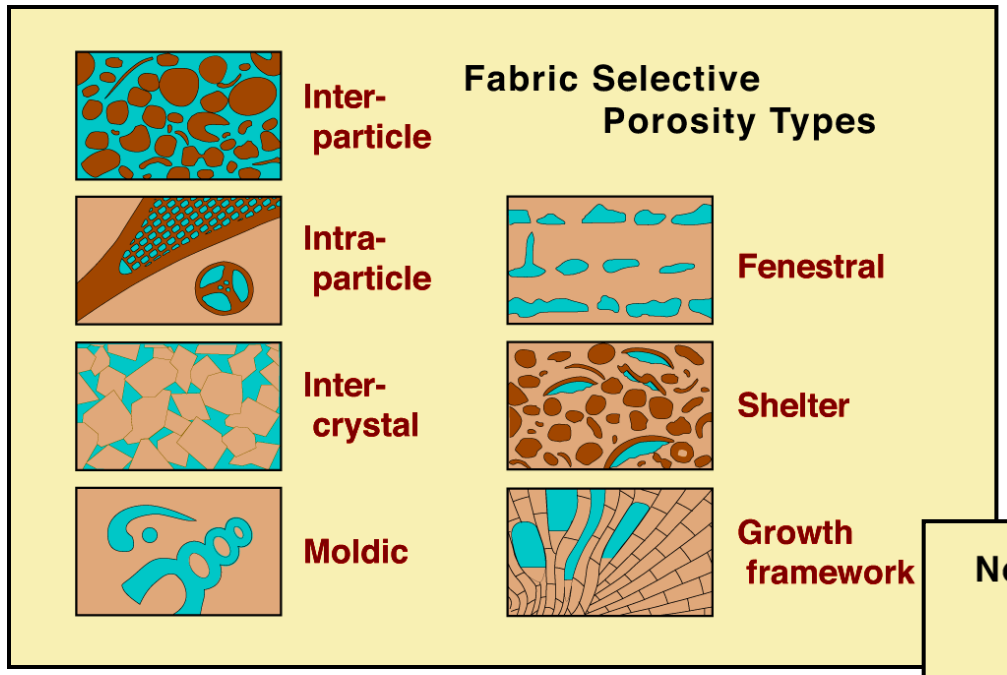






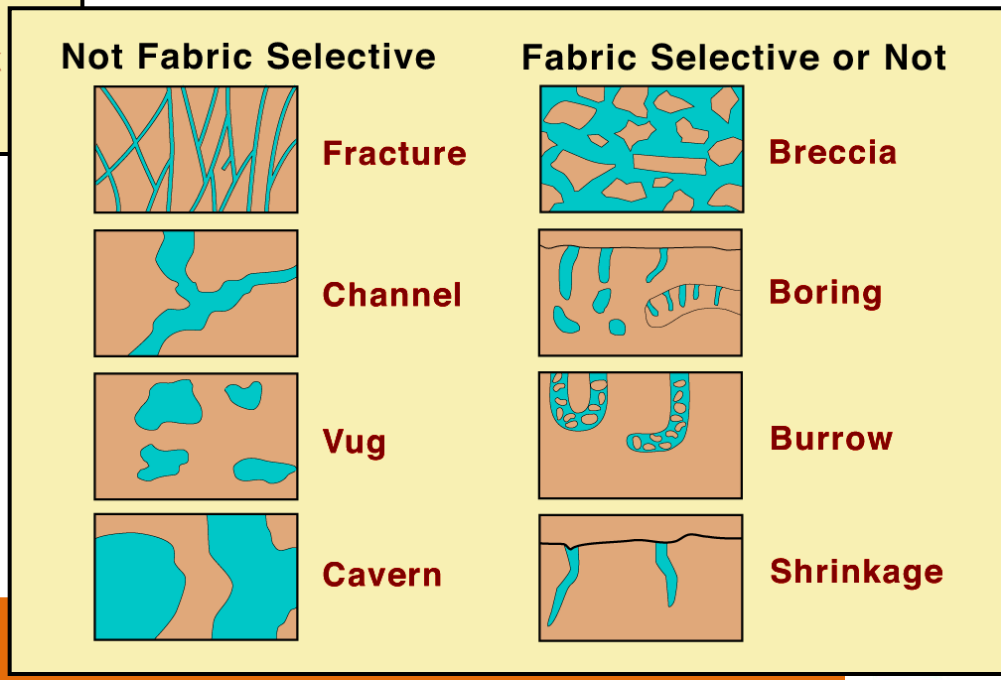
Carbonate pore types

(Choquette and Pray, 1970)



Porosity in carbonates is a function of:

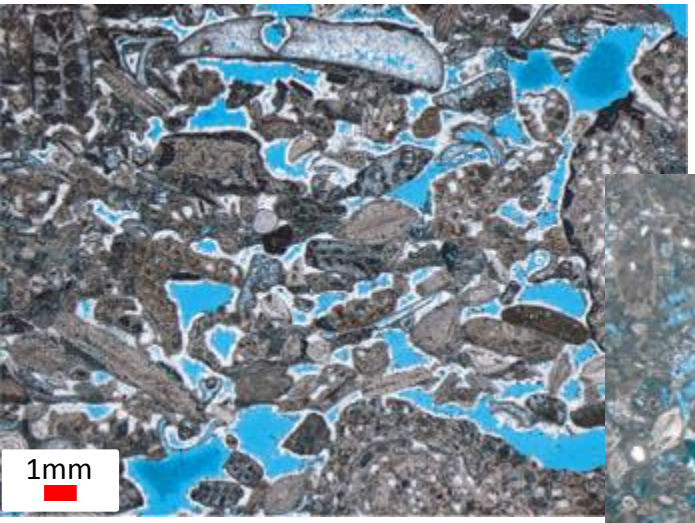
1. Depositional Processes
2. Diagenetic Processes



Images from AAPG Memoir 77

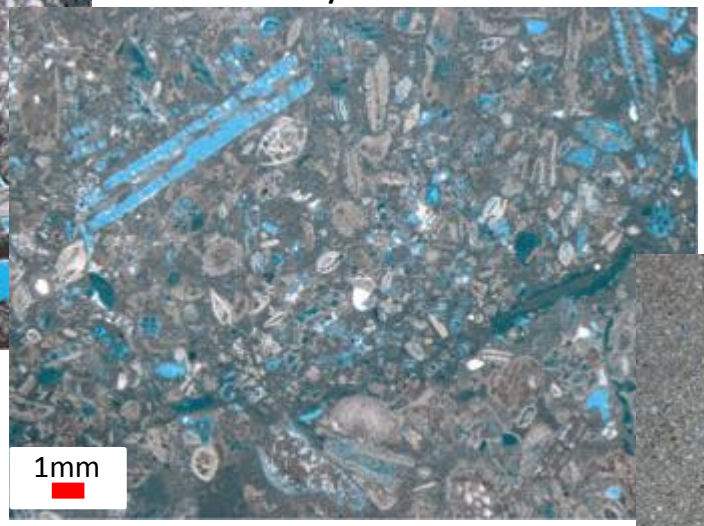
Porosity, pore size, and permeability

Coarse Grainstone



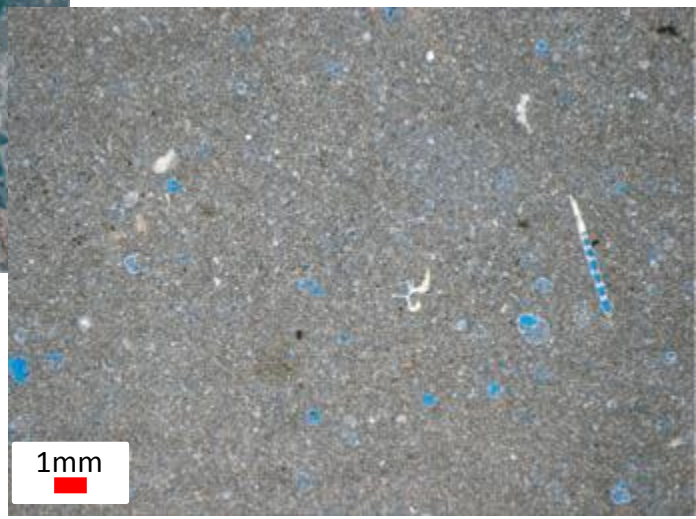
Porosity: 19.7%
Permeability: 10751mD

Packstone/Wackestone



Porosity: 19.3%
Permeability: 1.54mD

Fine/V. Fine Packstone

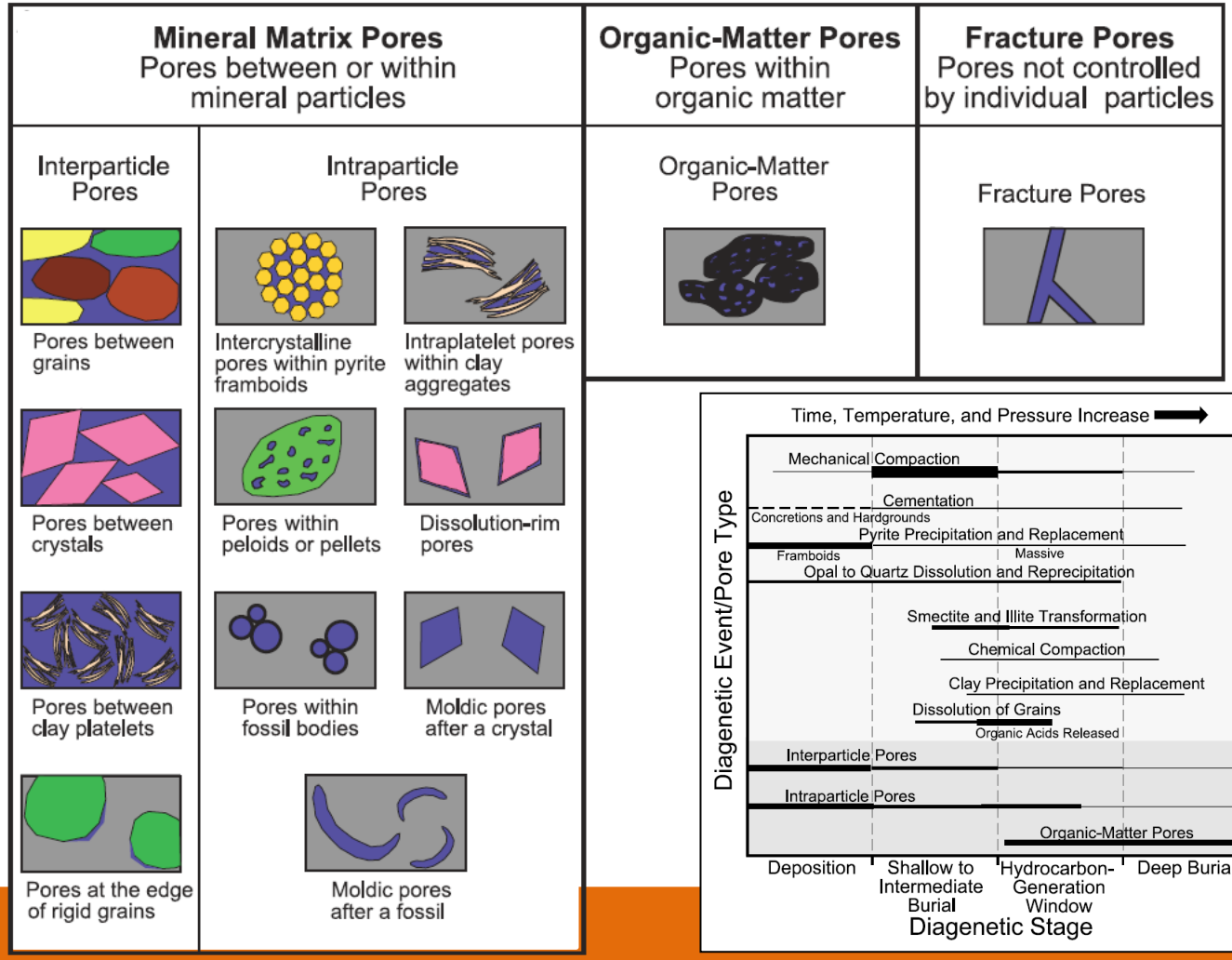


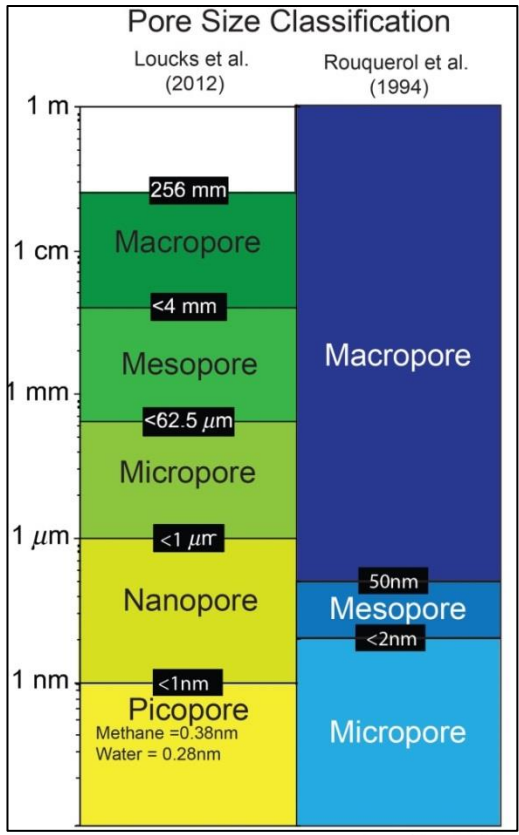
Porosity: 28%
Permeability: 0.06mD

Photos from Ehrenberg et al. 2006

Characterization of mudrock pore architecture

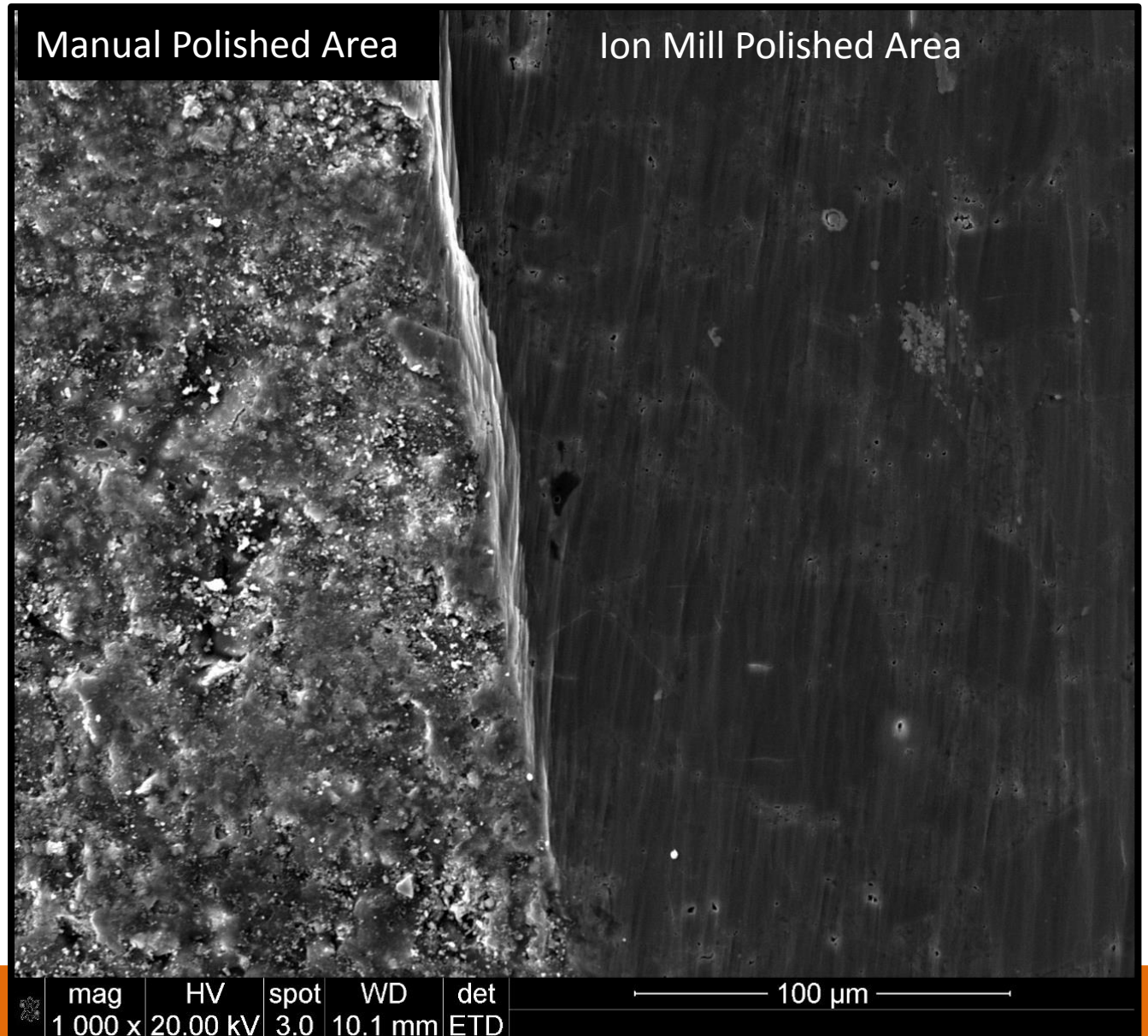
- Siliciclastic mudrock reservoir pore classification: Active discussion
- Pore descriptions: combine carbonate and siliciclastic features



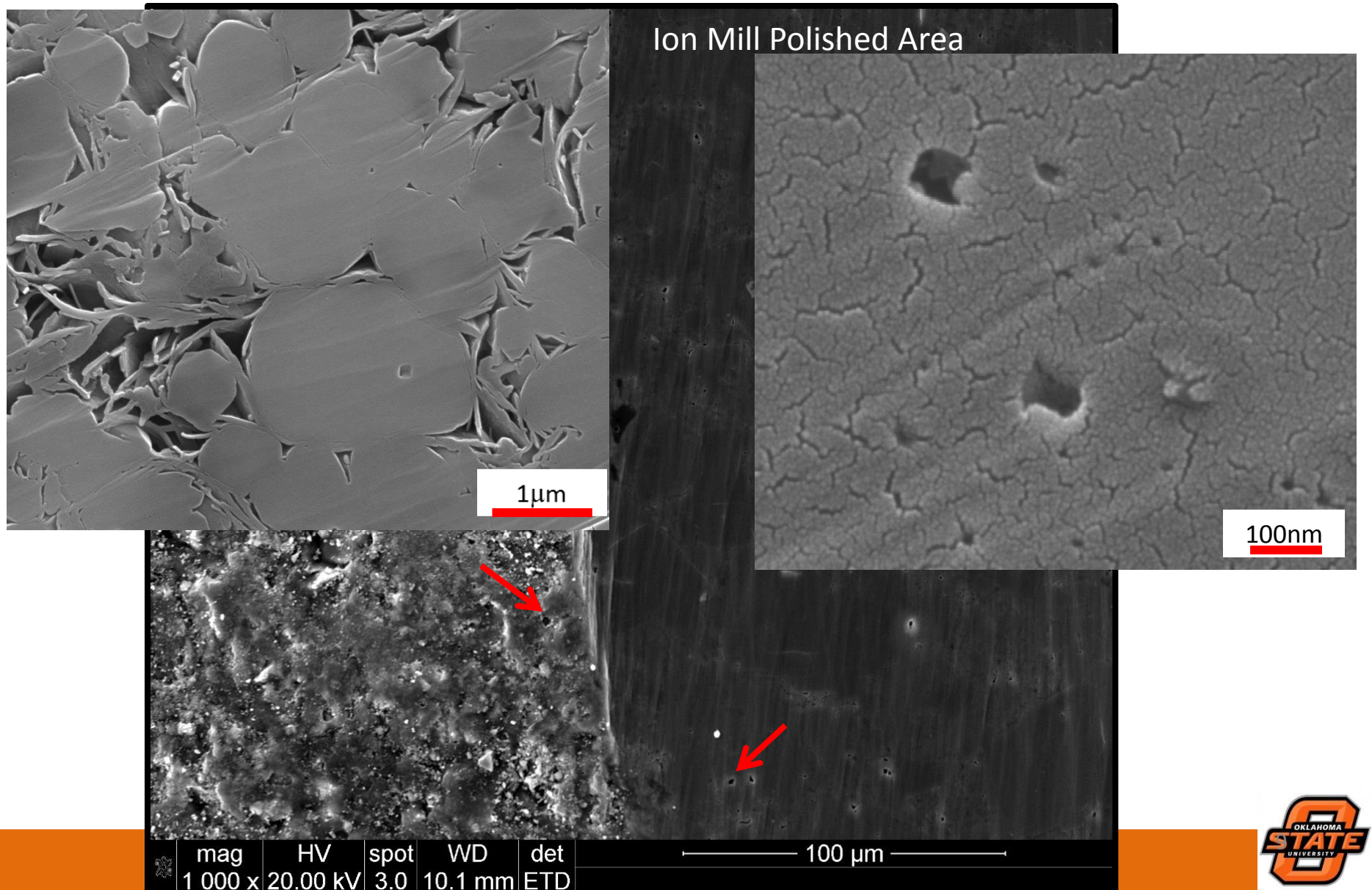


Figures Modified from Loucks et al. 2012

Characterizing the pore architecture



Characterizing the pore architecture



Digital Image Analysis
Link to quantitative permeability assessment

2-D Image Analysis

Photomicrographs

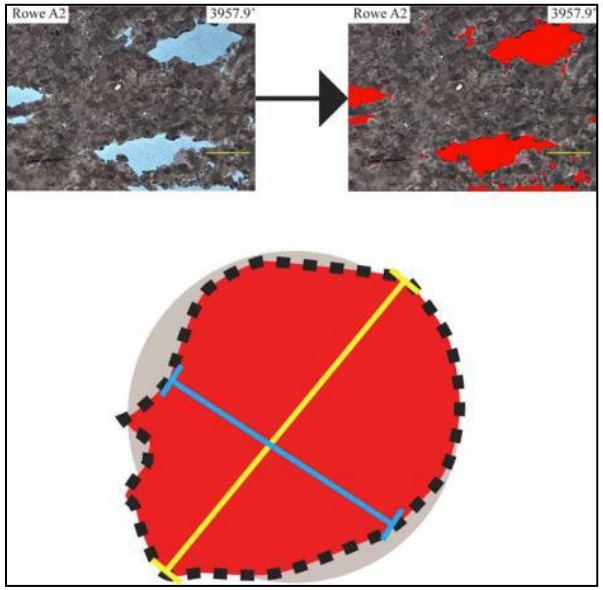
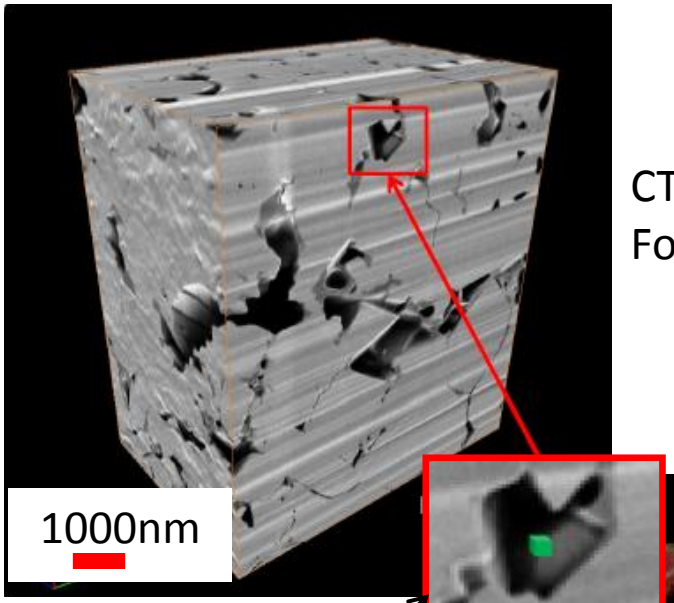


Figure Thornton and Grammer 2012



Cube = 1,000,000 Oil Molecules

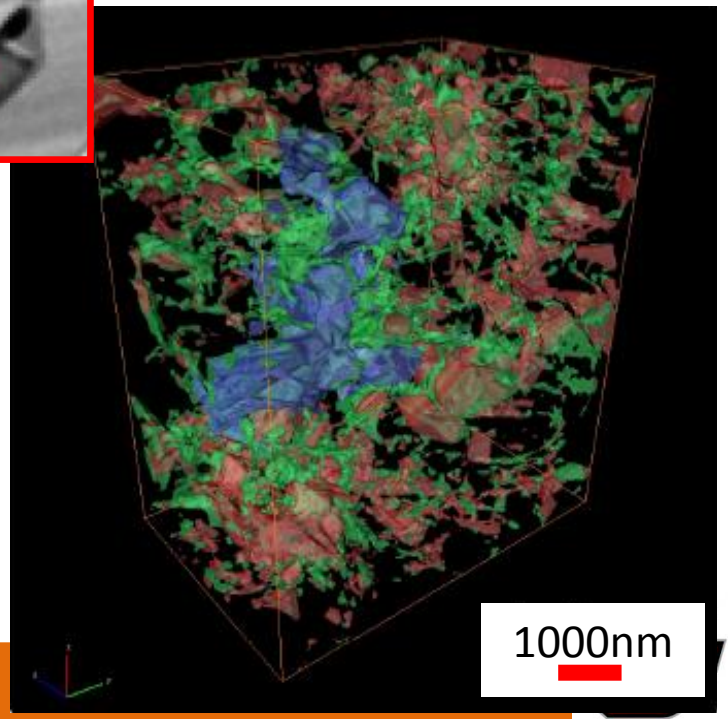
15nm slices
10nm resolution

FIB images Courtesy of EOG Resources, Used with permission from G.M. Grammer

3-D Image Analysis

CT-Scans

Focused Ion Beam – SEM imaging



Sonic velocity to predict permeability in carbonates

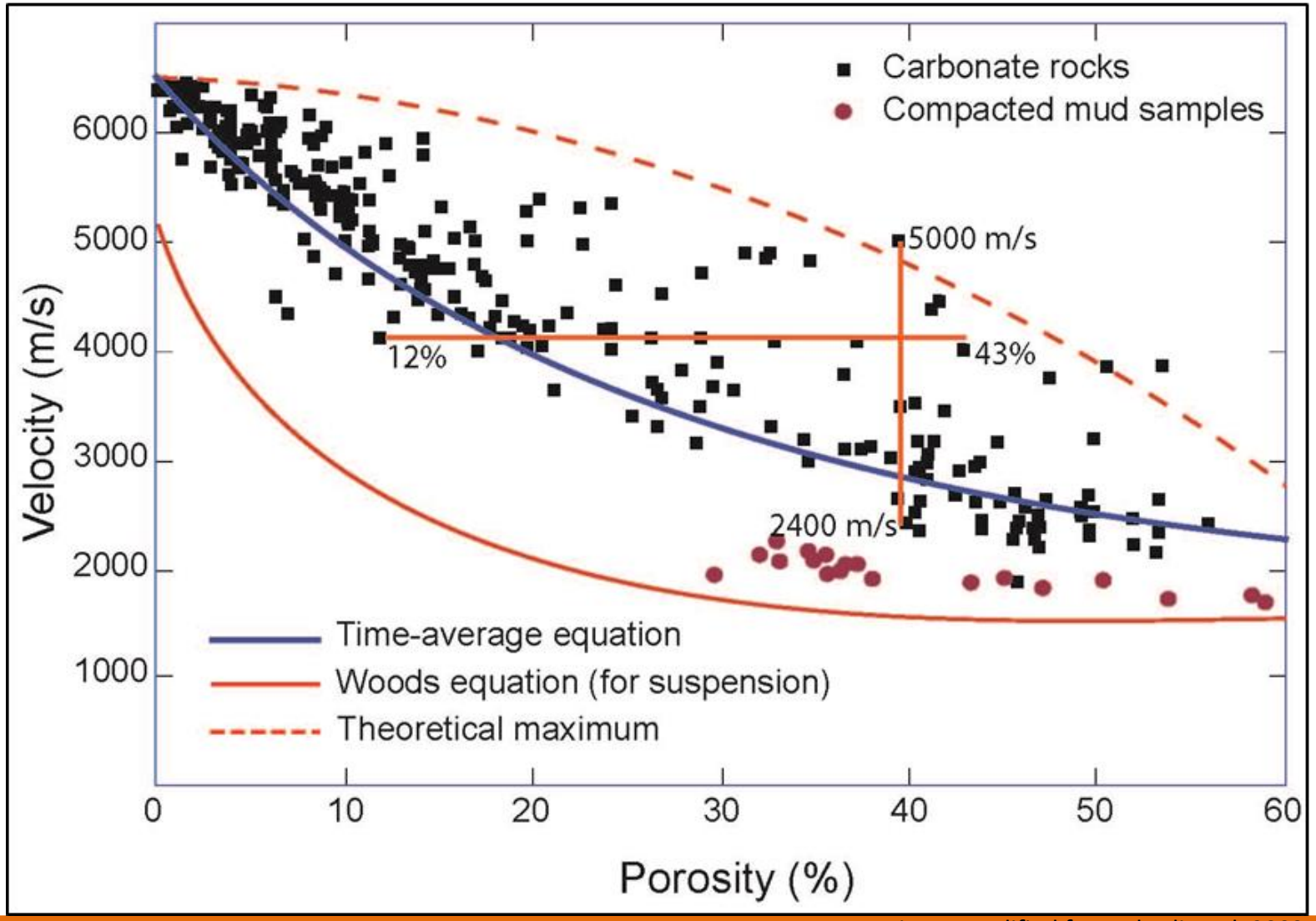


Figure Modified from Eberli et al. 2003
and used with permission from G. Eberli

Predictable acoustic response

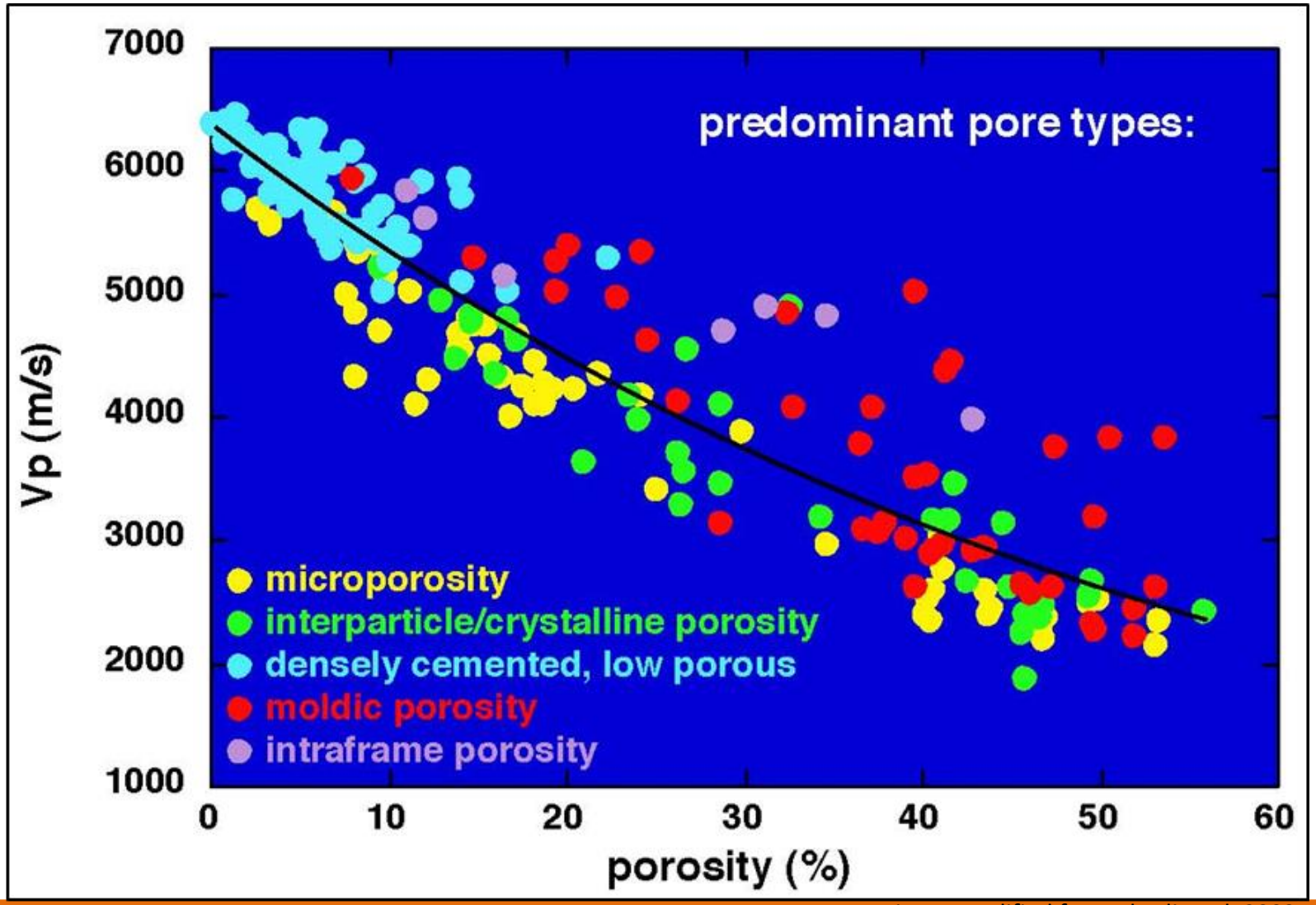


Figure Modified from Eberli et al. 2003

Predictable acoustic response

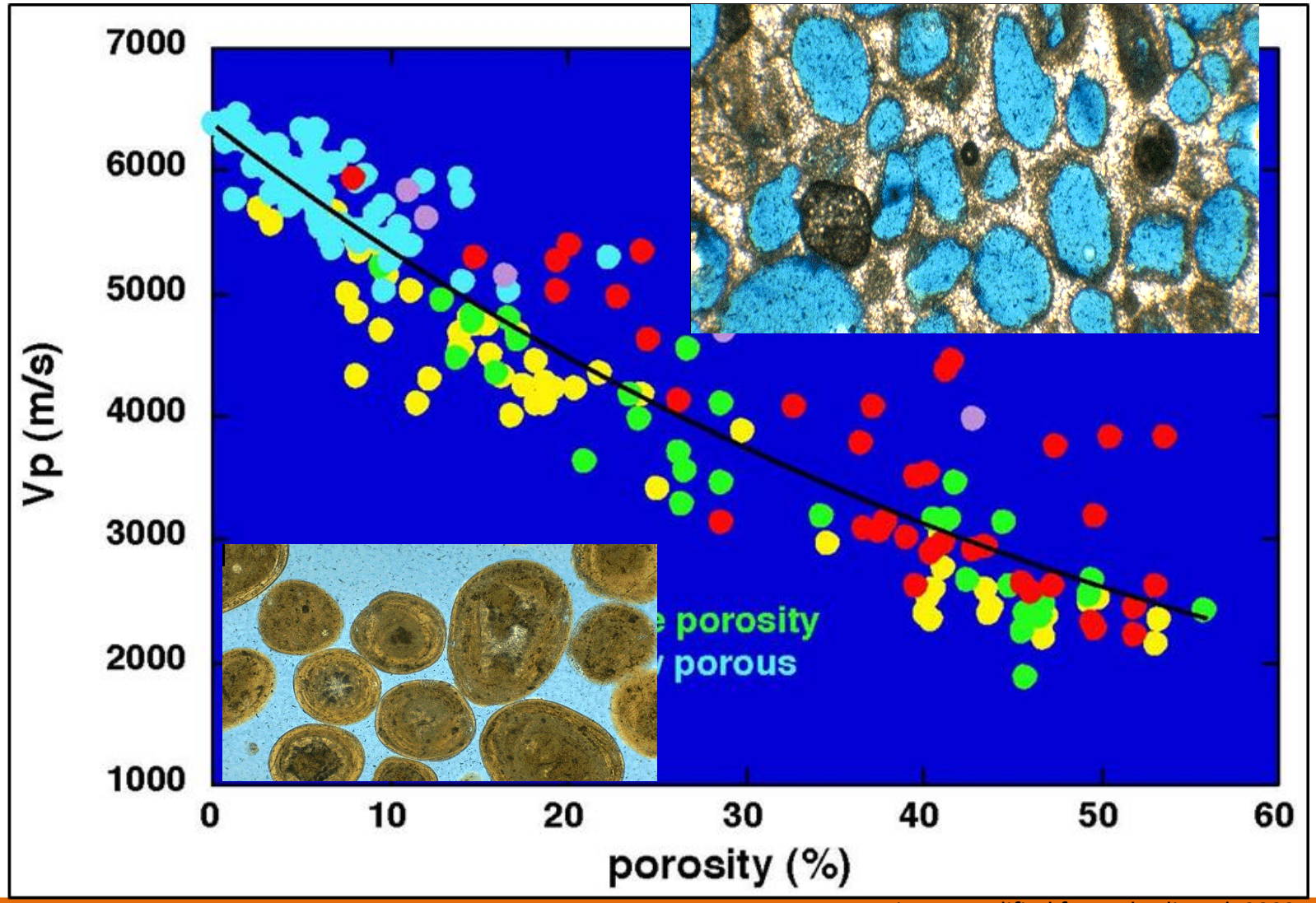
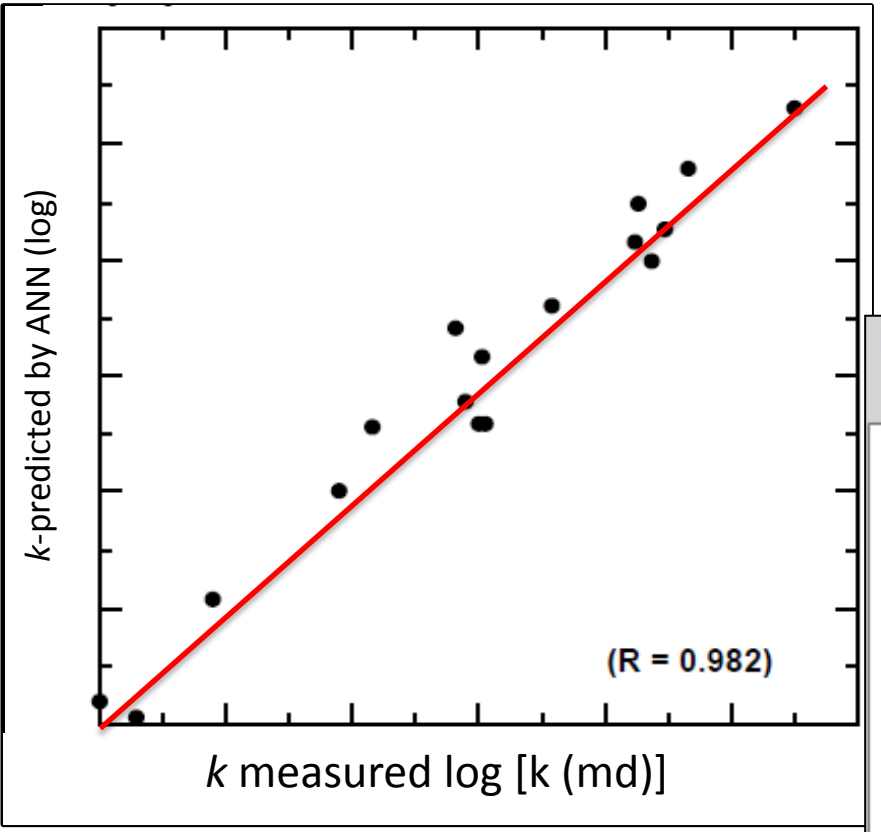


Figure Modified from Eberli et al. 2003

Quantitative permeability prediction

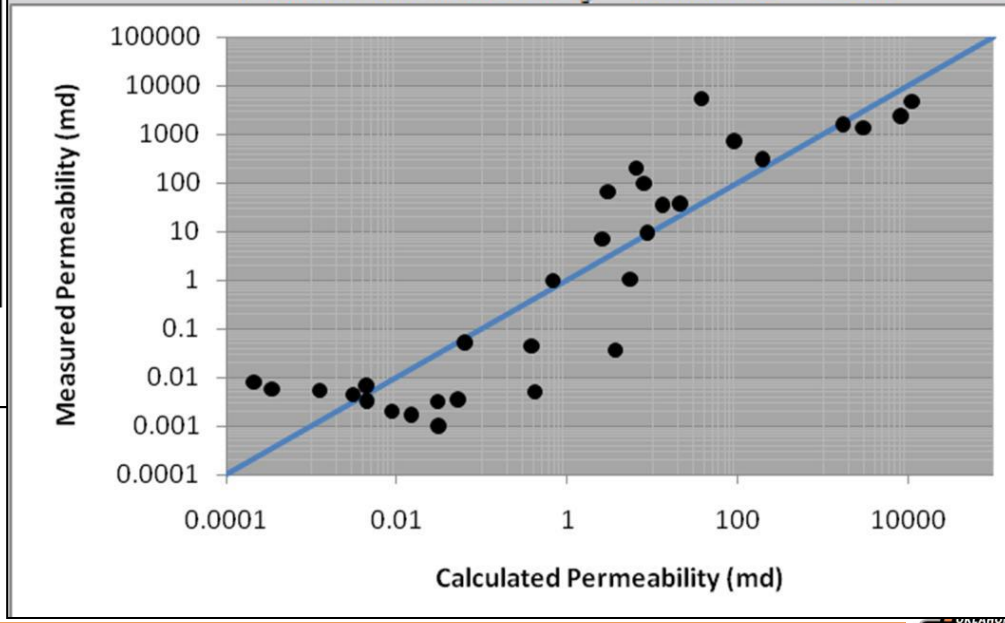
Artificial Neural Network



Anselmetti et al. 1998

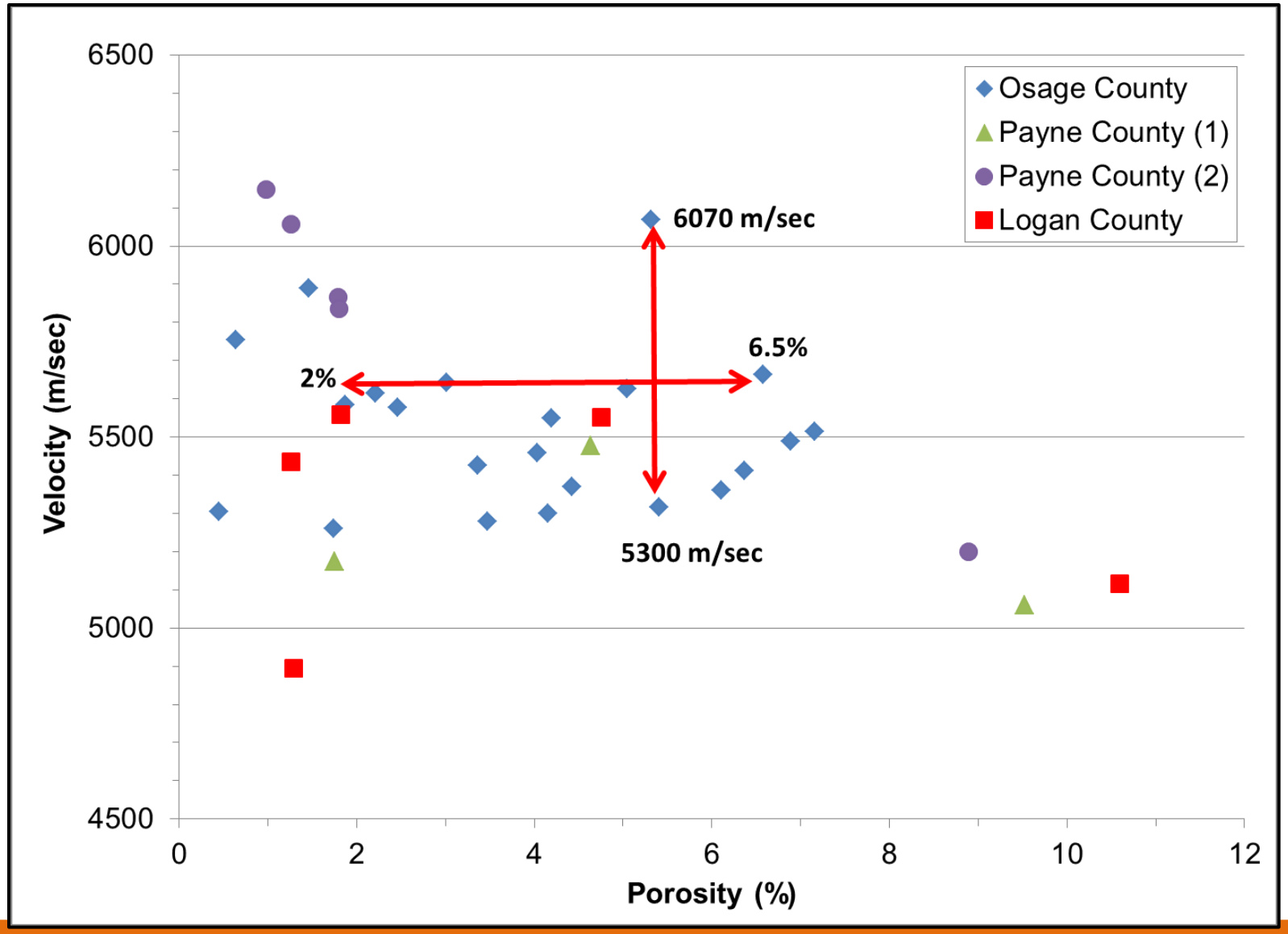
Multivariate Statistical Analysis

$$lnK = 3.906lnV_p + 2.263ln\Phi - 41.722ln\rho_b + 3.955ln\gamma - 0.926lnPOA + 1.005lnAR + 0.697lnV_s - 0.310lnDS - 7.013$$ $R^2 = 0.817$

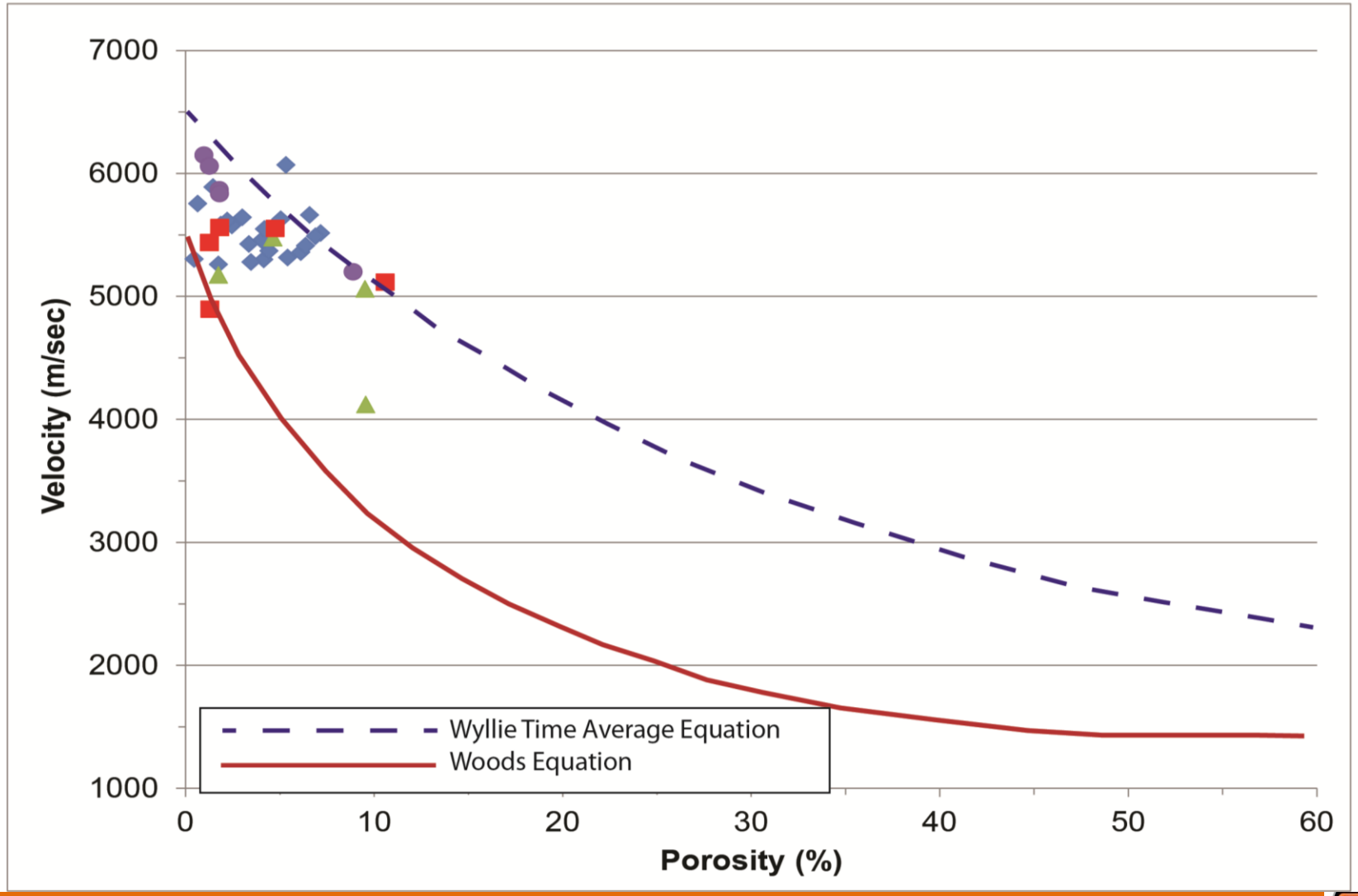


Thornton and Grammer 2012

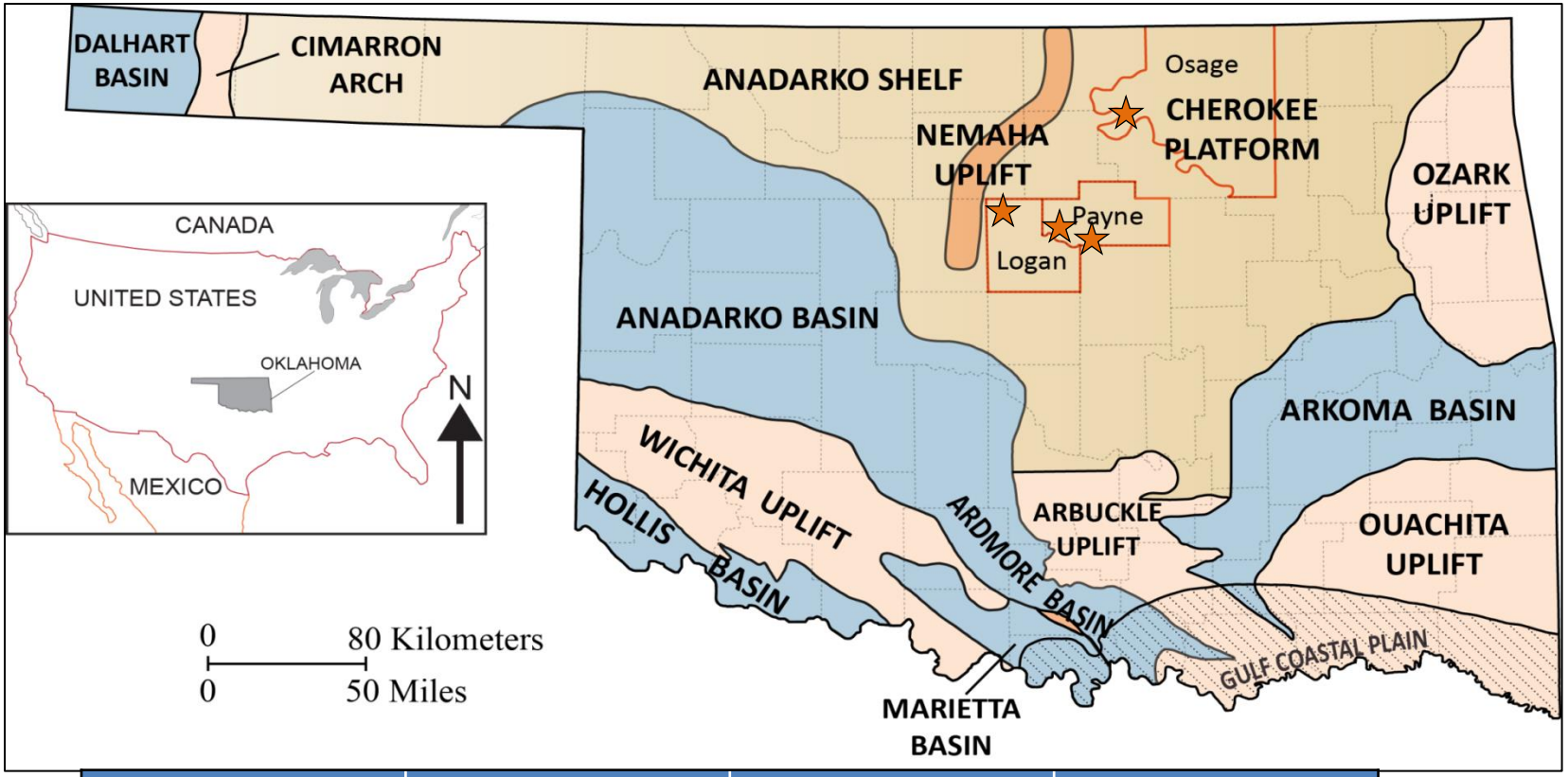
Carbonate mudrock acoustic response



Unconventional carbonate mudrock acoustic response relationship to empirical equations

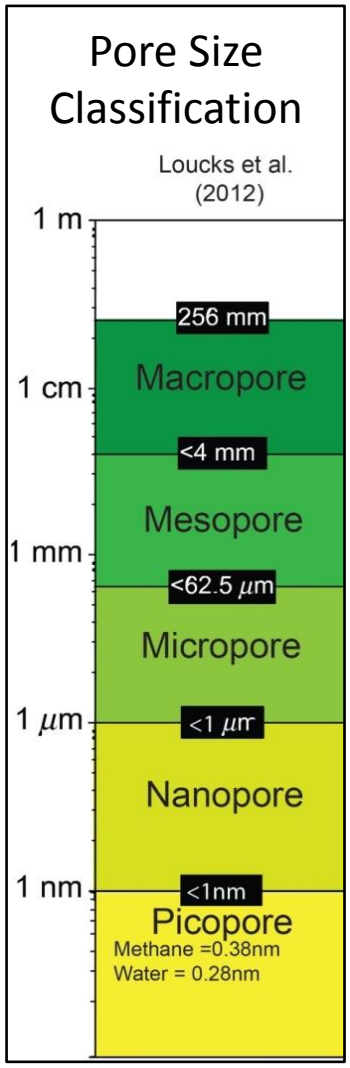


Study area and core locations

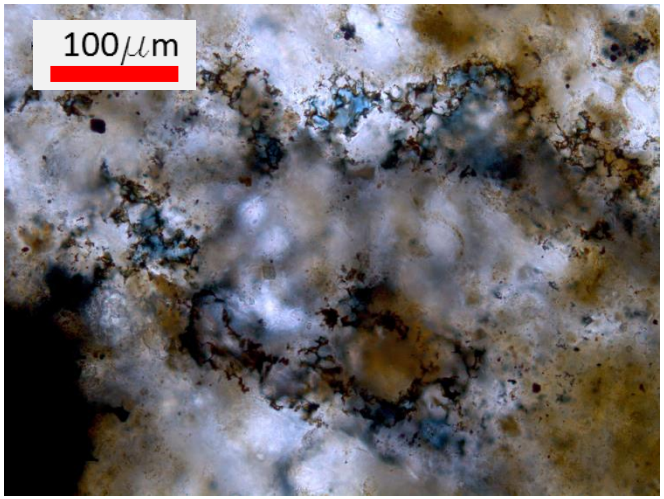


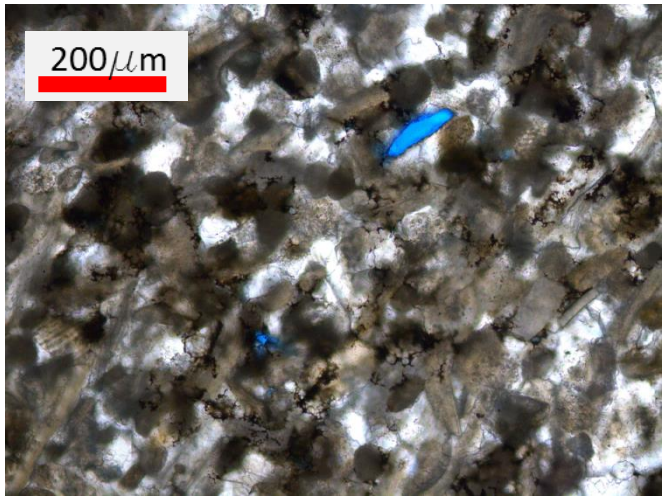
County Name	Cored Miss. Interval (feet)	Thin Sections	SEM (in progress)
Osage	278	47	15
Payne	144	20	16
Payne	190	66	13
Logan	324	67	15

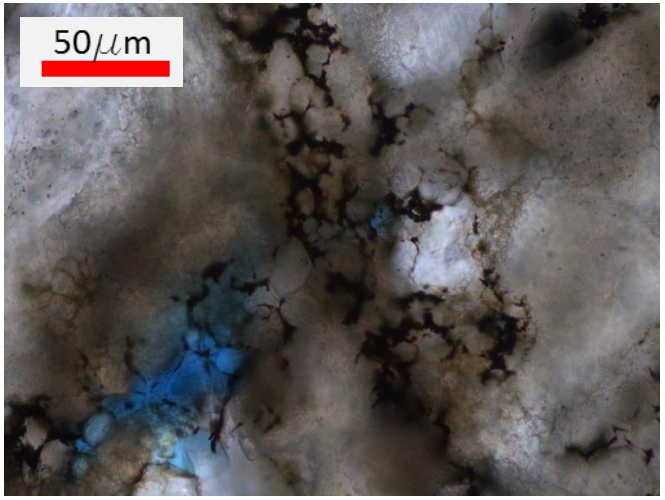
Thin section analysis: Pore architecture

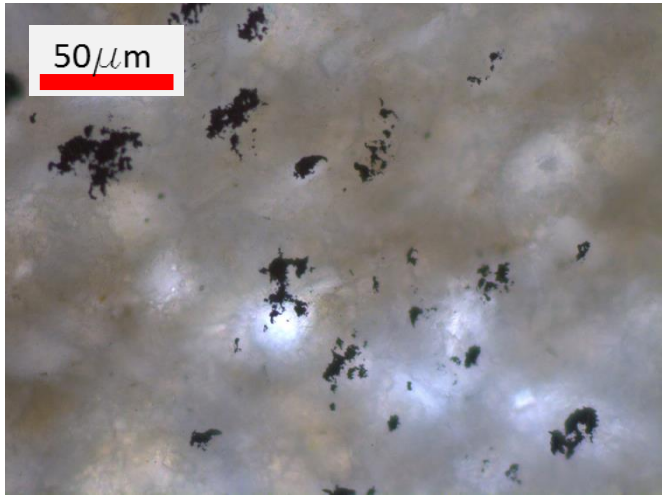


Loucks et al. 2012

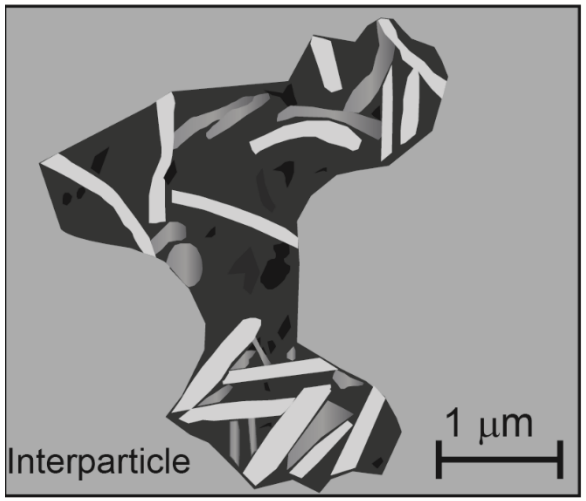


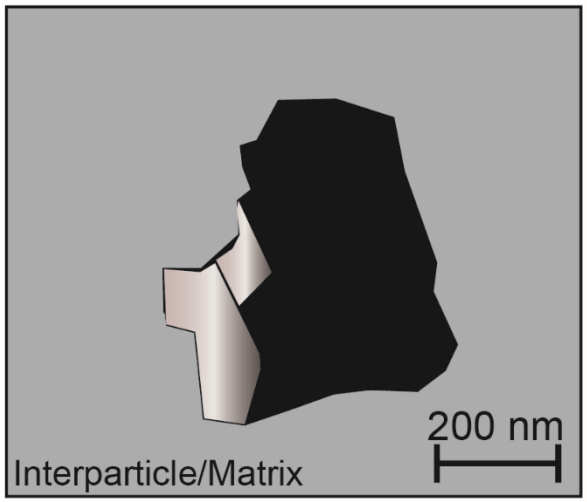


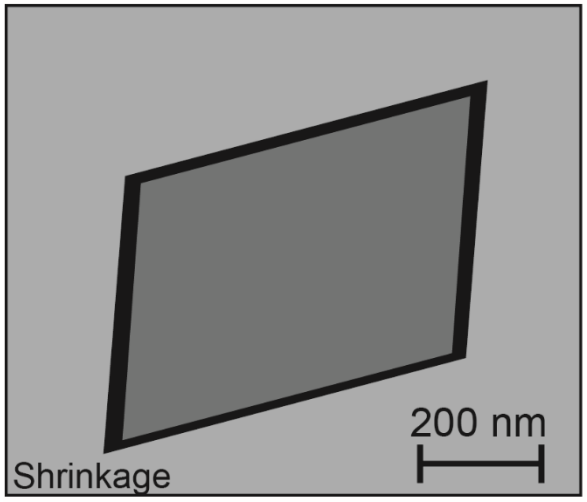


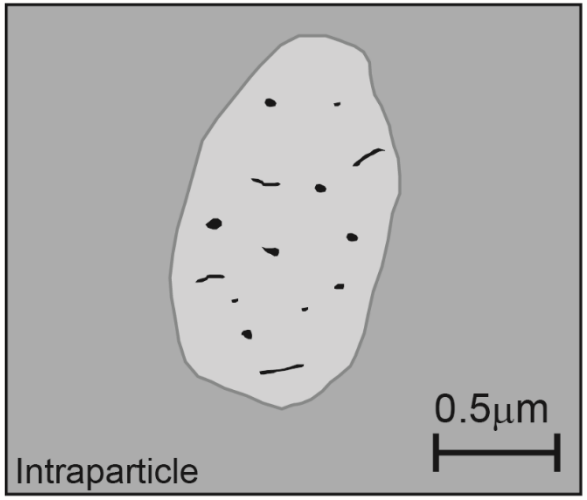


Scanning Electron Microscope: Pore architecture









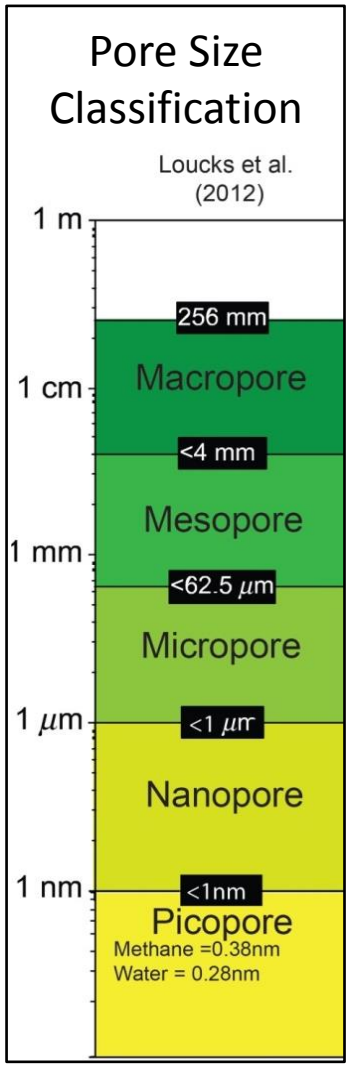
'Matrix' surrounding pores

Pore filling clays

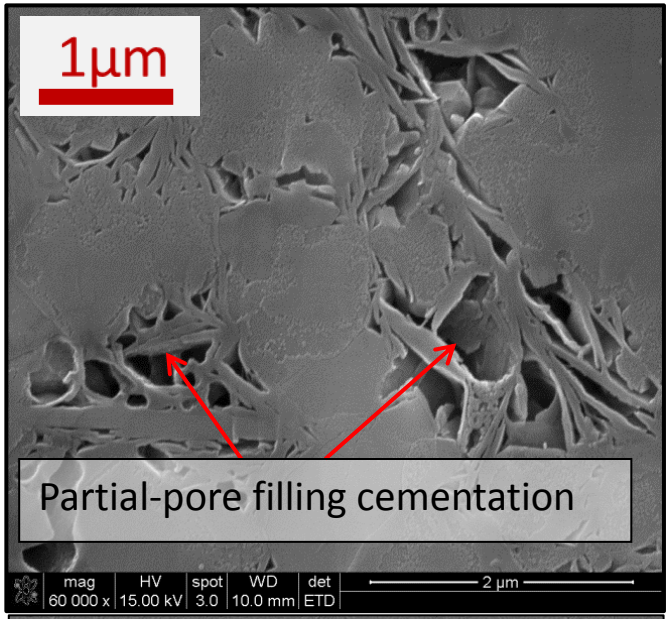
Pore/void space

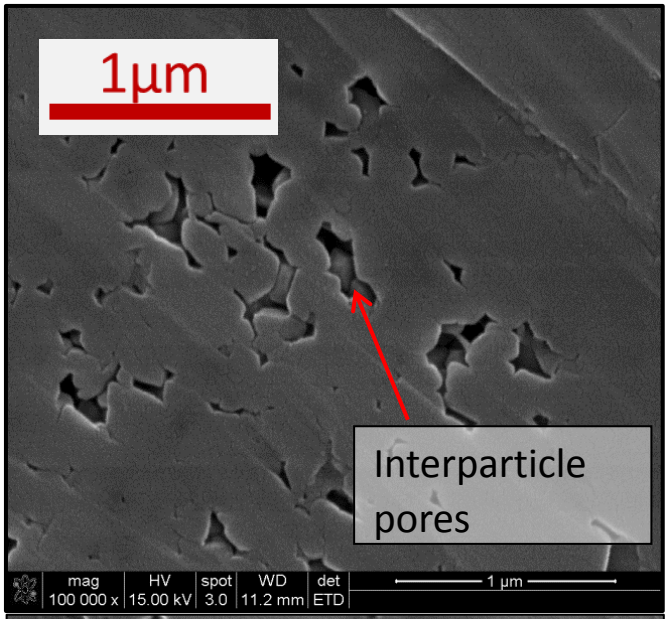
Pore filling calcite

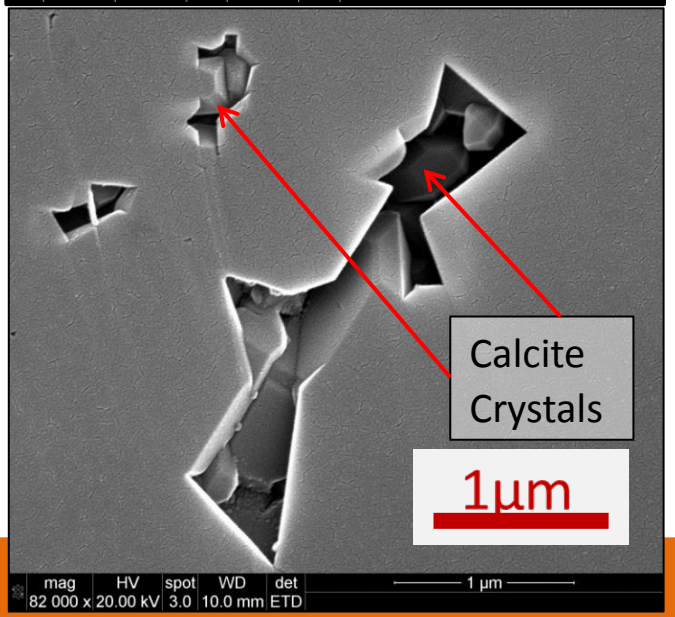
SEM Photomicrographs

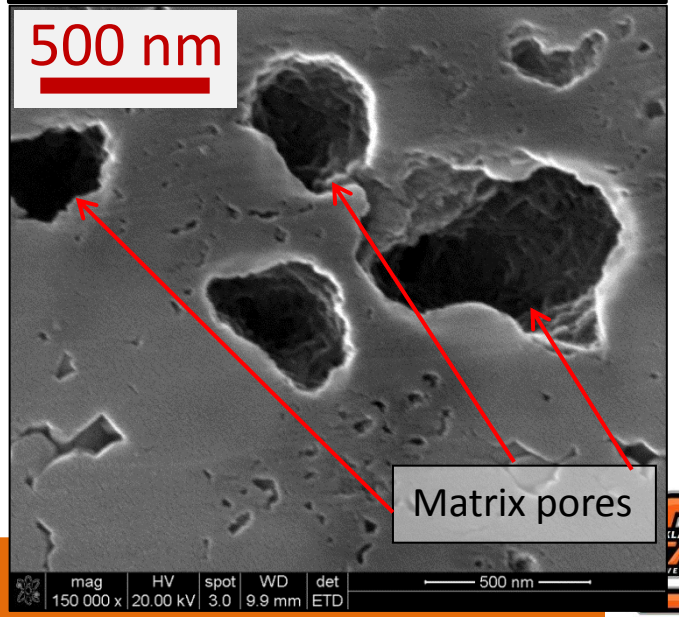


Loucks et al. 2012

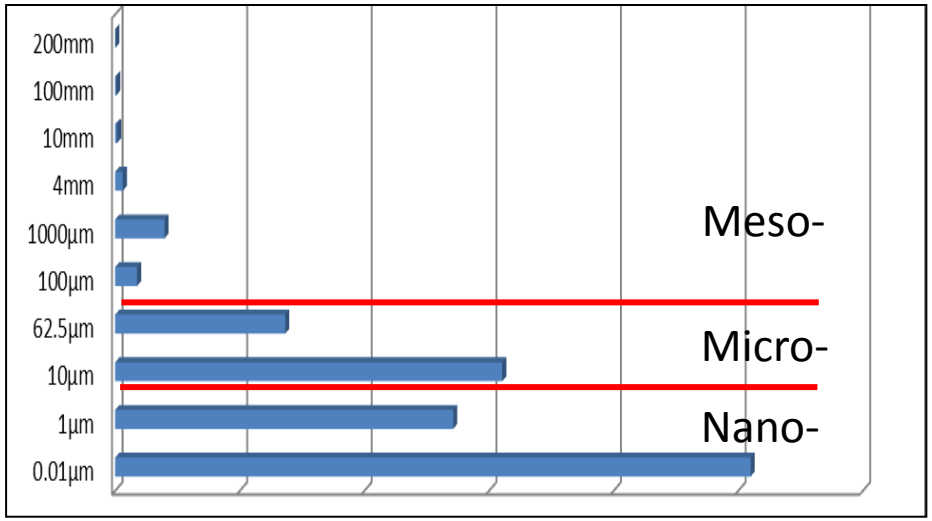


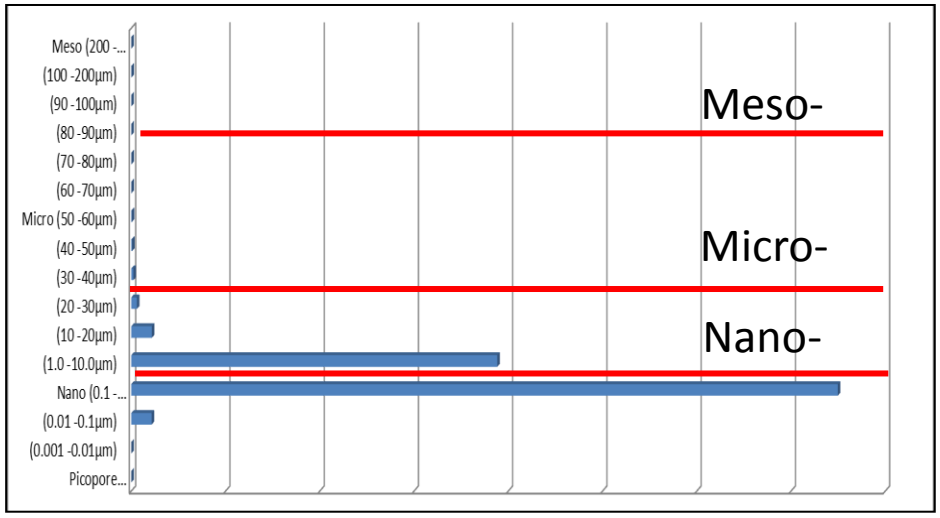


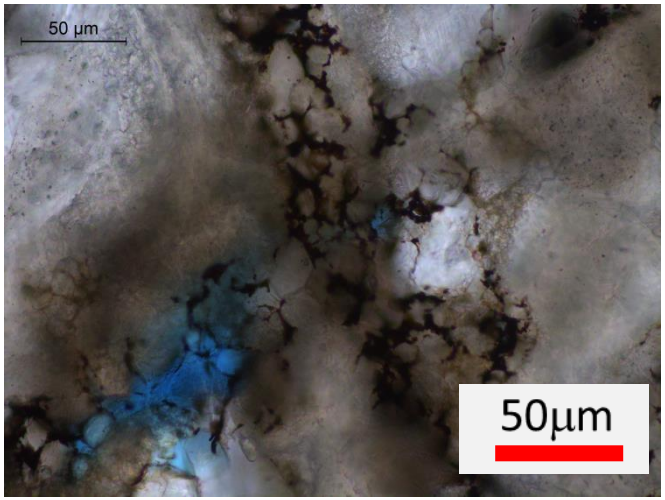


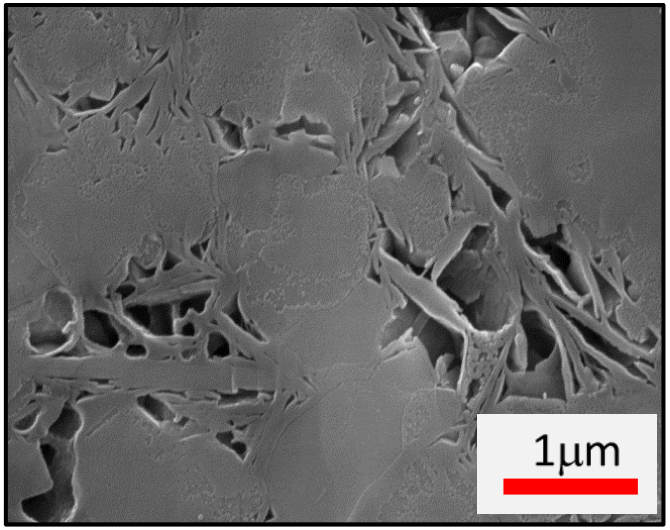


Pore size distribution and permeability



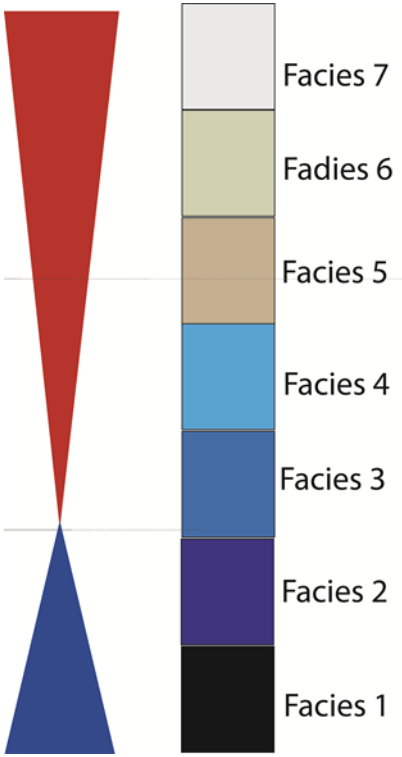




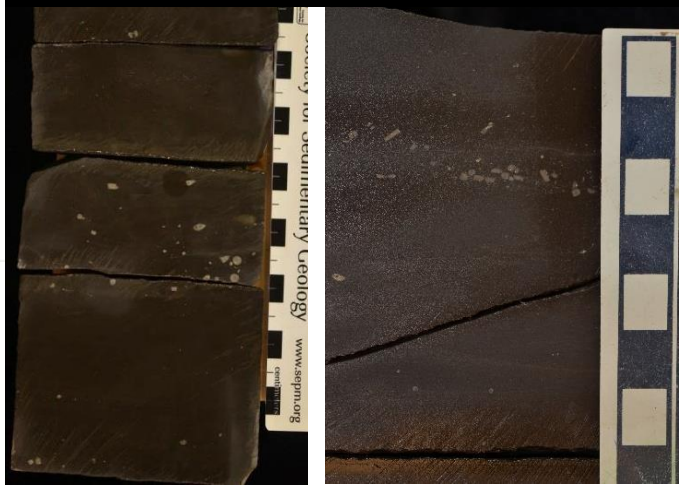


Facies Characterization

Osage County



Facies 1
Spiculitic Mudstone to Wackestone



Facies 2
Bioturbated Mudstone to Skeletal Wackestone

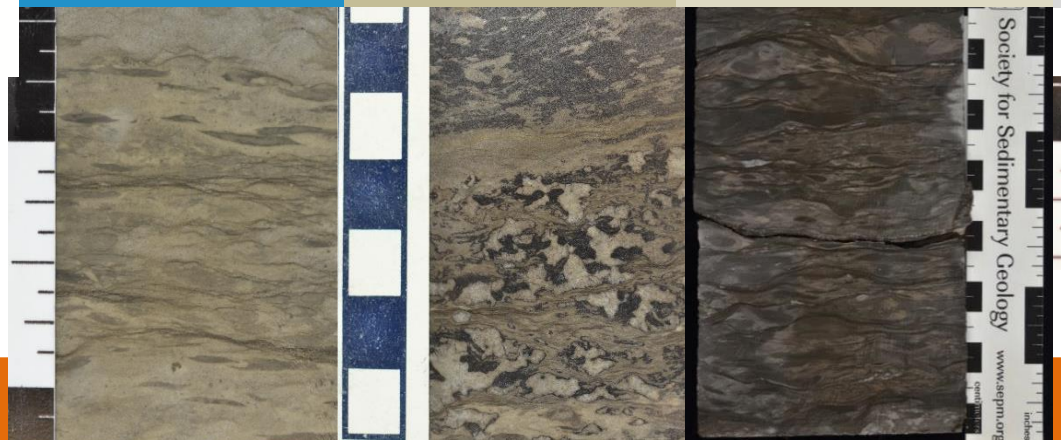
Facies 3
Peloidal-Skeletal-Ooid-Wackestone to Packstone

Facies 4
Bioturbated Skeletal-Peloidal Wackestone

Facies 5
Bioturbated Wackestone

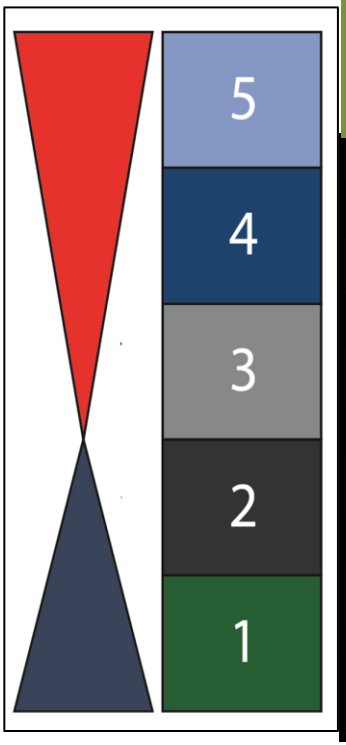
Facies 6
Bioturbated Skeletal-Peloidal Wackestone

Facies 7
Bioturbated Mudstone to Skeletal Wackestone



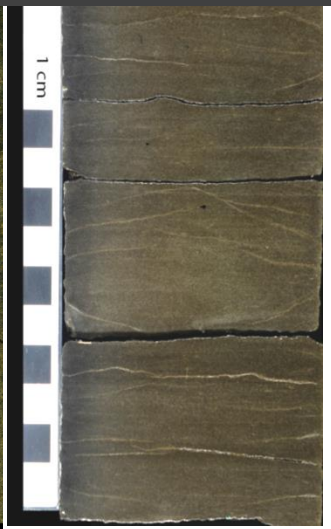
Facies Characterization

Logan and Payne County



Facies 1 Glauconitic Sandstone

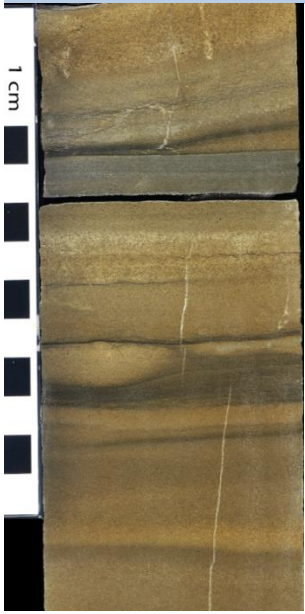
Facies 2 Burrowed Calcareous Mudstone-Wackestone



Facies 3 Bioturbated Wackestone -

Facies 4 Peloidal Packstone - Grainstone

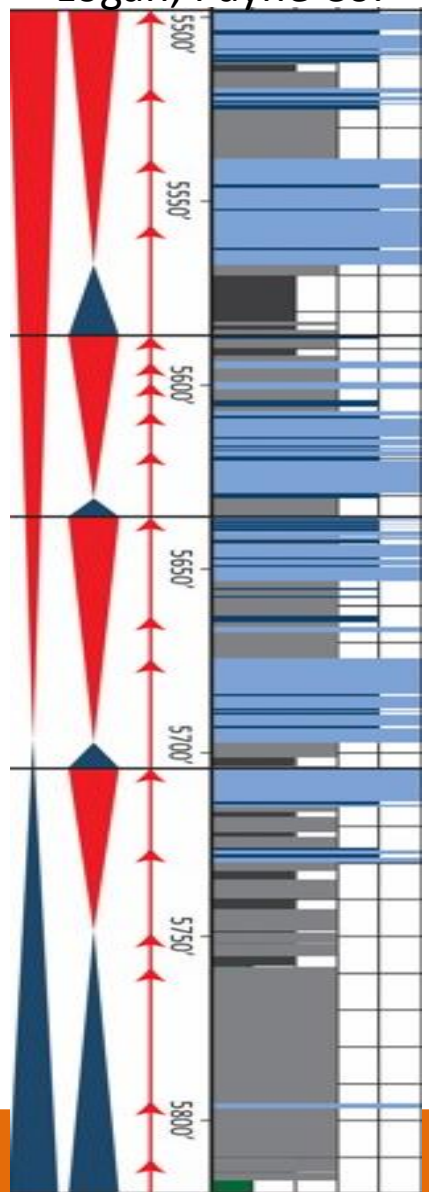
Facies 5 Skeletal Packstone - Grainstone



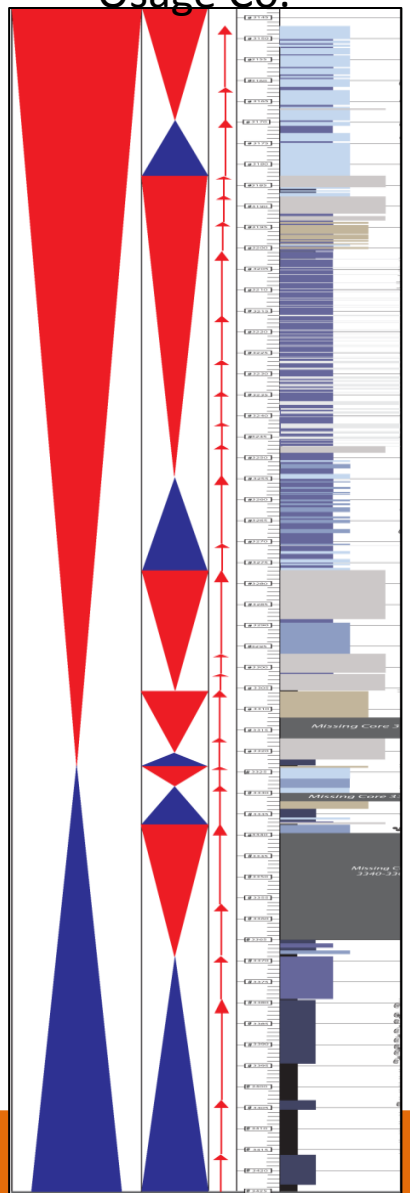
Sequence Stratigraphic Framework

Depositional Variability

Logan, Payne Co.



Osage Co.



Logan & Payne County

- Shallowing upward sequence
- Relative hierarchy:
- One 3rd order sequence
- Classic shoaling upward facies succession
- Siliciclastic input with original deposition
- Reservoir facies primarily at the top of the Miss. section
- No evidence of exposure interval

Osage County

- Shallowing upward sequence
- Relative hierarchy:
- One 3rd order sequence
- Restricted environment facies
- Limited original siliciclastic input
- Potential reservoir throughout, tied to post depositional diagenesis
- Well defined exposure horizon

Rationale for observed differences

- Different locations within the basin
- Potentially different time periods captured
- Different depositional environments relative to basin topography and continental, siliciclastic influences

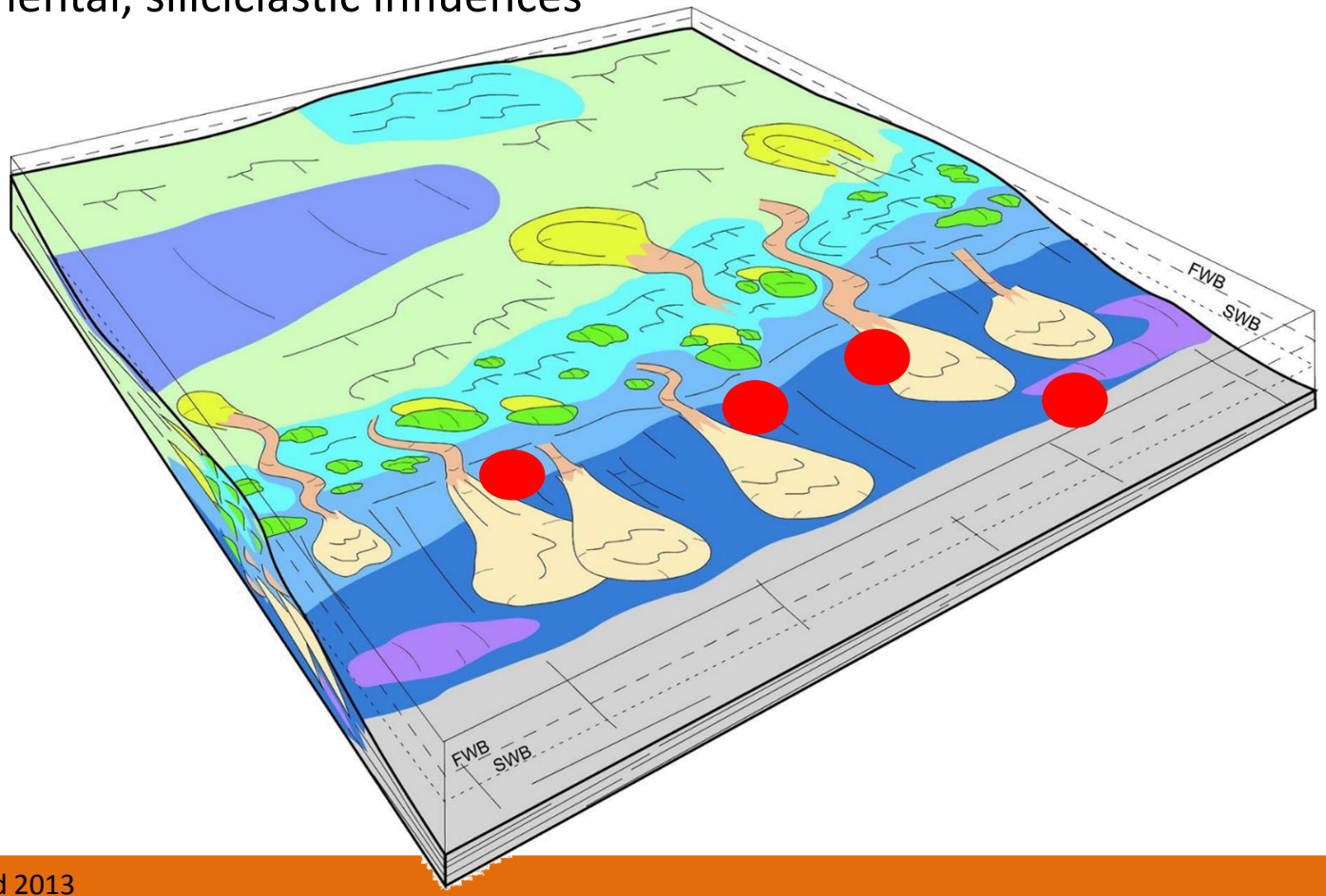
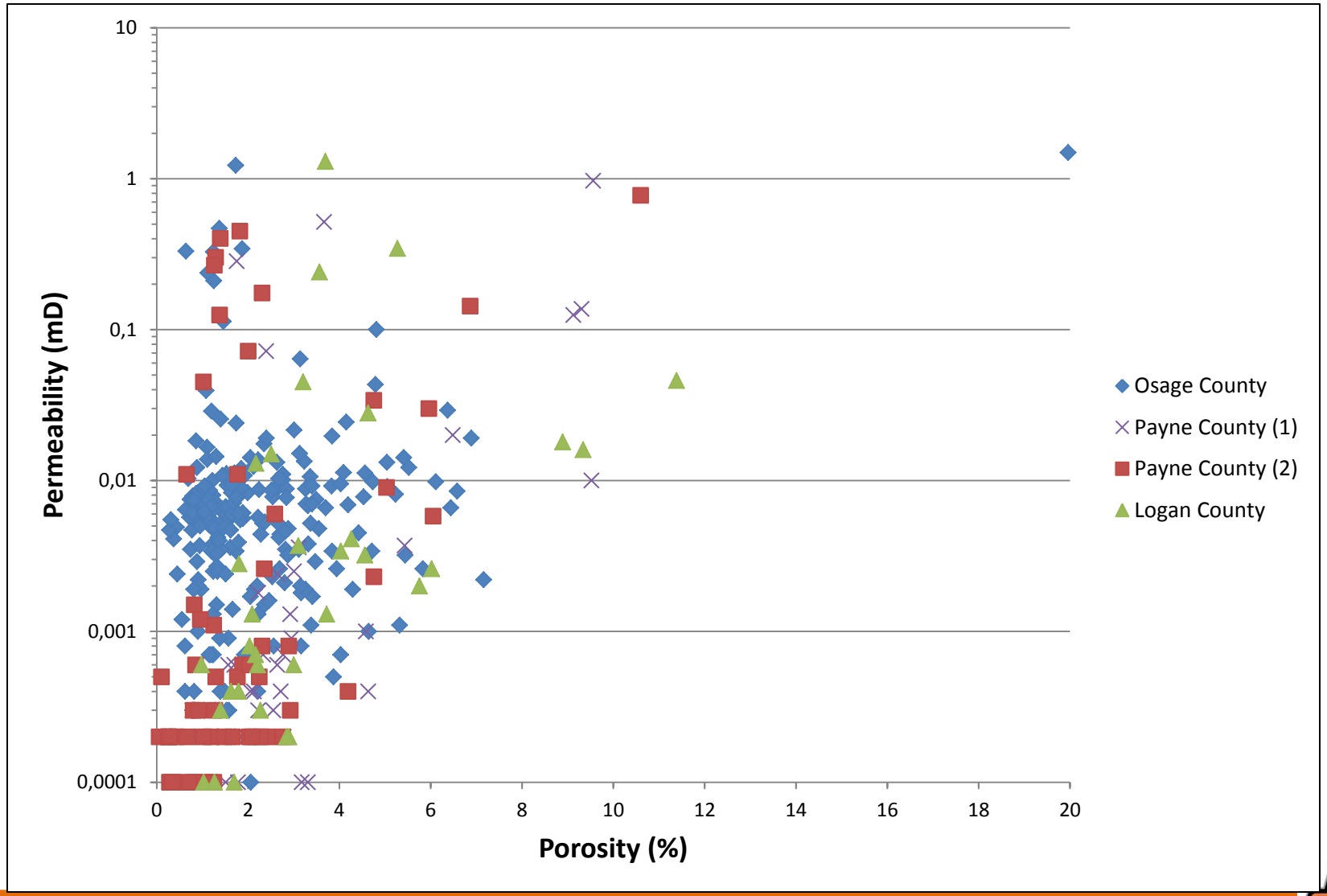


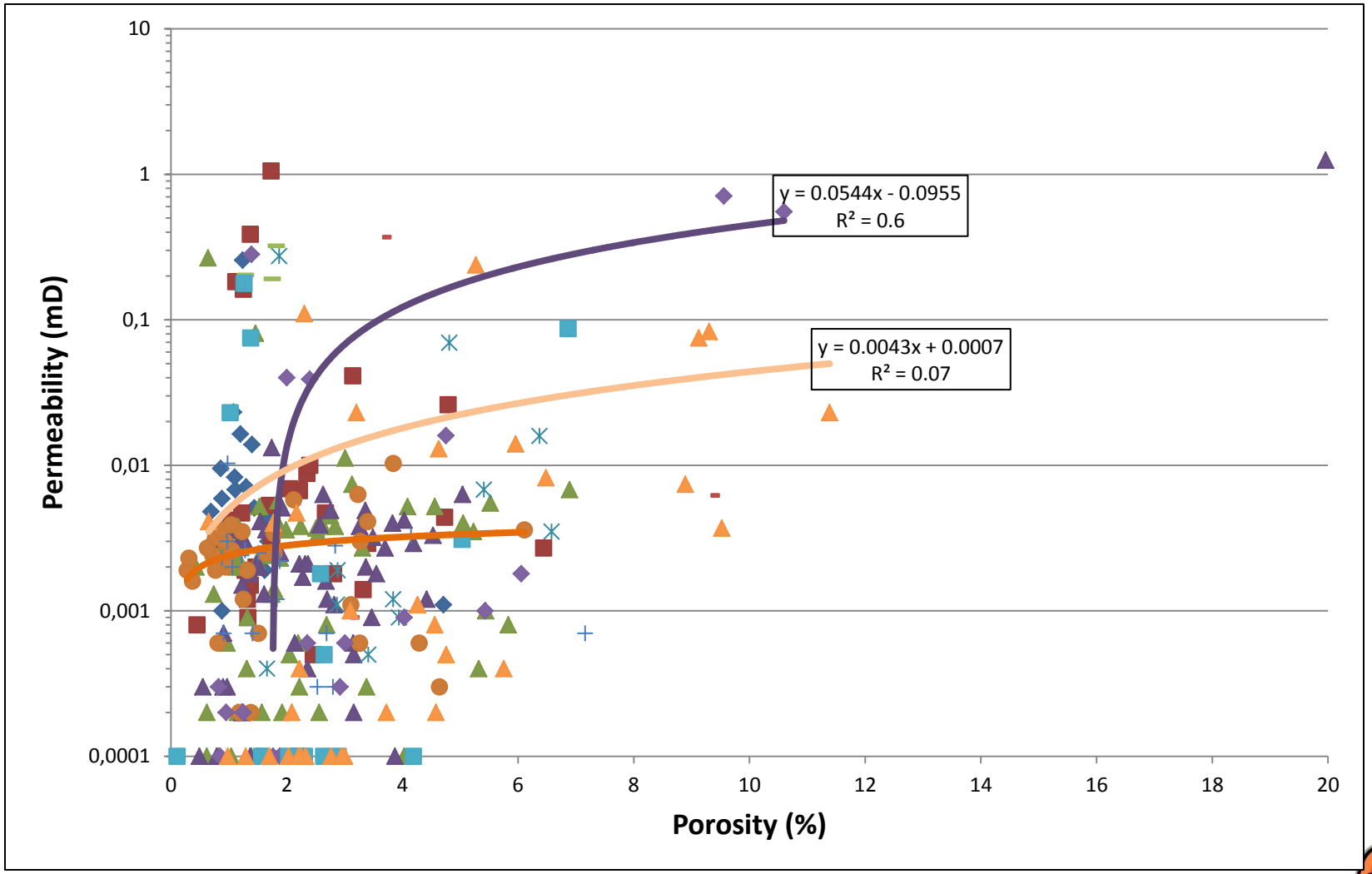
Figure from Handford 2013

Porosity, permeability, and facies



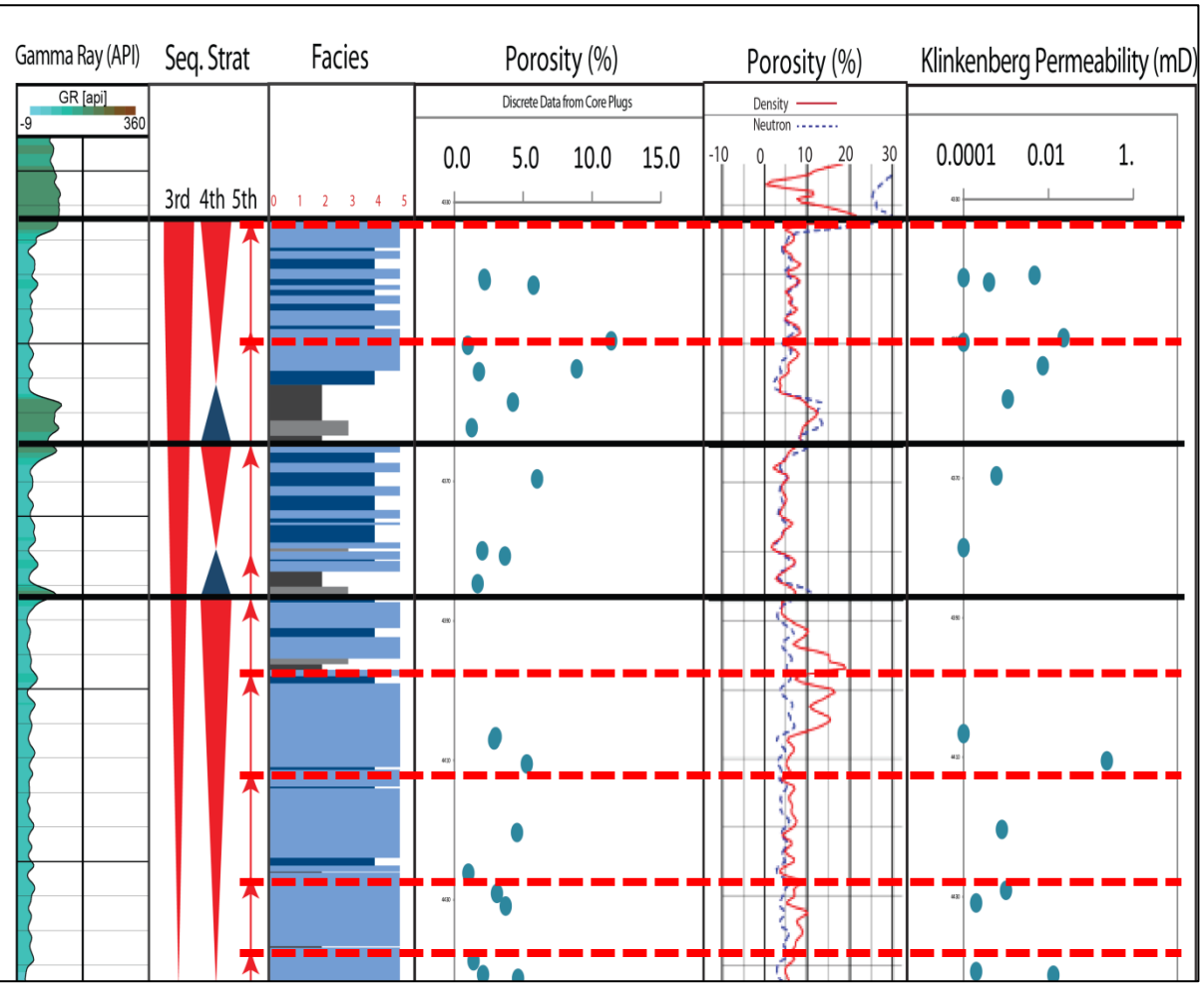
Data set results (Osage County)

Porosity, permeability, facies relationship



High Resolution Sequence Stratigraphy

Predicting porosity and permeability



Predictable correlation with sequence stratigraphic framework, porosity and permeability

Wireline logs (GR) correlate to 4th order sequences

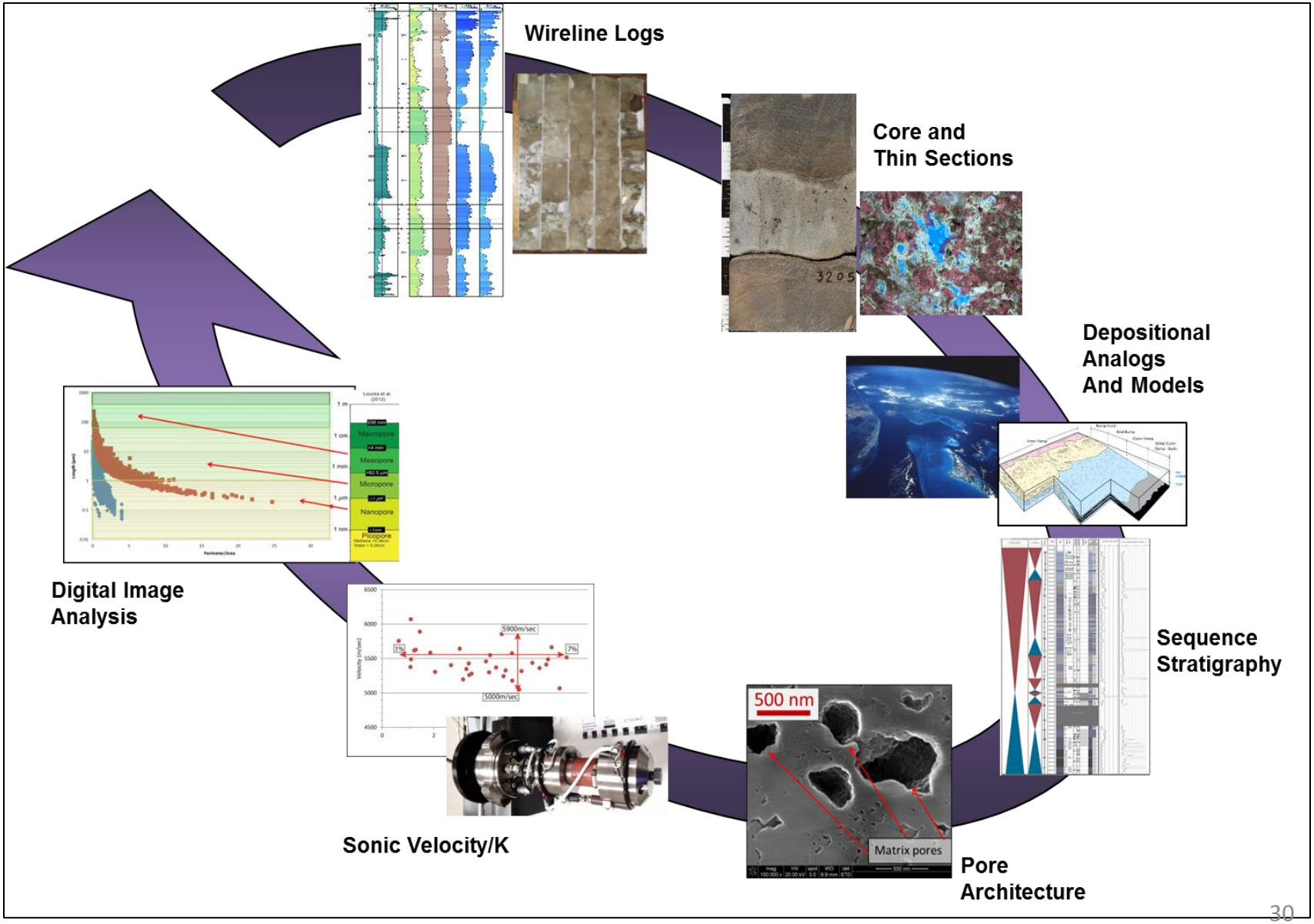
4^{th} order regressive phase within the 3^{rd} order regressive sequence:

- Highest porosity & permeability at the top of 5^{th} order cycle.

Summary and Preliminary Conclusions

- Facies preserved highlight how quickly depositional environments can change across relatively short horizontal distances
- Similar fundamental sequence stratigraphic architecture
- Wireline logs and high resolution sequence stratigraphic analysis enhances predictability of high porosity and high permeability intervals
- Simple scatter plots and cross-plots of porosity and permeability data are unlikely to reveal significant trends in carbonate mudrocks
- Pore architecture characterization can help explain deviations to expected relationships in facies and petrophysical properties
- Acoustic response data indicate potential to enhance the predictability of key petrophysical properties

Thank you!


Wireline Logs
Core and
Thin Sections
Depositional
Analogs
And Models
Digital Image
Analysis
Sequence
Stratigraphy
5900m/sec
5000m/sec
1%
7%
Sonic Velocity/K
500 nm
Matrix pores
Pore
Architecture