Using Carbonate Mudrock Pore Architecture to Provide Insight into Porosity and Permeability Trends in Unconventional Carbonate Reservoirs: Examples from the Mid-Continent Mississippian Limestone*

Beth Vanden Berg[1] and G. Michael Grammer[1]

Search and Discovery Article#51095 (2015)**
Posted June 15, 2015

*Adapted from presentation at Tulsa Geological Society luncheon meeting, April 28, 2015.
Editor's note: Please refer to the following related articles by the authors and colleagues: Unconventional Carbonate Reservoir Characterization Using Sonic Velocity and Characterization of Pore Architecture: An Example From the Mid-Continent Mississippian Limestone," Search and Discovery Article #50979 (2014) and "Combining Pore Architecture and Sonic Velocity Response to Predict Reservoir Quality: An Example from a Mid-Continent Mississippian Carbonate, " Search and Discovery Article #10547 (2013).

[1]Boone Pickens School of Geology, Oklahoma State University, Stillwater, Oklahoma (beth.vanden_berg@okstate.edu)

Abstract

The Mid-Continent Mississippian Limestone is an unconventional carbonate reservoir with a complex depositional and diagenetic history. Oil and gas have been produced from vertical wells for over 50 years, but recent horizontal activity in low porosity, low permeability zones have illustrated how crucial it is to understand the petrophysical characteristics to better target producing intervals. Because of the wide variability and complexity of pore systems in carbonate reservoirs, simple porosity and permeability transforms developed for siliciclastic reservoirs often provide erroneous results for carbonates. Recent research has only started to identify the complexity of the pore architecture observed in carbonate mudrocks and the applicability of conventional carbonate pore relationships to describing carbonate mudrock systems.

The current study shows examples of how fundamental relationships between pore shape, porosity, permeability, and acoustic response differ in carbonate mudrocks with micro- to pico-porosity (<62μm diameter) compared to conventional carbonates with primarily macropore (256-4mm diameter) systems. Quantitative data show positive correlations exist between porosity and permeability, but negative to no correlation between pore shape and associated porosity and permeability. In addition, there is a significant shift in the acoustic response relative to values calculated from empirically derived equations for porosity in

carbonate mudrocks. Deviations from quantitative data trends are explained through qualitative observations of the pore types and differing internal pore geometries. Visual observations of the pore morphology show how post-depositional cementation can increase the complexity of the internal pore network by sub-dividing pores. When correlated to facies, the internal pore geometry helps explain deviations to general relationships between basic quantitative pore architecture measurements, porosity, and permeability. Although there is an added level of complexity in the pore architecture of carbonate mudrocks, there are fundamental relationships that exist between the pore architecture, pore shape, porosity, permeability, acoustic response, facies, and sequence stratigraphic framework with variable levels of predictability that, when used as an integrated data set, can be used to enhance the predictability of key petrophysical properties within these types of reservoir systems.

References Cited

Anselmetti, F.S., and G.P. Eberli, 1999, The velocity-deviation log; a tool to predict pore type and permeability trends in carbonate drill holes:from sonic and porosity or density logs: AAPG Bulletin, v. 83/3, p. 450-466.

Anselmetti, F.S., S.M. Luthi, and G.P. Eberli, 1998, Quantitative characterization of carbonate pore systems by digital image analysis: AAPG Bulletin, v. 82/10, p. 1815-1836.

Baechle, G.T., R. Weger, J.L. Massaferro, and G.P. Eberli, , 2004, The role of macroporosity and microporosity in constraining uncertainties and in relating velocity to permeability in carbonate rocks: Annual International Meeting Expanded Abstracts, Society of Exploration Geophysicists, Denver Colorado.

Eberli, G.P., G.T.,Baechle, F.S. Anselmetti, and M.L. Incze, 2003, Factors controlling elastic properties in carbonate sediments and rocks: The Leading Edge, v. 22, p. 654-660.

Grammer, G.M., 2013, An integrated approach to characterization and modeling of carbonate reservoirs: Search and Discovery Article #50784 (2013). Web accessed May 26, 2015. http://www.searchanddiscovery.com/documents/2013/50784grammer/ndx_grammer.pdf

Harris, S.A., 1975, Hydrocarbon accumulation in "Meramec-Osage" (Mississippian) rocks, Sooner Trend, northwest-central Oklahoma: AAPG Bulletin, v. 59, p. 633-664.

Loucks, R.G., R.M. Reed, S.C. Ruppel, and U. Hammes, 2012, Spectrum of pore types and networks in mudrocks and a descriptive classification for matrix-related mudrock pores: AAPG Bulletin, v. 96/6, p. 1071–1098.

Rouquerol, J., D. Avnir, C.W. Fairbridge, D.H. Everett, J. H. Haynes, N. Pernicone, J.D.F. Sing, and K.K. Unger, 1994, Recommendations for the characterization of porous solids: Pure and Applied Chemistry, v. 66, p. 1739–1758,

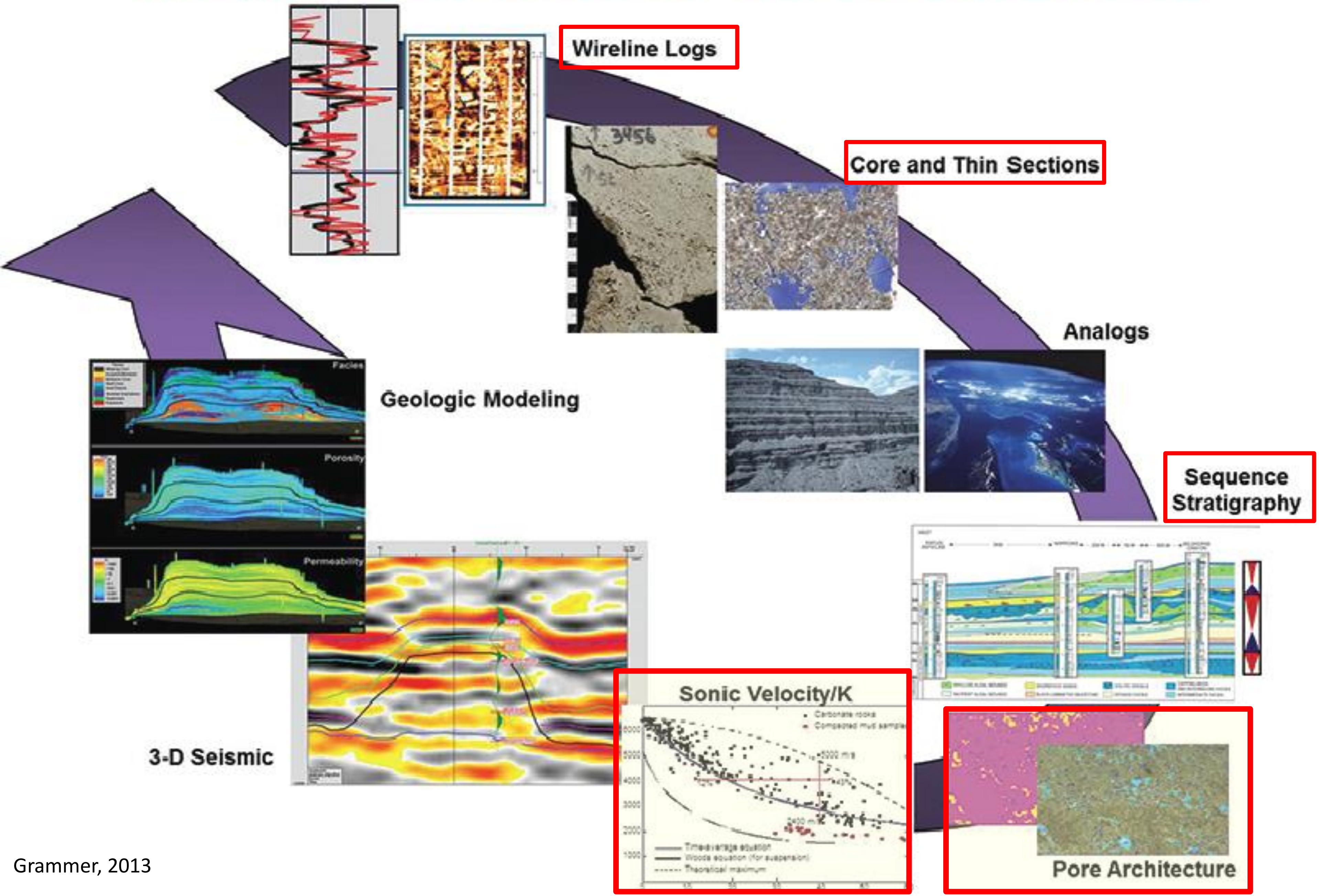
Thornton, J.E., and G.M. Grammer, 2012, Enhanced reservoir characterization and permeability prediction of heterogeneous carbonate reservoirs from sonic velocity and digital image analysis: Search and Discovery Article #50689 (2012). Website accessed May 26, 2015. http://www.searchanddiscovery.com/documents/2012/50689thornton/ndx_thornton.pdf.

Using Carbonate Mudrock Pore Architecture to provide insight into porosity and permeability trends in Unconventional Carbonate Reservoirs: examples from the Mid-Continent Mississippian Limestone

Beth Vanden Berg

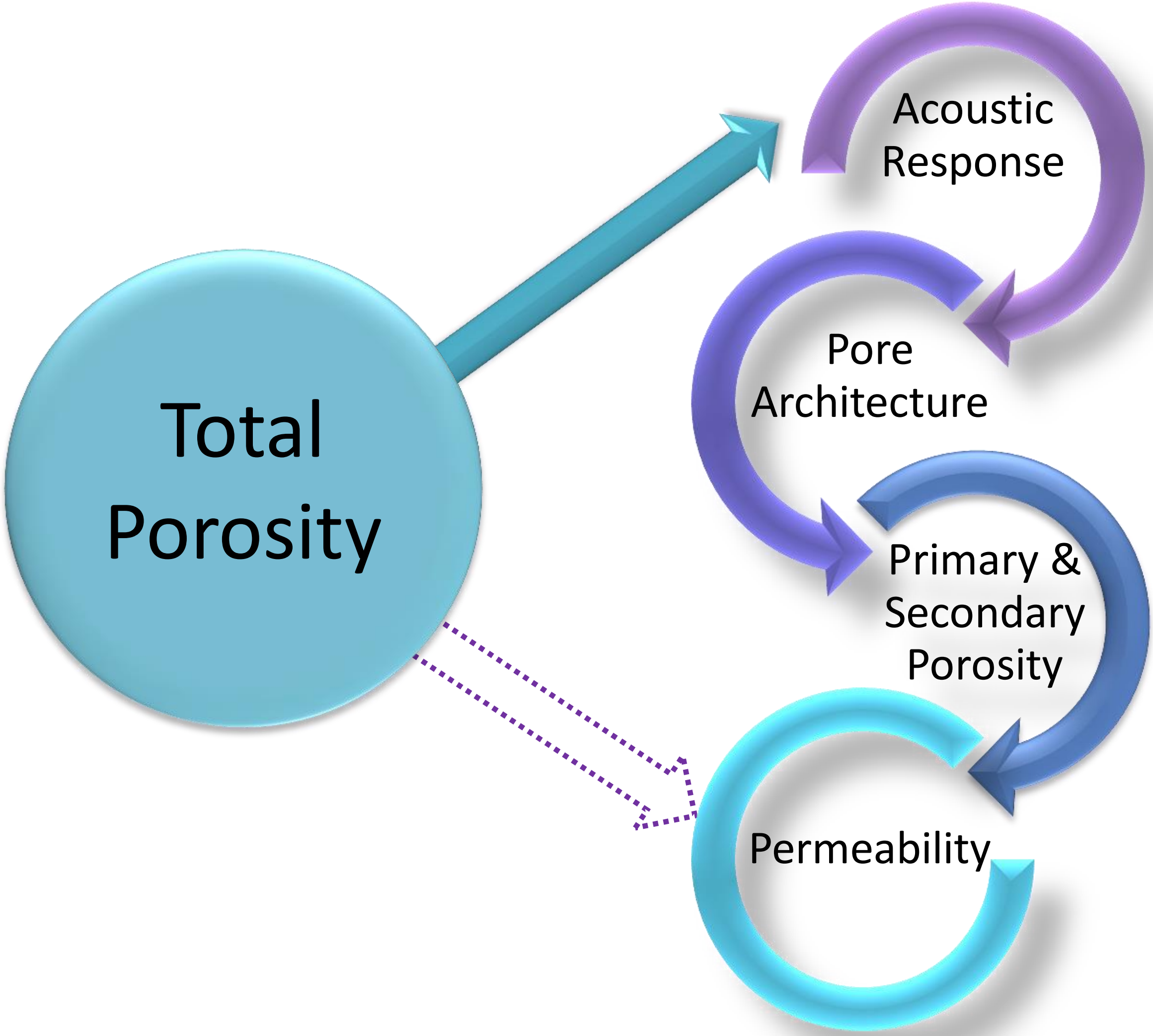
G. Michael Grammer

Integrated Reservoir Characterization



Grammer, 2013

Predicting Reservoir Permeability



Conventional Carbonate Acoustic Response

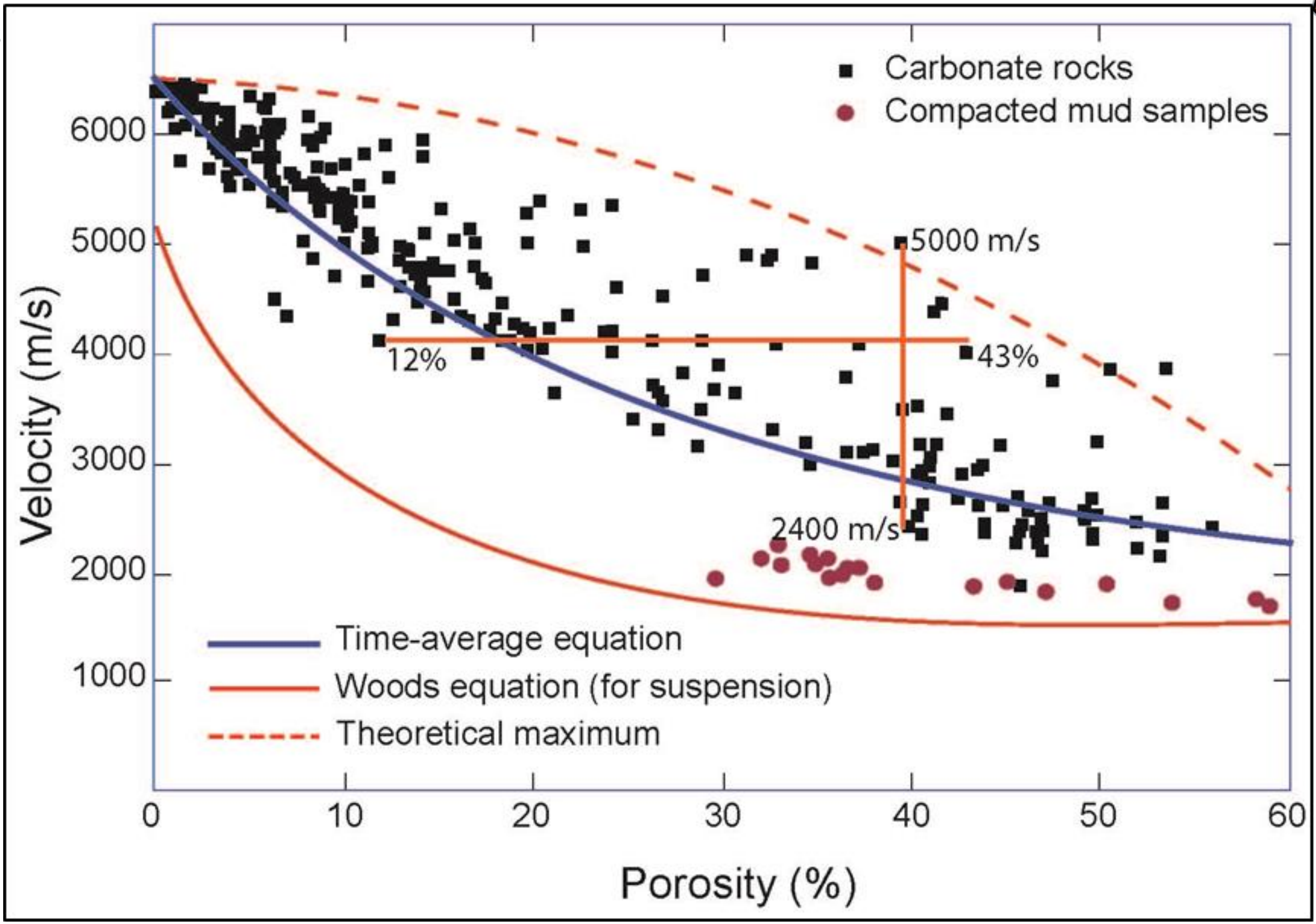
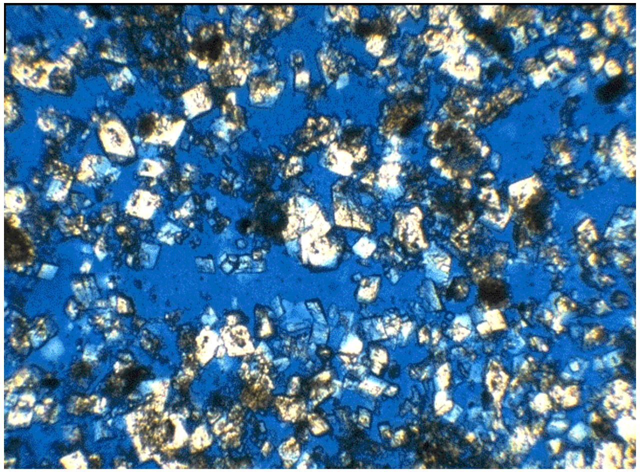
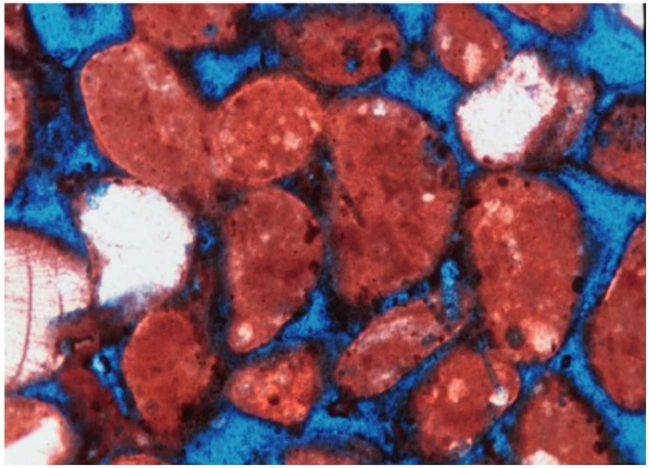


Figure Modified from Eberli et al. 2003
and used with permission from G. Eberli

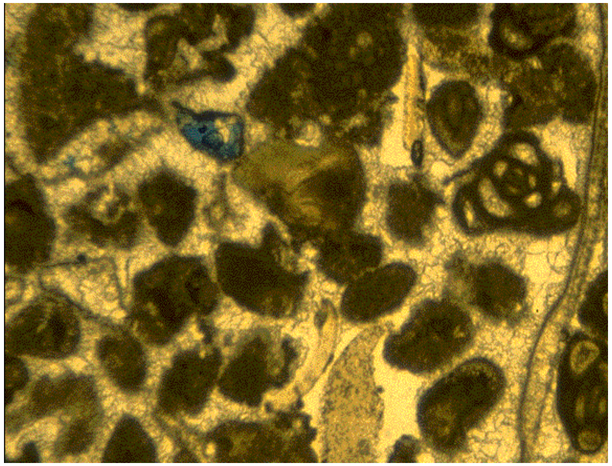
Carbonate Pore Types in Thin Section



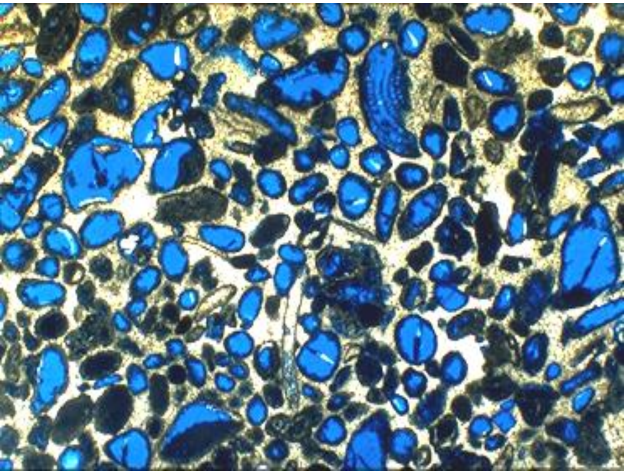
Intercrystalline



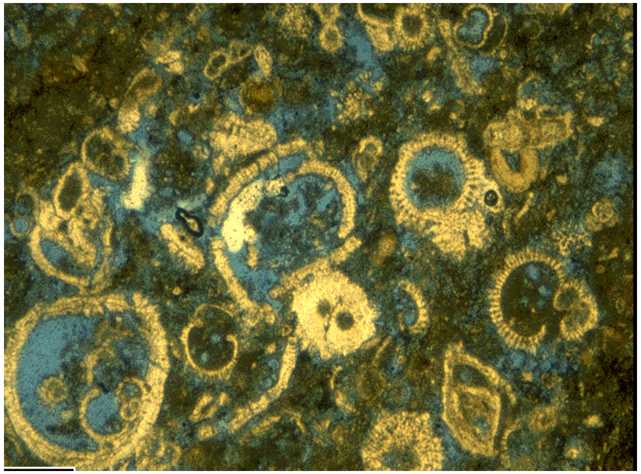
Interparticle



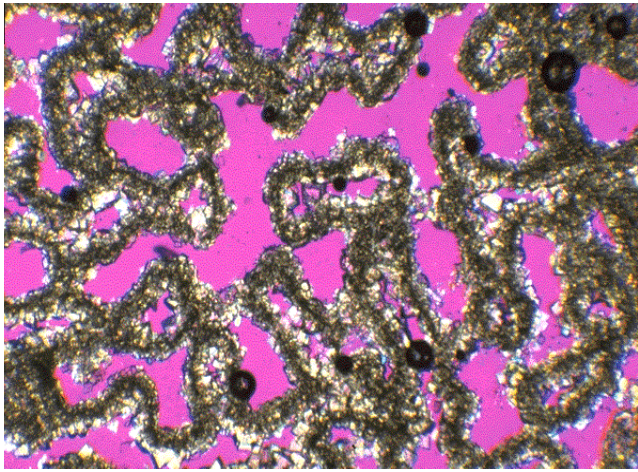
Cemented



Moldic (Vuggy)



Intraparticle



Framework

Predictable Acoustic Response

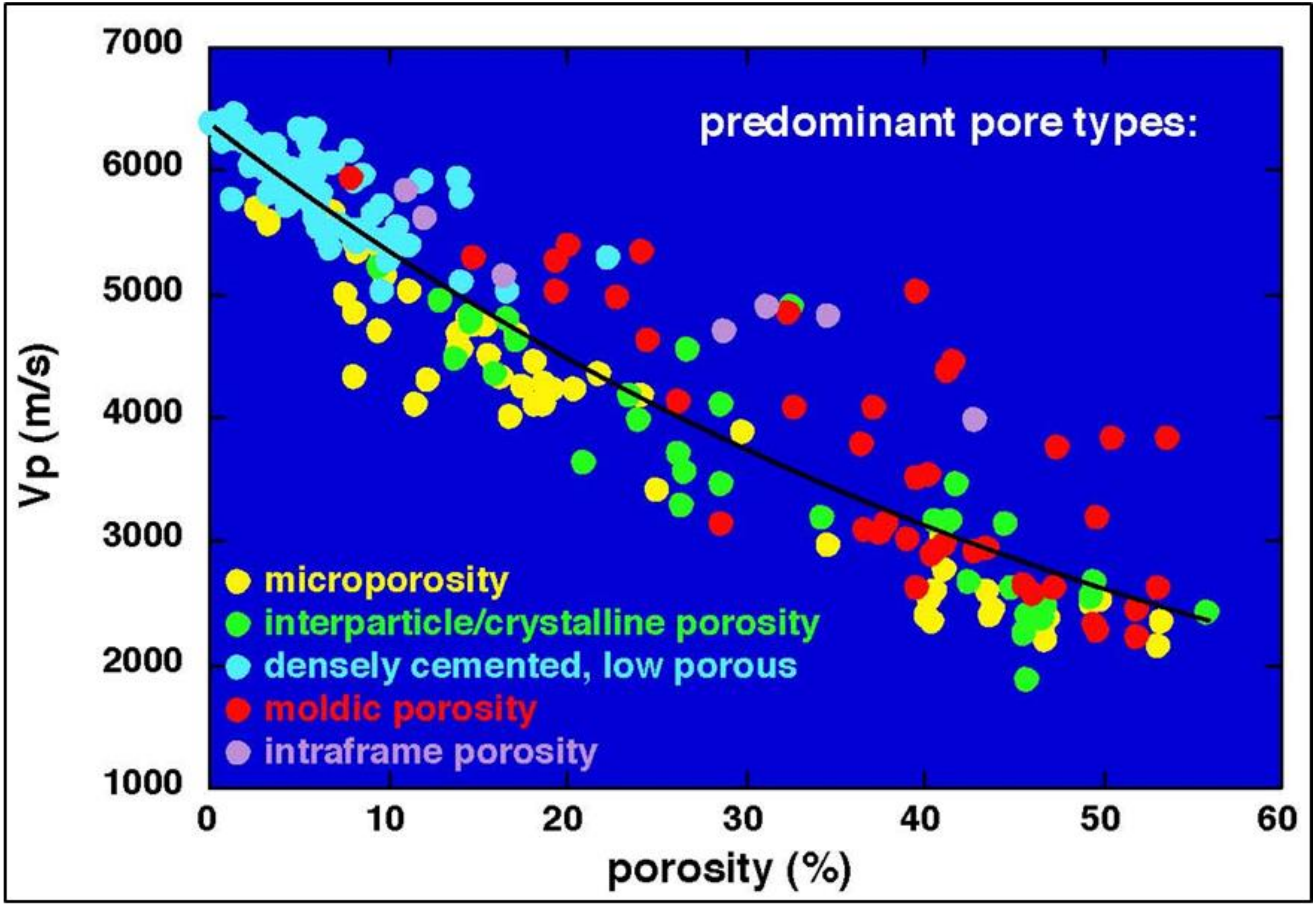
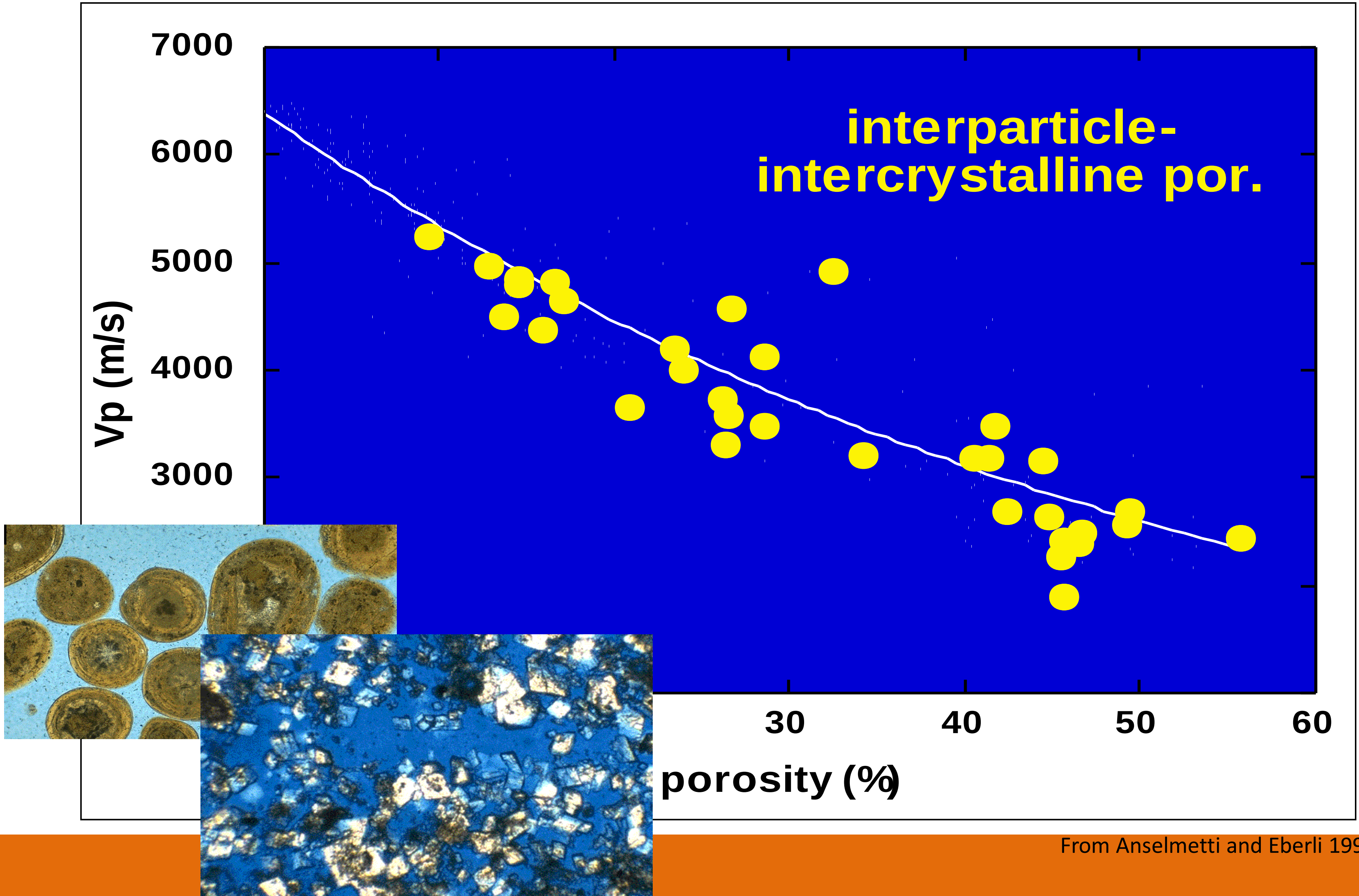


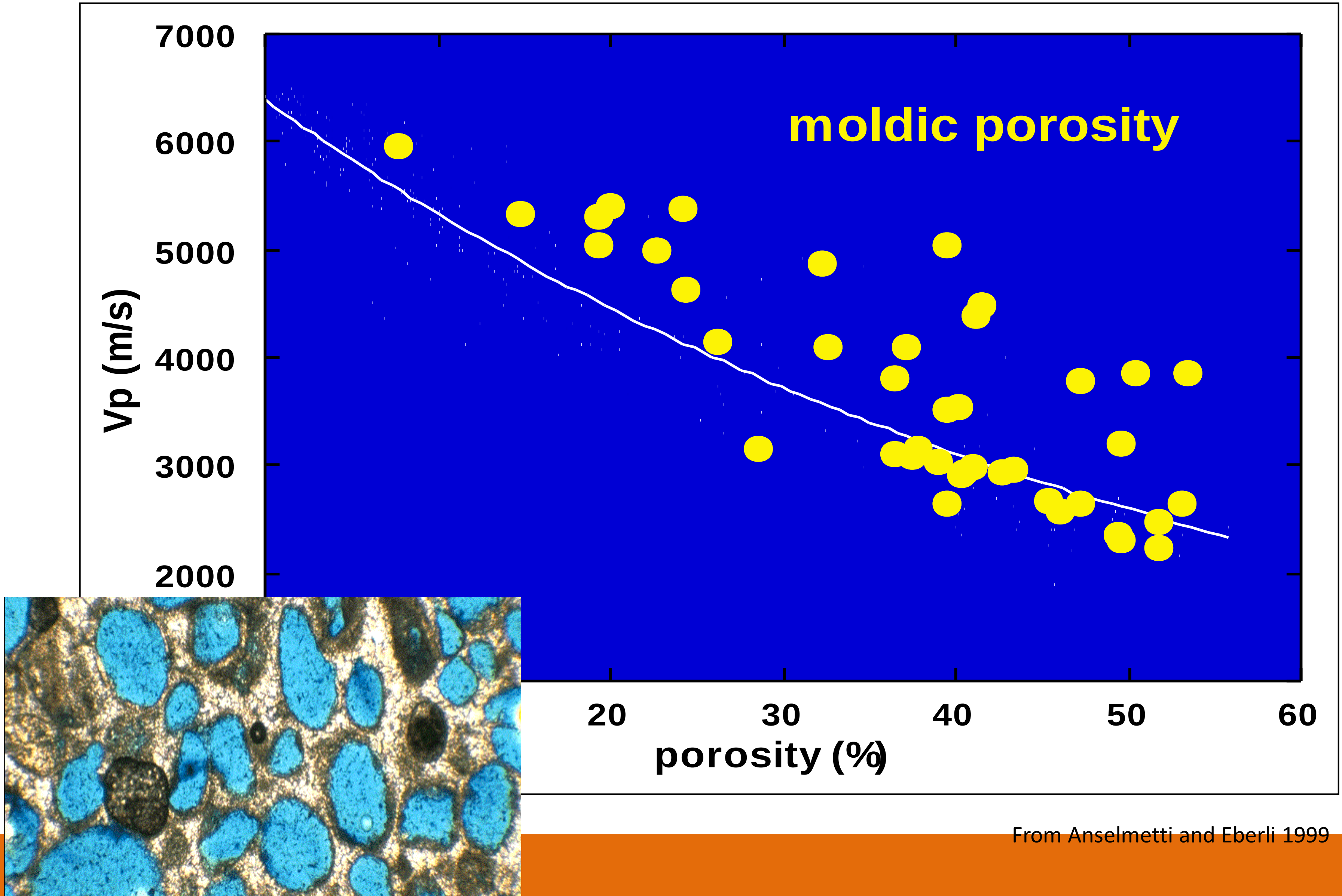
Figure Modified from Eberli et al. 2003

Acoustic Response Relationship to Permeability



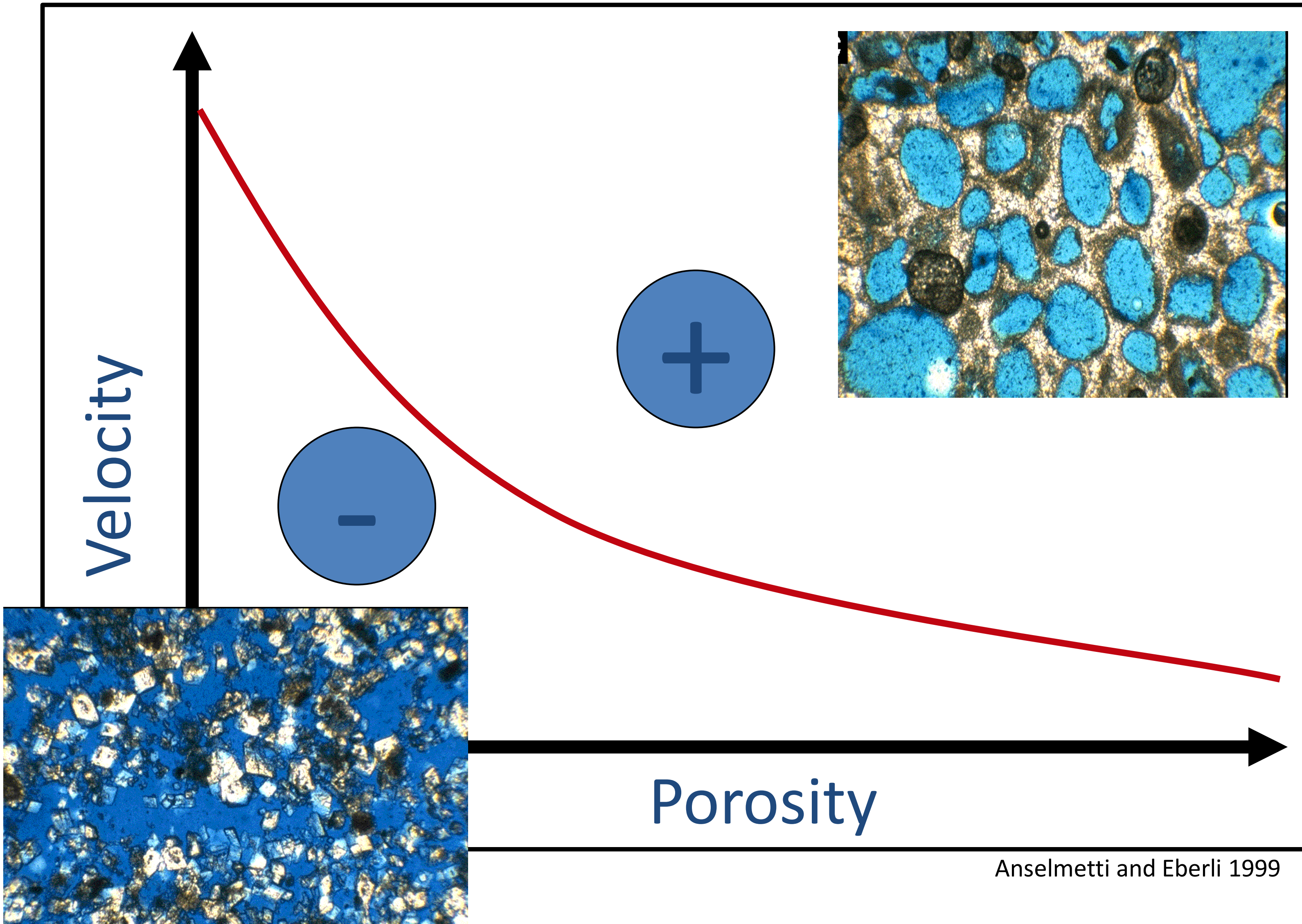
From Anselmetti and Eberli 1999

Acoustic Response Relationship to Permeability



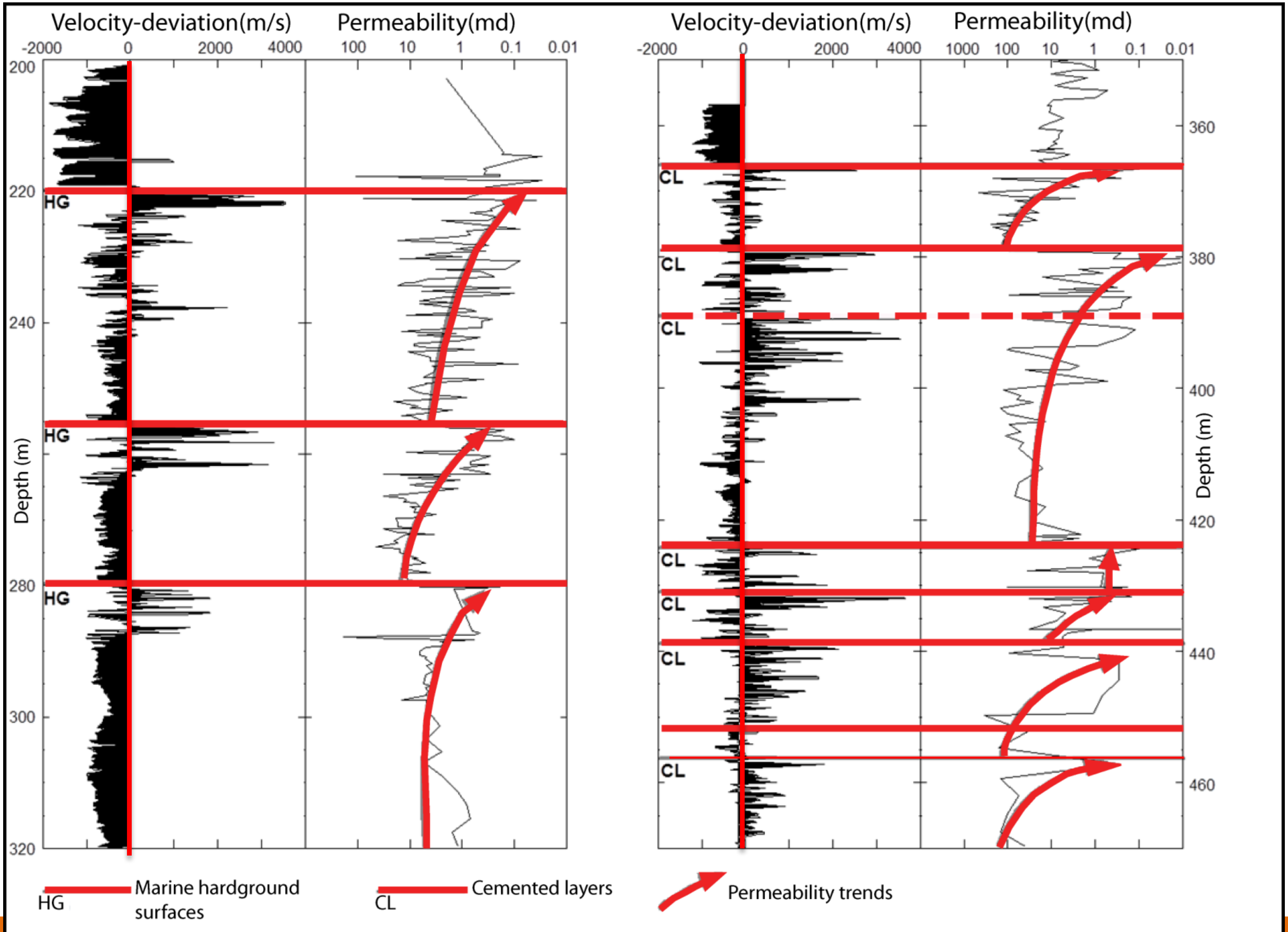
From Anselmetti and Eberli 1999

Acoustic Response Relationship to Permeability



Anselmetti and Eberli 1999

Qualitative Permeability from Velocity



Modified from Anselmetti and Eberli 1999

Digital Image Analysis: Link to quantitative prediction

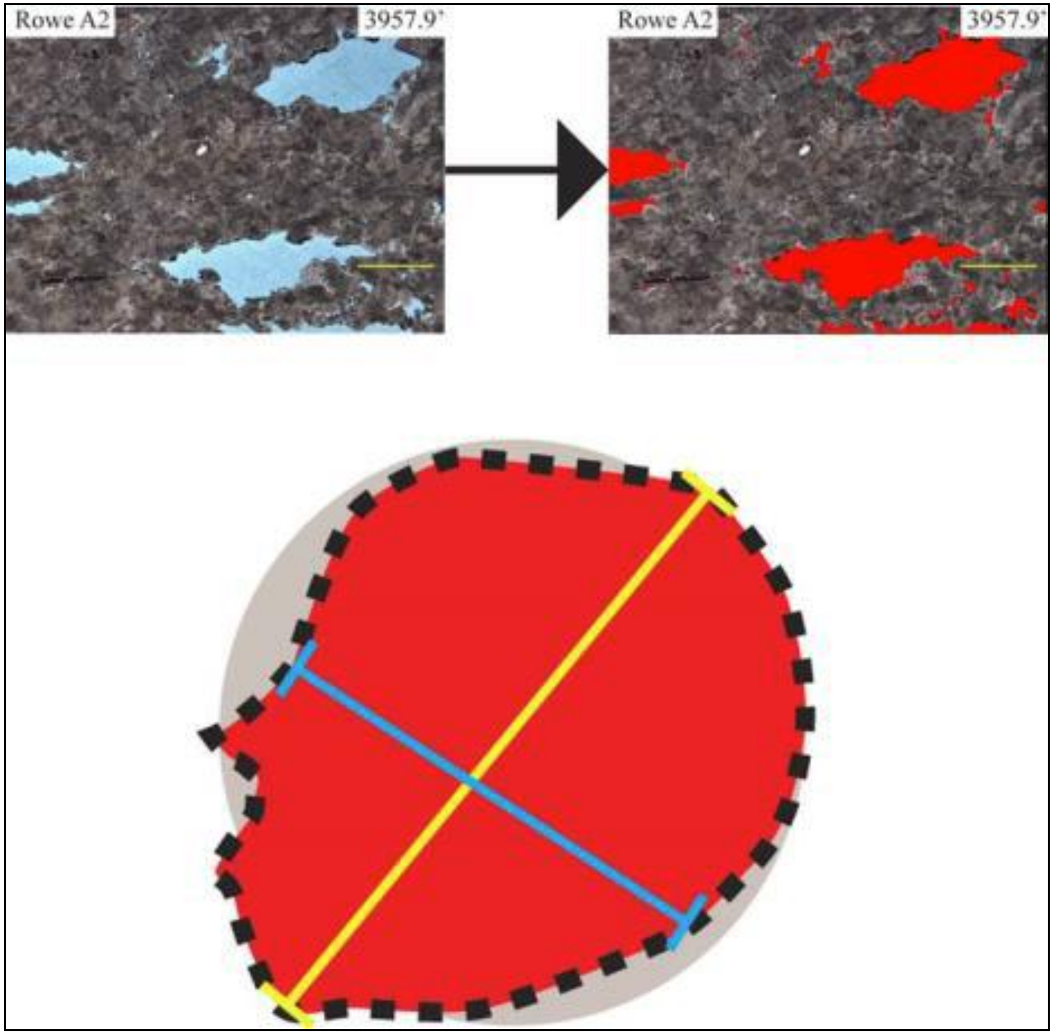


Figure Thornton and Grammer 2012

Color Segmentation to identify the pore space

Key Parameters:

Length

Width

Perimeter (P)

Area (A)[Pore Size]

Perimeter/Area (P/A)

Dominant Pore Size

Pore Shape (γ)

Pore Architecture: Pore Size

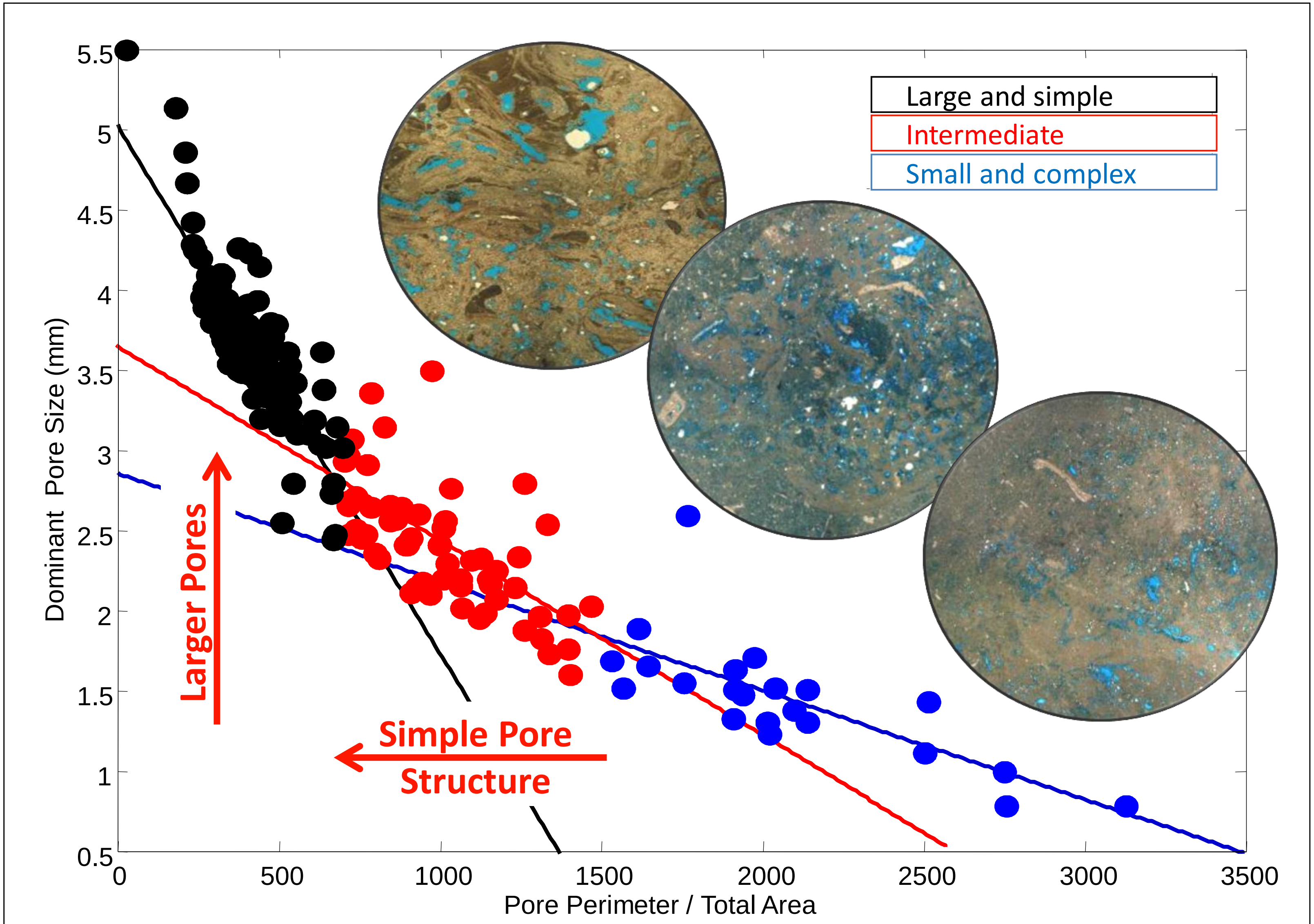


Figure and images used with permission from G. Eberli

Quantitative Permeability Prediction

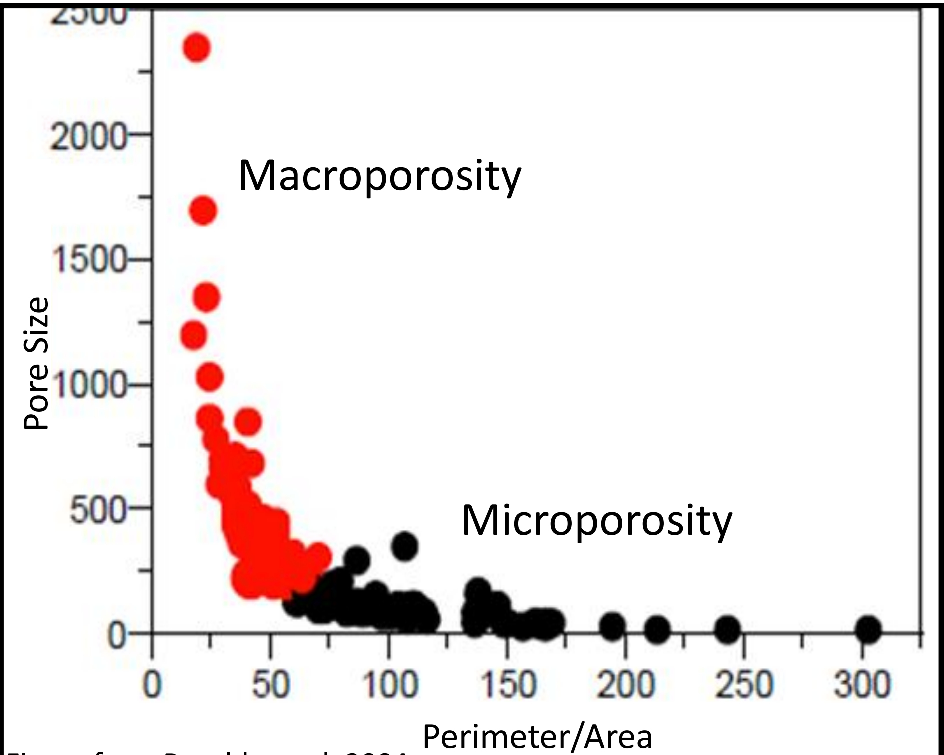


Figure from Baechle et al. 2004

Quantified acoustic response
+Quantified pore architecture
+Quantified macro- and microporosity

Predictable Permeability

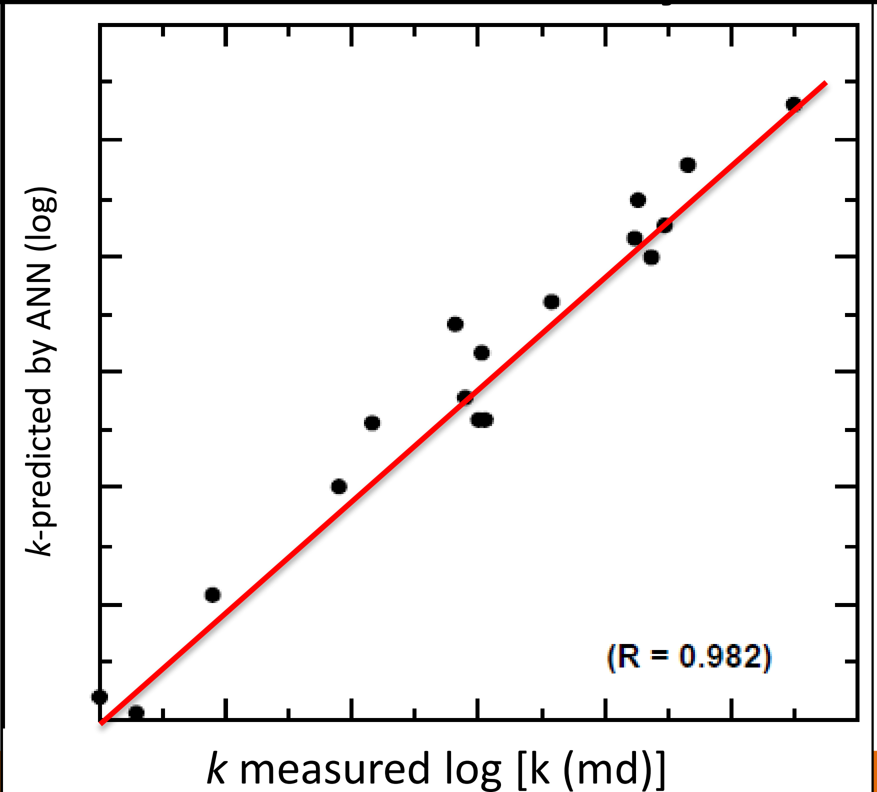


Figure from Anselmetti et al. 1998

Quantitative Permeability Prediction

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

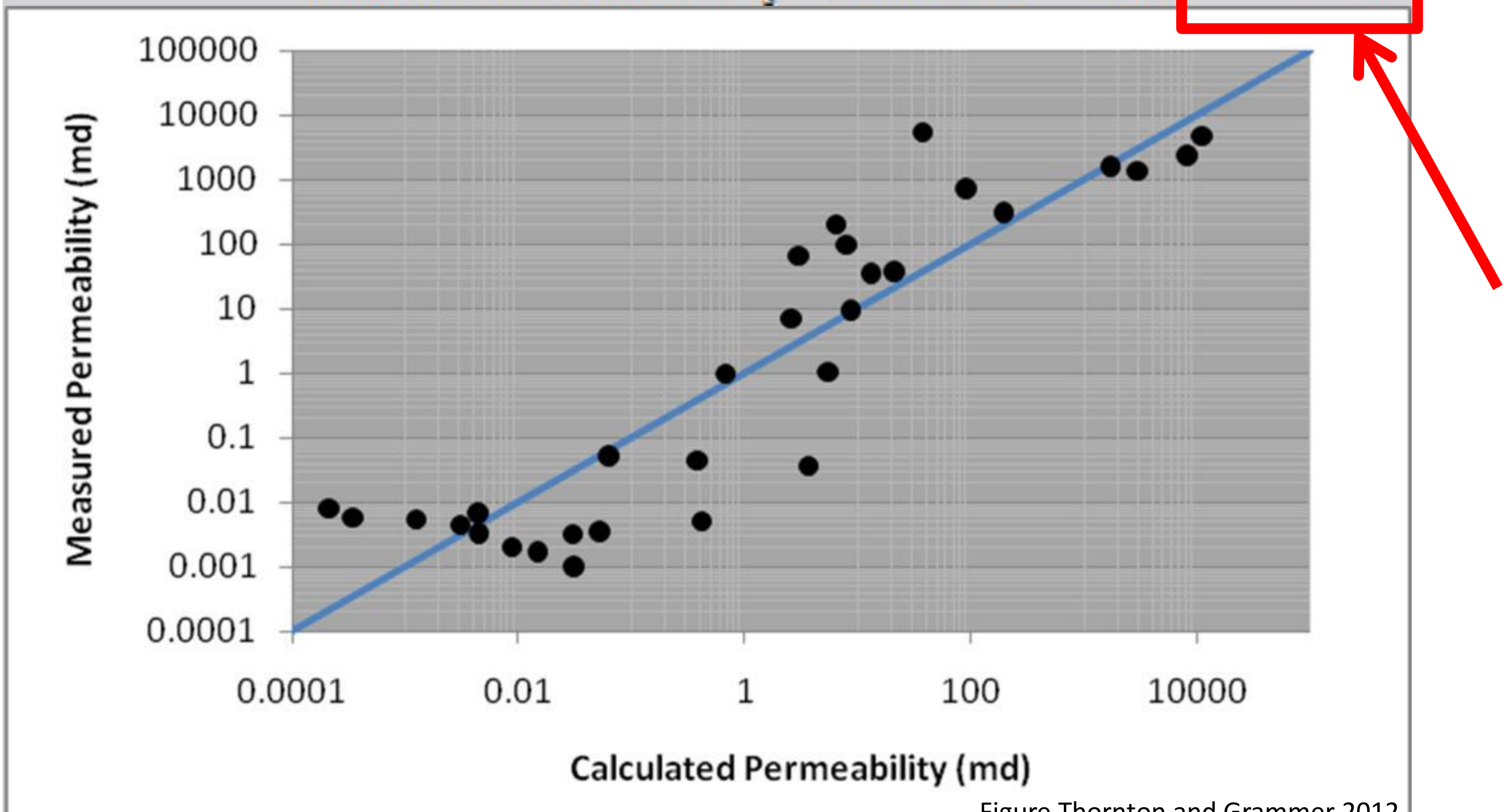


Figure Thornton and Grammer 2012

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

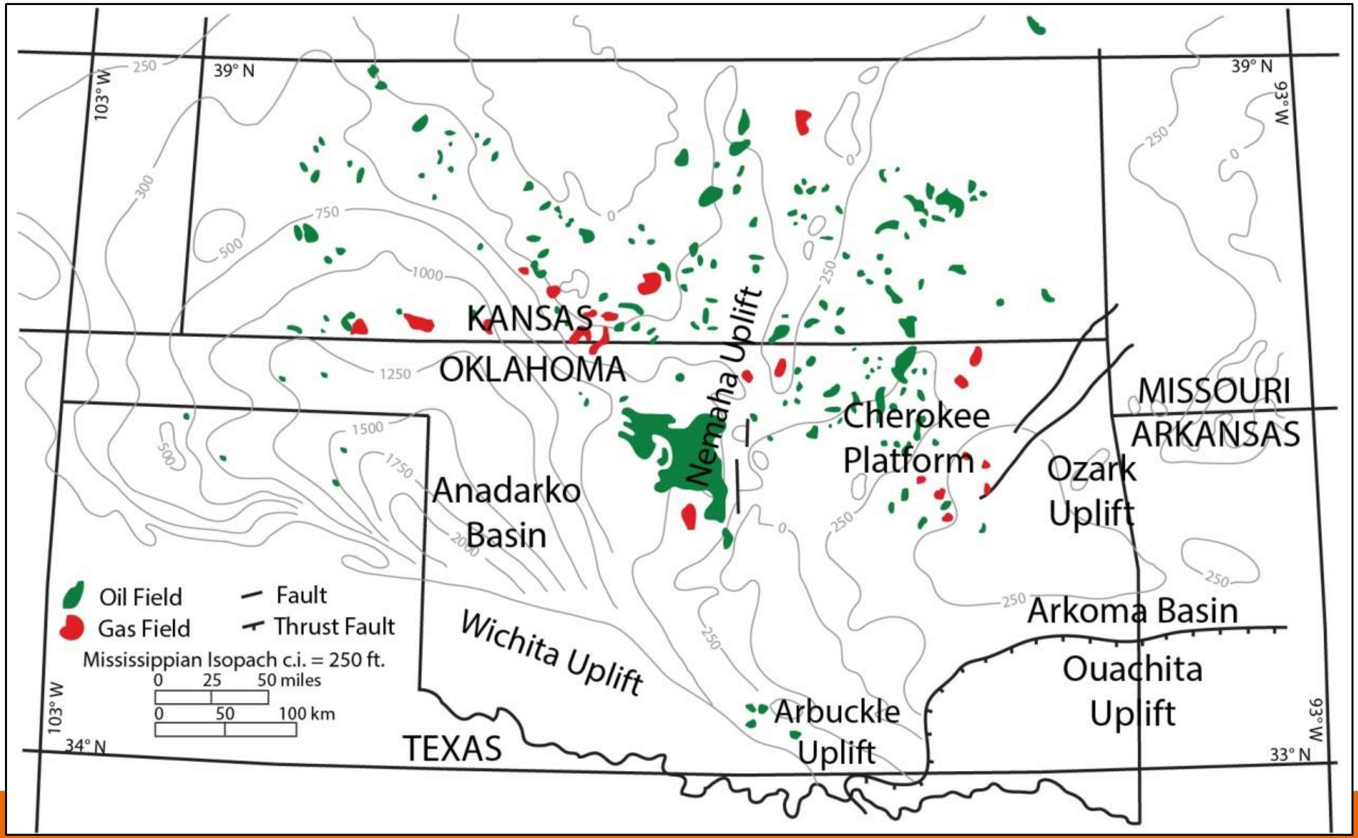
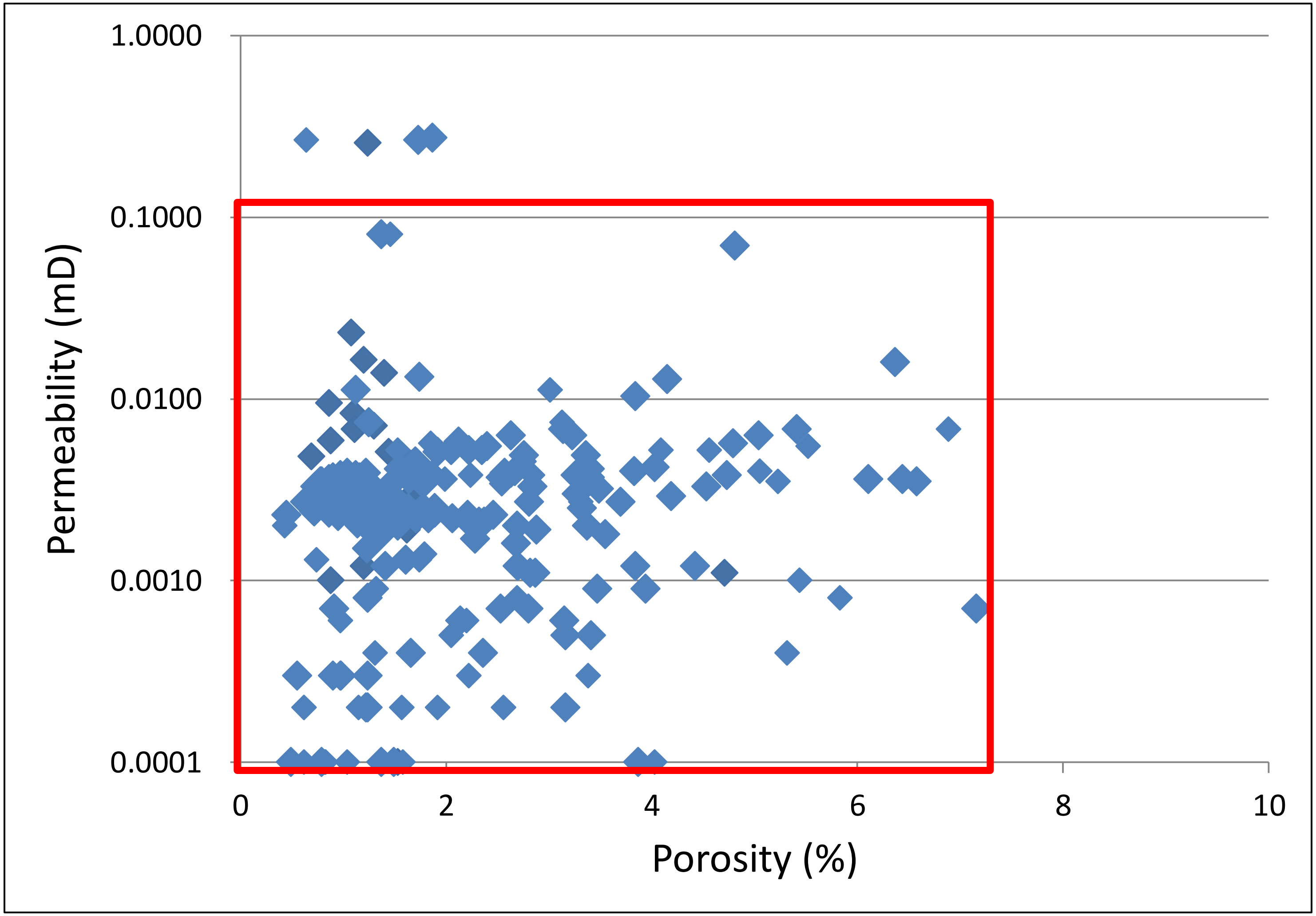
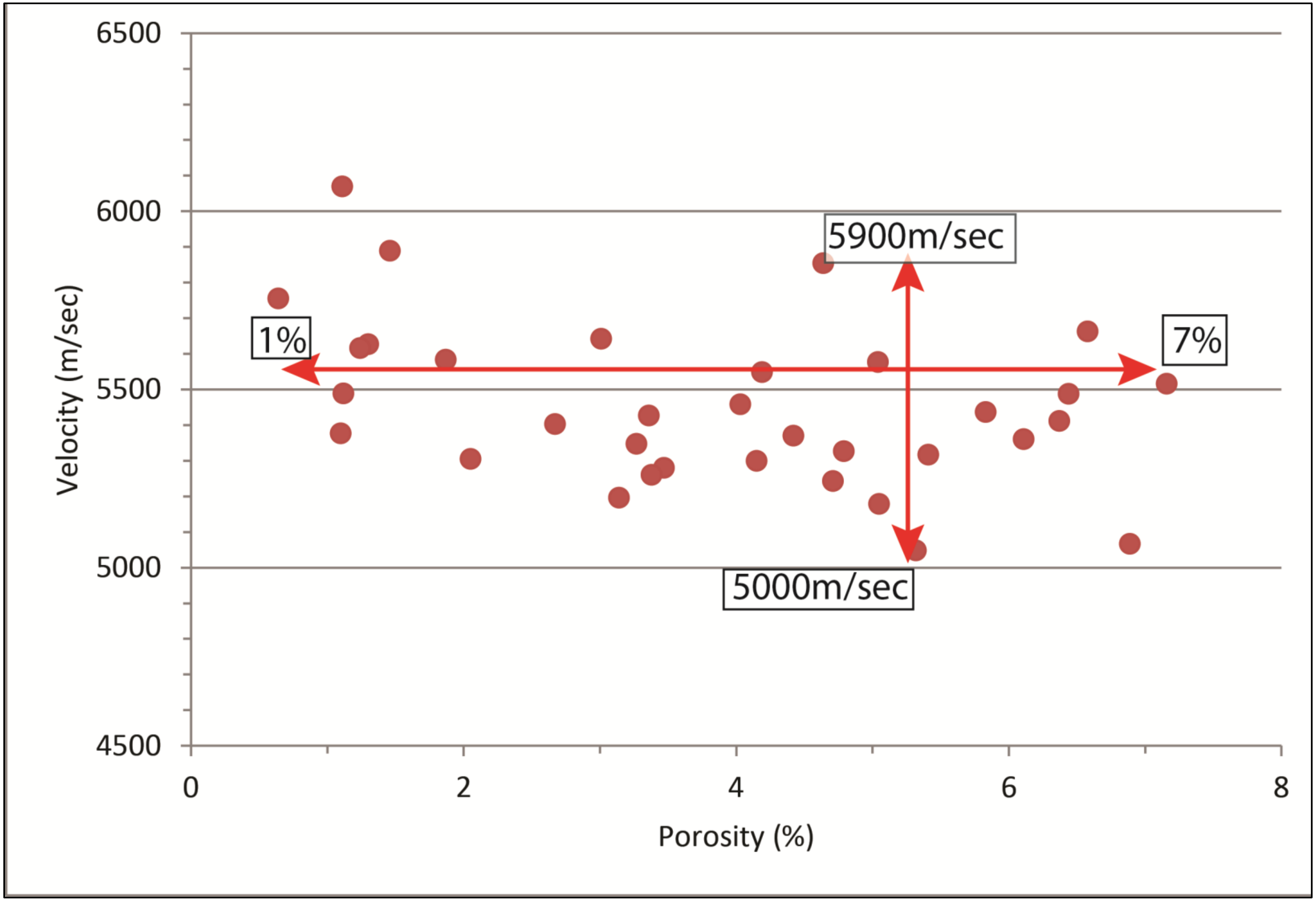


Figure modified from Harris (1975)

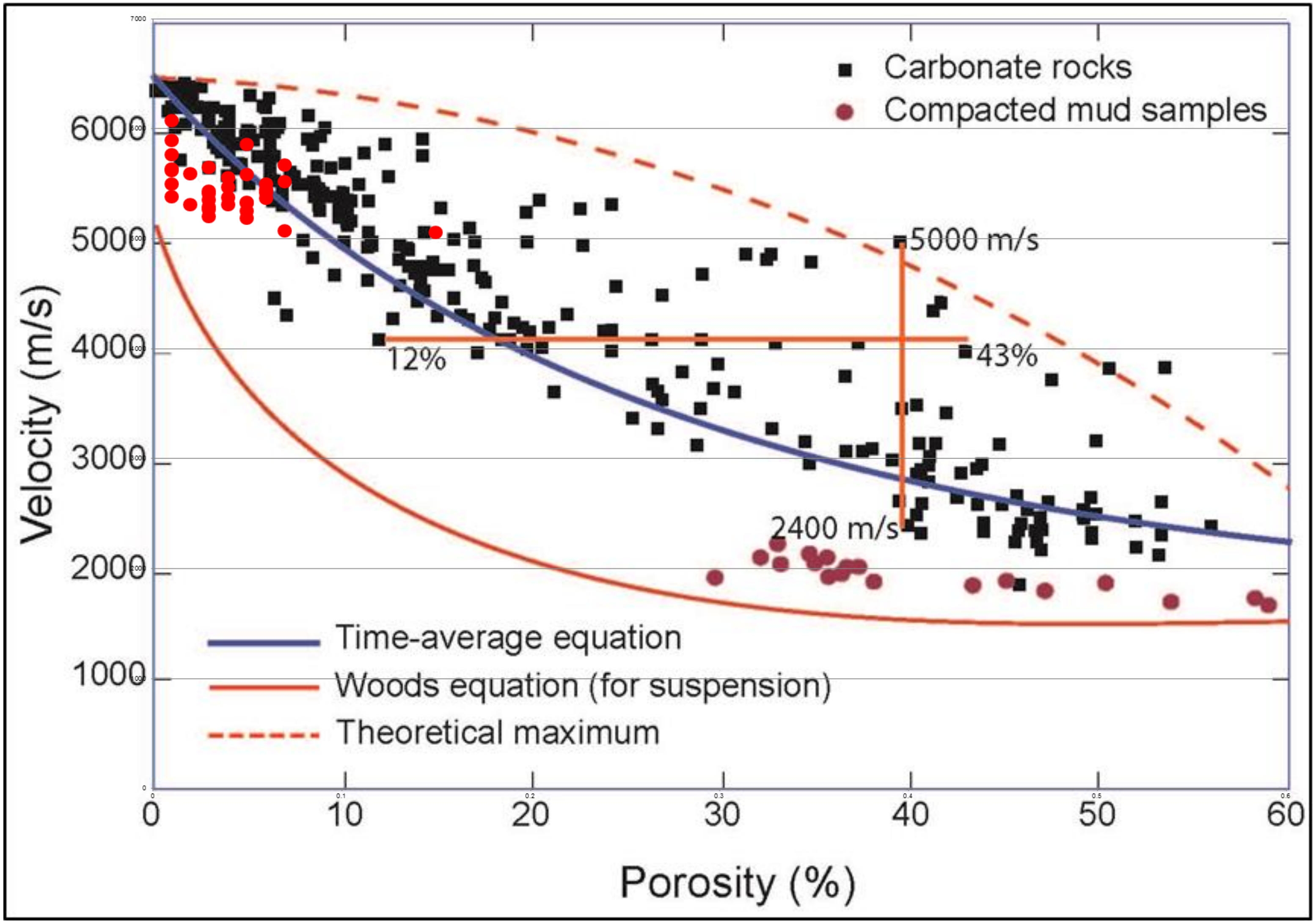
Carbonate Mudrock porosity and permeability range



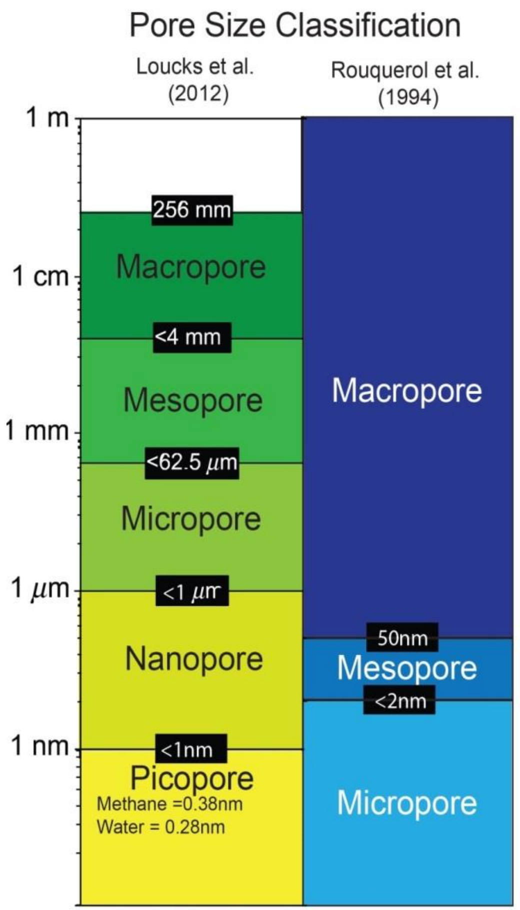
Carbonate mudrock velocity – porosity relationship

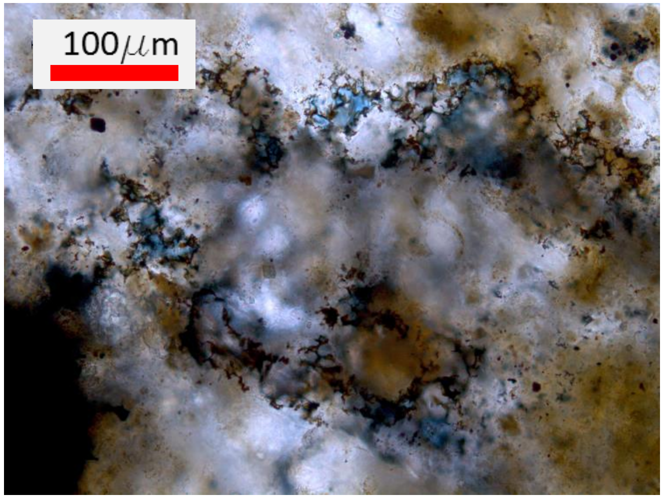


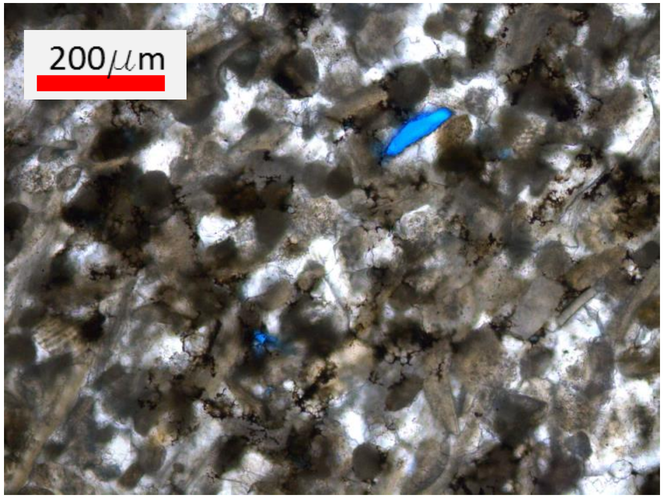
Unconventional carbonate mudrock vs. conventional carbonate velocity response

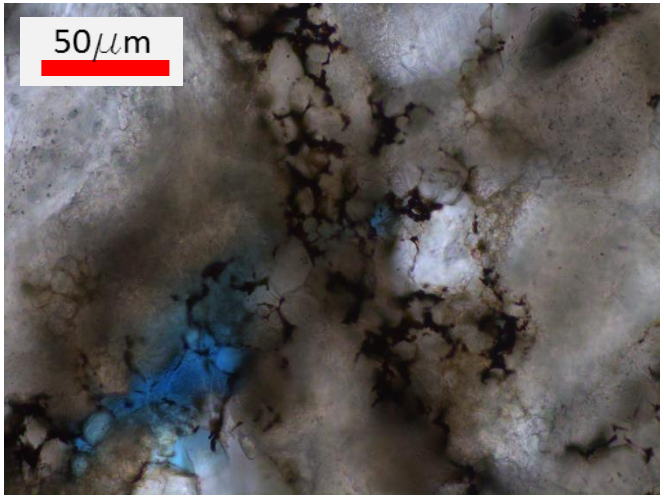


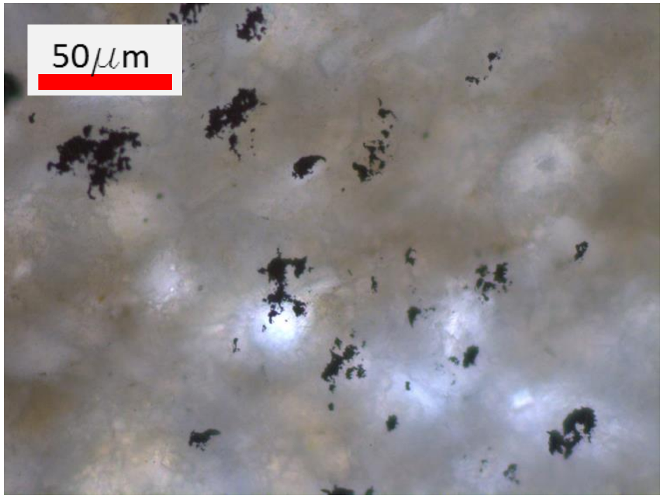
Pore Architecture:
Thin Section Photomicrographs



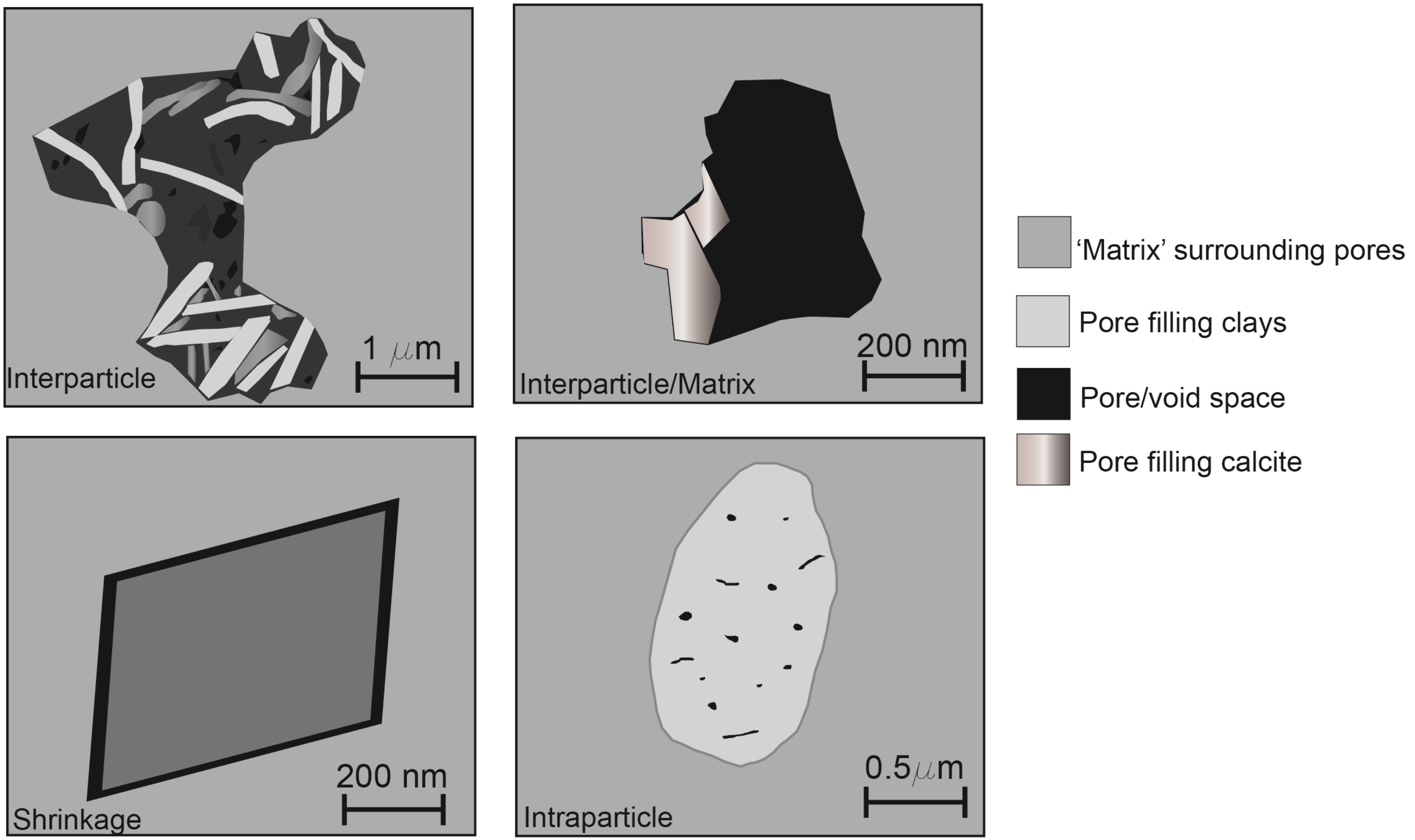




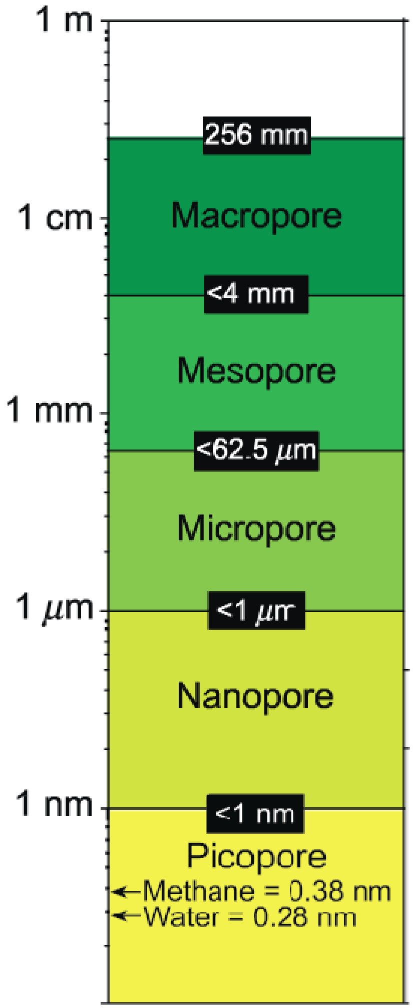




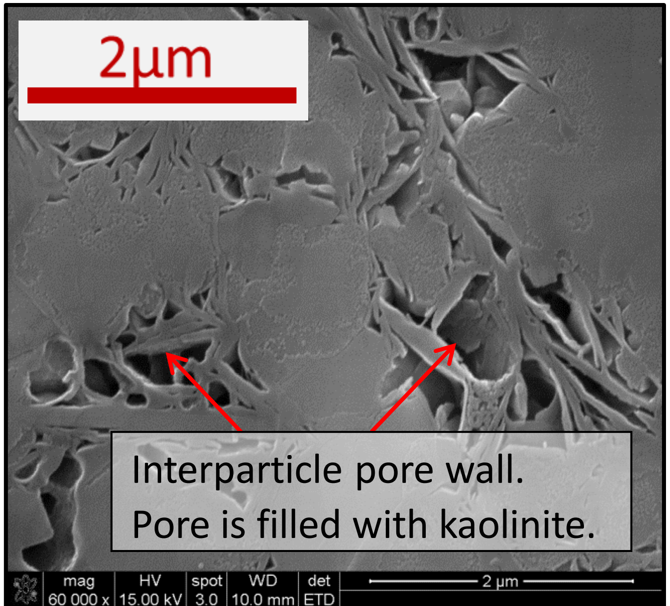
Basic Pore Types Observed

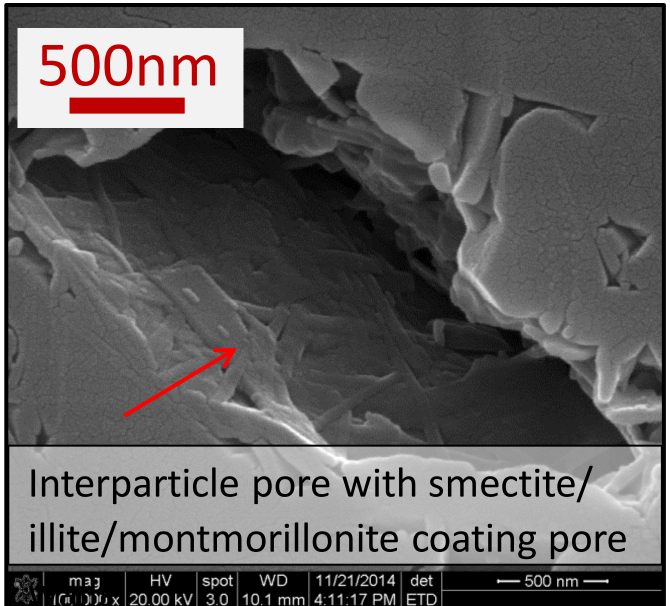


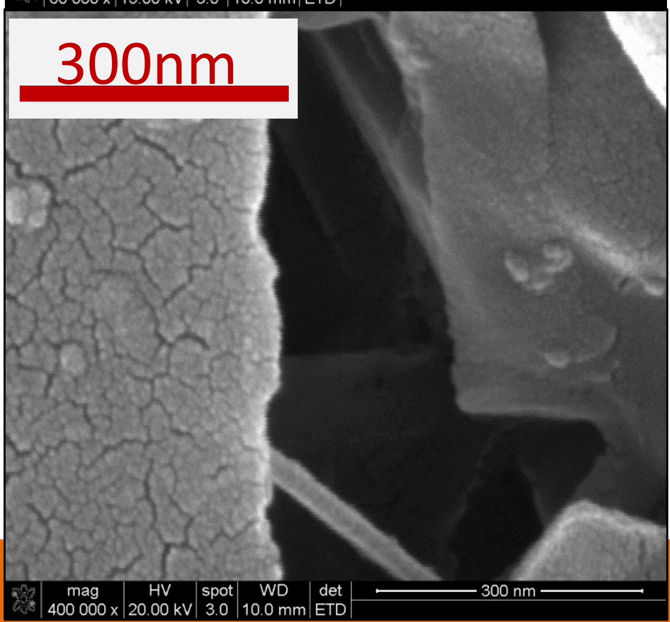
Pore Architecture: Pore types and size
SEM Photomicrographs

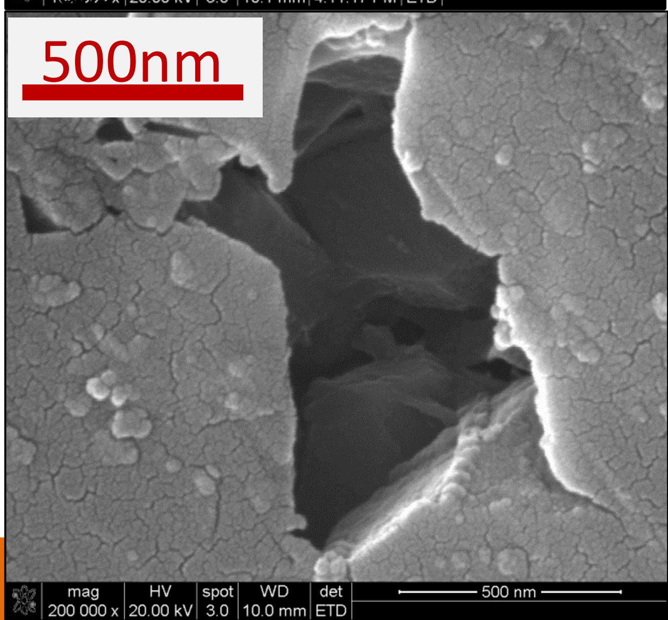


Loucks et al., 2012



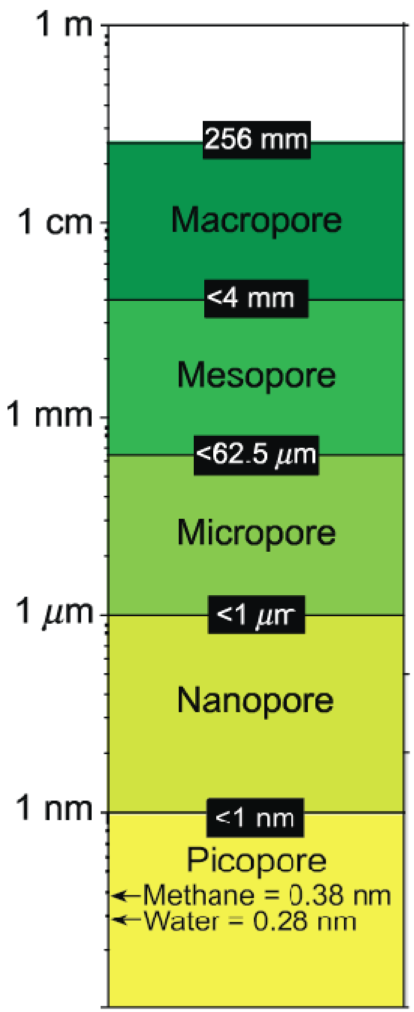




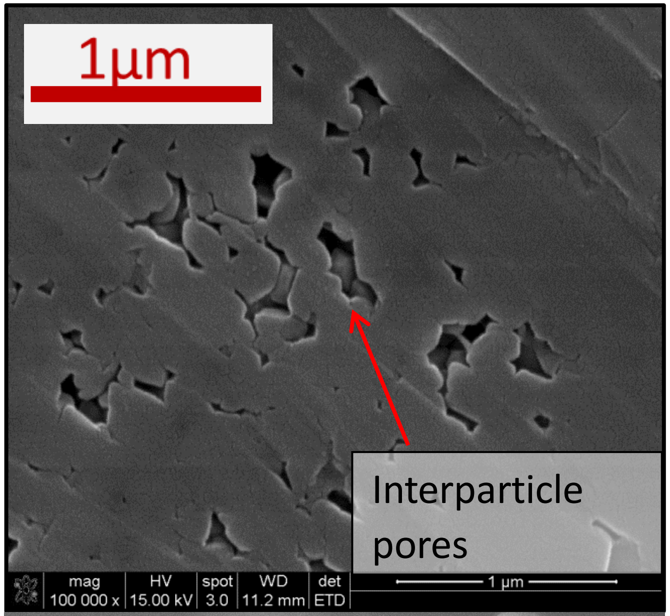


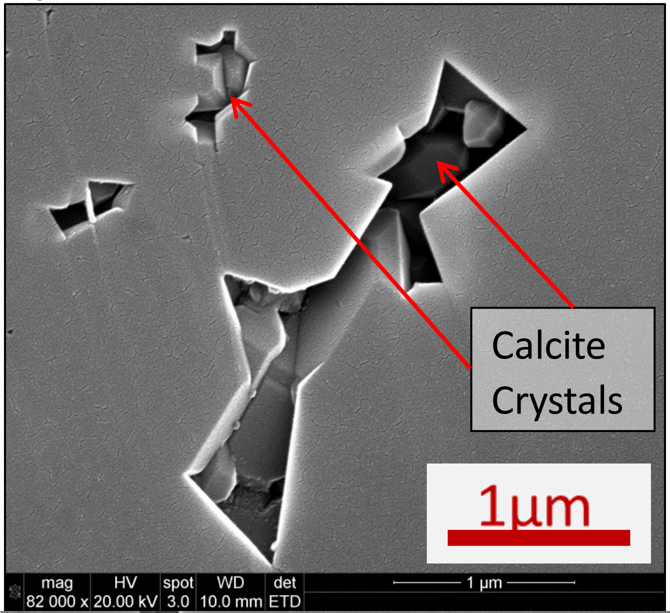
Pore Architecture: Pore types and size

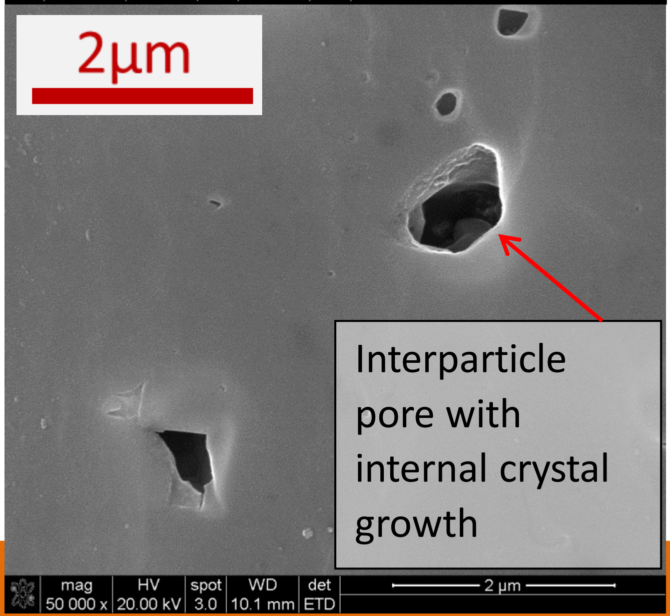
SEM Photomicrographs

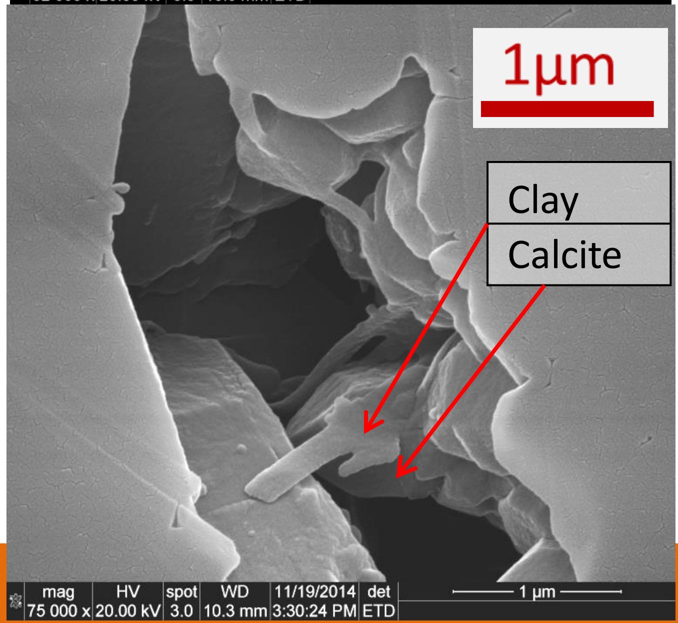


Loucks et al., 2012

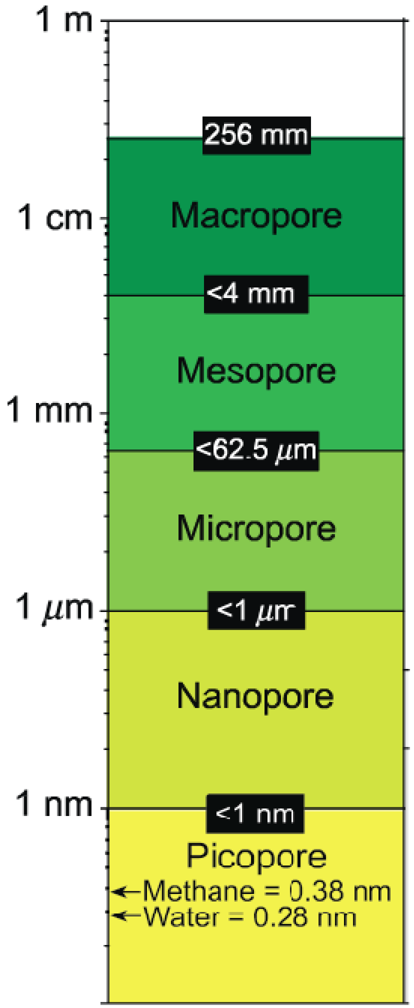




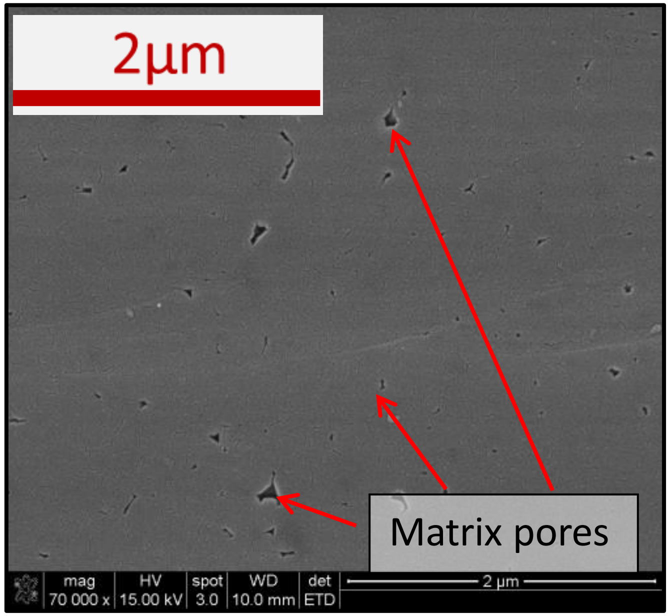


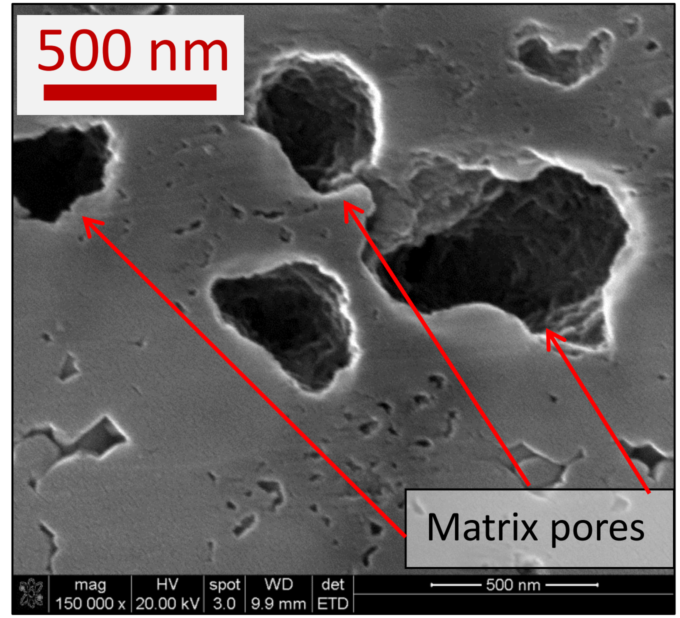


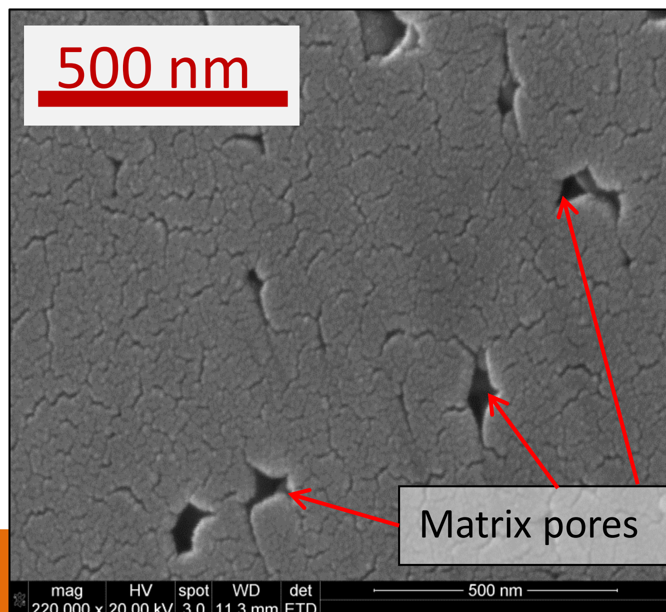
Pore Architecture: Pore types and size
SEM Photomicrographs

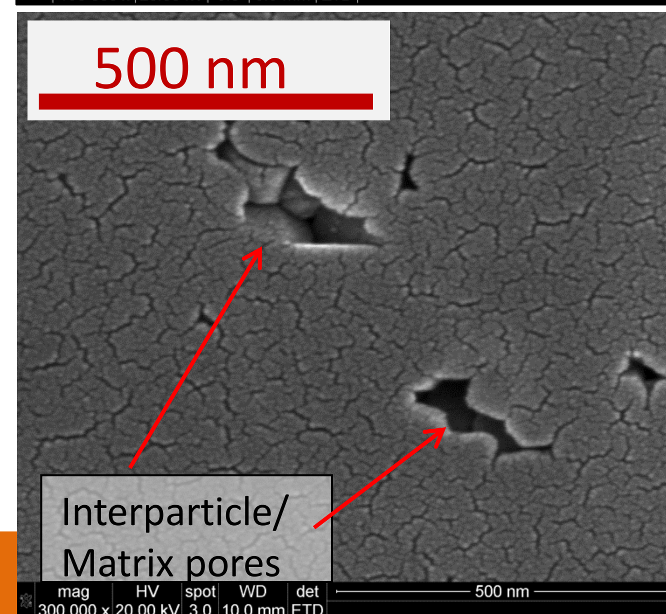


Loucks et al., 2012

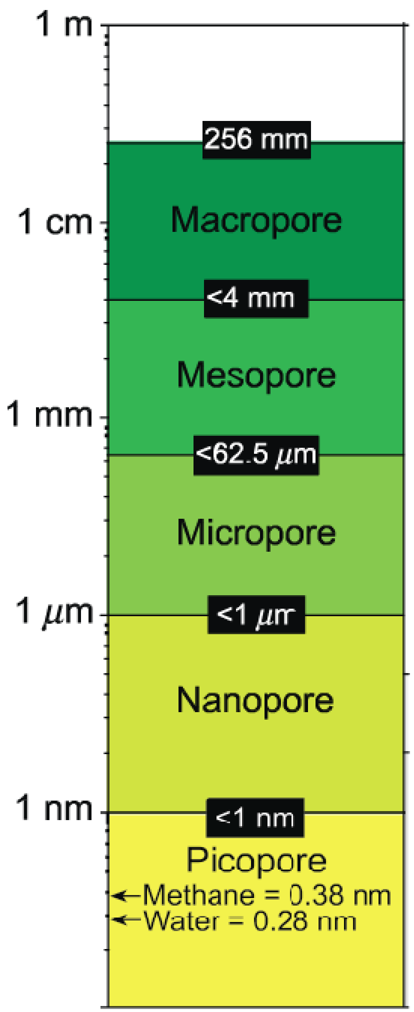




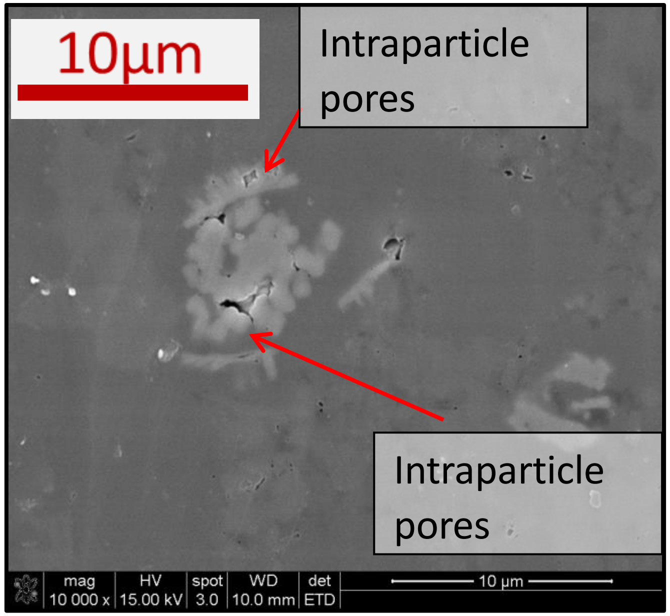


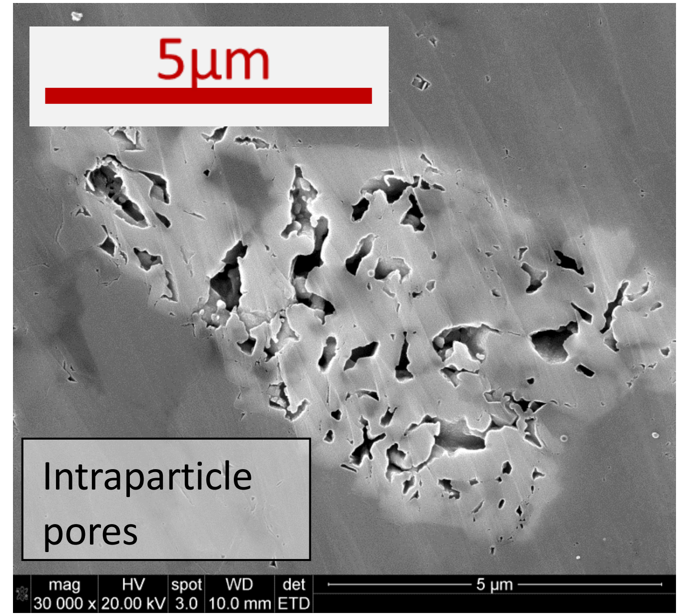


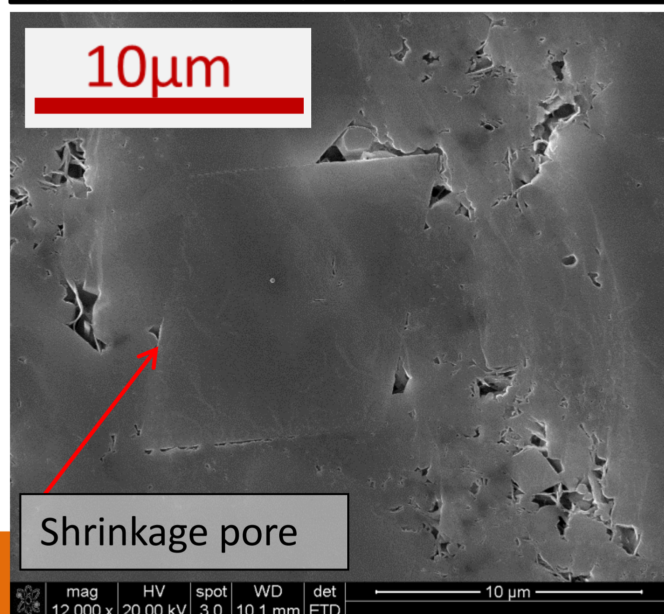
Pore Architecture: Pore types and size
SEM Photomicrographs

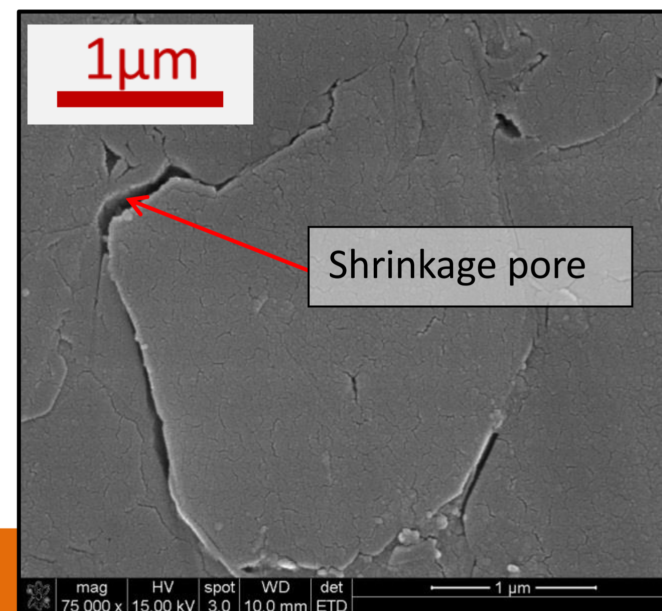


Loucks et al., 2012



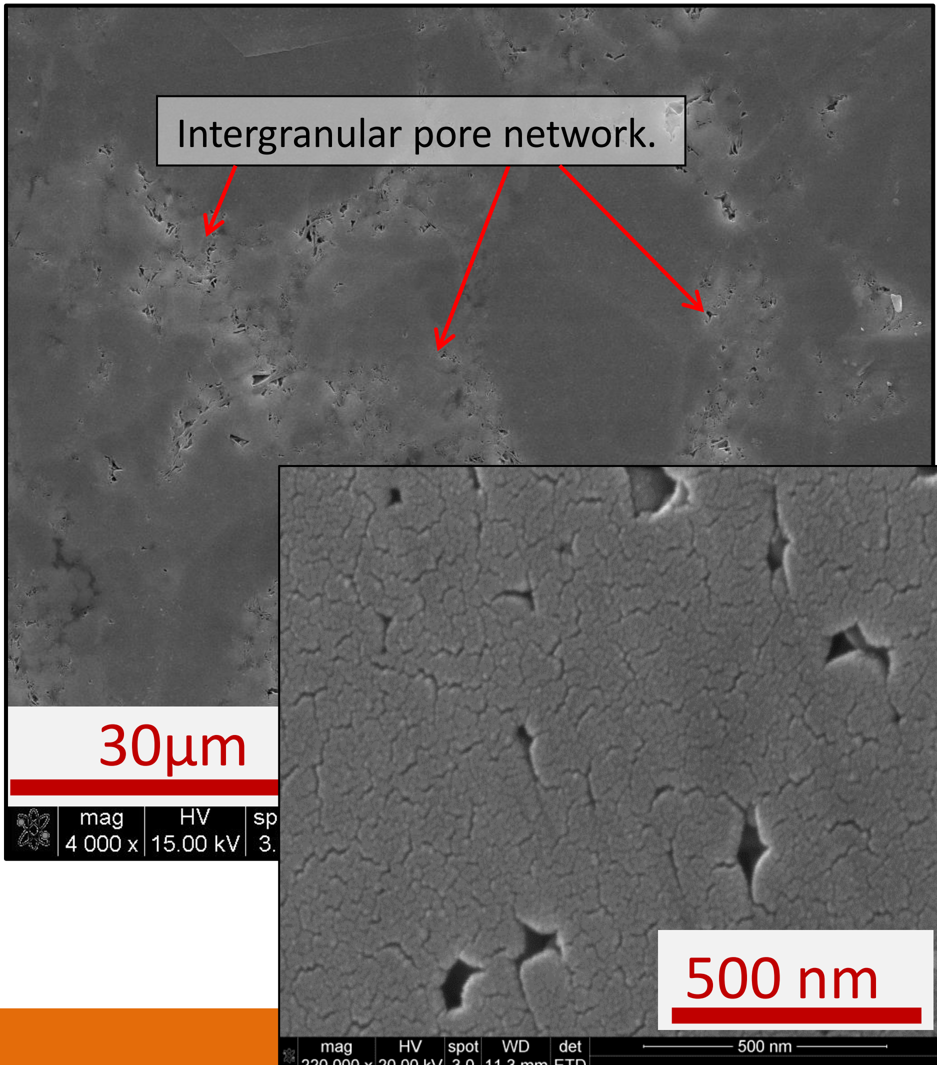


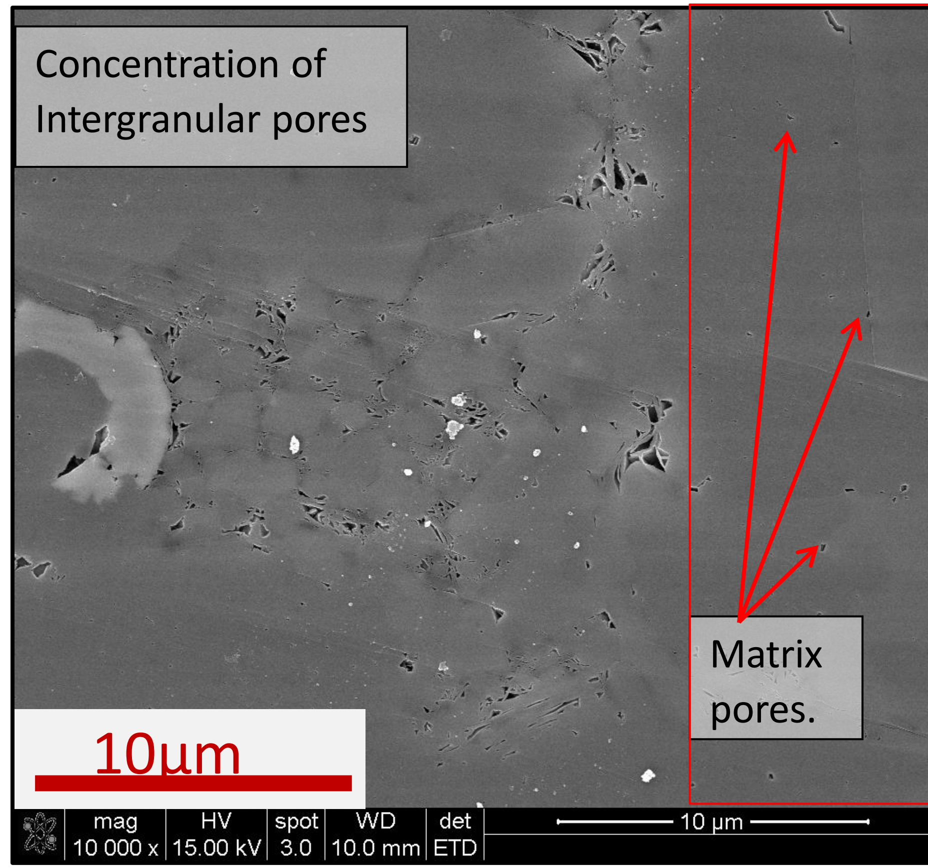




Pore Architecture: Pore distribution

SEM Photomicrographs – Ion milled surface





Pore Architecture Data Summary

Analysis completed: Osage County core, North-Central Oklahoma

- 277 feet from 3147.10 – 3424.10ft bgs.
- 305 photomicrographs analyzed using digital image analysis
  - 47 thin sections, 420 photomicrographs, 175 images analyzed for DIA
  - 15 samples, 430 photomicrographs, 130 SEM images

Image analysis summary:

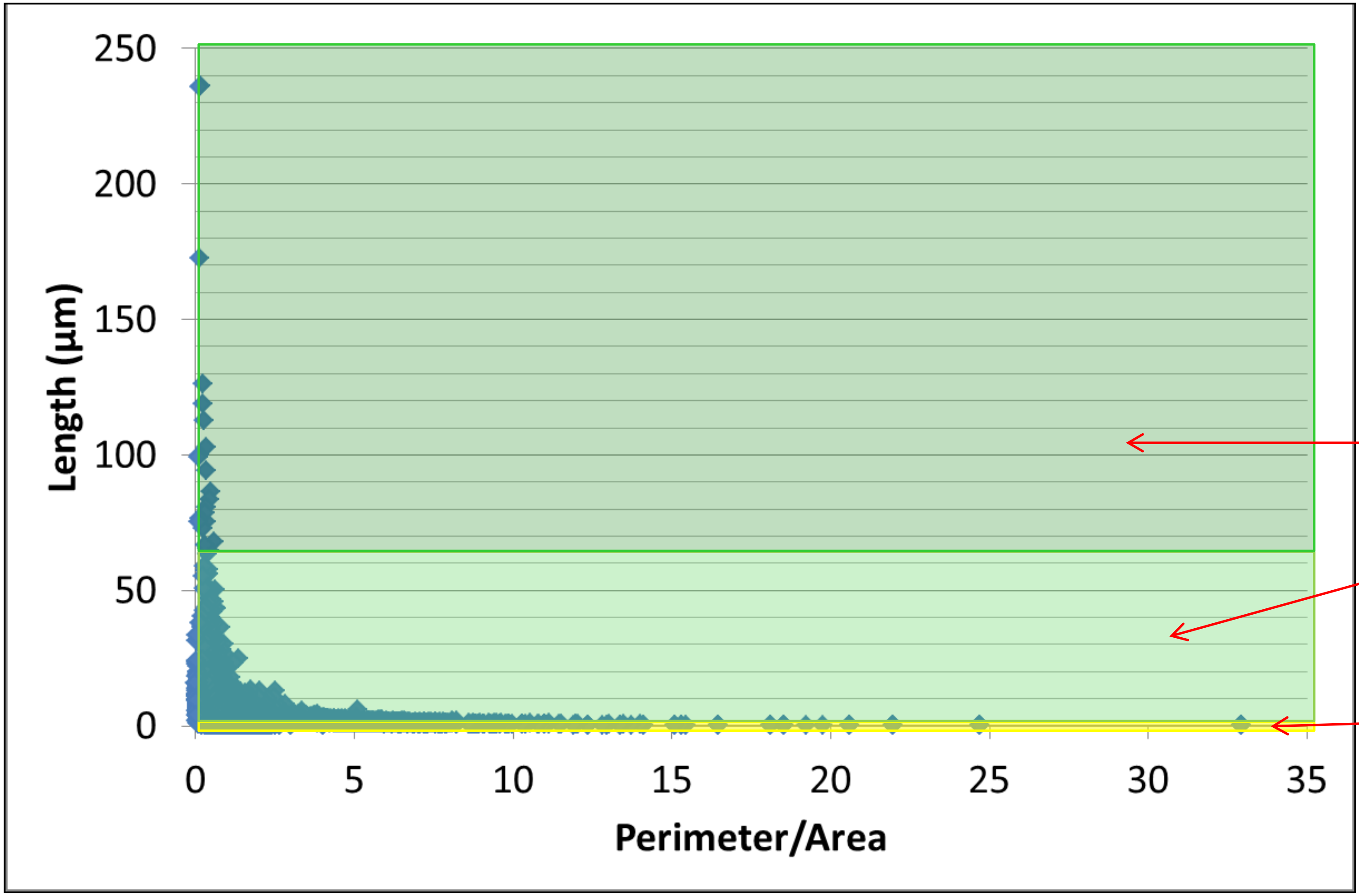
- Pores Identified: 140,330
- Image analysis porosity: 23-65% *(biased samples)*
- Length: Nanopore to Mesopore scale
- Width: Picopore to Micropore scale
- Shape: slightly elongate

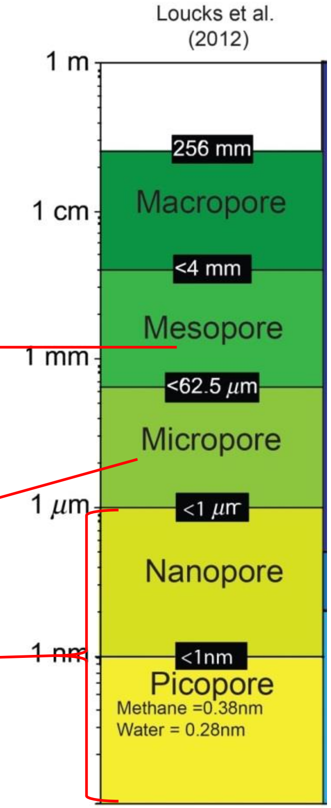
Sonic velocity response:

- 80 samples: velocity response, dry
- 34 samples: velocity response, saturated in 35ppt NaCl brine solution
- Vp: 4852-6333
- Vs: 2768-3700

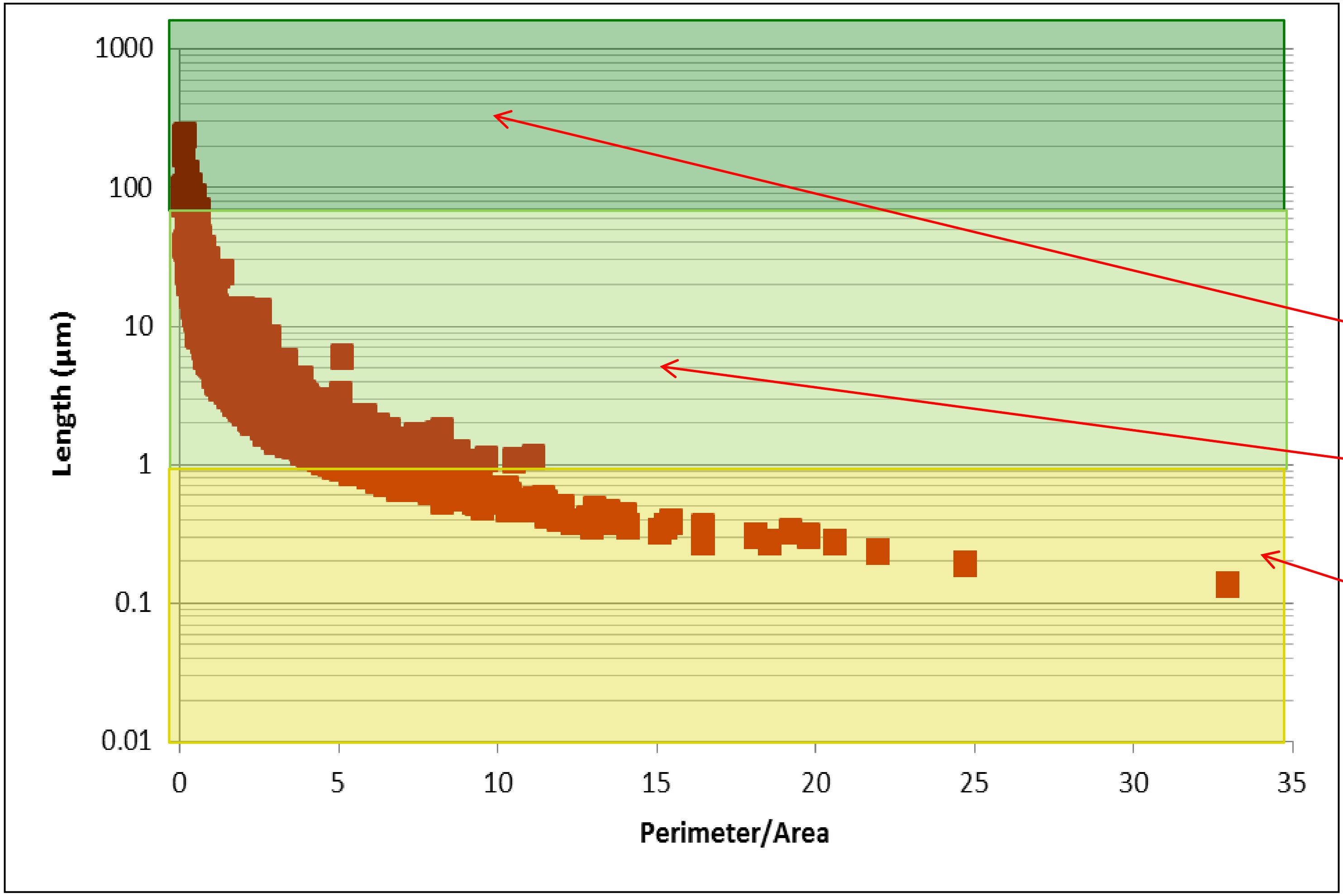
XRD analysis: 22 samples

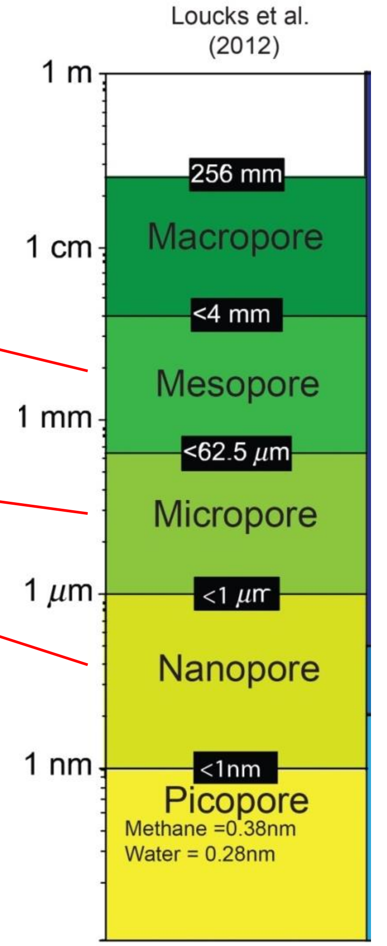
Digital Image Analysis:
Pore size distribution



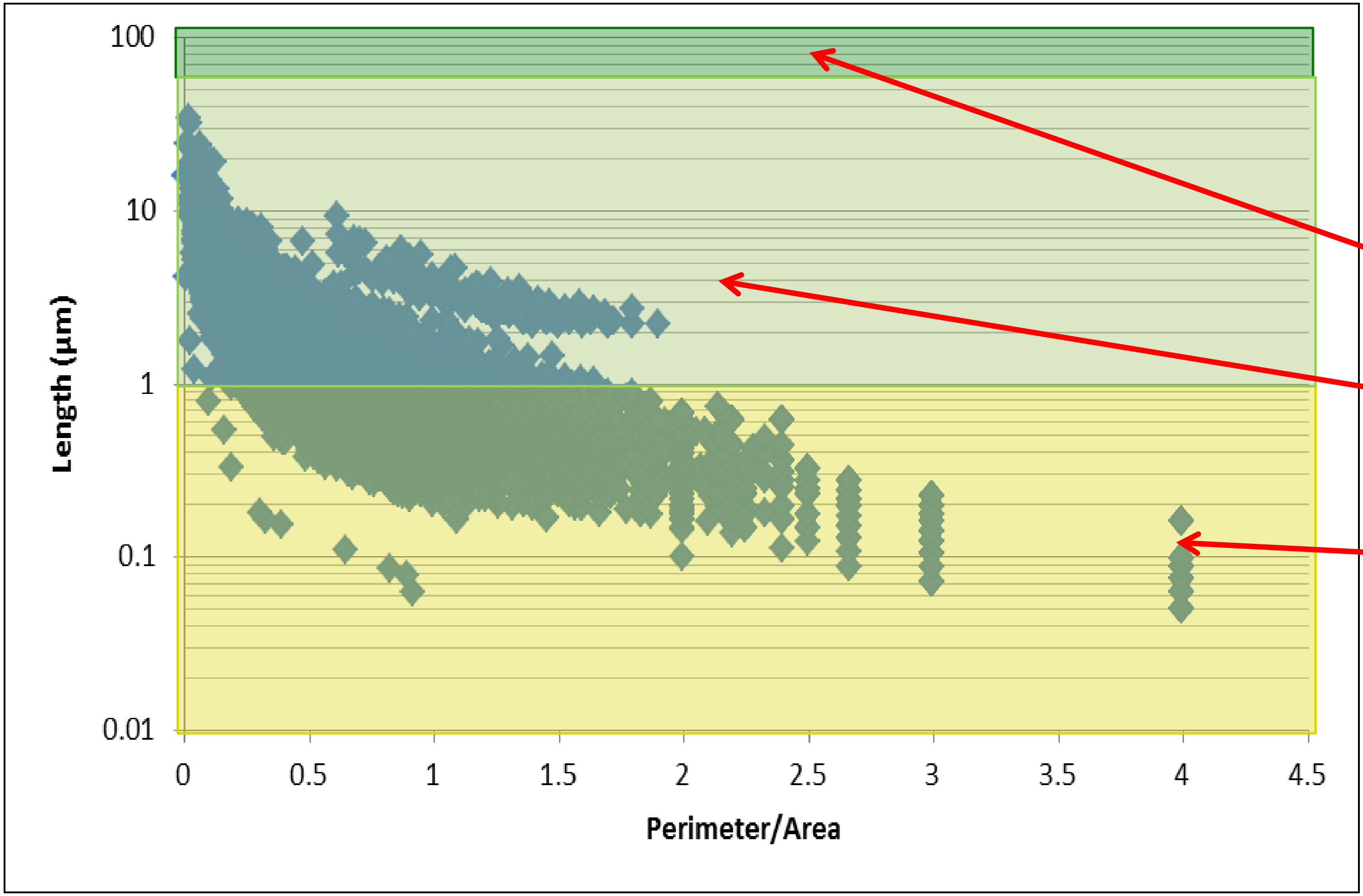


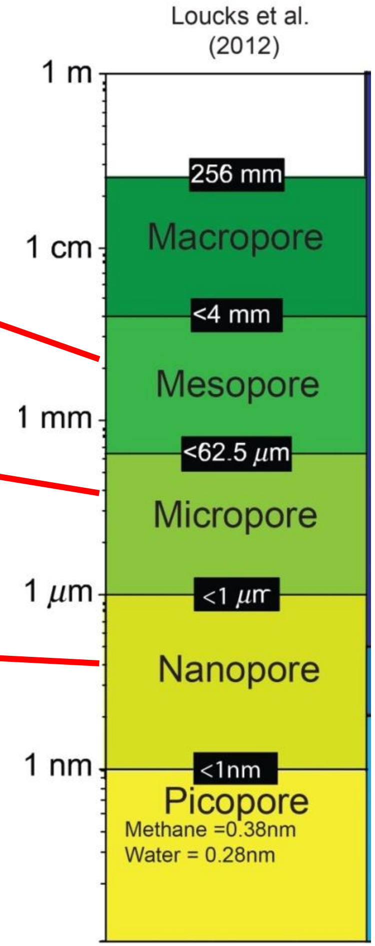
Digital Image Analysis:
Pore size distribution (thin section)



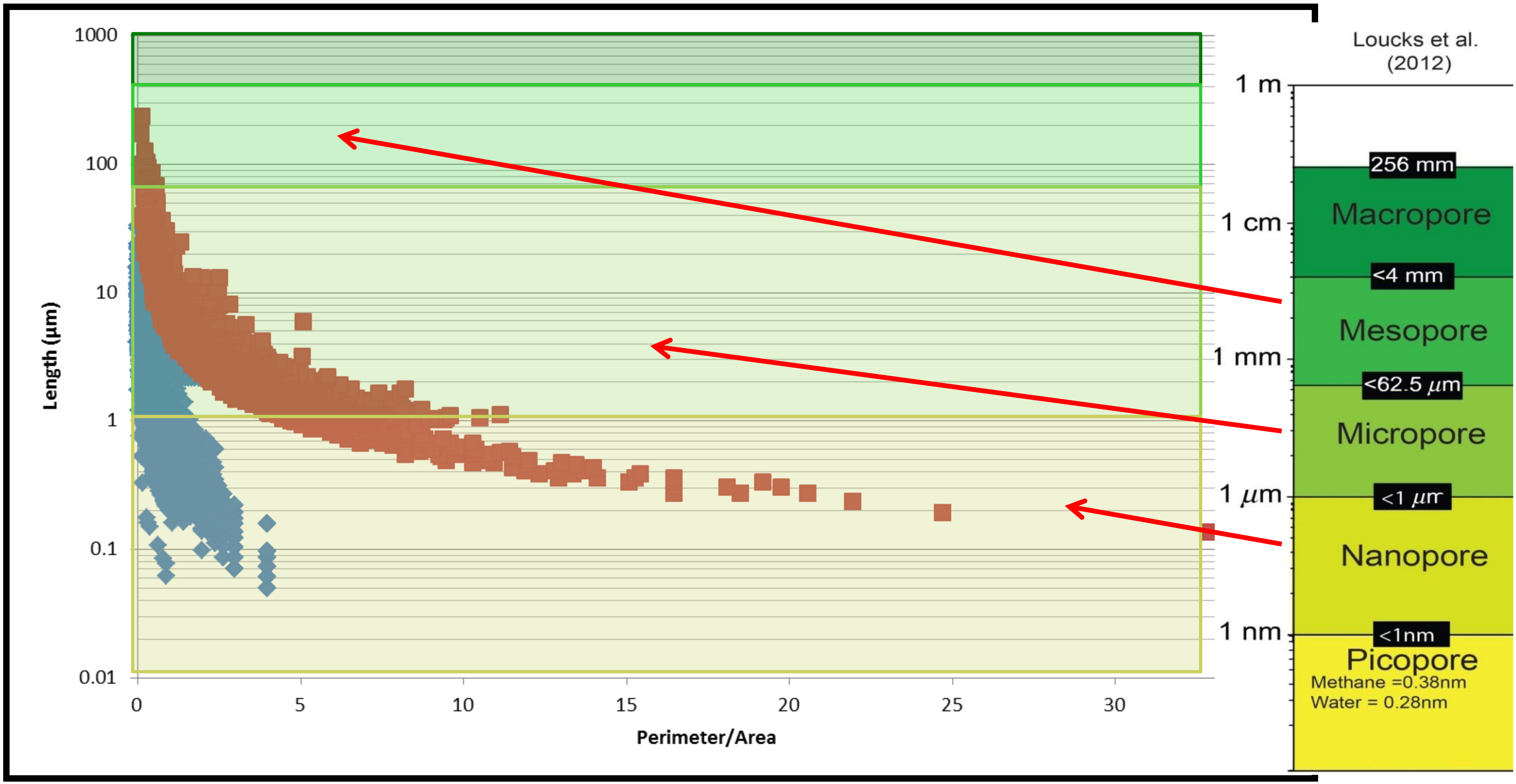


Pore architecture:
Pore size distribution (ESEM images)





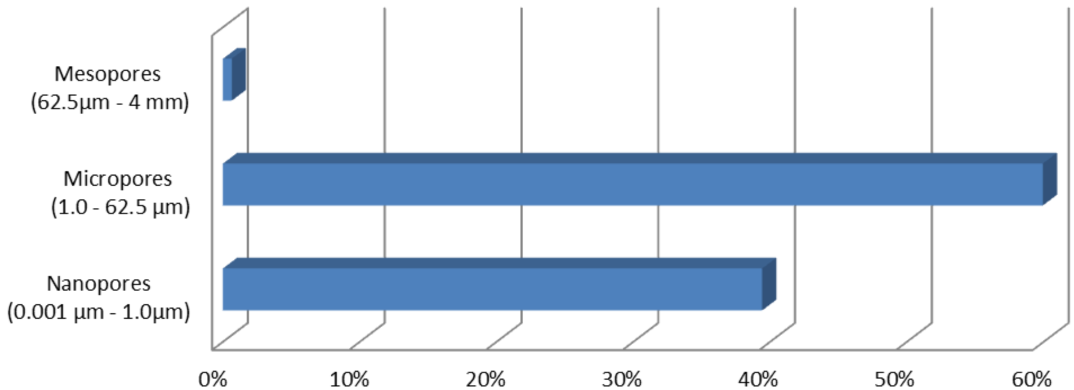
Pore architecture:
Digital image analysis (thin section & ESEM images)



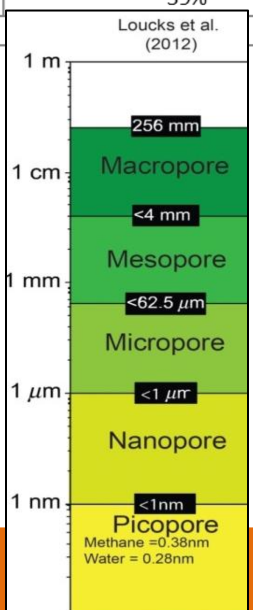
Pore Architecture:
Thin section vs. ESEM Pore Size Distribution

- Dominant Pore Size: micro- to nanopore range.
- Bi-modal distribution between micro- and nanopores

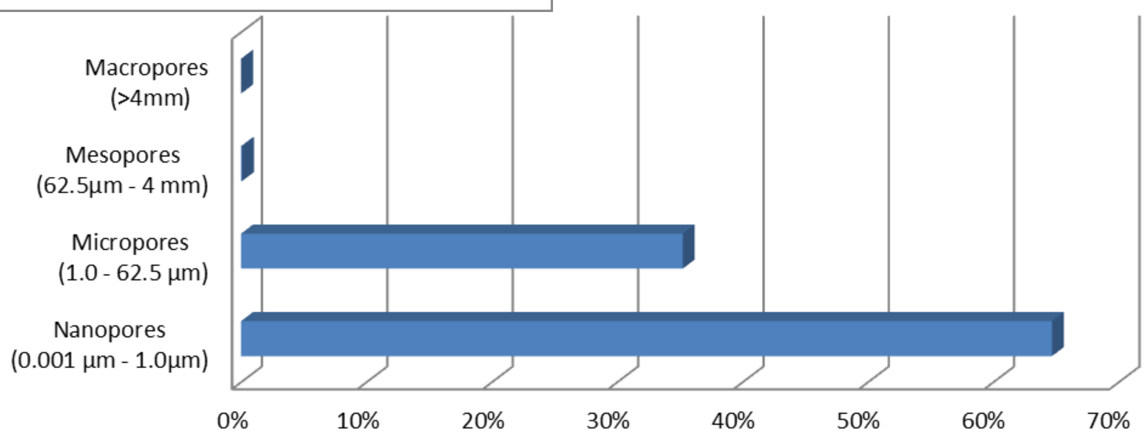
Thin Section Data: Average Percentage of Pores Per Size Category
(48 samples, 175 photos)



	Nanopores (0.001 µm - 1.0µm)	Micropores (1.0 - 62.5 µm)	Mesopores (62.5µm - 4 mm)
.	39%	60%	1%



ores Per Size Category
)5 photomicrographs)

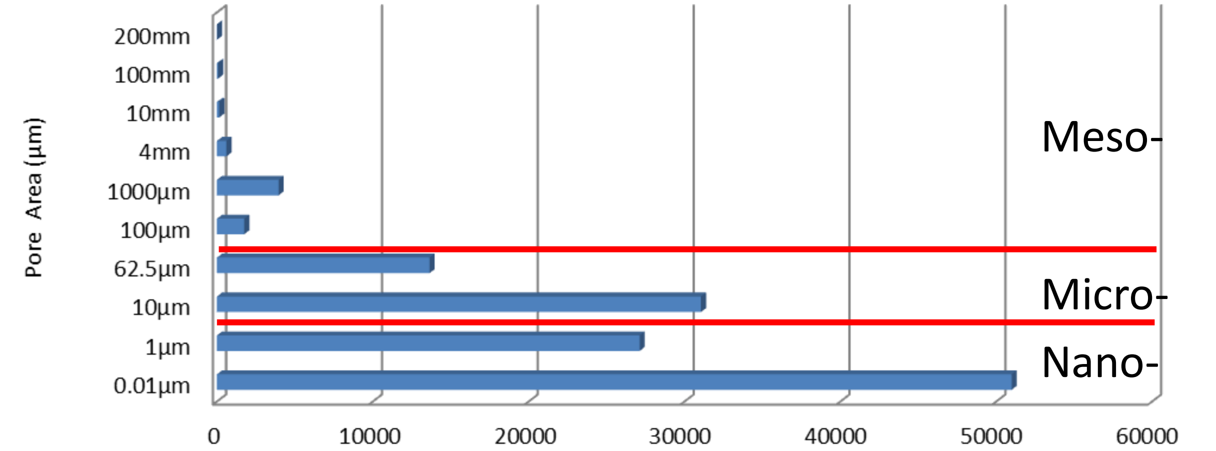


	Nanopores (0.001 µm - 1.0µm)	Micropores (1.0 - 62.5 µm)	Mesopores (62.5µm - 4 mm)	Macropores (>4mm)
.	65%	35%	0.1%	0%

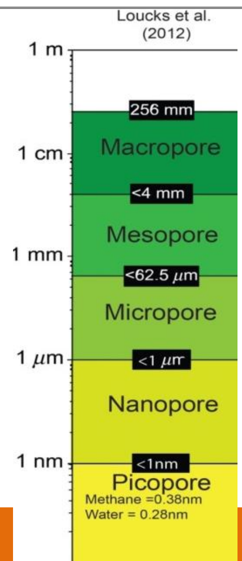
Pore Architecture:
ESEM Detailed Pore Size Distribution

- Dominant Pore Size: micro- to nanopore range.
- Bi-modal distribution within the micro- and nanopores

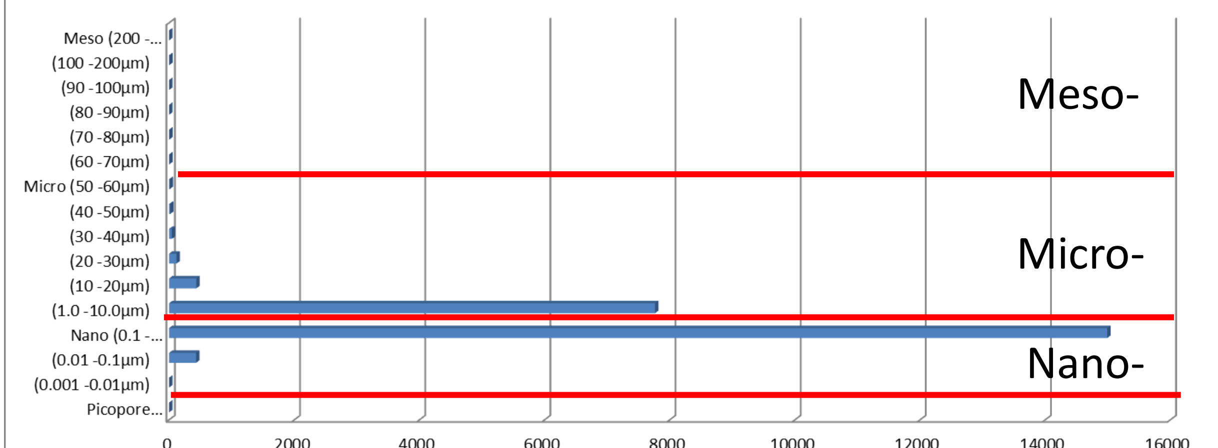
Thin Section Data: Number of Pores Per Size Category
(48 samples, 175 photos)



	0.01µm	1µm	10µm	62.5µm	100µm	1000µm	4mm	10mm	100mm	200mm
Pores Counted	50988	27118	31055	13639	1750	3954	605	142	74	7

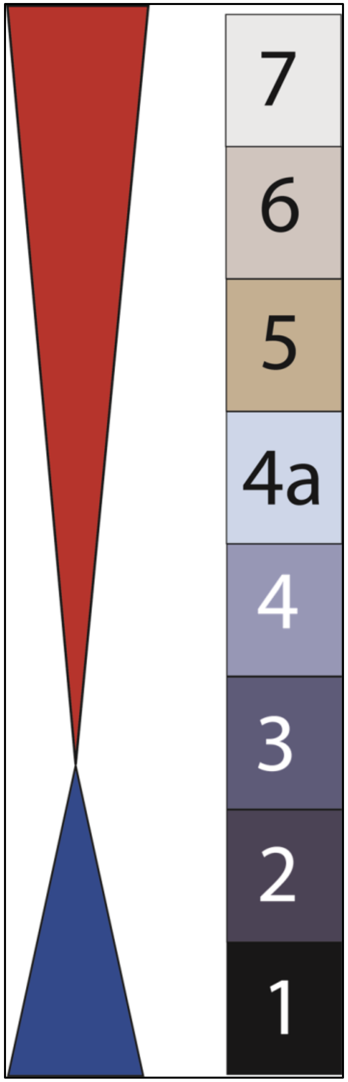


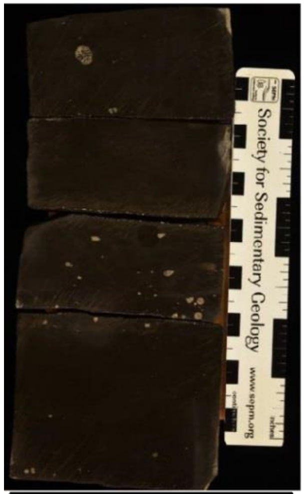
within Major Category Classification
amples, 305 photos)



	Picopore (<0.001µm)	(0.001 - 0.01µm)	(0.01 - 0.1µm)	Nano (0.1 - 1.0µm)	(1.0 - 10.0µm)	(10 - 20µm)	(20 - 30µm)	(30 - 40µm)	(40 - 50µm)	Micro (50 -60µm)	(60 - 70µm)	(70 - 80µm)	(80 - 90µm)	(90 - 100µm)	(100 - 200µm)	Meso (200 - 300µm)
Series1	0	0	432	14994	7767	436	120	46	19	10	5	5	3	3	5	2

Facies Characterization





Facies 1
Spiculitic Mudstone to Wackestone

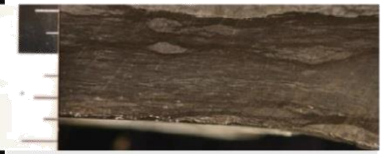
Facies 2
Mudstone to Skeletal Wackestone

Facies 3
Peloidal-Skeletal-Ooid-Wackestone

Facies 4
Skeletal-Peloidal Wackestone

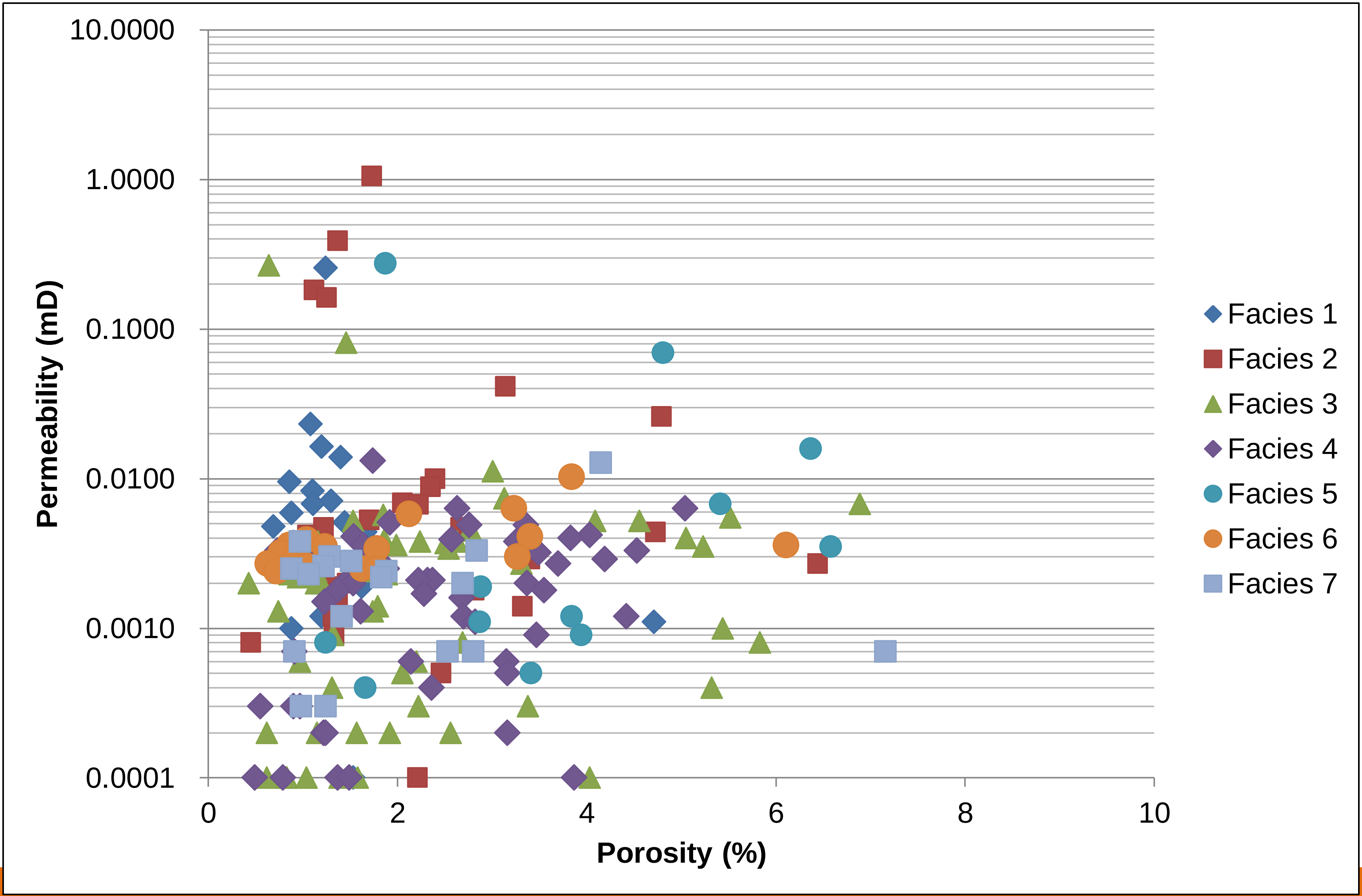
Facies 5
Wackestone

Facies 6
Skeletal-Peloidal Wackestone



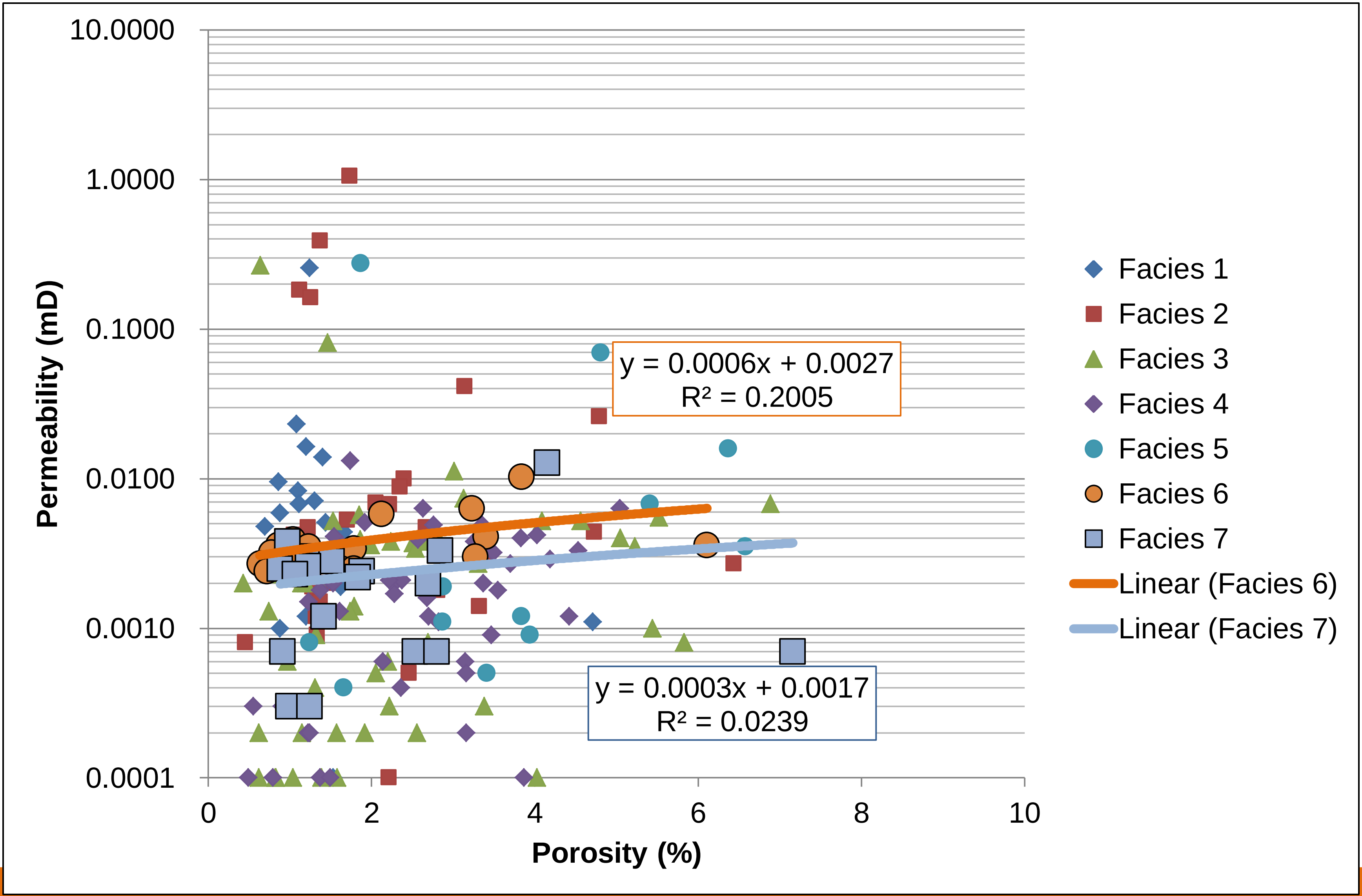
Facies 7
Mudstone to Skeletal Wackestone

Predicting key petrophysical properties:
Porosity and permeability, classified by facies

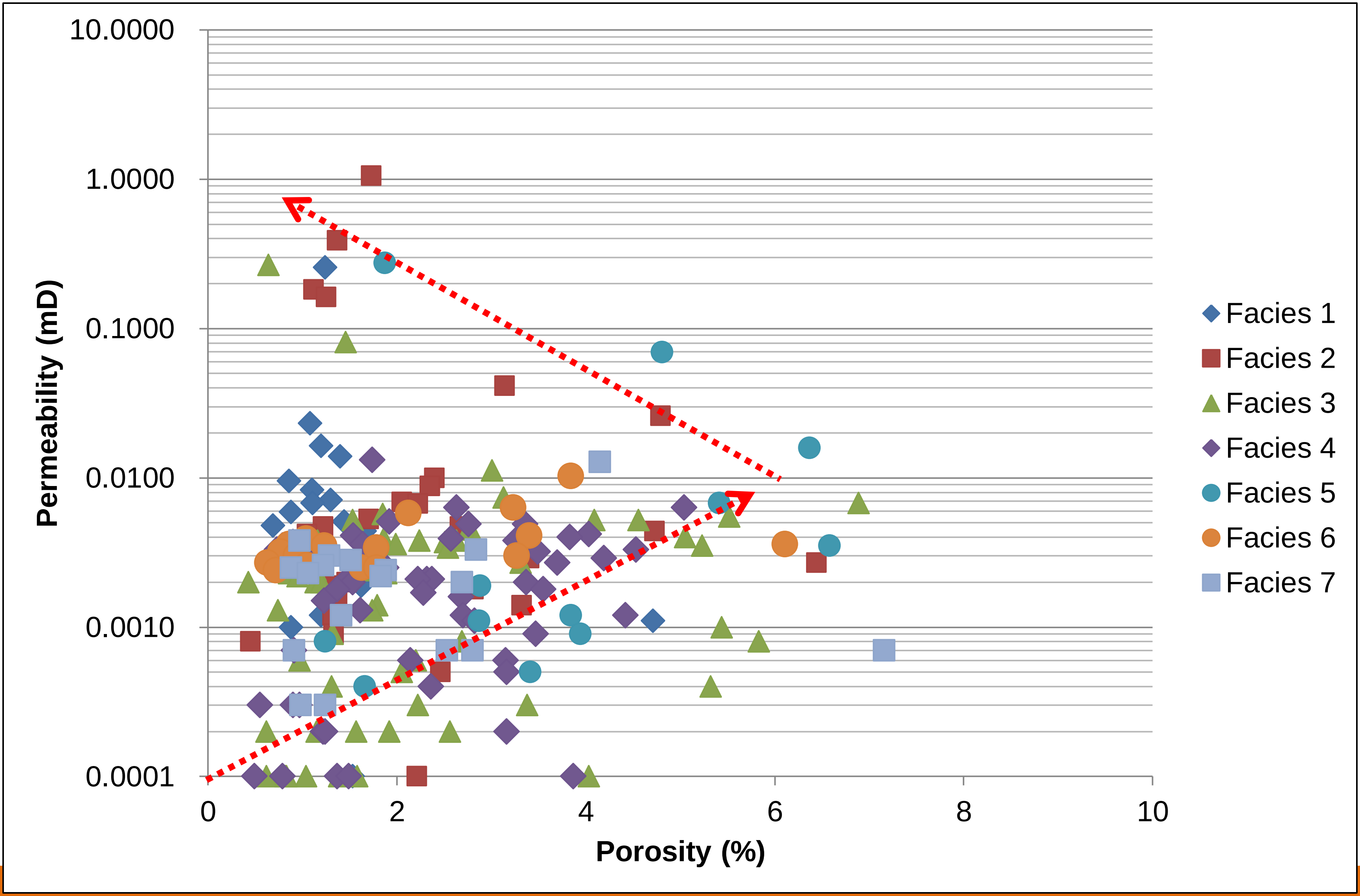


Predicting key petrophysical properties:

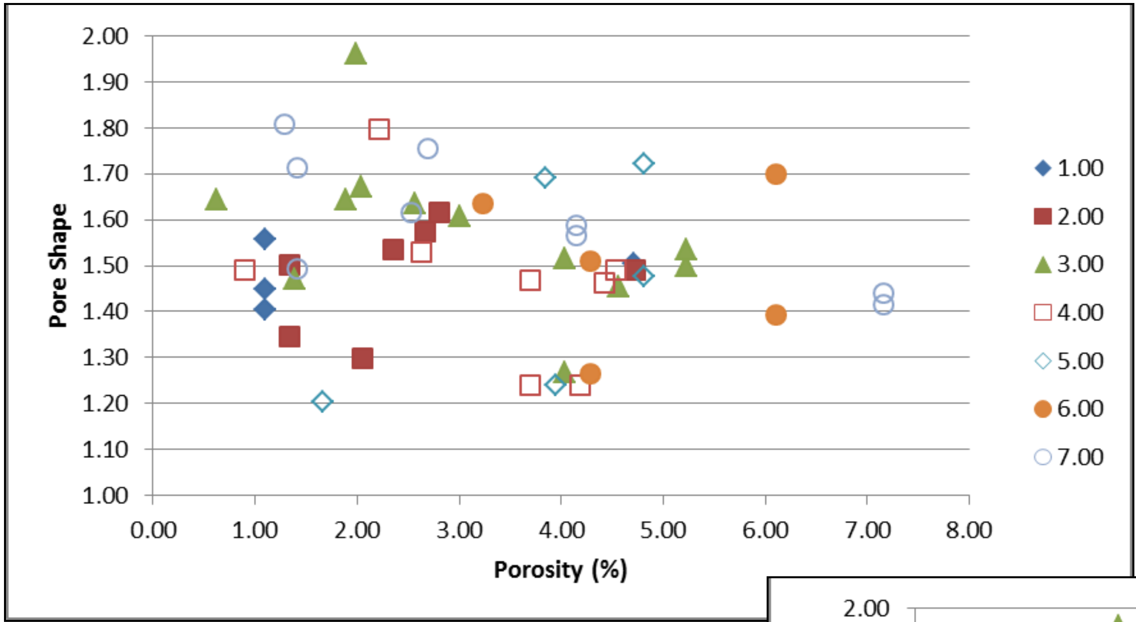
Porosity and permeability, classified by facies



Predicting key petrophysical properties:
Porosity and permeability, classified by facies



Pore Architecture:
Pore shape relationship to porosity



Pore Shape (1 = perfect sphere):

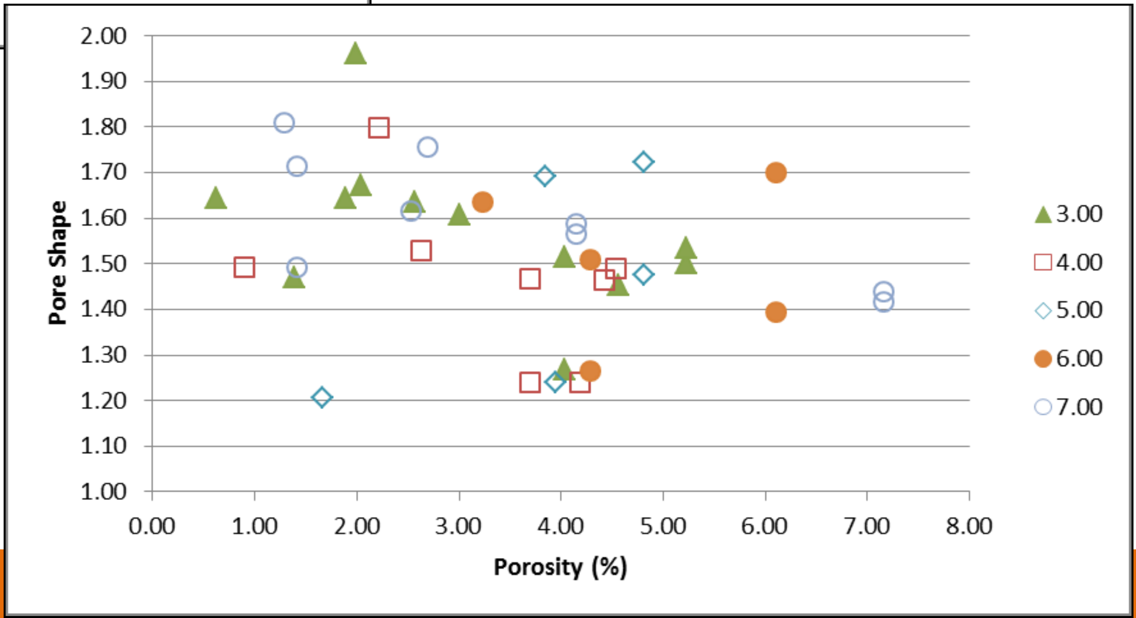
Pore Shape (γ) = $\frac{P}{2\sqrt{\pi A}}$

P = perimeter

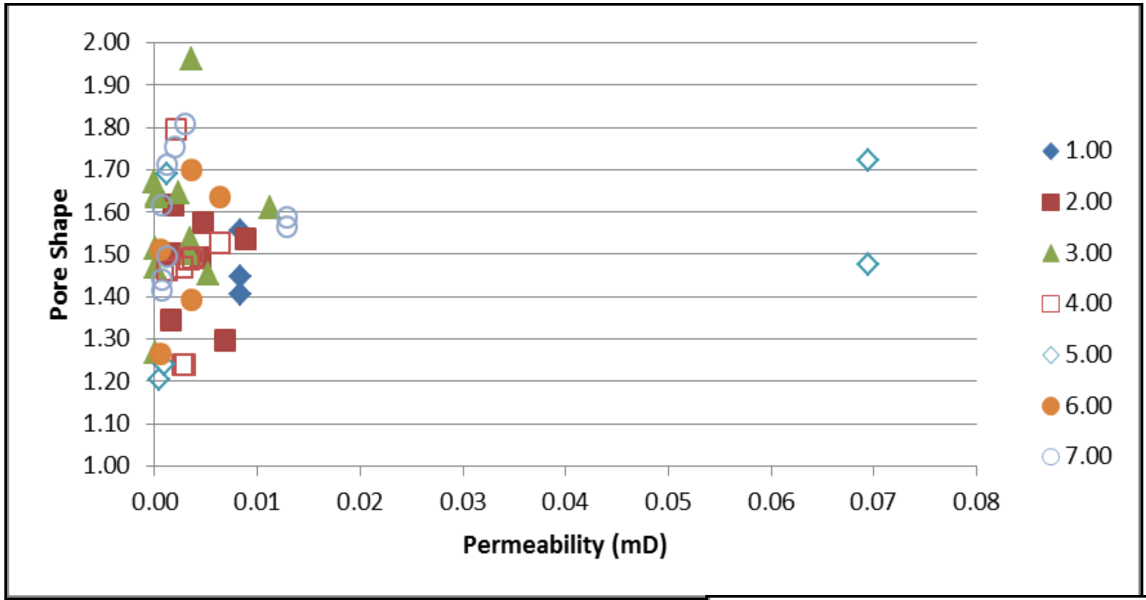
A = Area

Eqn. from (Anselmetti et al. 1998)

Inverse relationship, except in facies 1 and 2

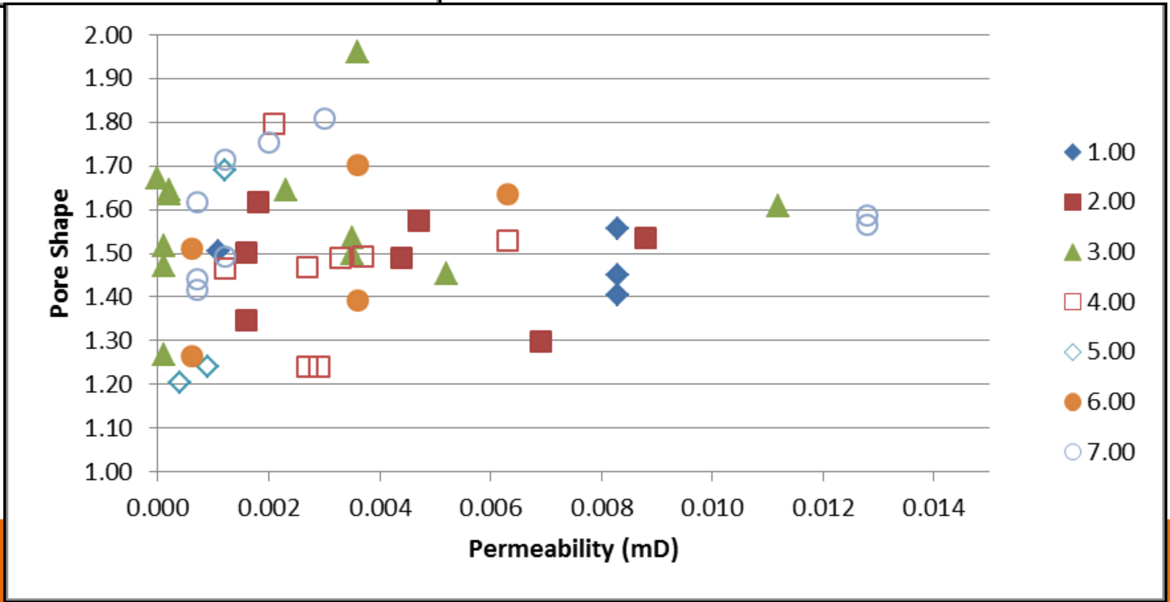


Pore Architecture:
Pore shape relationship to permeability

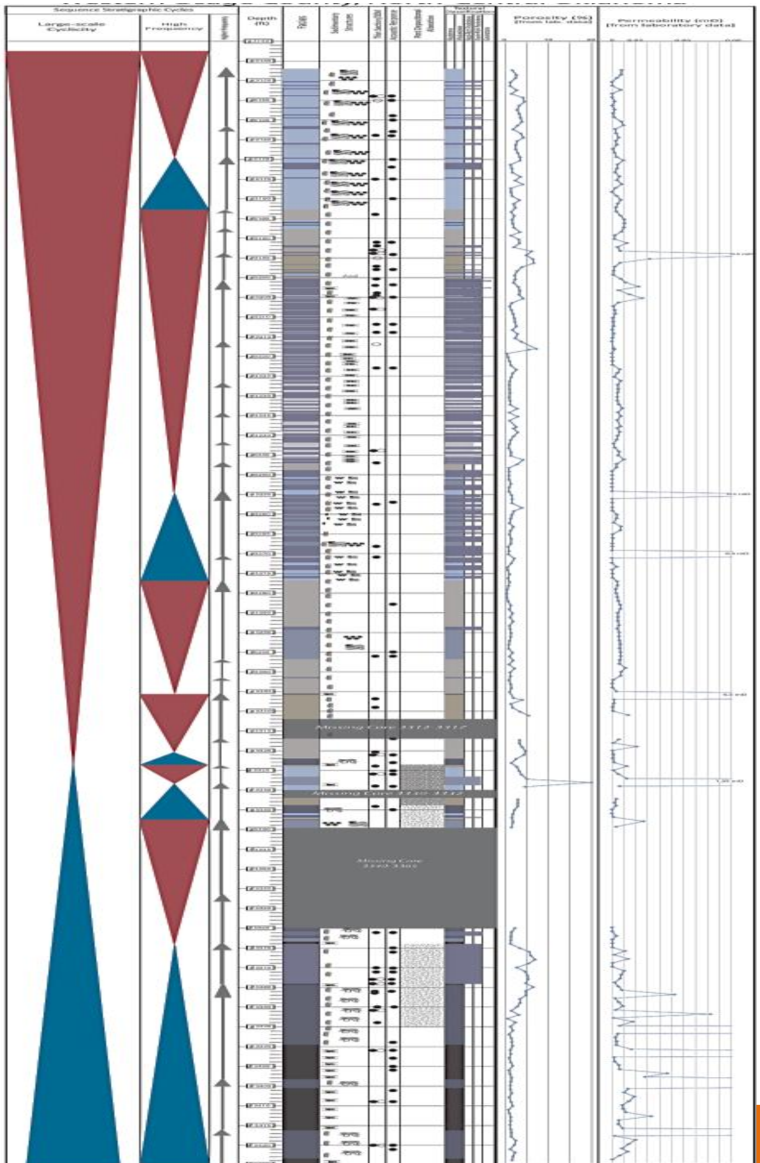


Positive relationship, skewed perspective from 2 data points.

Outlier points removed shows no clear relationship.



Sequence Stratigraphy:
Predicting Porosity and Permeability



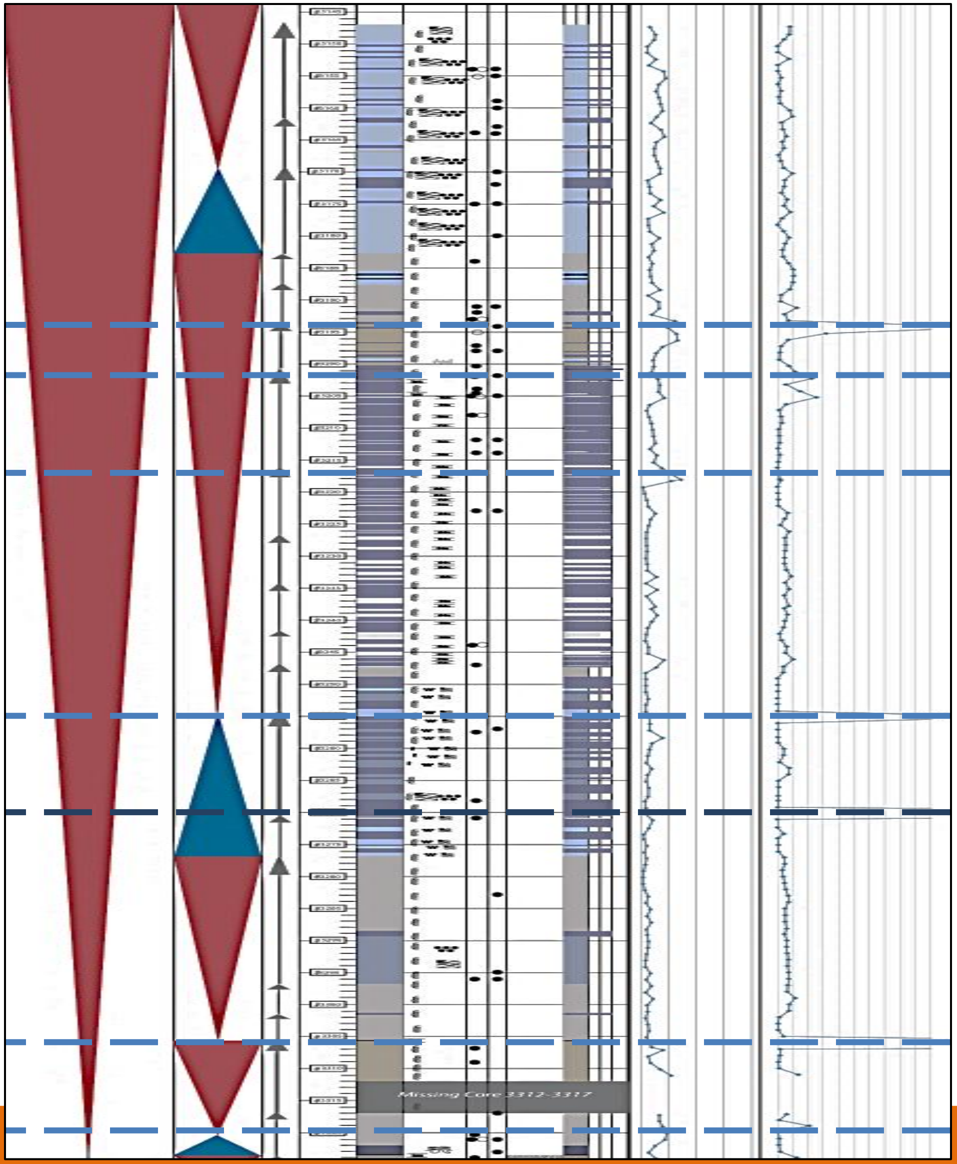
Two unique correlations between porosity and permeability associated with the sequence stratigraphic framework

Correlation within the 3rd order transgressive and regressive sequences

Exceptions:
Post-deposition alteration

Sequence Stratigraphy:

Predicting Porosity and Permeability



<u>Regressive Phase:</u>

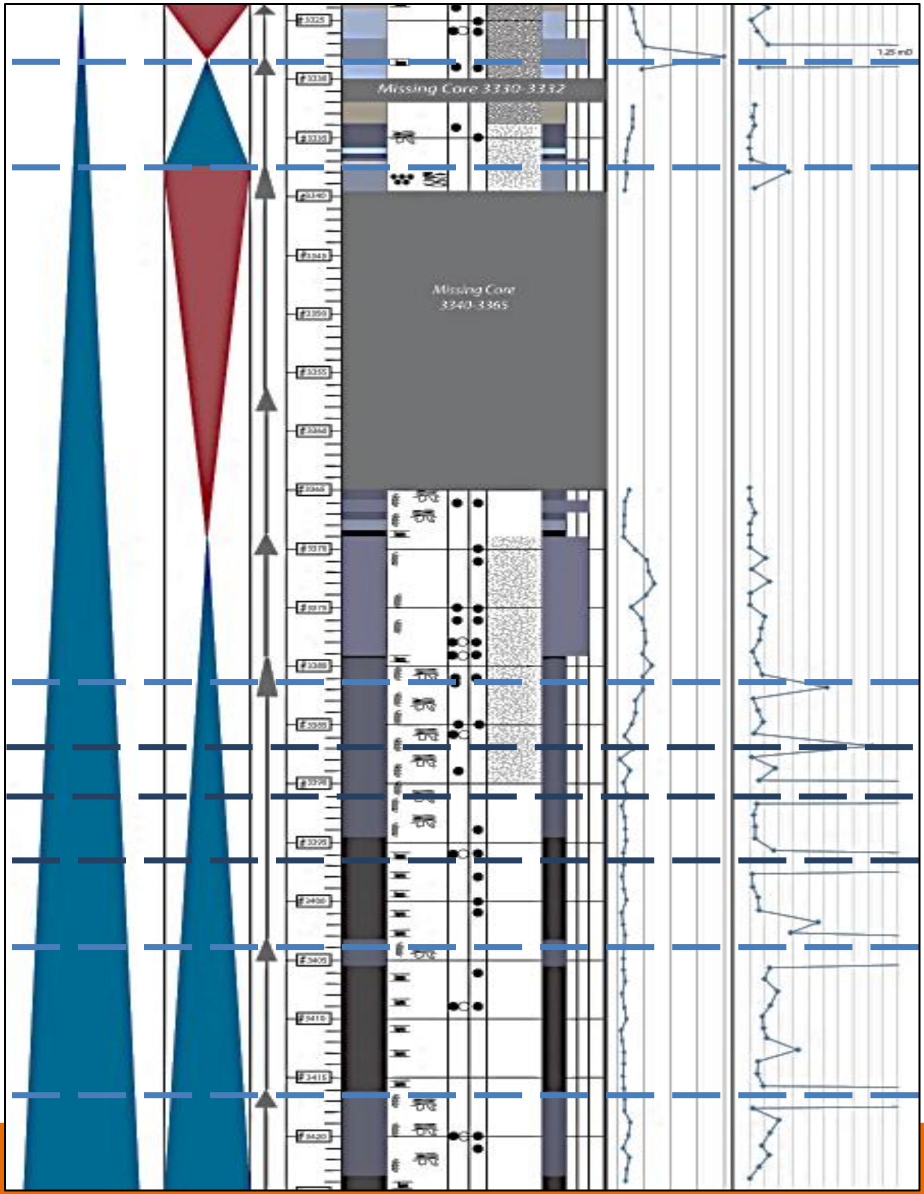
Highest porosity & permeability

Within the regressive phase and at the top of 5^{th} order cycle.

Exceptions:

Extensive post-deposition silicification

Sequence Stratigraphy:
Predicting Porosity and Permeability



<u>Transgressive Phase:</u>
Highest porosity & permeability

Within the transgressive phase and at the top of 5th order transgressive cycles.

Exceptions:
Post-deposition, hydrothermal brecciation.

Conclusions

- Sonic velocity data:
  - Significant shift in the acoustic response relative to values calculated from empirically derived equations for porosity in carbonate mudrocks
  - Data boundaries are the Wyllie Time Average equation and the Woods equation
- Image analysis data:
  - Post-depositional cementation can increase the complexity of the internal pore network by sub-dividing pores
  - Pore architecture correlation to facies: the internal pore geometry helps explain deviations to general relationships between basic quantitative pore architecture measurements, porosity, and permeability
  - Positive correlations between porosity and permeability
  - No clear relationship between pore shape and associated porosity or permeability
- Sequence stratigraphic framework:
  - Most predictable to locate highest porosity and permeability intervals
- The fundamental relationships that exist in conventional carbonates are not well defined in carbonate mudrocks
- An integrated data set enhances the predictability of key petrophysical properties within these types of reservoir systems

Continued Work

- Expand the data set using 4 Mid-Continent Mississippian Limestone cores

  Payne, County, OK; Logan County, OK; Reno County, Kansas
  - Sonic velocity response
  - Digital image analysis from thin section and ESEM photomicrograph
  - Qualitative and quantitative characterization of pore architecture
  - Identify relationships between sonic velocity, porosity, permeability, and pore architecture
  - Define multivariate algorithm to quantitatively predict permeability
  - Relate predictable relationships to sequence stratigraphic framework to reveal predictability of petrophysical properties
- CT-scanning to view permeability in 3-D
  - Relate 3-D images to 2-D data