Unconventional Carbonate Reservoir Characterization Using Sonic Velocity and Characterization of Pore Architecture: An Example From the Mid-Continent Mississippian Limestone*

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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 makes it crucial to understand the petrophysical characteristics to target producing intervals. Sonic velocity, or acoustic response, in carbonate rocks has predictable trends based on porosity, pore architecture, and location within a sequence stratigraphic framework. Previous work has shown that quantification of primary reservoir pore types (macro- vs. micro-) may increase the predictability of reservoir permeability within a basin. Facies are characterized by a hierarchy of shoaling-upward packages defined by planar-bedded mudstone at the base, followed by bioturbated, very fine- to fine-grain sand size crinoid-brachiopod skeletal wackestones, and massively bedded, peloidal-skeletal wackestone to grainstones at the top. A sequence stratigraphic hierarchy of shoaling-upward cycles are observed in core and wireline logs at third-, fourth-, and fifth-order scale. Acoustic response (compressional and shear wave) for a sub-set of samples from the Mississippian Limestone varies from 6500 to 5000m/sec (Vp) and 4500-2500m/sec (Vs). Overall trends of the data confirm observations from previous studies regarding the expected range of acoustic response for low-porosity, low-permeability carbonates. Porosity in the horizontal direction, in the current data set, ranges from 0.5-7%, although locally, porosity values may be as high as 20%. Pore diameter ranges in size from the mesopore (4mm-62.5 µm) to nanopore (1µm-1nm) size, with the majority of the porosity in the micro- to nanopore scale. Pores viewed with SEM show that the largest pores are mostly oblong- to oval-shaped intercrystalline to vuggy mesopores, with a diameter of 100µm x 25µm, whereas the smallest are circular-shaped, intercrystalline to vuggy nanopores, with diameters of 5-10µm and 50-100nm pore throats. Petrophysical analyses have been integrated into high-resolution sequence stratigraphic analyses of core and outcrops from Oklahoma, Missouri, and Arkansas. Sonic velocity, coupled with characterization of macro- to nanoscale pore architecture, wireline logs and high-resolution sequence stratigraphic analyses, shows promise of predicting both key reservoir facies and key producing intervals within an unconventional carbonate reservoir.

References Cited

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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.

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.

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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.

Weger, R.J., Baechle, G.T., Masaferro, J.L., and Eberli, G.P., 2004, Effects of pore structure on sonic velocity in carbonates: SEG Expanded Abstracts, v. 23, p. 1774.

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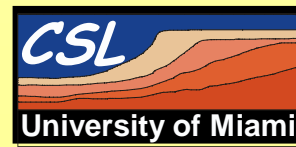
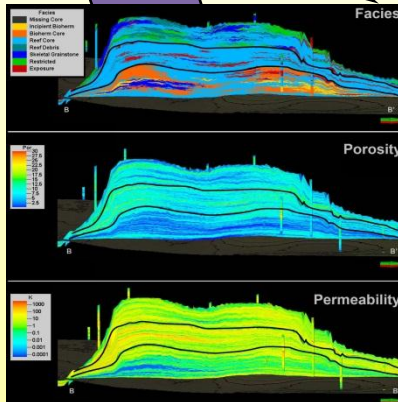# Integrated Reservoir Characterization
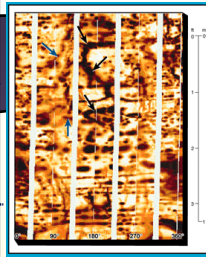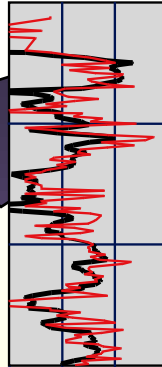
Wireline Logs

Core and Thin Sections

Analogs

Geologic Modeling

Facies
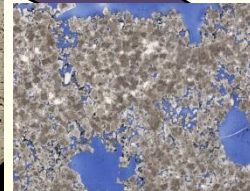
Porosity

Permeability

Sequence Stratigraphy

Sonic Velocity/K

3-D Seismic

Pore Architecture

Grammer, 2013
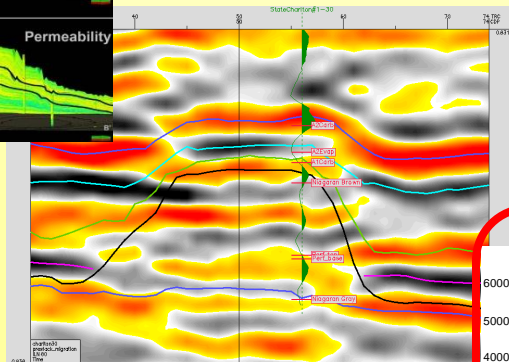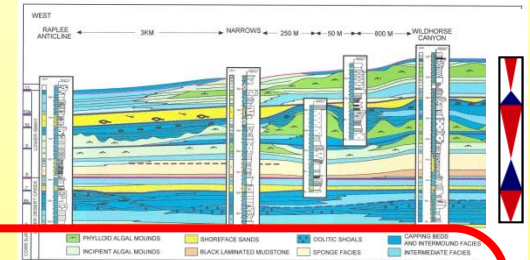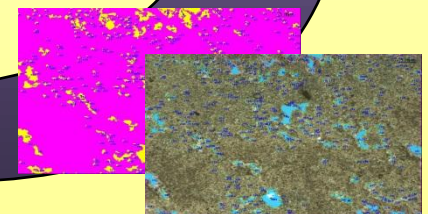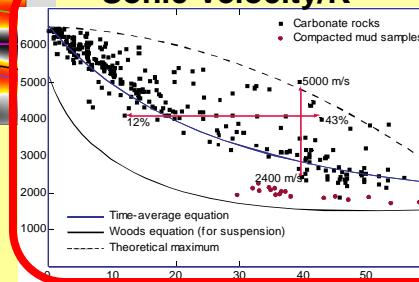
Porosity and Permeability Relationships
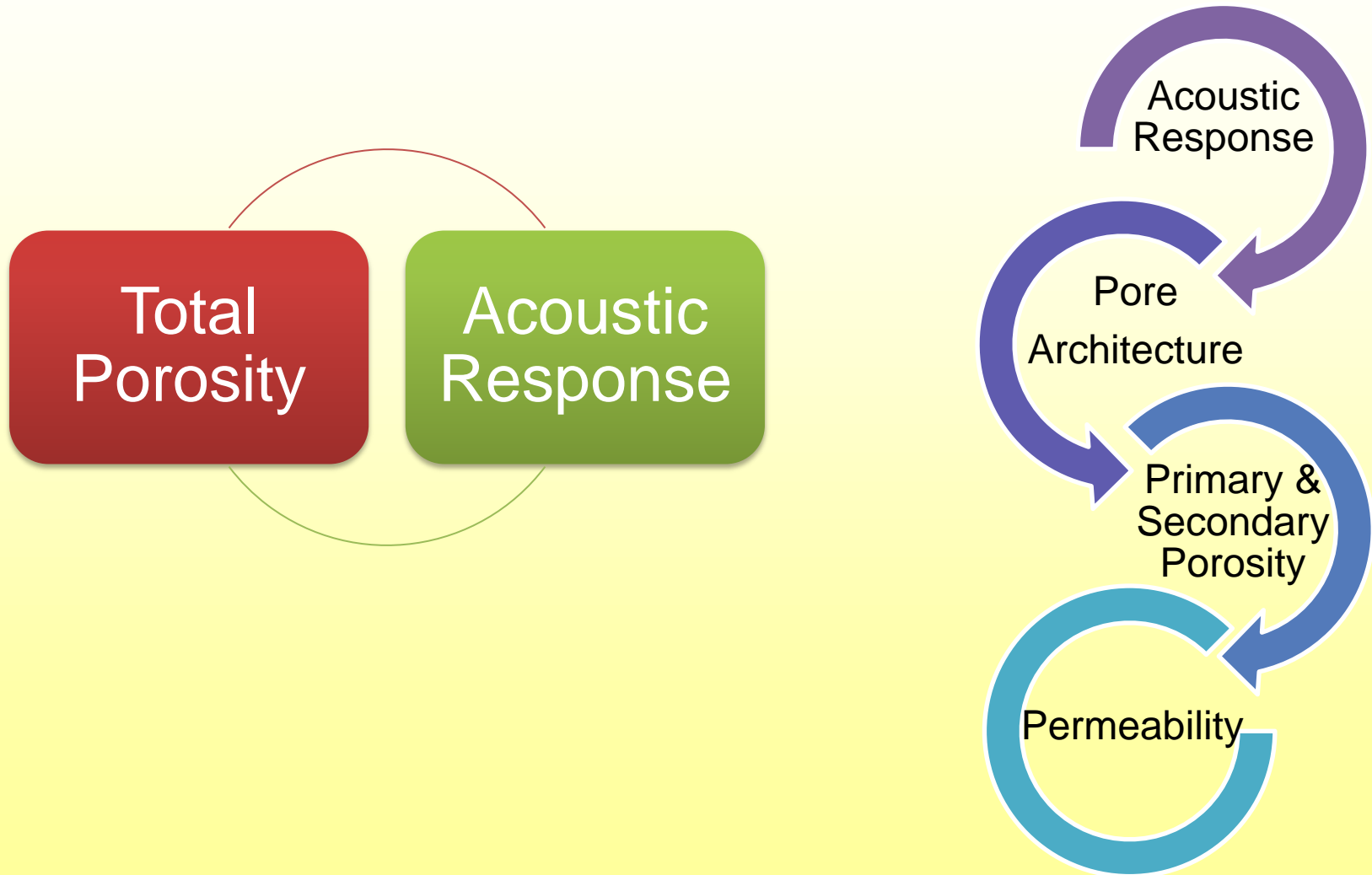
Velocity – Porosity Relationship in Carbonates
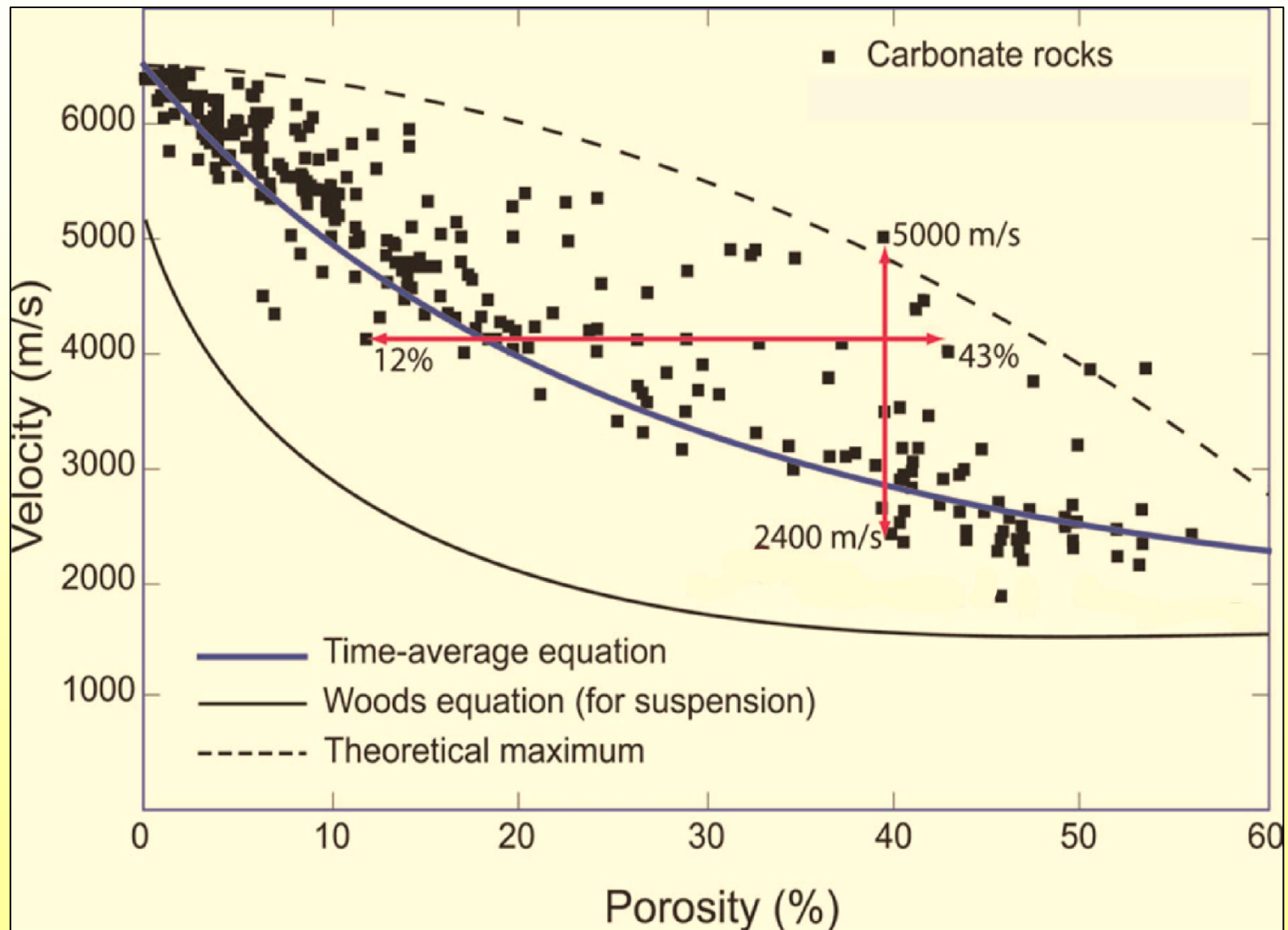
Velocity - Pore Type Relationship

Velocity

Porosity

Anselmetti and Eberli 1999
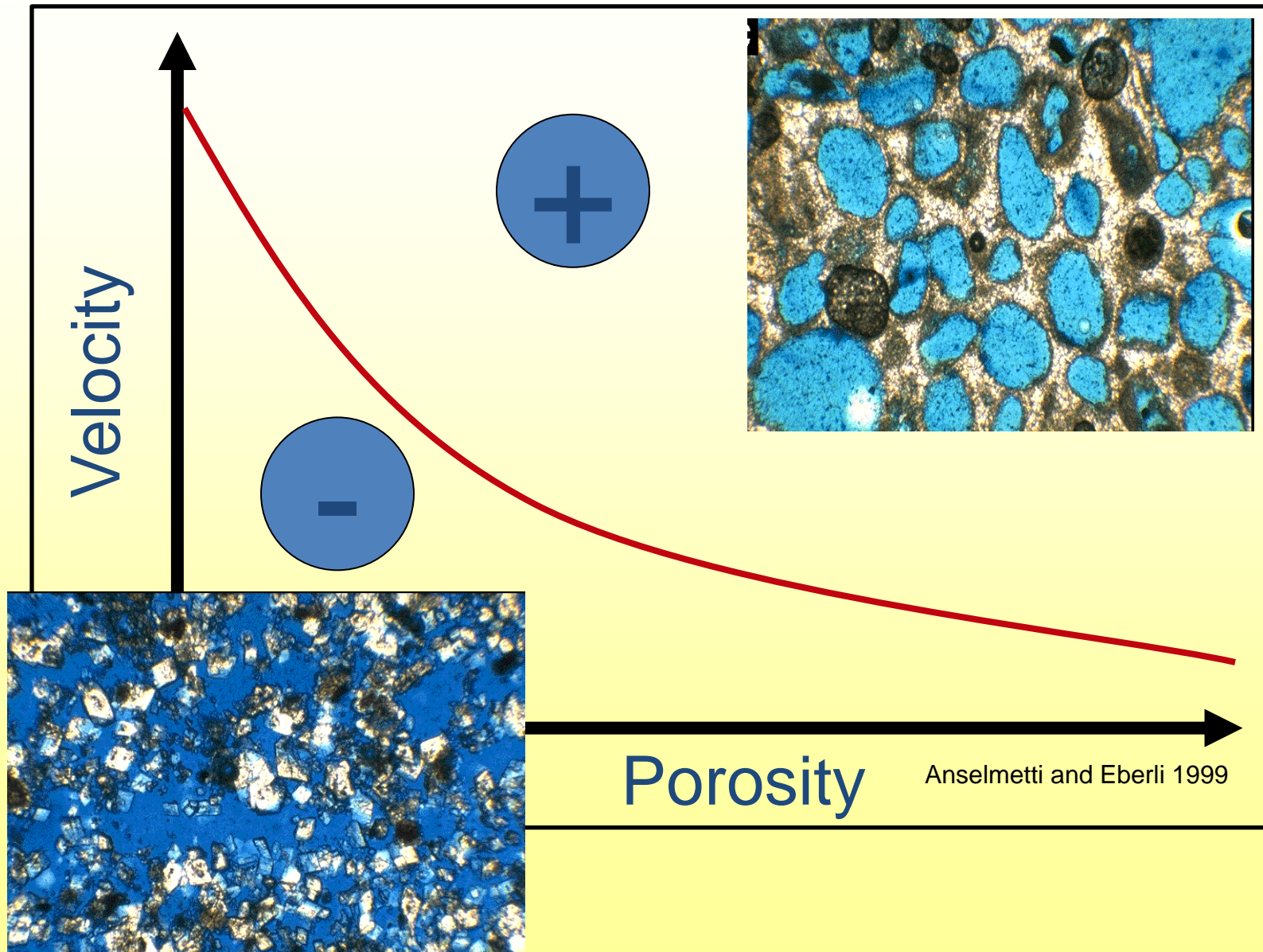
Velocity Correlation to Pore Type

From Anselmetti and Eberli 1999
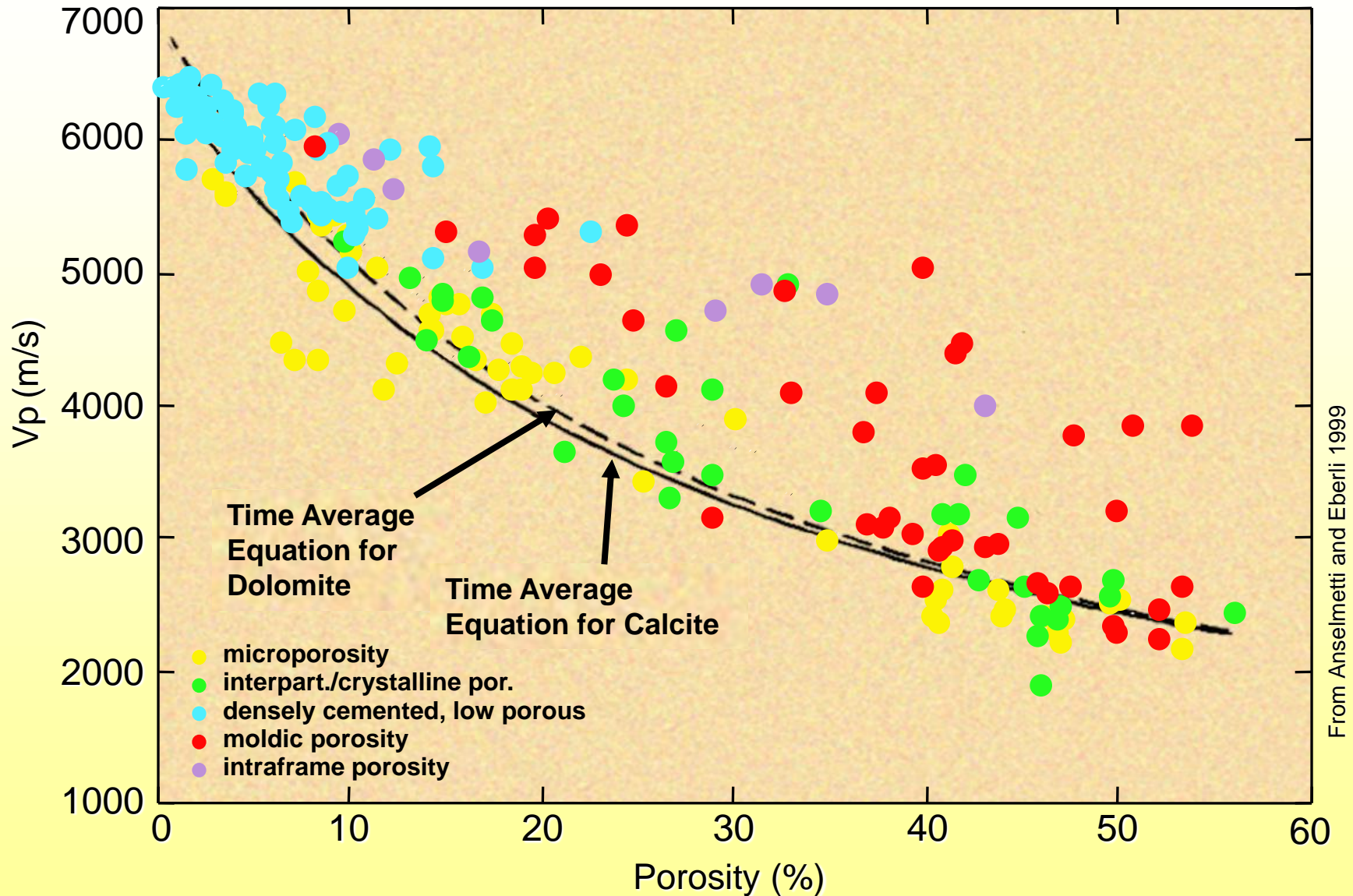
Velocity – Permeability Relationship
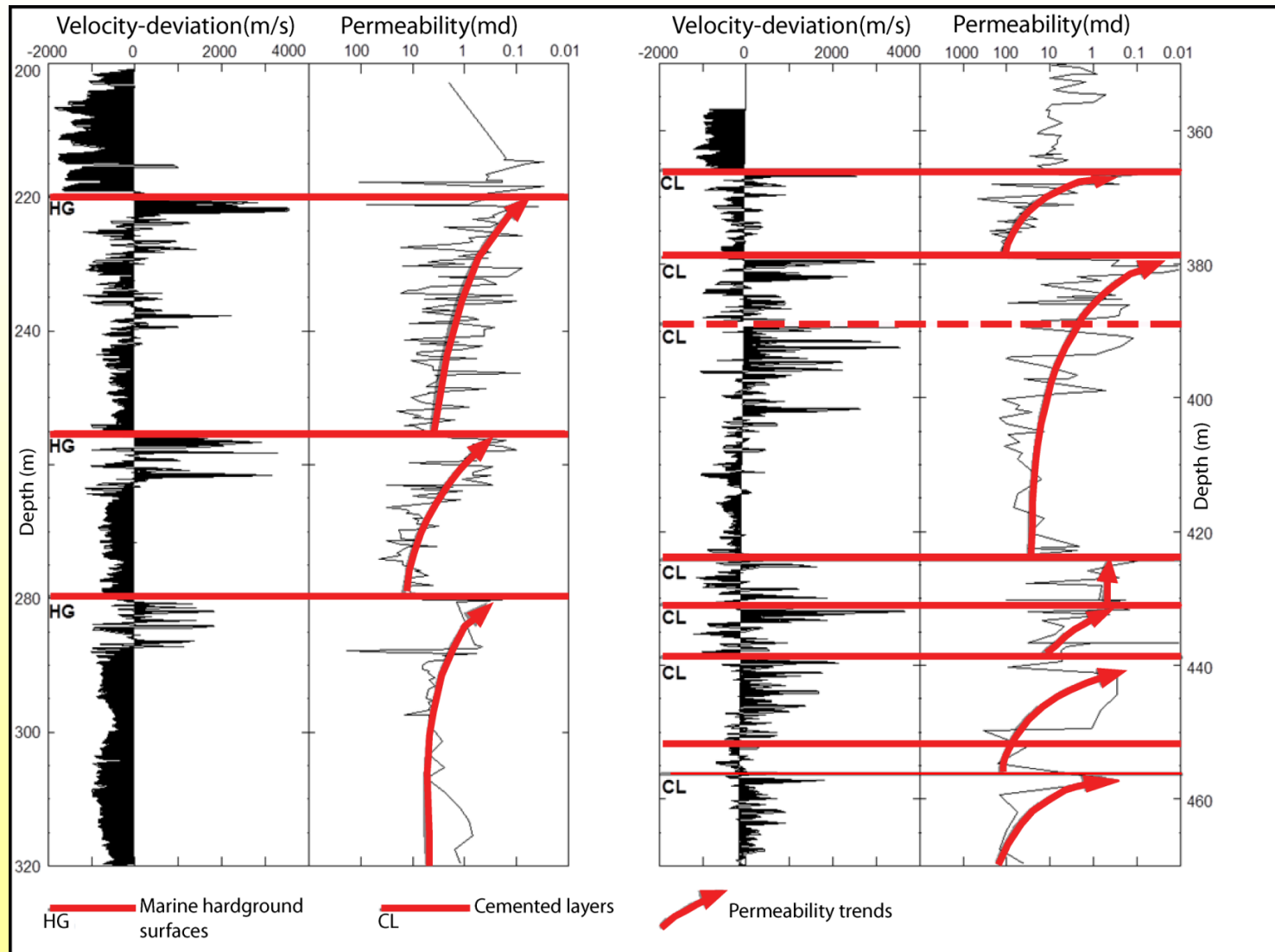
Modified from Anselmetti and Eberli 1999

Digital Image Analysis and Permeability Prediction
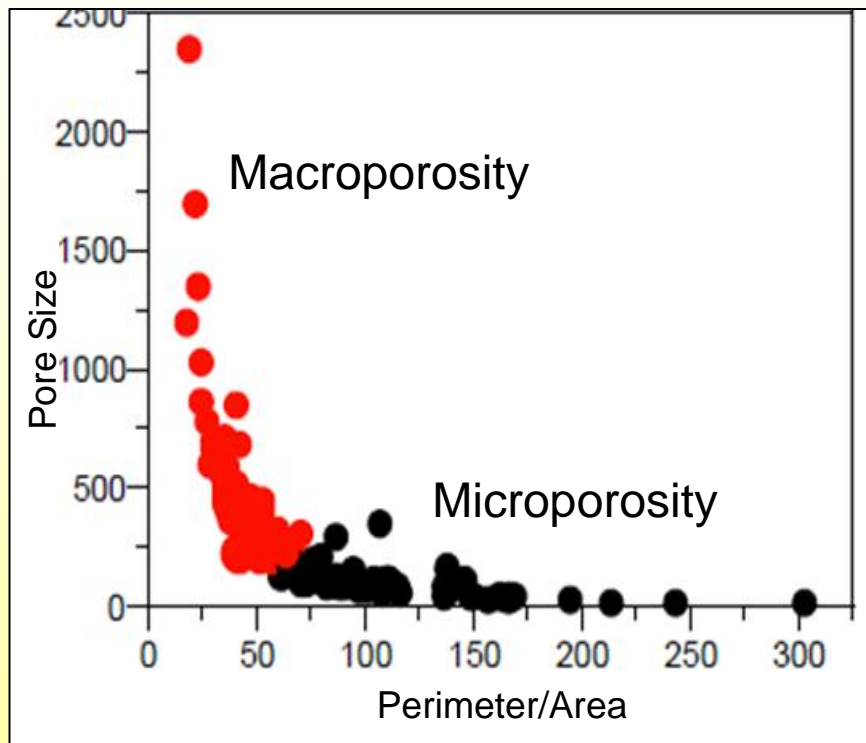
Weger et al. 2004

Quantified acoustic response
+Quantified pore architecture
+Quantified macro- and microporosity
Predictable Permeability
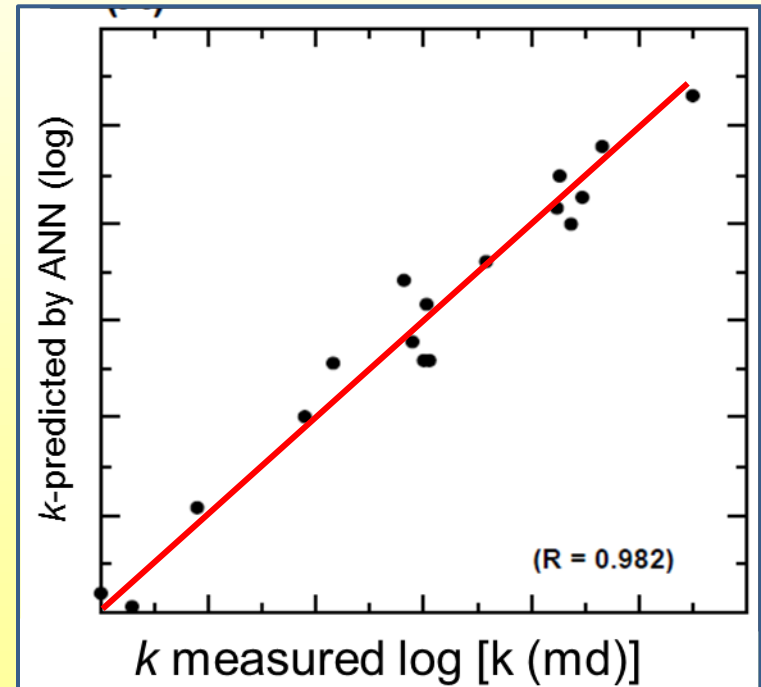
Weger et al. 2004
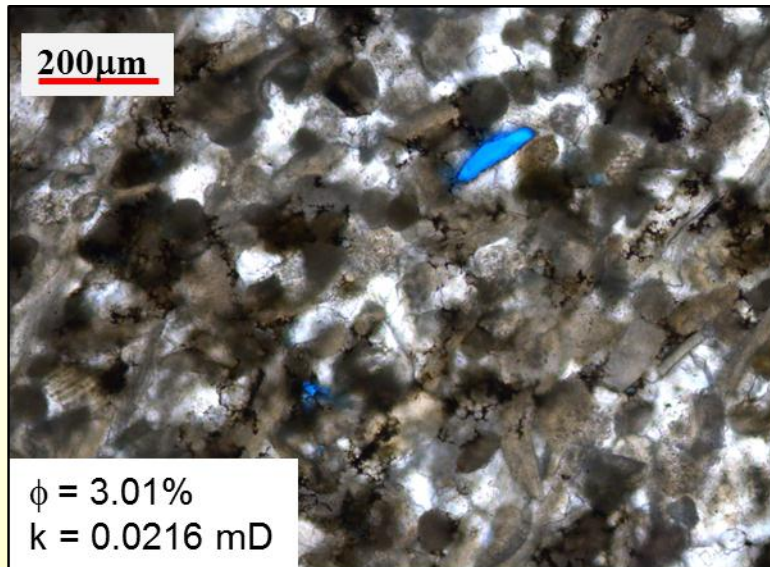
Mississippian Limestone Reservoir Data Location Map
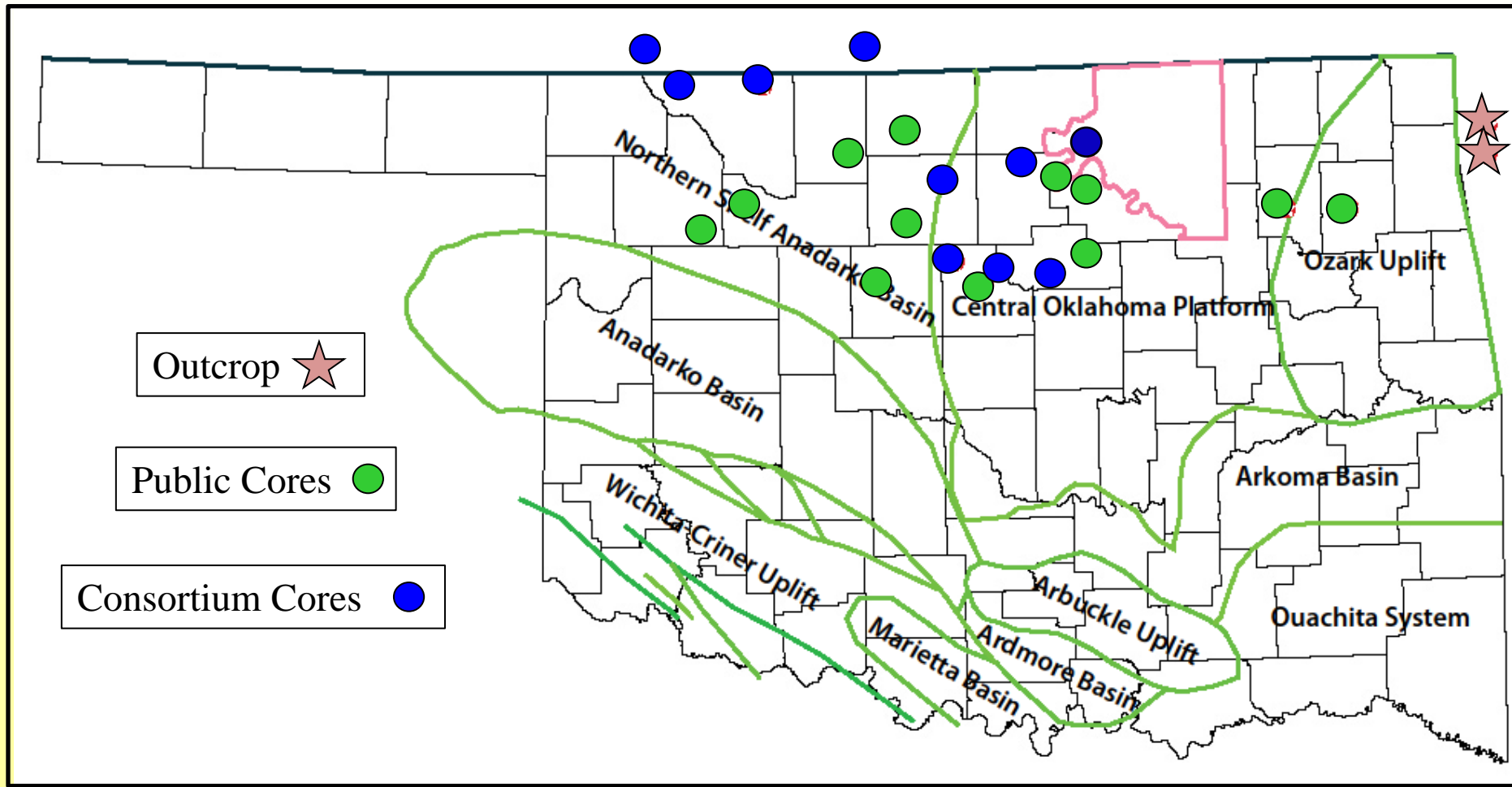
Mudrock Pore Classification

1 m

256 mm
1 cm — Macropore
<4 mm
1 mm — Mesopore
<62.5 μm
Micropore
1 μm — <1 μm
Nanopore
1 nm — <1 nm
Picopore
←Methane = 0.38 nm
←Water = 0.28 nm

Macropore
Meso
Micropore

Modified from Loucks et al. 2012

$\phi = 9\%$
$k = 0.02$ mD

Interparticle porosity

1 μm

Interparticle porosity

2 μm

Vuggy, Intercrystalline, Interparticle Porosity (Miss.)

1 μm

mag HV spot WD 12/9/2013 det
50 000 x 20.00 kV 3.0 10.0 mm 12:02:36 PM ETD — 1 μm —

Interparticle porosity

2 μm

Pore Architecture:
Thin Section Photomicrographs

200μm

φ = 3.01%
k = 0.0216 mD

100μm

φ = 19.96%
k = 1.49 mD

50μm

φ = 3.23%
k = 0.0134 mD

50μm

φ = 2.5%
k = 0.0026 mD

Pore Architecture:
Thin-Section Photomicrographs
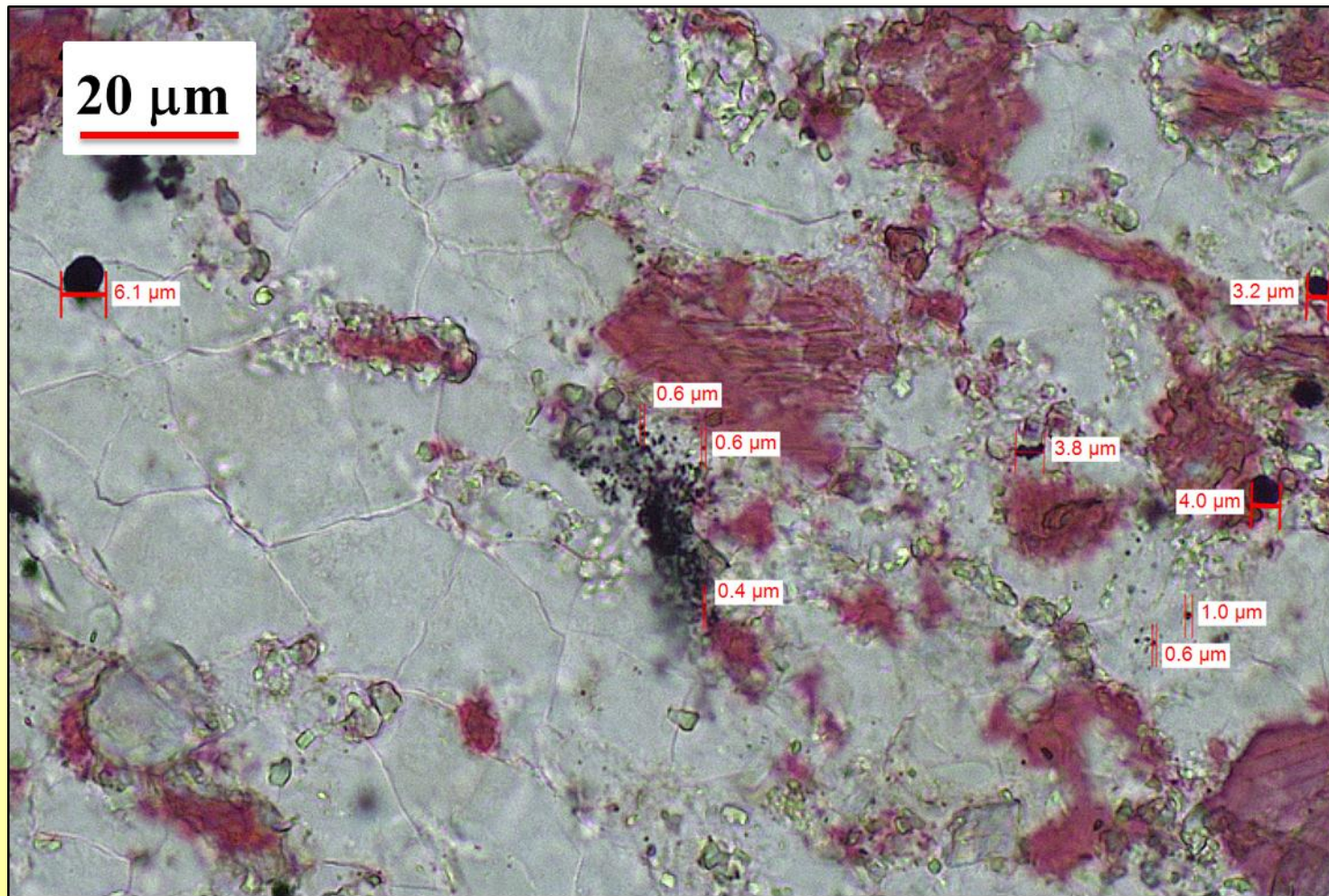
Intercrystalline,
Vuggy, Pin-point

$\phi = 2.5\%$
k = 0.0026 mD
DIA ϕ = 3.5%
Total porosity
over-estimated
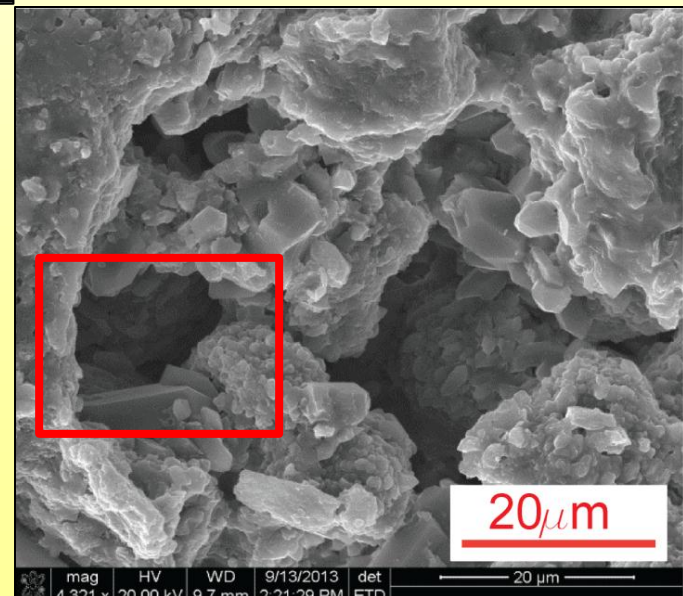
Pore Architecture
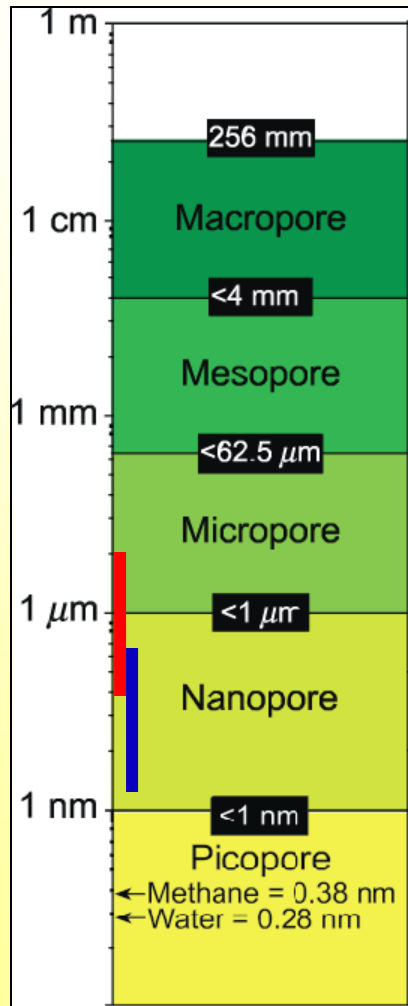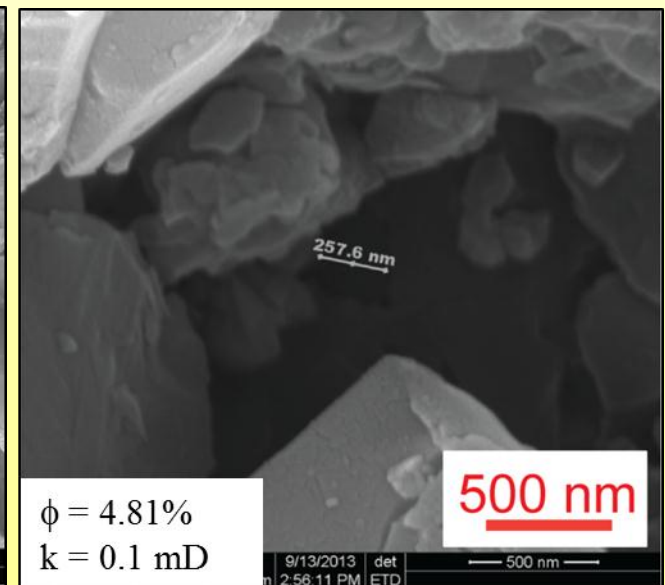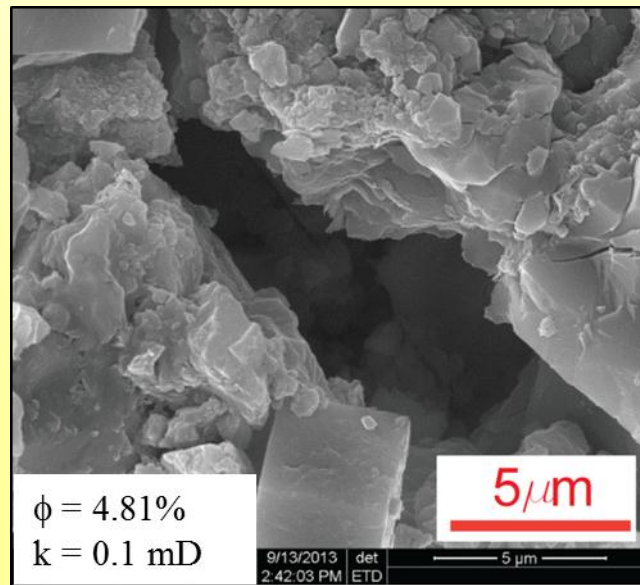## SEM Photomicrographs – Core #1
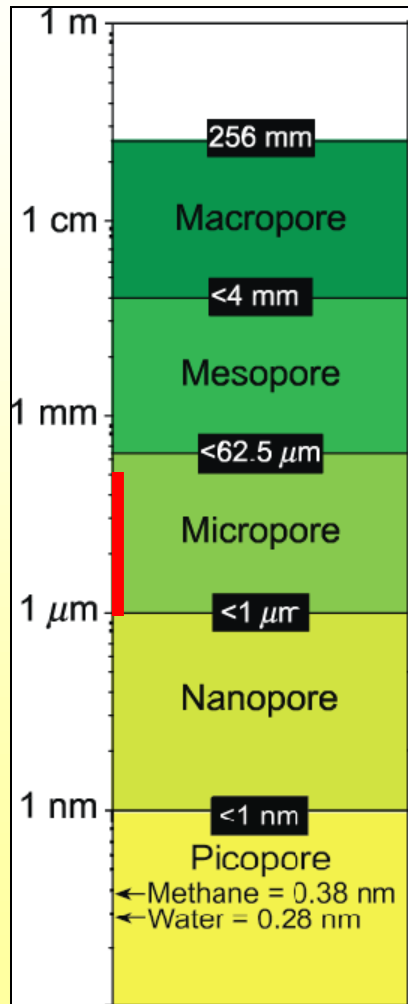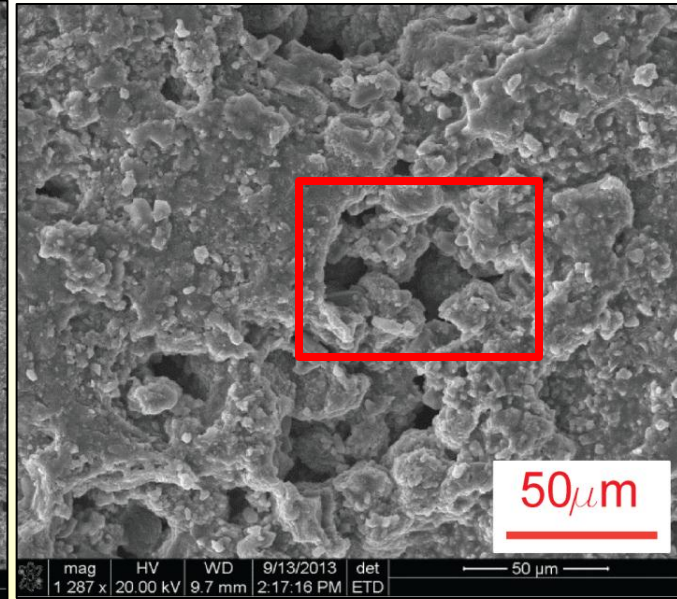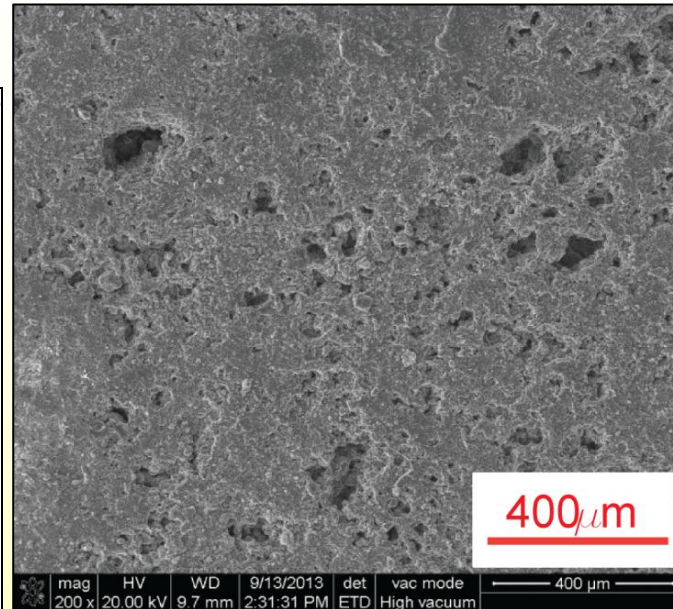
Loucks et al., 2012

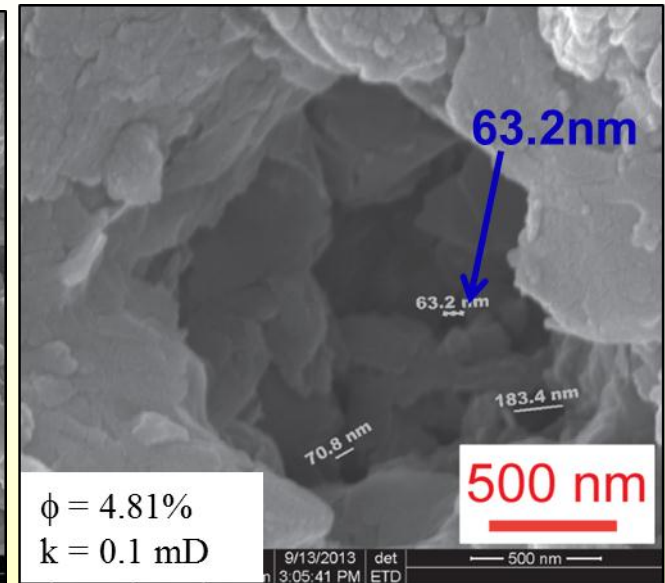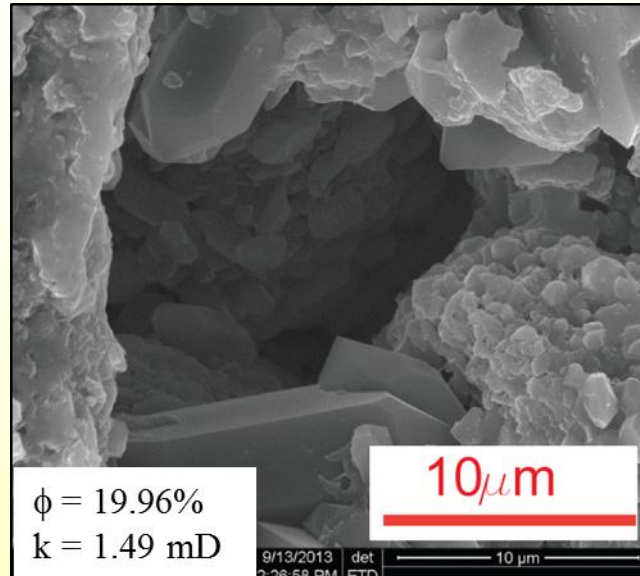Vuggy, Dissolution, Intercrystalline Pores

ϕ = 19.96%
k = 1.49 mD

Pore Architecture
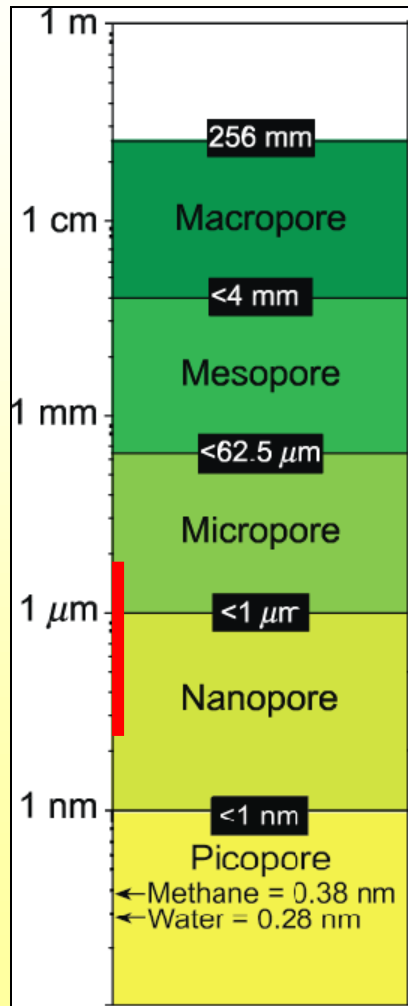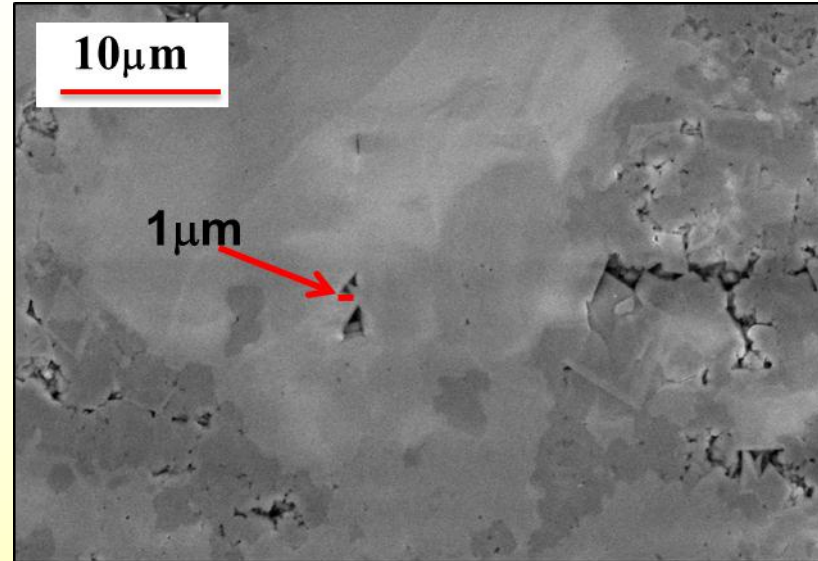## SEM Photomicrographs – Core #1
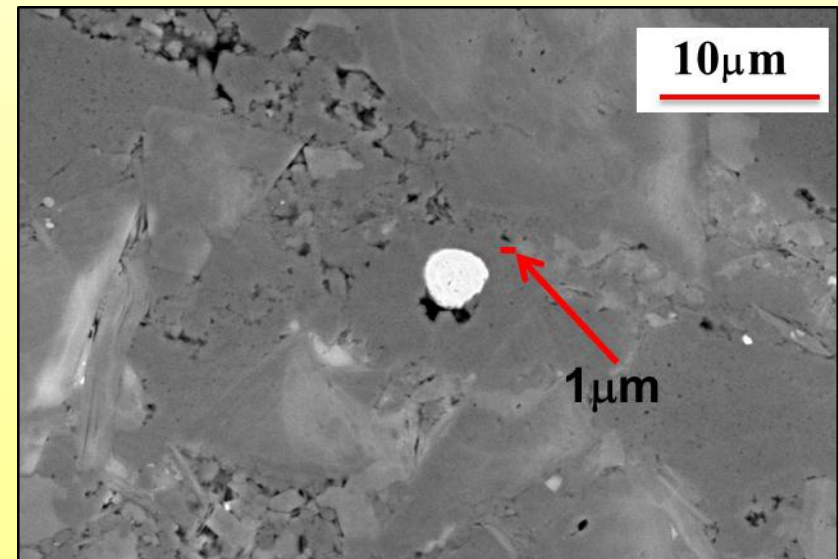

Loucks et al., 2012

Pore Architecture
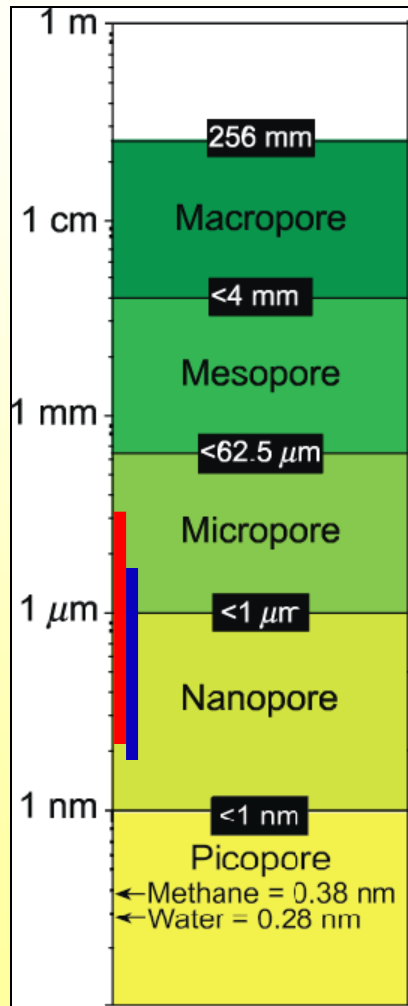## SEM Photomicrographs – Core #1

Loucks et al., 2012

Intercrystalline, Vuggy
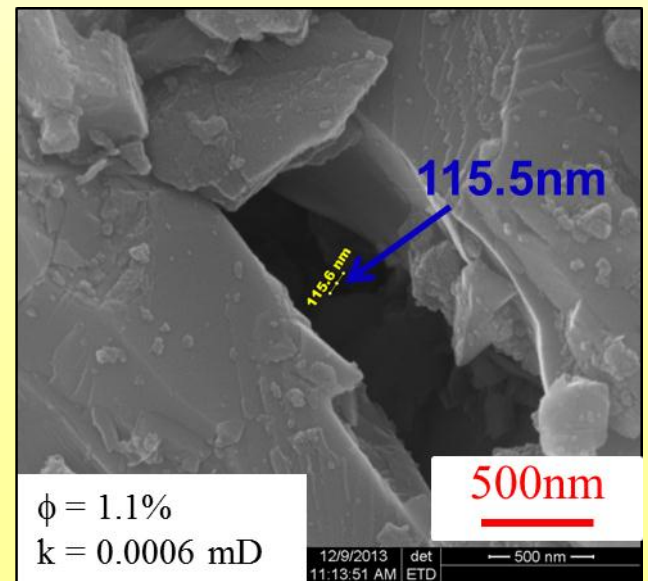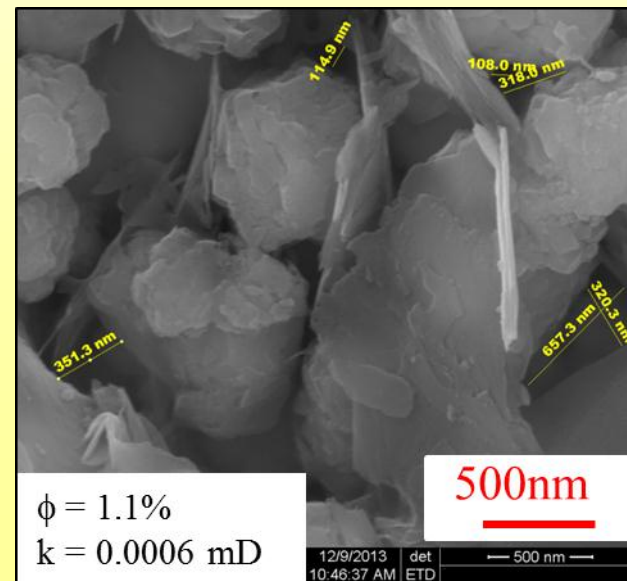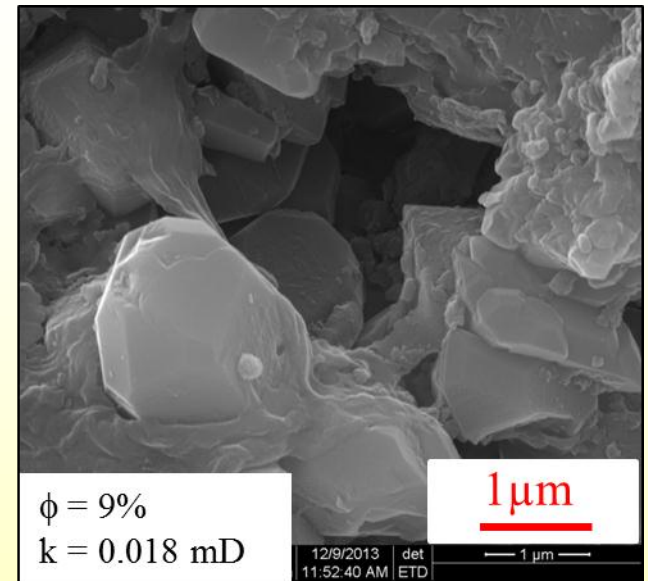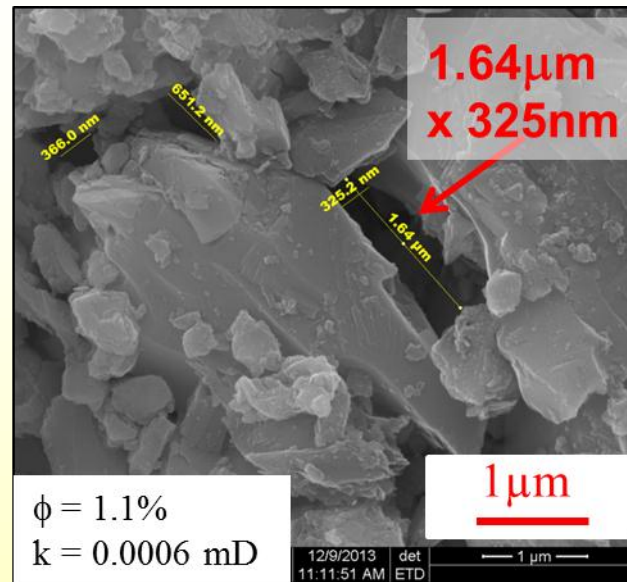$\phi = 4.42\%$
$k = 0.004$ mD
98% Microporosity

Intercrystalline, Vuggy
$\phi = 5.23\%$
$k = 0.008$ mD
98% Microporosity

Pore Architecture
SEM Photomicrographs – Core #2

Loucks et al., 2012

1.64μm x 325nm

φ = 1.1%
k = 0.0006 mD

1μm

φ = 9%
k = 0.018 mD

1μm

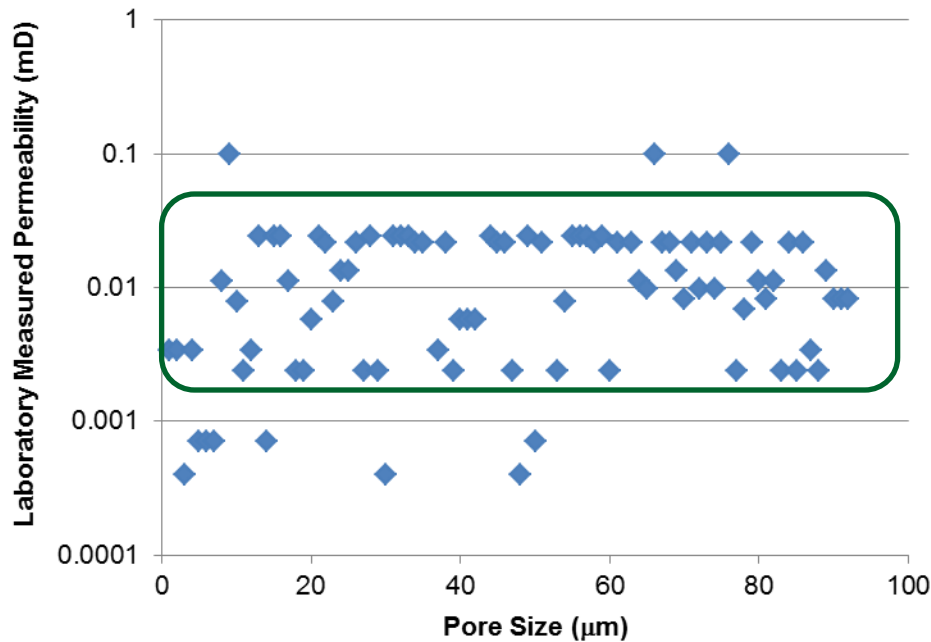φ = 1.1%
k = 0.0006 mD

500nm

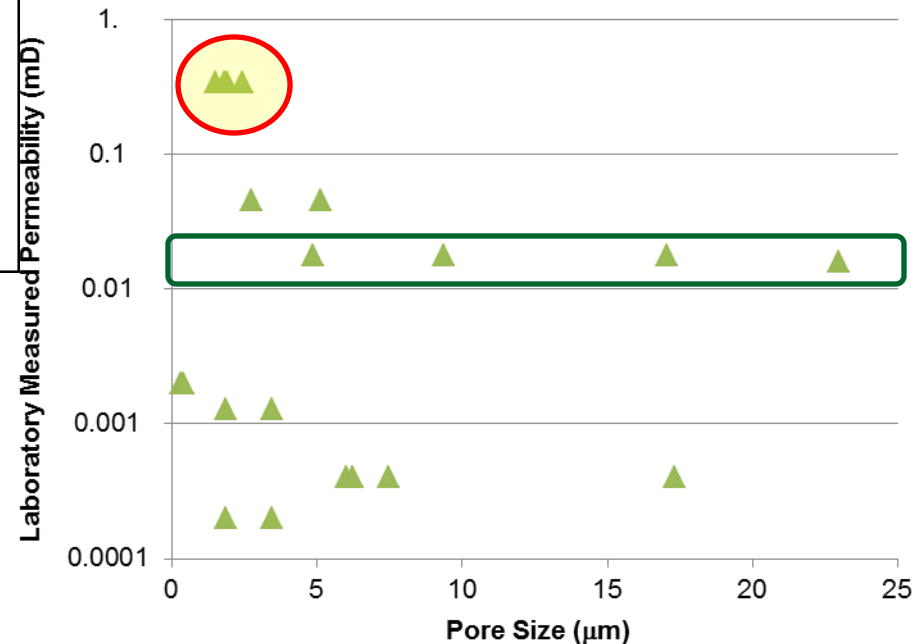115.5nm

φ = 1.1%
k = 0.0006 mD

500nm

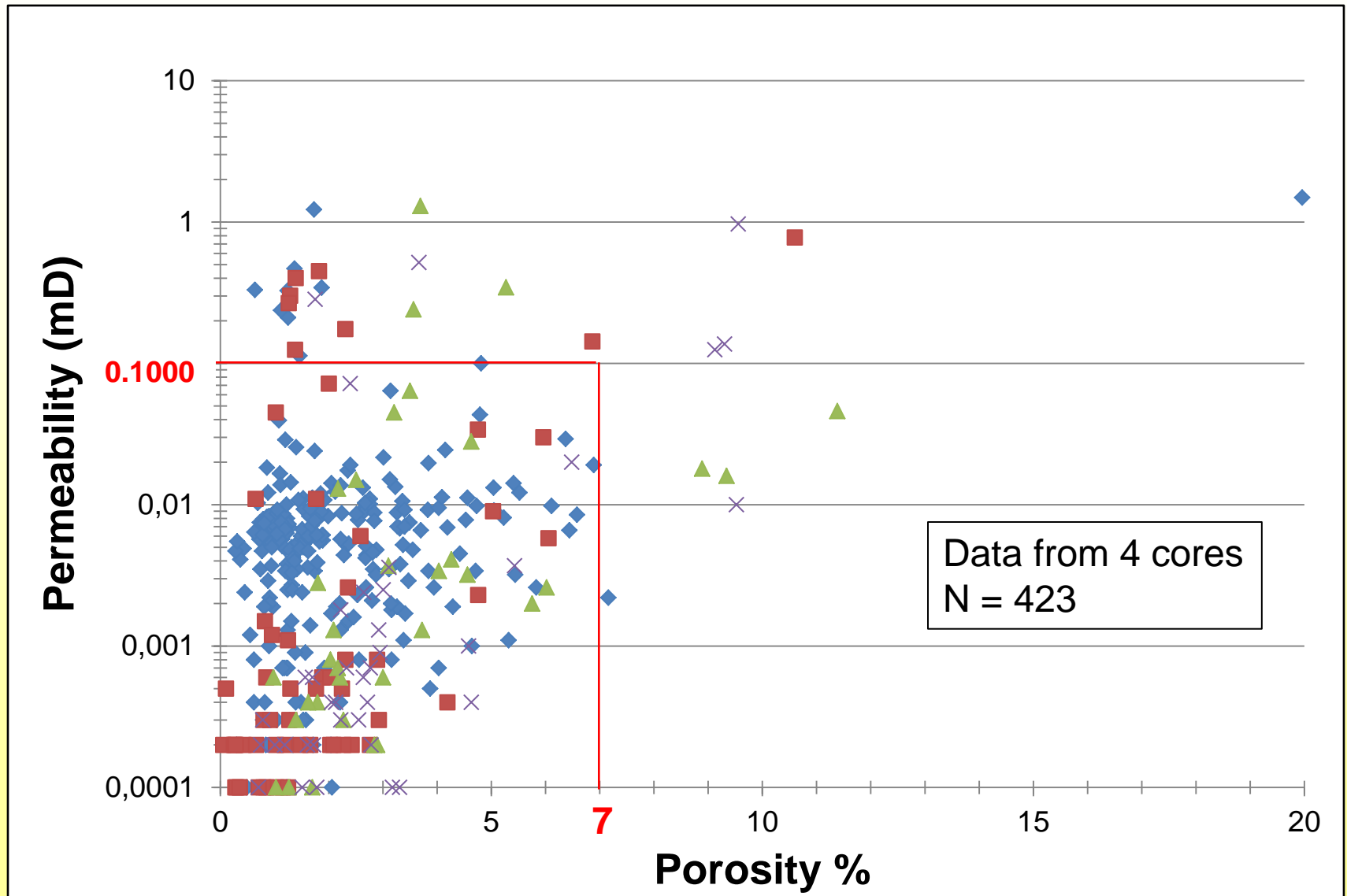# Pore Size, Porosity, and Permeability Relationship

Pore Size vs. Permeability

-- Larger pores ≠ greater permeability

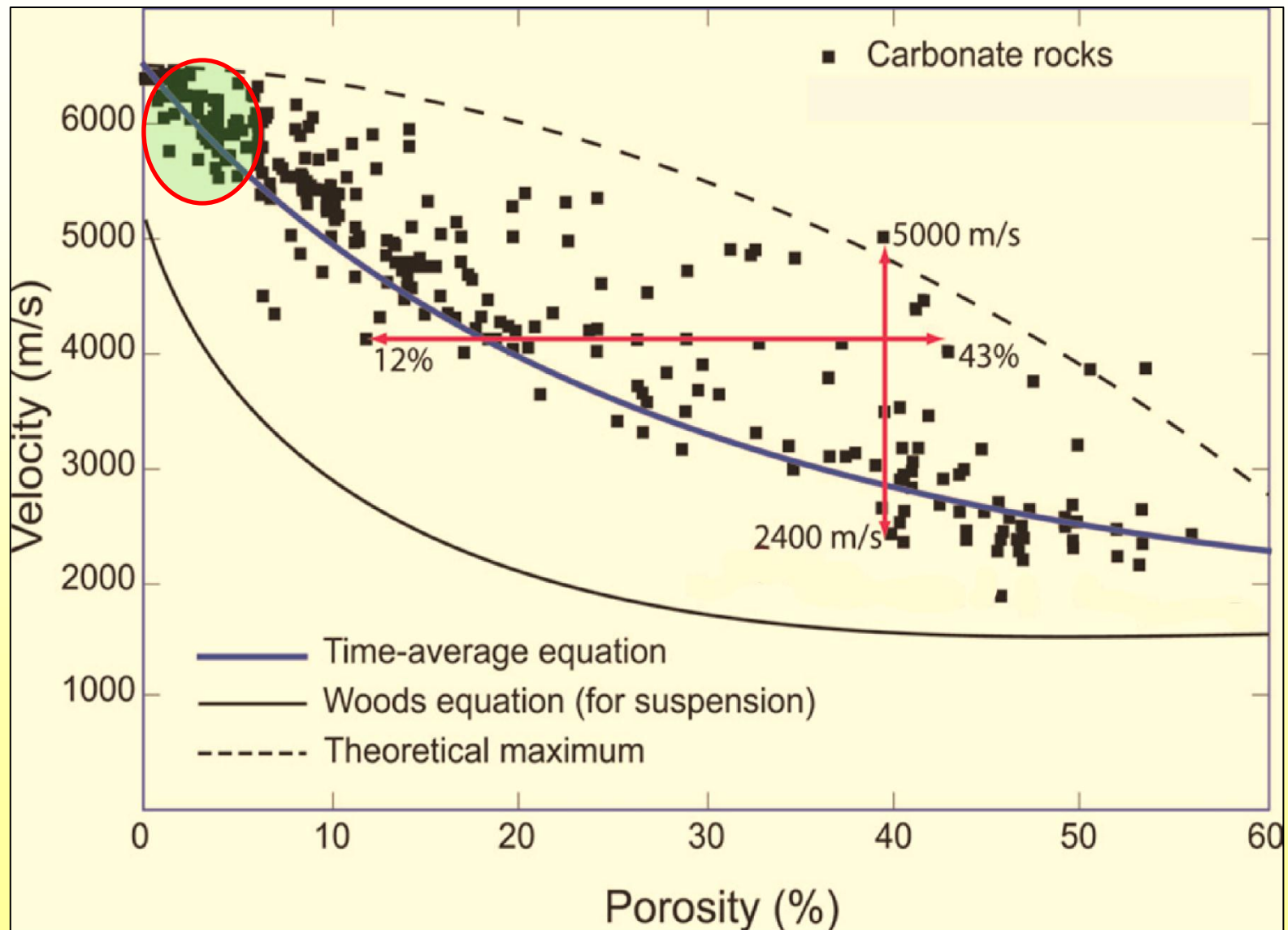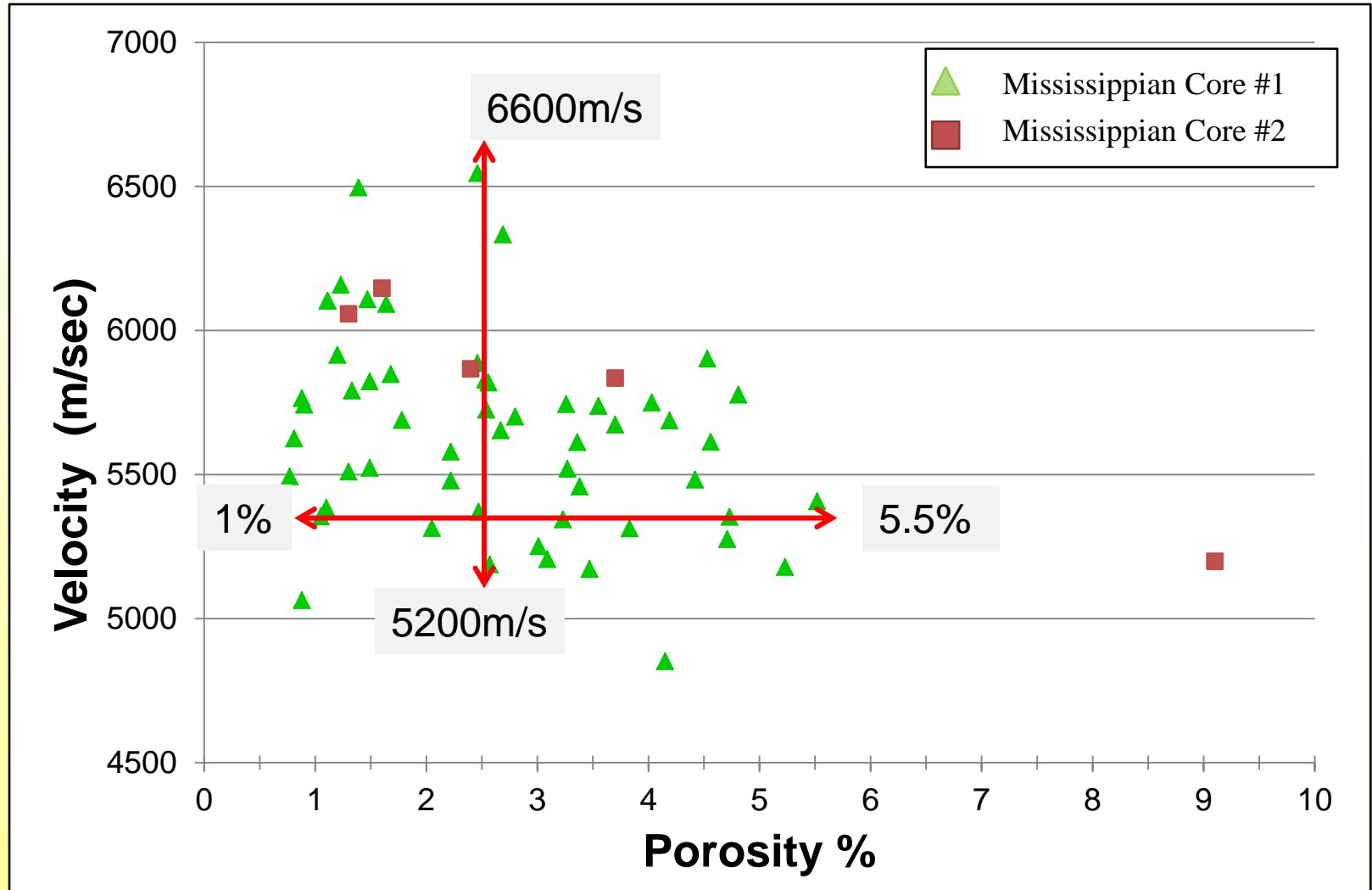-- Smaller pores can have greater connectivity
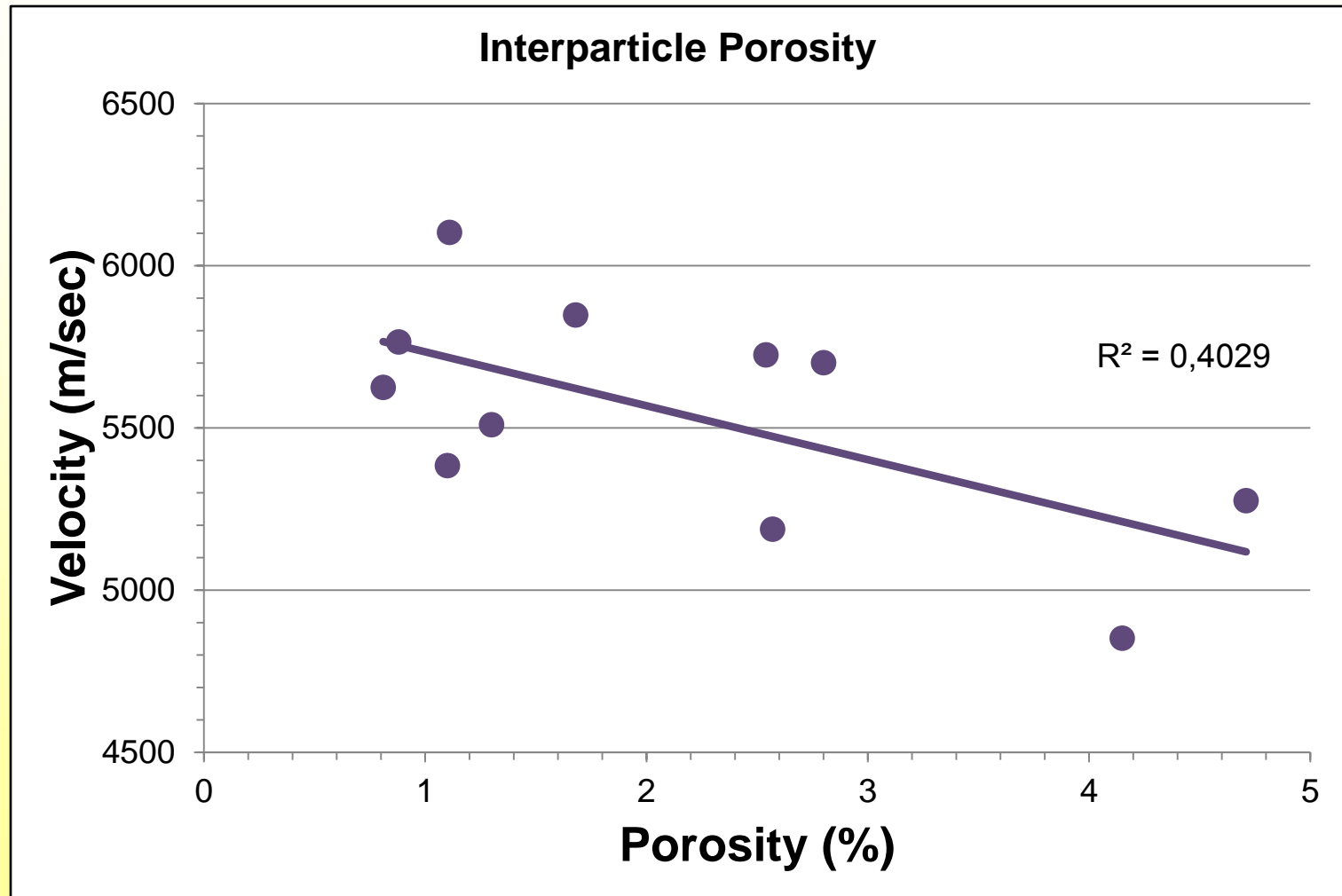
Porosity and Permeability (1" Plugs)

Velocity – Porosity Relationship in Carbonates

Velocity – Porosity Relationship in Carbonate Mudrocks
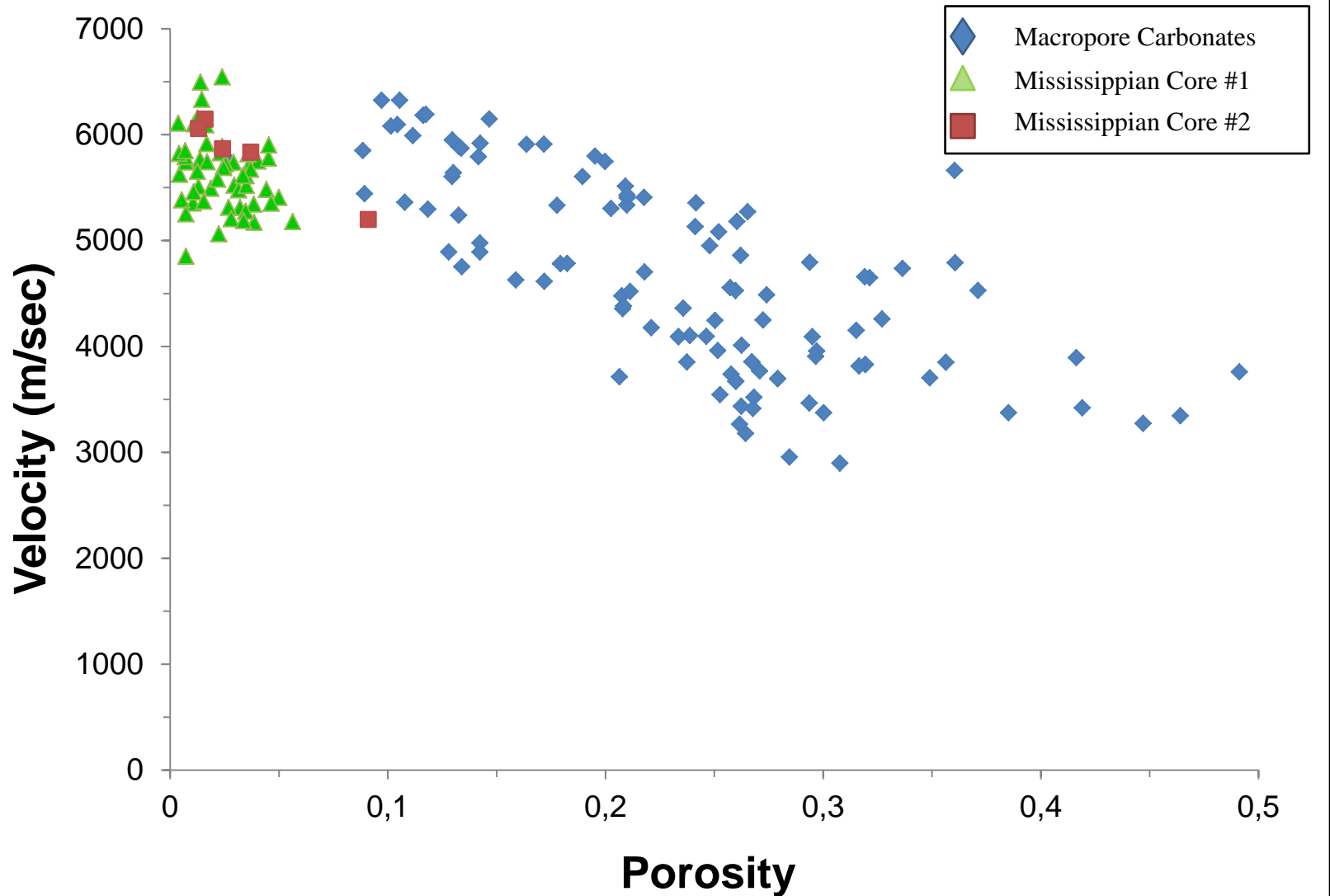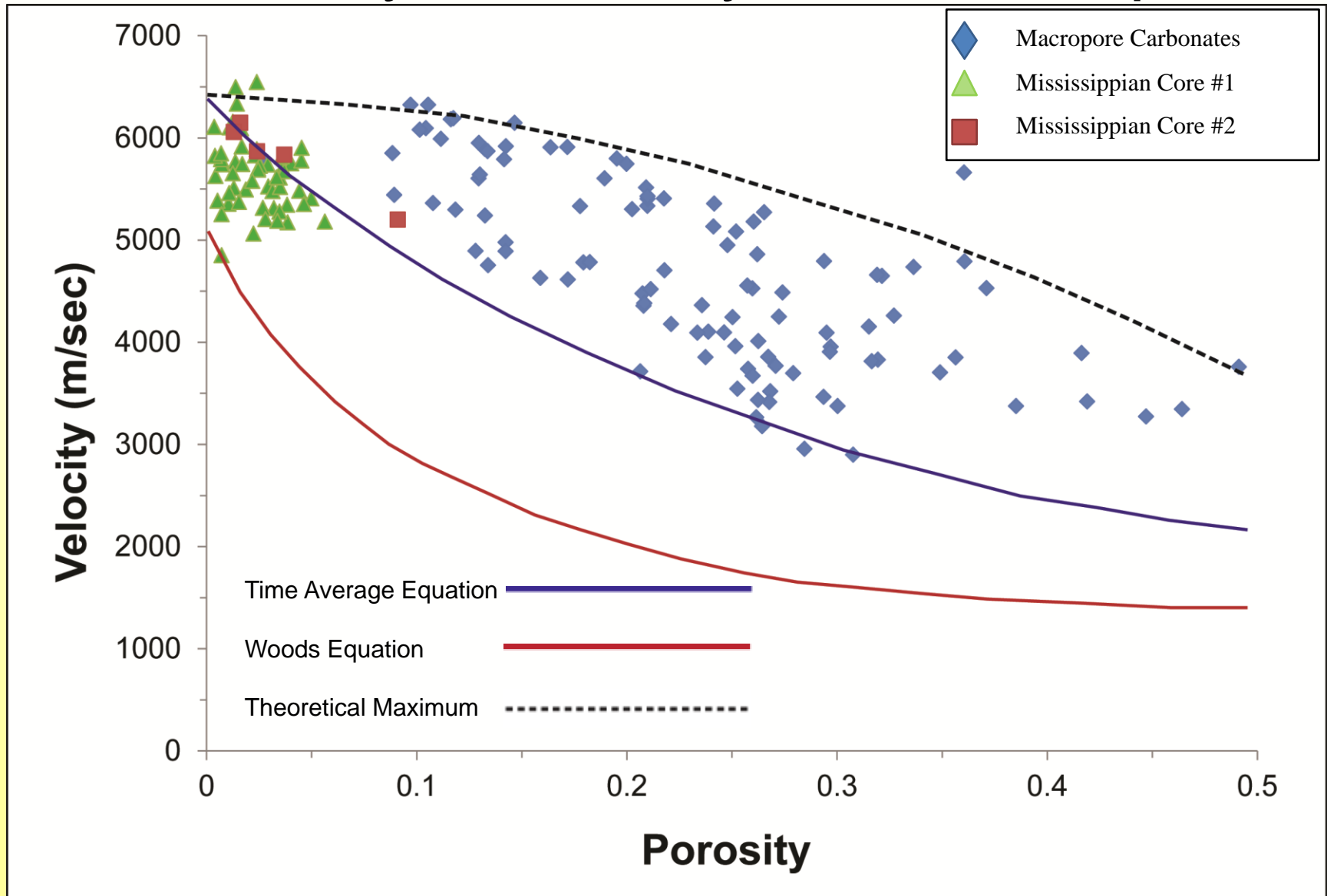
Velocity – Porosity Relationship Classified by Primary Pore Type

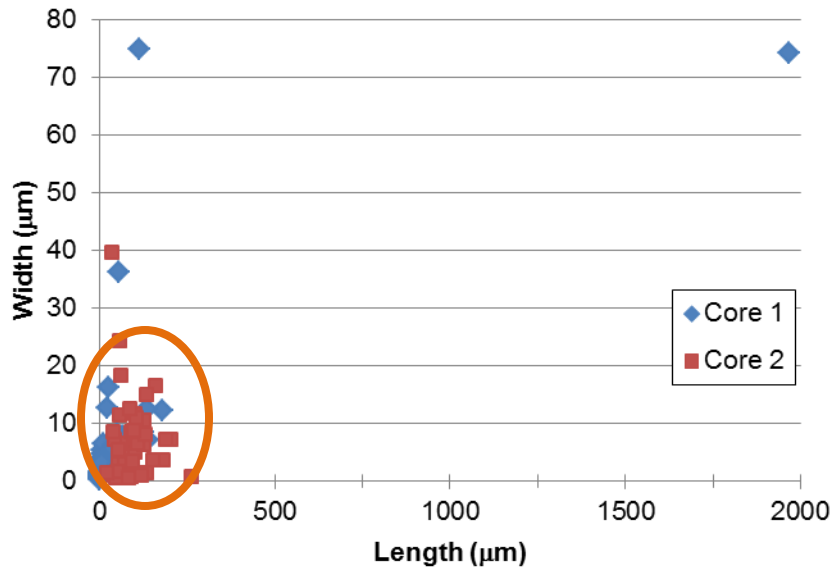# Macropore vs. Nanopore
Velocity – Porosity Relationship

Macropore vs. Nanopore
Velocity – Porosity Relationship
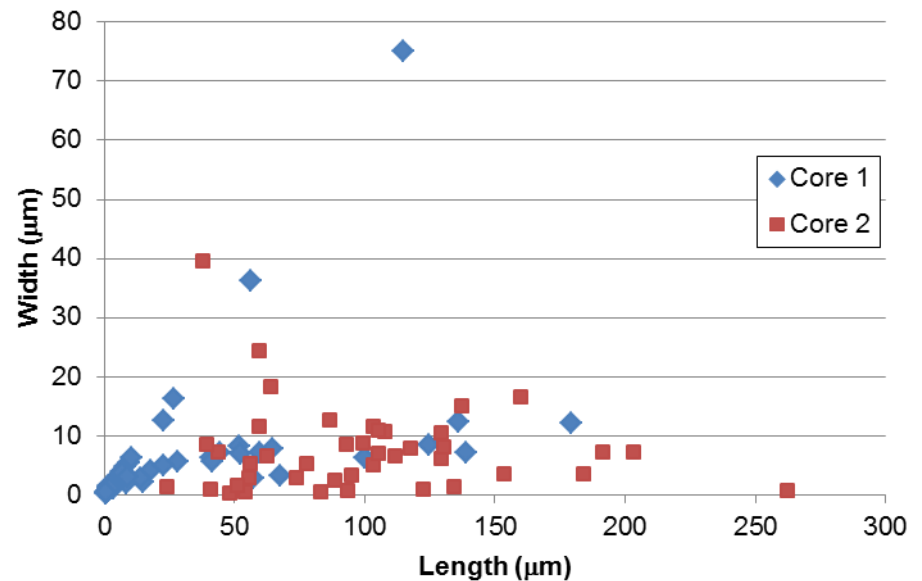
Digital Image Analysis: Pore Size
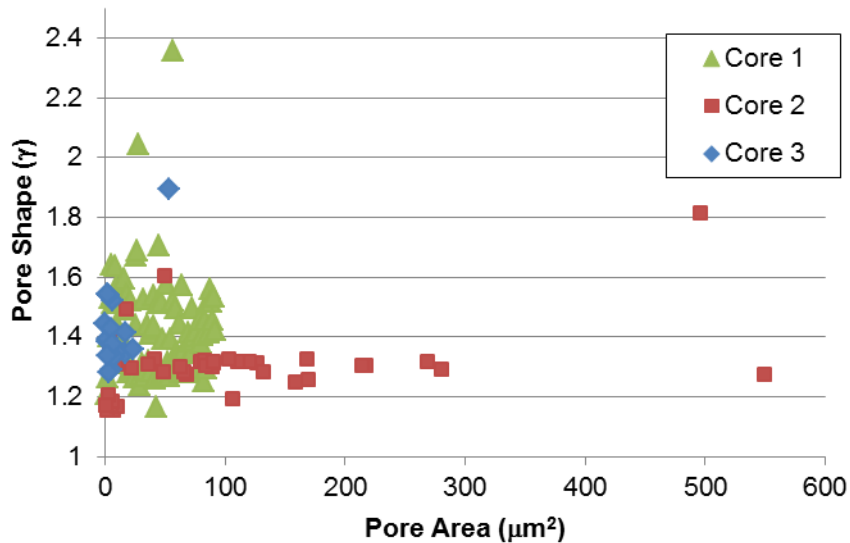

Pore Size

Pore Length/Width:
- Most Pores are <200µm x 20µm
- Class size: Mesopore to Nanopore
  - Most: Micro- to Nanopore

Average Pore Size

Digital Image Analysis:
Pore Shape and Pore-Size Distribution

Average Pore Shape (γ)

Legend:
- Core 1
- Core 2
- Core 3

Y-axis: Pore Shape (γ)
X-axis: Pore Area (μm²)

Pore Shape (1 = perfect sphere):

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

P = perimeter
A = Area

Eqn. from (Anselmetti et al. 1998)

Geometry: Oval to oblong
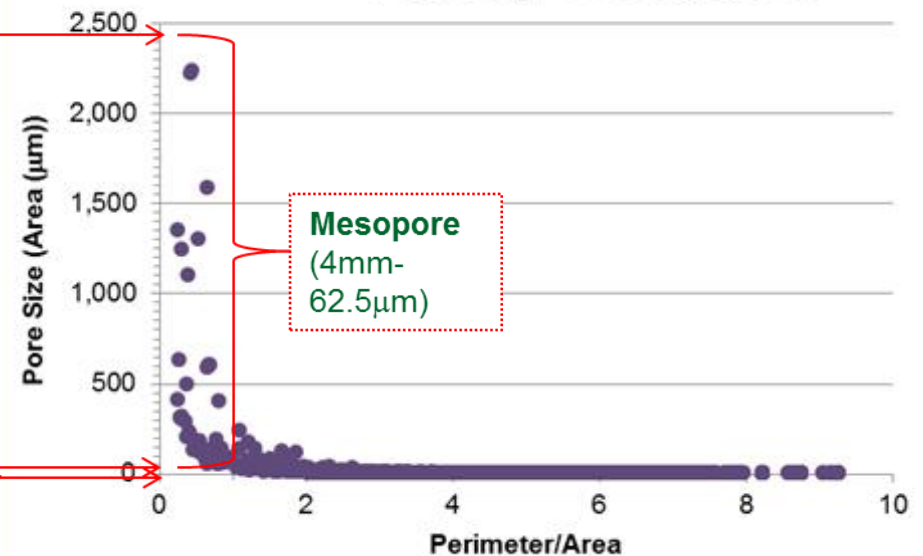
Greater irregularity correlates with greater connectivity (permeability) in macropore systems

Macro- and Microporosity Contribution:
10% Macroporosity
90% Meso-, Micro- and Nanoporosity

Macro/Microporosity Contribution

Y-axis: Pore Size (Area (μm))
X-axis: Perimeter/Area

Mesopore (4mm- 62.5μm)

Micropore (62.5μm - 1μm)

Digital Image Analysis:
# Accuracy of Porosity Prediction
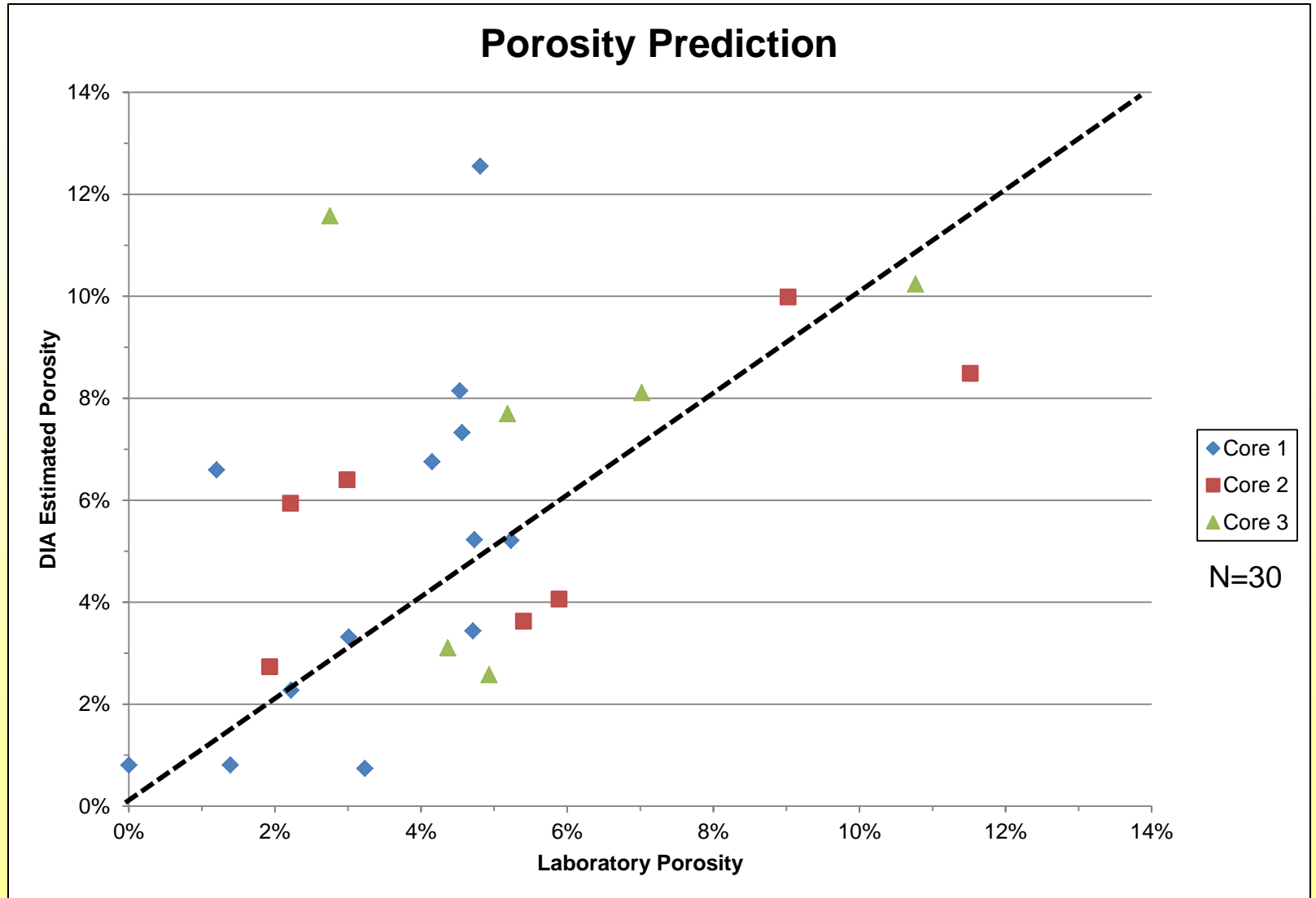
Preliminary Conclusions

- Pores in carbonate mudrocks are meso- to nanoscale size but primarily micro- to nanoscale size.

- Sonic velocity response has a predictable relationship to porosity in carbonate mudrocks, with a relationship similar to what is observed in carbonates with predominantly macropore systems.

- Current data indicates carbonate mudrock sonic velocity response is less than the velocity predicted by the time average equation.

- Based on porosity prediction from DIA, permeability prediction is possible with multivariate statistics.
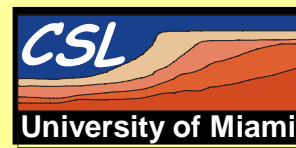
Continued Research

- Additional sonic velocity response from core and outcrop samples.
- Argon milling coupled with SEM and digital image analysis to characterize the pore architecture.
- High resolution CT-scans to view the pore architecture in 3-D.
- Correlate porosity, permeability and acoustic response to high-resolution sequence stratigraphic analysis of core and outcrops in Northern Oklahoma, Southern Kansas, Arkansas and Missouri.
- Create a static 3-D model to test the predictability of petrophysical properties in carbonate mudrocks.
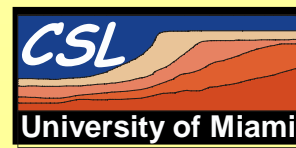
Acknowledgement

Oklahoma State University Consortium to Evaluate the Reservoir Characteristics of the Mid-Continent Mississippian Limestone

Questions?

50μm