Prediction of Petrophysical Properties of Trenton-Black River (Ordovician) Reservoirs by Comparing Pore Architecture and Permeability to Sonic Velocity*

John E. Thornton[1,2] and G. Michael Grammer[1]

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Editor's note: Please view a companion article by these authors, entitled "Enhanced Reservoir Characterization and Permeability Prediction of Heterogeneous Carbonate Reservoirs from Sonic Velocity and Digital Image Analysis," Search and Discovery Article #50689 (2012).

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Abstract

Reservoir characterization of carbonate rocks is complicated by heterogeneous pore architecture related to primary depositional facies and subsequent diagenesis; this is especially true in diagenetically-altered and structurally-influenced Trenton-Black River reservoirs of the Michigan Basin. Accurate and reliable prediction of reservoir properties within hydrothermal dolomite (HTD) reservoirs through the use of acoustic properties would significantly aid exploration and reservoir characterization efforts in HTD reservoirs both within and outside of the Michigan Basin.

Results indicate that digital image analysis of thin sections and laboratory measures of sonic velocity both quantify pore architecture of carbonate rocks. Integration of measures of pore architecture and physical properties into multiple variable linear regression can accurately predict permeability of core plugs. Additionally, use of minipermeametry and comparison of core plug and whole core measures of porosity and permeability indicate that Trenton-Black River textures are petrophysically heterogeneous from the millimeter to meter scale. This is due to the influence of bioturbation on primary depositional textures and their subsequent diagenetic pathways as well as facies stacking patterns within a 1-D sequence stratigraphic framework.

Integrating modern borehole measures of physical properties and measures of pore architecture derived from cuttings data may increase the predictability of permeability within hydrothermal dolomite reservoirs over log data alone. Care must be taken when upscaling petrophysical measurements from core plugs to reservoir flow units in highly heterogeneous carbonate reservoirs.

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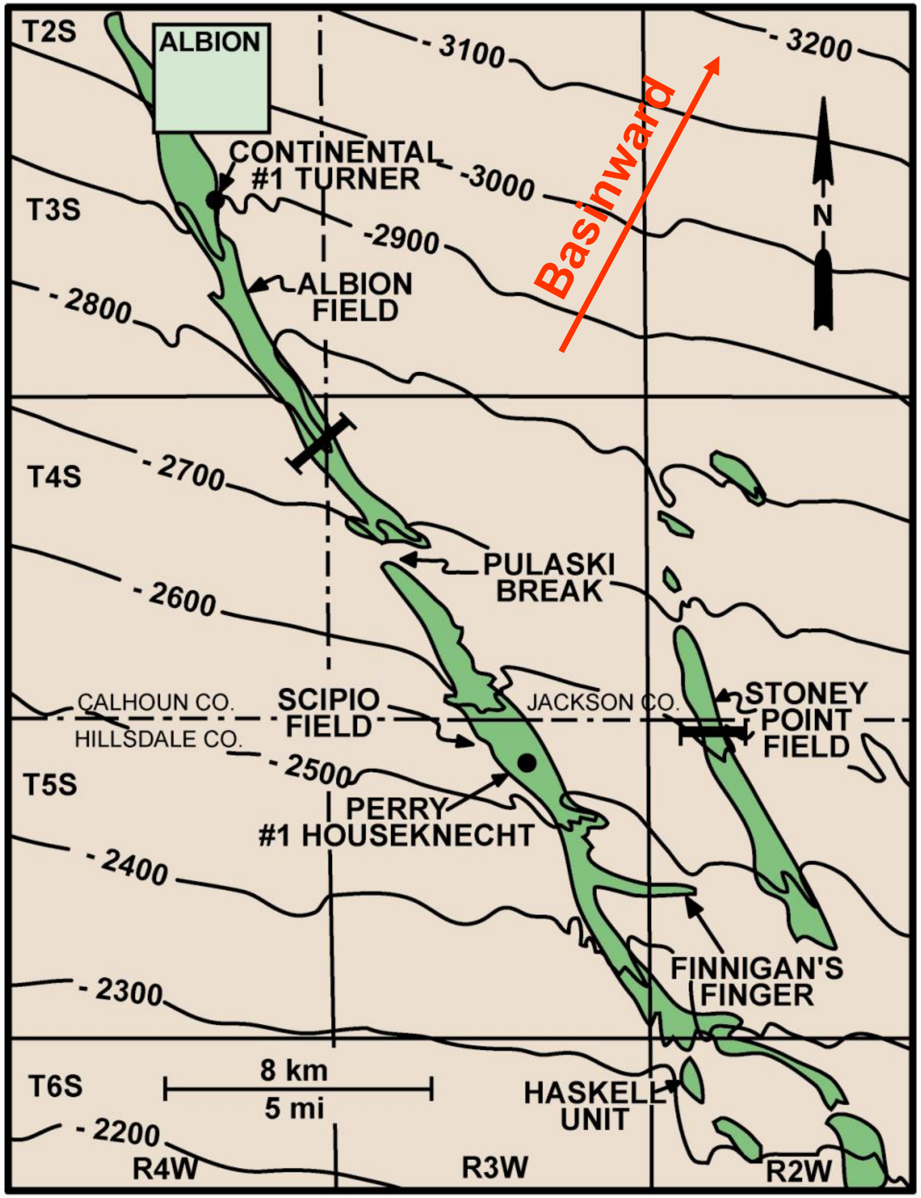
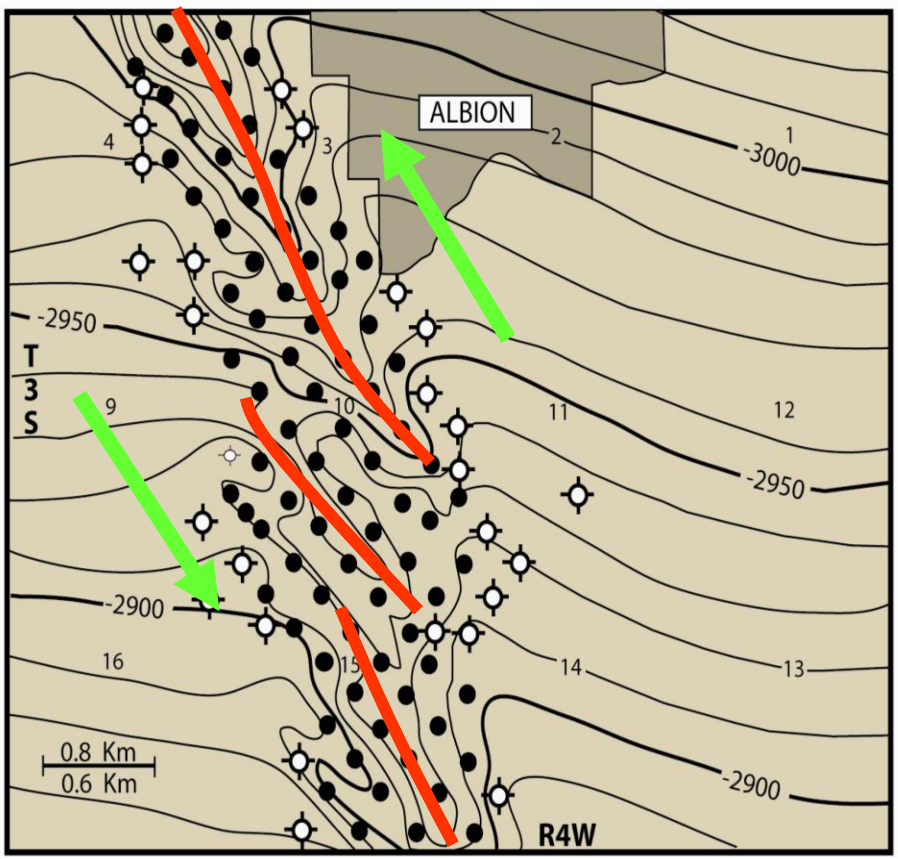
Albion-Scipio and Stoney Point

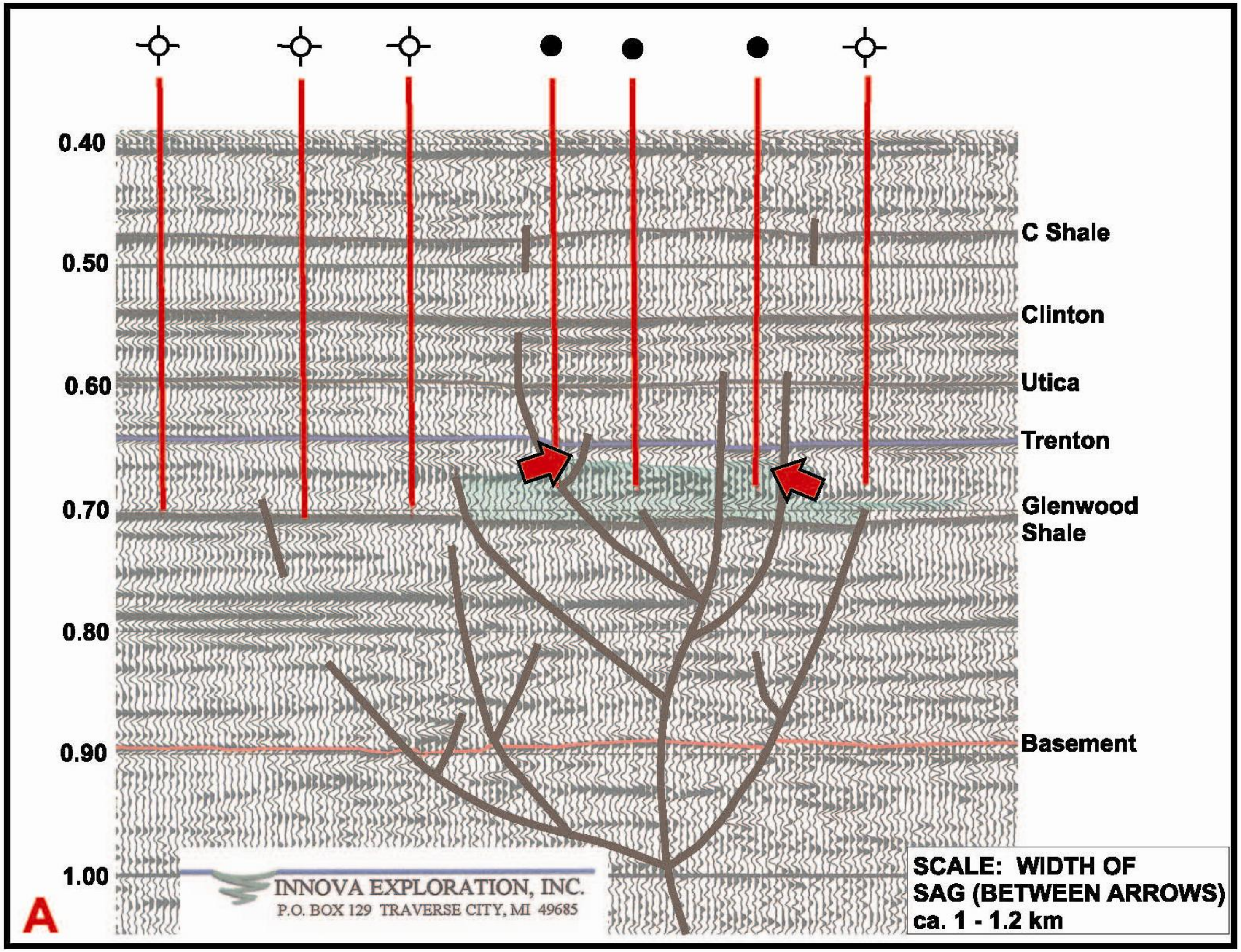
**Linear trend with history of close step-out dry holes



Modified from Hurley and Budros, 1990

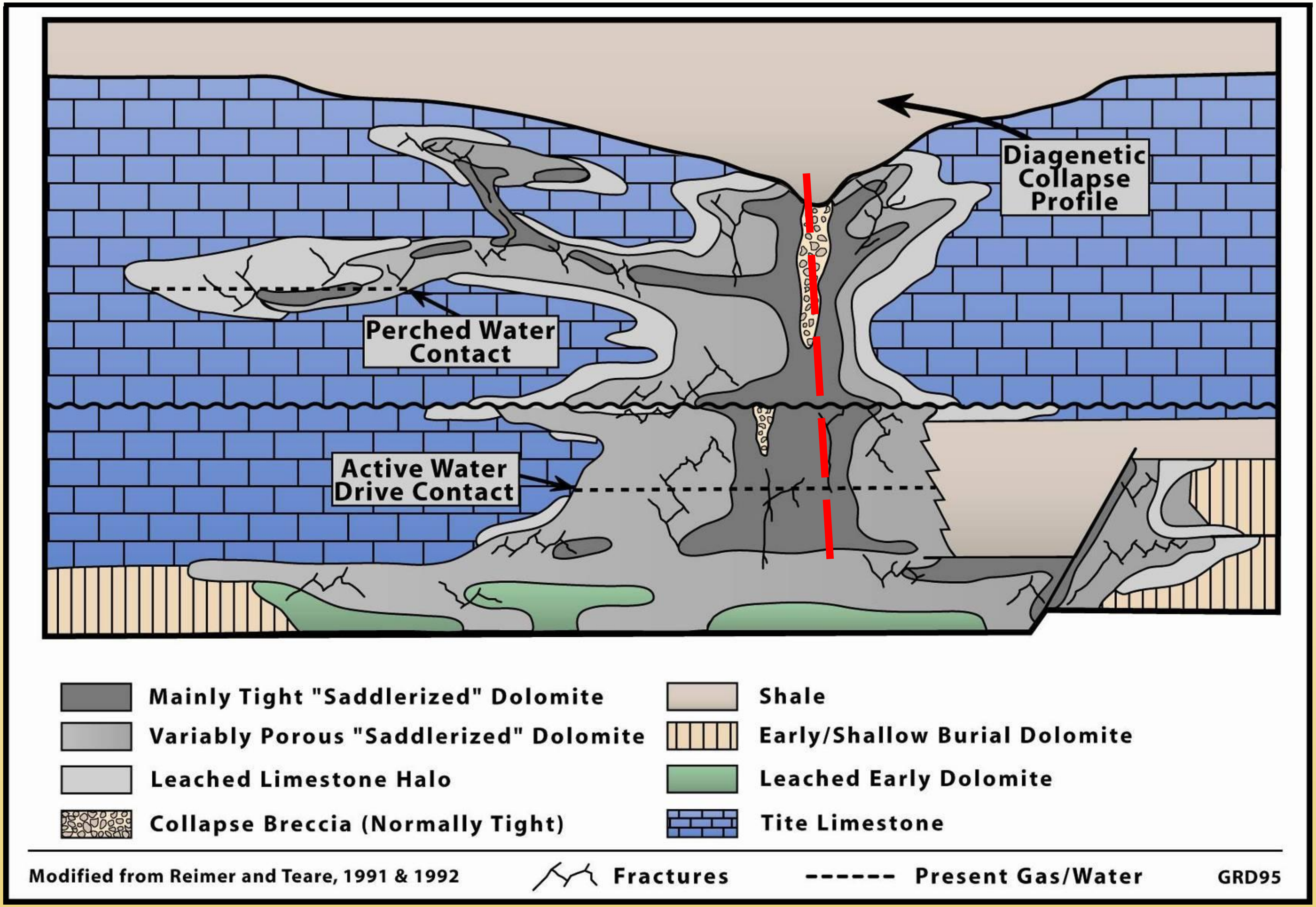


Seismic “sag” and negative flower structures (Ord., Michigan)



Davies and Smith, 2006

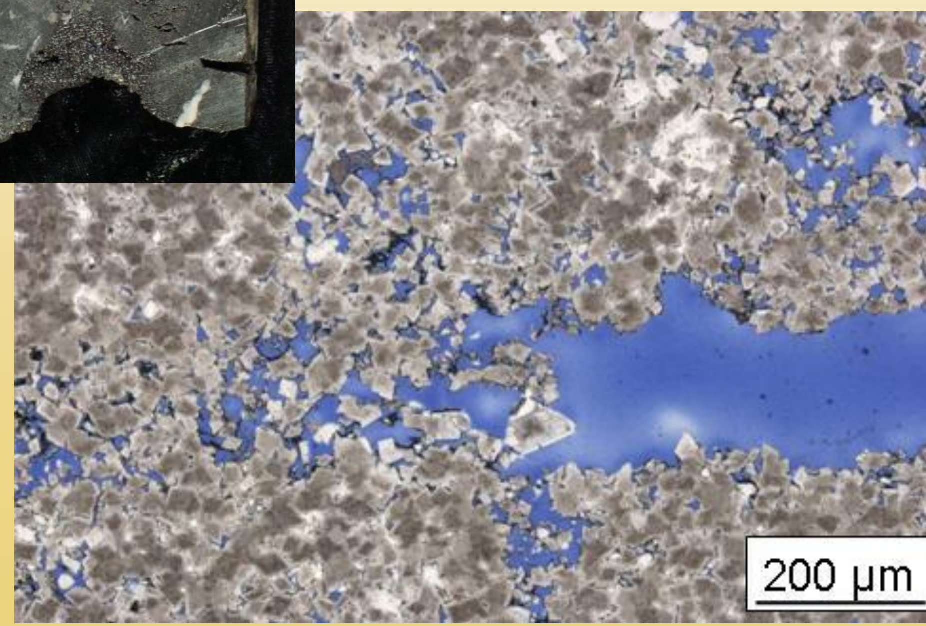
Stratigraphic control on lateral variability in HTD reservoirs (Slave point field, Western Canada, Devonian)



Modified from Davies (2000) after Reimer and Teare (1991, 1992)

HTD Reservoirs

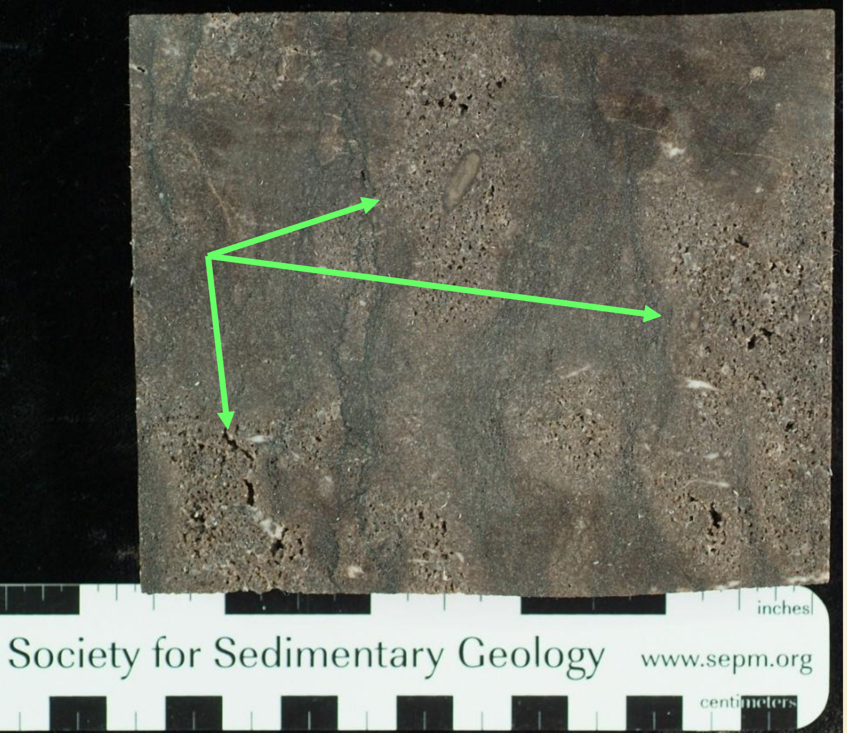
Albion-Scipio and Stoney Point

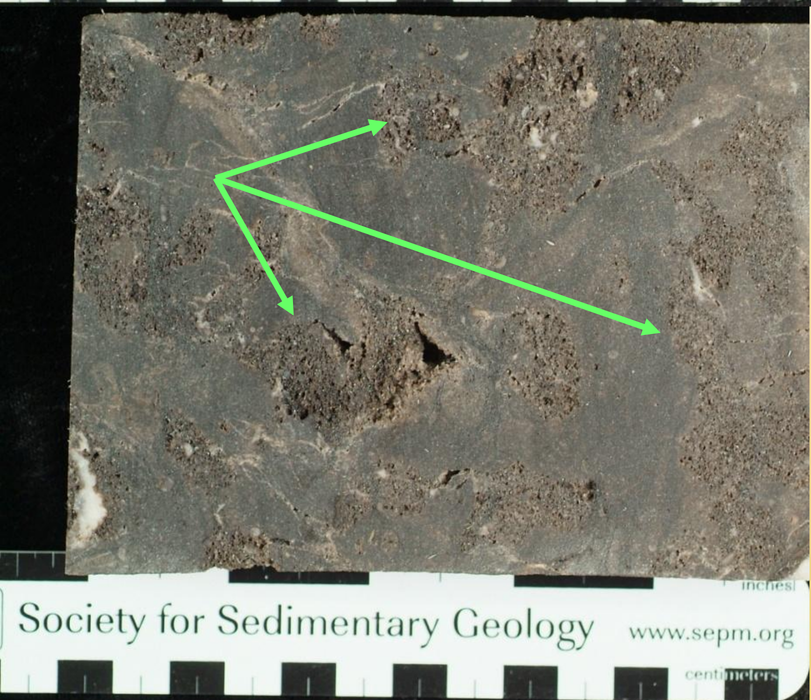


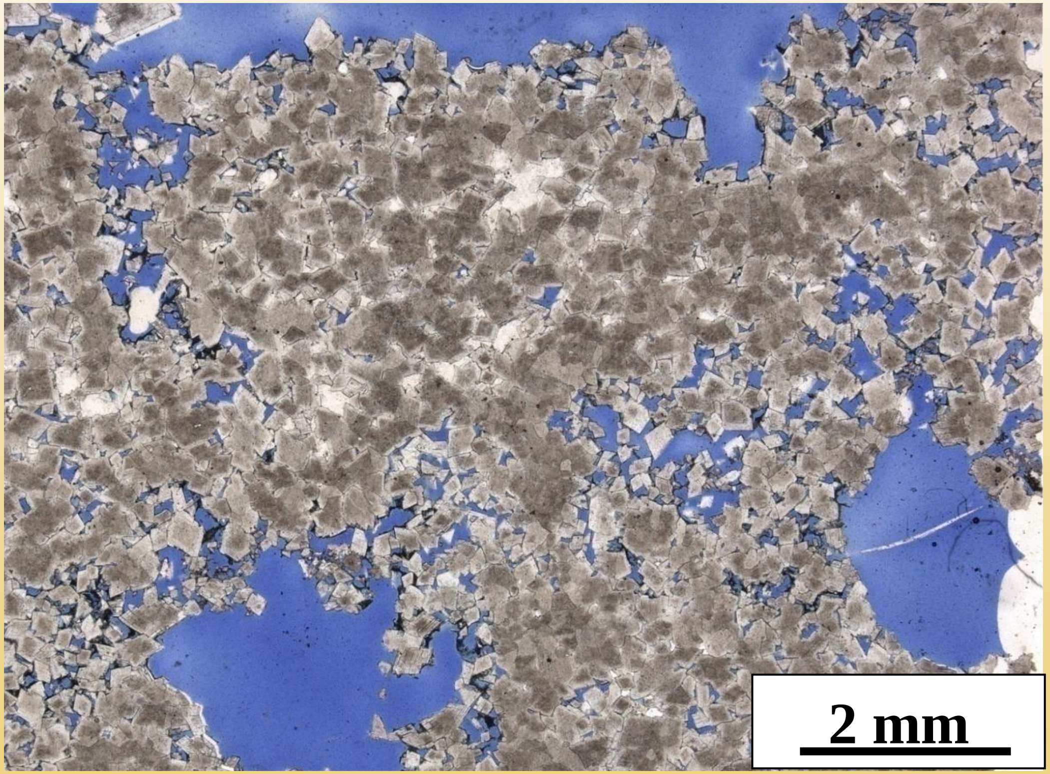
Primary facies control on distribution of HTD in matrix and formation of reservoir facies

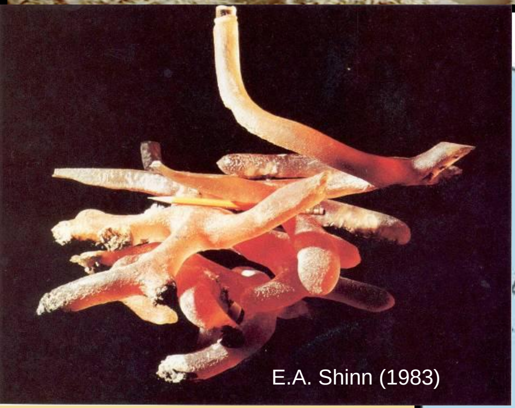
1. Primary facies controls original pore system architecture
2. Primary facies and stratigraphic architecture control early diagenetic modification which can enhance or limit subsequent porosity development
3. Facies/Depositional Environment provides insight into expected 3-D geometry and continuity of reservoir in subsurface

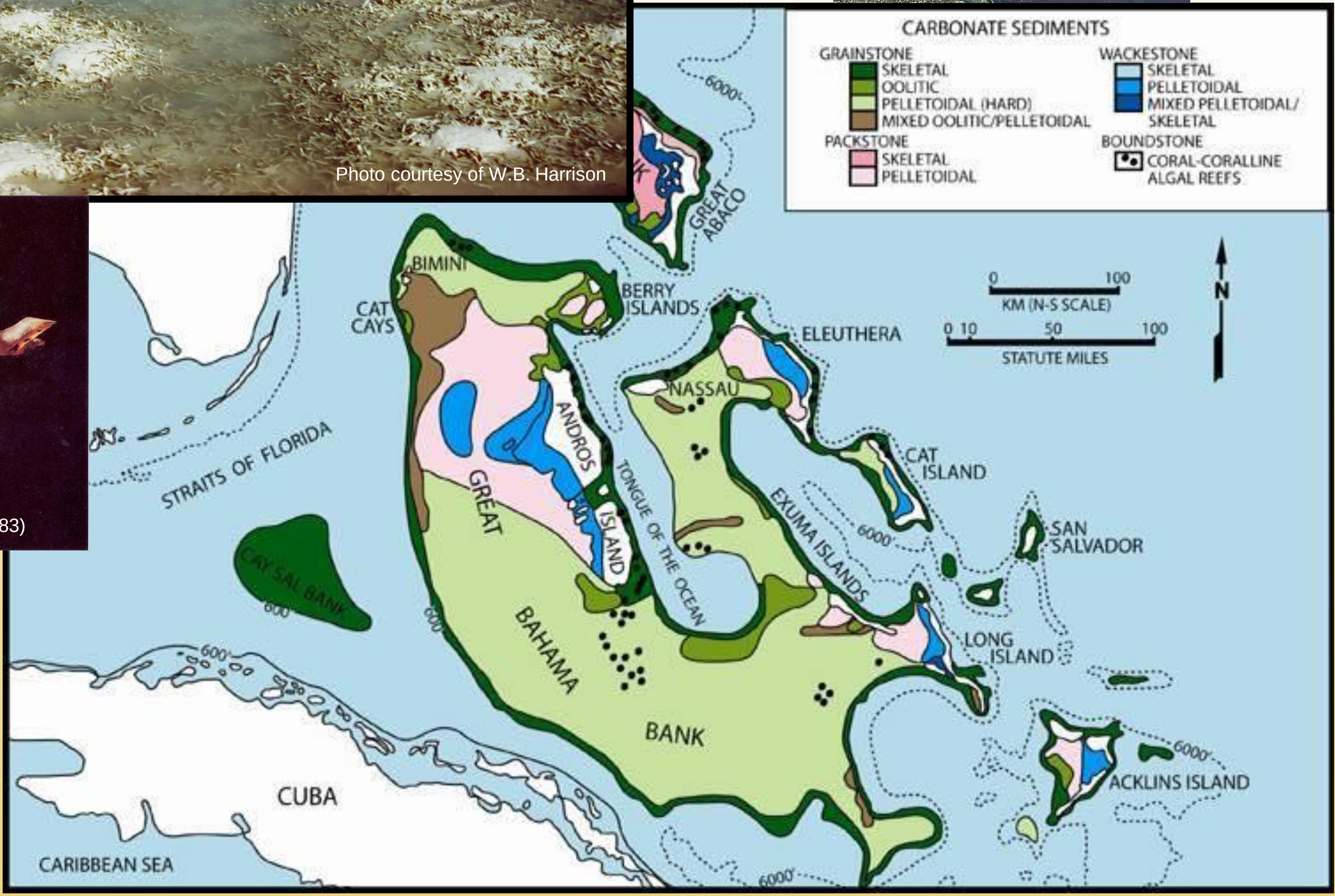
Primary facies control on distribution of HTD in matrix and formation of T/BR reservoir facies (Ordovician, Michigan) 6-10% and 50-100mD





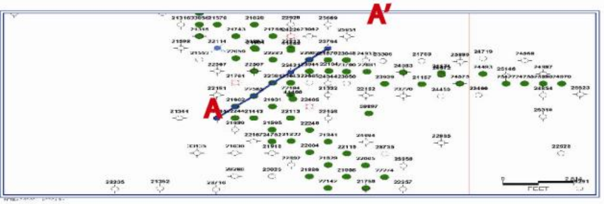


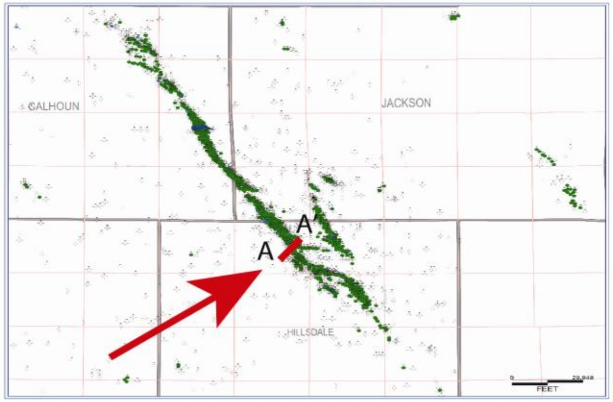


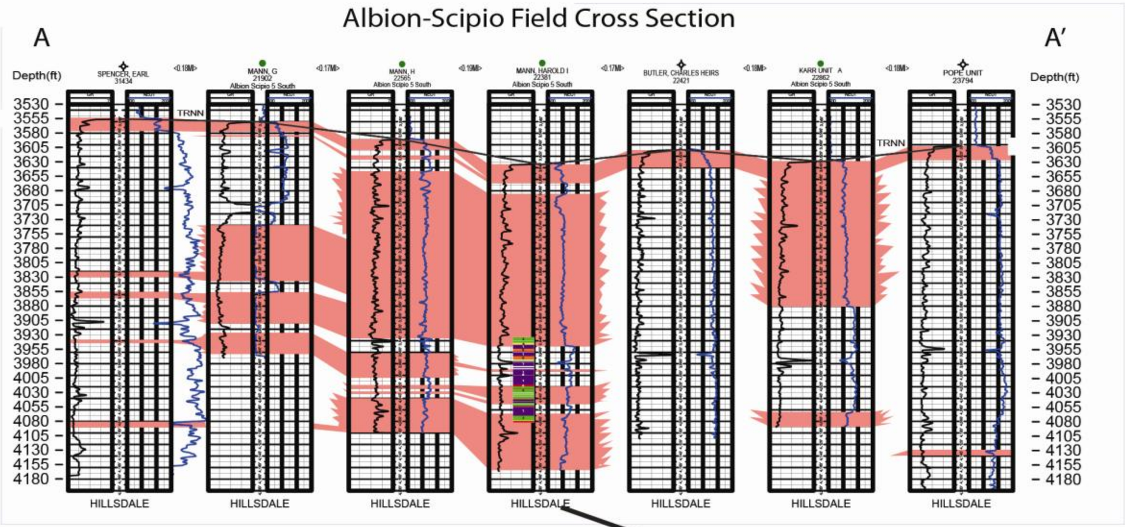


Enos and Perkins, 1976

Facies and Stratigraphic Control on Reservoir Stacking and Lateral Variability







Facies

1 Outer Ramp or Lagoon Facies
-Burrow-mottled mudstone to wackestone

2 Mid-ramp Facies
-Bryozoan wackestone to packstone

3 Mid-ramp Facies
-Burrow-mottled wackestone to packstone

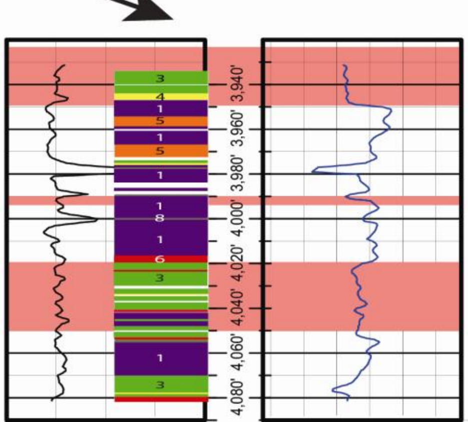
4 Ramp Crest Facies
-Skeletal grainstone

5 Lagoon Facies
-Peloidal packstone

6 Tidal Flat Facies
-Fine grained, oxidized mudstone with fenestral pores

7 Debris Flow Facies
-Intraclastic floatstone

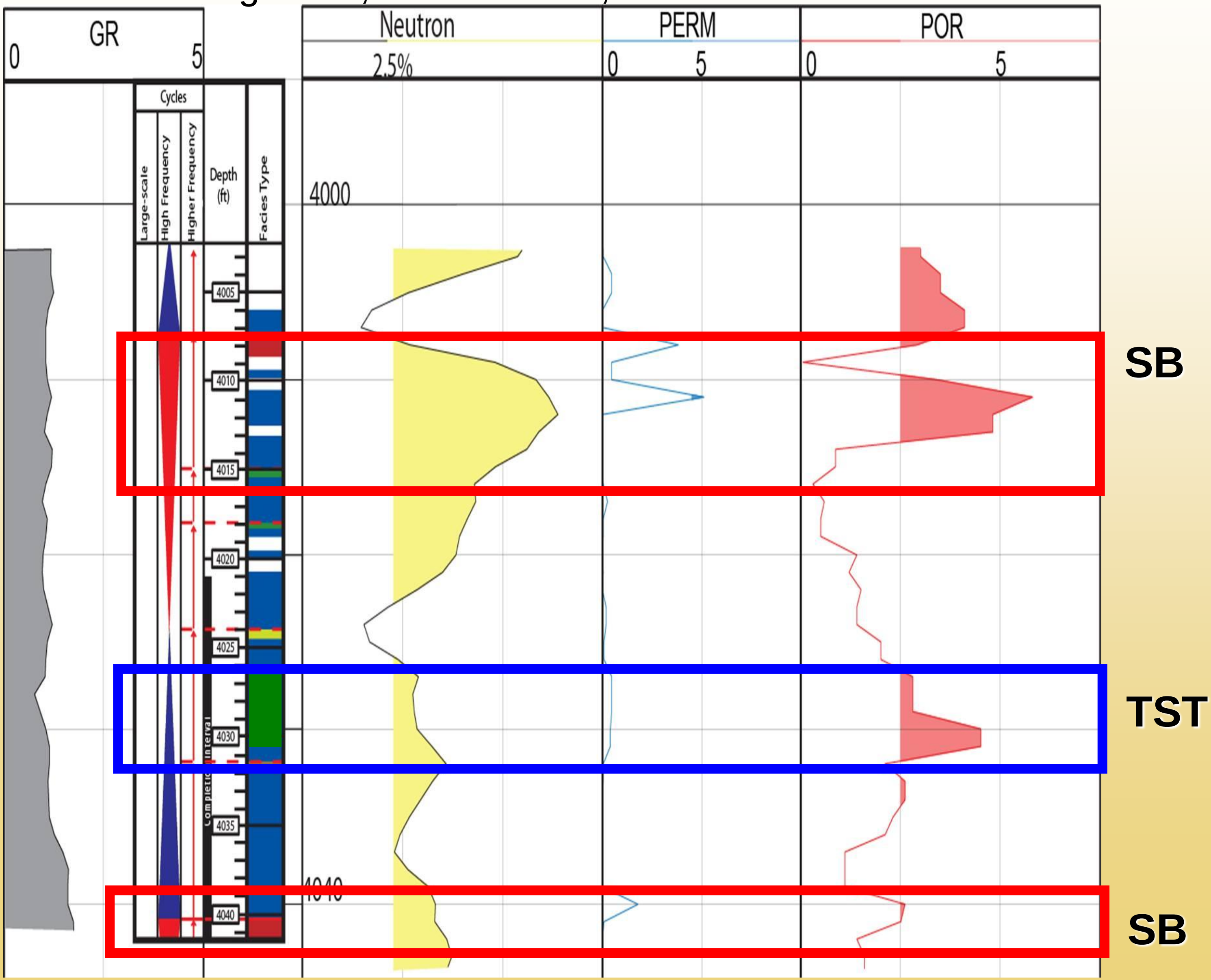
8 Shale and Volcanic Ash Facies



Feutz (2011)

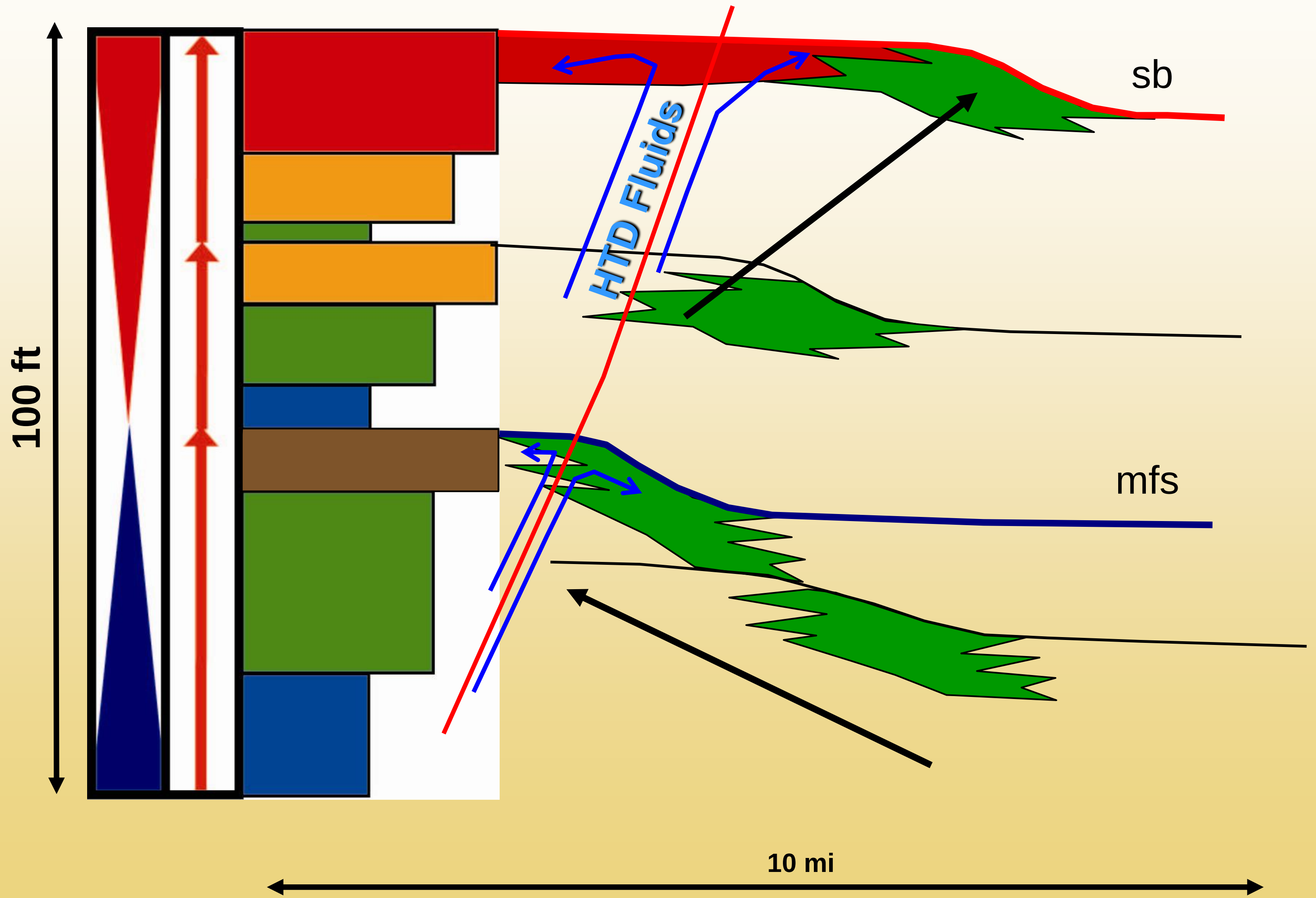
Stratigraphic Control on Reservoir Distribution

Hergert #2, Hillsdale Co., Permit #22196



Schulz (2010)

Facies and Sequence Stratigraphic Control on Reservoir Distribution



Schulz (2010)

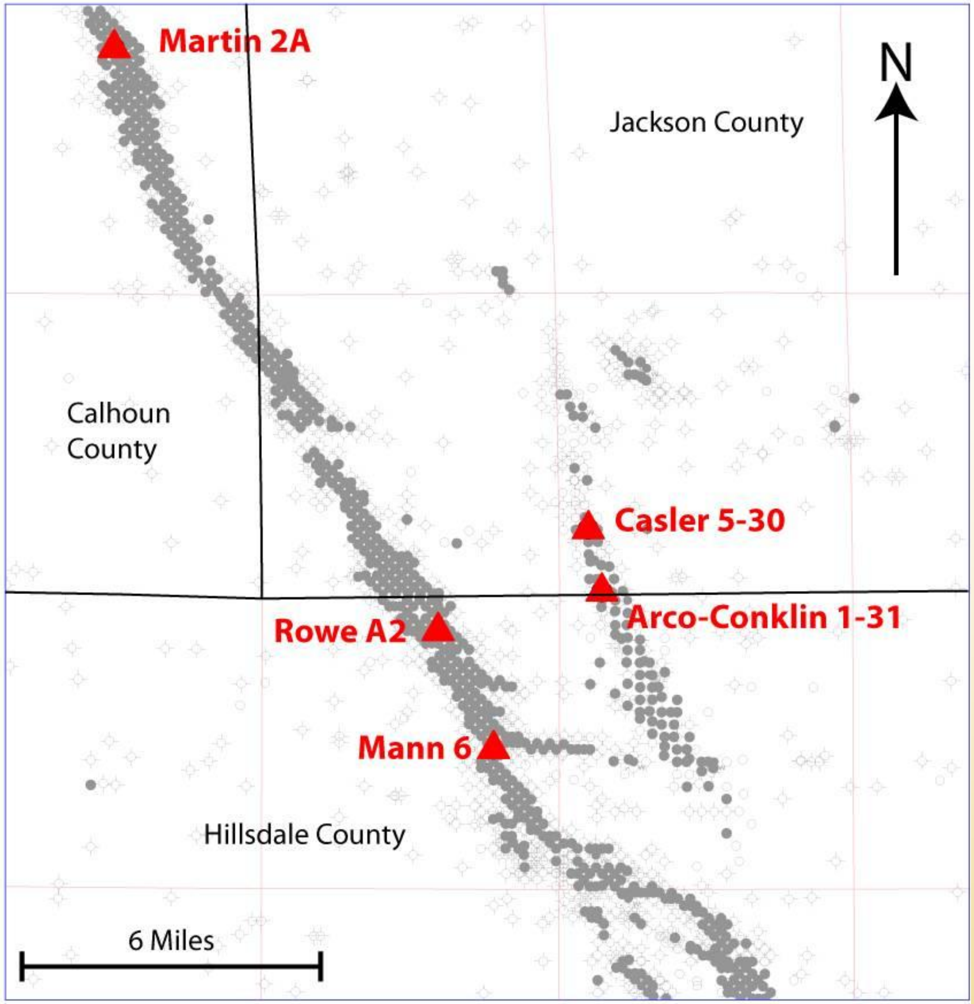
Goals of Current Study

1. Increase predictability of reservoir away from faults and fractures
2. Understand scale dependence of petrophysical measurements
3. Test previously established correlation between pore architecture/permeability and Vs in Paleozoic rocks
4. Test the viability of predicting permeability from pore architecture
5. Test the tie between sonic velocity and permeability

Methods and Materials

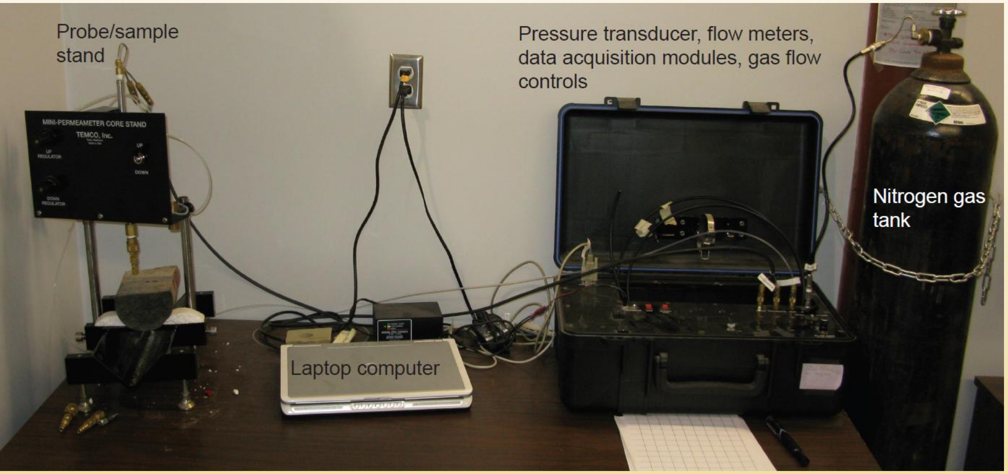
- Definition of petrophysical facies
- Digital image analysis of thin sections
- Laboratory sonic velocity
- Minipermeametry
- Comparison of porosity and permeability measurements
- Multiple variable linear regression

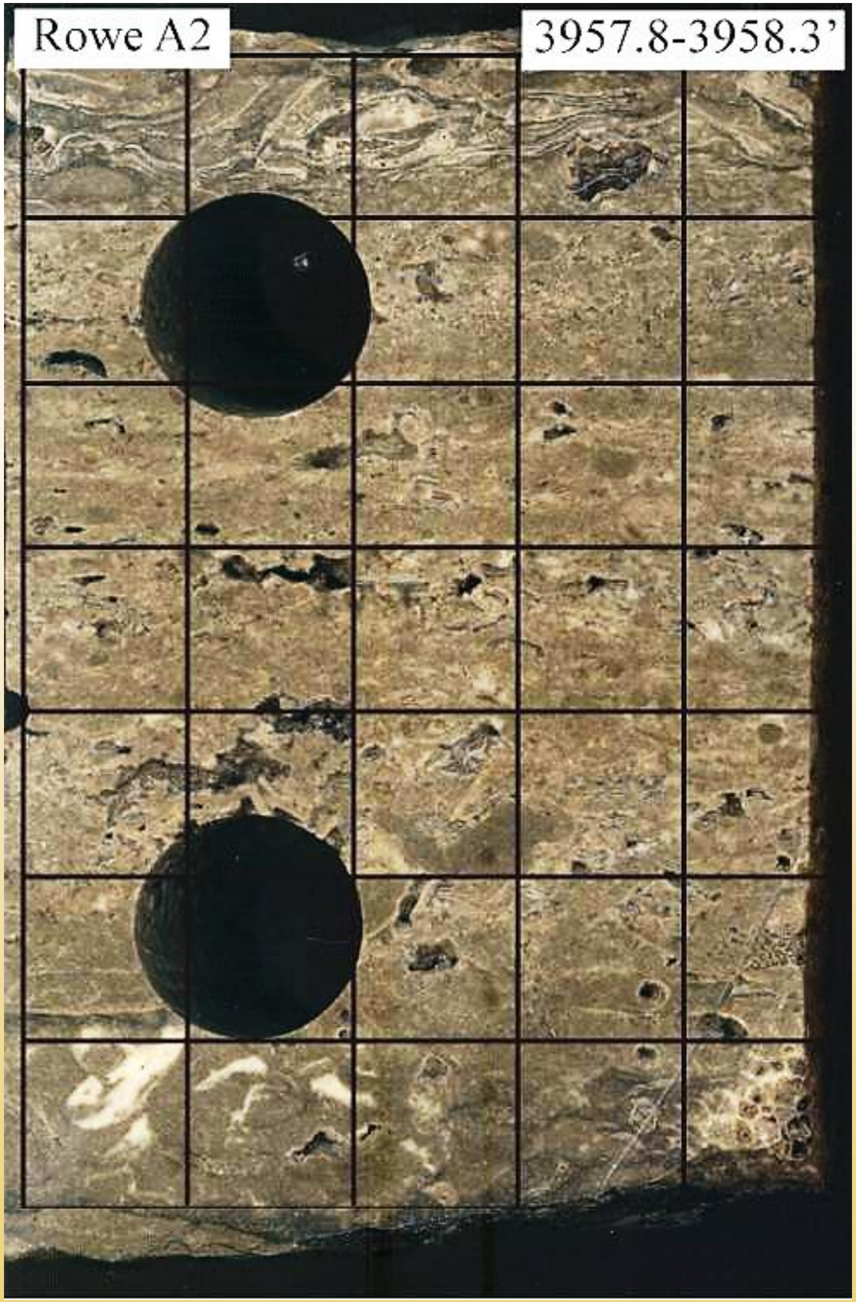
- 5 cores with core analyses and wireline logs
- 61 core plugs with porosity and permeability
- 61 thin sections cut from core plugs
- Lab sonic velocity 37/61 core plugs



Permit Number	Well Name	County	Field	Production
22083	Martin #2A	Calhoun	Albion-Scipio	Oil
21381	Rowe #A2	Hillsdale	Albion-Scipio	Oil
22381	Mann #6	Hillsdale	Albion-Scipio	Oil
36587	Casler #5-30	Jackson	Stoney Point	Oil
37385	Arco-Conklin #1-31	Jackson	Stoney Point	Oil

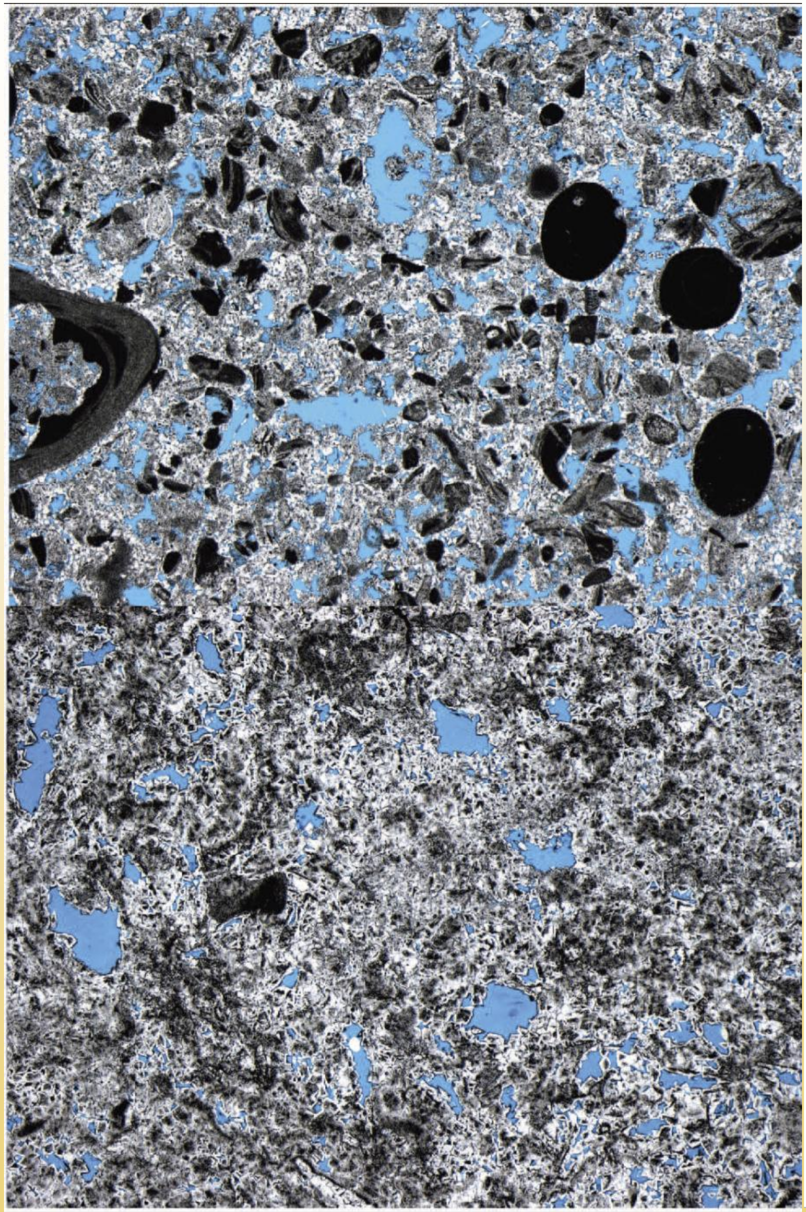
Minipermeameter measurements

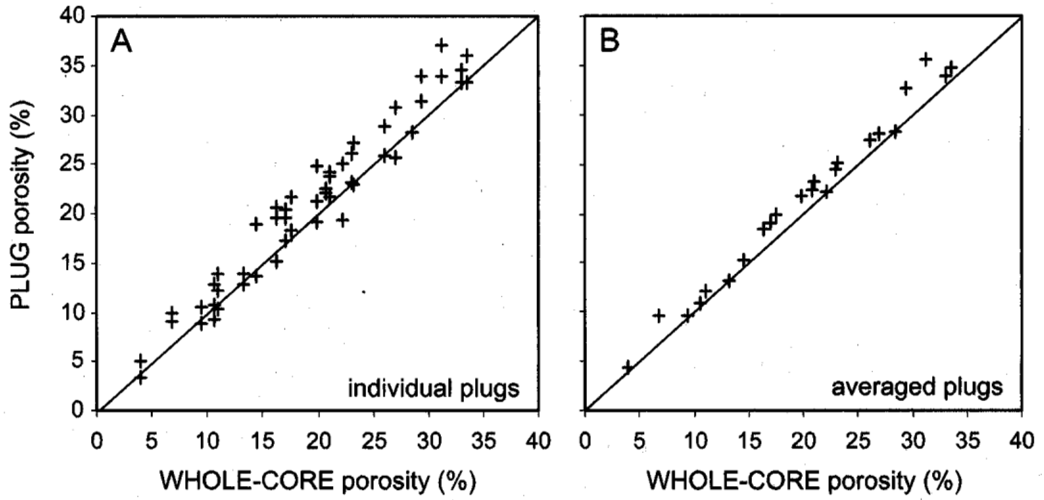


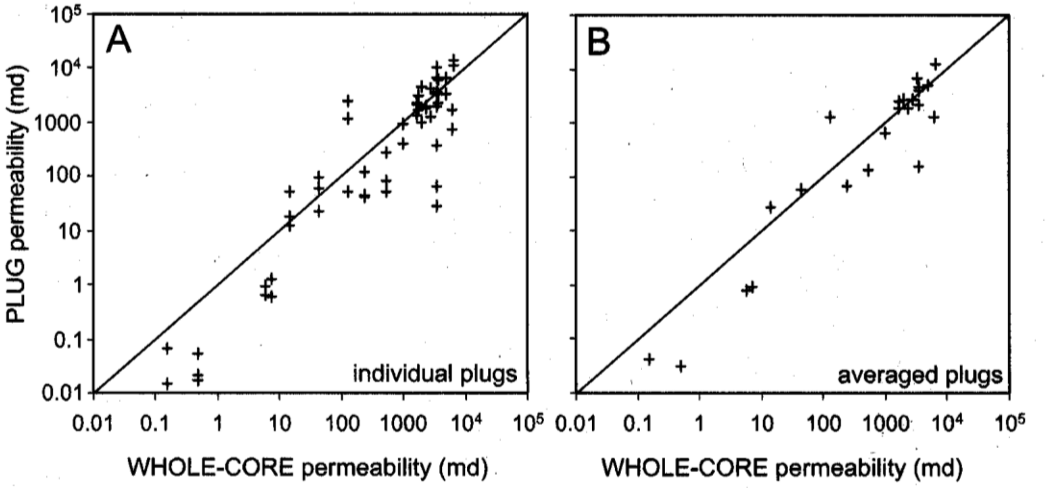


Grid: 2cm x 2cm

Whole Core vs. Plug Porosity and Permeability

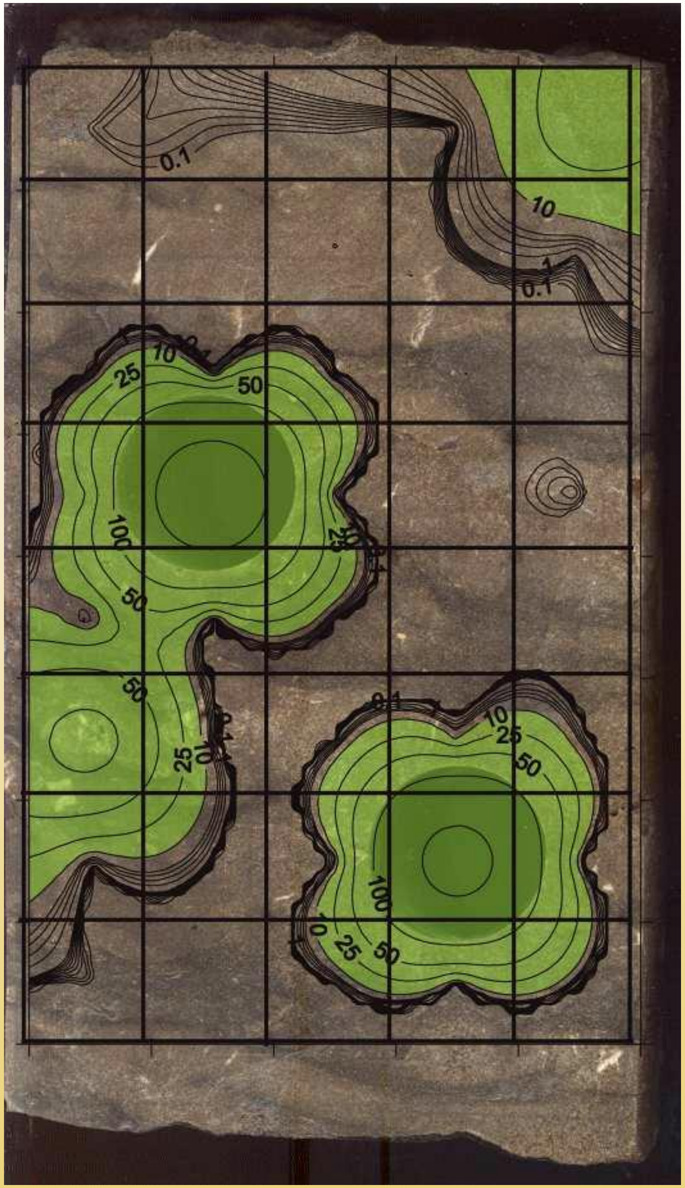




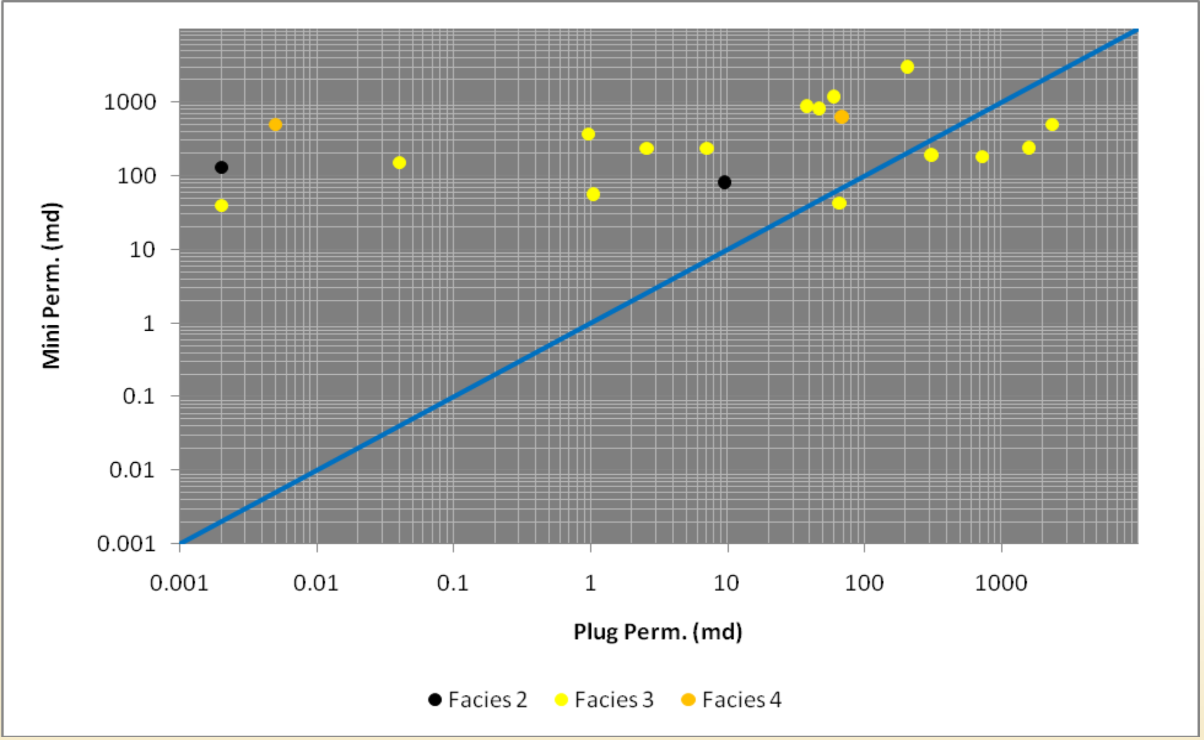


Ehrenberg (2007)

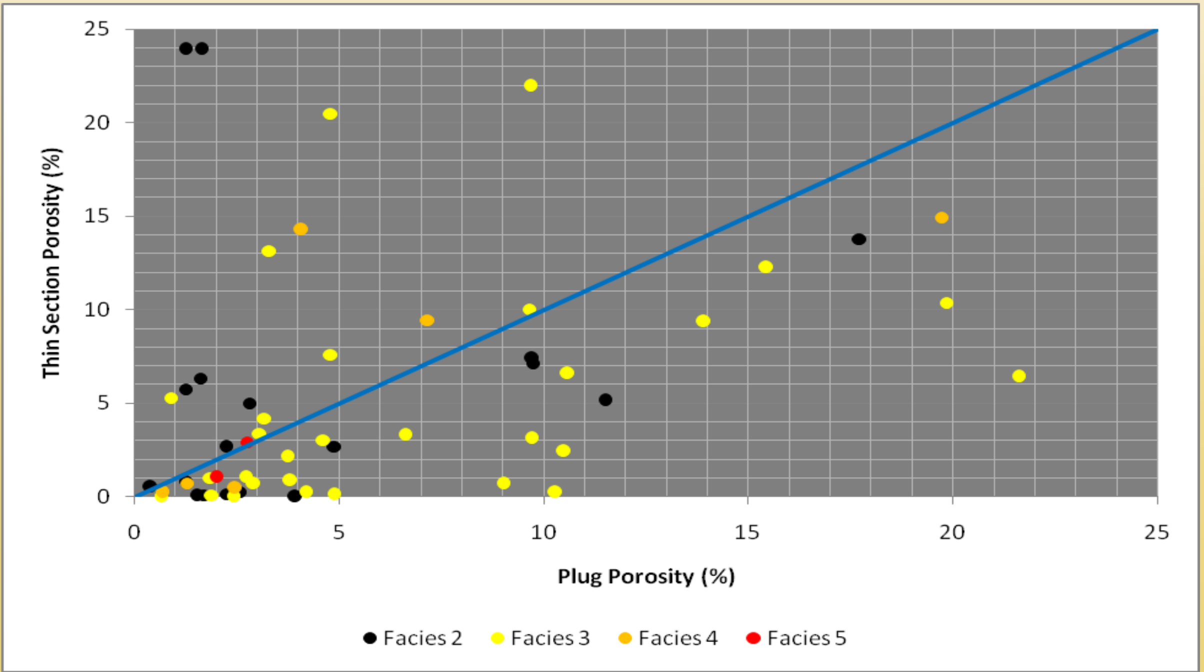
Variations in Reservoir Permeability at the cm-scale
Burrowed Facies



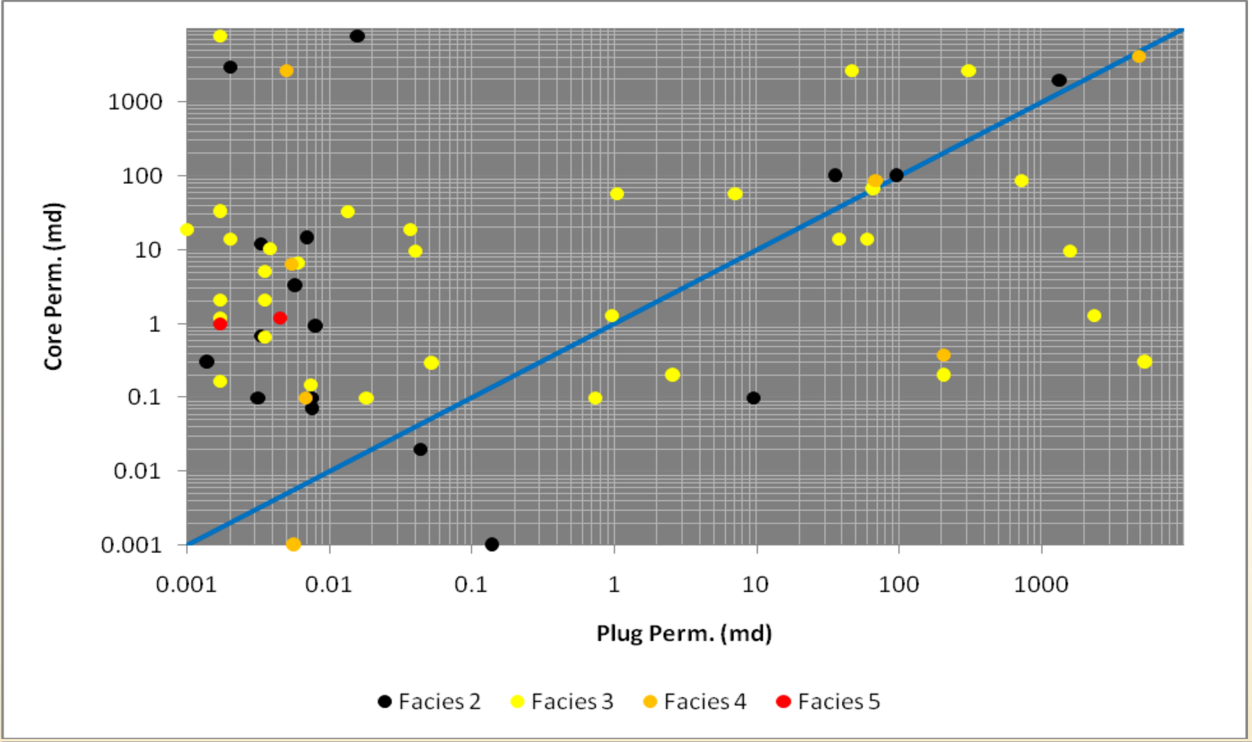
Thornton and Grammer (2010)



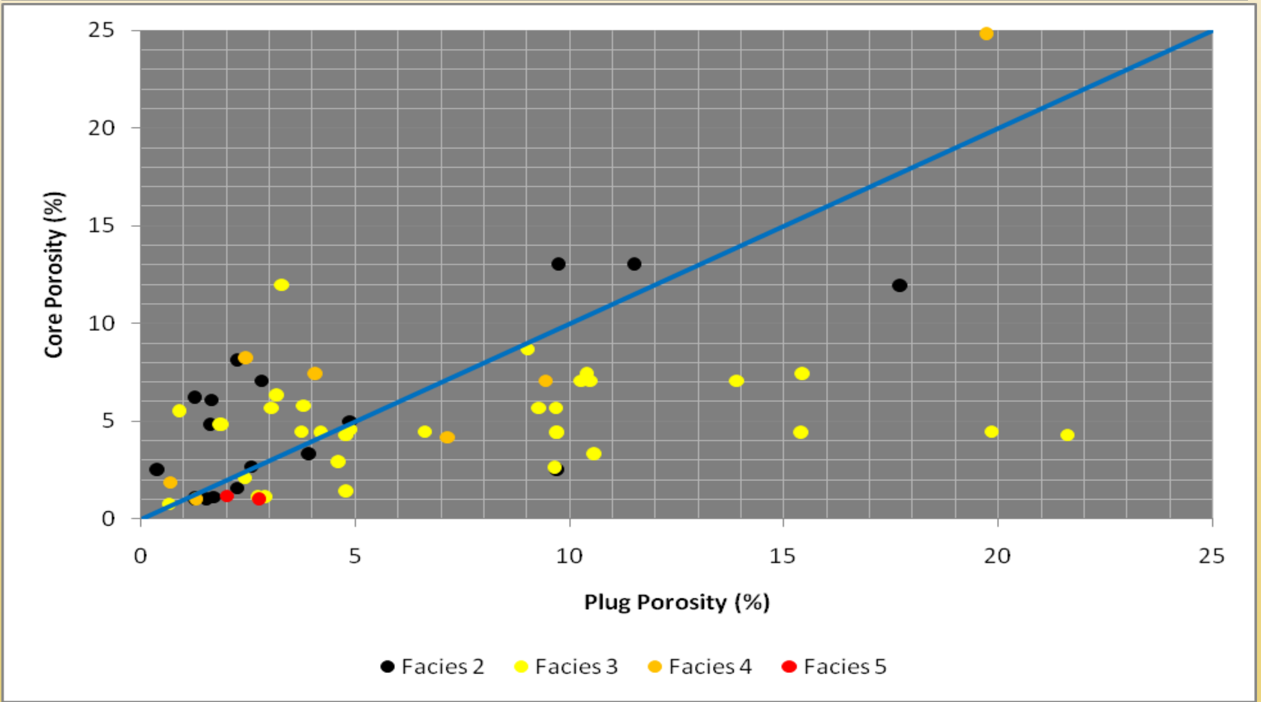
mm-cm scale permeability variation



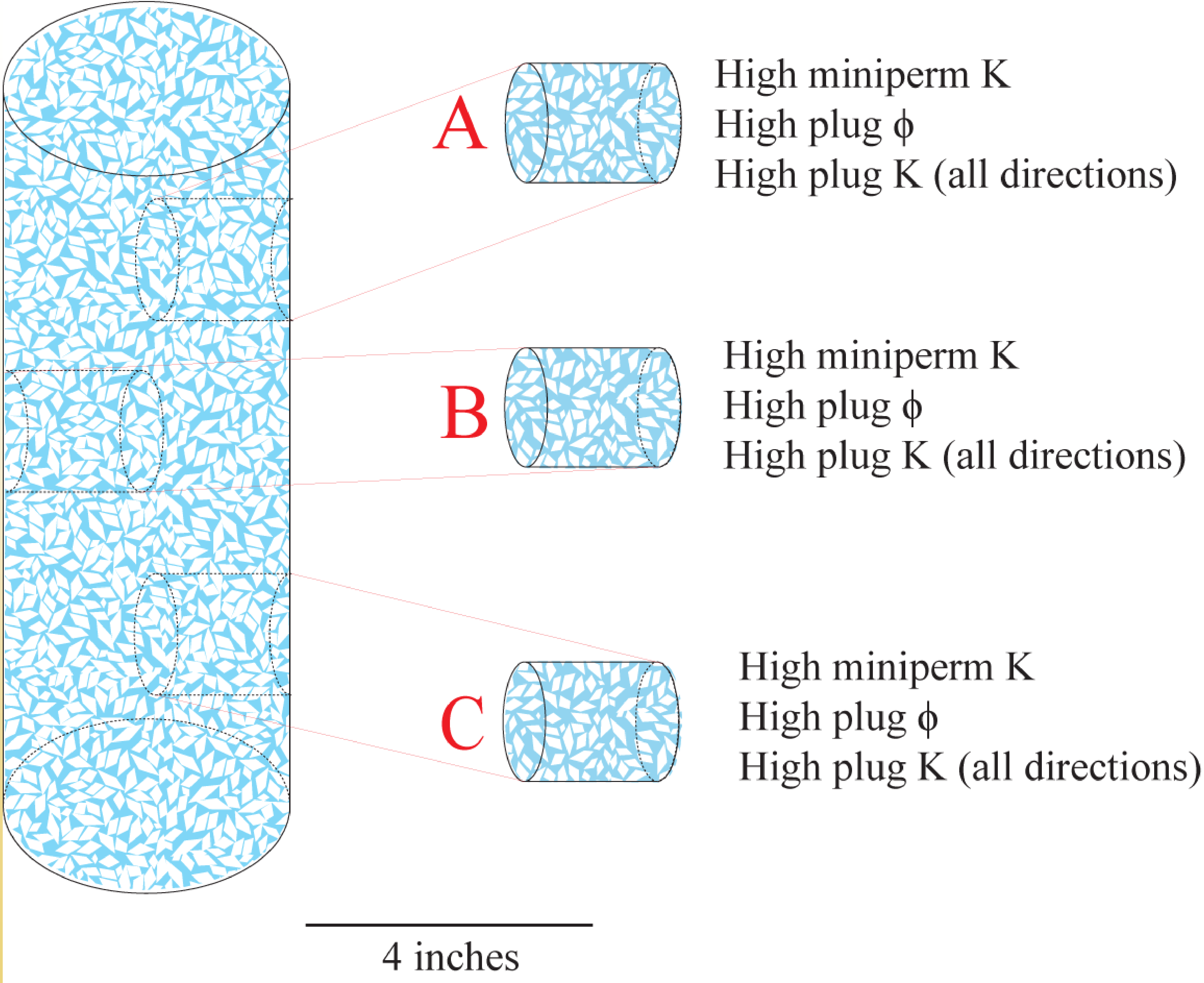
mm-cm scale porosity variation

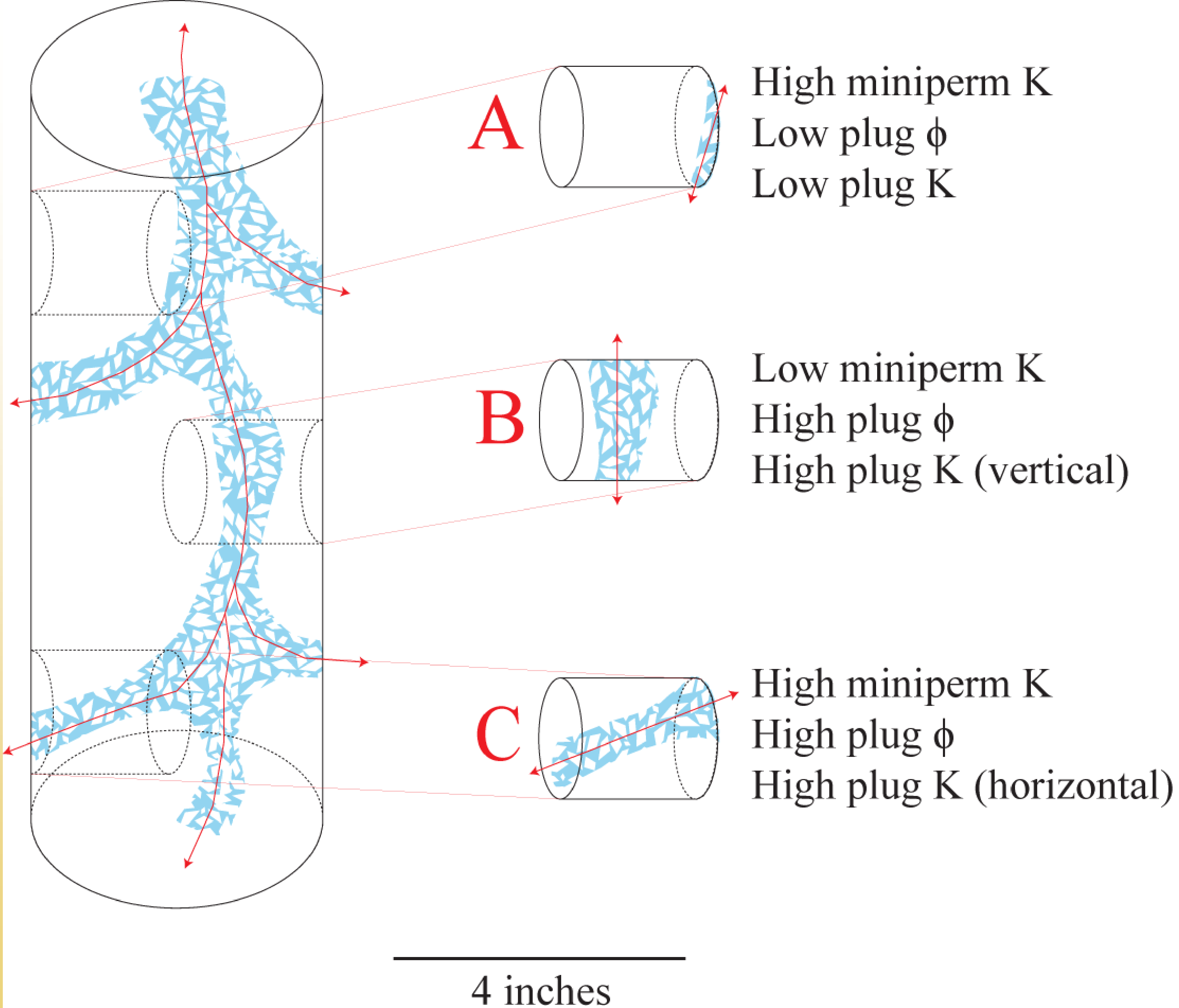


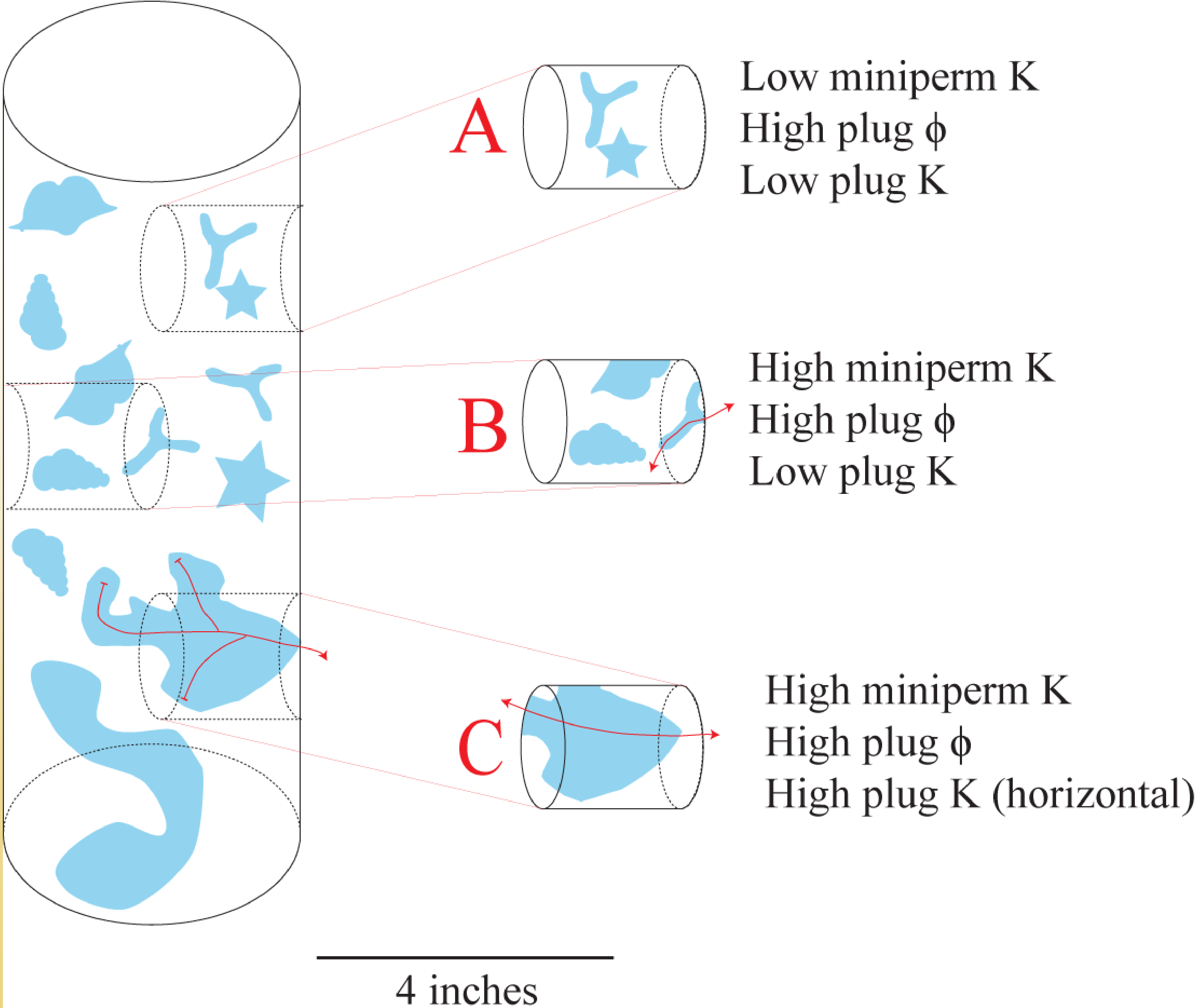
cm-dm scale permeability variation



cm-dm scale porosity variation

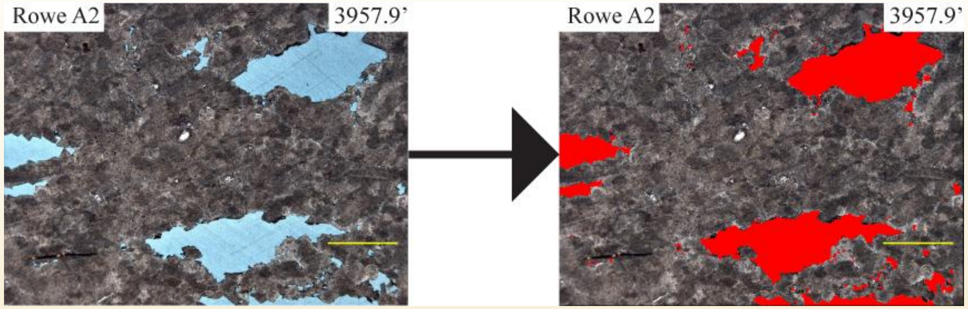

A
High miniperm K
High plug ϕ
High plug K (all directions)
B
High miniperm K
High plug ϕ
High plug K (all directions)
C
High miniperm K
High plug ϕ
High plug K (all directions)
4 inches

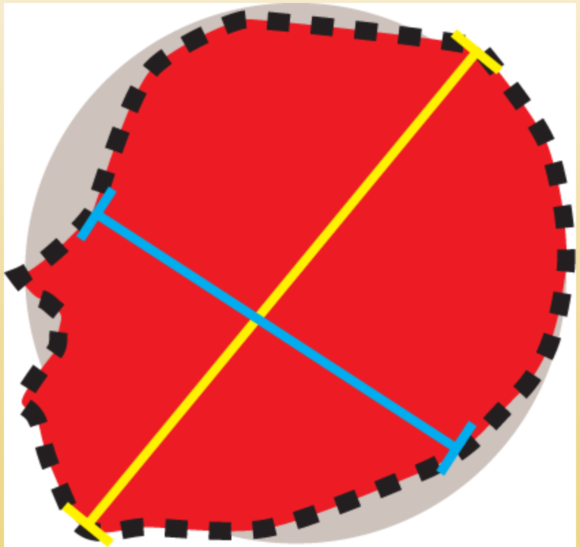

A
High miniperm K
Low plug ϕ
Low plug K
B
Low miniperm K
High plug ϕ
High plug K (vertical)
C
High miniperm K
High plug ϕ
High plug K (horizontal)
4 inches


A
Low miniperm K
High plug ϕ
Low plug K
B
High miniperm K
High plug ϕ
Low plug K
C
High miniperm K
High plug ϕ
High plug K (horizontal)
4 inches

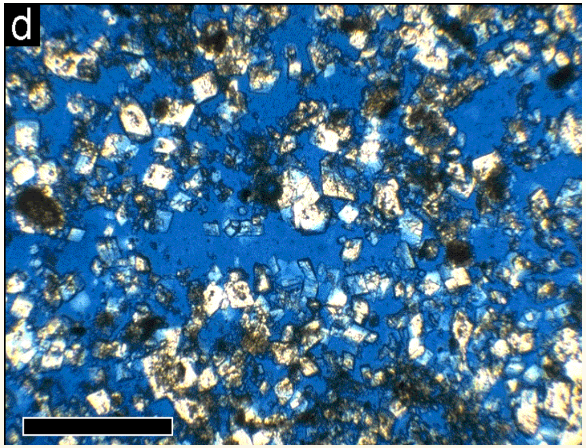
Digital Image Analysis

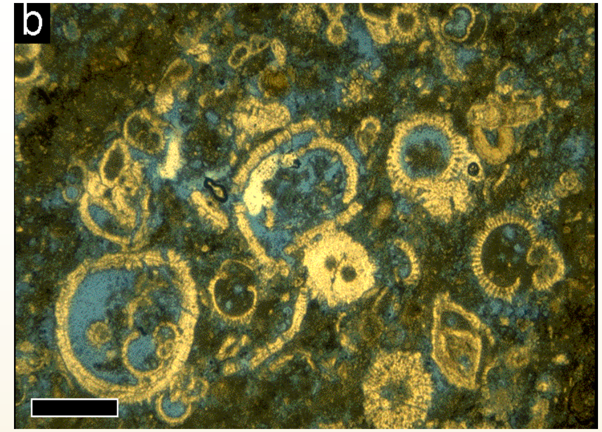
- ImagePro Plus
- Color-cube segmentation
- Can measure parameters for each pore
  - Area, length, width, roundness, perimeter
- Pore parameters (measures of pore architecture) are calculated

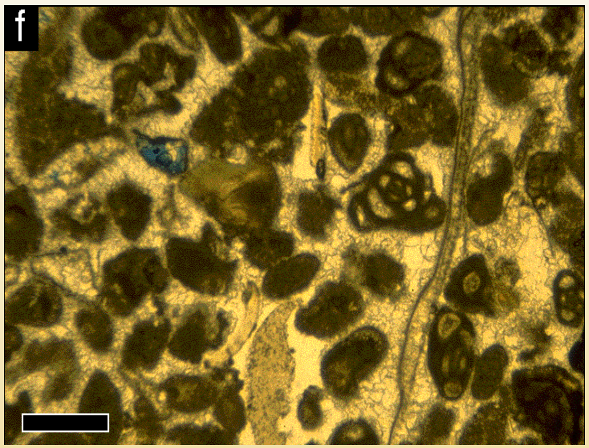


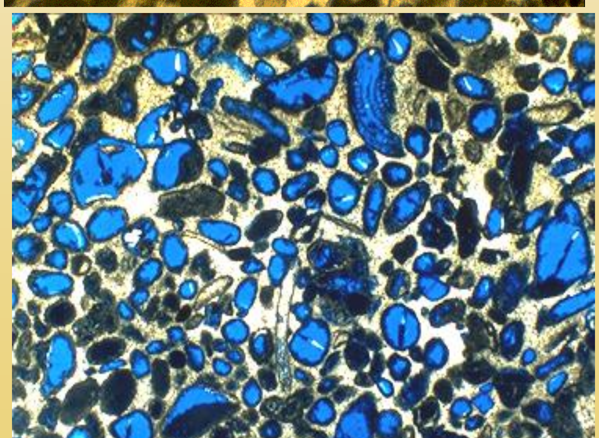


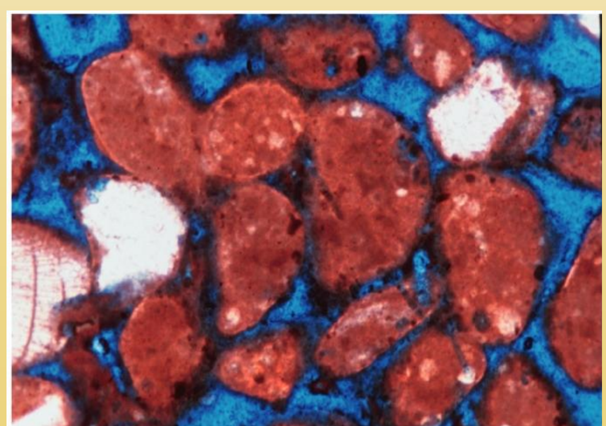
Carbonates have varying pore types that influence permeability

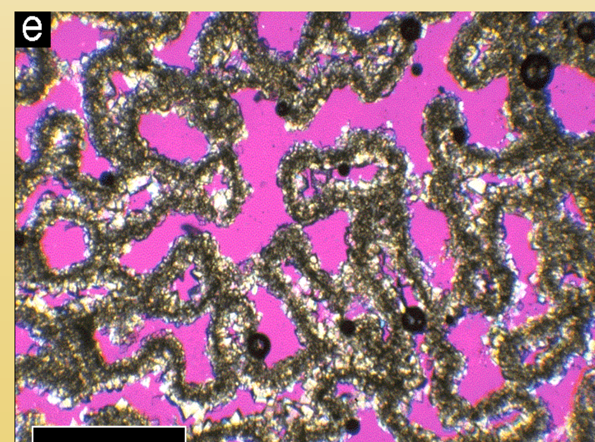






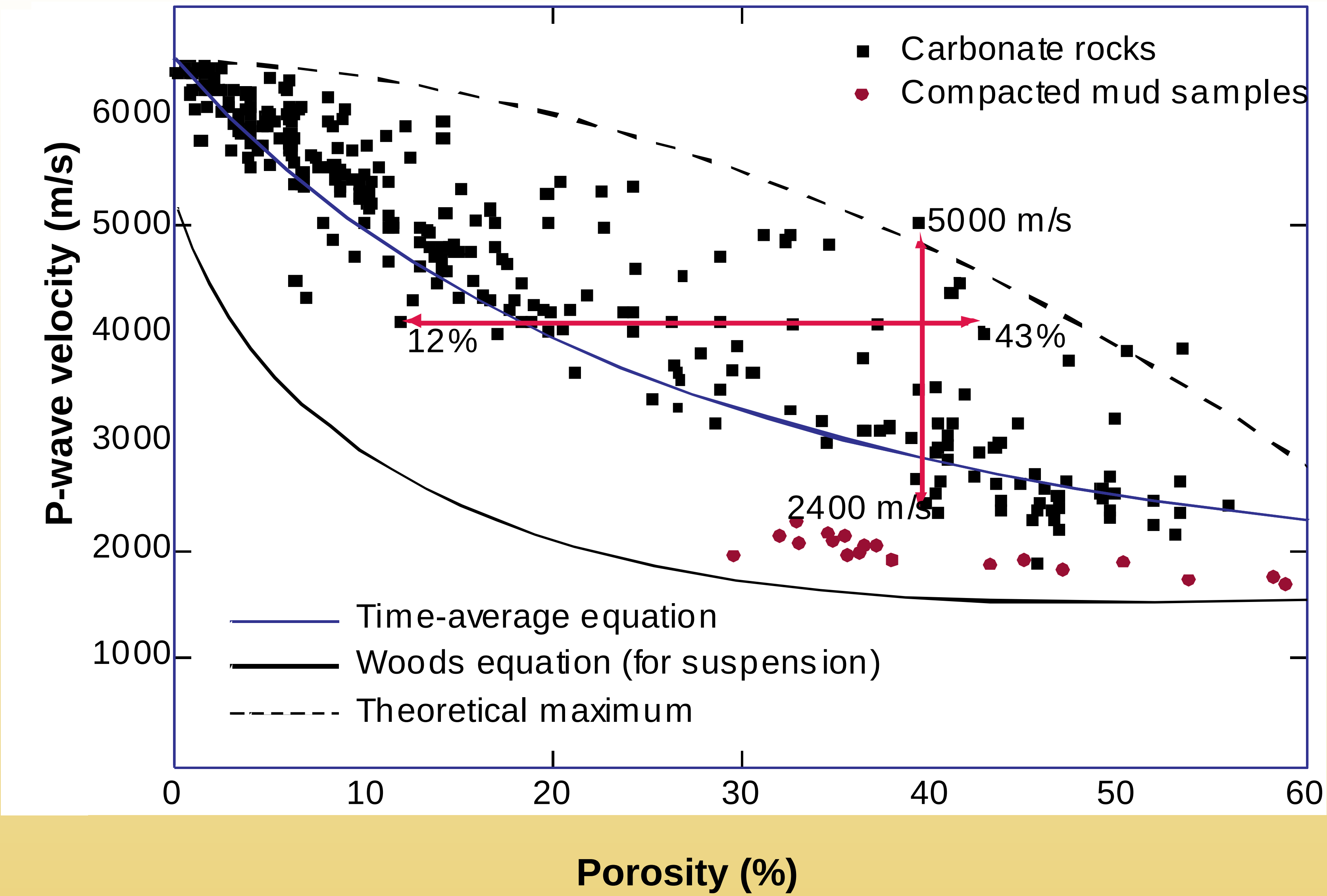




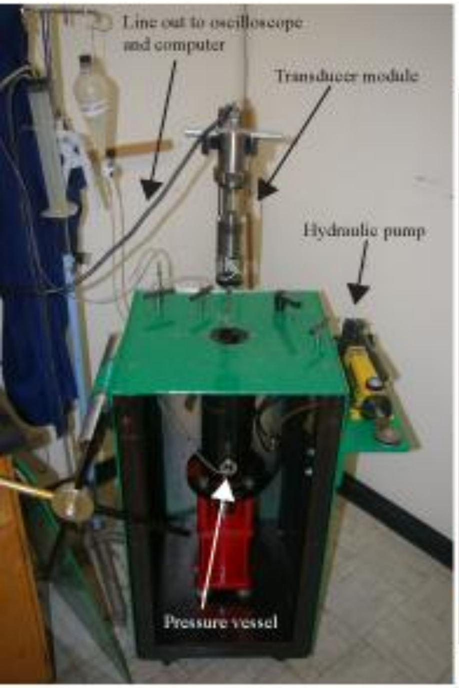


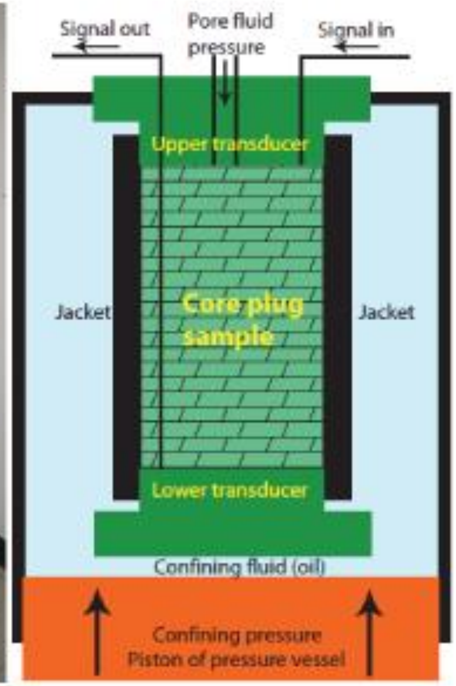
Eberli, 2000

Velocity versus Porosity in Carbonates

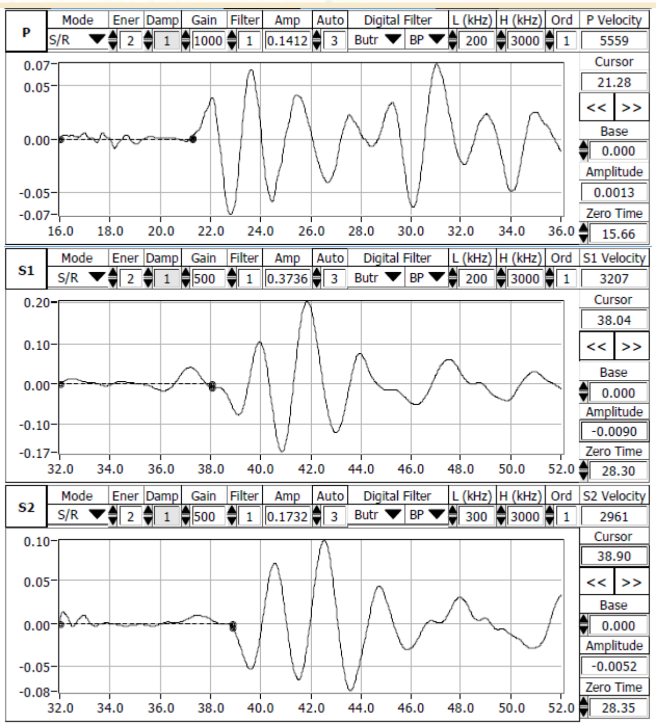


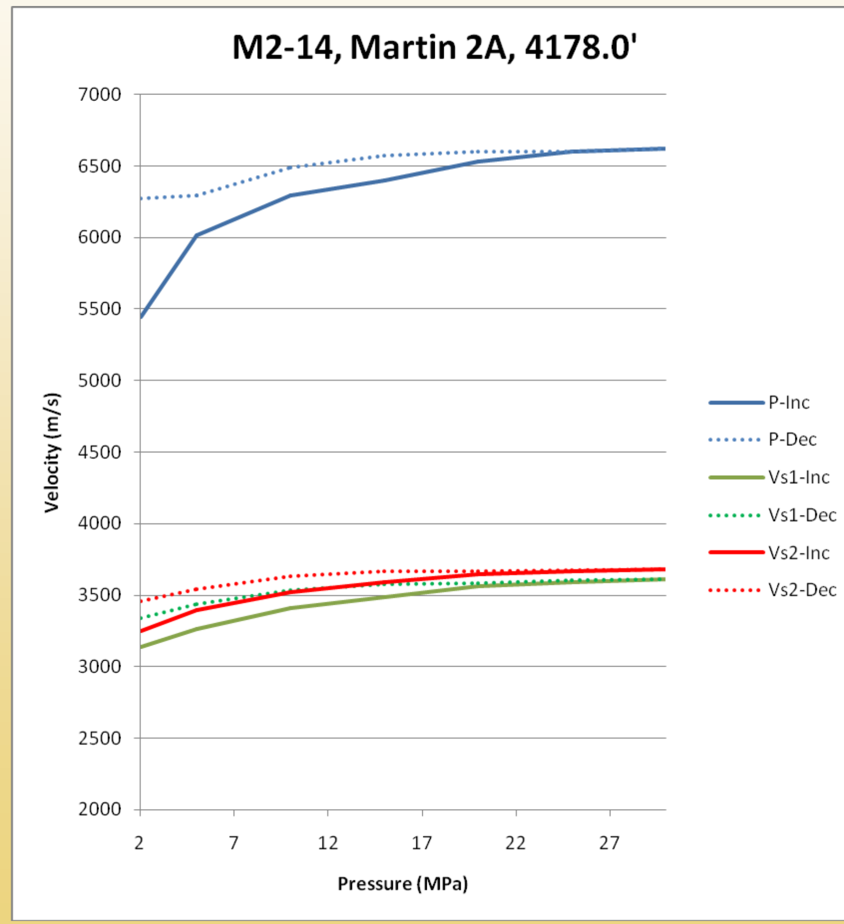
Anselmetti and Eberli (1999)





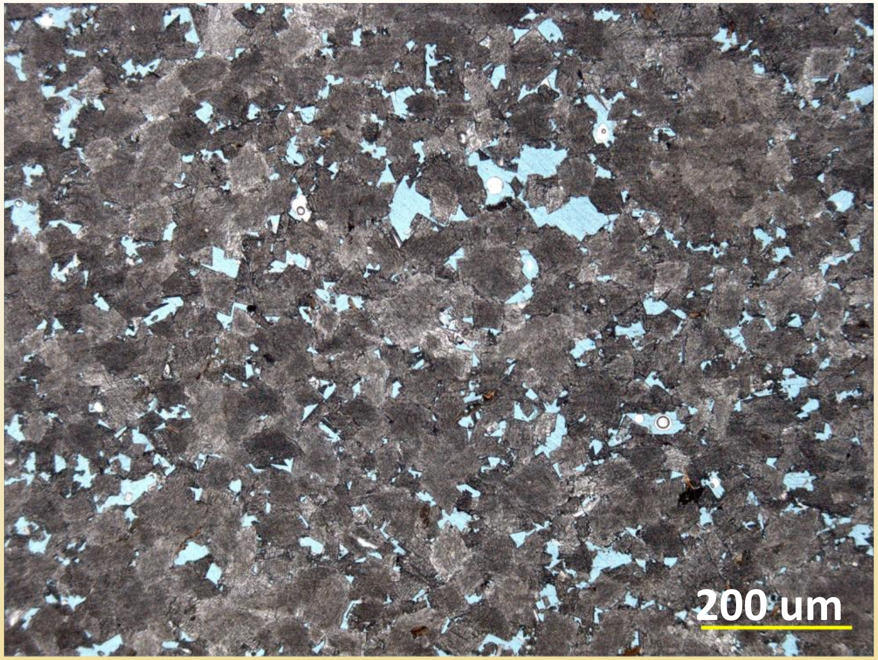
37 Core Plugs were measured for sonic velocity under confining pressures at Univ. Miami/CSL





Core Plug Values

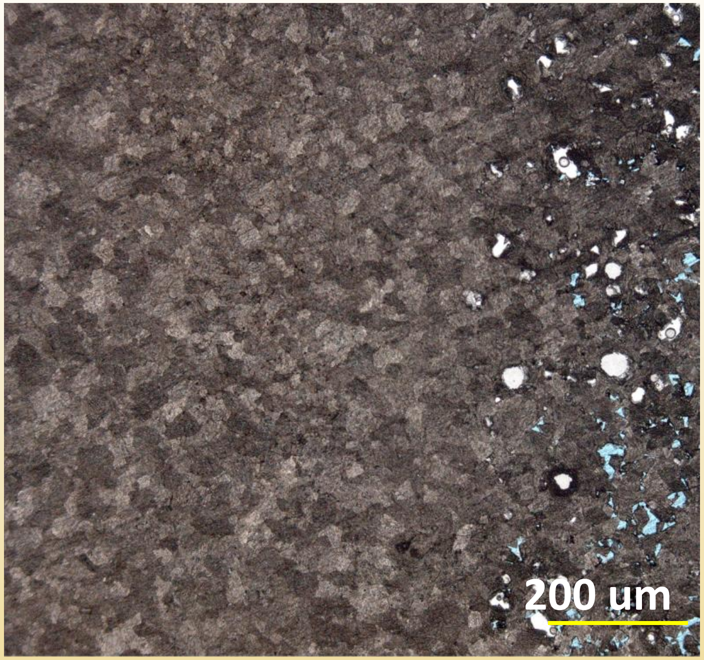
Φ = 10.59%
K = 66.5 mD



Vp = 4866 m/s

Core Plug Values

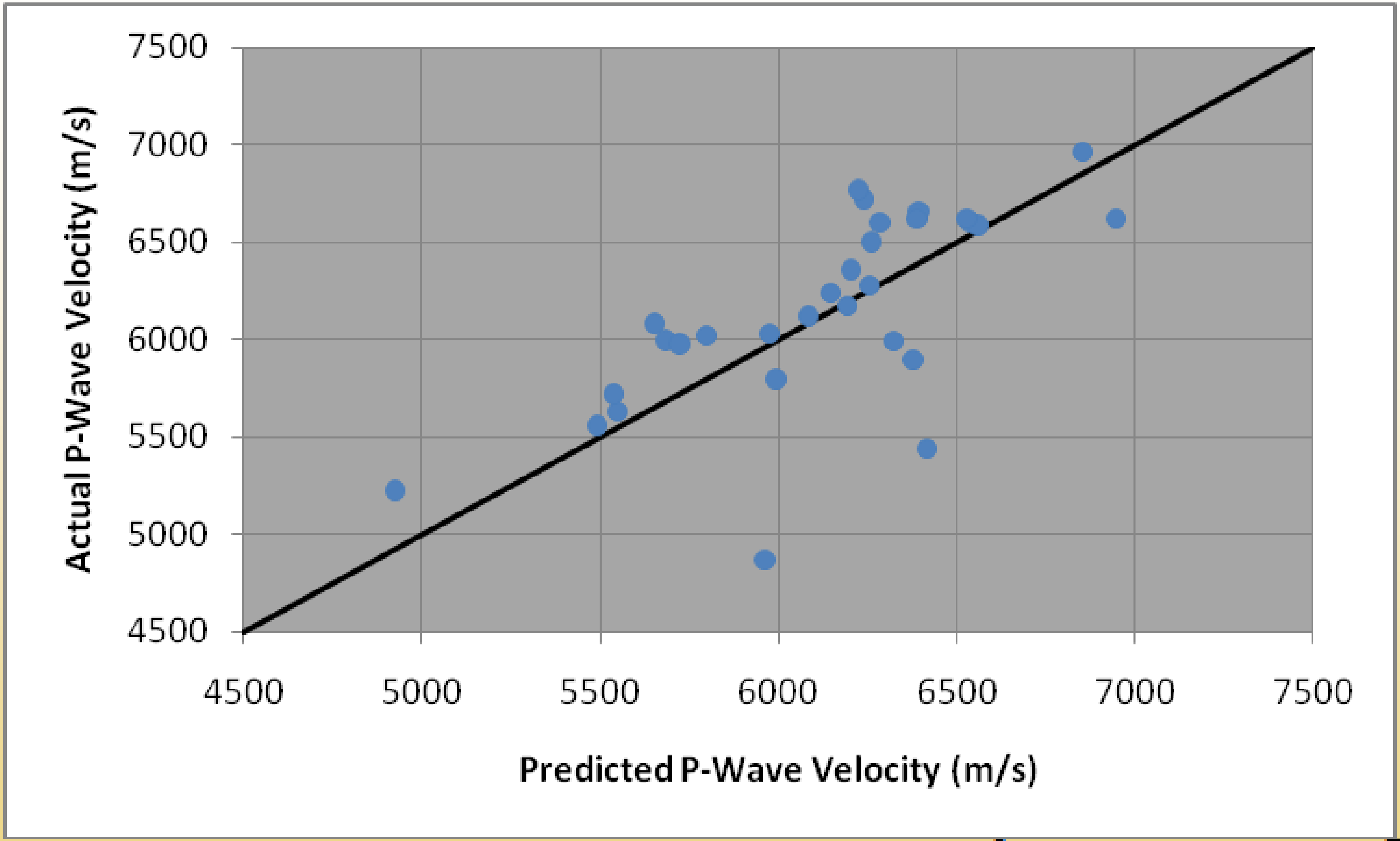
Φ = 10.50%
K = 1.04 mD



Vp = 6023 m/s

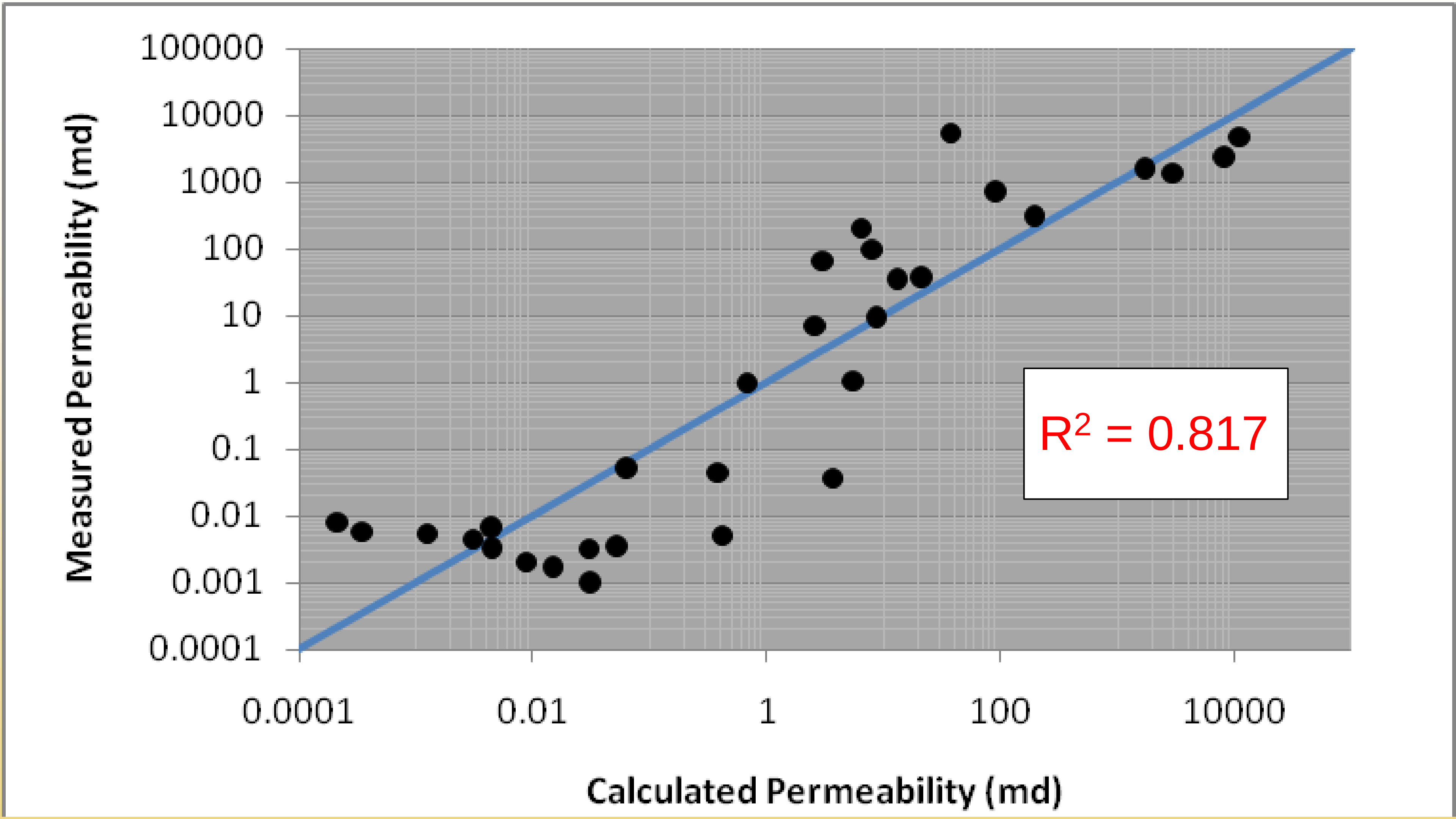
Thornton and Grammer (2010)

Average percent error between actual and predicted p-wave velocity = 5.31%



$$V_P = 388.626\gamma + 3.890A_{ds} - 85.650\Phi - 62.812\,{}^{L}/_{W} - 270.858\ln{}^{P}/_{A} + 5694.809$$

Integrating porosity, P- and S-wave velocities, density and DIA parameters



$$lnK = 3.906lnV_p + 2.263ln\Phi - 41.722ln\rho_b + 3.955ln\gamma - 0.926lnPOA$$

$$+ 1.005lnAR + 0.697lnV_s - 0.310lnDS - 7.013$$

Summary – General Trends in Trenton and Black River Reservoirs

1. Reservoir quality has a direct correlation to primary depositional facies
2. Because of this, the predictability of reservoir distribution, both laterally and vertically, may be enhanced by the development of a sequence stratigraphic framework
3. Porosity and permeability (i.e. reservoir quality) is a direct function of pore architecture, which again is often tied to primary depositional facies and/or position within a sequence stratigraphic framework
4. Detailed characterization of pore architecture should lead to a better understanding of the 3-D distribution and connectivity of pores – image analysis and CT scans, along with laboratory measured Vs, may lend insight into the acoustic properties of different reservoir and non-reservoir facies