Integrated Reservoir Characterization of Mississippian-Age Mid-Continent Carbonates*

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Abstract

Carbonate reservoirs are characterized by significant heterogeneity at a number of scales, ranging from exploration to production and enhanced production scale. An understanding of how primary depositional facies, diagenesis, and the sequence stratigraphic framework control the development of pores in carbonate rocks, and how the variation in pore architecture influences reservoir permeability is a fundamental process in the accurate characterization of carbonate reservoirs. In addition, with the ubiquitous use of geostatistical models to define and predict 3-D reservoir architecture in the subsurface, it has become increasingly important to accurately define the probable geometric distribution of potential reservoirs and seals at multiple scales to provide geologically-based, three dimensional reservoir models that can be used to develop dynamic reservoir simulation and flow models. To effectively do this, the challenge is to integrate data on the primary depositional environment (facies, probable geometry, and susceptibility to diagenetic modification), the sequence stratigraphic framework, and the petrophysical characteristics of carbonates at multiple scales utilizing a combination of core, wireline logs, 3D seismic and the incorporation of both modern and ancient analogs.

Mississippian carbonates of the Mid-Continent have been highly productive for several decades but with a move towards horizontal rather than vertical drilling, the internal heterogeneity of the unit has become even more apparent. A combination of outcrop and core work illustrates a distinct hierarchy in shallowing upward packages within most Mississippian reservoir units, with cycles ranging from a few meters thick, to 10's of meters, and larger. Understanding the sequence stratigraphic framework at the meter and tens of meter scale will aid the producer in identifying key producing intervals and also enhance the prediction of internal flow units and seals.

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Key Questions to be addressed by Project

- Regional Biostratigraphy (conodonts)
- Regional subsurface mapping
- Development of Depositional Models (regional and production scale)
- Characterize Reservoir Types
- Develop high-frequency chronostratigraphy
- Diagenesis – evolution of porosity
- Petrophysics – tie to porosity and permeability and seismic attributes

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devon

NEWFIELD

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REDFORK ENERGY

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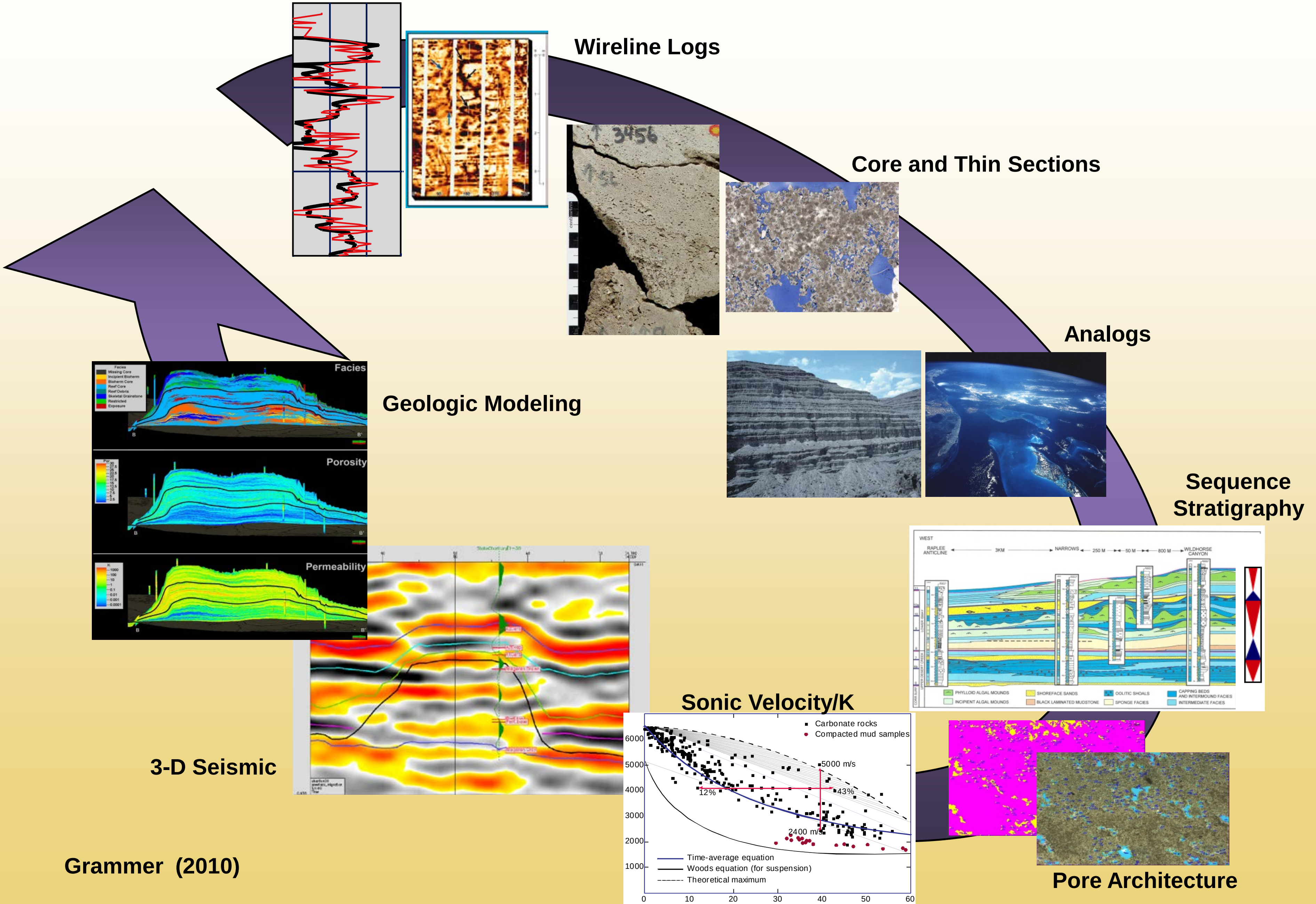
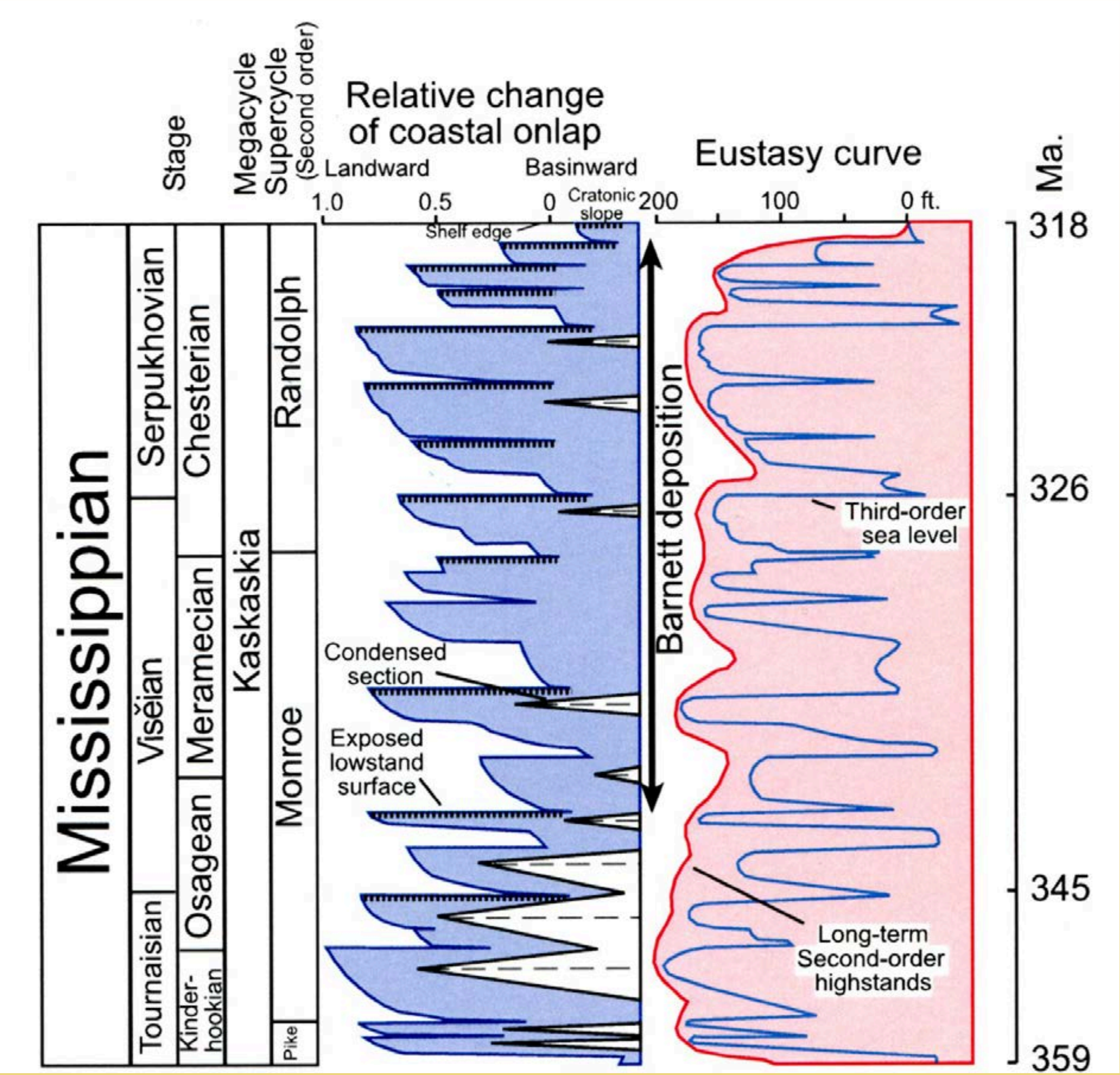
OKLAHOMA STATE UNIVERSITY

Integrated Reservoir Characterization



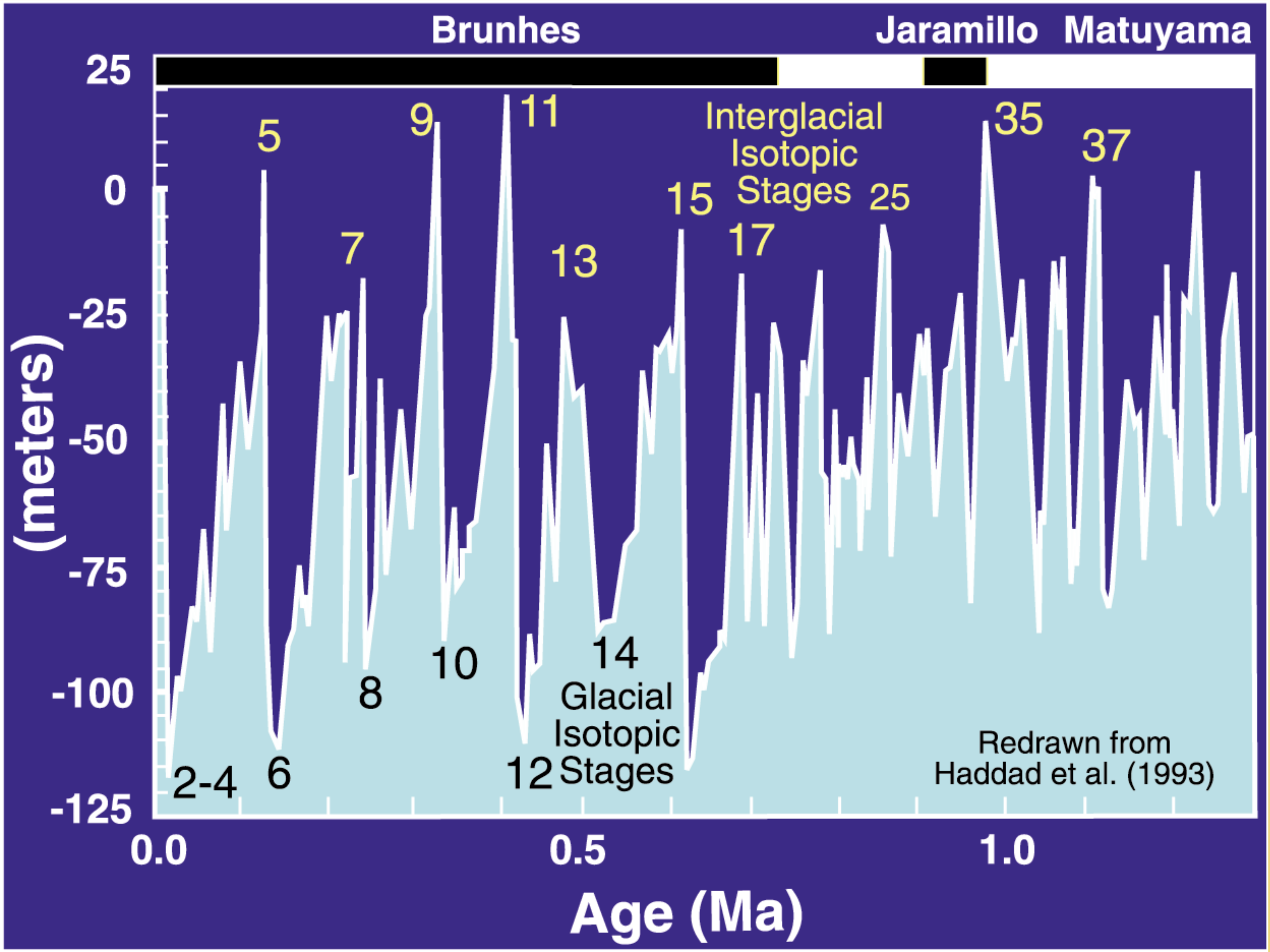
Grammer (2010)

Importance of Sequence Stratigraphy

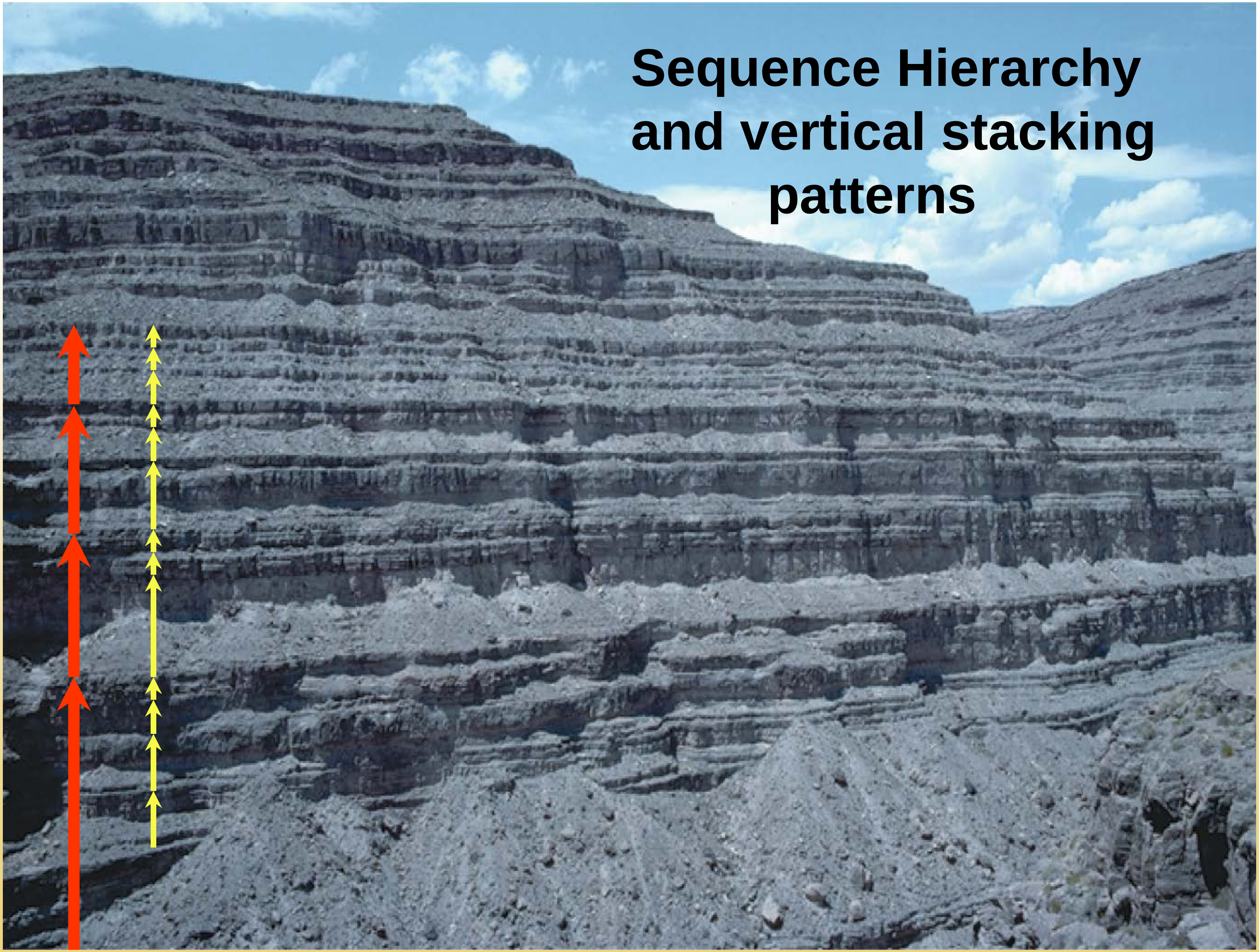


Loucks and Ruppel (1997)

High Frequency Sea-level changes (Milankovitch driven)

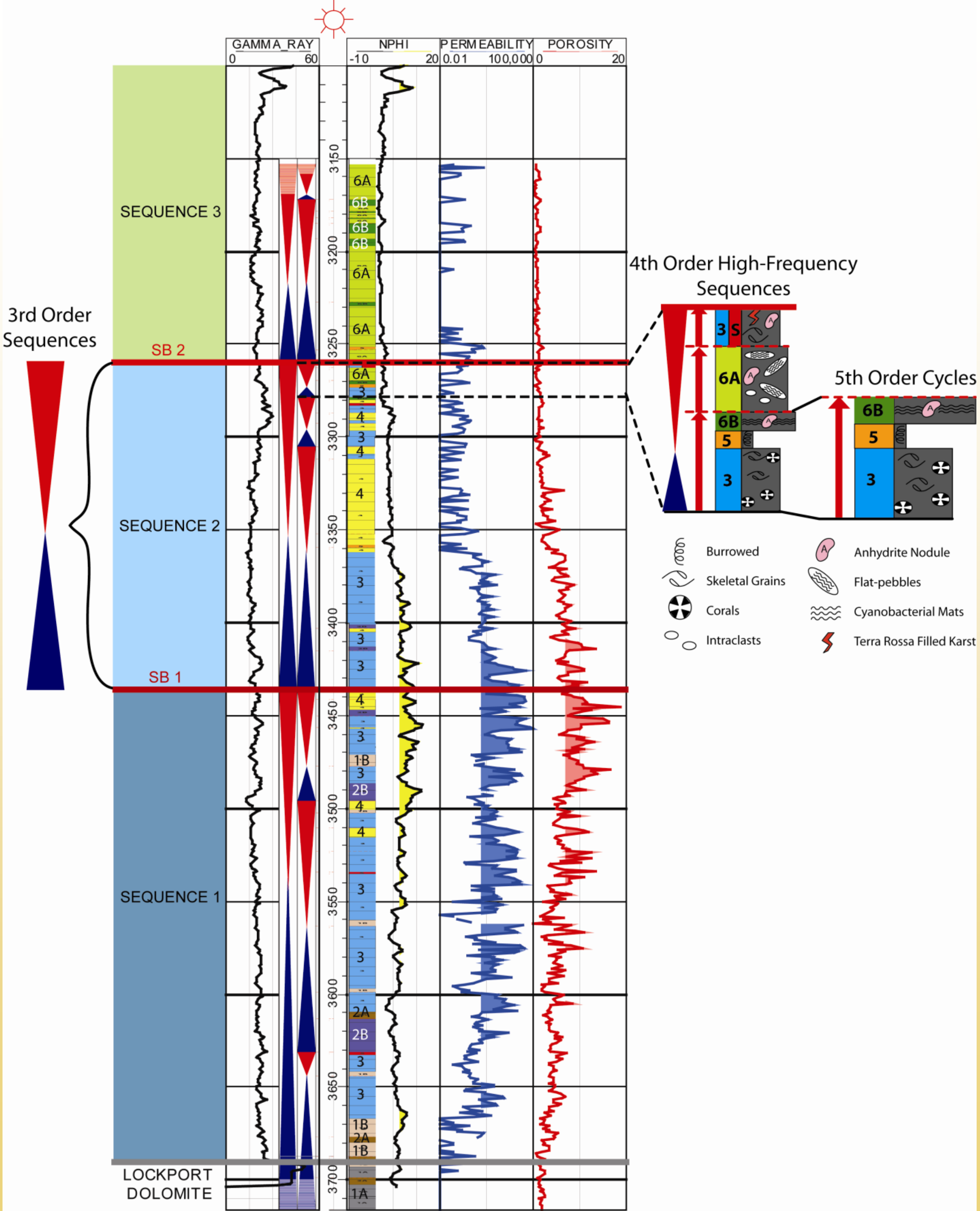


Sequence Hierarchy and vertical stacking patterns

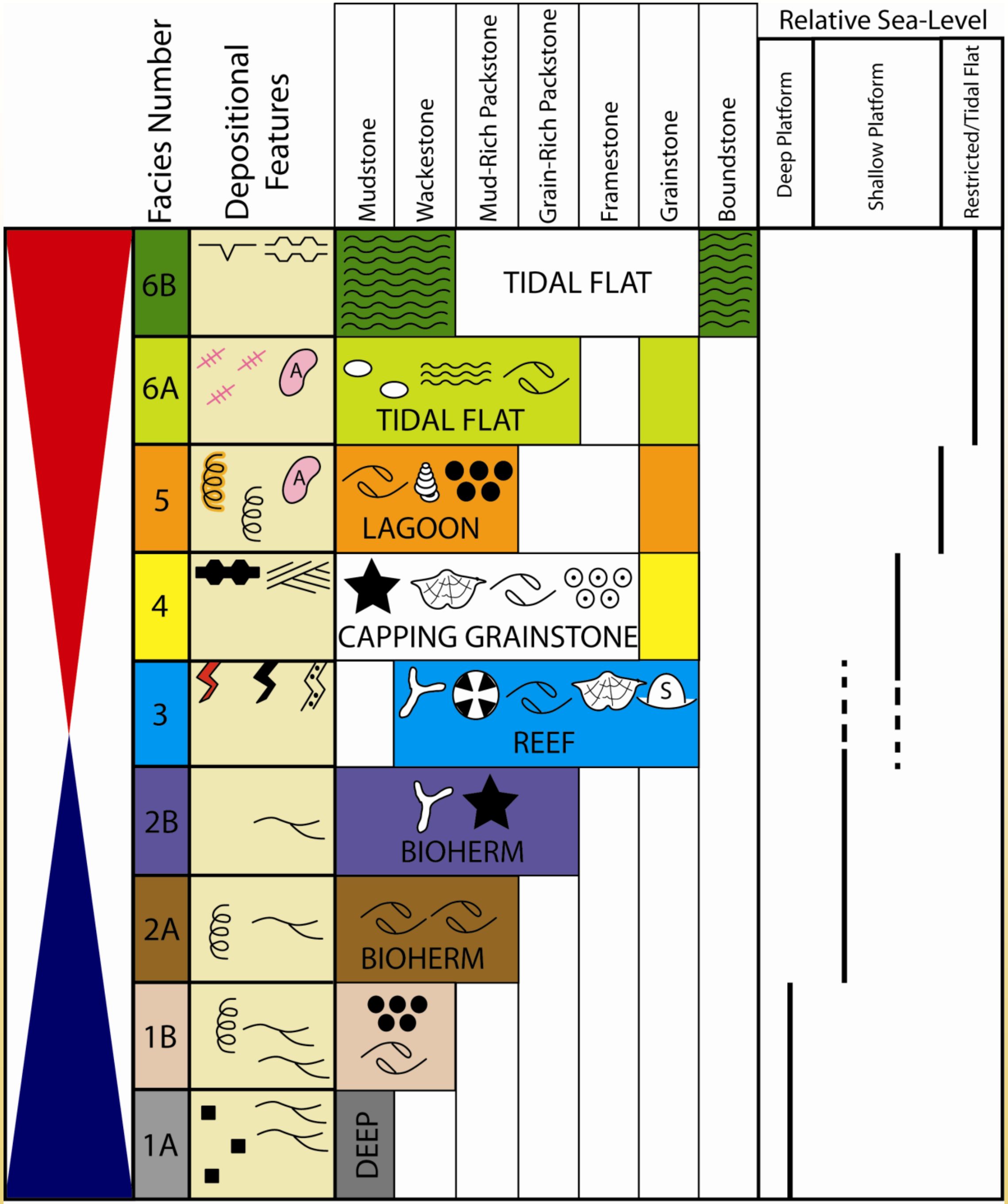


Grammer et al., 2004

Establishing the Sequence Stratigraphic Hierarchy



Ritter and Grammer (2008)

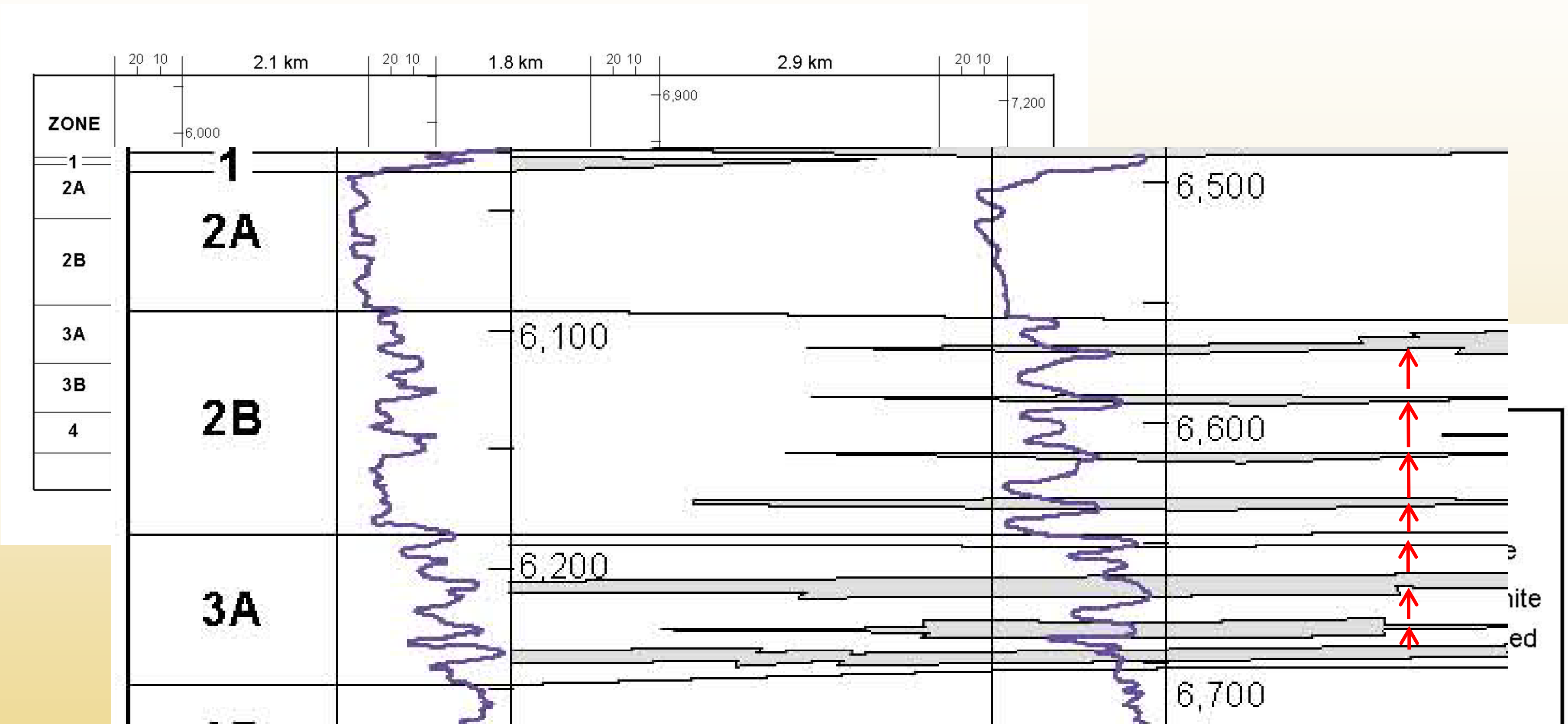


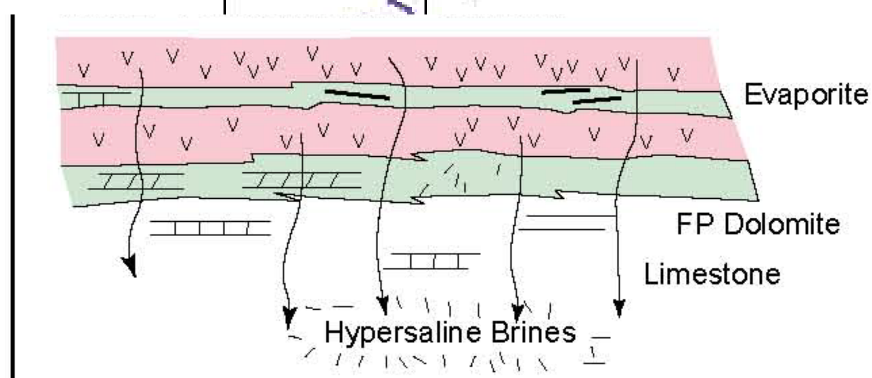
Ritter and Grammer (2008)

Idealized Facies Succession from Core (High Frequency Cycle)

- Define shallowing-upward cycles
- Transgressive and regressive patterns
- Porosity enhanced <u>or</u> occluded at cycle caps depending on diagenesis
- **Define basic reservoir flow units**

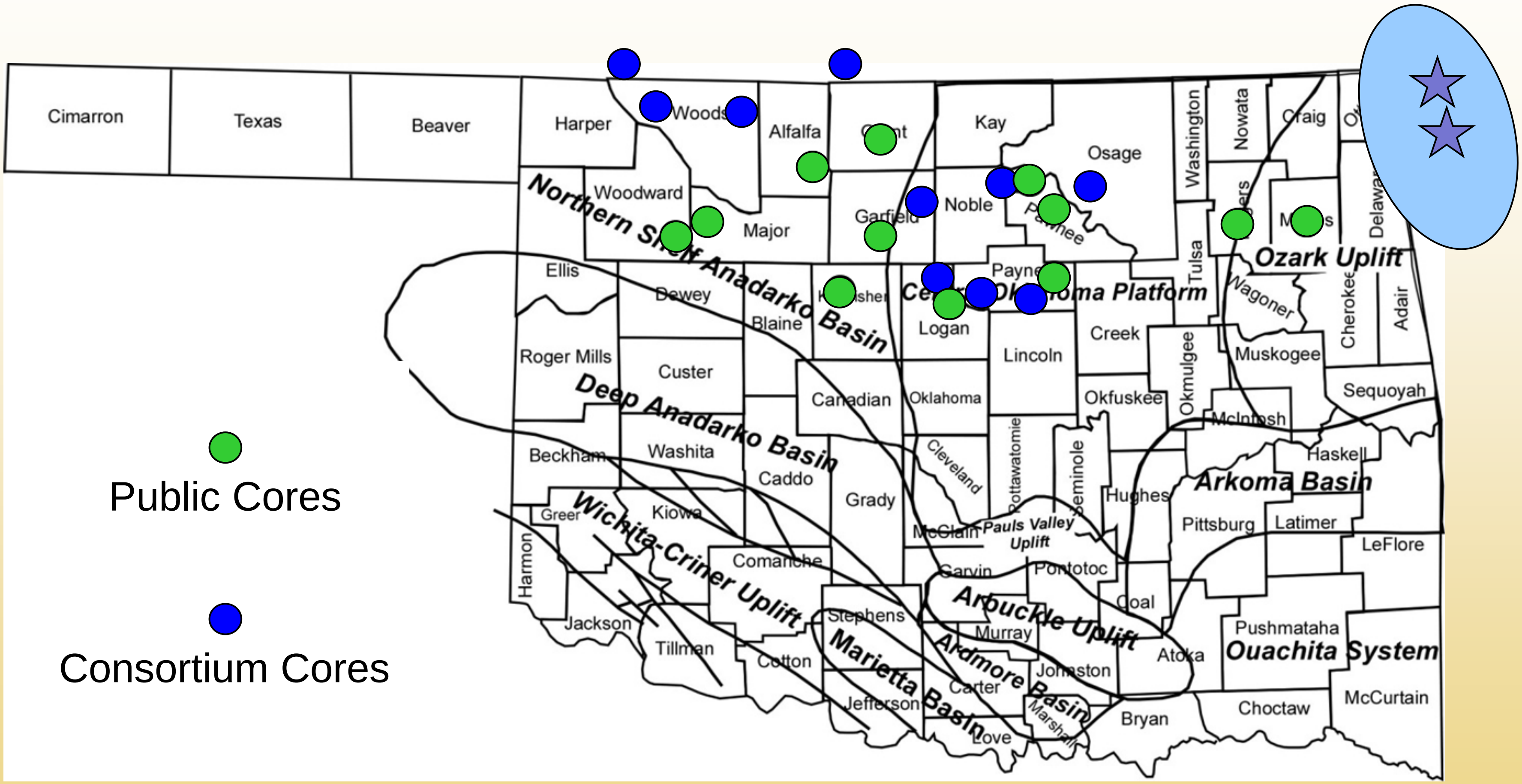
Thin reservoir units controlled by high frequency cyclicity – Ghawar field, Saudi Arabia





Cantrell et al. (2004)

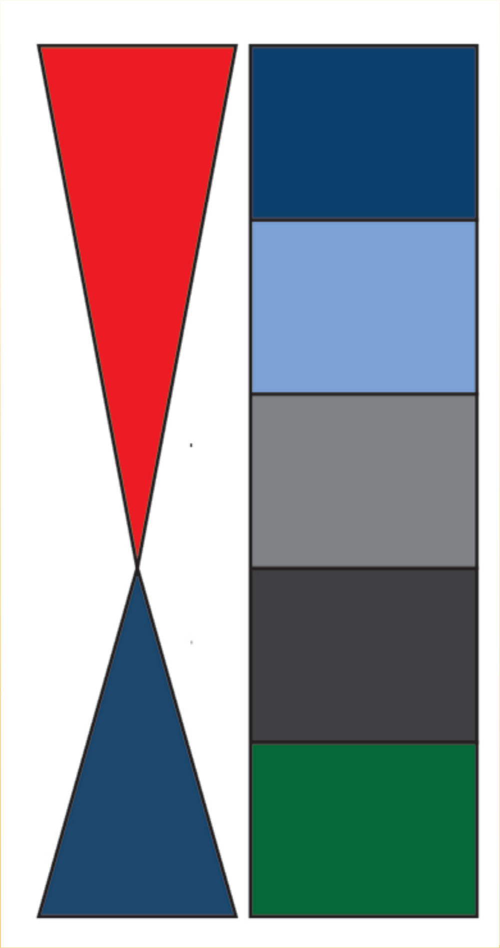
Current Outcrop and Subsurface Data Sets



Public Cores

Consortium Cores

Idealized Vertical Facies Succession – Core (Meramecean?)



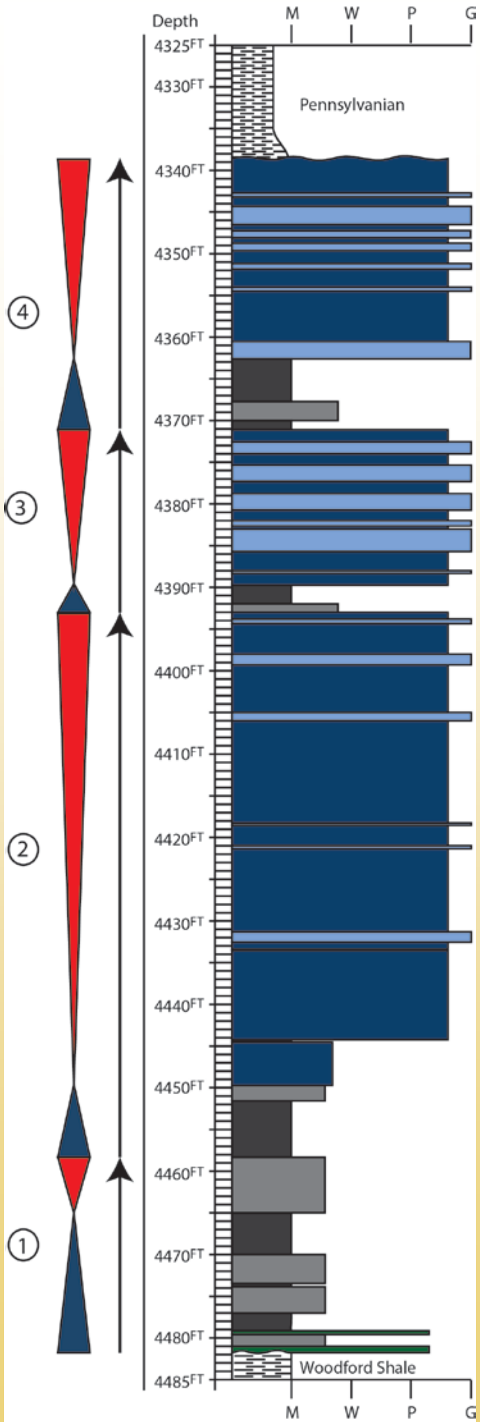
Skeletal grainstone with traction laminations and cross laminations, coarse grained

Skeletal packstone-grainstone, massive and fine grained

Bioturbated mudstone-wackestone, *Thalassinoides*

Mudstone with localized millimeter-scale burrows

Laminated mudstone, Glauconitic sandstone



Traction Current Grainstone Facies

- 1-10% porosity (avg. 4%)
- Detrital silt present (quartz)
- Contains sponge spicules, crinoid and brachiopod fragments, bryozoans, peloids, and some organics

Massive Bedded Grainstone Facies

- Approximately 4% porosity
- Detrital silt and sand present (quartz)
- Contains sponge spicules, crinoid fragments, and peloids

Burrowed Mudstone-Wackestone Facies

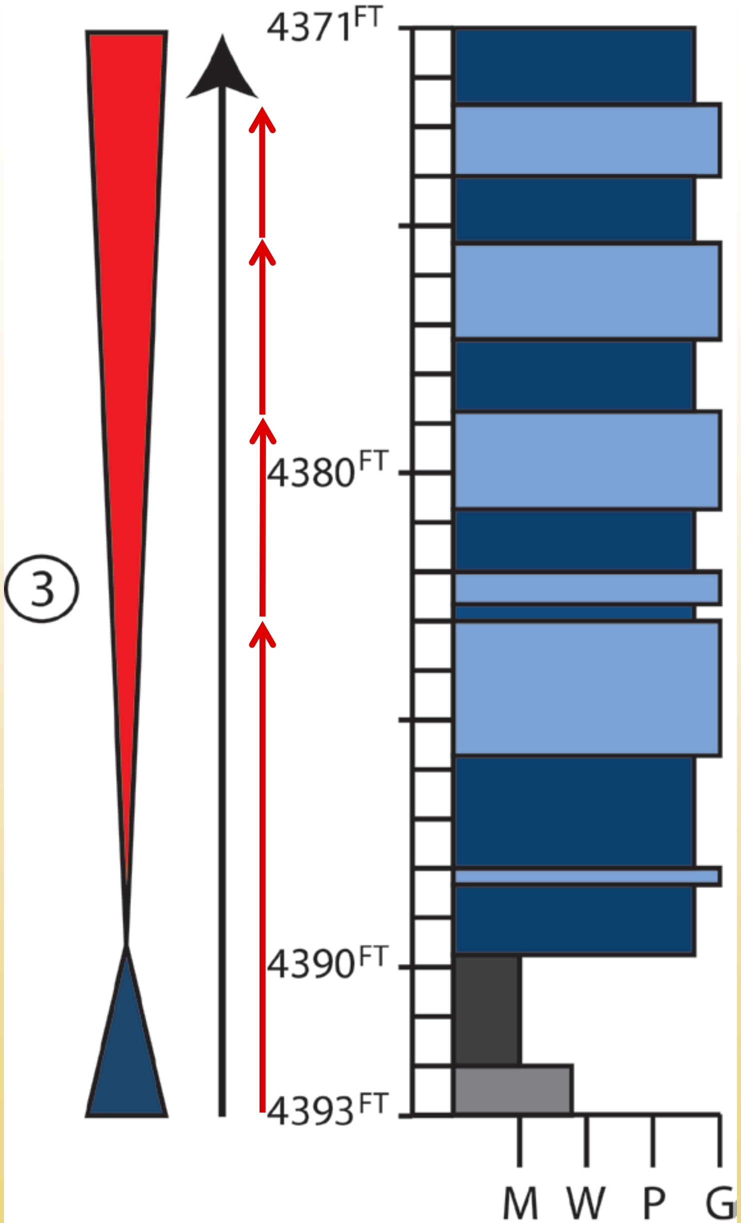
- Approximately 3% porosity
- Detrital silt present
- Contains sponge spicules and crinoid and brachiopod fragments

Burrowed Calcareous Mudstone Facies

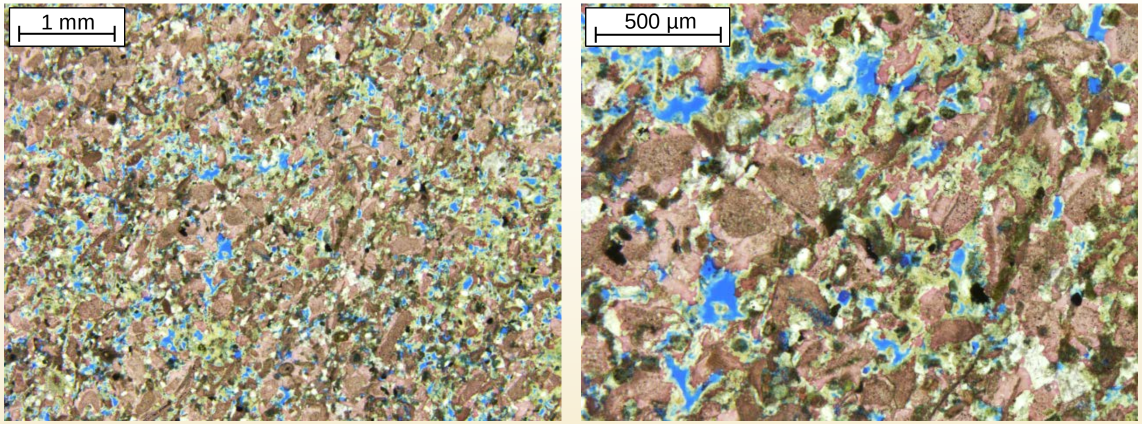
- 1-2% porosity
- Detrital silt present
- Contains brachiopods, scattered sponge spicules, and some organics

Glauconitic Sandstone Facies

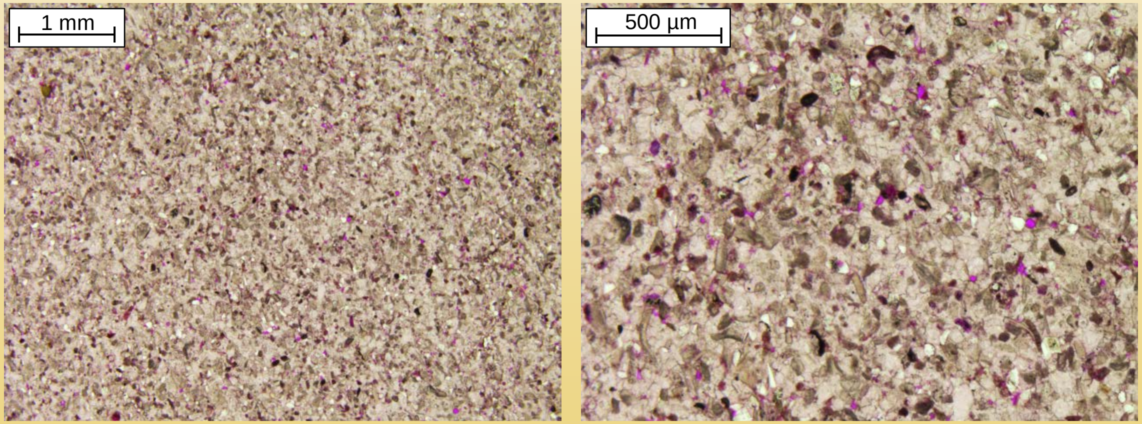
- Approximately 9% porosity
- Silt and clay present
- Contains phosphatic bone fragments, conodont fragments, and brachiopod fragments



Traction and XL Grainstone Facies



Massive Bedded Pkst-Grnst Facies

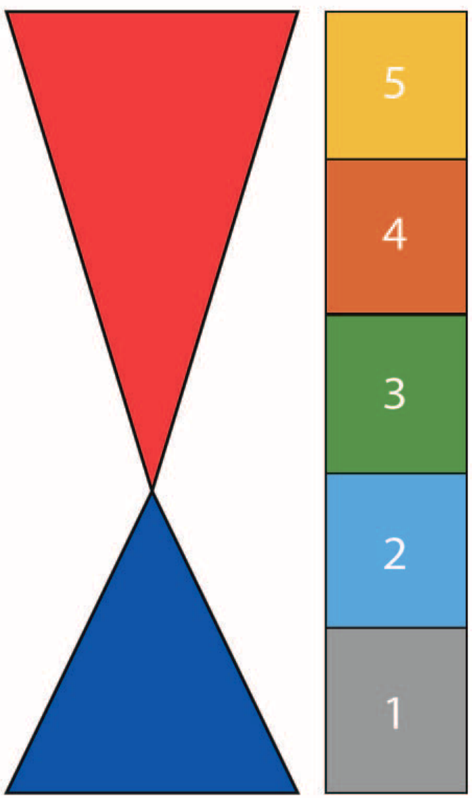


Burrowed Mudstone-Wackestone Facies

Burrowed Calcareous Mudstone Facies

Bentonville Formation Hwy 71

Idealized Facies Succession



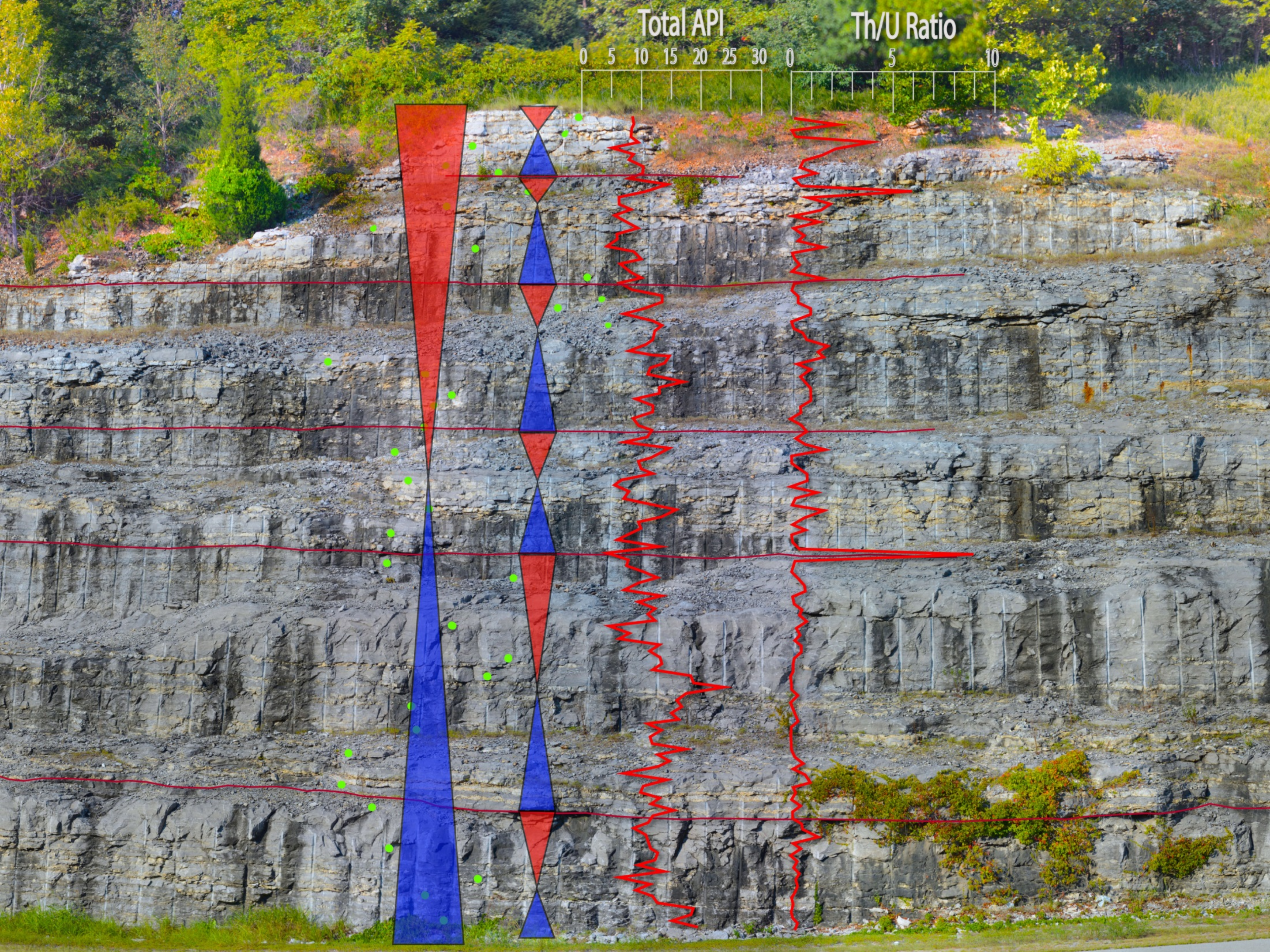
Crinoidal grainstone
coarse sand - cobble size

Crinoidal packstone-grainstone
medium sand size

Crinoidal, skeletal packstone
fine sand size

Skeletal packstone

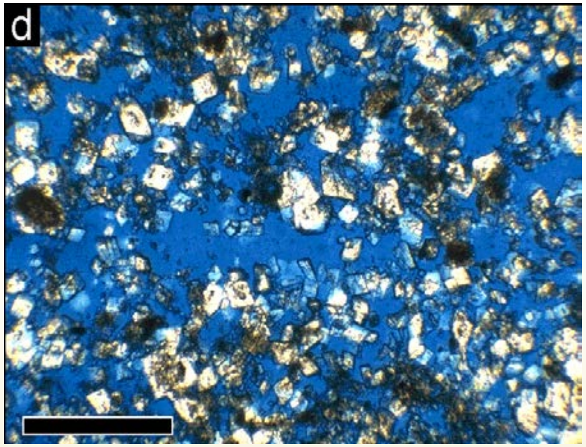
Bioturbated skeletal packstone

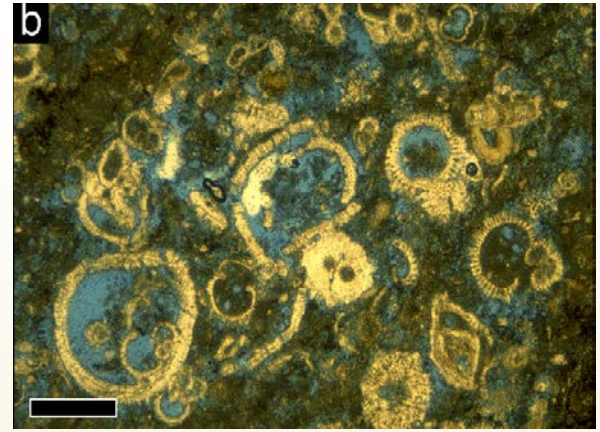


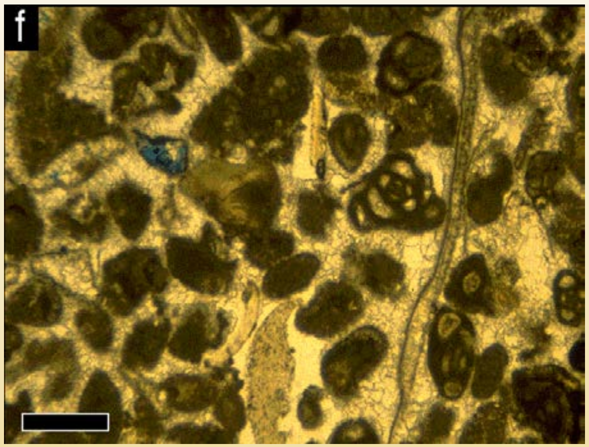
Total API
0
5
10
15
20
25
30
Th/U Ratio
0
5
10

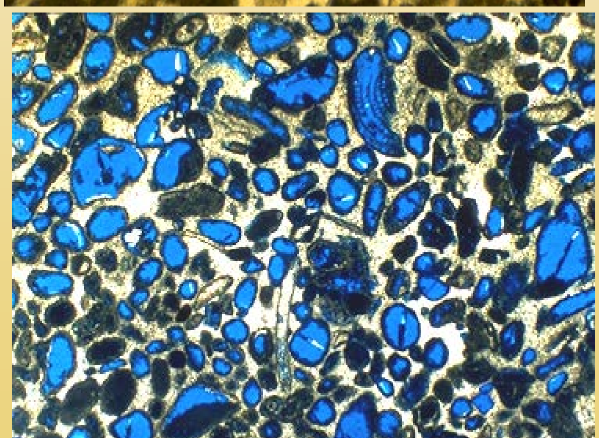
Characterization of Carbonate Pore Architecture and Relationship to Permeability

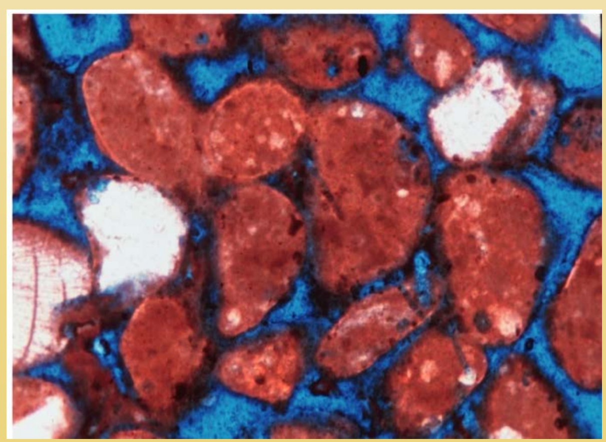
Carbonates have varying pore types that influence permeability

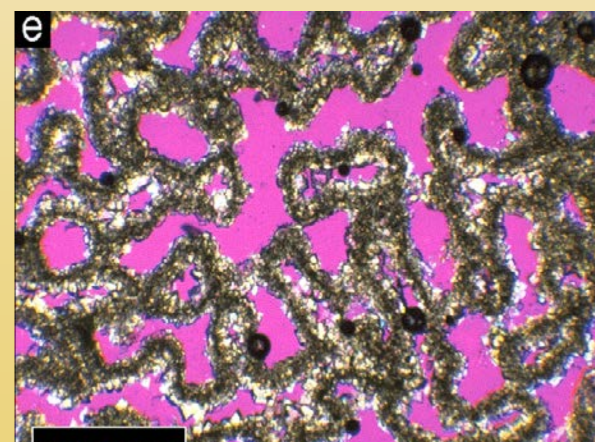






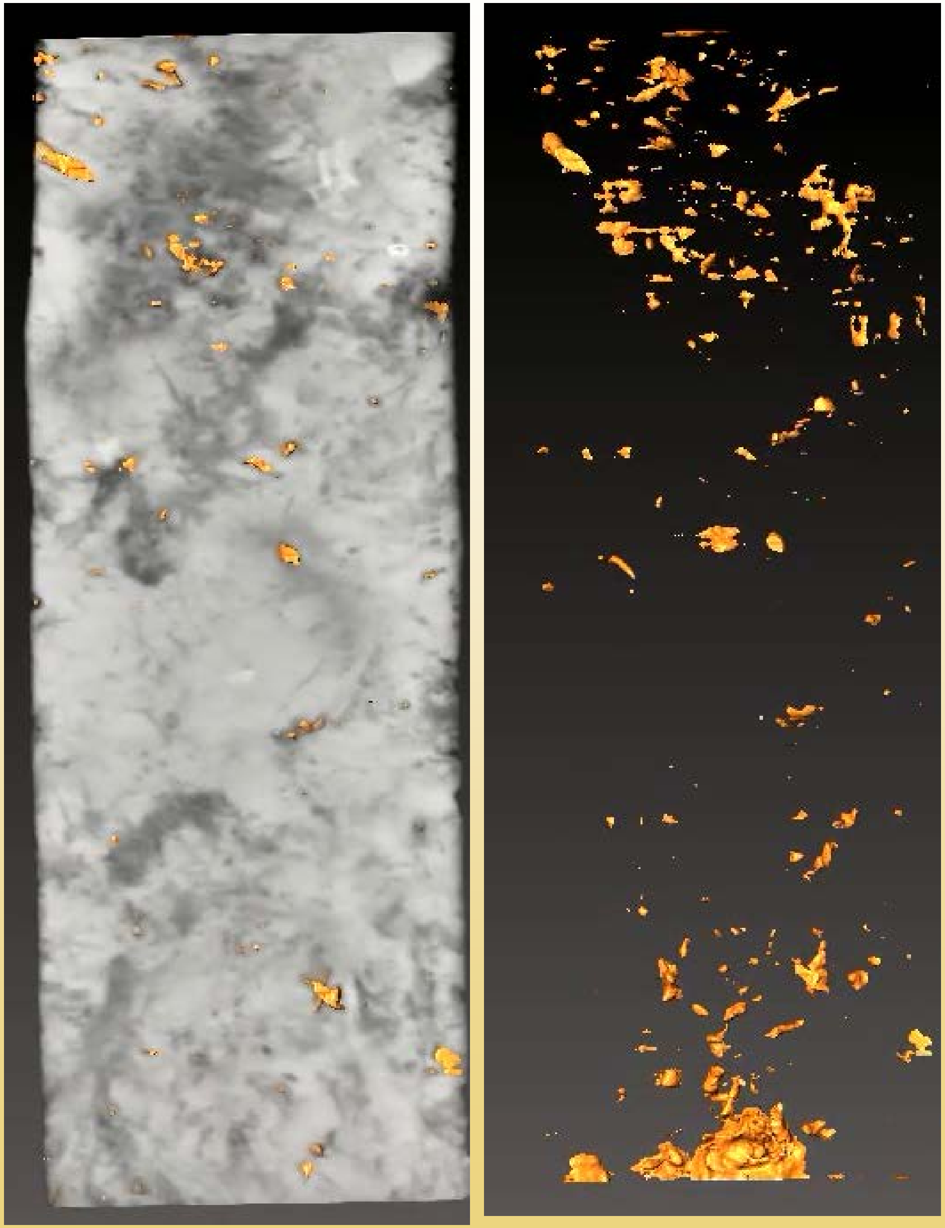




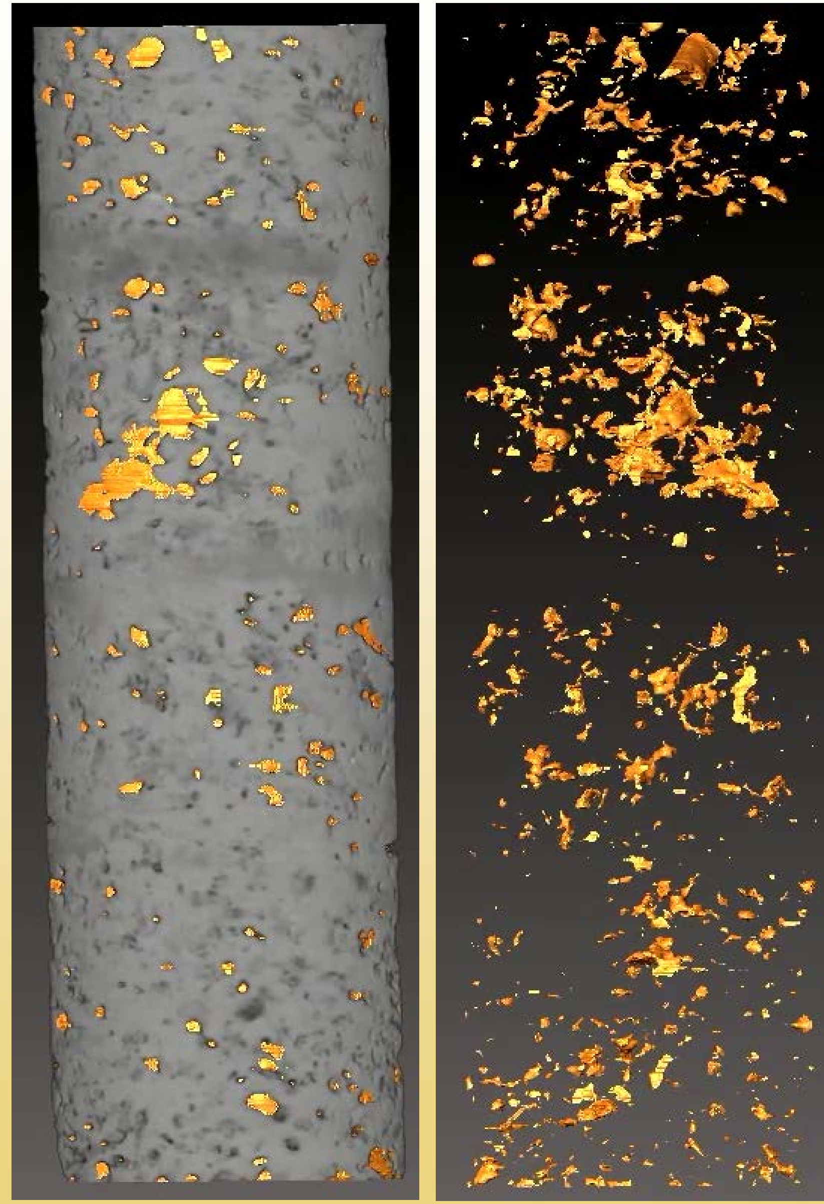


Eberli, 2000

CT Scans of Core for Pore Architecture

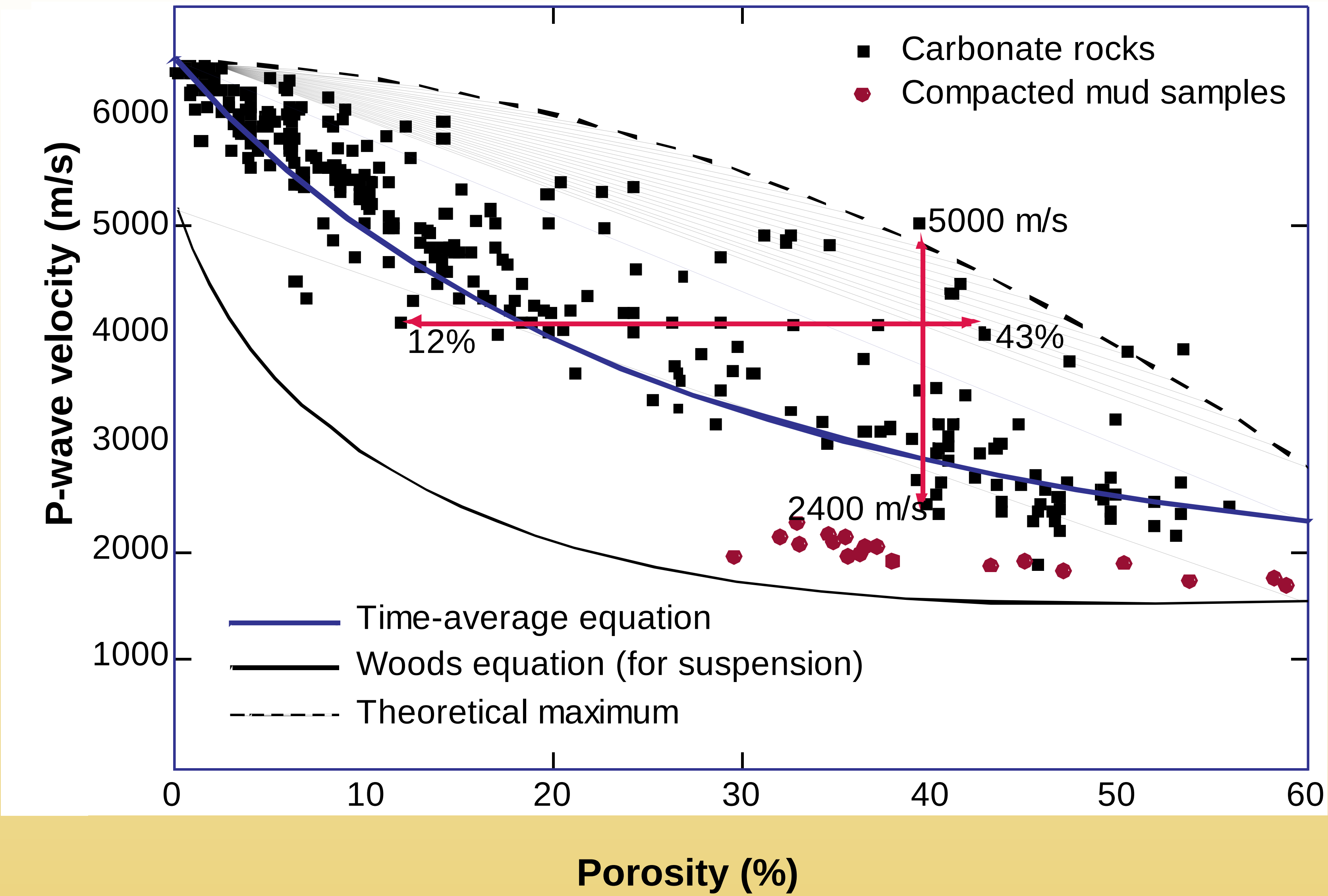


Jacob (3164-3165 ft)



Lask (3157-3158 ft)

Velocity versus Porosity in Carbonates

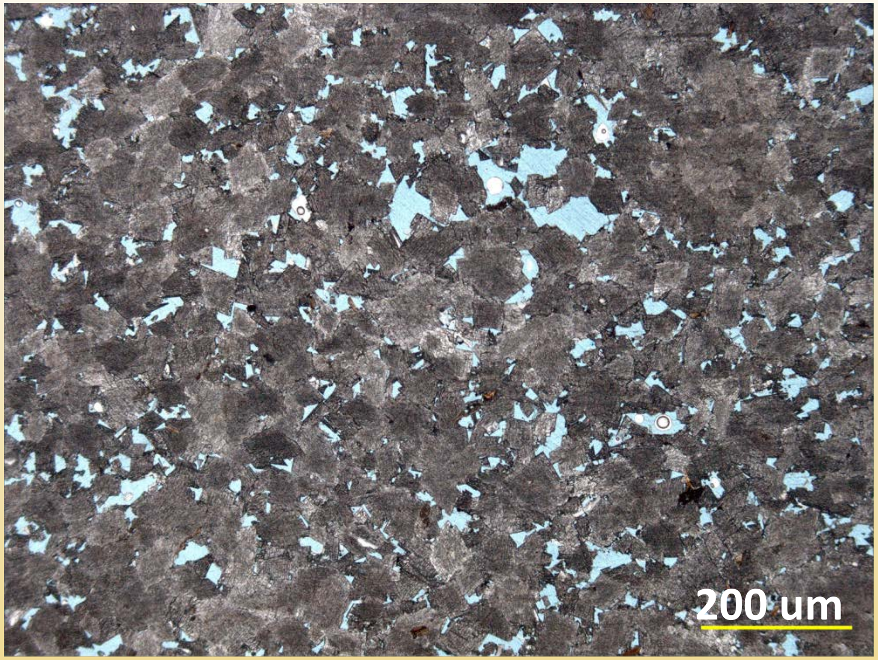


Anselmetti and Eberli (1999)

Predicting Permeability from Sonic Velocity?

Core Plug Values

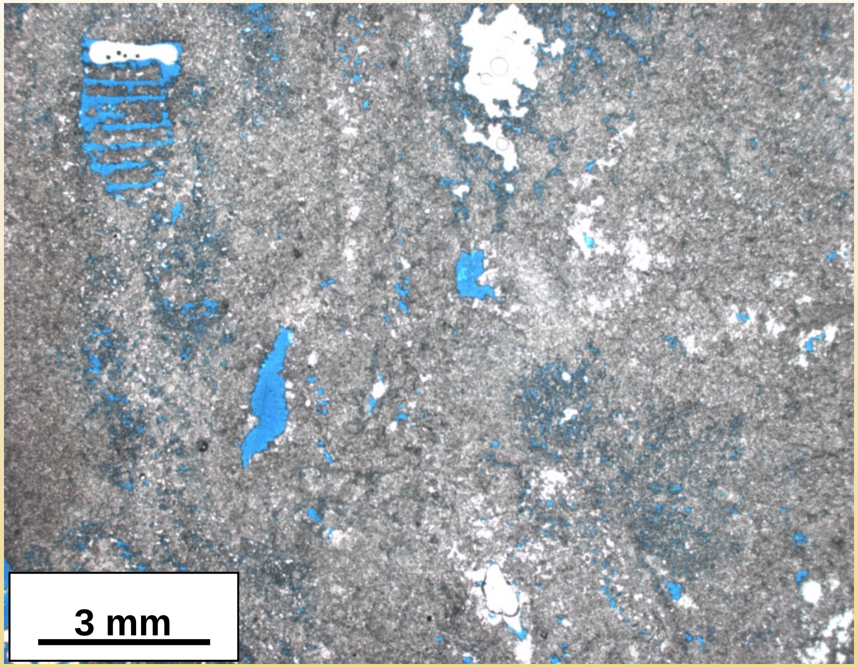
Φ = 10.59%
K = 66.5 mD



Vp = 4866 m/s

Core Plug Values

Φ = 13.0%
K = 17.34 mD



Vp = 5900 m/s

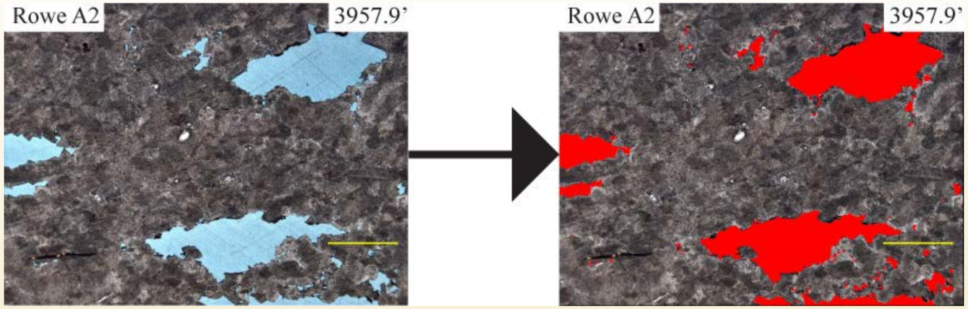
Thornton and Grammer (2010)

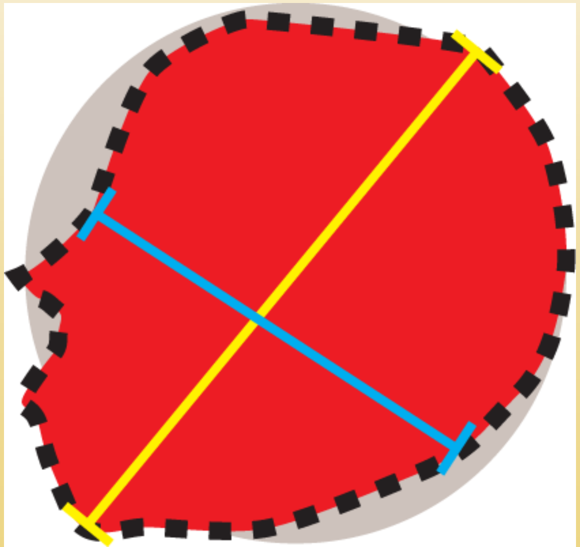
Pore Architecture tied to Petrophysical Properties – can we Predict Permeability???

1. Relate rock fabric to pore types by developing petrophysically significant facies
2. Relate pore architecture to pore connectivity (permeability) to determine reservoir quality
3. Use laboratory and log measured sonic velocity to establish a first order relationship between sonic velocity and pore type/pore network connectivity
4. Tie to Wireline Logs

Quantifying Pores: Digital Image Analysis

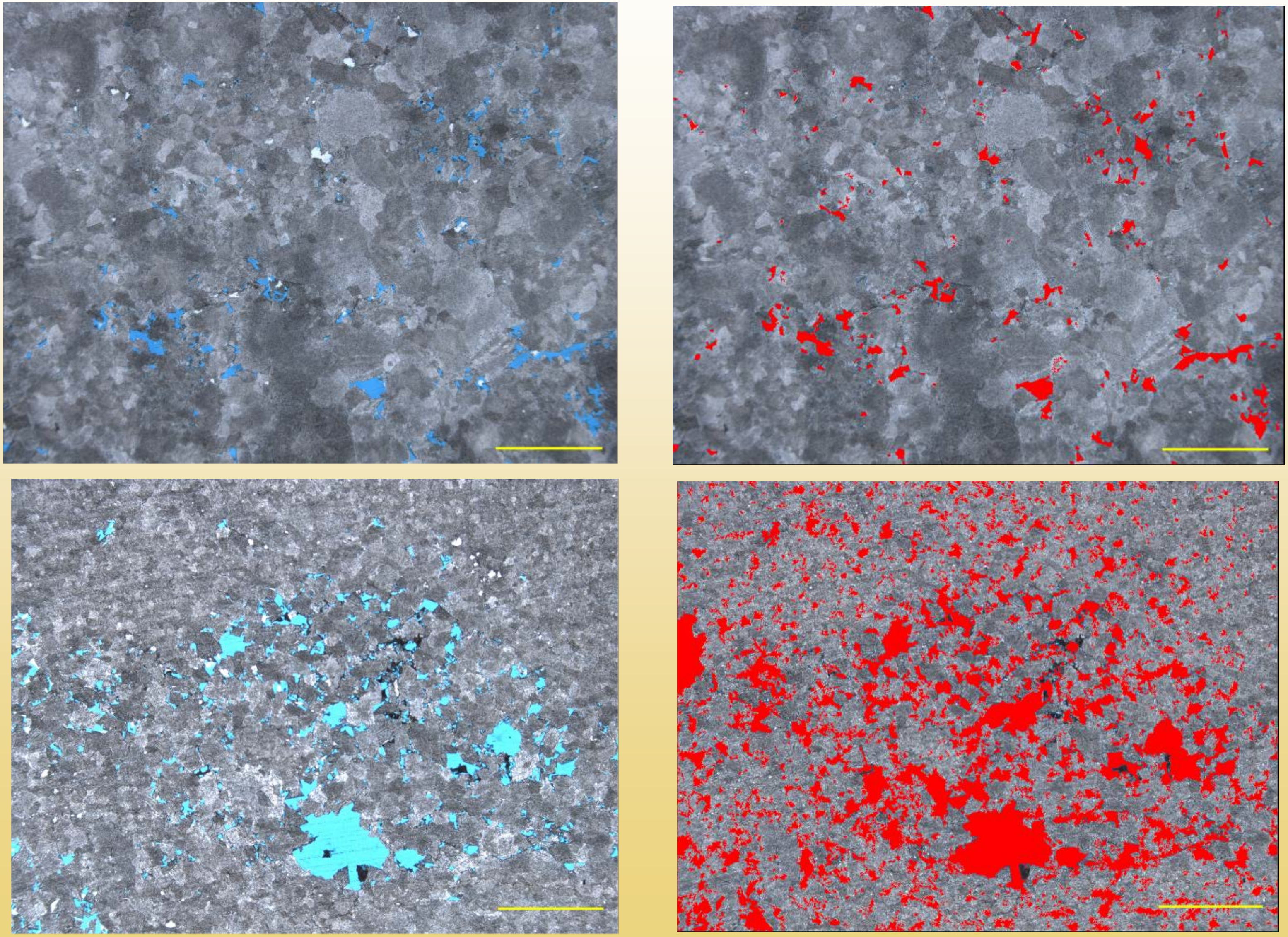
- ImagePro Plus
- Color-cube segmentation
- Can measure parameters for each pore
  - Area, length, width, roundness, perimeter
- Pore parameters (measures of pore architecture) are calculated





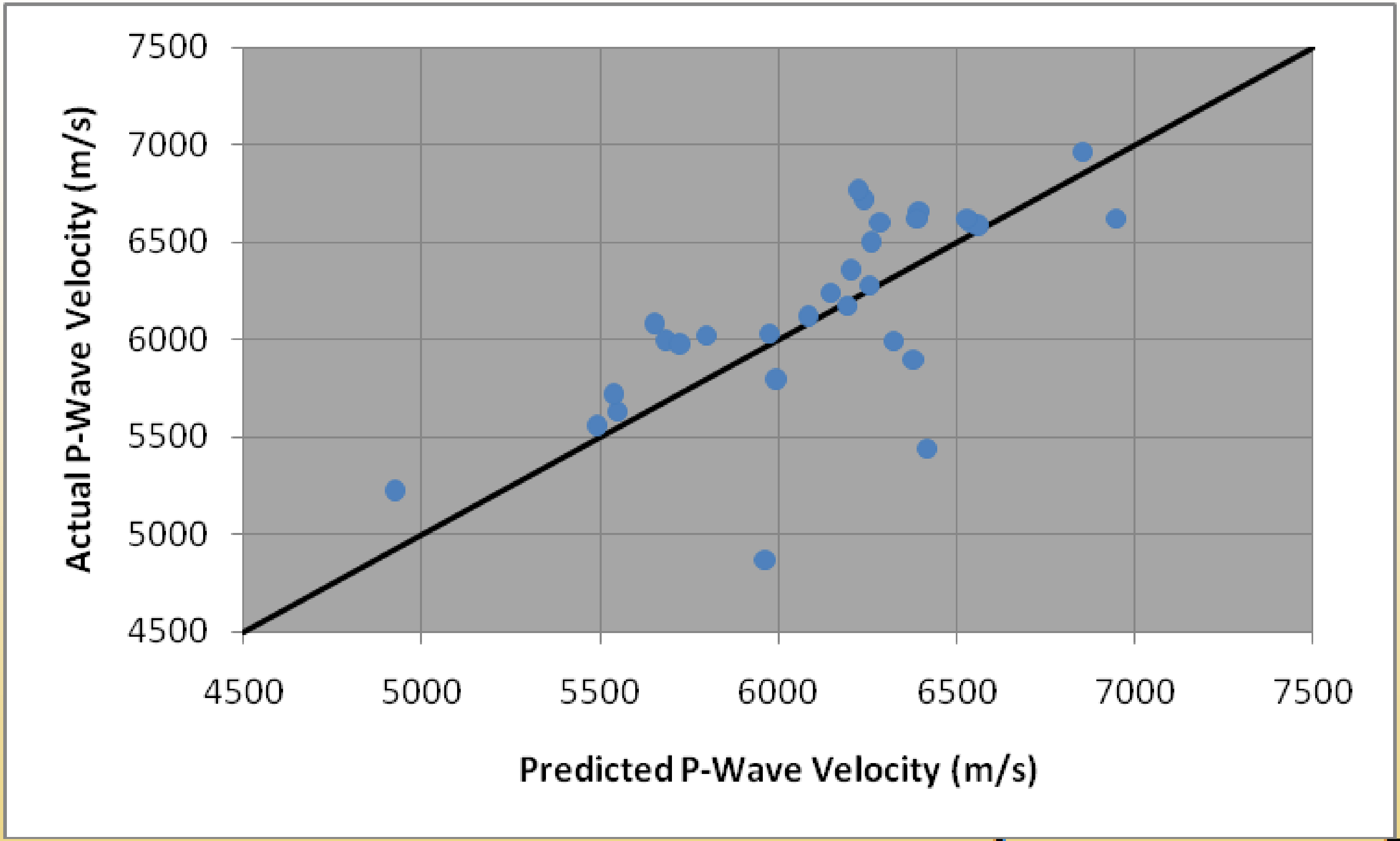
Thornton and Grammer (2010)

Image Analysis to characterize size, shape and distribution of pores in thin section



Thornton and Grammer (2010)

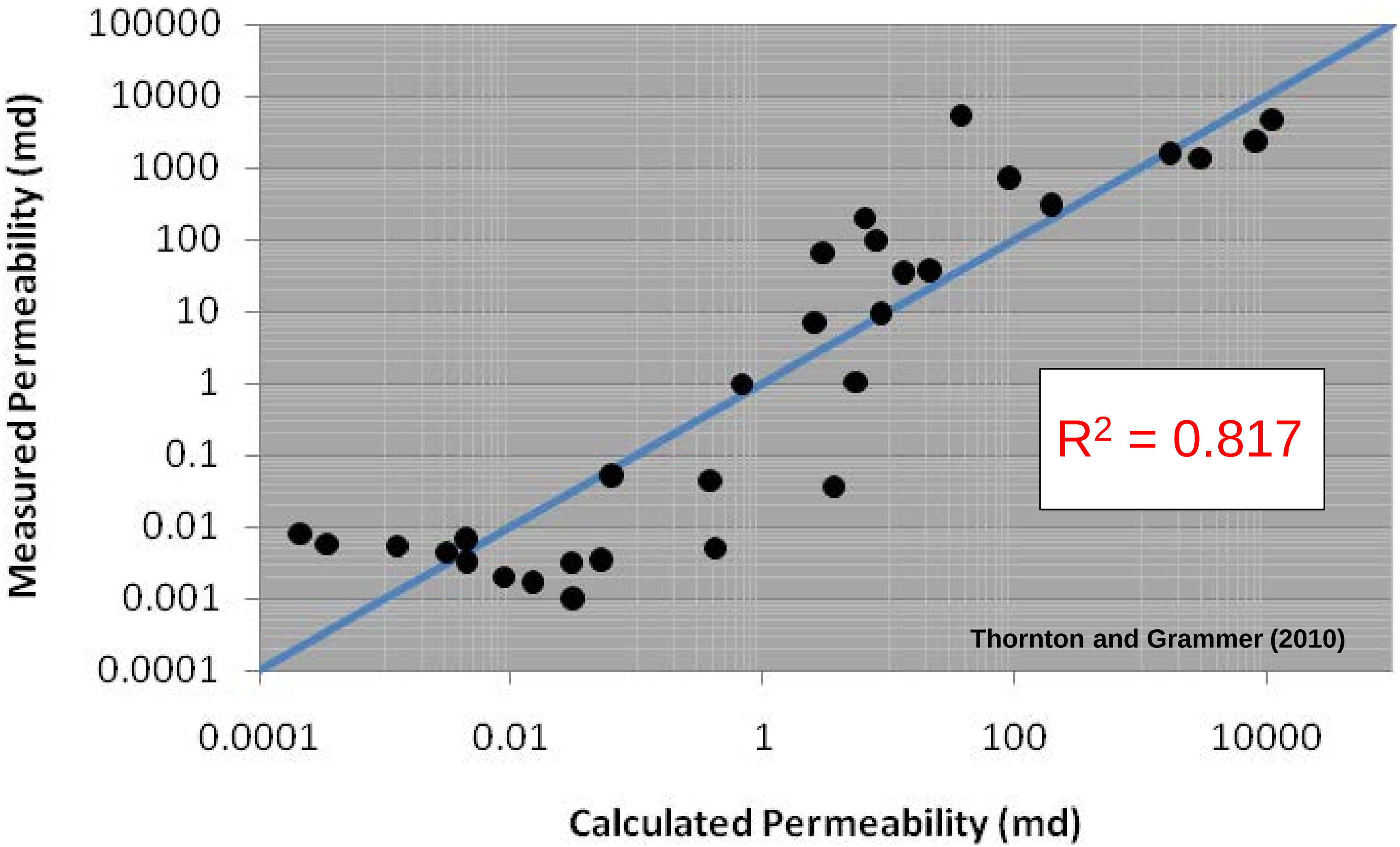
Average percent error between actual and predicted p-wave velocity = 5.31%



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

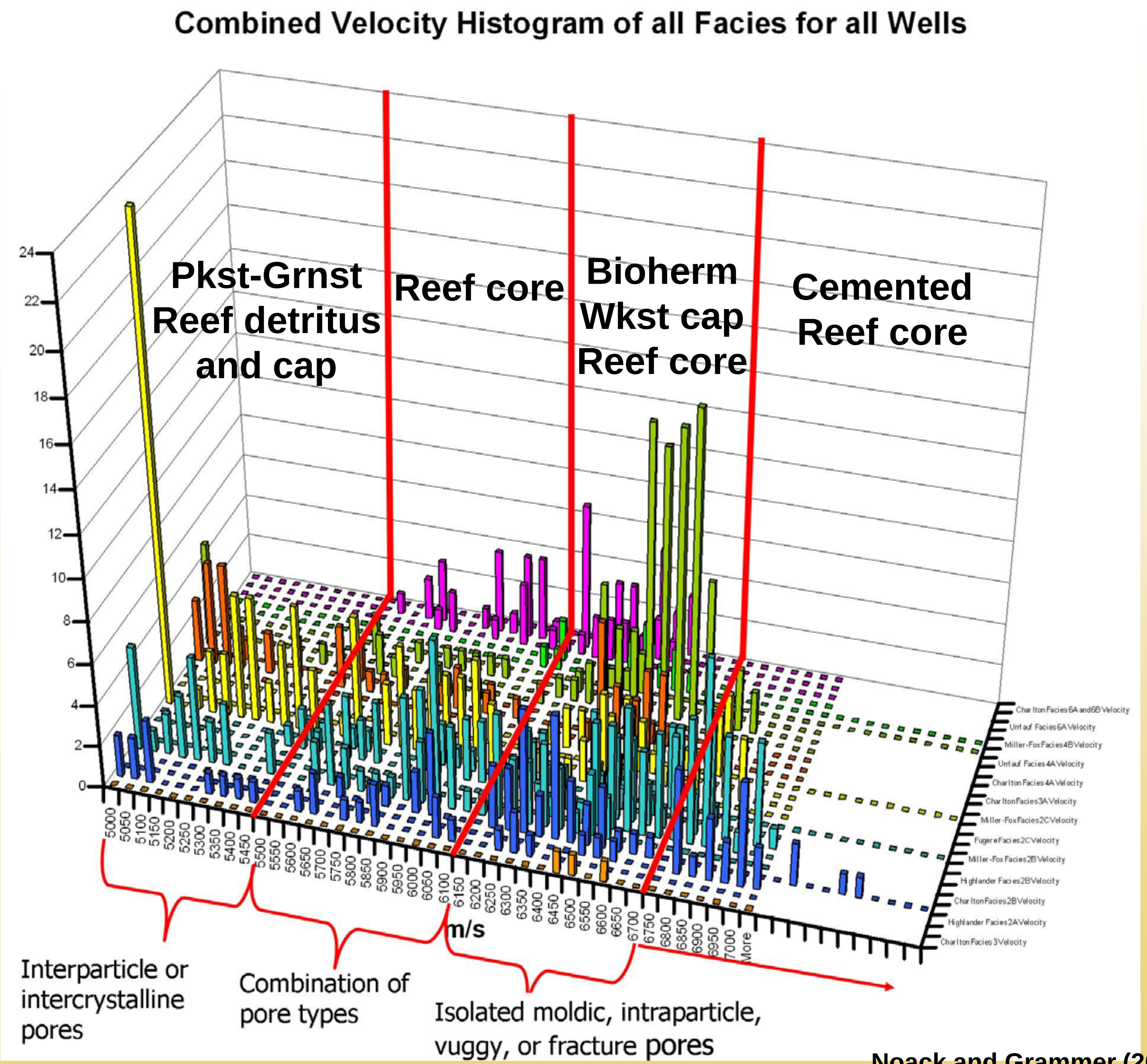
Thornton and Grammer (2010)

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



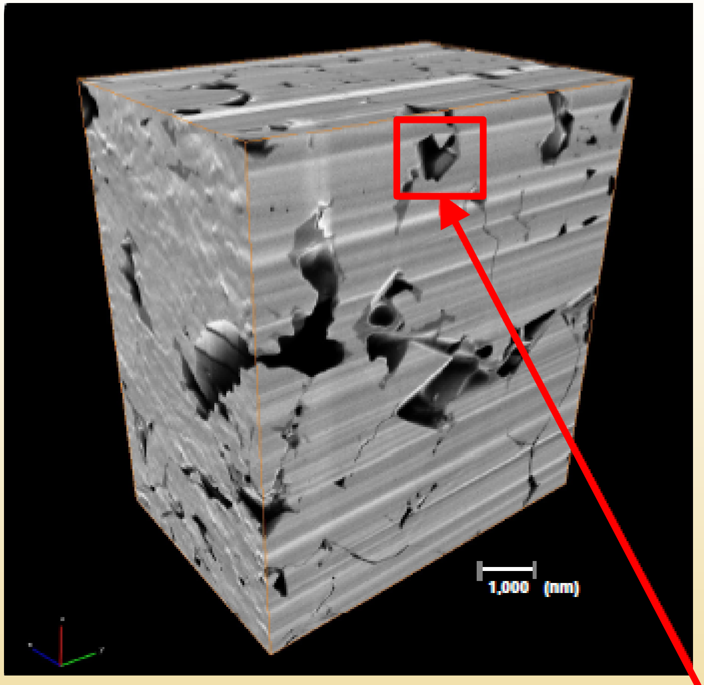
$$lnK = 3.906 lnV_p + 2.263 ln\Phi - 41.722 ln\rho_b + 3.955 ln\gamma - 0.926 lnPOA$$

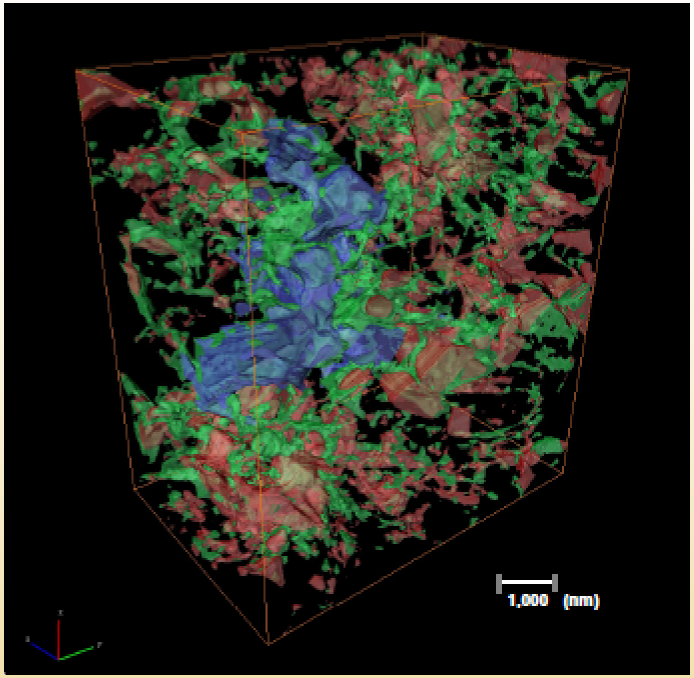
$$+ 1.005 lnAR + 0.697 lnV_s - 0.310 lnDS - 7.013$$



Noack and Grammer (2008)

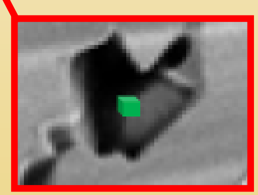
Nano-Scale Porosity and Permeability





Field Emission Scanning Electron Microscopy (SEM)

- Cube of Focused Ion Beam Cuts (15 nm Slices)
- 10 nm Resolution



Cube = 1,000,000 Oil Molecules

Connected Pore Network

- 1,300 nD Permeability

Courtesy R. Garrison

Summary – Some General Thoughts and Trends for Carbonate 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 sonic velocity, may lend insight into the acoustic properties of different reservoir and non-reservoir facies.
5. Modern and ancient analogs may provide critical understanding of process, geometry and evolution of carbonate reservoirs.