An Integrated Approach to Characterization and Modeling of Carbonate Reservoirs*

G. Michael Grammer[1]

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[1]Chesapeake Energy Chair of Petroleum Geology, Oklahoma State University, Stillwater (michael.grammer@okstate.edu)

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-log, 3D seismic data and the incorporation of both modern and ancient analogs. Examples from the Michigan Basin and other productive basins provide a means to review the controls on carbonate reservoir heterogeneity, ranging from the pore architecture scale to geometrical attributes of flow units at the reservoir-scale and to discuss how these parameters can be incorporated and integrated into the development of viable, petrophysically based reservoir models of carbonate reservoirs.

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An Integrated Approach to the Characterization and Modeling of Carbonate Reservoirs

G. Michael Grammer

Chesapeake Energy Chair of Petroleum Geology
Boone Pickens School of Geology
Oklahoma State University

NATIONAL ENERGY TECHNOLOGY LABORATORY

RPSEA
Research Partnership to Secure Energy for America

OKLAHOMA STATE UNIVERSITY

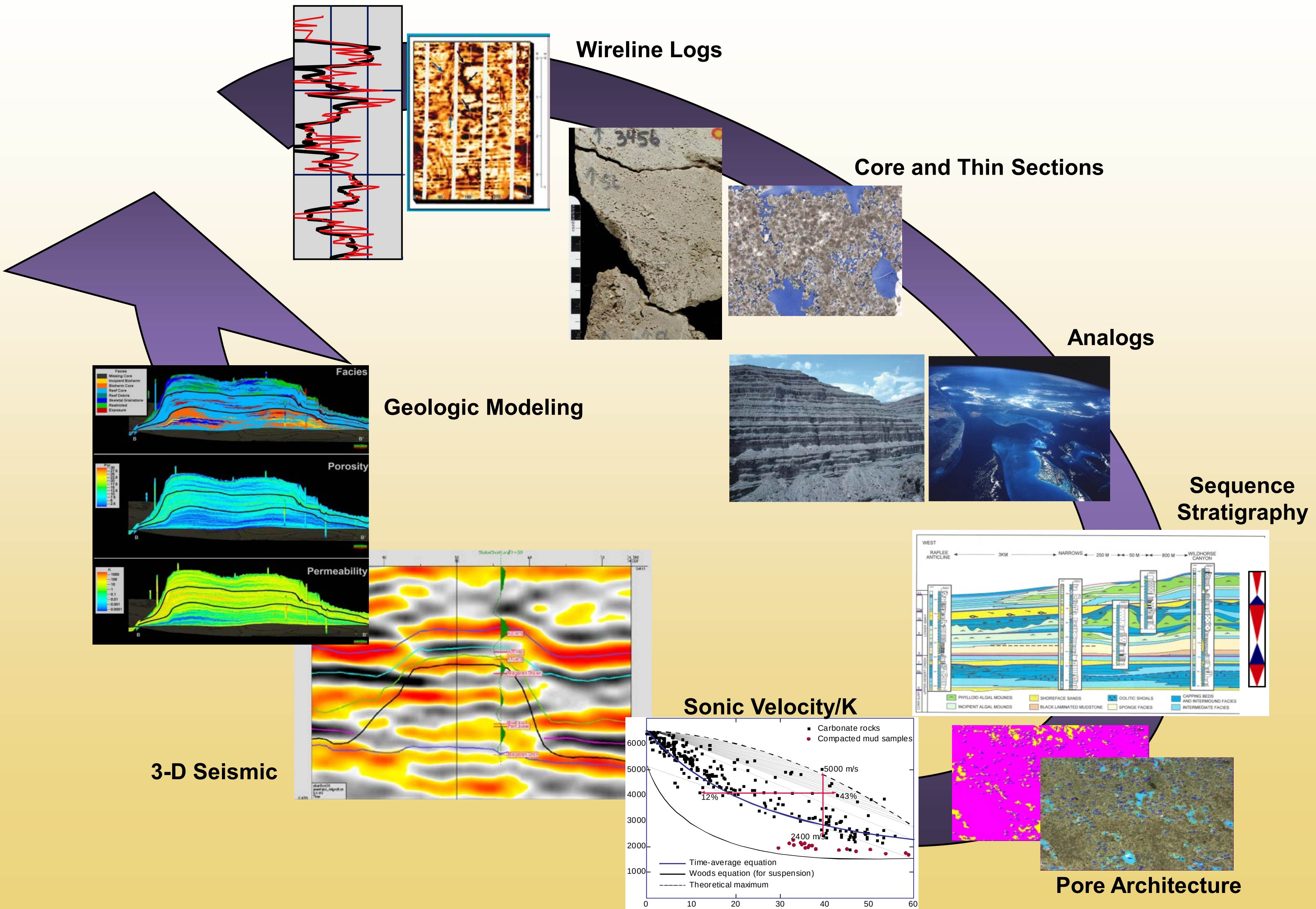
Geologically Constrained Reservoir Characterization – Is it worth the effort?

“The use of *oversimplified geological models* based on data from a limited number of widely spaced wells is probably one of the most important reasons for the failures in predicting field performance.”

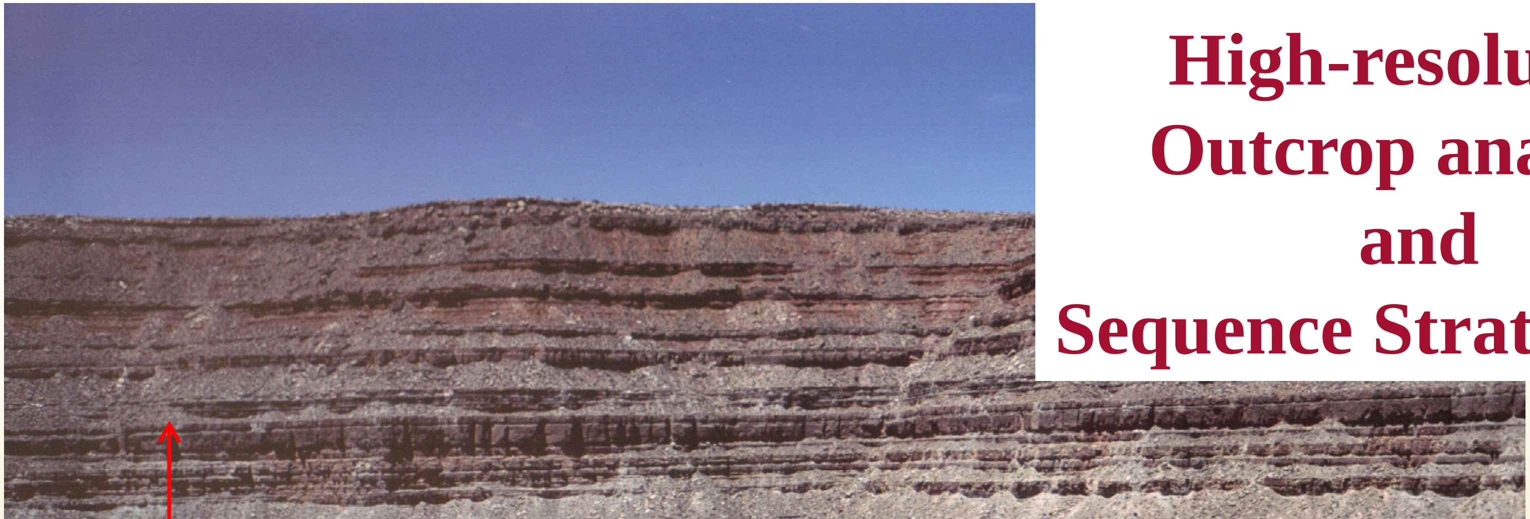
Damsleth et al.
JPT (April 1992)

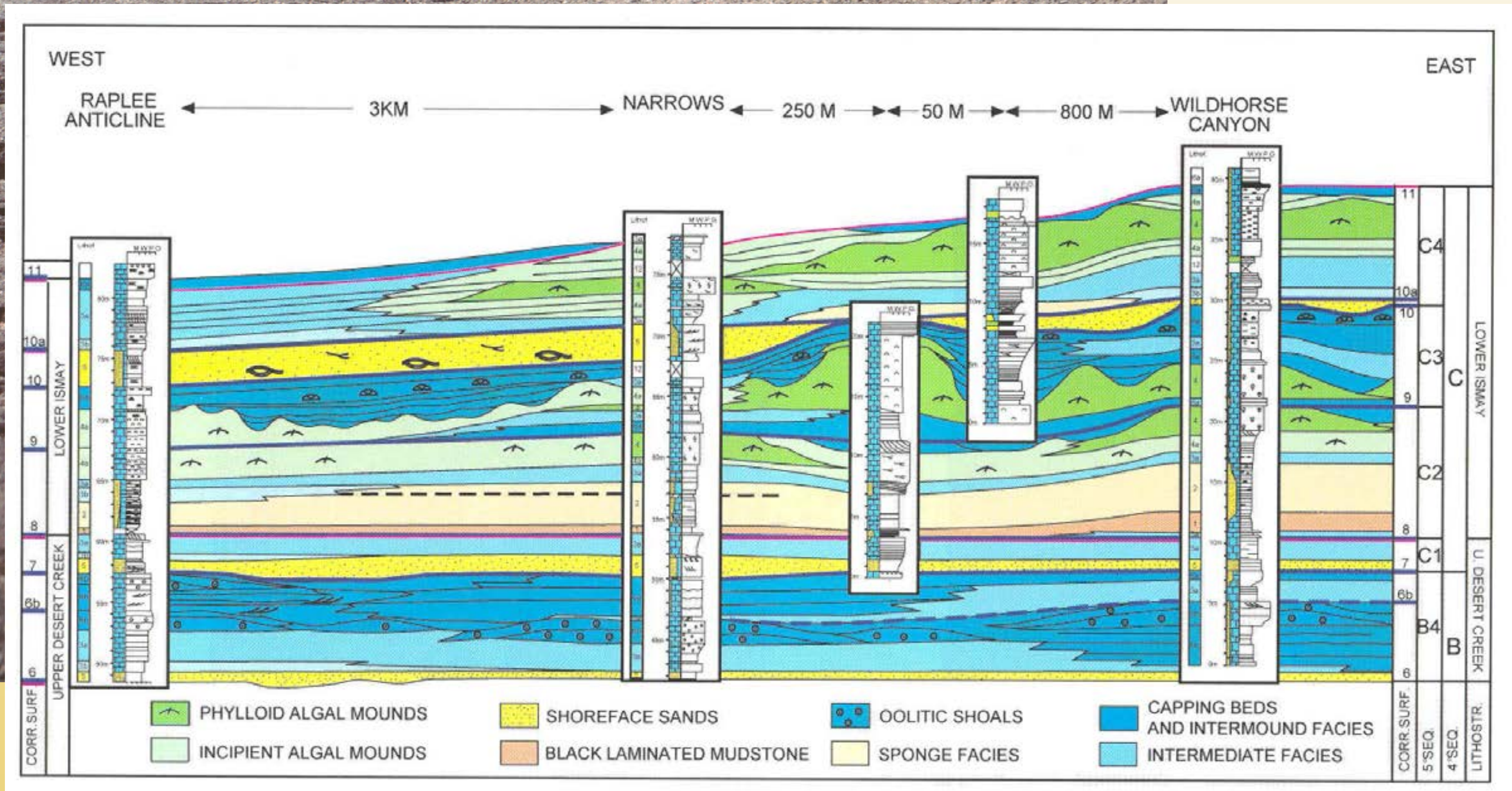
Especially true in carbonates, which are typically very heterogeneous, both laterally and vertically at both exploration and production scales!!!

Integrated Reservoir Characterization



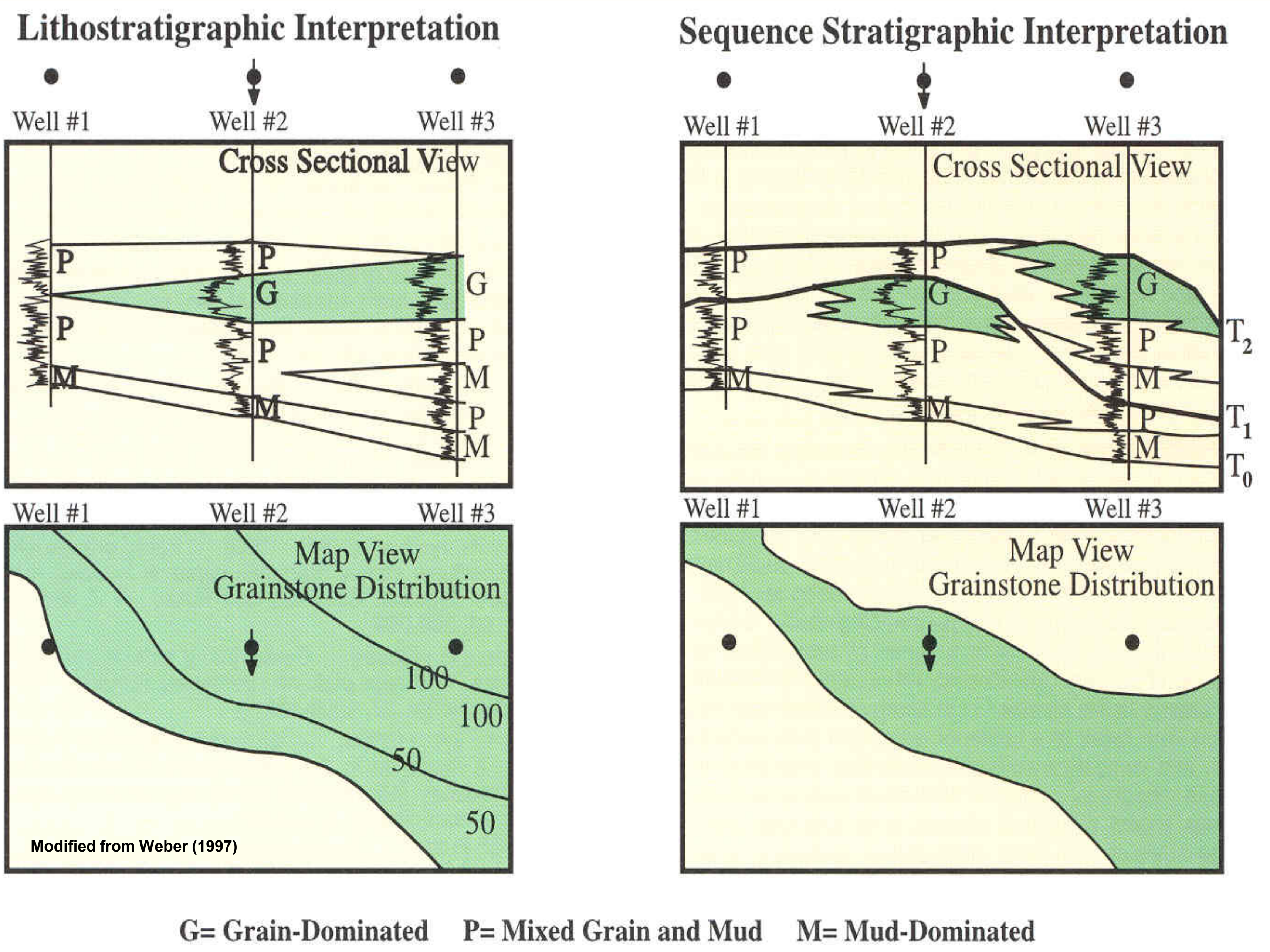
High-resolution Outcrop analysis and Sequence Stratigraphy

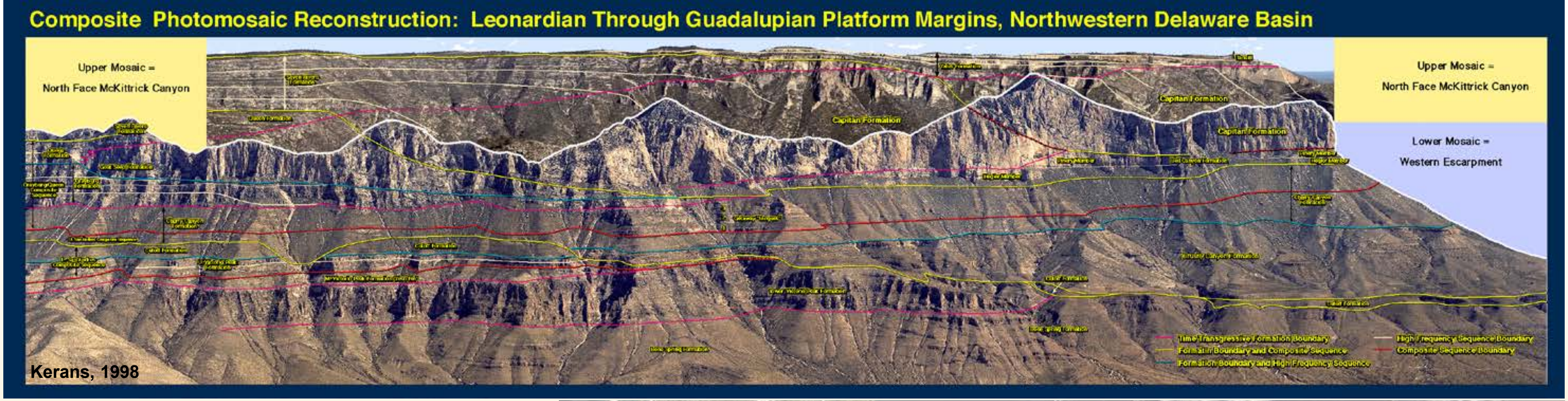




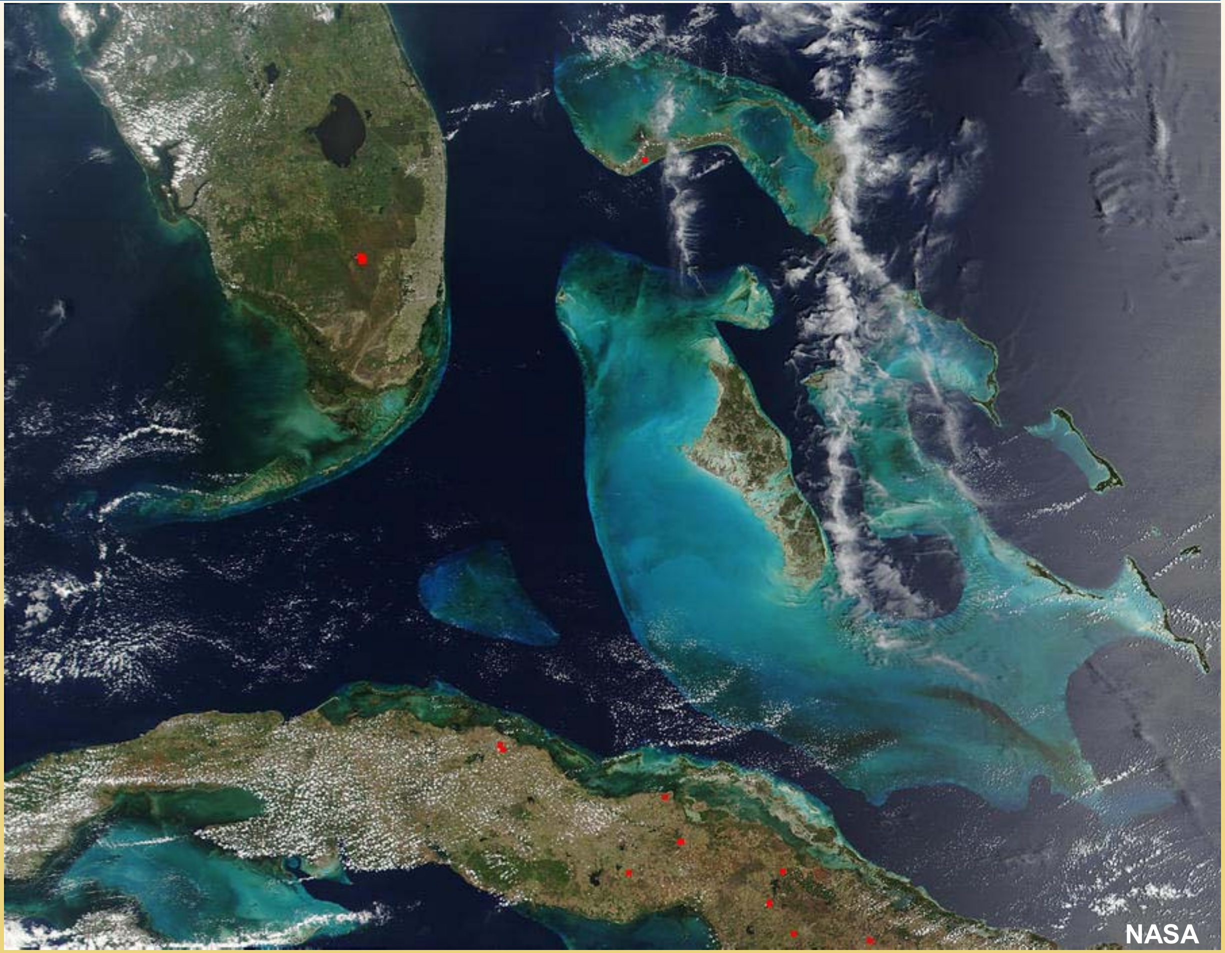
Grammer et al. (1996, 2002)

Sequence Stratigraphy for Reservoir Characterization

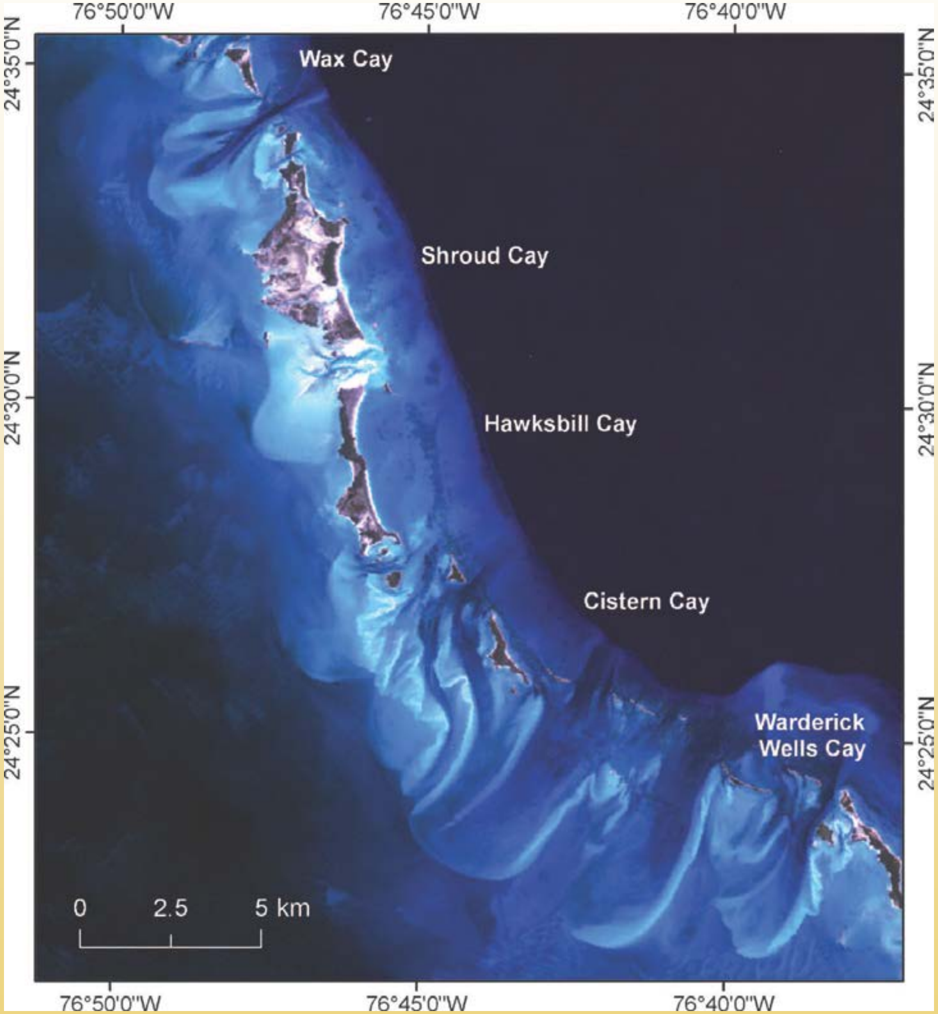


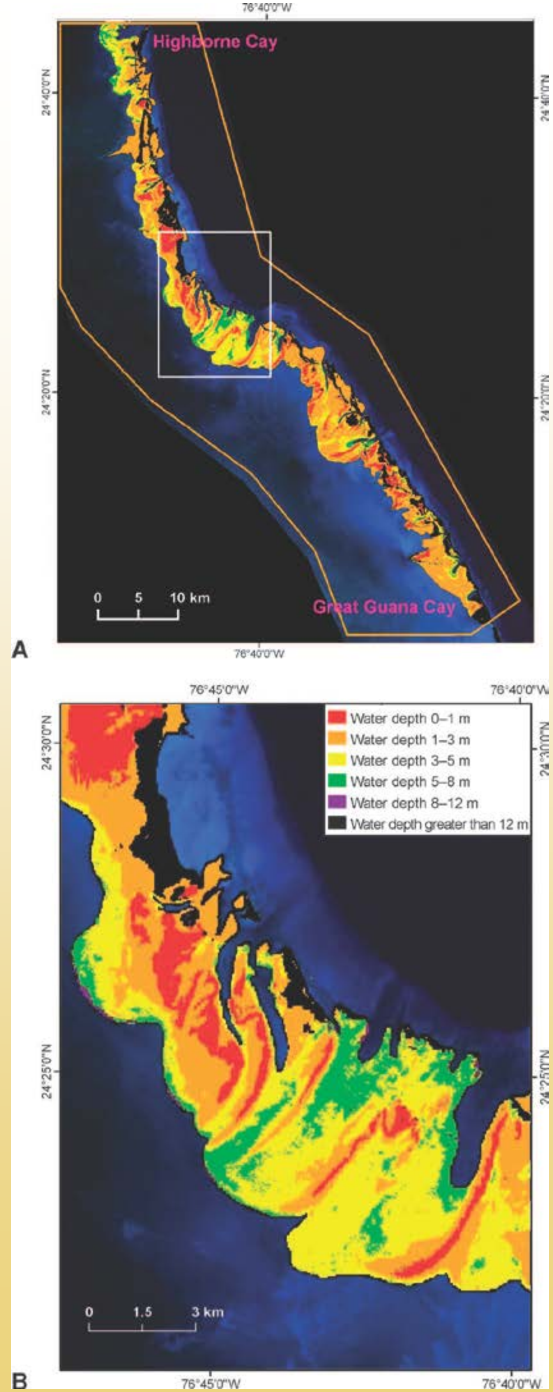


Importance of Combining Outcrop and Modern Analogs



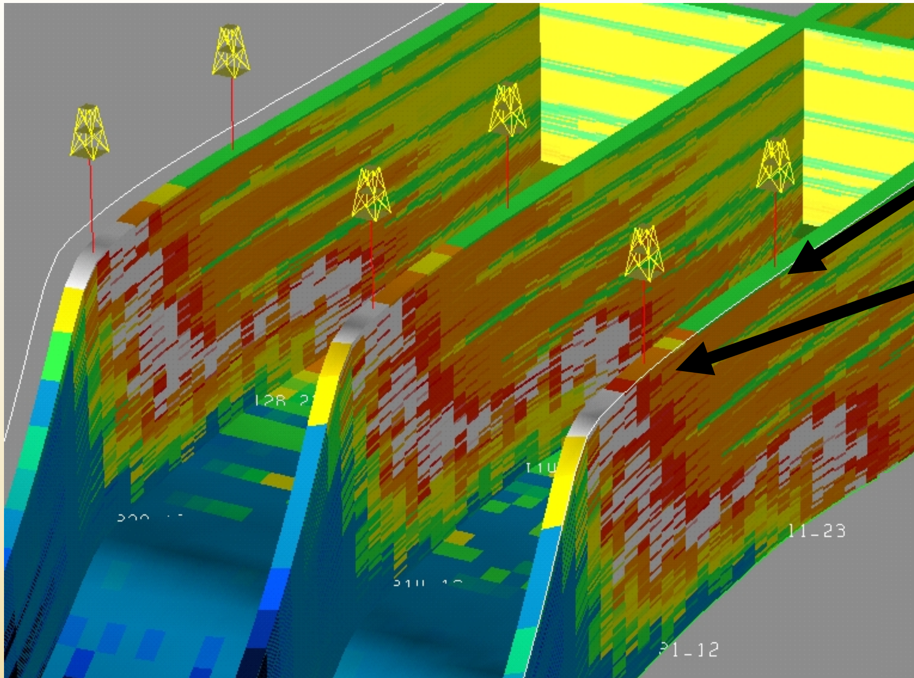
Detailed Facies Mapping from Ground-truthed Satellite Images (ex. Exumas, GBB)





Harris (2010)

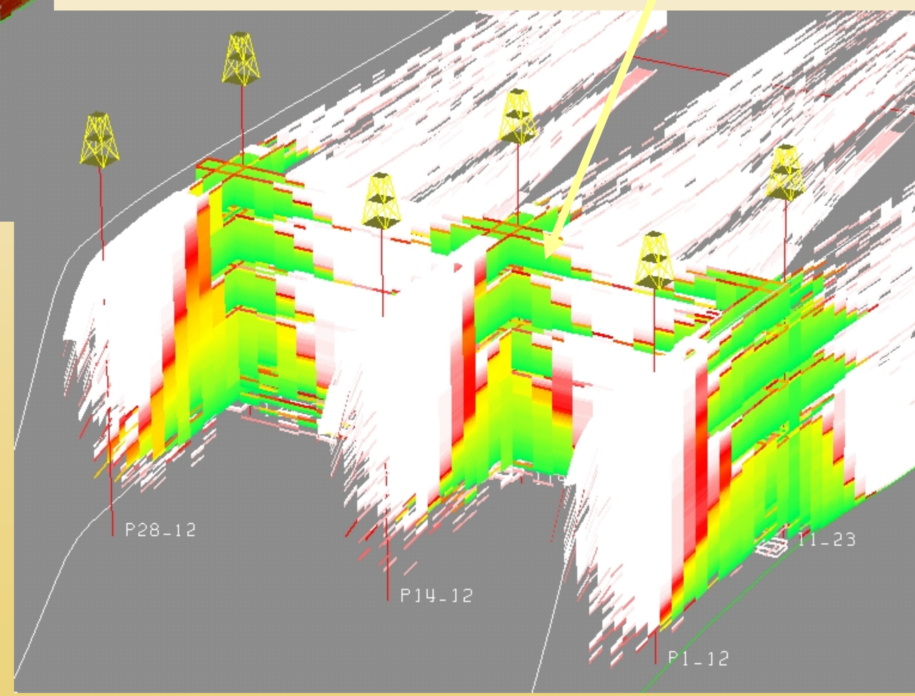
Stratigraphic and Flow Simulation Modeling



Line of Injectors

Line of Producers

Vertical flow up reef tract (high Kx, Kz in this model)



Water front moving away from injectors (green). Note flow constrained by vertical facies boundaries.

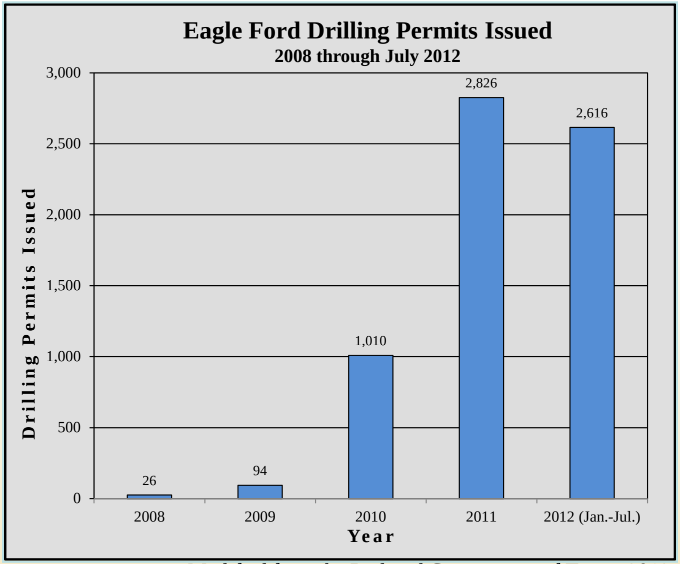
Courtesy of P.M. Harris

Reservoir Characterization – An Integrated Approach

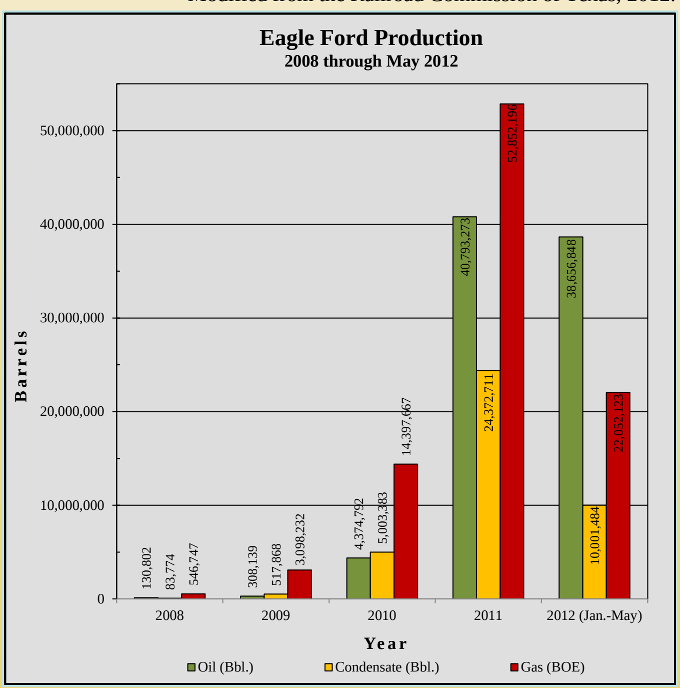
- Interpretation of lithofacies and depositional environment
- Original porosity & permeability
  - modification potential
- Sequence stratigraphic framework
- Stacking patterns tied to wireline logs
- Reservoir geometry (lateral & vertical distribution)
- Pore network characterization & petrophysical effects
- Distribution of reservoir flow units
- Reservoir modeling

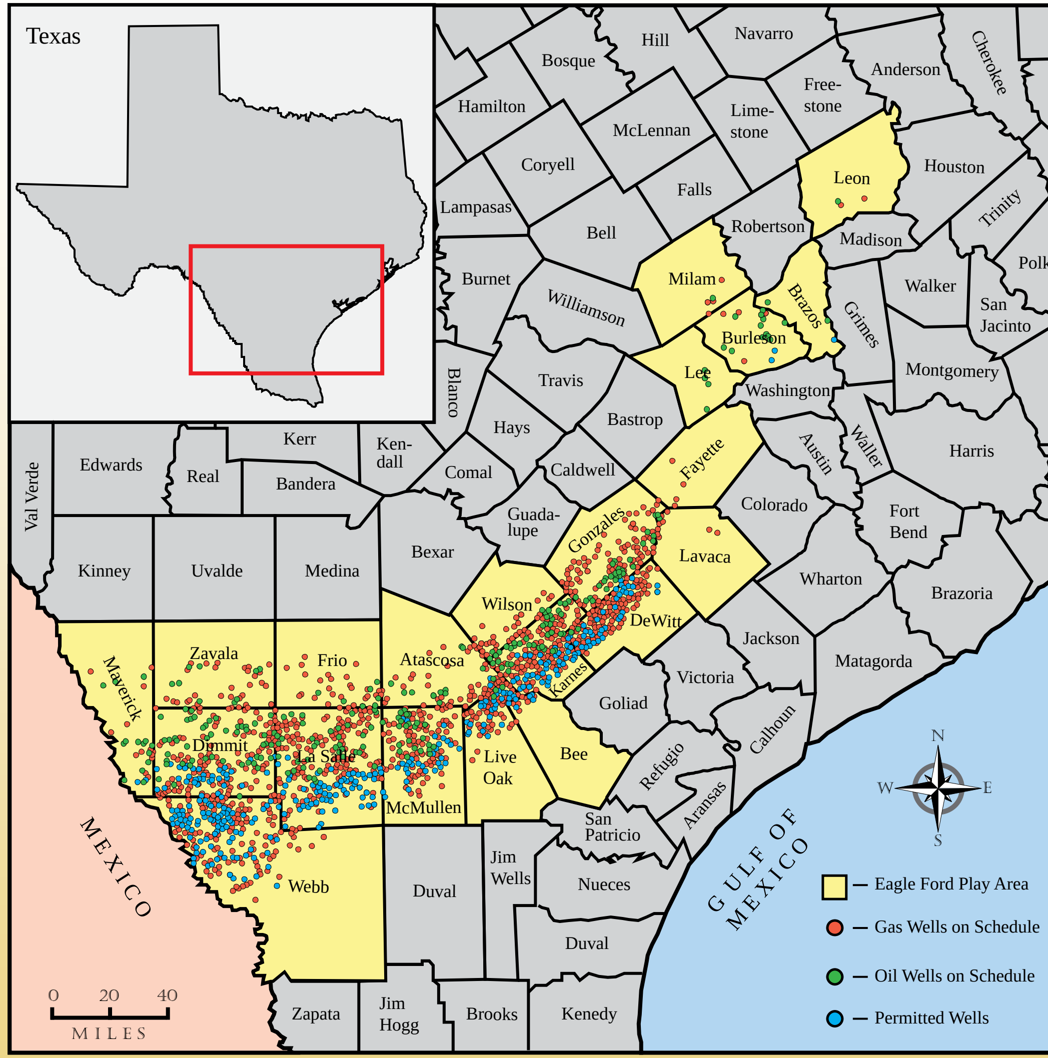
Data Input: Seismic (3-D), Wireline Logs, Cores, Cuttings, Modern and Ancient Analogs, Modeling

Example - Eagle Ford Shale Play



Modified from the Railroad Commission of Texas, 2012.



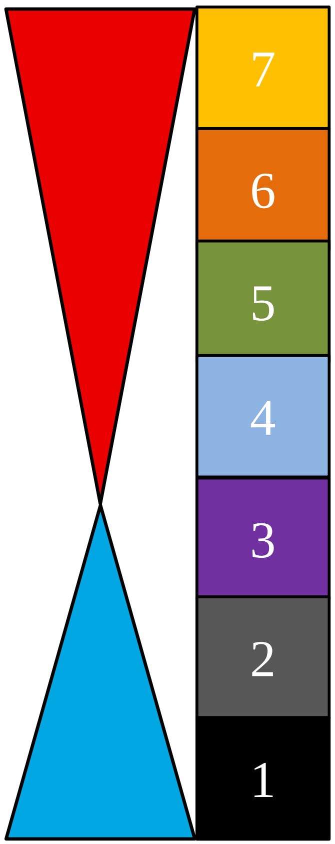


Modified from the Railroad Commission of Texas, 2011.

- **Explain Lateral and Vertical Heterogeneity**
- **Predict Vertical Compartmentalization (Seq Strat in Deep Water CO3's?)**

Eagle Ford “Shale”
Vertical Stacking Patterns and Sequence Stratigraphic Framework

Idealized Facies Succession



Facies 7: Foraminiferal Packstone to Grainstone

Facies 6: Skeletal Packstone to Wackestone

Facies 5: Laminated Inoceramid and Foraminiferal Wackestone to Packstone

Facies 4: Bioturbated Skeletal Lime Wackestone

Facies 3: Laminated Foraminiferal Wackestone

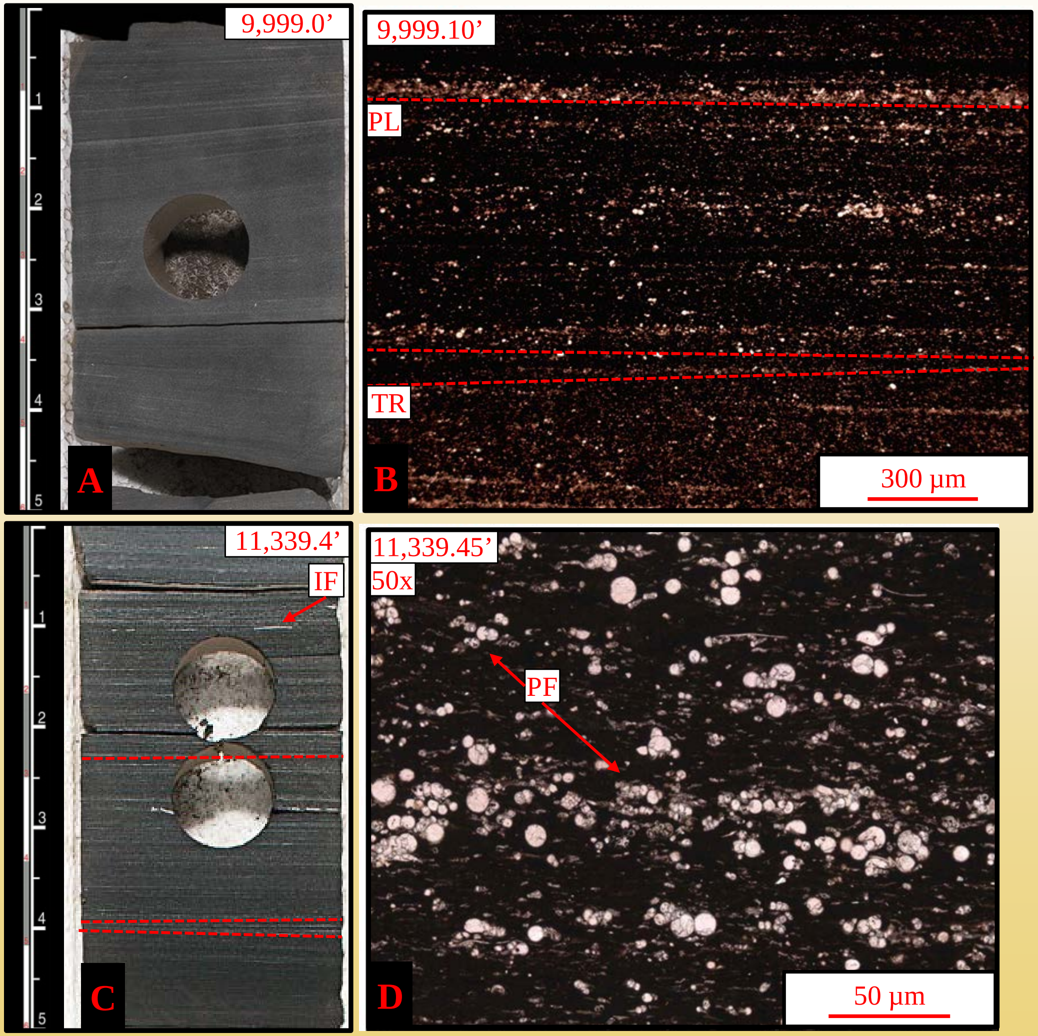
Facies 2: Weakly Laminated Calcareous Foraminiferal Mudstone

Facies 1: Laminated Argillaceous Mudstone

Workman and Grammer (2013)

Eagle Ford: Reservoir Facies

- Laminated Foram Wkst
  (3-5% ϕ / 2-6 nD)
- Late transgressive- to early highstand- deposits near storm wave base.
- Light- to medium- grey
- Organic-rich
- Planktonic foram tests form mm-scaled traction laminae with erosive bases indicative of reworking by weak contour currents.



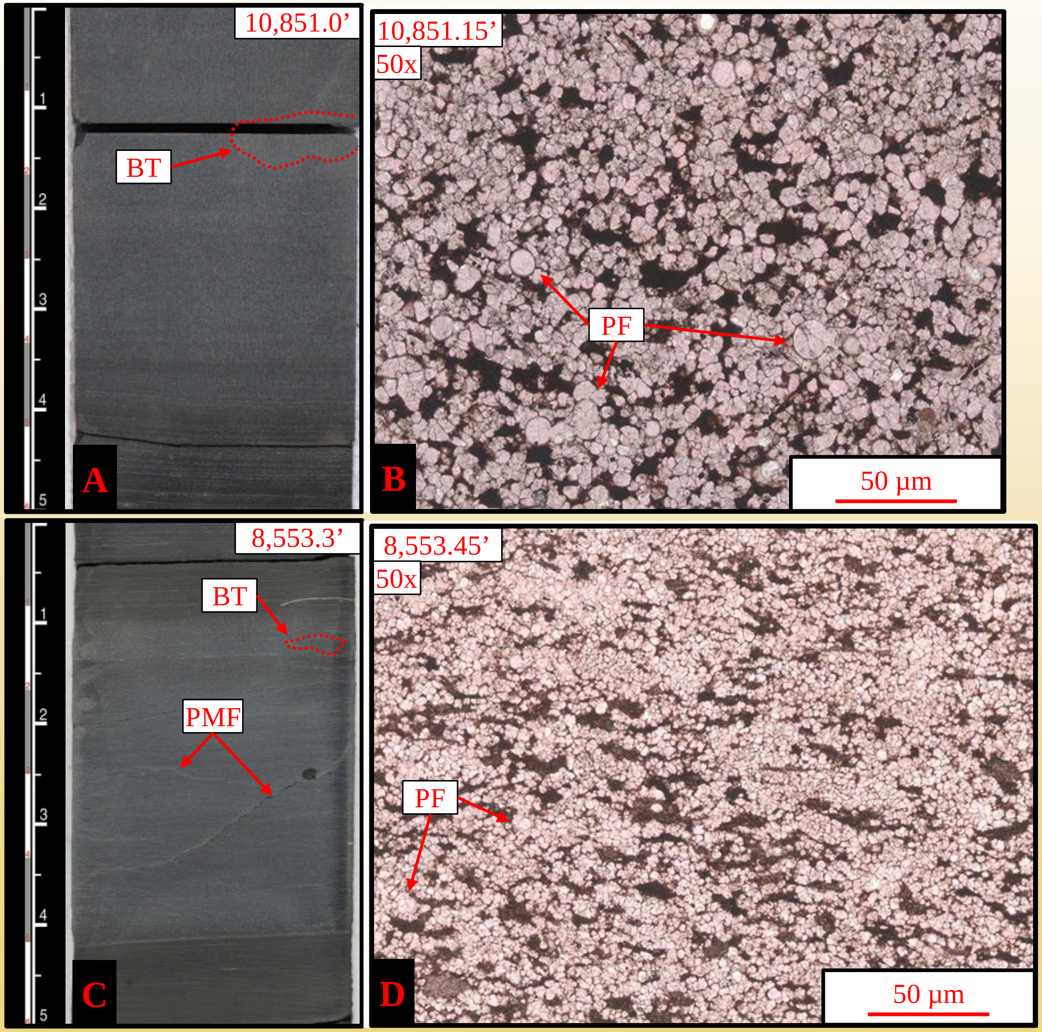
Dominant Mineralogy (Avg. %)			TOC
Clays	Quartz	Calcite	(Avg. %)
11.80 (n=27)	9.19 (n=27)	71.47 (n=27)	2.46 (n=12)

Workman and Grammer (2013)

Eagle Ford: Intra-formational Seal

- Foram Pkst/Grnst
  (~2% ϕ / 1-2 nD)
- Light grey & highly cyclic (m scale)
- Mid- to upper slope, latest highstand deposits
- Well lithified beds (3-10’s of cm thick) of planktonic foram tests.
- Brittle

Dominant Mineralogy (Avg. %)			TOC
Clays	Quartz	Calcite	(Avg. %)
4.63 (n=15)	7.56 (n=15)	84.19 (n=15)	0.57 (n=2)



Workman and Grammer (2013)

Sequence Stratigraphy in “deep water” Carbonates

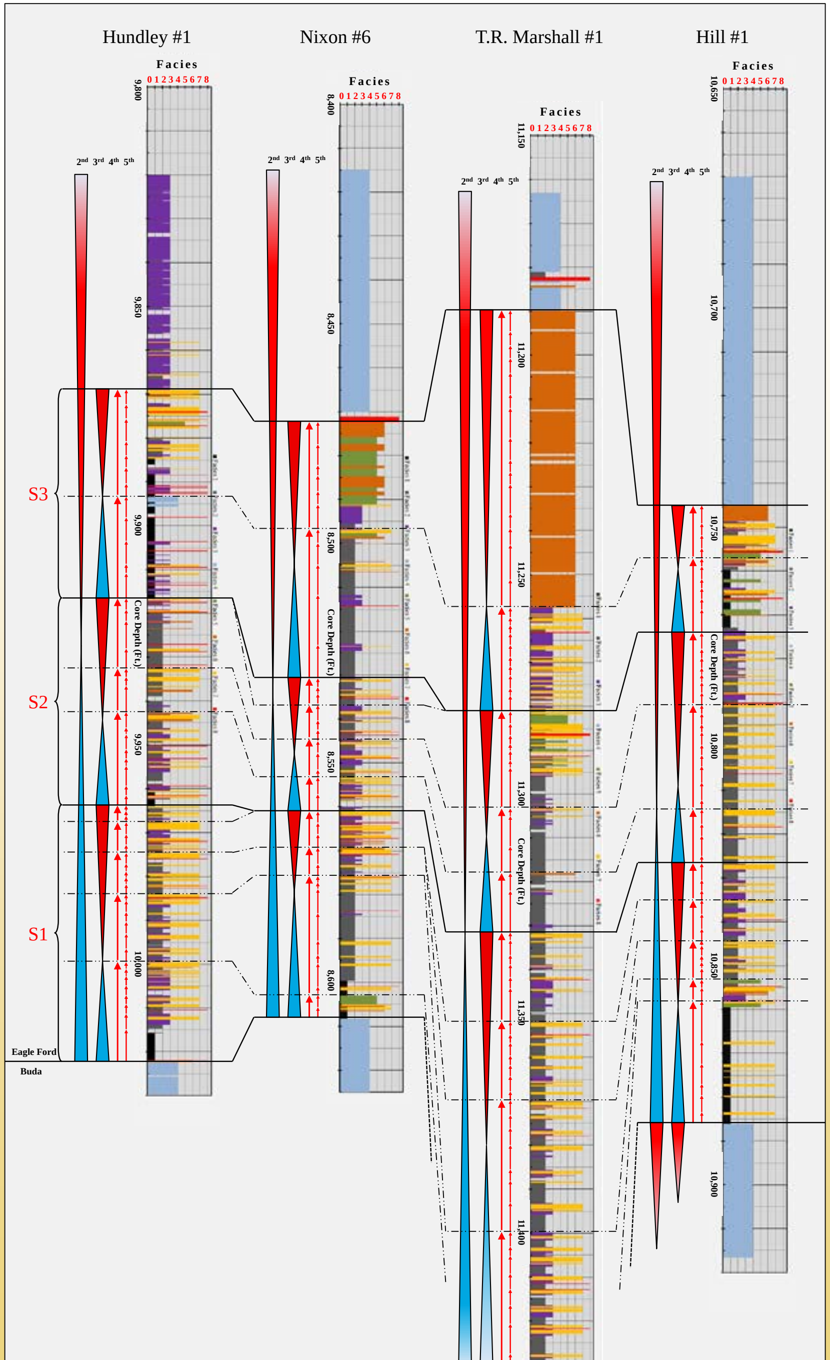
<u>4th Order HFS’s</u>:

- Total of 39 HFS’s, shallowing-upward sequences

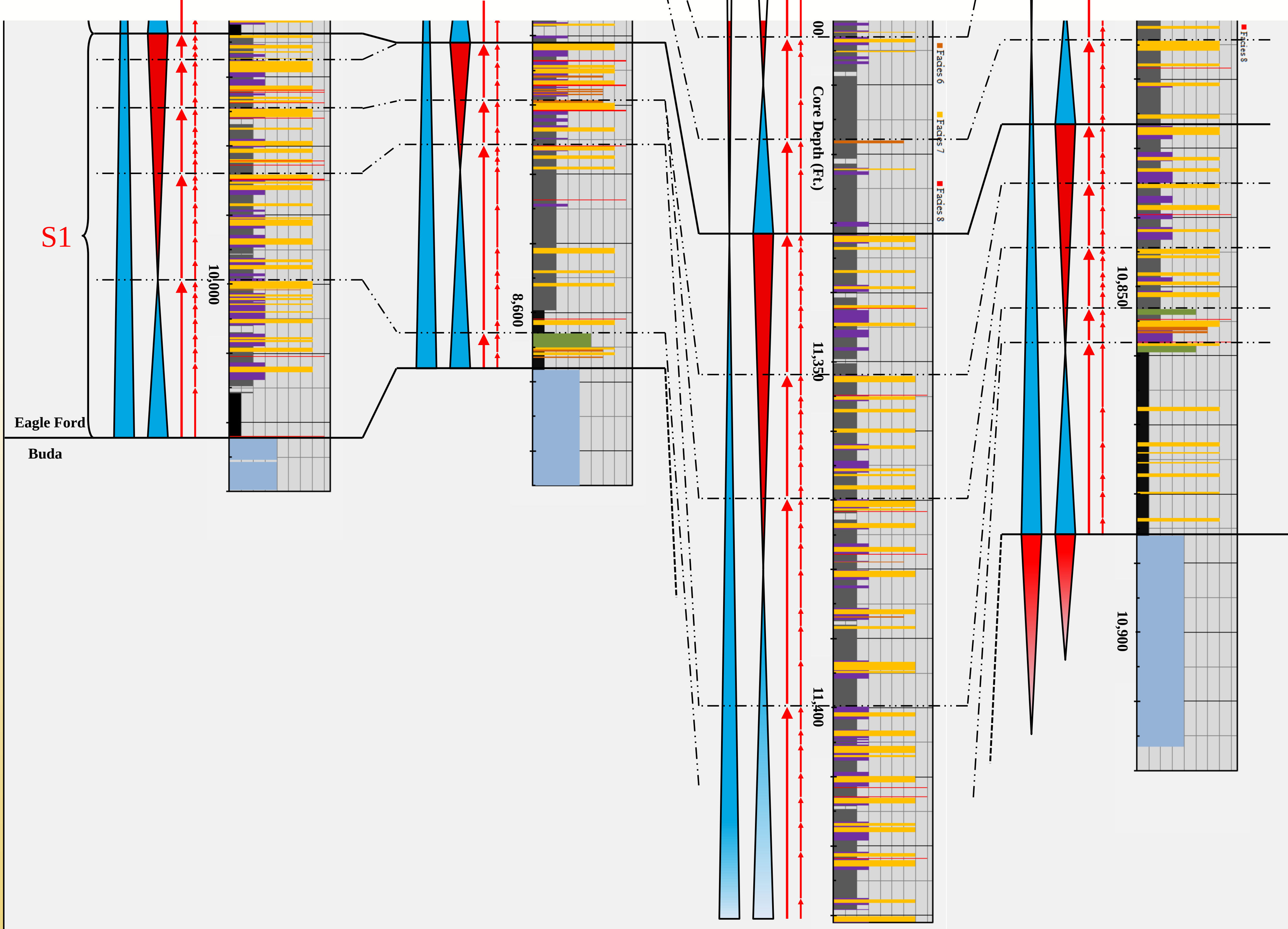
- Thickness related to structural setting.

- Influence of allocyclic and autocyclic processes.

- **Use for the correlation and evaluation of the lateral and vertical variability and continuity of facies belts (potential reservoir units and seals).**

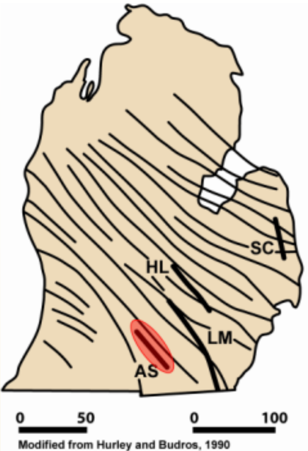


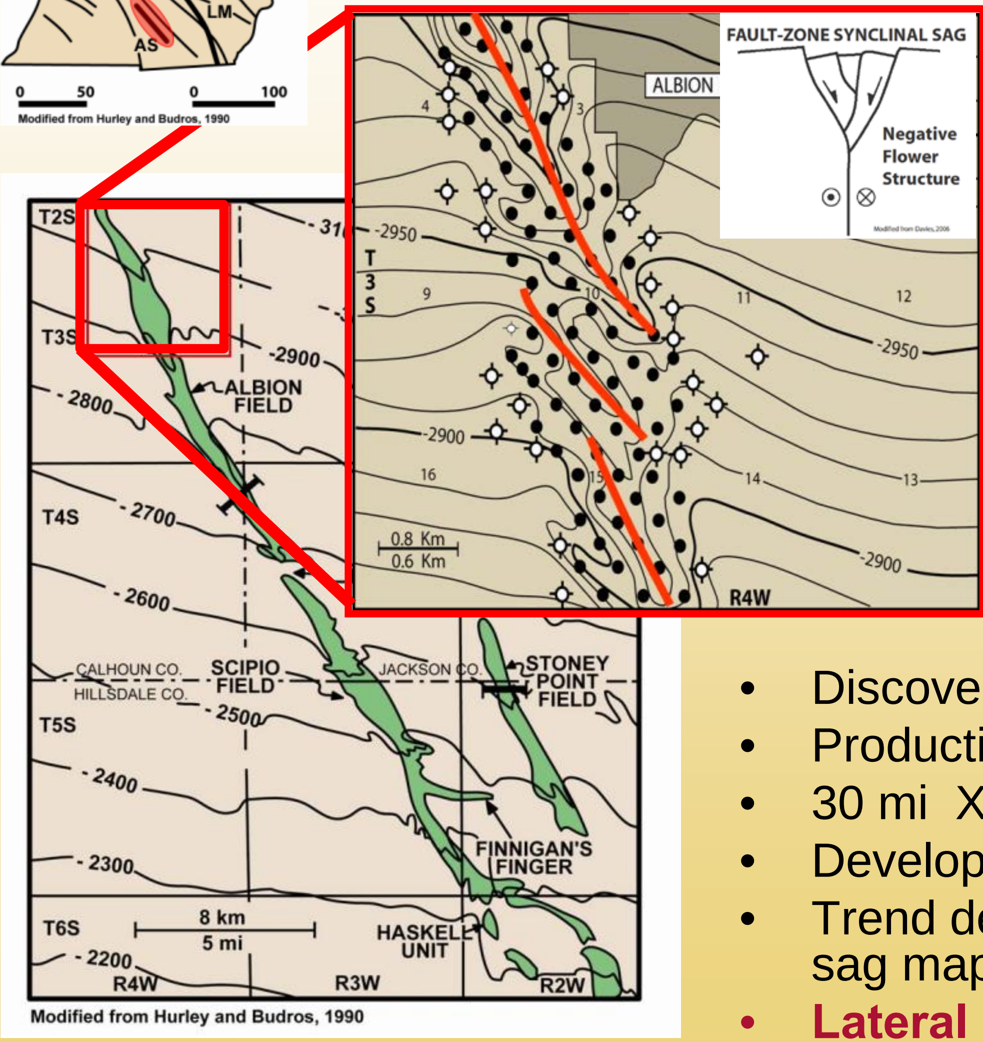
Workman and Grammer (2013)

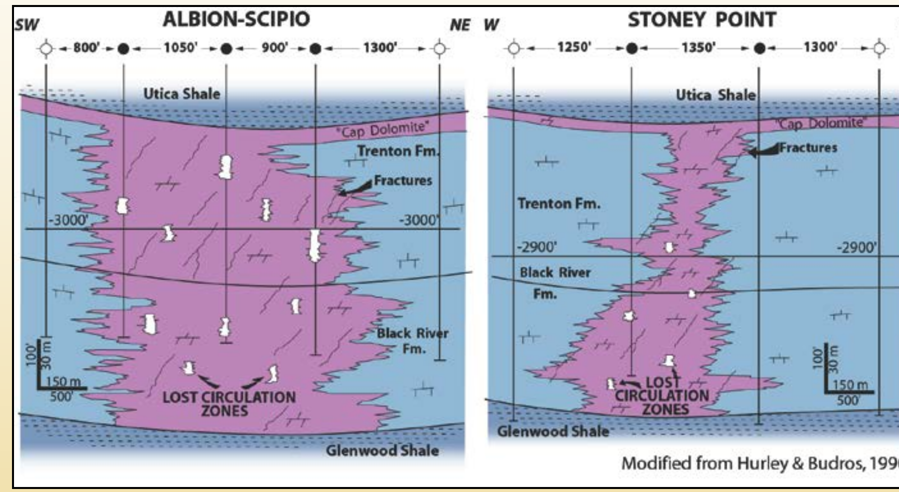


Workman and Grammer (2013)

Example:
Albion-Scipio Trend (HTD)

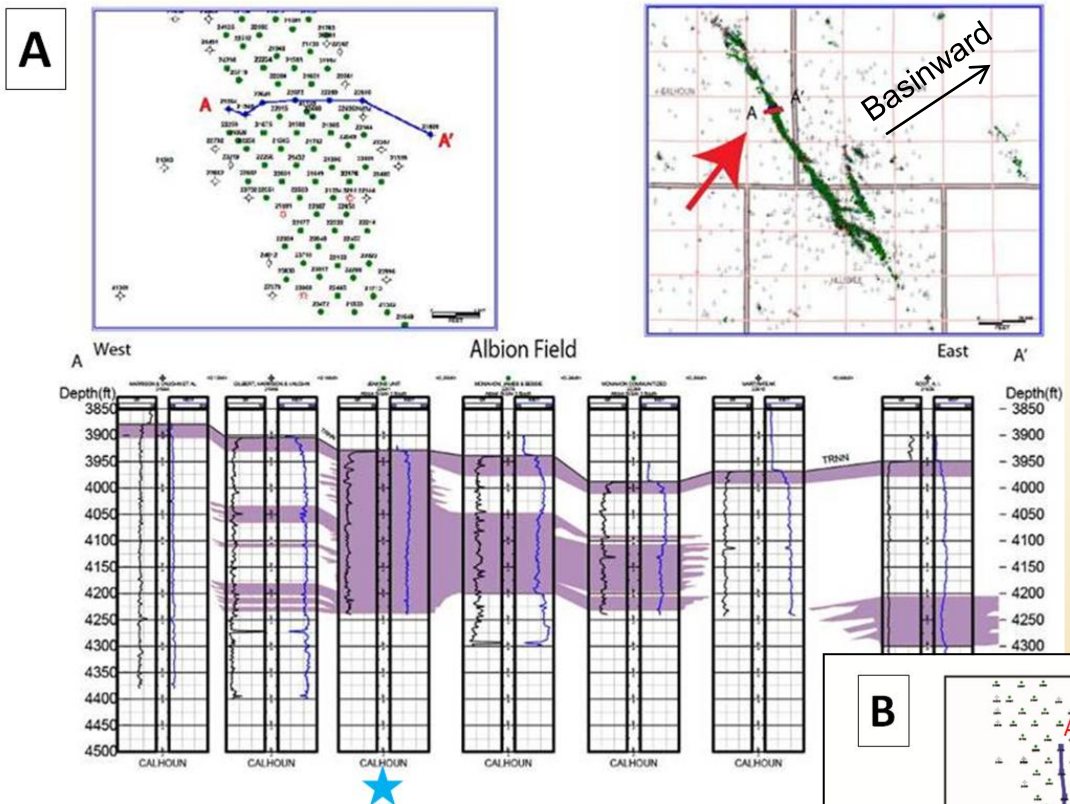


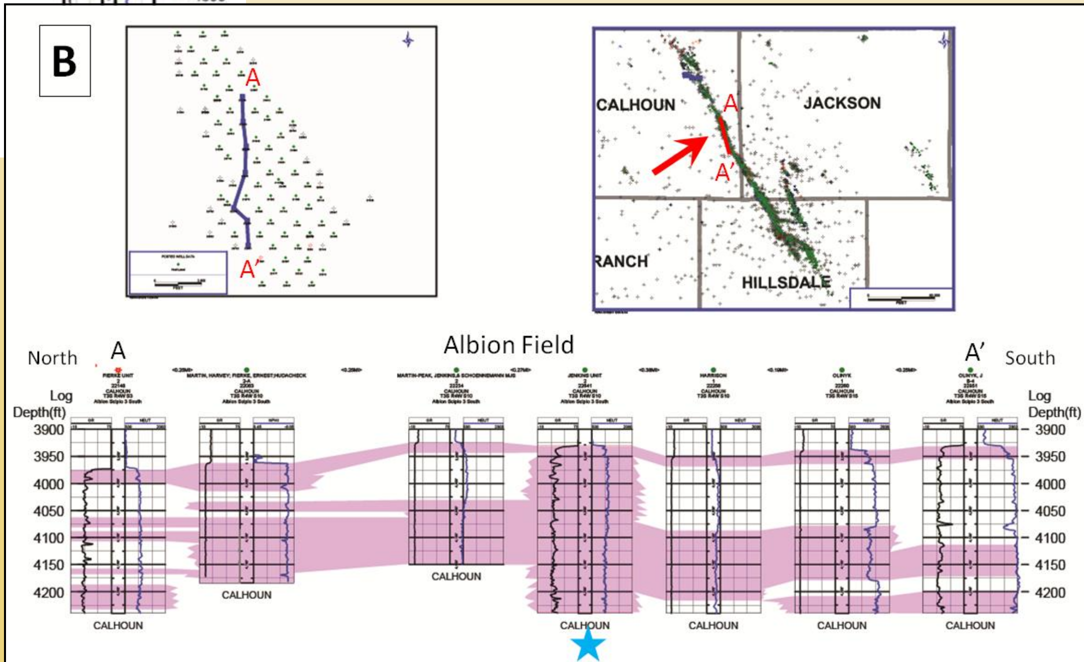




- Discovered in 1957
- Production: >147 MMBO, 260 BCF (A-S)
- 30 mi X 1 mi
- Developed on 20-acre spacing
- Trend development based primarily on structural sag mapping
- **Lateral and Vertical Heterogeneity**

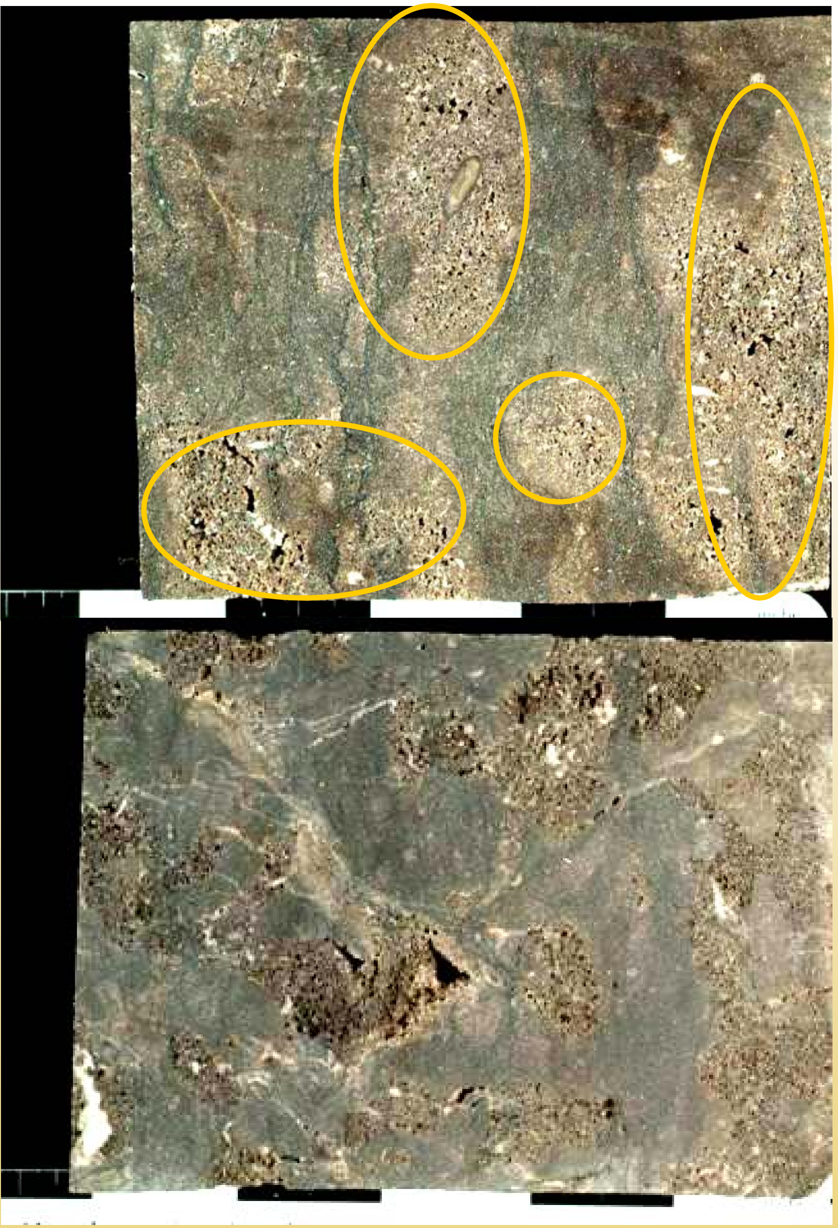
Lateral Distribution of HTD in AlbioScipio

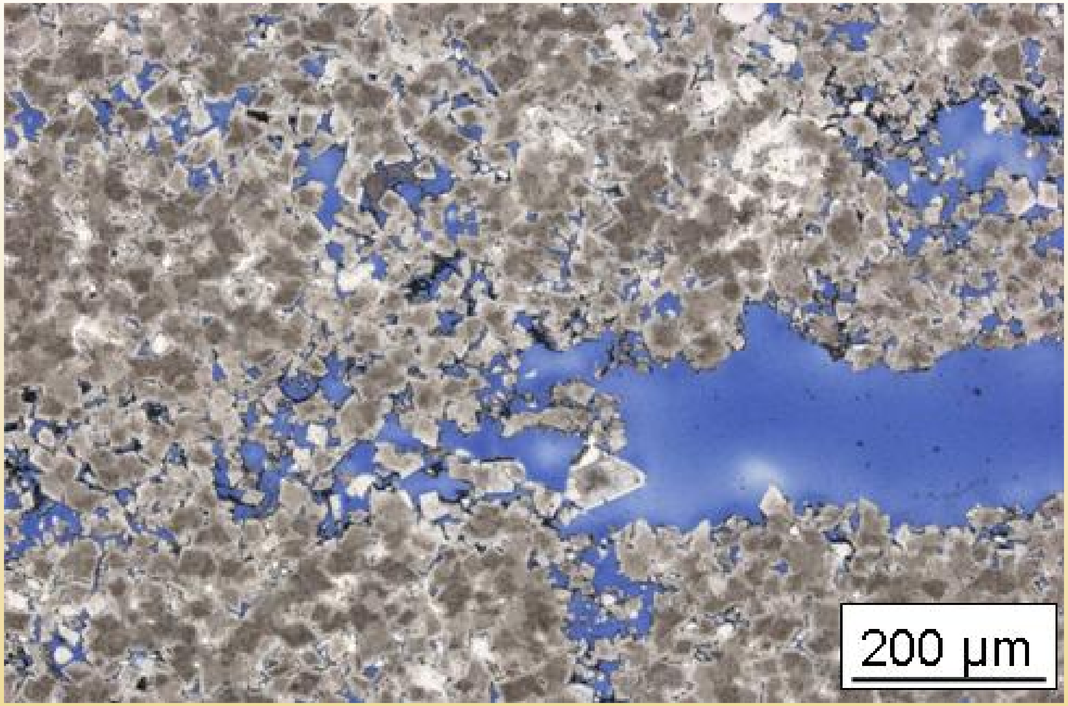




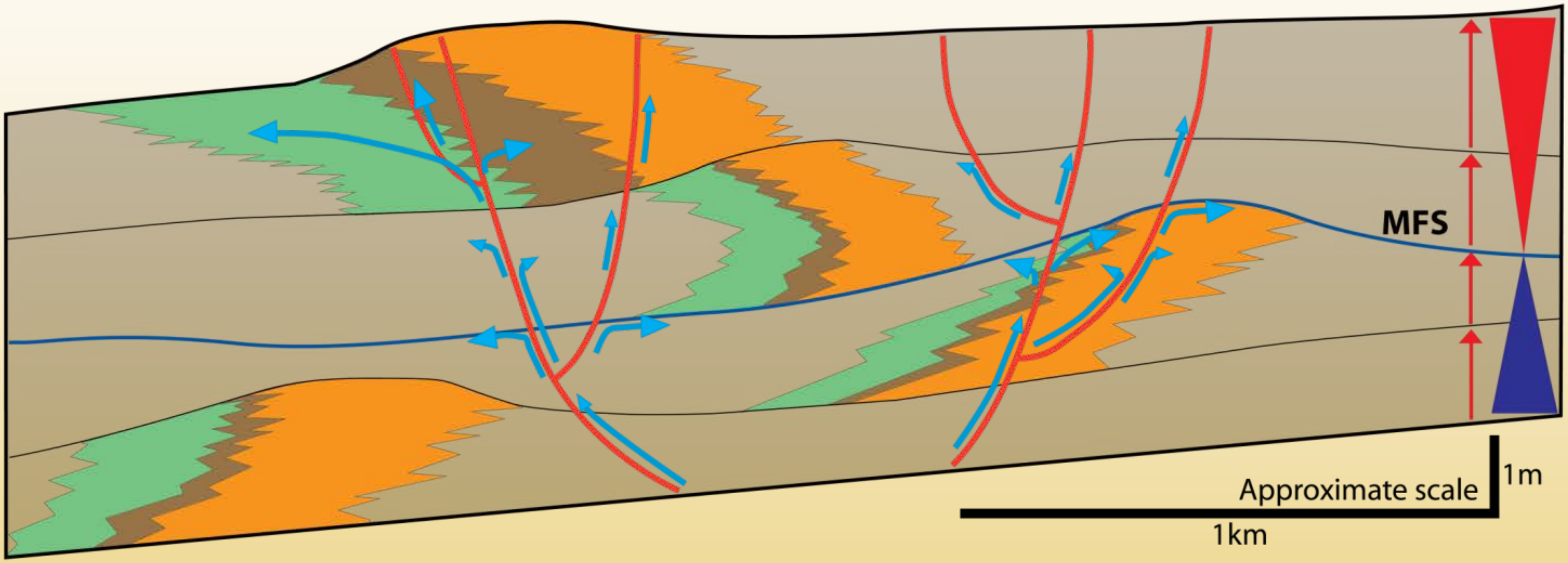
Burrowed Facies -

Primary stratigraphic reservoir



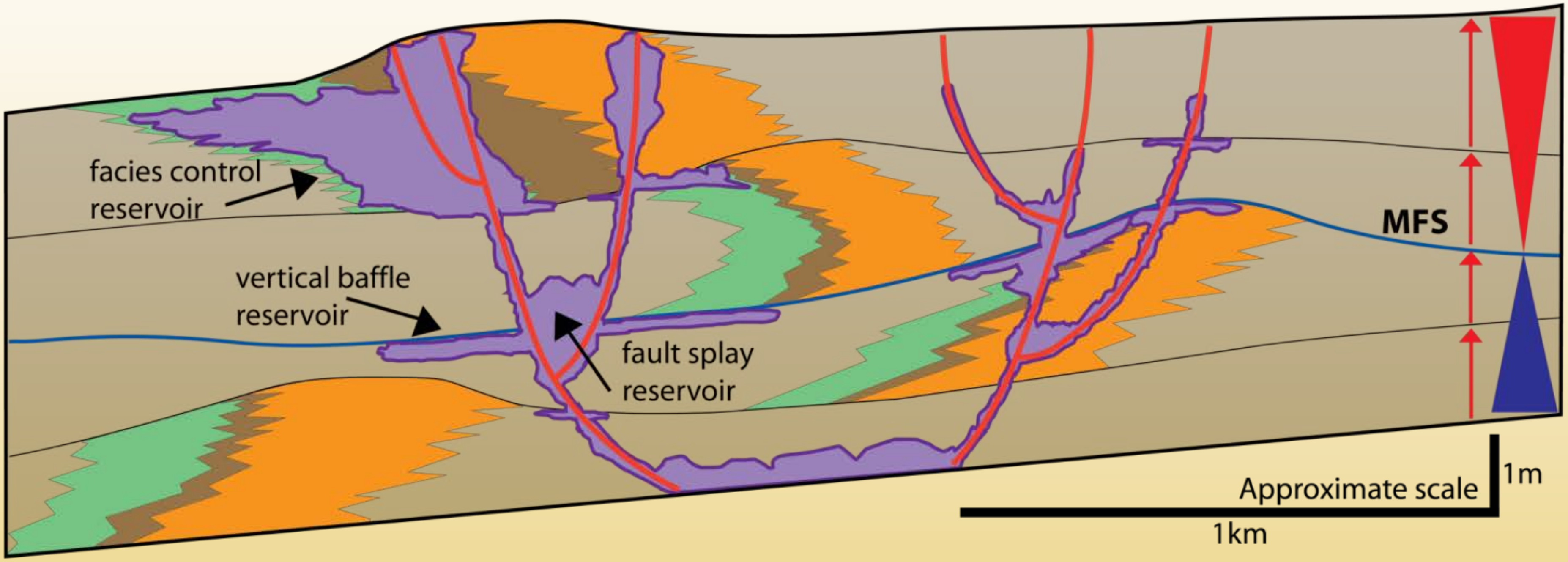


Stratigraphic Control on the Distribution of HTD Reservoirs



HTD (Φ, **K**) distribution is controlled by <u>primary fabric</u> and <u>depositional geometries</u> (lateral) in addition to structural surfaces (vertical).

Stratigraphic Control on the Distribution of HTD Reservoirs

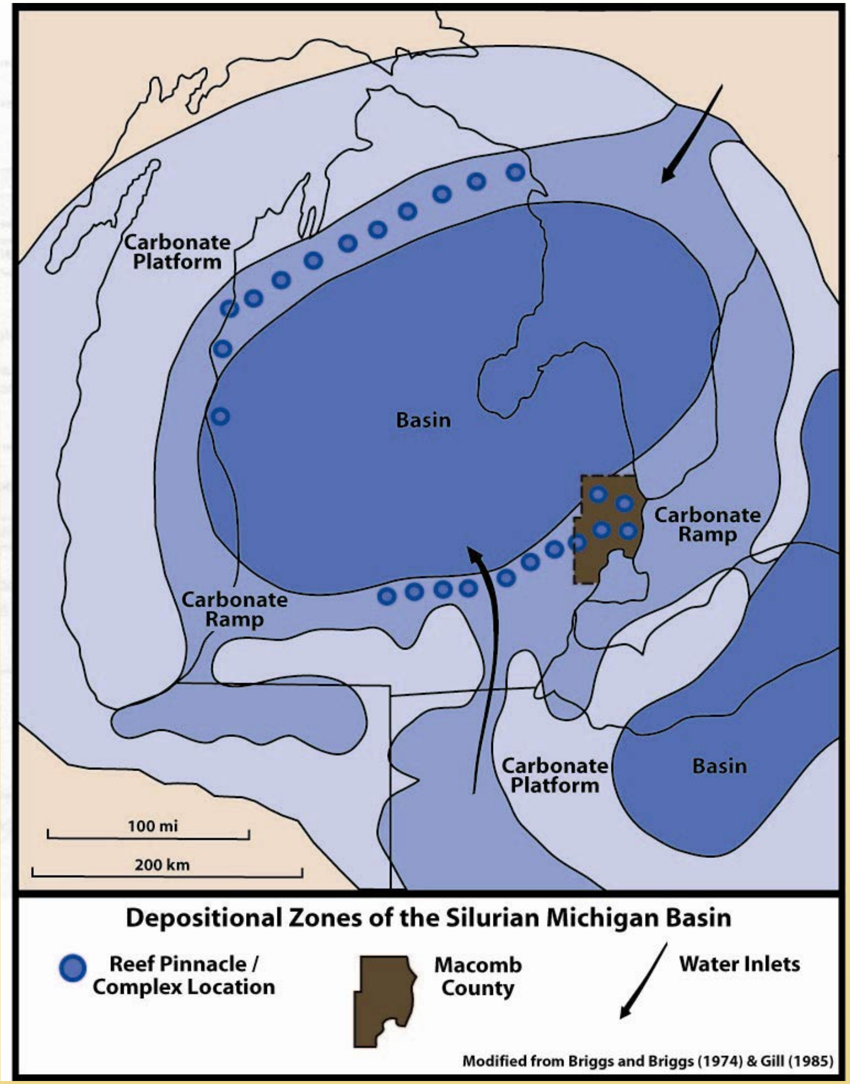


HTD (Φ, **K**) distribution is controlled by <u>primary fabric</u> and <u>depositional geometries</u> (lateral) in addition to structural surfaces (vertical).

Silurian (Niagaran) Reefs in the Michigan Basin

- **Over 1000 pinnacle reefs discovered**
- **Good porosity and permeability in various facies <u>but significant reservoir heterogeneity</u>**
- **Regional Seal (A-2 Evaporite)**
- **The reef play is the most successful play in Michigan**
  - production of 475 MMBO and 2.8 TCF of gas
- **Ultimate recovery**
  - 1 billion BOE from over 1,000 pinnacle reefs
- **Gas storage**

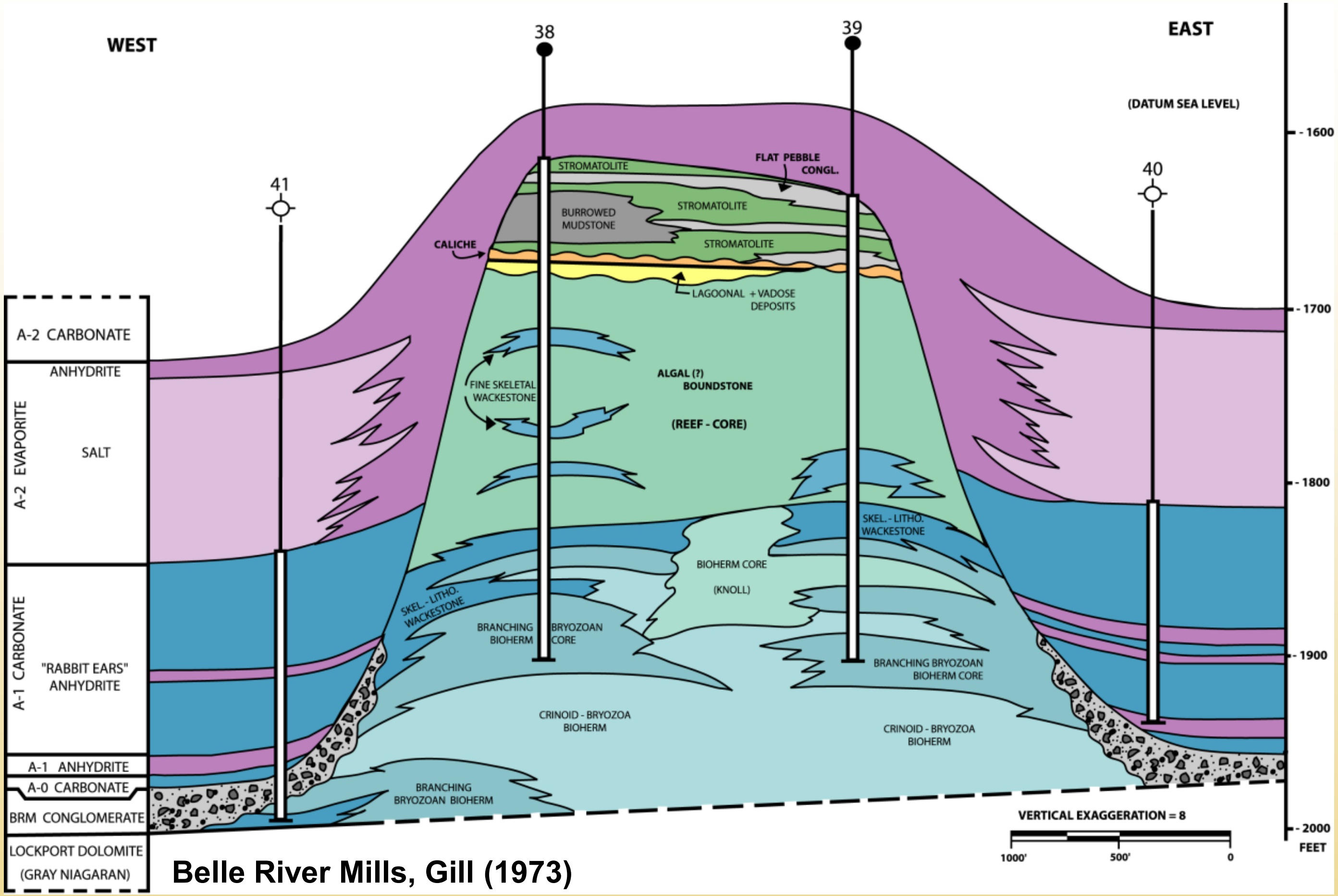
Regional Setting



(modified from Briggs et al., 1980)

- During the Niagaran the Michigan Basin was a shallow intracratonic sea measuring 155 mi (250 km) wide and up to 650 ft (200m) water depth at basin center.
- ~30 degrees south latitude
- Three 3rd order eustatic sea level changes in Niagaran time
- Three depositional zones:
  - Carbonate Platform
  - Carbonate "Ramp" with Pinnacle and Reef Complexes
  - Deep Basin

Niagaran Reef Reservoir Model (pre-2008)

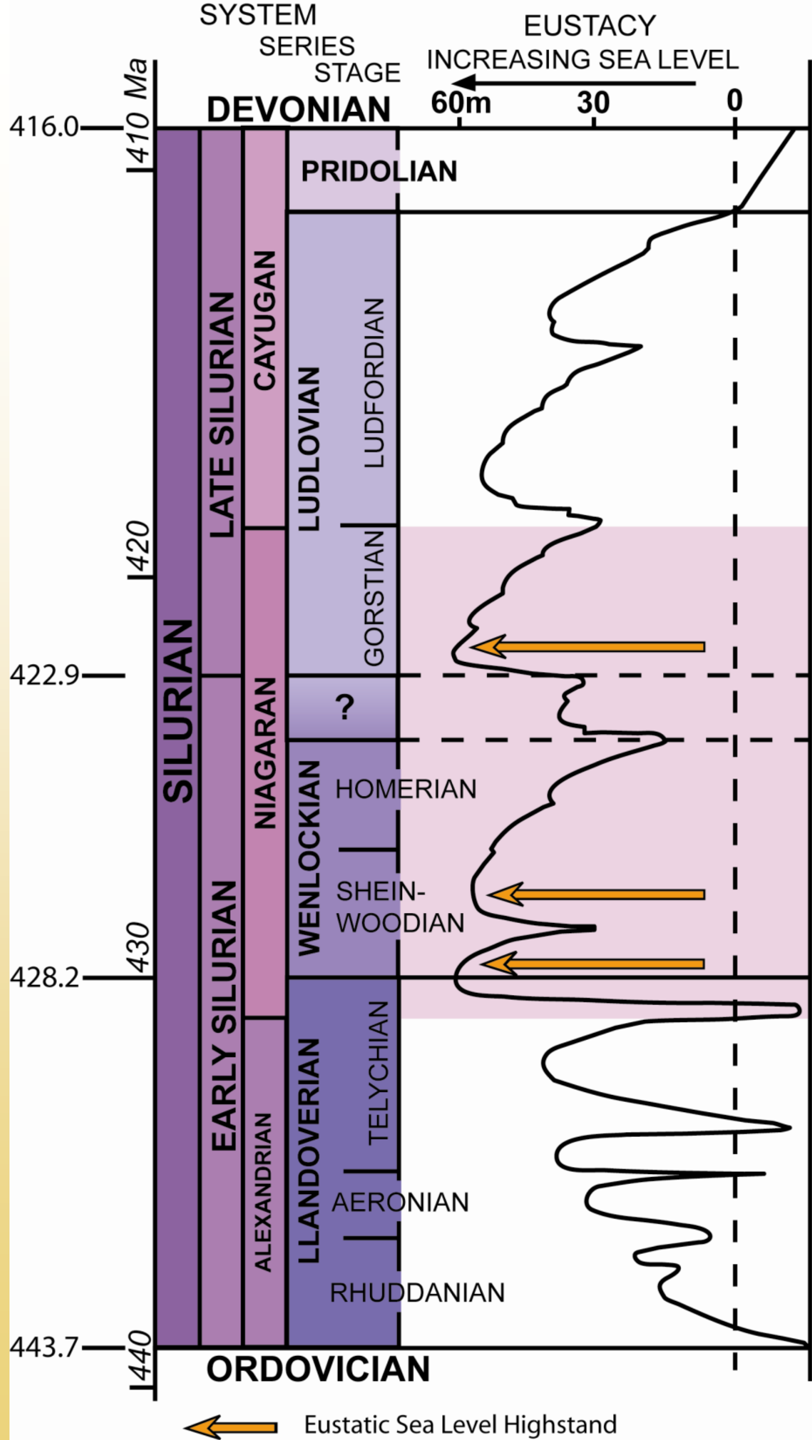


Belle River Mills, Gill (1973)

- •Earlier focus was on models for reef growth and facies distribution
- •Stacking patterns start to become recognizable in early models, but wasn’t focus of earlier studies
- •Reservoirs characterized by significant lateral and vertical heterogeneity

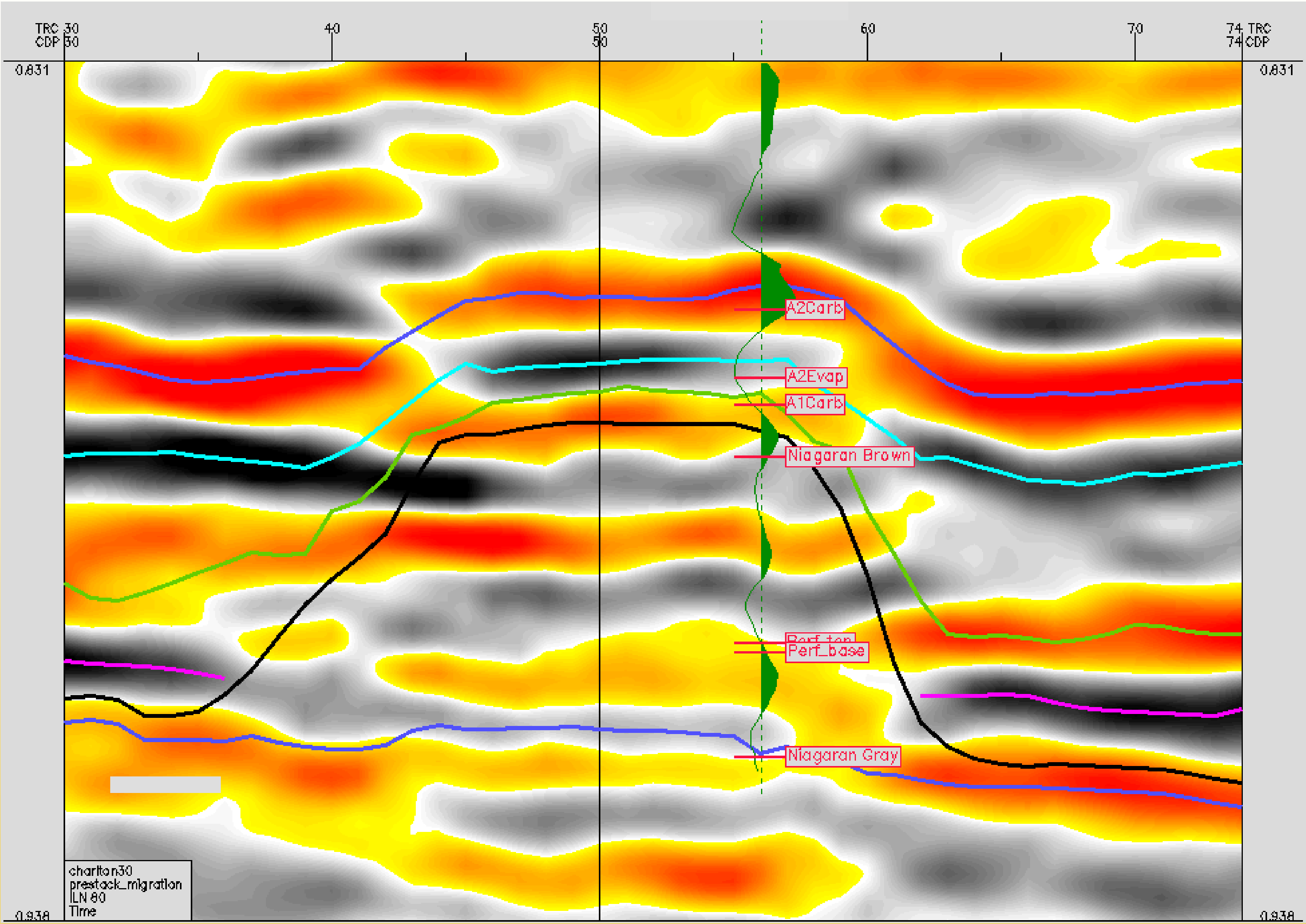
Silurian Sea Level

Three eustatic sea level fluctuations occurred during the Niagaran (Wenlockian) and into the Ludlovian.



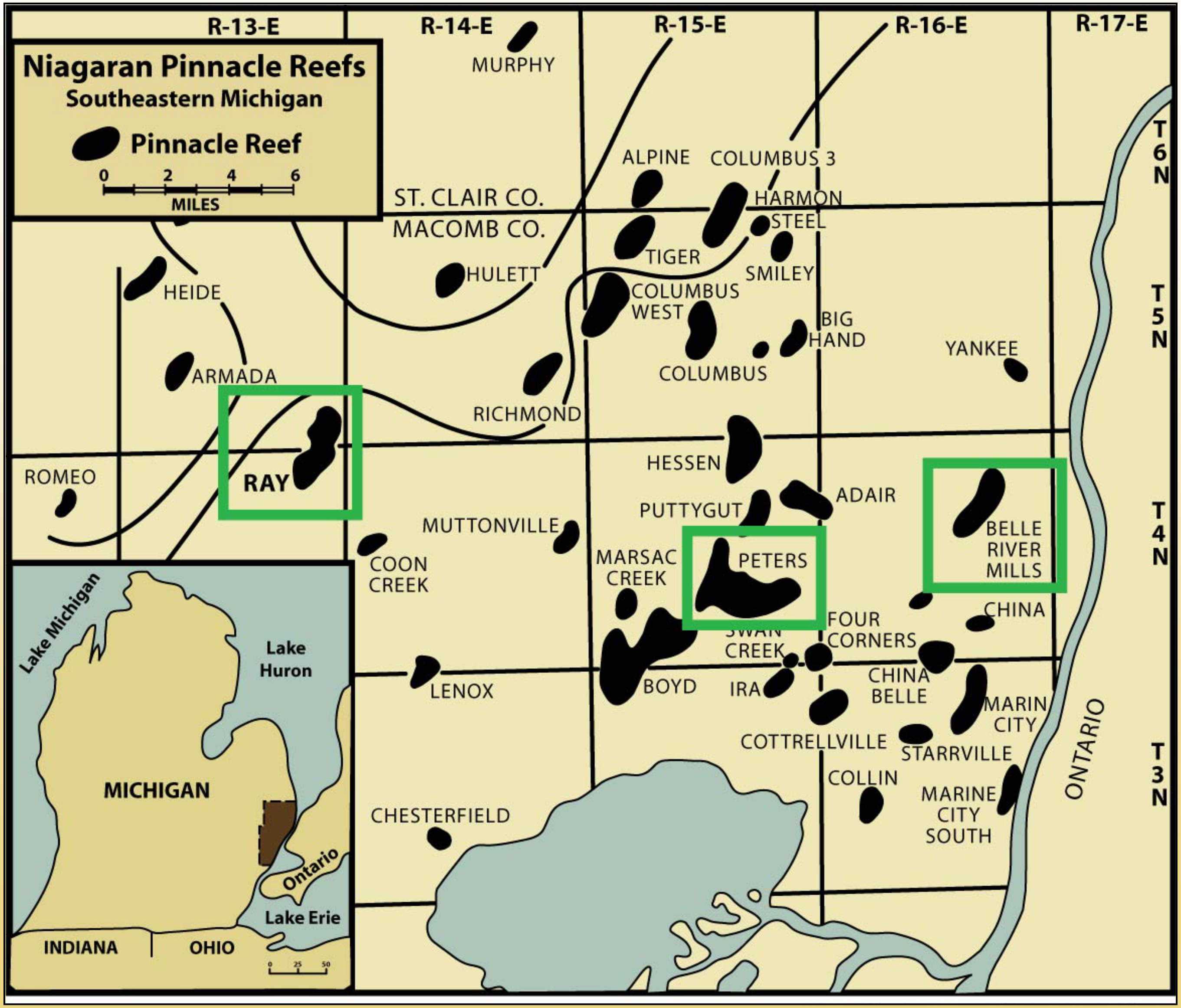
Modified from Ross & Ross, 1996

3-D Seismic over Niagaran Reef (Northern Trend)



Toelle et al. (2009)

Reservoir Characterization of Niagaran Reefs

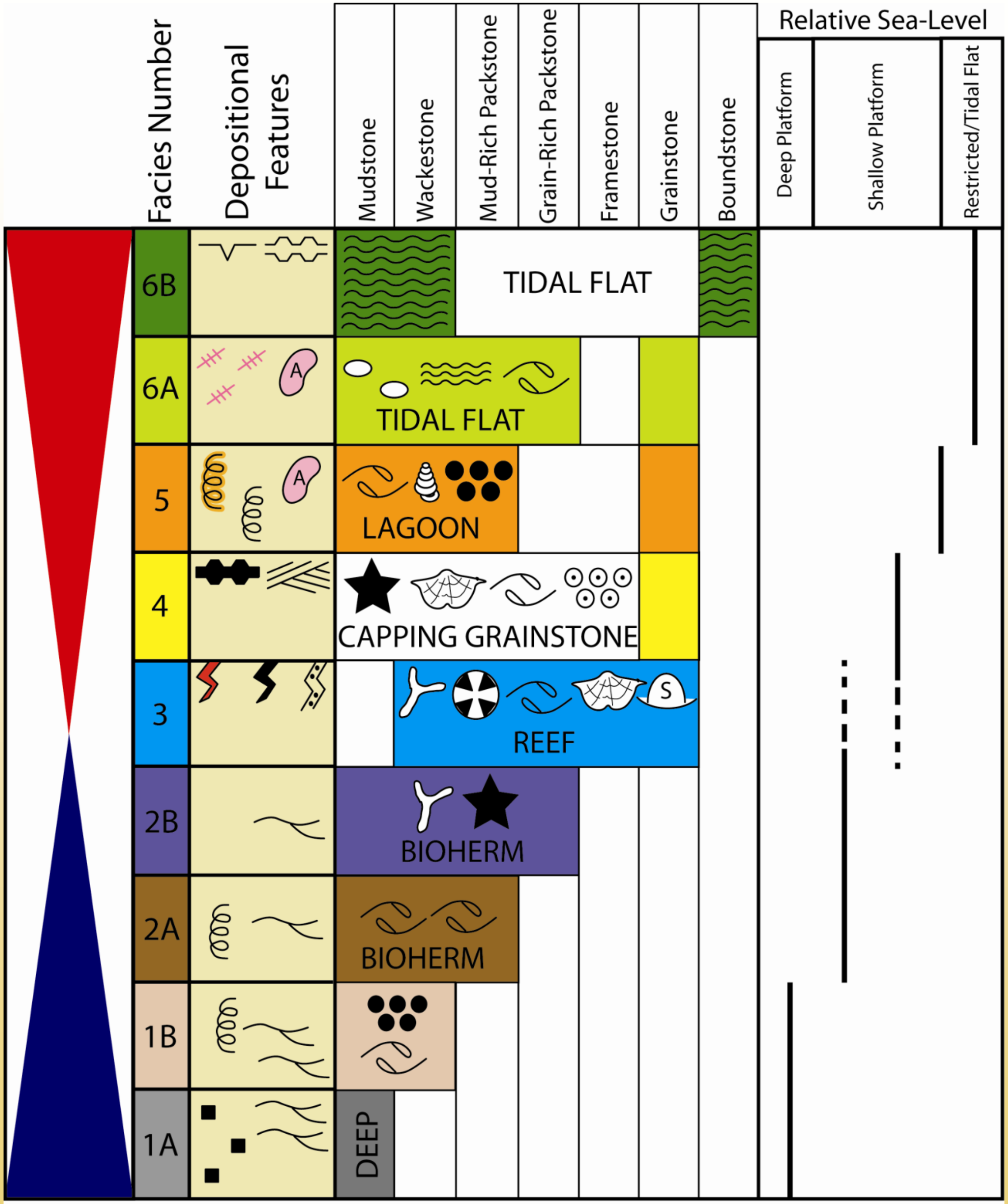


Gill (1973, 1977)

Modeling Workflow

Integrate Data from:

1. Wireline Logs from 94 wells
2. Facies data from 32 cores
3. Porosity/permeability from whole core analysis and minipermeameter
4. Sequence stratigraphic architecture (timelines)



Ritter and Grammer (2008)

Idealized Facies Succession from Core

Restricted Environments -
- Cyanobacterial Mat Boundstones
- Brecciated, Cyanobacterial Mat Boundstone
- Burrowed, Peloidal Wackestones to Grainstones

Higher-Energy, Shoals (Back Reef) -
- Skeletal Grainstones

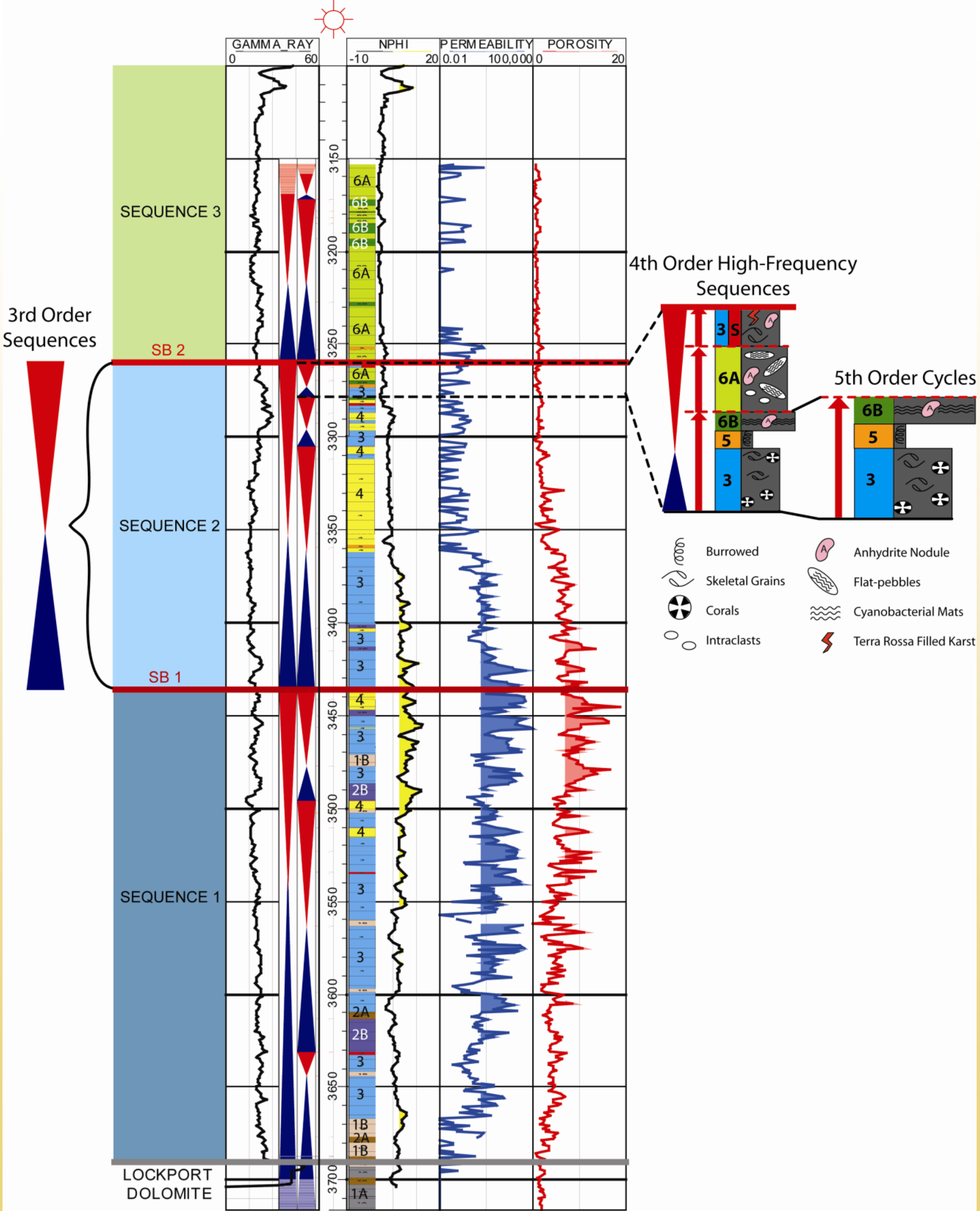
Reef Core –
- Coral/Stromatoporoid Framestone

Muddy Bioherm -
- Bryozoan/Crinoidal Wackestone to Packstone
- Mudstone to Skeletal Grainstone with Stromatactis Texture

Deeper-Water -
- Burrowed, Mudstone to Peloidal Mud-rich Packstone
- Graptolite Mudstone to Wackestone

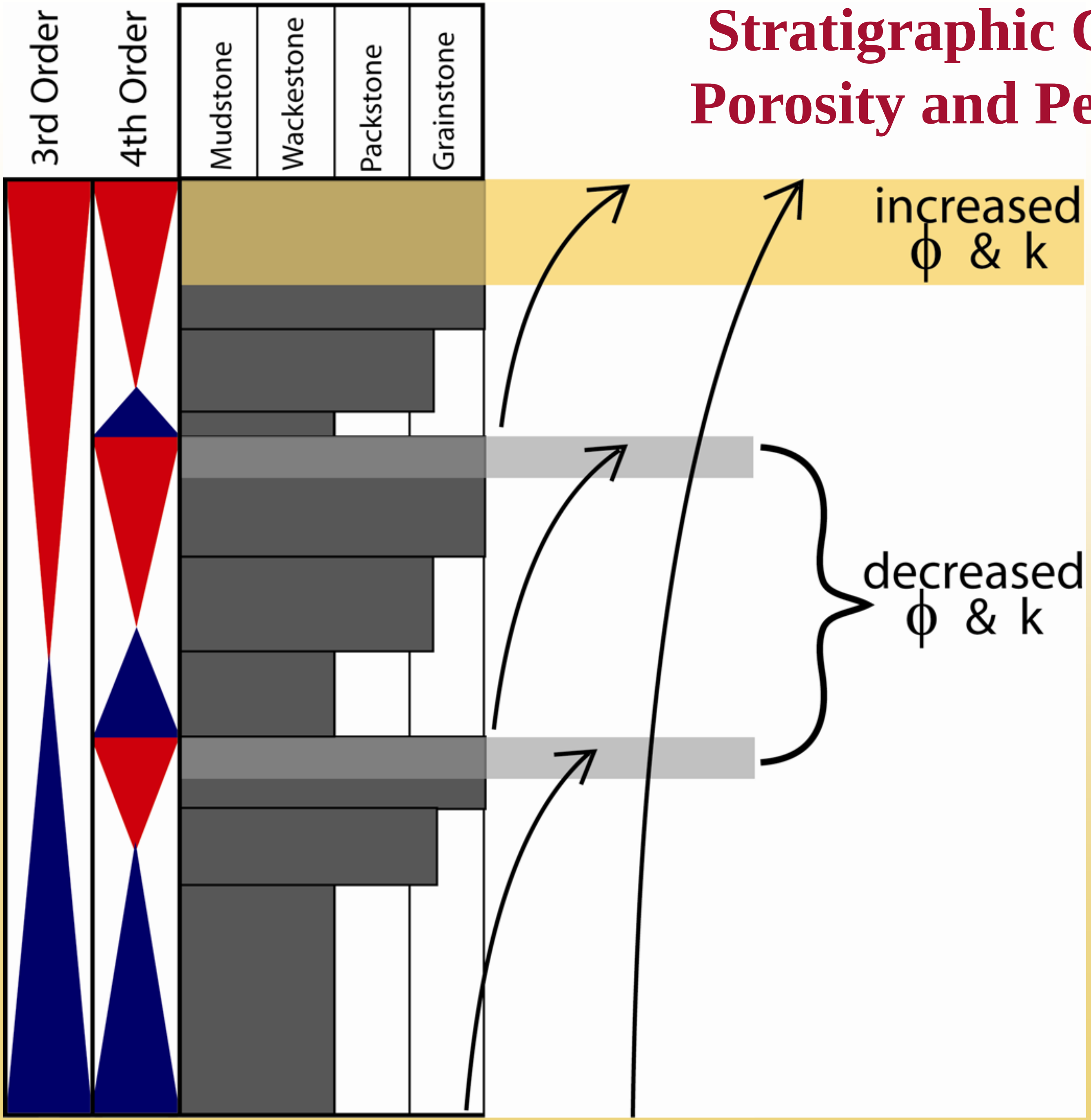
Sequence Stratigraphic Hierarchy in Niagaran Reefs

(northern and southern trends)



Ritter and Grammer (2008)

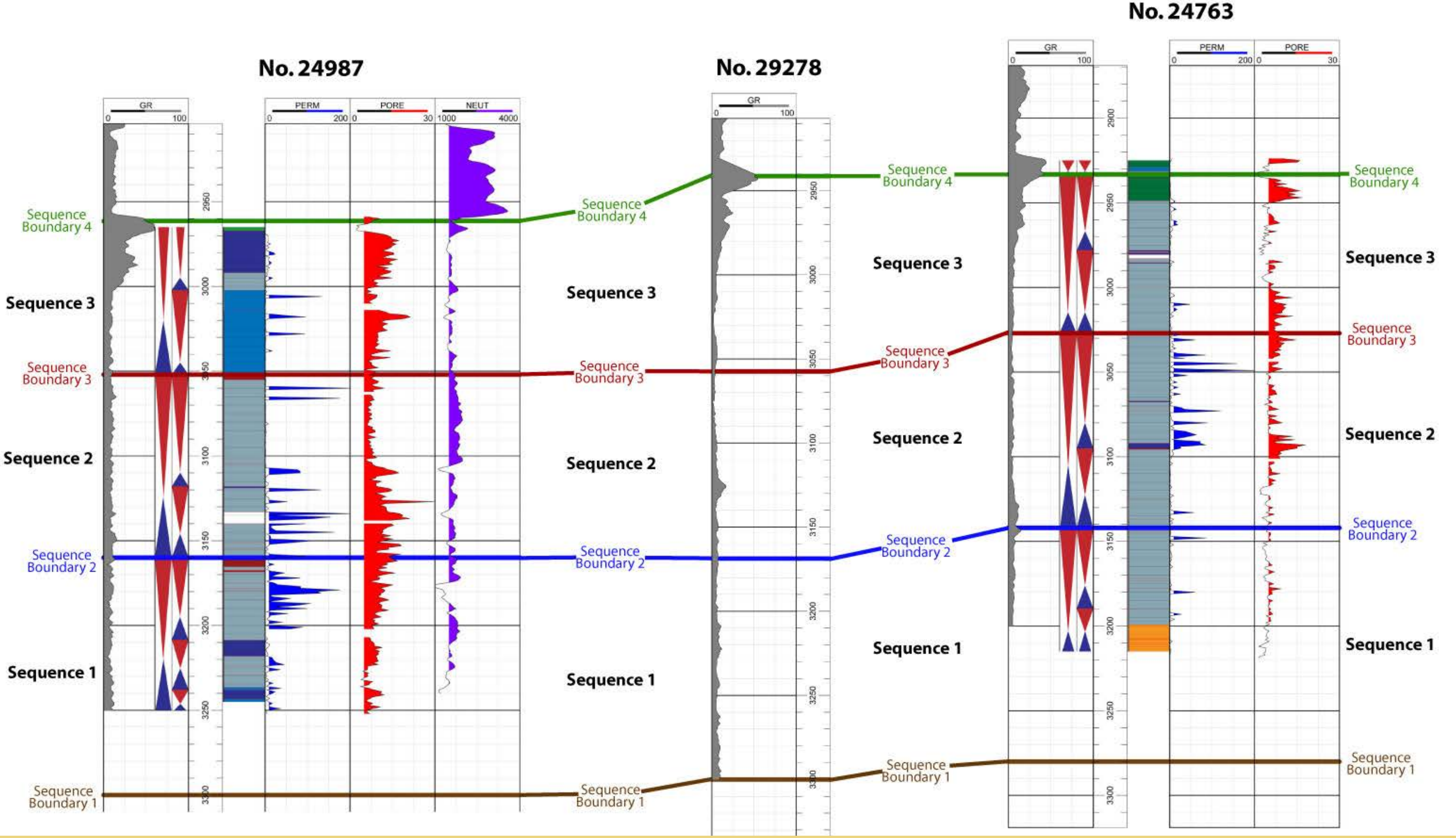
Stratigraphic Control on Porosity and Permeability



Ritter and Grammer (2008)

Sequence Boundaries – Ray Reef

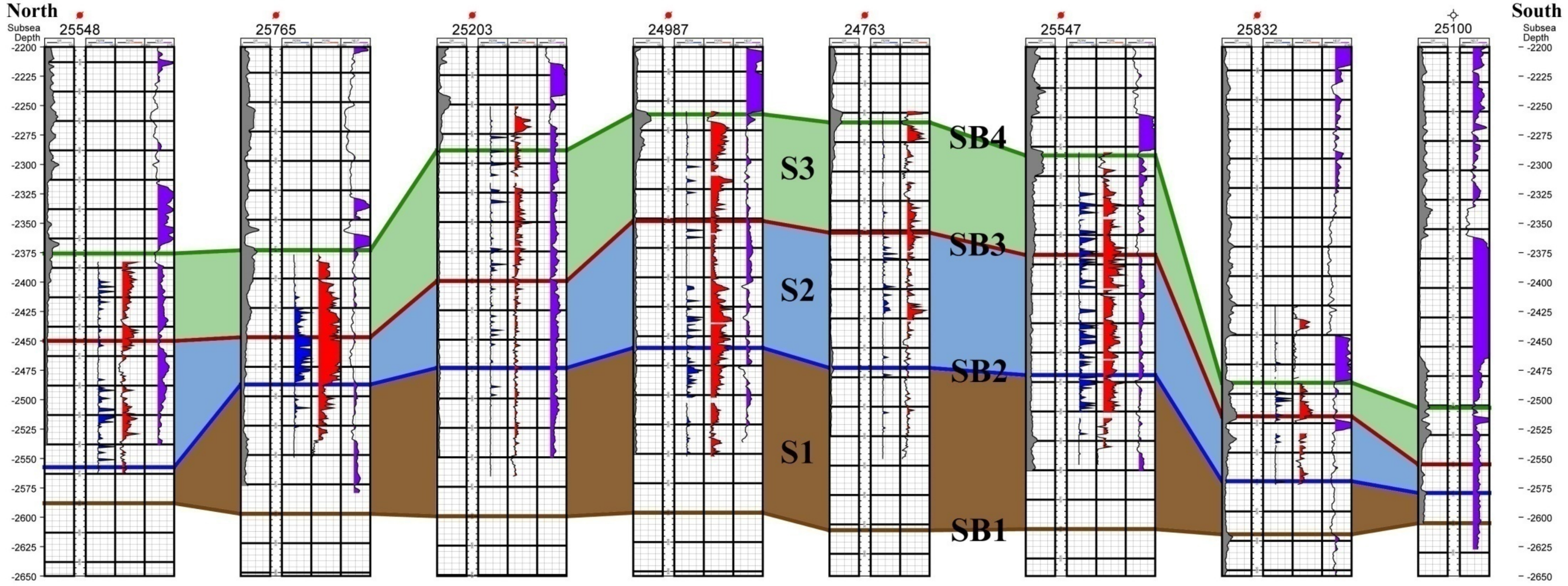
(tie core to wireline logs and extrapolate)



Wold and Grammer (2008)

Sequence Framework – Ray Reef

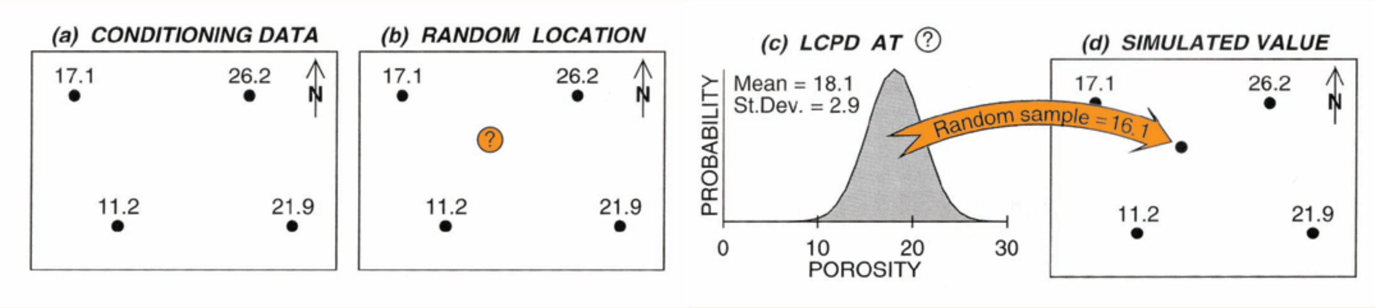
- **Skeletal Outline of the Model constrained by sequence boundaries**
- **Surfaces honor the geometry of the reef from reef crest to the off-reef position**
- **High Resolution porosity, permeability, and facies data incorporated into model**

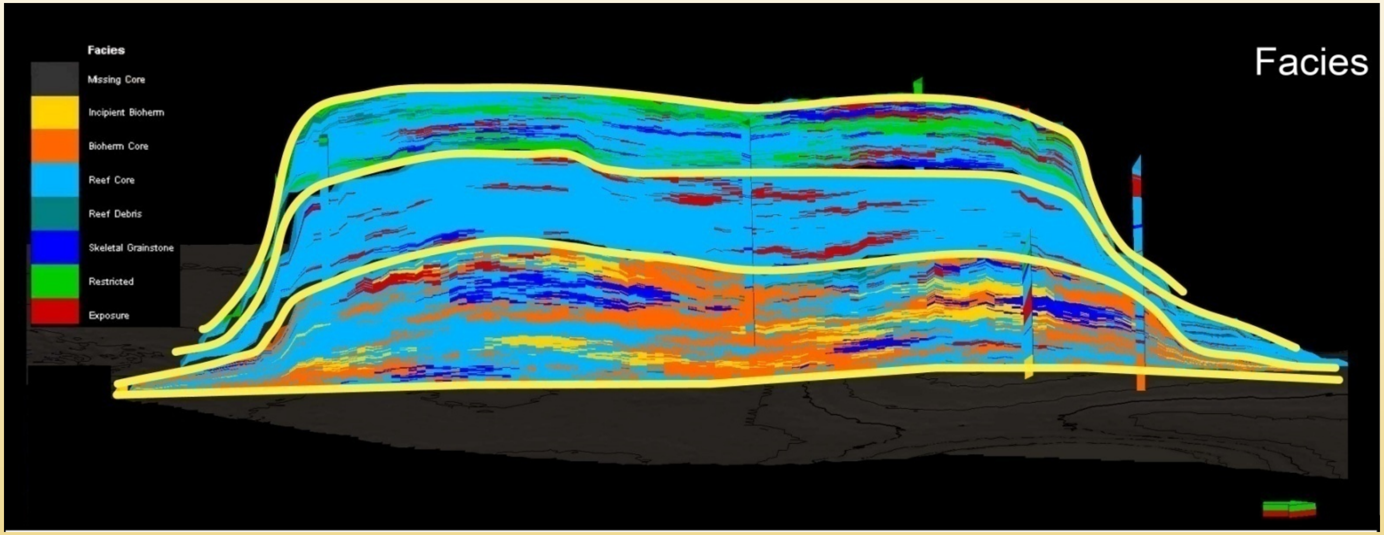


Wold and Grammer (2008)

Algorithm for Modeling Surfaces (SGS)

Sequential Gaussian Simulation Algorithm

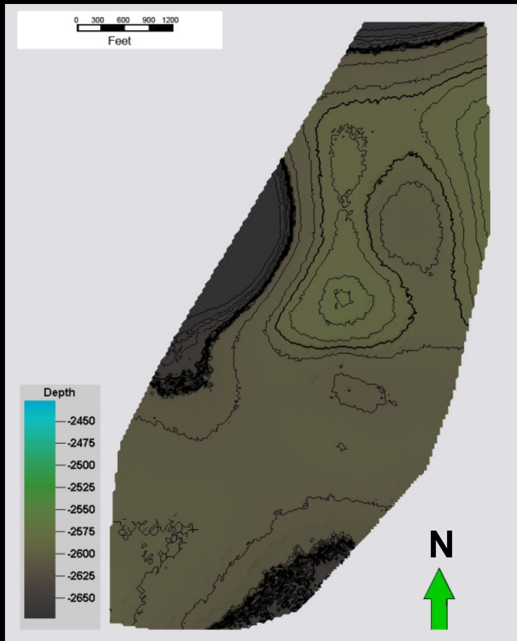




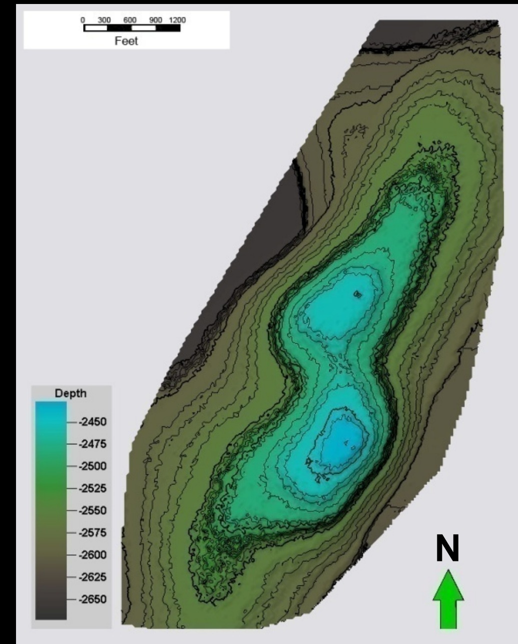
Model consists of three zones:

- **6.8 million 3-D cells per zone**
- **Cell size of 50 x 50 x 1 ft (x,y,z)**
- **200 layers of data**

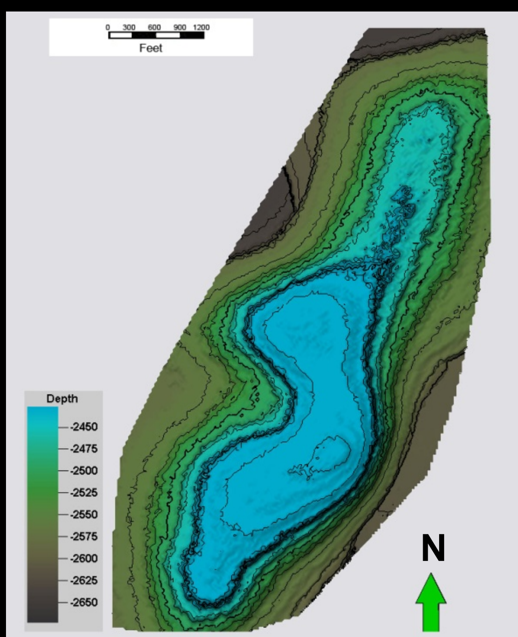
Wold and Grammer (2008)



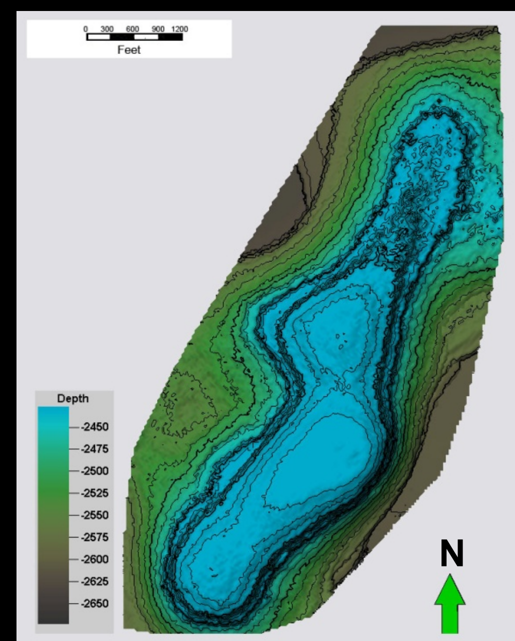
Sequence Boundary 1



Sequence Boundary 2



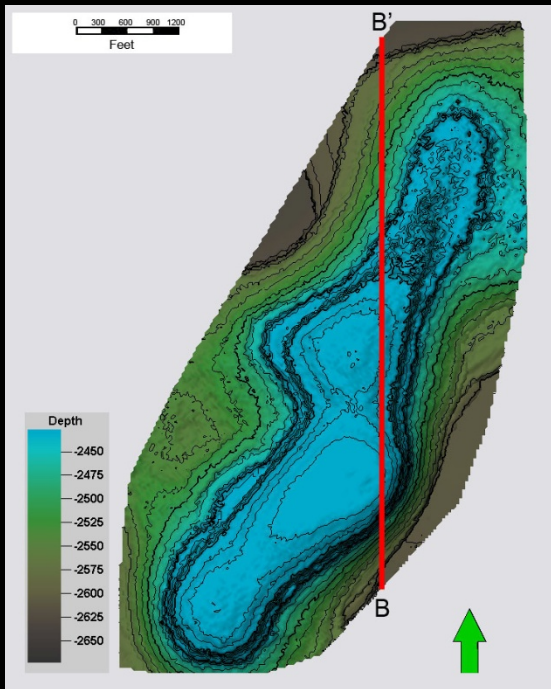
Sequence Boundary 3

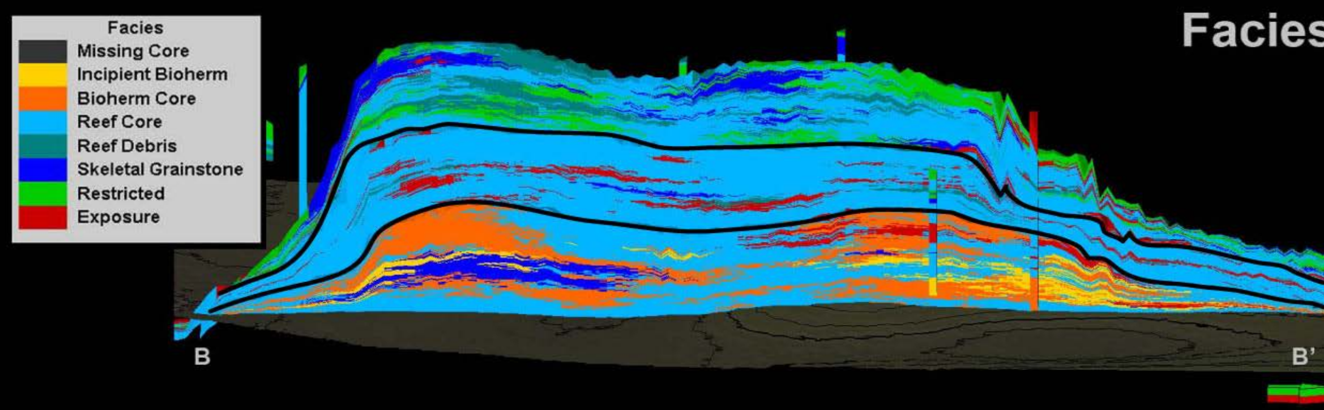


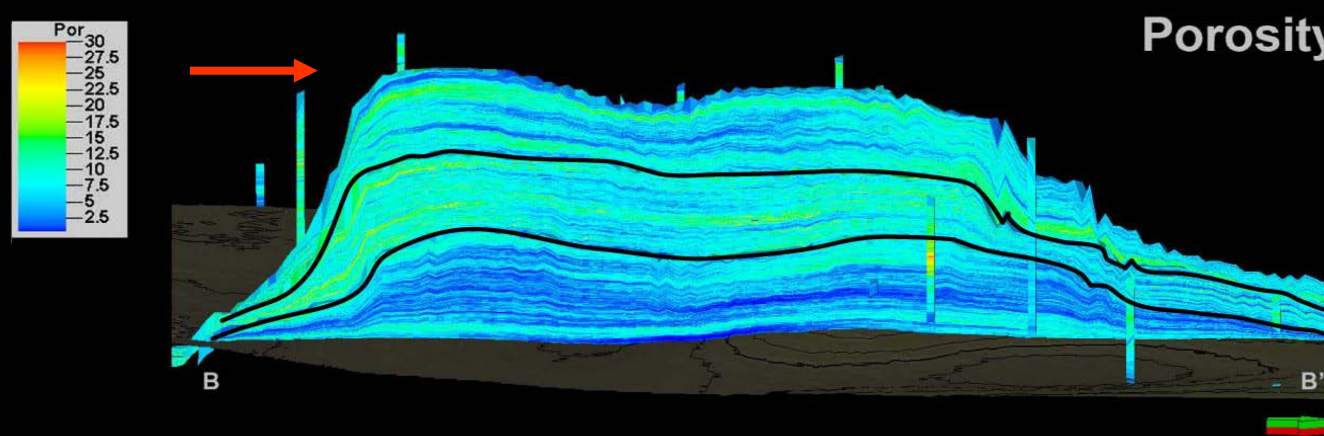
Sequence Boundary 4

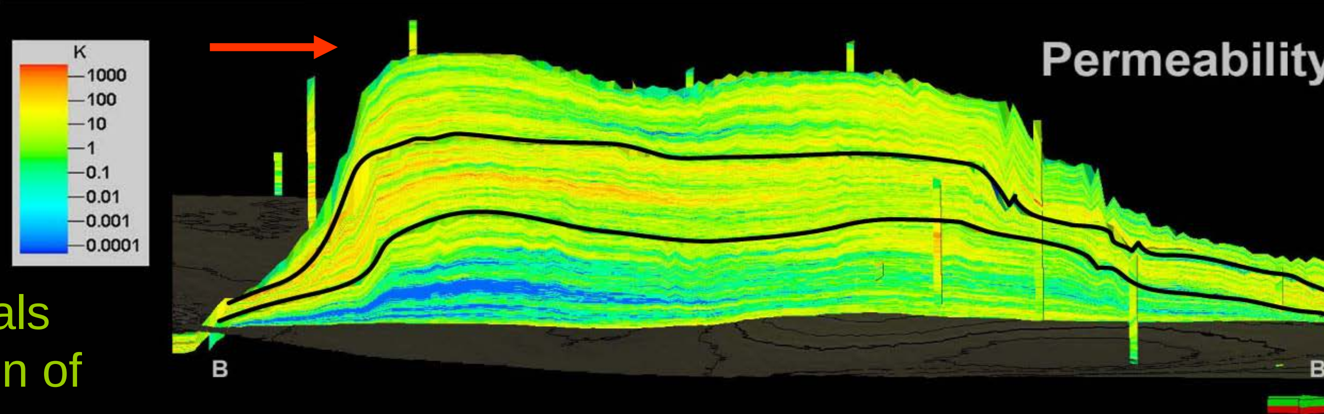
Wold and Grammer (2008)

B - B’ Cross-Section





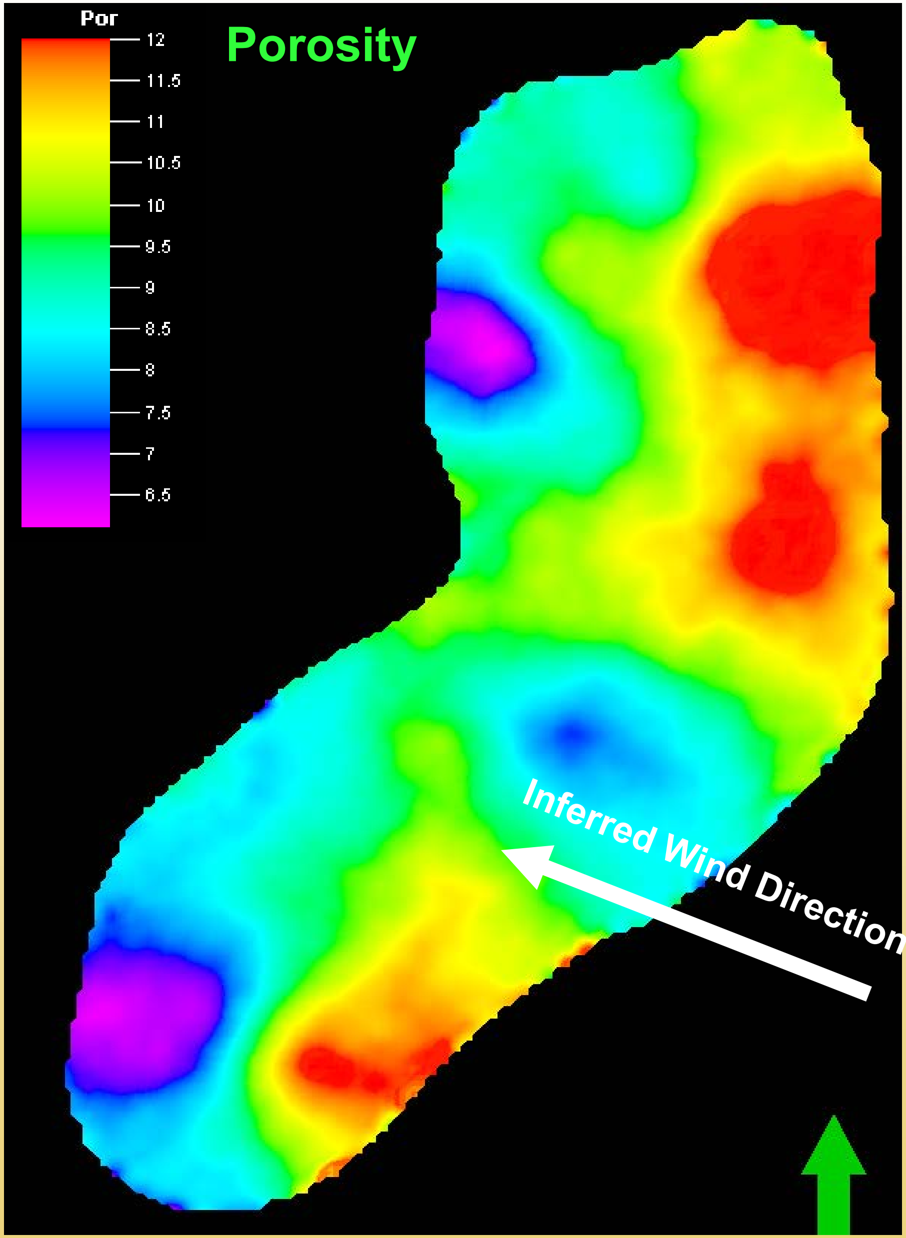


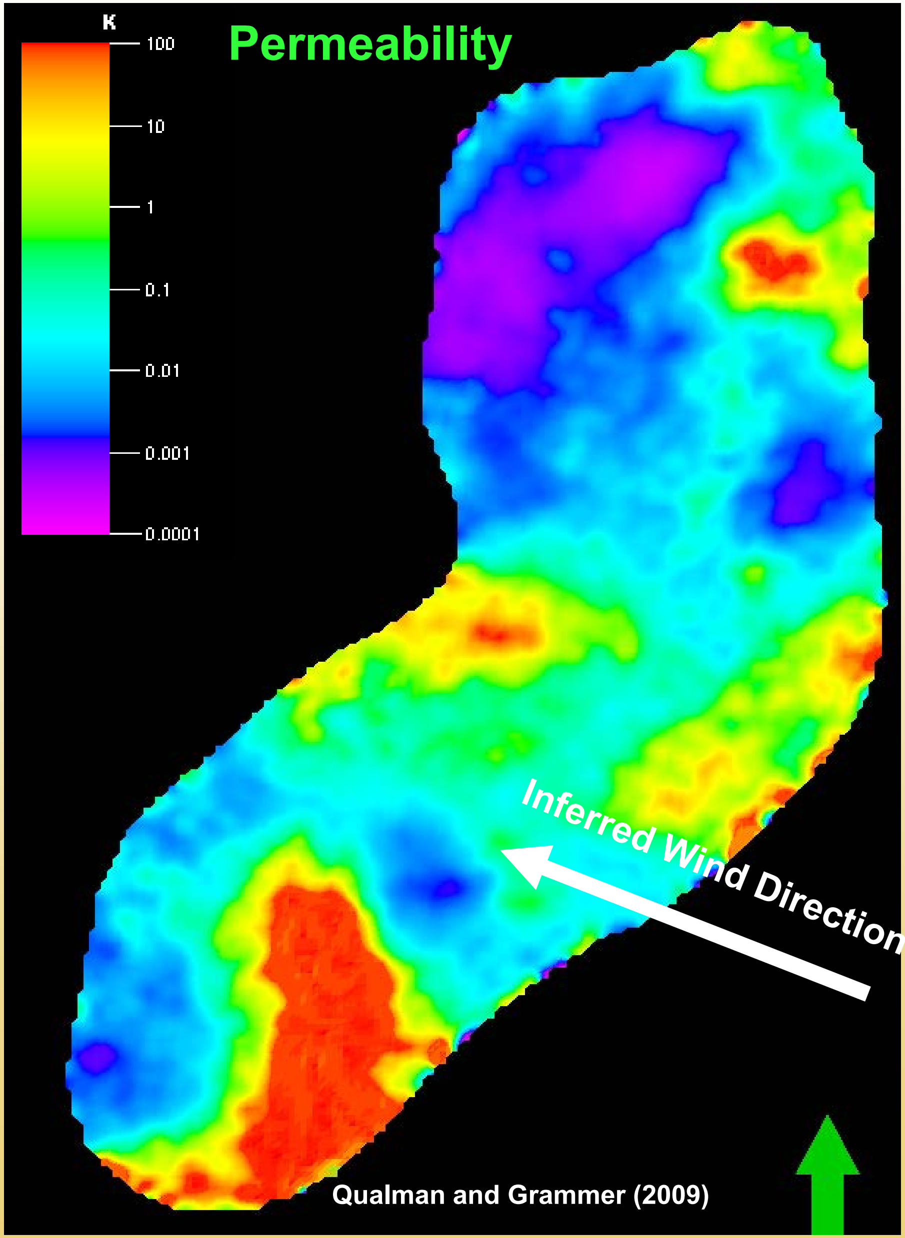


- Progradational vs. Aggradational Growth
- Windward vs. Leeward Margins
- Potential reservoir intervals along the windward margin of the reef complex.

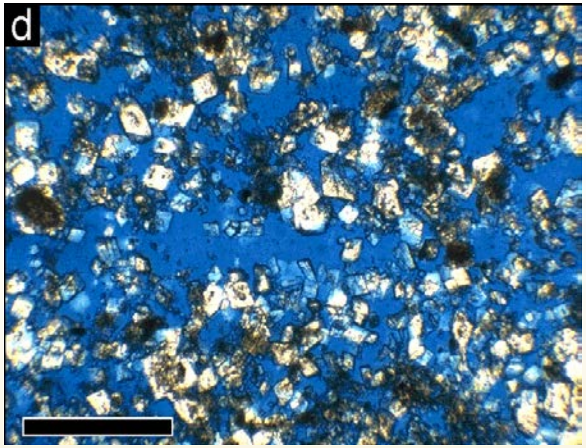
Wold and Grammer (2008)

Lateral Reservoir Property Distribution

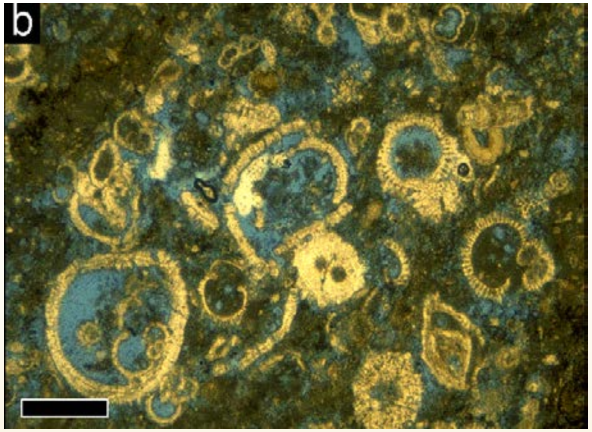


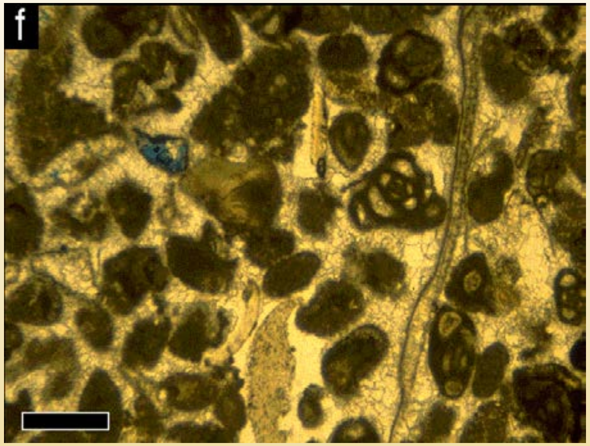


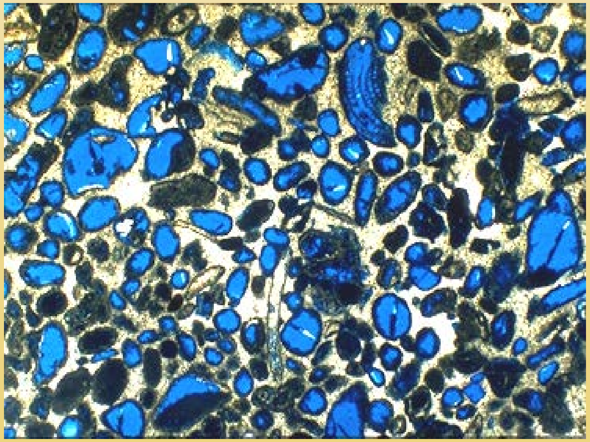
Characterization of Carbonate Pore Architecture and Relationship to Permeability

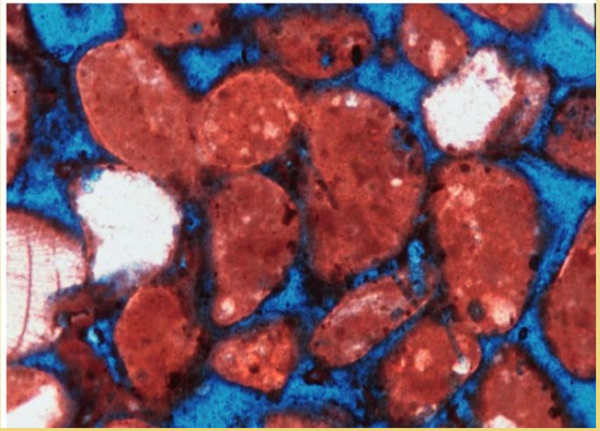


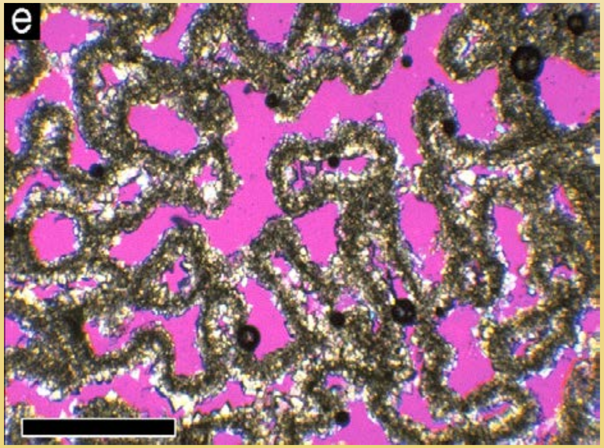
Carbonates have varying pore types that influence permeability





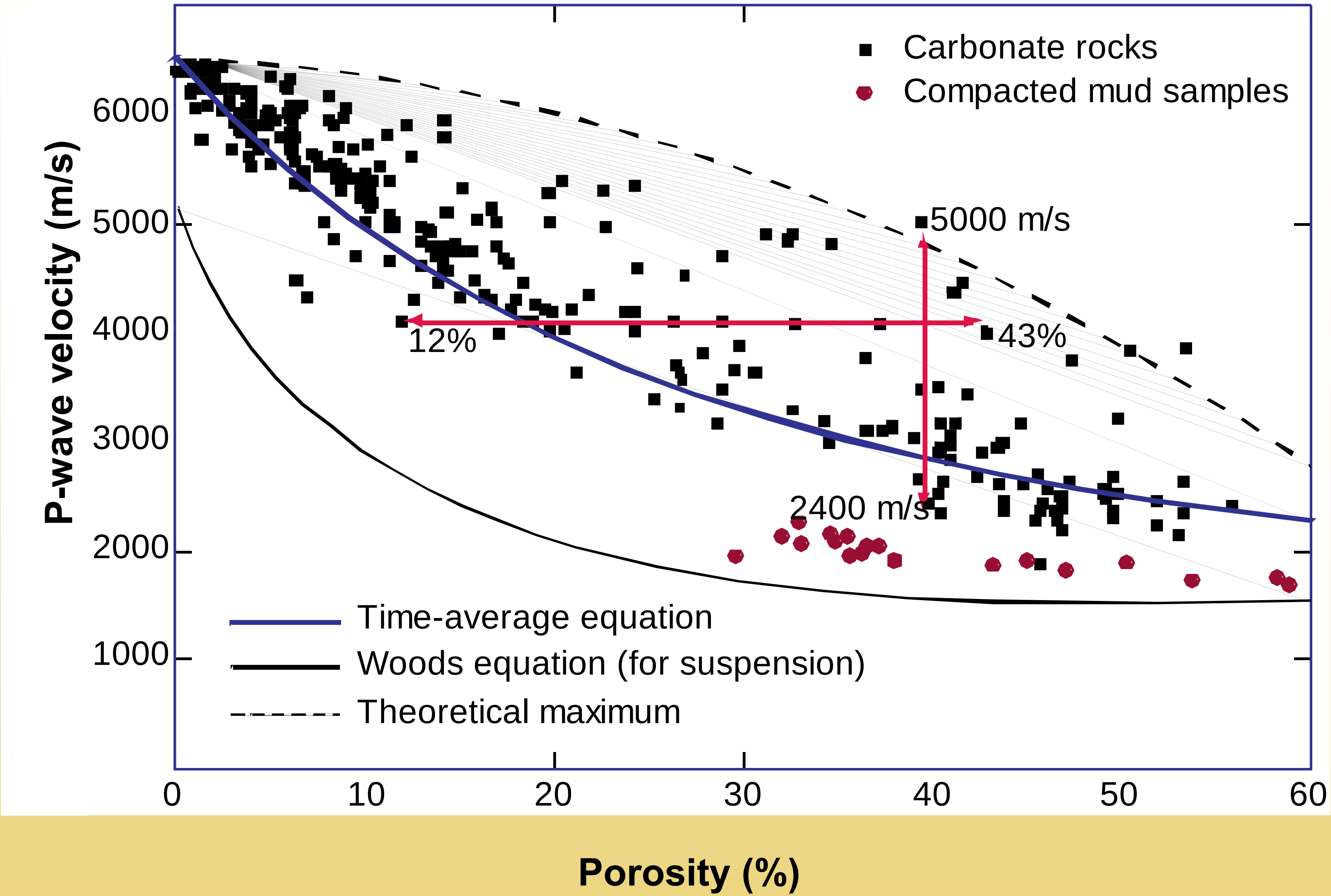






Eberli, 2000

Velocity versus Porosity in Carbonates

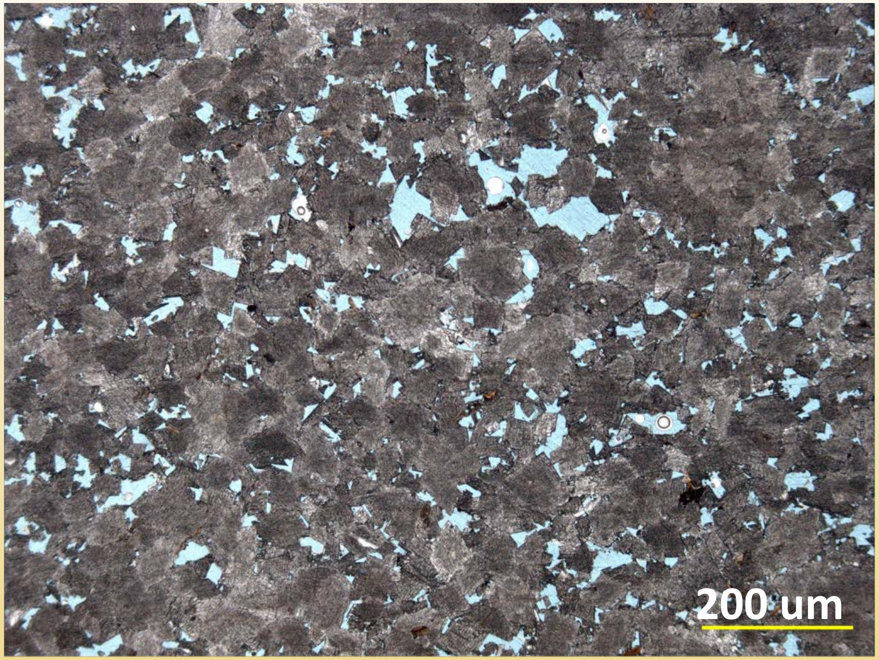


Anselmetti and Eberli (1999)
Grammer et al. (2006)

Predicting Permeability from Sonic Velocity?

Core Plug Values

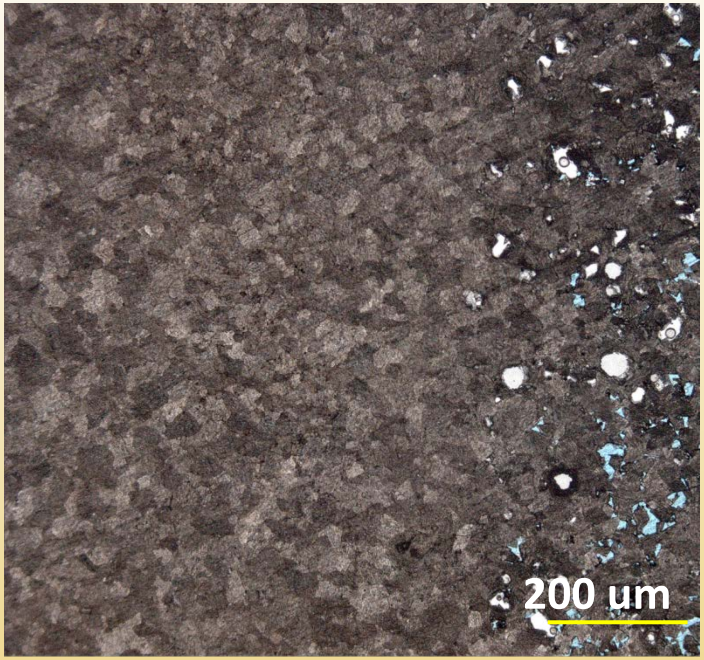
Φ = 10.59%
K = 66.5 mD



Vp = 4866 m/s

Core Plug Values

Φ = 10.50%
K = 1.04 mD



Vp = 6023 m/s

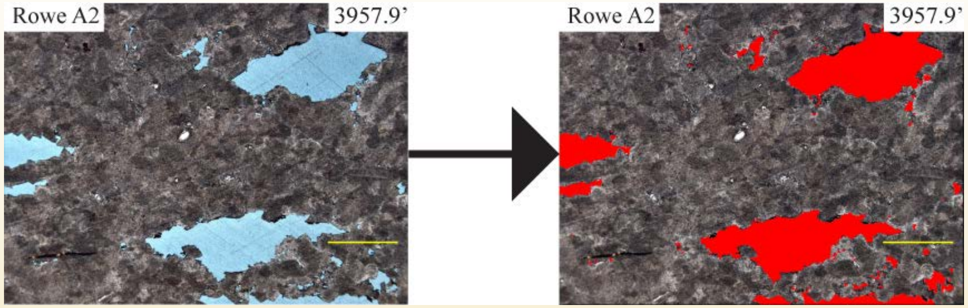
Thornton and Grammer (2010)

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



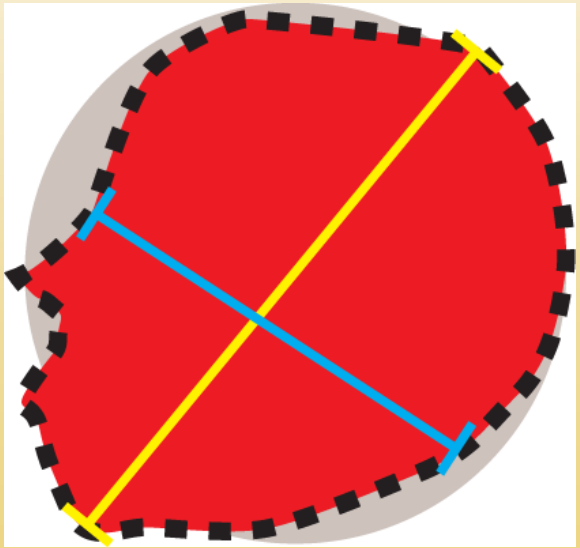
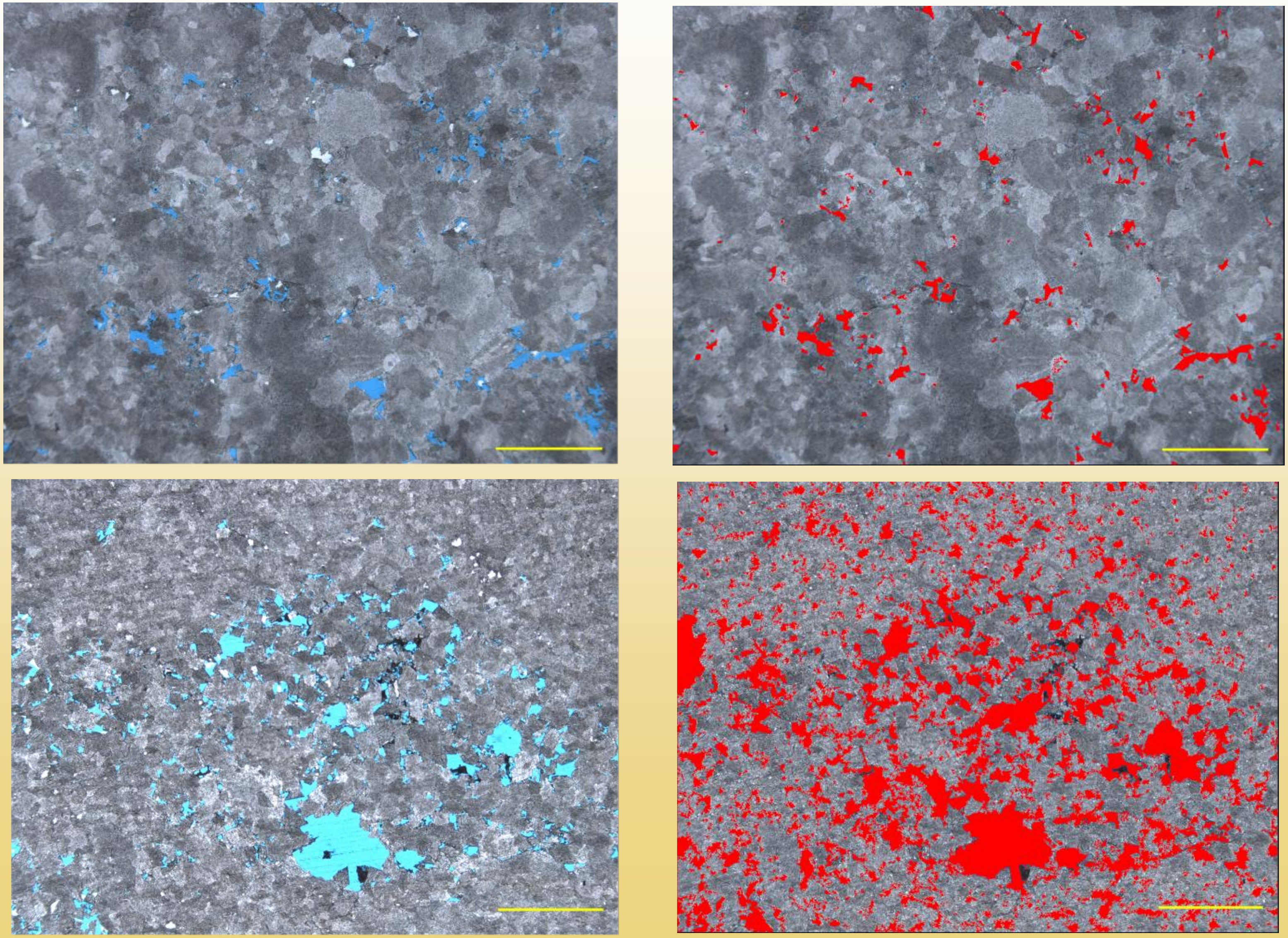
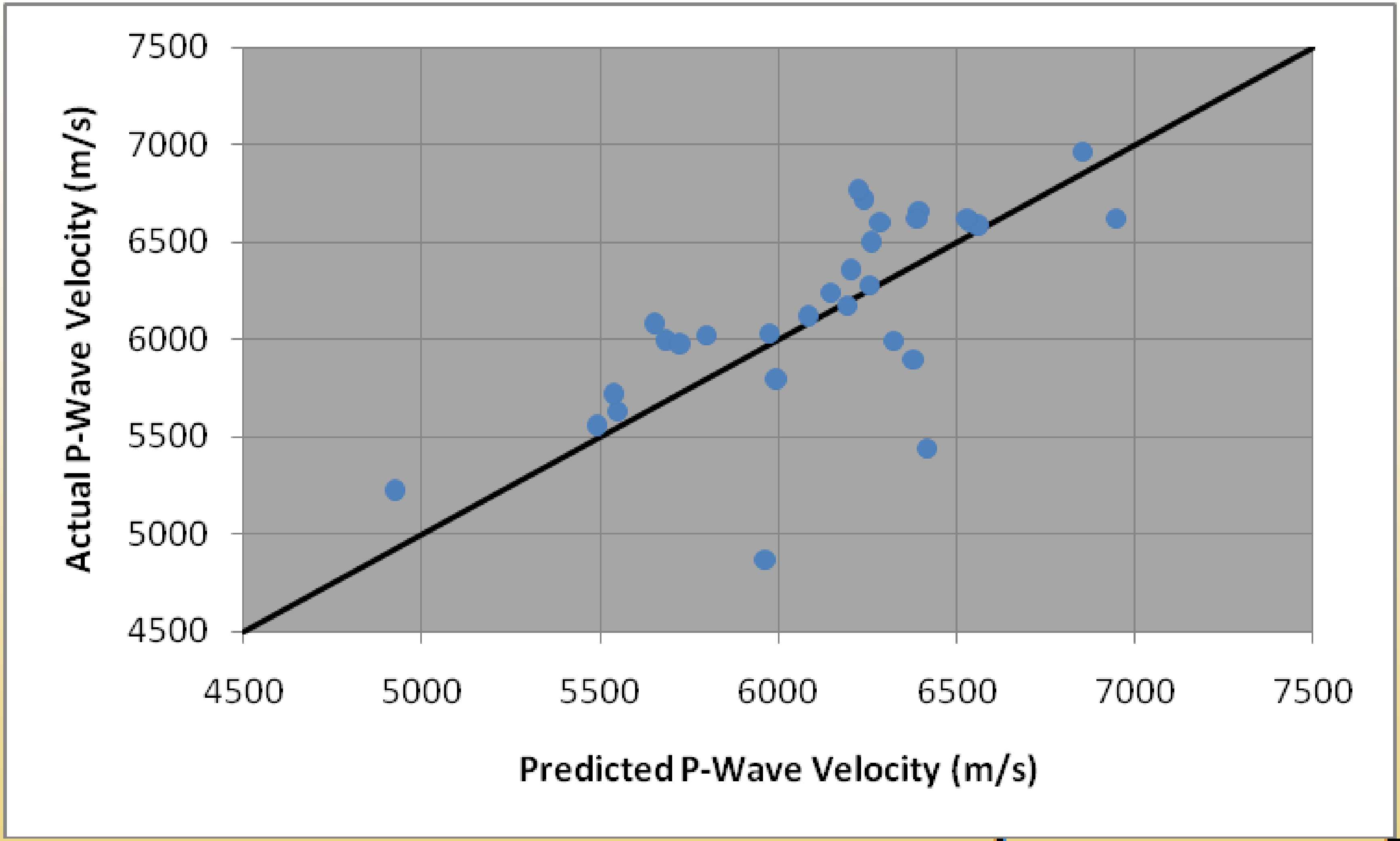


Image Analysis to characterize size, shape and distribution of pores in thin section



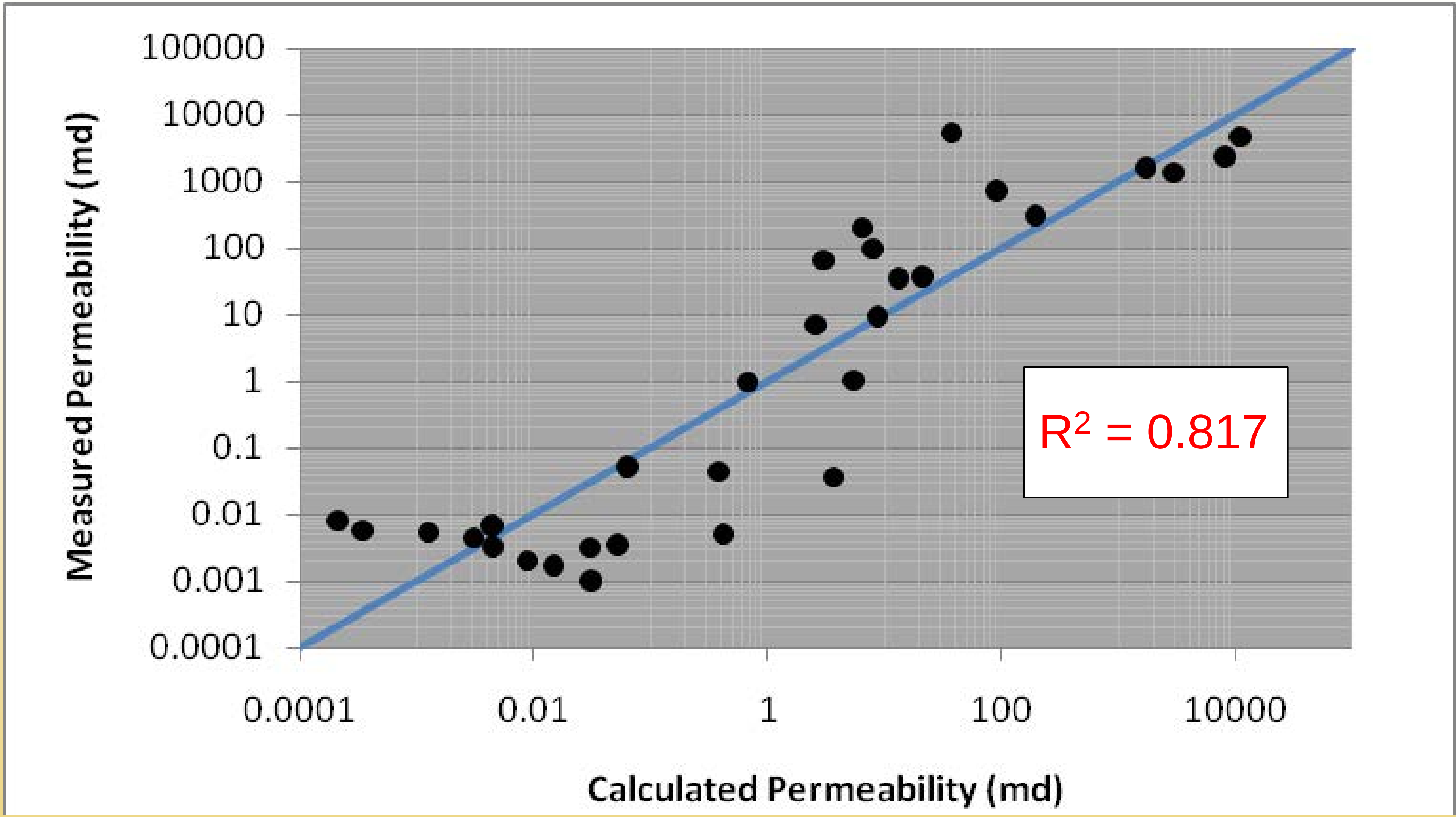
Thornton and Grammer (2010)

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



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

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



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

Summary – General Thoughts and Trends in 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.