Reservoir Characterization of Silurian (Niagaran) "Pinnacle" Reefs in the Michigan Basin*

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Abstract

Silurian (Niagaran) reefs are significant hydrocarbon reservoirs in the Michigan Basin, having produced over 490 MMBO and 2.9 TCF of gas. Primary production from these reservoirs is typically low, averaging about 25%, due to the complex internal heterogeneity of the reservoir. Incorporating a detailed sequence stratigraphic framework into the reservoir characterization and geostatistical modeling of these reefs provide an enhanced understanding of the complex lateral and vertical variability of reservoir facies often observed in the subsurface, and should lead to better reservoir prediction at both exploration and production scales.

The sequence stratigraphic hierarchy within the reefs is manifested by 4th order high-frequency sequences (10's of meters thick), and thinner 5th order cycles (few meters thick) resulting from relative sea level variations. Incorporating the sequence stratigraphic framework into a 3-D stratigraphic model illustrates the episodic nature of reef growth as exhibited by the stacked nature of framework reef and capping grainstones, with sequence boundaries often characterized by well developed exposure horizons. In addition to a predictable facies-stacking pattern that controls vertical reservoir heterogeneity, the reef complexes show distinct differences between windward and leeward margins, illustrated in both the reef geometry and the resulting distribution of reservoir facies. Windward margins are steeper due to higher rates of aggradational growth and typically contain better reservoir quality in both the reef core and fore reef facies. In contrast, leeward margins are characterized by more gently dipping slopes made up of finer-grained facies that are of poorer reservoir quality.

The stratigraphic hierarchy plays a major role in controlling the overall quality and vertical heterogeneity of the reservoir units. Reservoir quality in reef and capping grainstones are best developed at 4th order boundaries due to extensive dissolution and resulting porosity development. Capping grainstones in 5th order cycles that are not associated with 4th order sequence boundaries, however, generally exhibit poor reservoir quality due to extensive cementation and porosity occlusion. Understanding of the sequence hierarchy in these Silurian reefs provides additional insight into the episodic growth of the reefs relative to sea level fluctuations, and provides a means to better predict the lateral and vertical reservoir heterogeneity.

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Outline

- Introduction
- Geologic Setting
- Previous Studies
- Sequence Stratigraphic Framework
- Modeling
- Image Analysis
- Sonic Velocity
- Summary and Conclusions

Niagaran Reefs

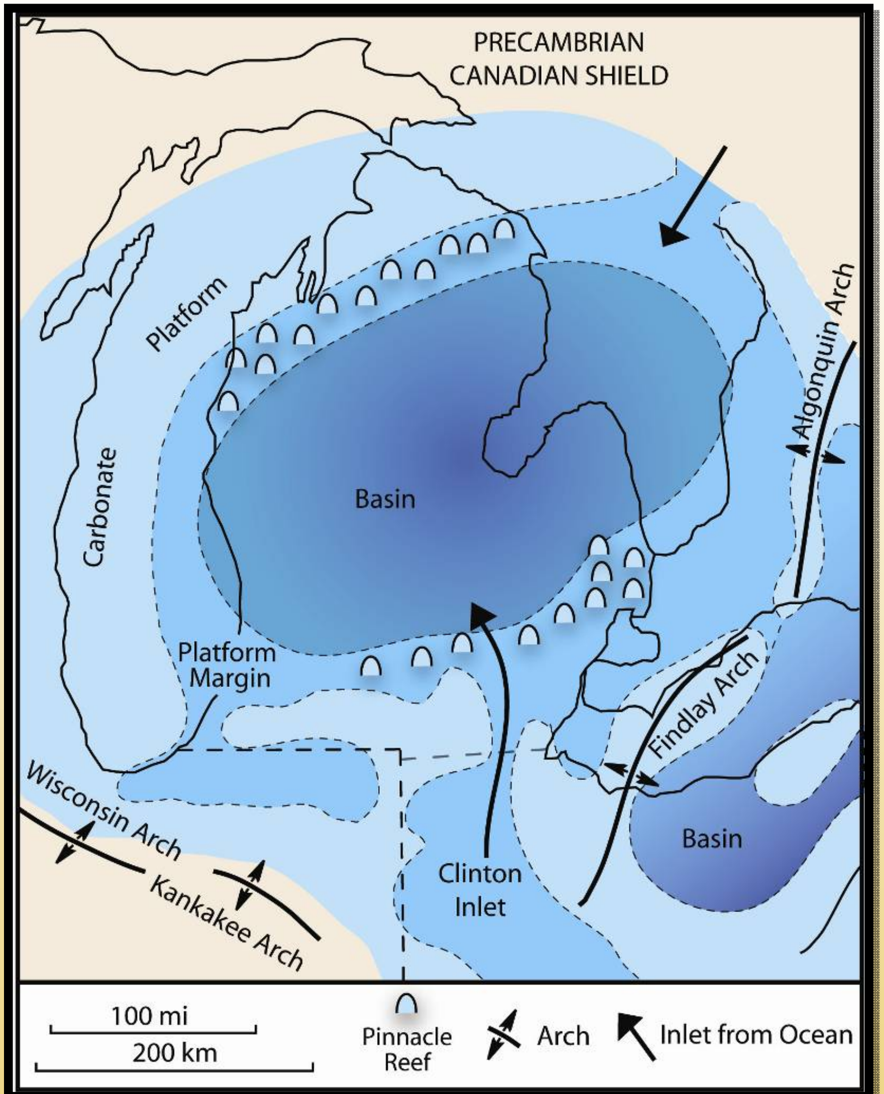
- **Good porosity and permeability in various facies but significant reservoir heterogeneity**
- **Regional Seal (A-2 Evaporite)**
- **The reef play is the most successful play in Michigan**
  - production of 475 MMBO and 2.8 TCF of gas
- **Ultimate recovery**
  - 1 billion BOE from over 1000 pinnacle reefs
- **Undiscovered resources**
  - 211 MMBO and 434 BCFG (USGS, 2005)
- **Gas storage**

Fundamental Questions for Niagaran Reefs in the Michigan Basin

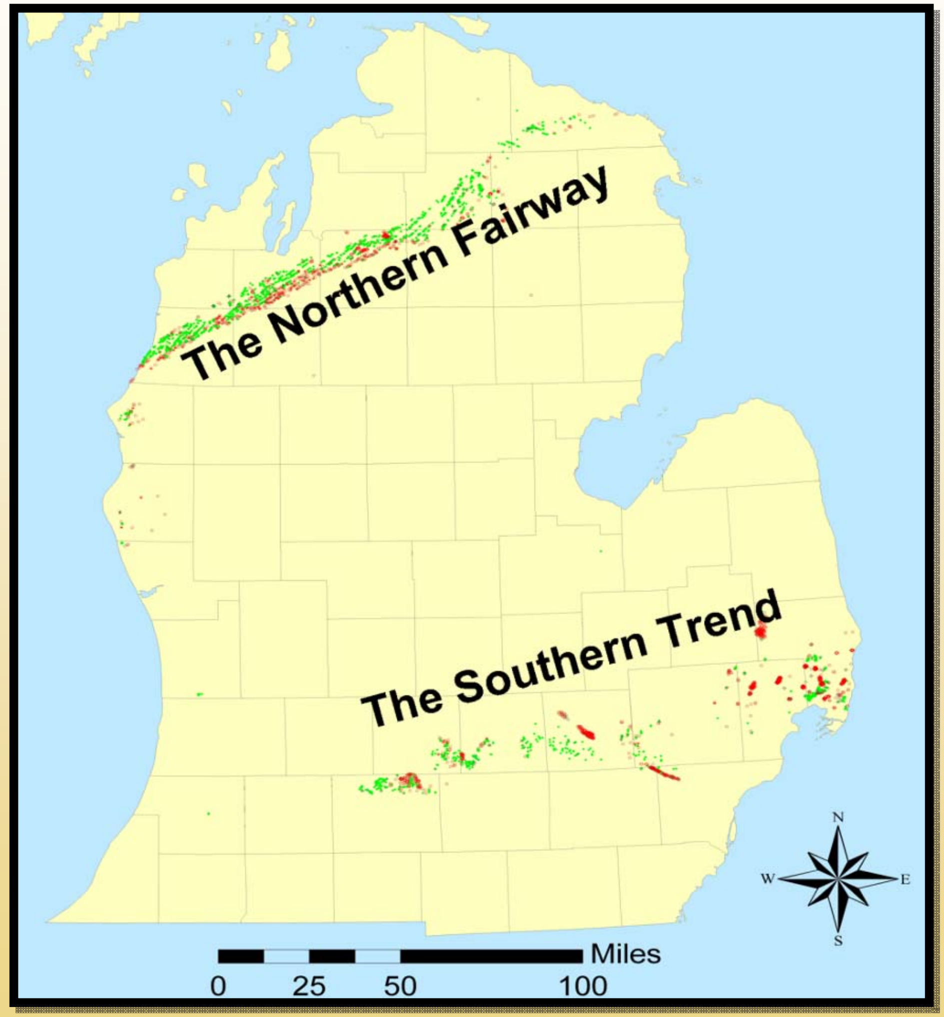
1. **What are the controlling factors on the deposition of Silurian Pinnacle reefs ?**
   - **Reef evolution (continuous growth vs. episodic)**
   - **Sea level control on facies types (circulation and bathymetry) and architecture**

2. **Do these controlling factors create complexity in the reservoir architecture of the reef?**
   - **What factors contribute to the variability in porosity & permeability ?**
   - **Correlation to facies type?**
   - **Patterns within sequence framework?**

Regional Setting

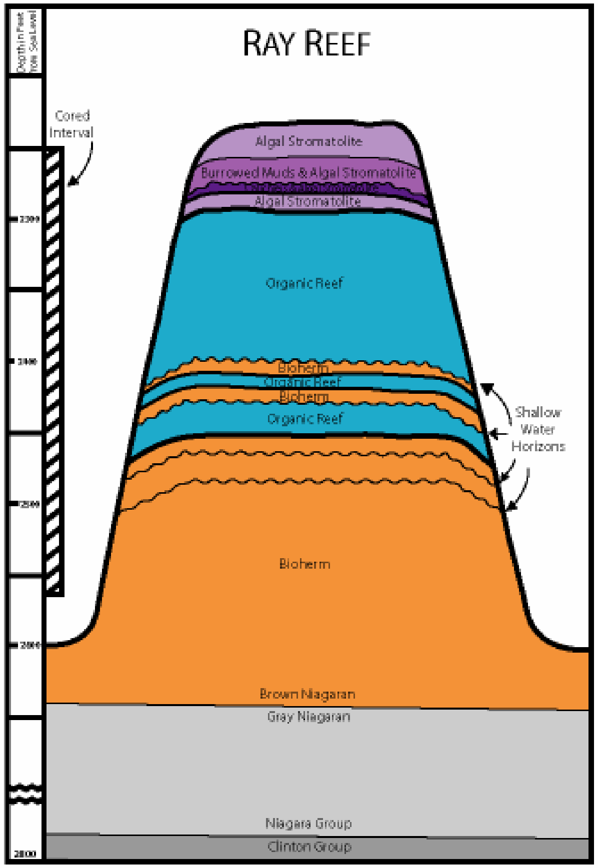


Middle Silurian (Niagaran) environments in the Michigan Basin (modified from Briggs et al., 1980)

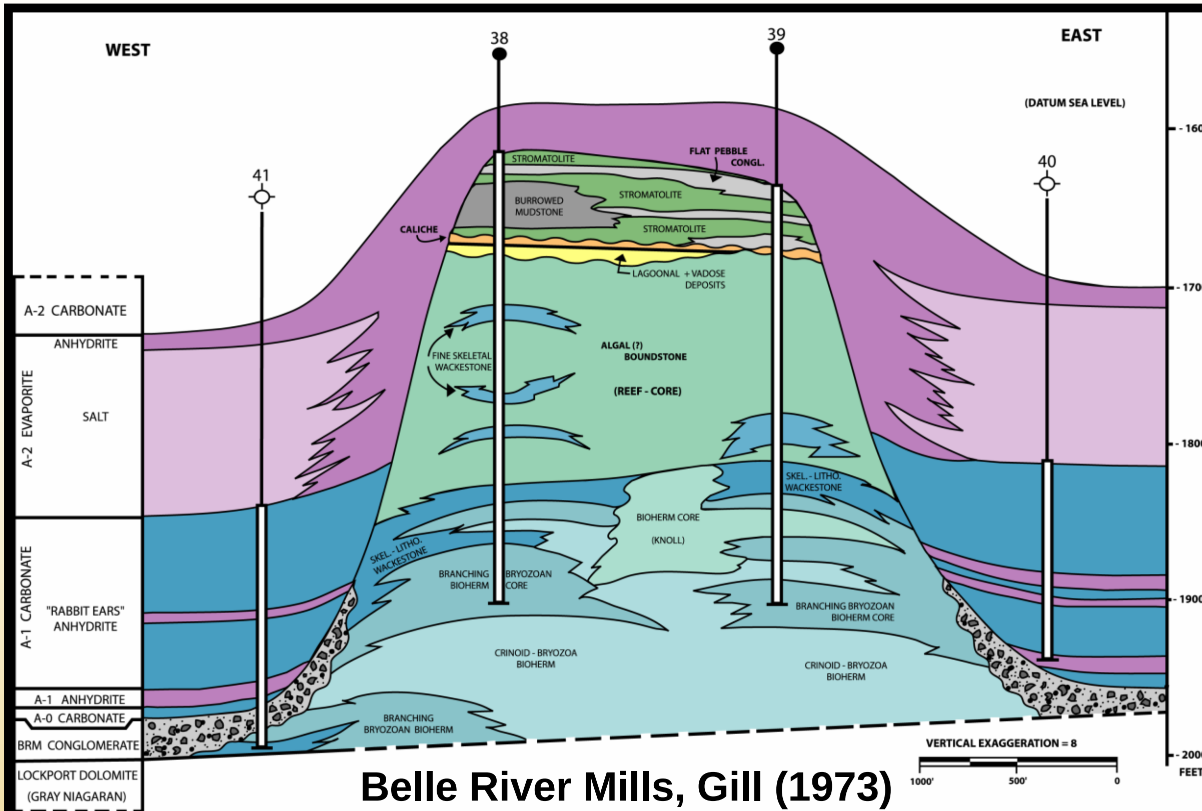


Northern and Southern Reef Trend Oil (green) and Gas (red) Producers (Michigan DNR ESRI ArcMap, 2006)

Previous Niagaran Reef Models



Balogh (1981)



Belle River Mills, Gill (1973)

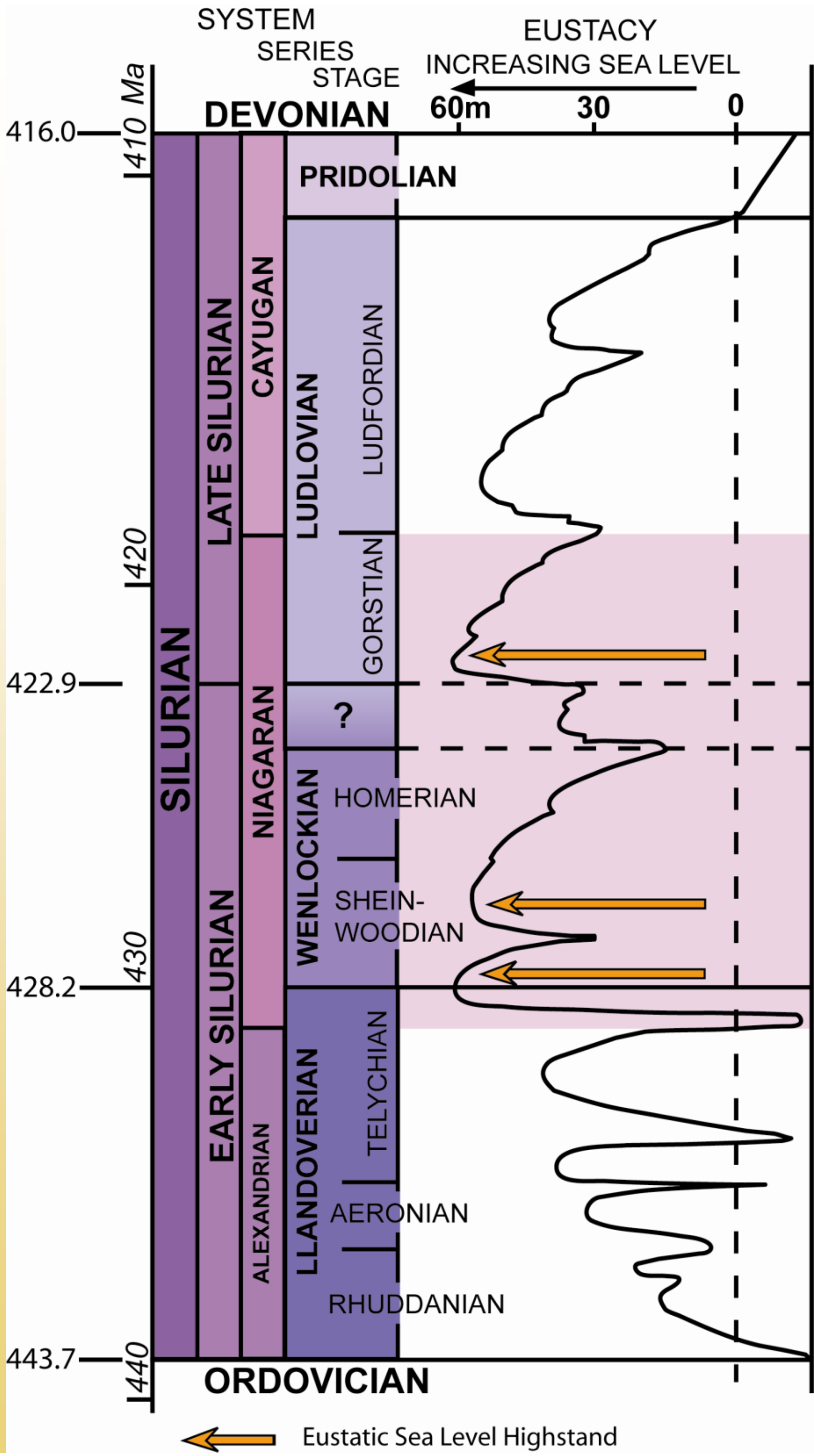
- •Focus was on models for reef growth and facies distribution
- •Stacking patterns start to become recognizable in early models, but they were not focus of earlier studies

Niagaran Reef
Sequence Stratigraphy

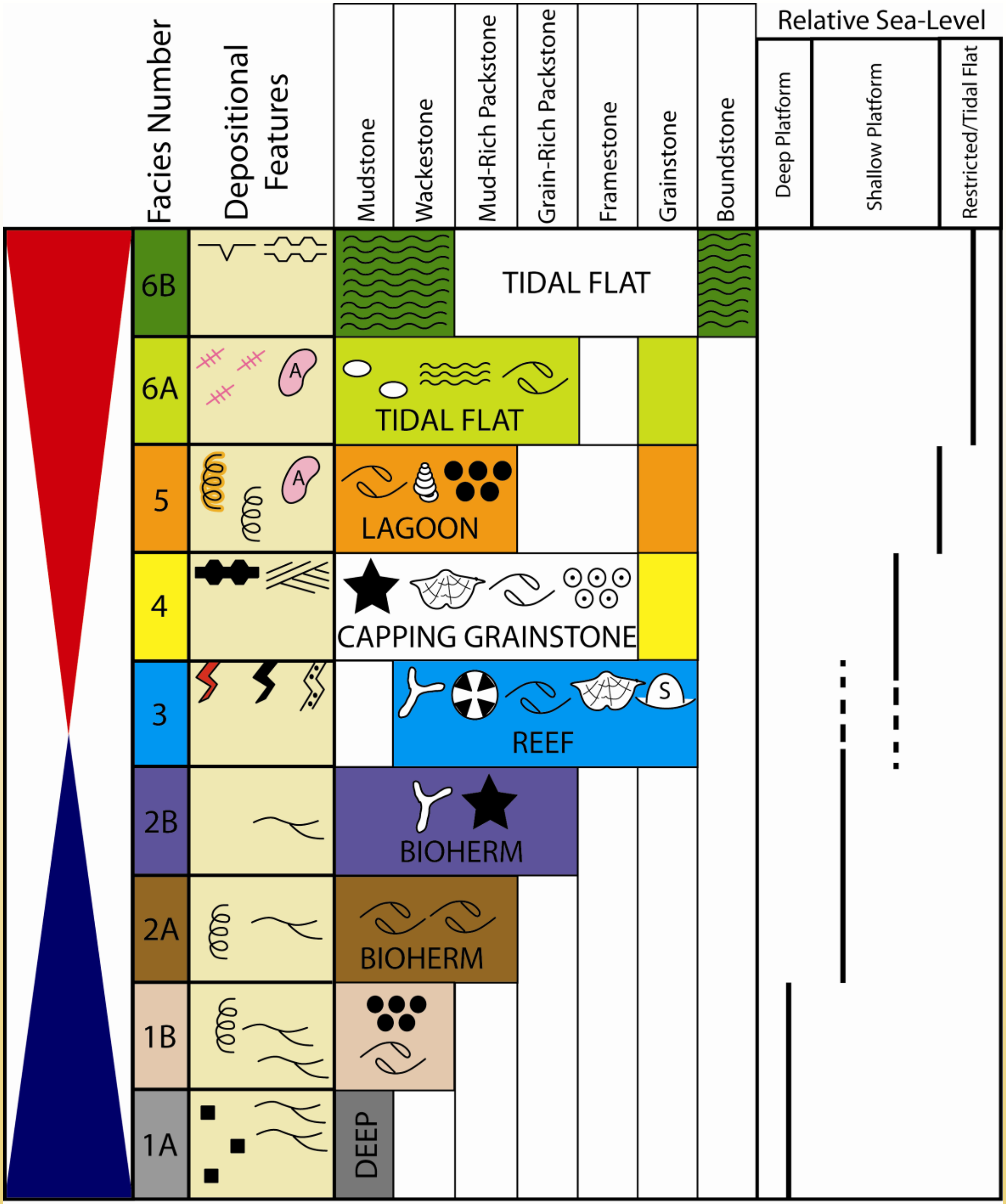
Silurian Sea Level

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

Modified from Ross & Ross, 1996



Generalized Facies Succession



Ritter (2008)

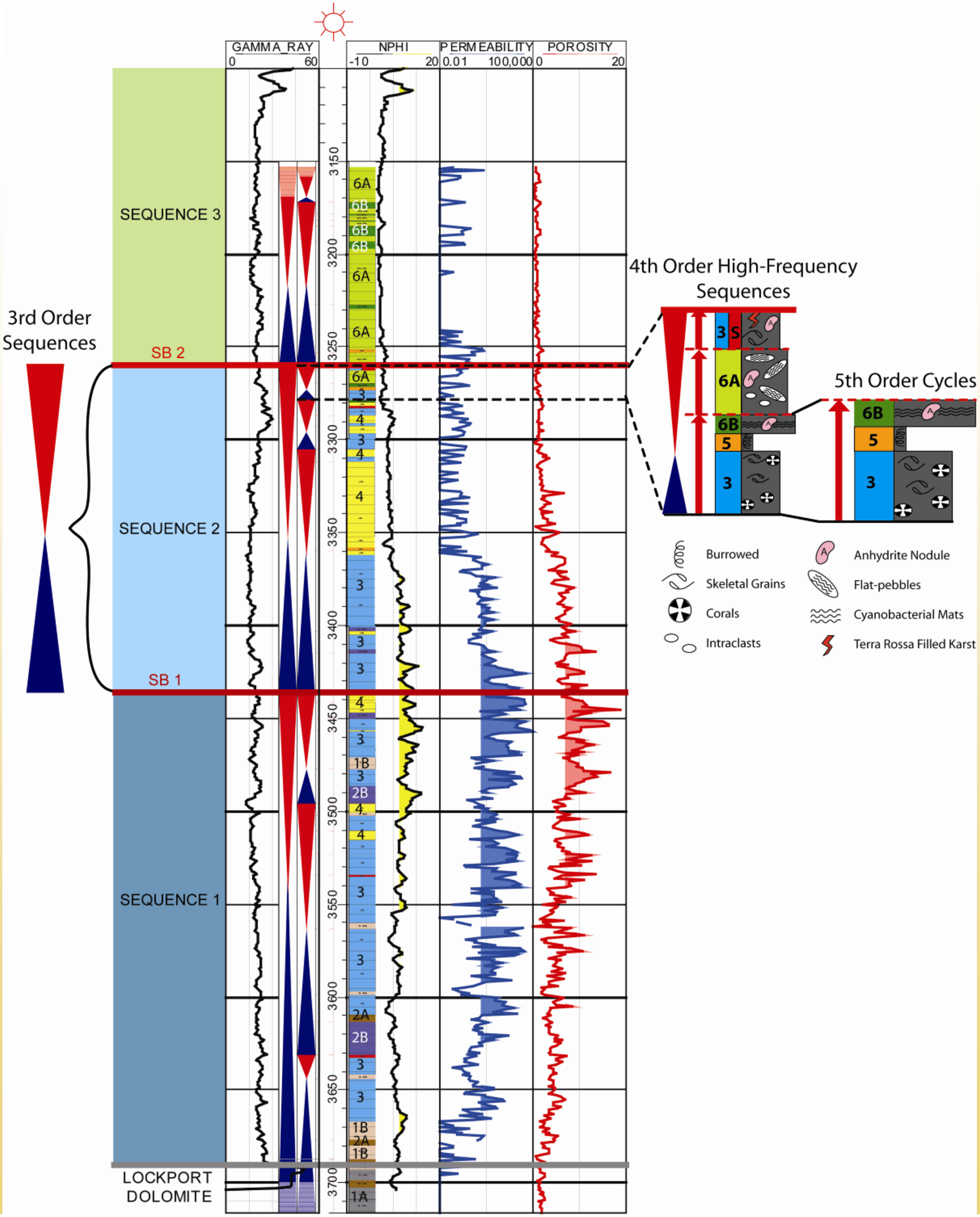
Restricted Environments -
- Cyanobacterial Mat Boundstones
- Brecciated, Cyanobacterial Mat Boundstone
- Burrowed, Peloidal Wackestones to Grainstones

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

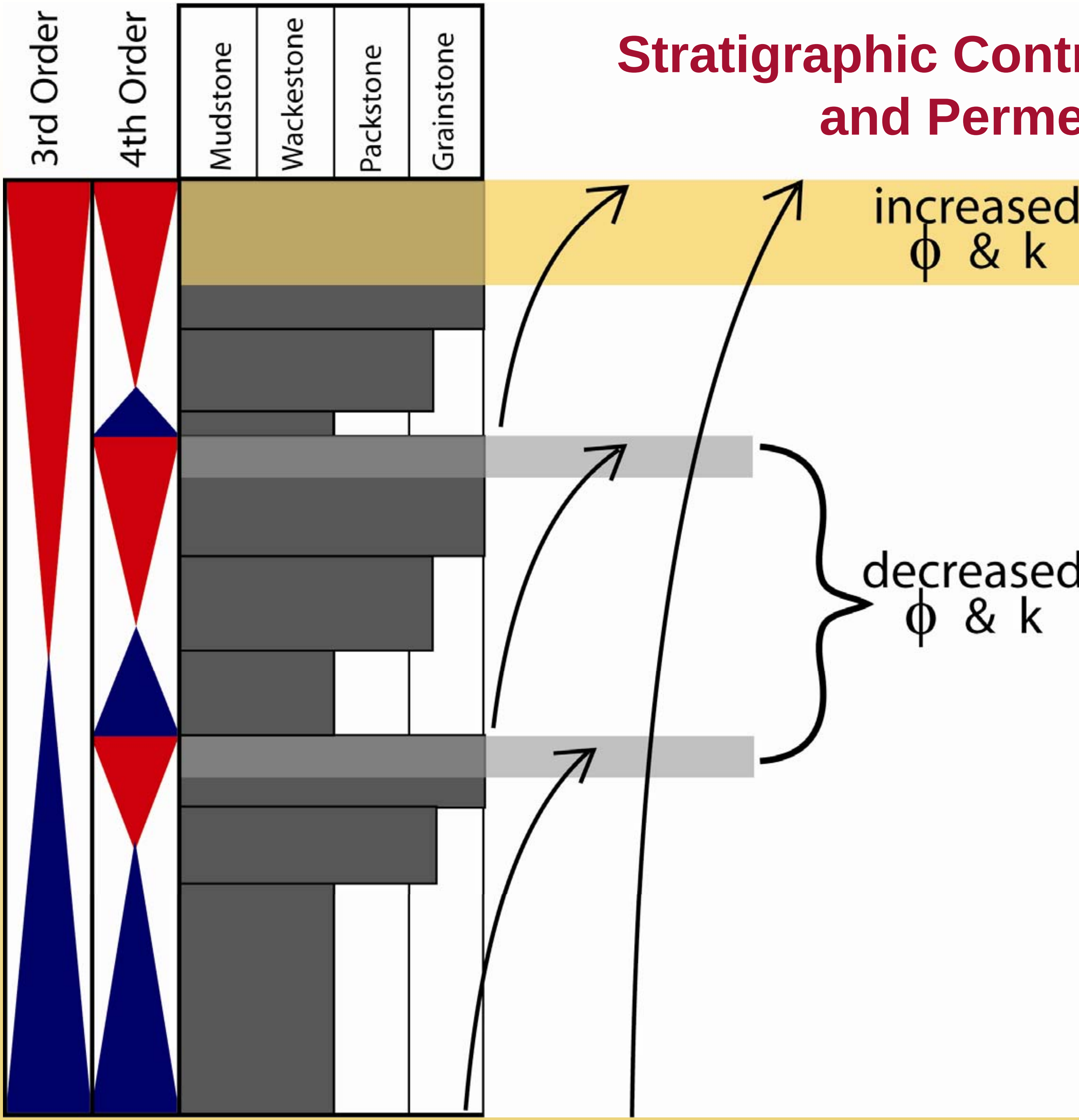


Sequence Stratigraphic Hierarchy in Niagaran Reefs

(northern and southern trends)

Ritter (2008)

Stratigraphic Control on Porosity and Permeability



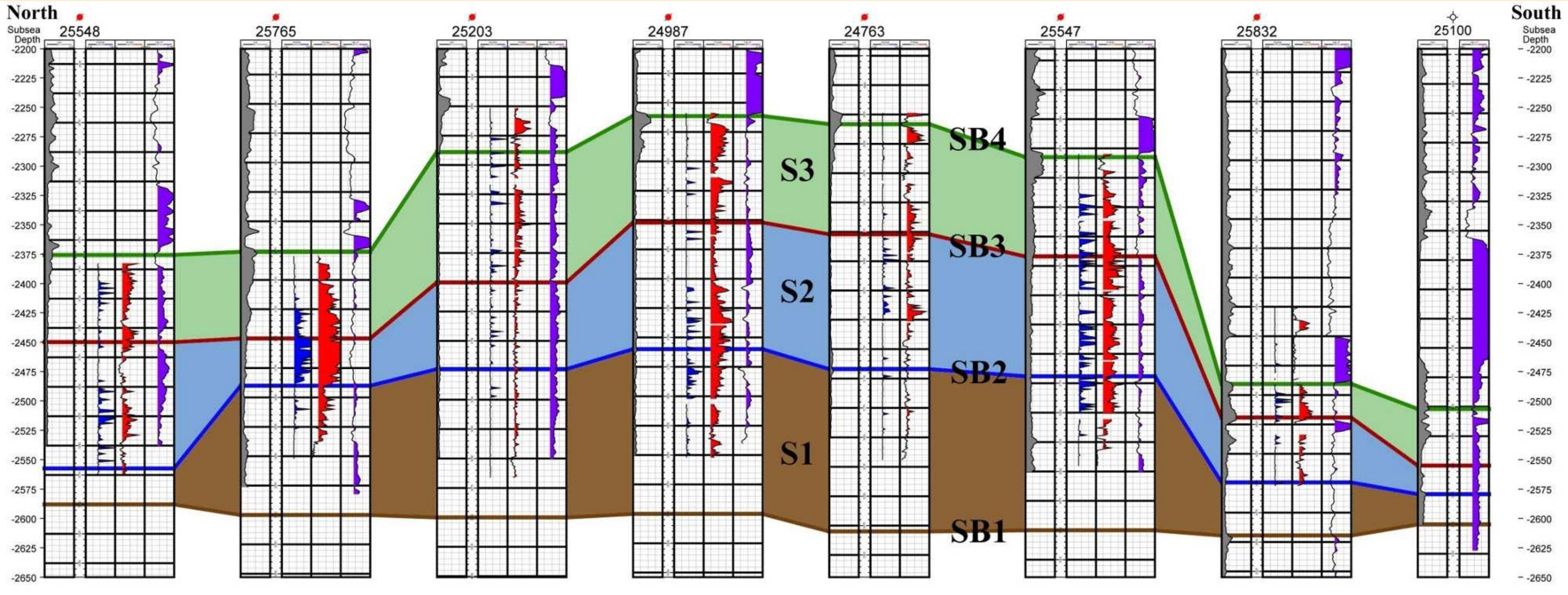
Ritter (2008)

Modeling

- **Fields Modeled:**
  - Ray Reef (Wold, 2008)
  - Belle River Mills (Qualman, 2009)
- **Data:**
  - Wireline Logs
  - Facies (from core)
  - Porosity/permeability from whole core analysis and minipermeameter
  - Sequence stratigraphic architecture (timelines)

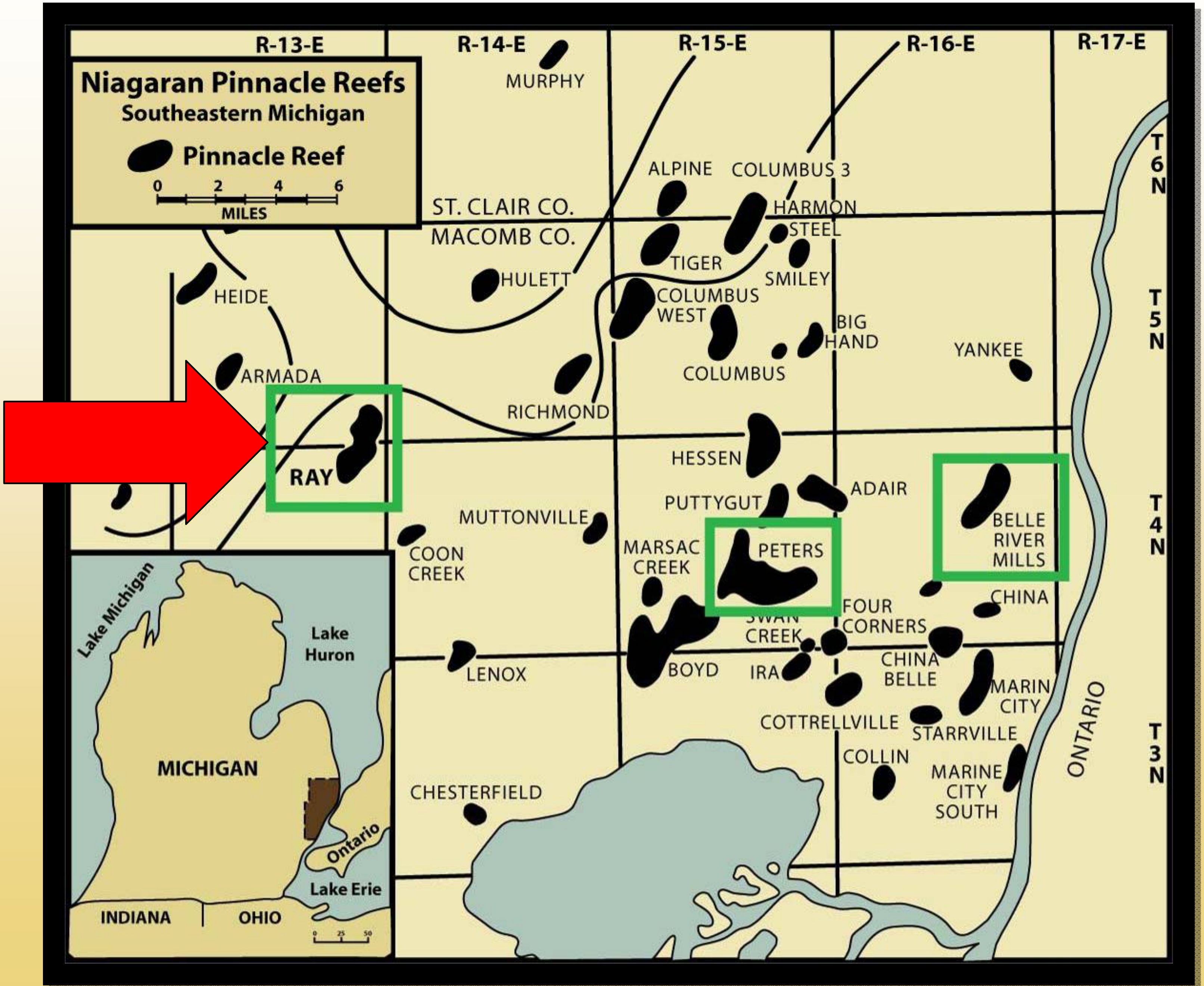
Sequence Framework – Ray Reef

- **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**



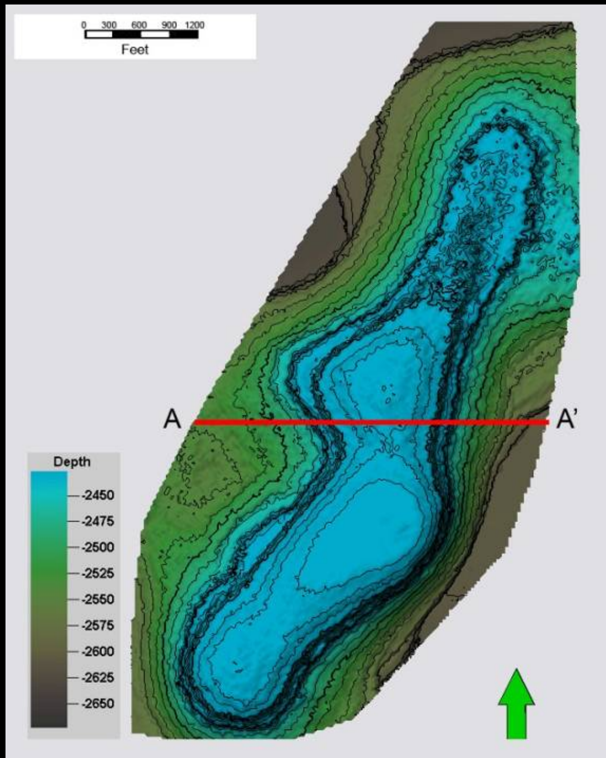
Wold (2008)

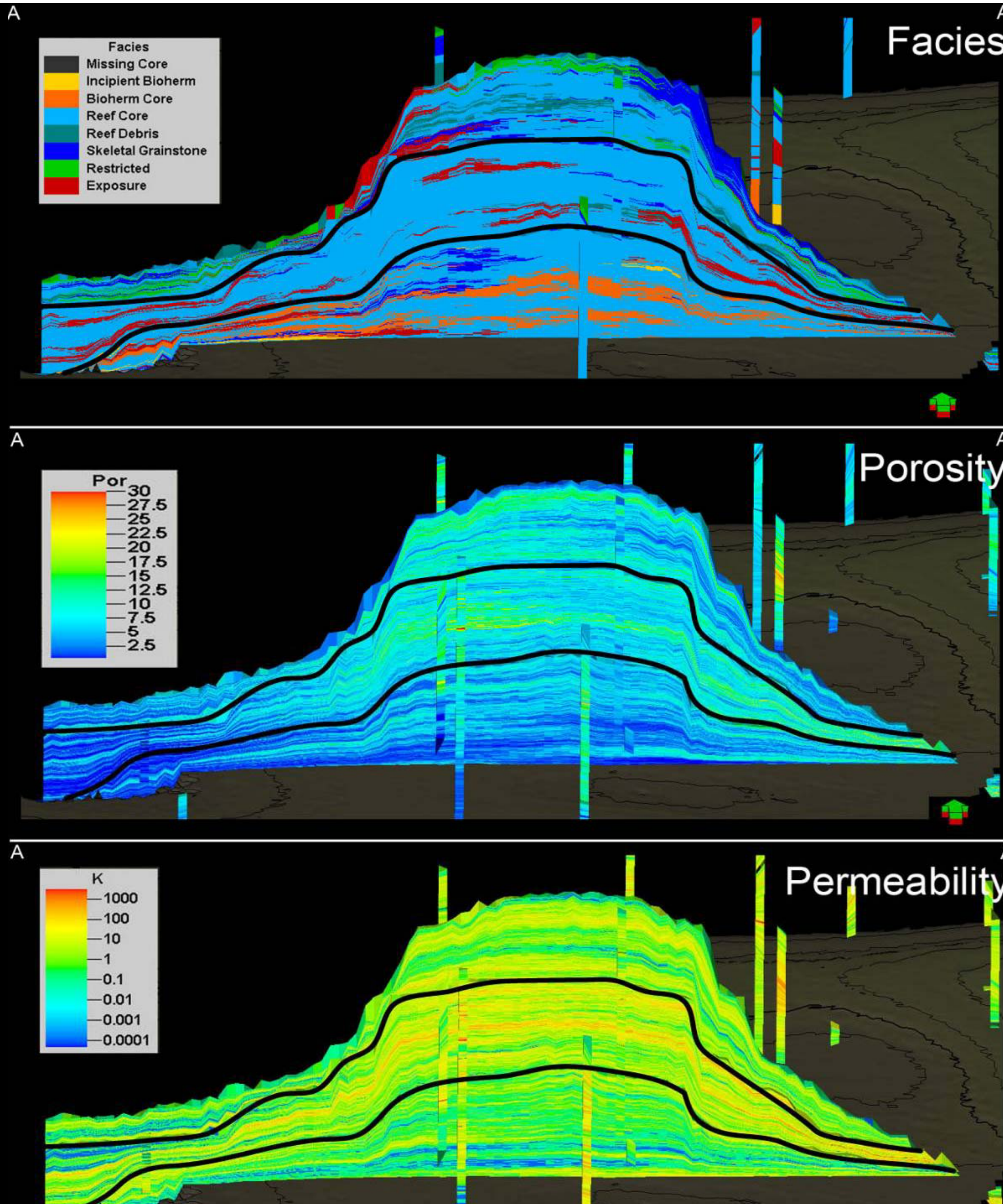
Niagaran Reefs in Southern Trend: Ray Reef



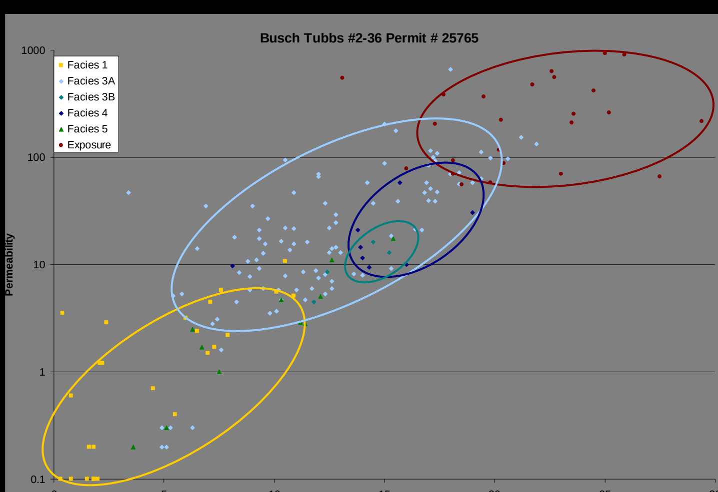
Gill (1973, 1977)

A - A' Cross-Section



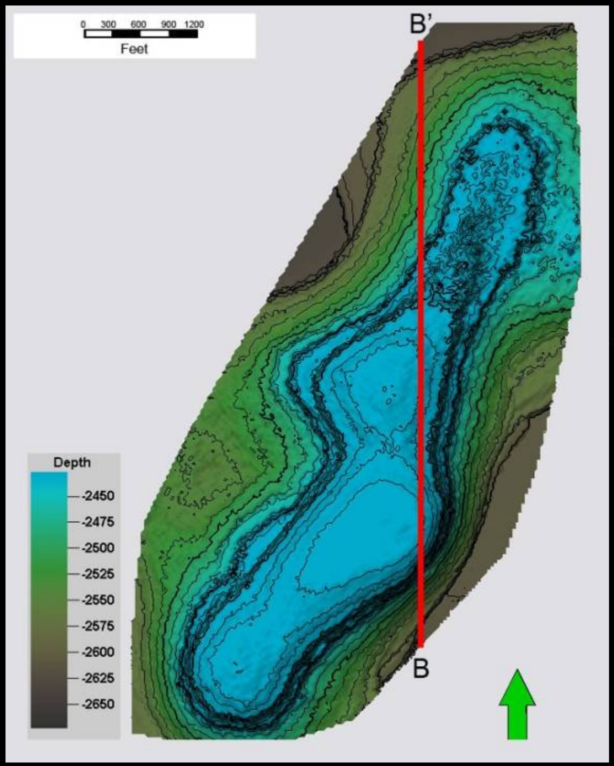


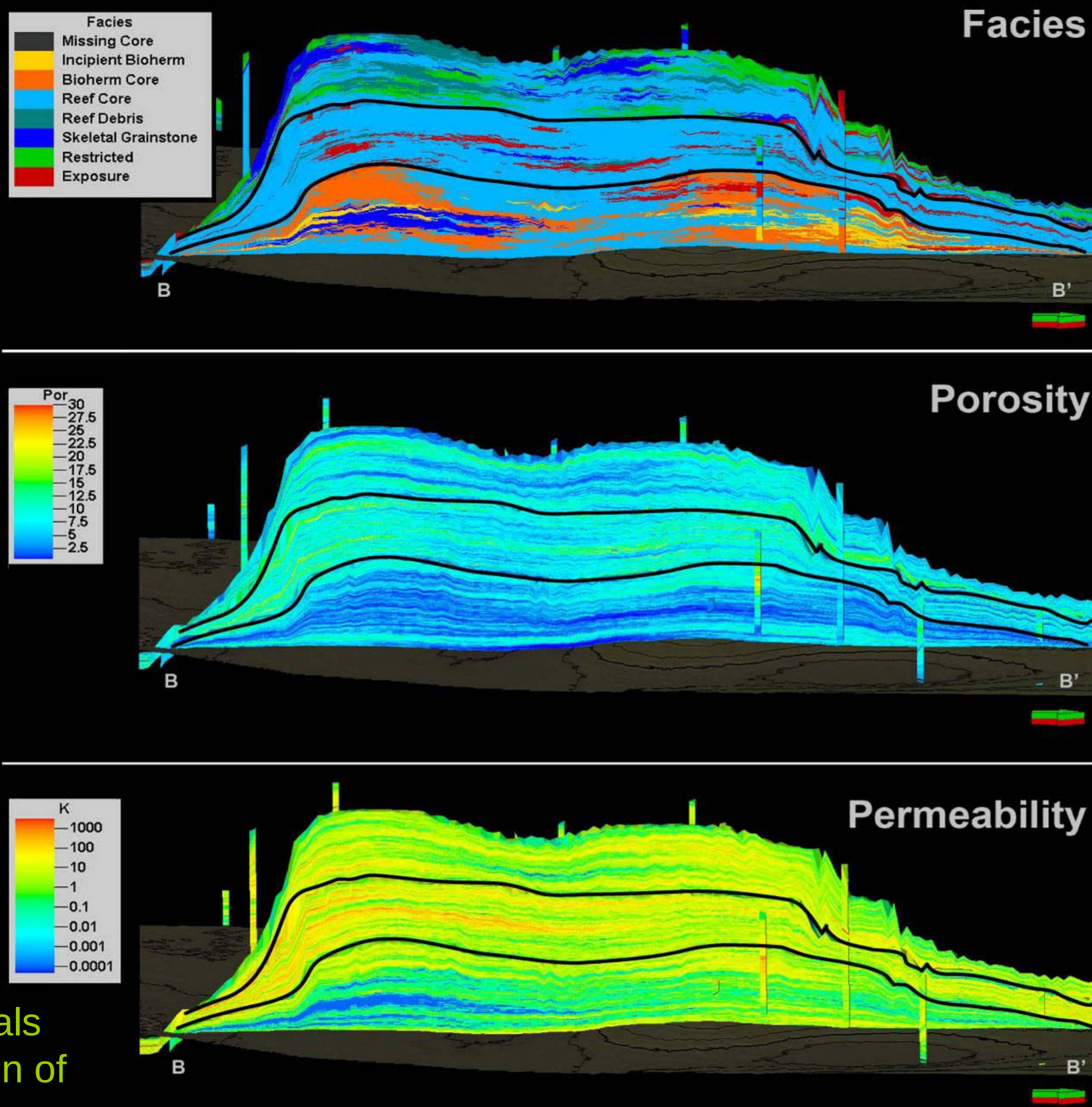
•Relationship between the primary depositional facies and petrophysical properties



Wold (2008)

B - B' Cross-Section

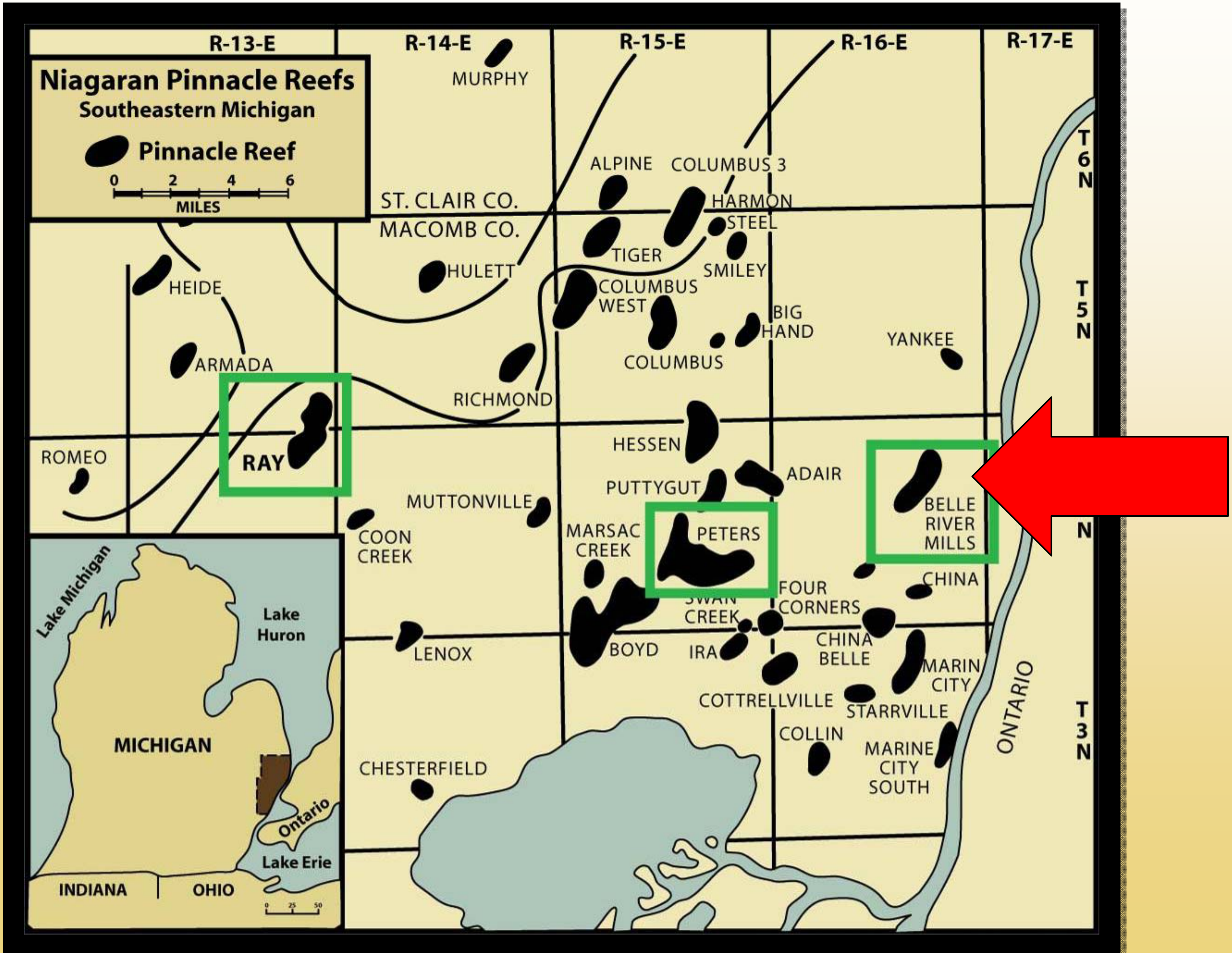




- Progradational vs. Aggradational Growth
- Windward vs. Leeward Margins
- Potential reservoir intervals along the windward margin of the reef complex.

Wold (2008)

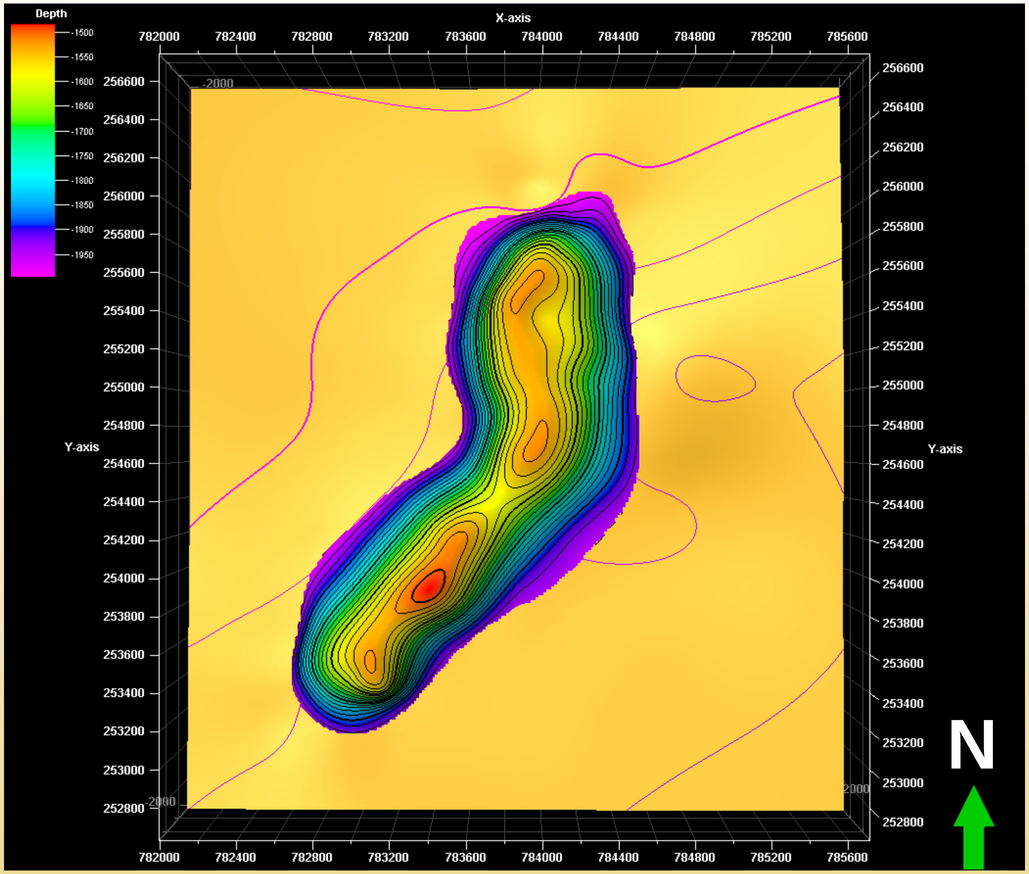
Niagaran Reefs in Southern Trend: BRM



Gill (1973, 1977)

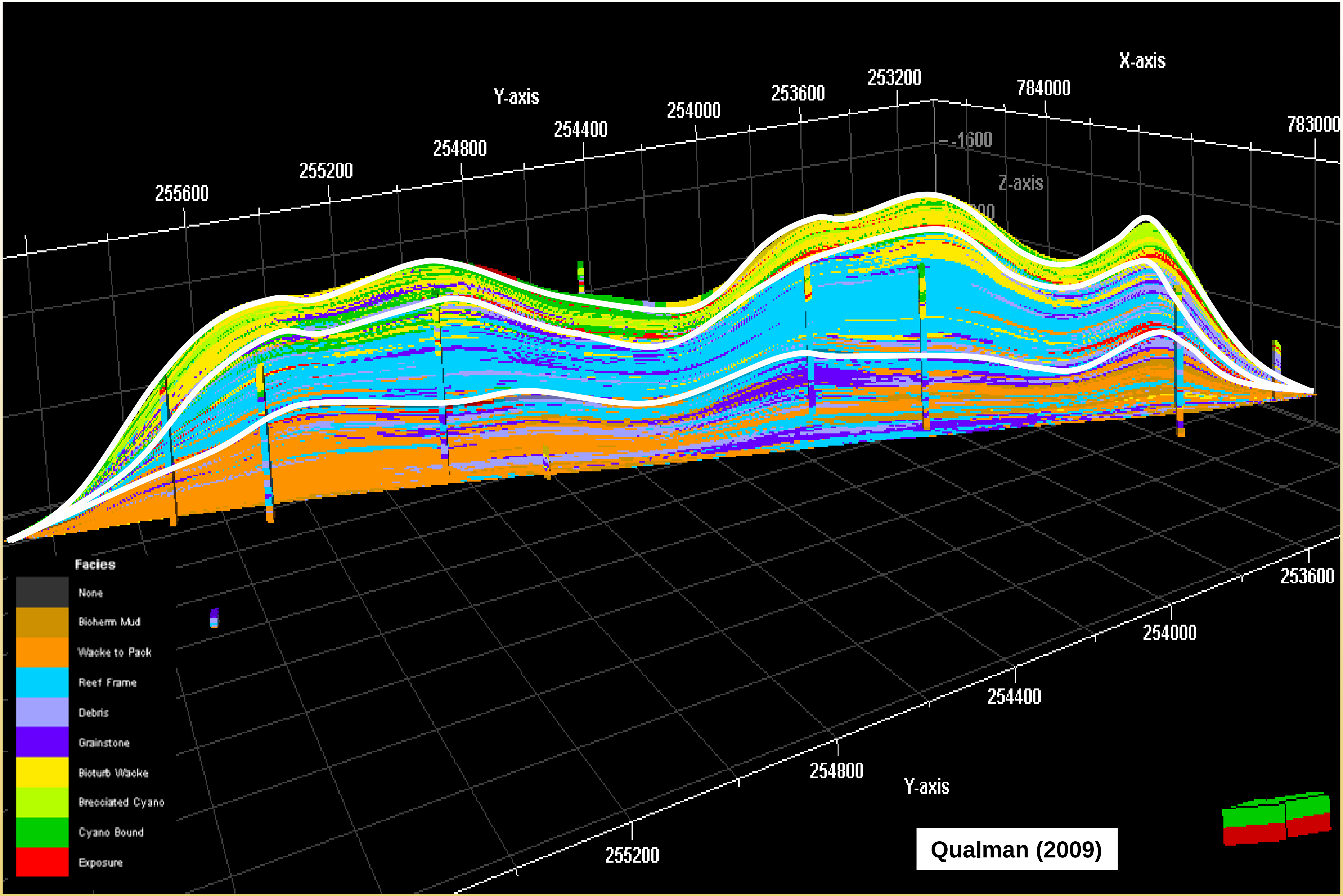
BRM Data

- 12 cores with detailed facies descriptions
- 54 Gamma Ray and Neutron API Logs
- ϕ/κ measurements from 35 core analysis reports

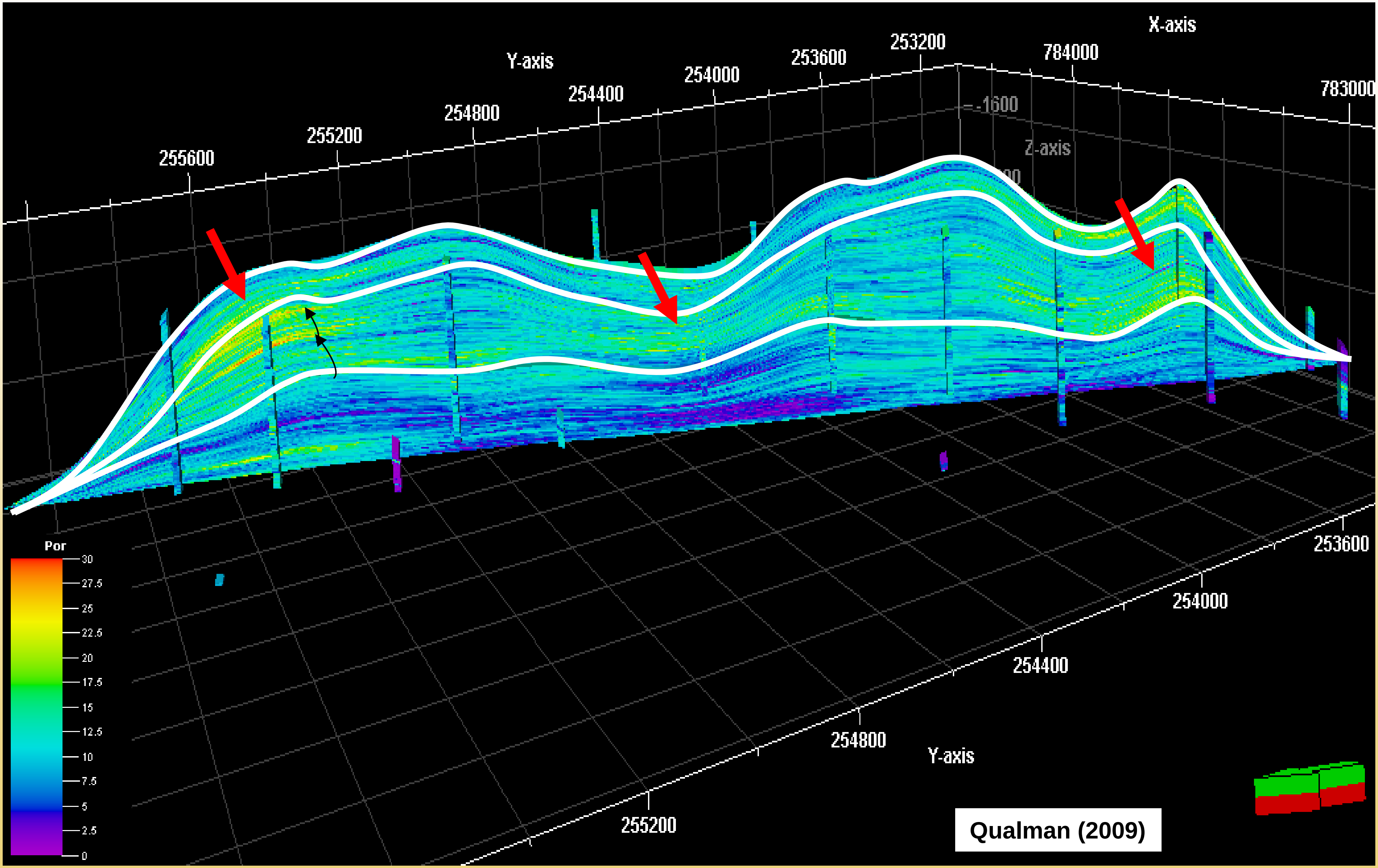


Qualman (2009)

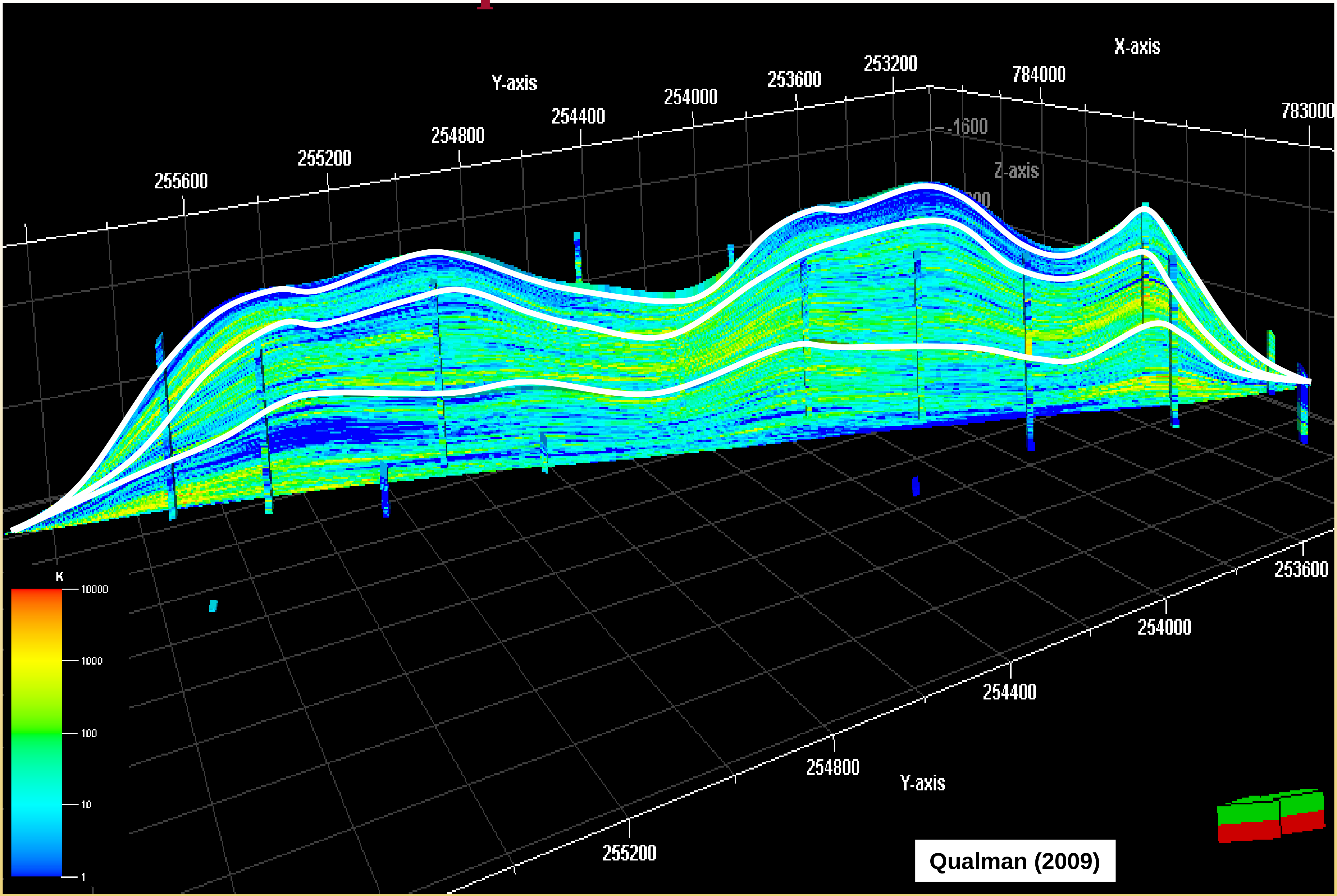
Facies Distribution constrained by Sequence Architecture



Porosity Distribution constrained by Sequence Architecture



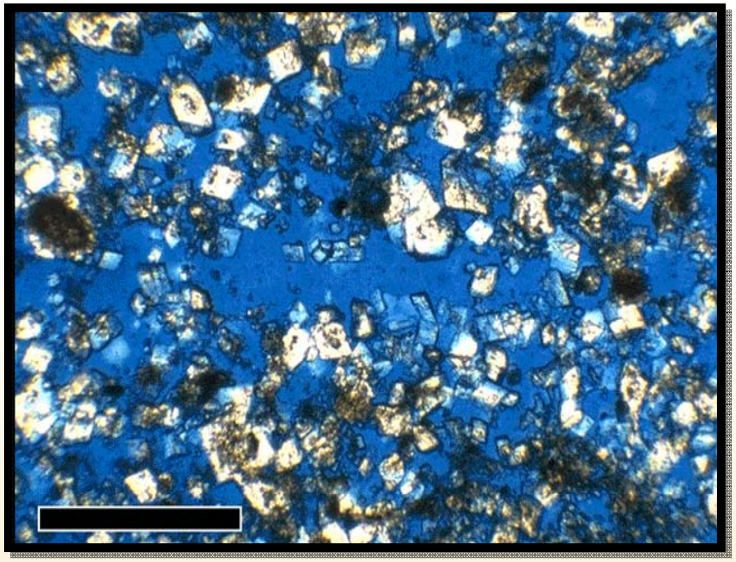
Permeability Distribution constrained by Sequence Architecture

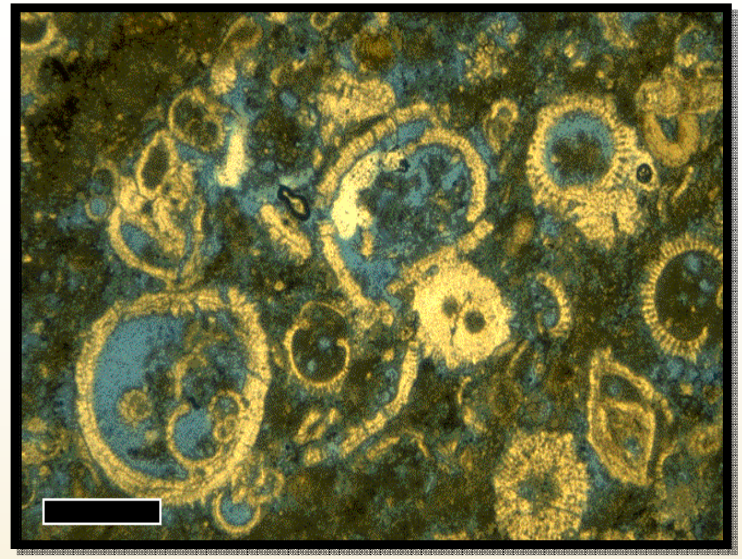


Facies Pore Architecture

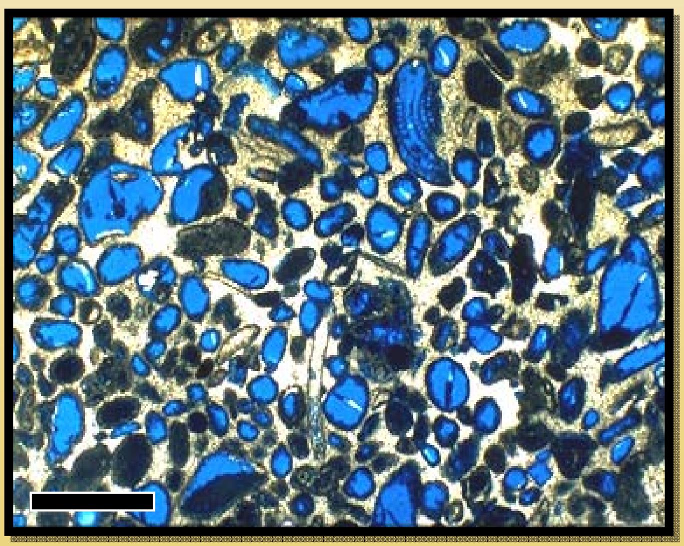
-Image Analysis

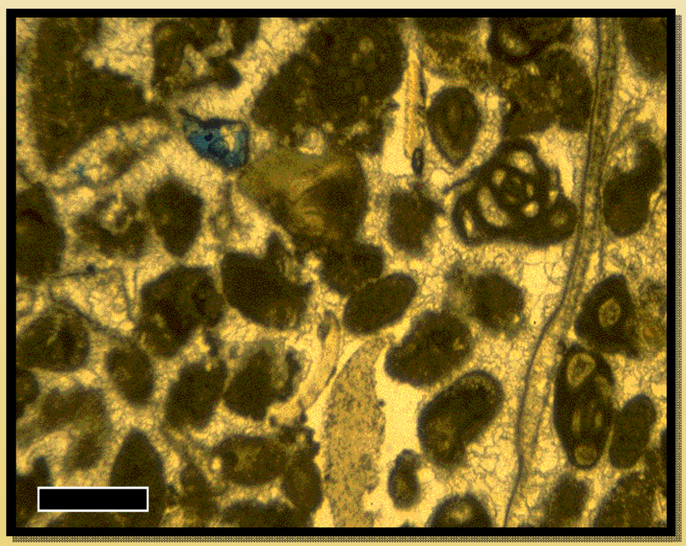
-Sonic Velocity

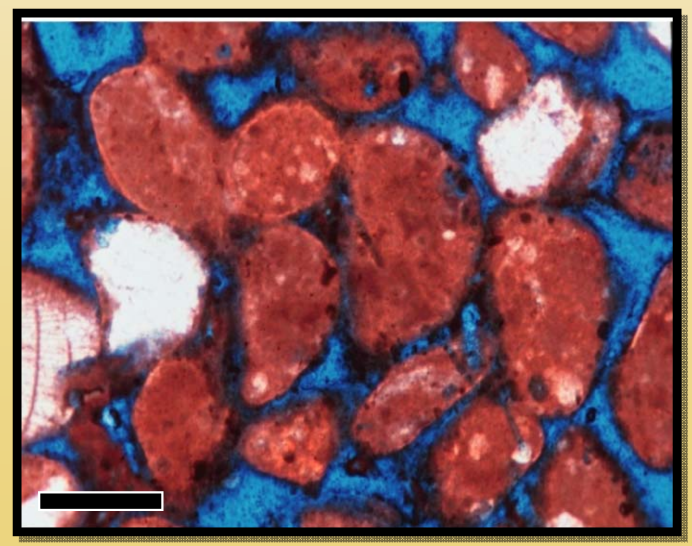




Carbonates have varying pore types that influence permeability

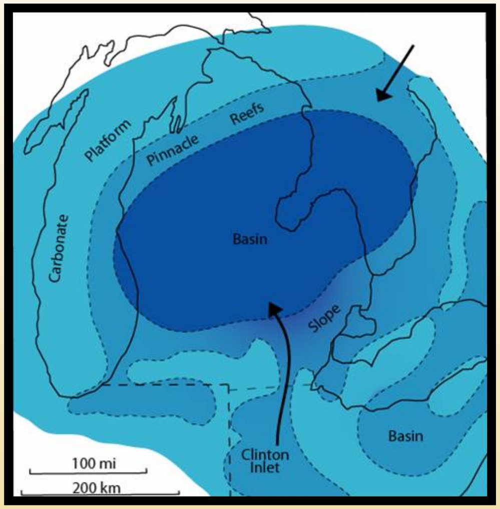






Eberli, 2000

Location of Wells



Middle Silurian (Niagaran) environments in the Michigan Basin (modified from Briggs et al., 1980)

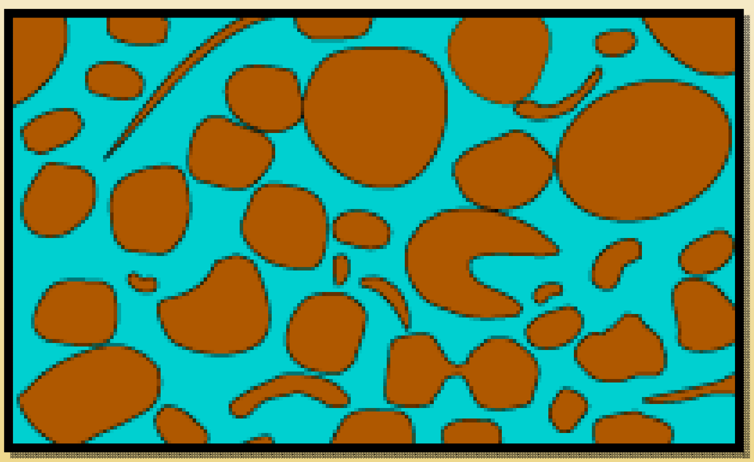
Niagaran cores chosen for this study

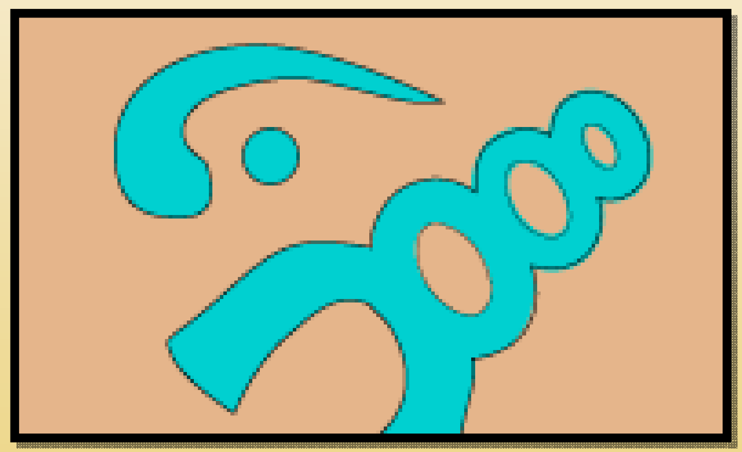
Pore Architecture tied to Petrophysical Properties

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**

Image Analysis

- Macropore shape affects overall permeability
- The more spherical pores that exist, the less connectivity (lower permeability)





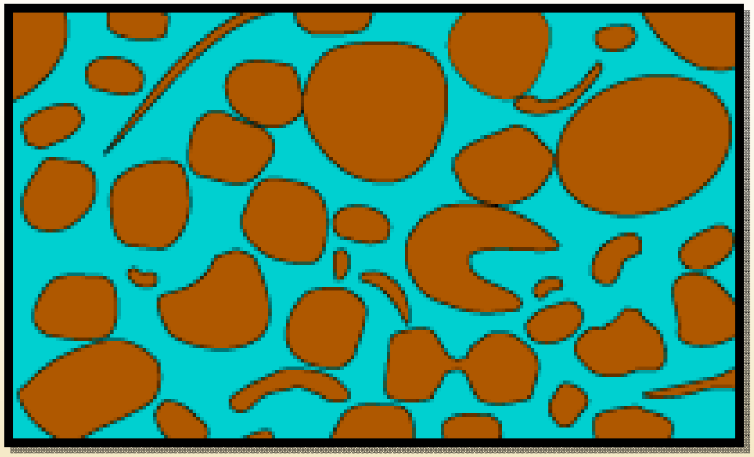
Scholle and Ulmer-Scholle, 2003

Comparison of Pore Shape Parameter (γ) to Permeability

•The roundness/sphericity parameter from the image analysis program is a ratio of the pore perimeter to the pore area

Roundness/"sphericity" = Perimeter^2 / (4 *π* Area)

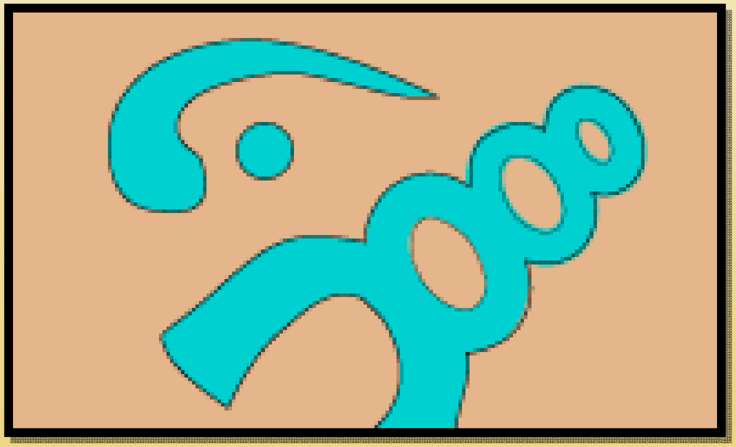
ϕ ~ 20%
γ ~ 2.40



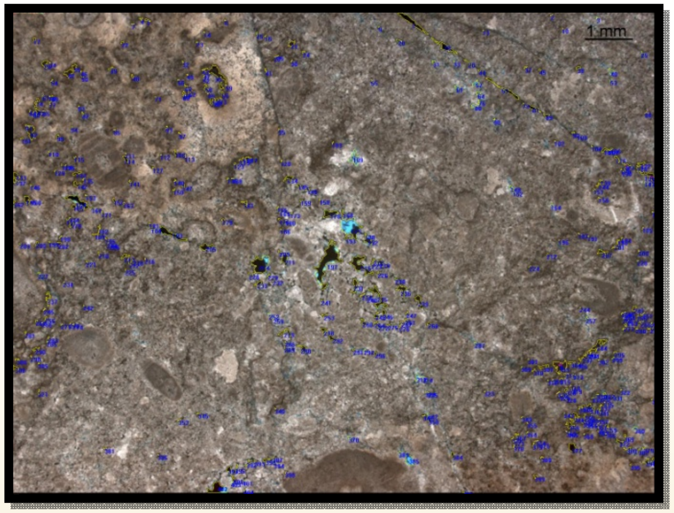
•However, another study by Anselmetti et al. (1998) suggests a similar roundness/"sphericity"/shape parameter

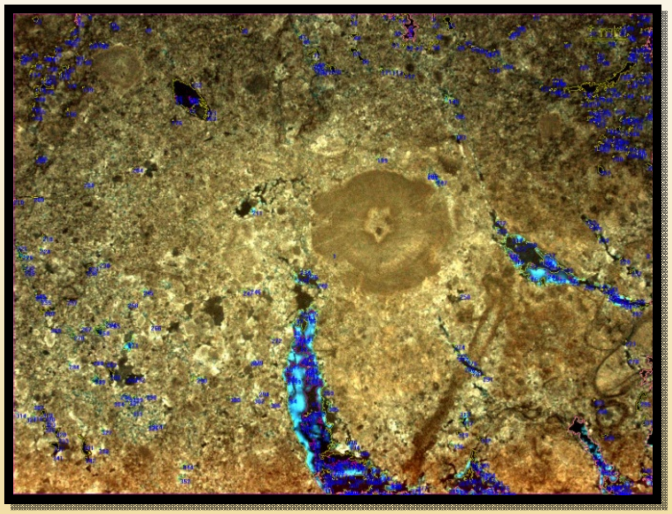
γ= Perimeter / (2 * √(π* Area))

ϕ ~ 20%
γ ~ 1.06



Scholle and Ulmer-Scholle, 2003



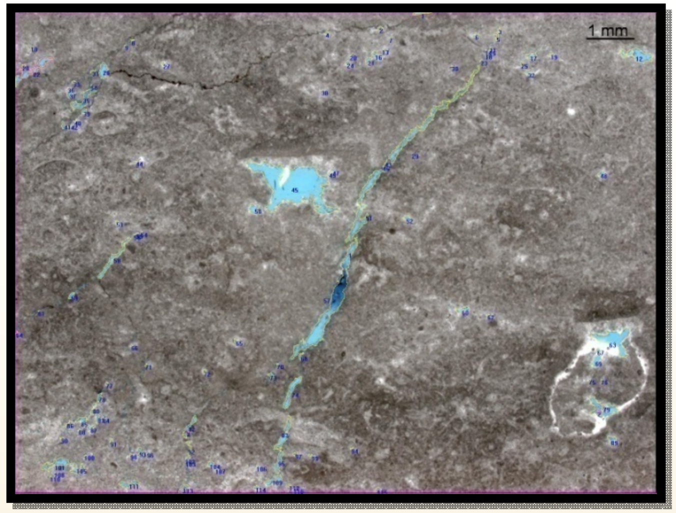


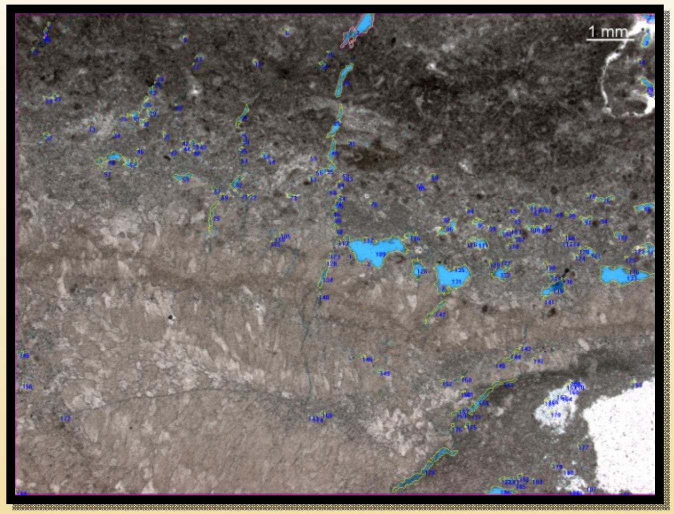
Charlton 4921’ IA Porosity:

Top: 1.8%

Bottom: 4.2%

Roundness: 1.7



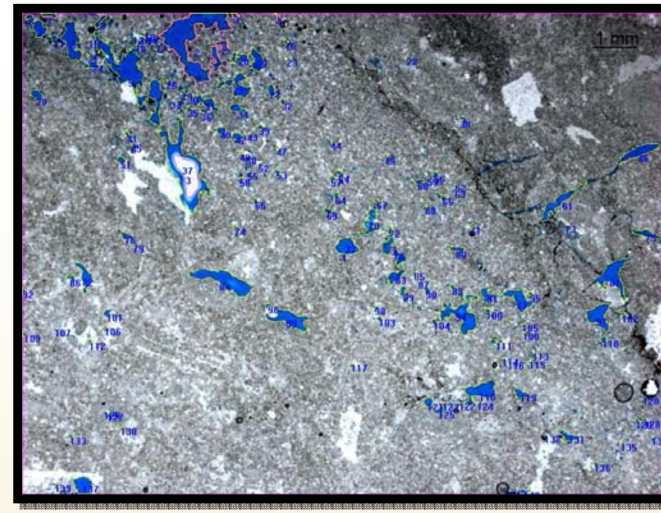


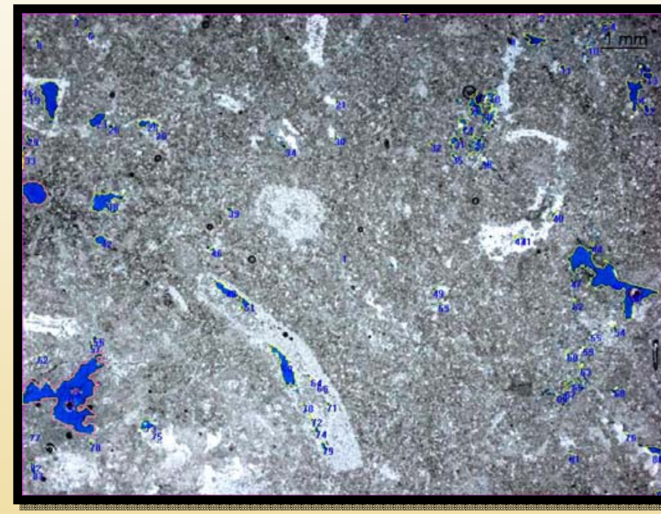
Fugere 4335’ IA Porosity:

Top: 2.7%

Bottom: 2.75%

Roundness: 1.5



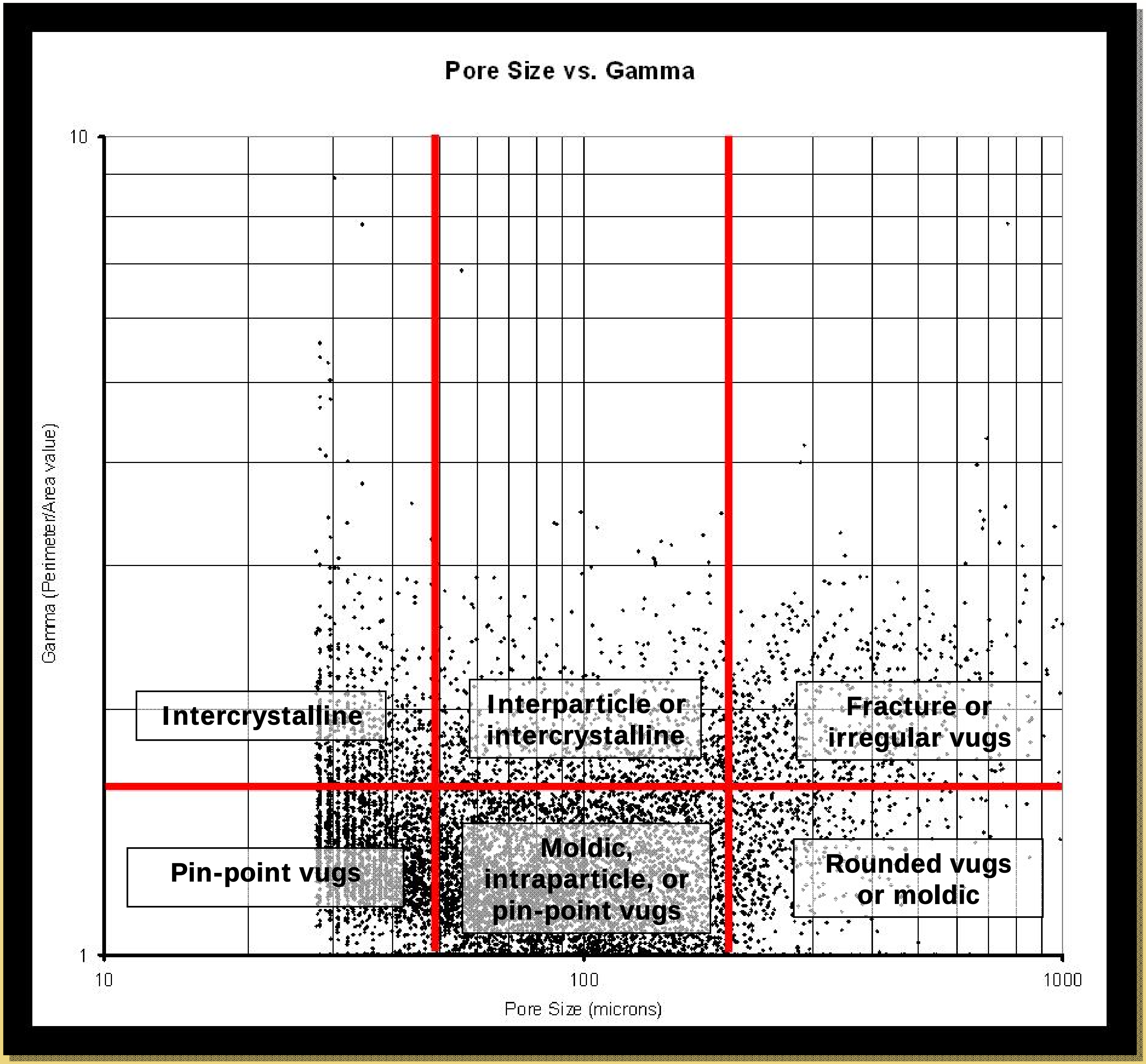


Miller-Fox 3611’ IA Porosity:

Top: 5.6%

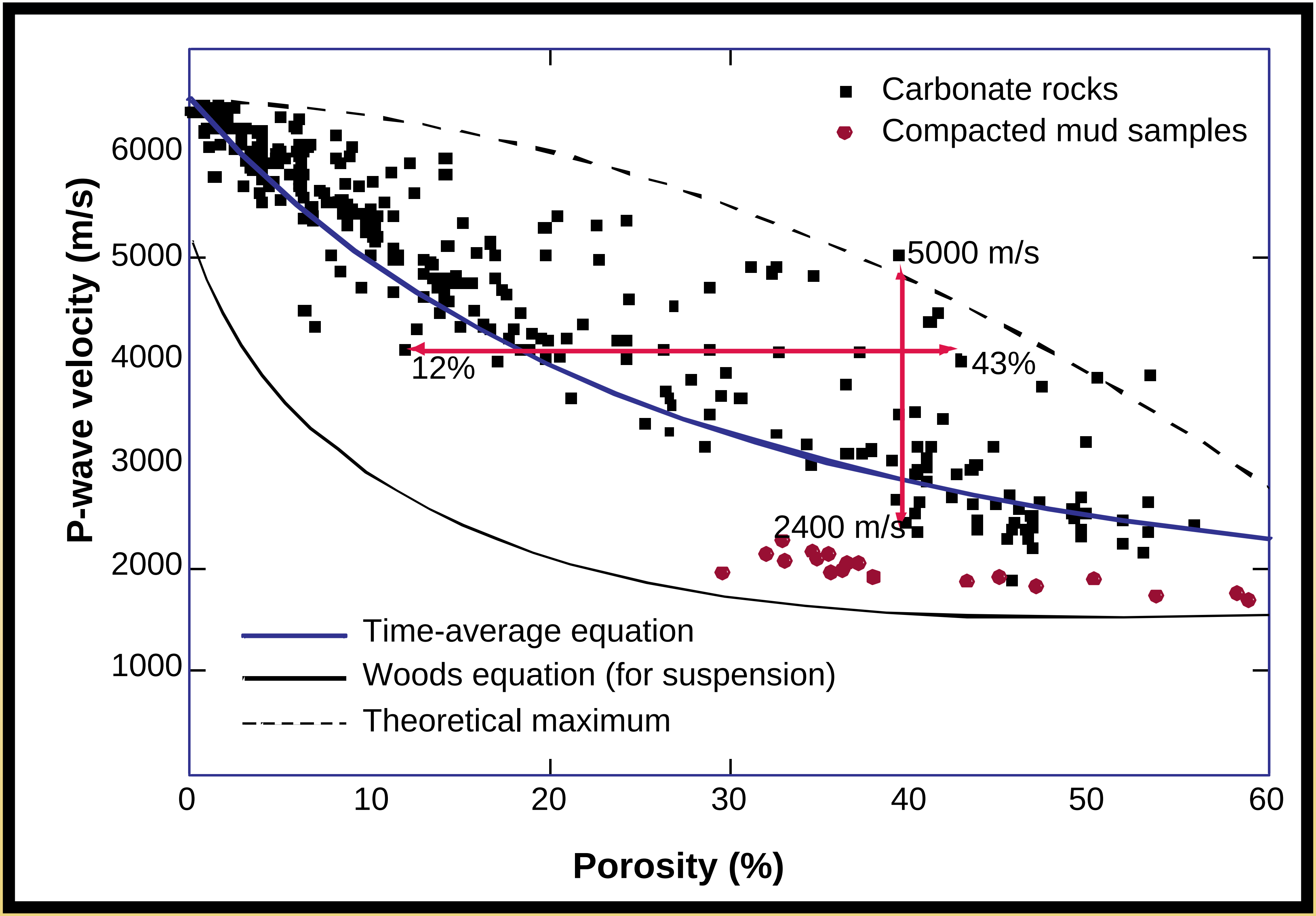
Bottom: 3.2%

Roundness: 1.2

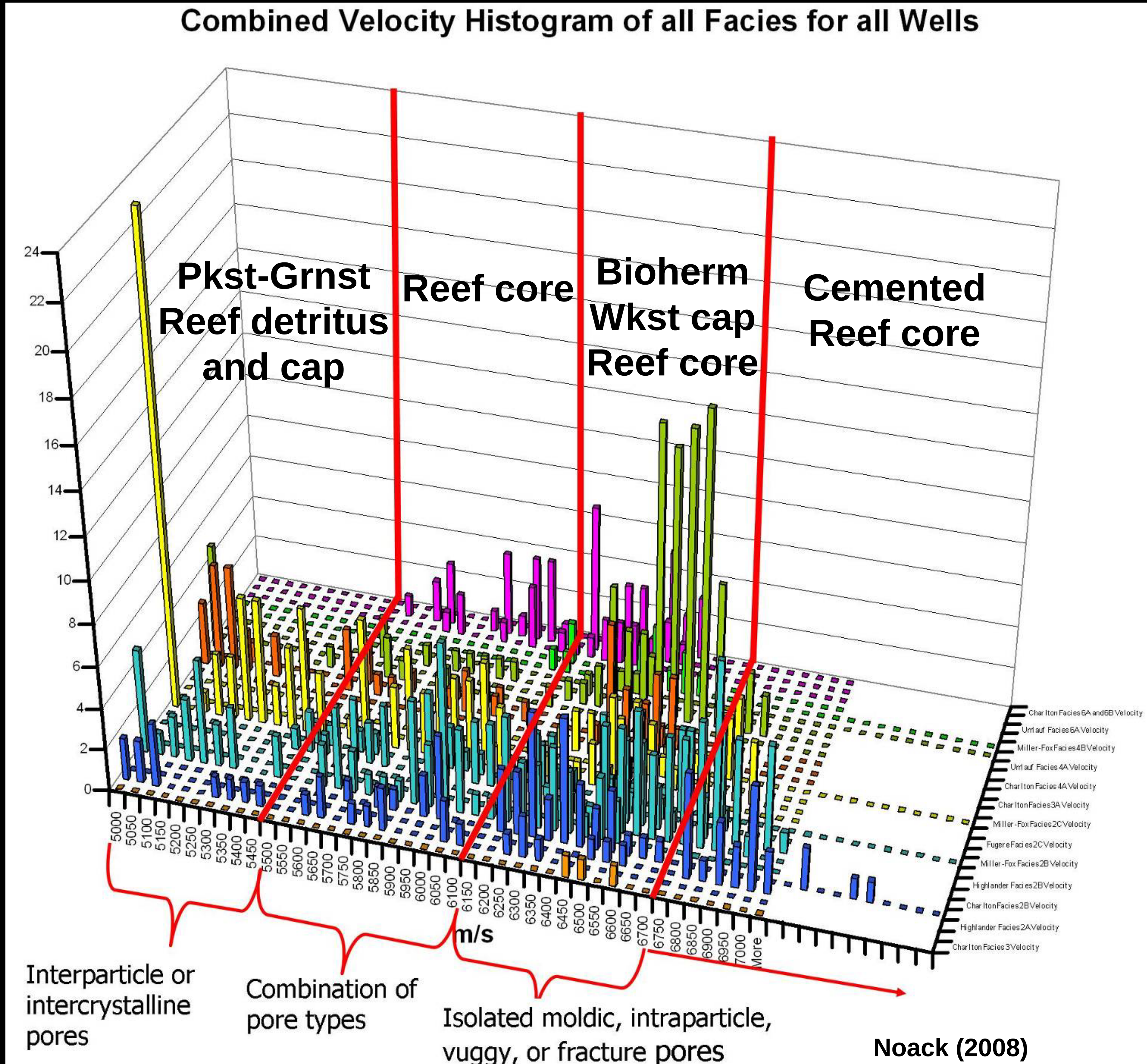

Pore Size vs. Gamma
Gamma (Perimeter/Area value)
10
1
10
100
1000
Pore Size (microns)
Intercrystalline
Interparticle or intercrystalline
Fracture or irregular vugs
Pin-point vugs
Moldic, intraparticle, or pin-point vugs
Rounded vugs or moldic

Noack (2008)

Velocity versus Porosity in Carbonates

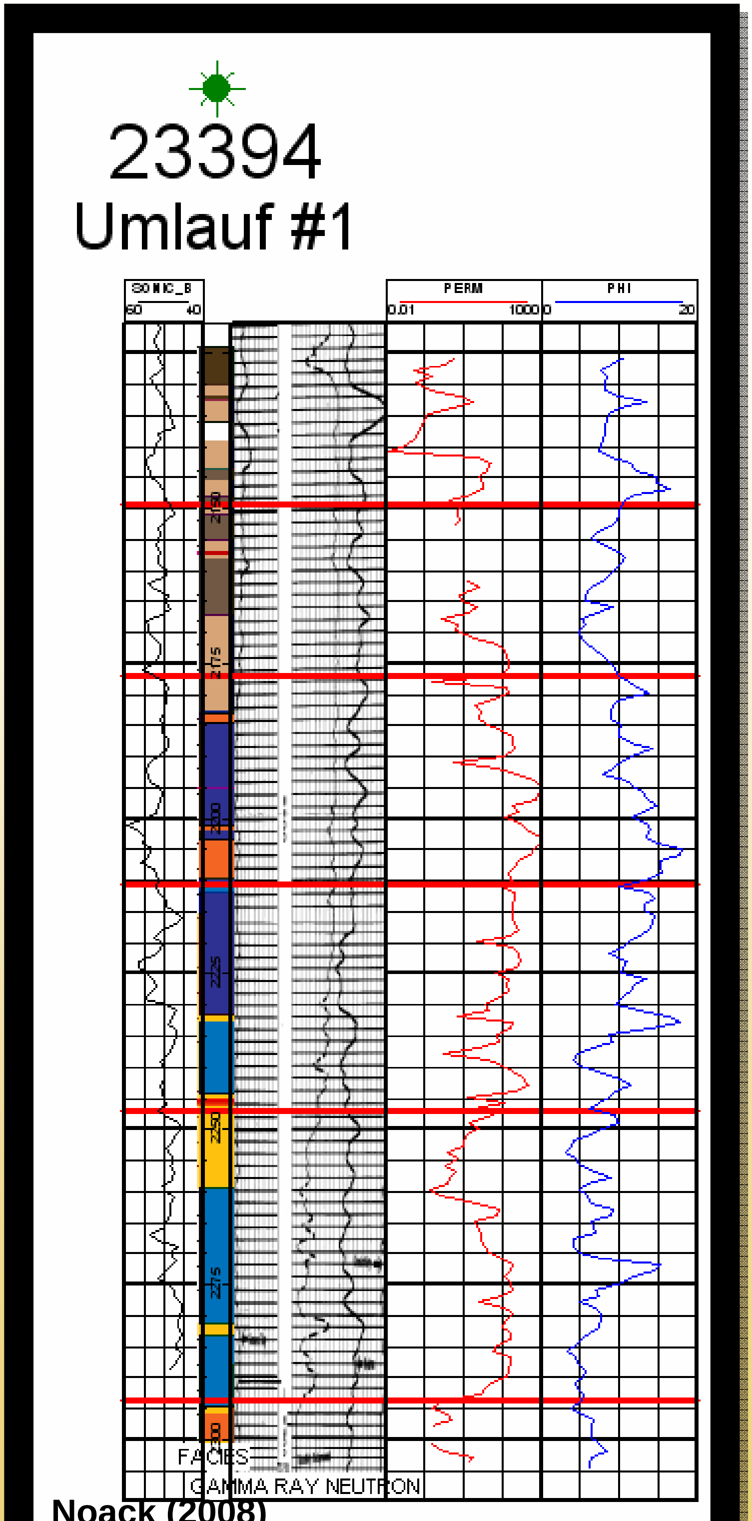


Anselmetti and Eberli (1999)



Combined Velocity Histogram of all Facies for all Wells
Pkst-Grnst Reef detritus and cap
Reef core
Bioherm Wkst cap Reef core
Cemented Reef core
24
22
20
18
16
14
12
10
8
6
4
2
0
5000 5050 5100 5150 5200 5250 5300 5350 5400 5450 5500 5550 5600 5650 5700 5750 5800 5850 5900 5950 6000 6050 6100 6150 6200 6250 6300 6350 6400 6450 6500 6550 6600 6650 6700 6750 6800 6850 6900 6950 7000 More
m/s
Charlton Facies 6A and 6B Velocity
Unrlauf Facies 6A Velocity
Miller-Fox Facies 4B Velocity
Unrlauf Facies 4A Velocity
Charlton Facies 4A Velocity
Charlton Facies 3A Velocity
Miller-Fox Facies 2C Velocity
Fugere Facies 2C Velocity
Miller-Fox Facies 2B Velocity
Highlander Facies 2B Velocity
Charlton Facies 2B Velocity
Highlander Facies 2A Velocity
Charlton Facies 3 Velocity
Interparticle or intercrystalline pores
Combination of pore types
Isolated moldic, intraparticle, vuggy, or fracture pores
Noack (2008)

- Variations in pore type can be observed in the sonic signal
- Pore architecture and connectivity affect permeability
- Inverse relationship between velocity and permeability
- Trend develops in sequence stratigraphic framework



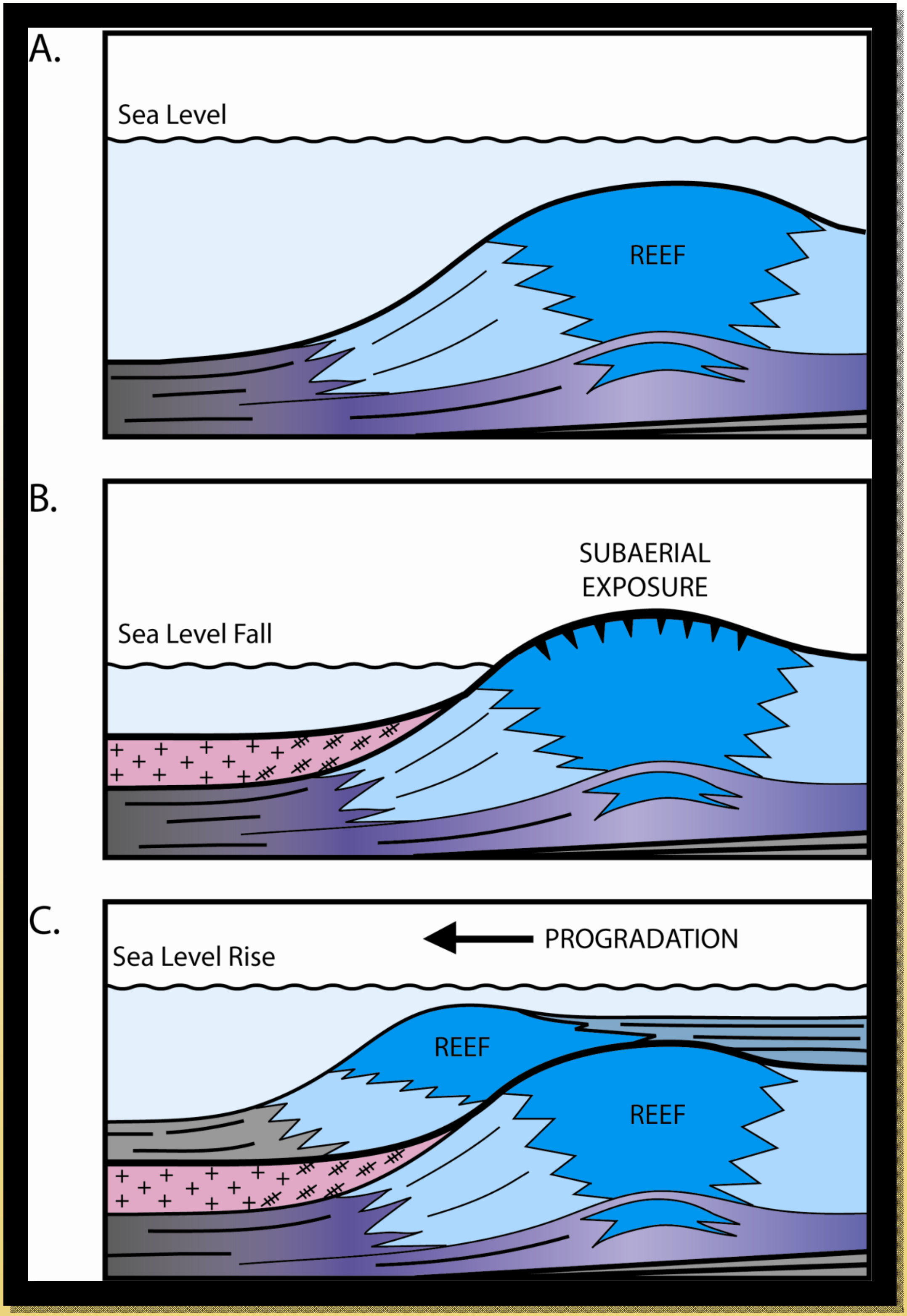
Noack (2008)

Summary

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

Conclusions

- Reef development during the TST/HST
- Evaporites were deposited during LST
- Reef development reestablished, and off-set from the original reef



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