Quantifying Pore Architecture by Facies for Enhanced Prediction of Reservoir Distribution in Silurian Pinnacle Reefs of the Michigan Basin*

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Abstract

Reservoir quality in carbonates is dependent on the complex relationship of rock fabric, porosity, and permeability. Simple porosity/permeability transforms do not provide sufficient information to estimate reservoir deliverability because permeability is dependent on pore architecture. As a result, Middle Silurian (Niagaran) Reef reservoirs in the Michigan Basin were evaluated to better understand this relationship. Additionally, pore types and associated geometries are thought to have a direct correlation with sonic velocity values. To confirm this relationship, Niagaran reef wells with both core and petrophysically measured sonic log values were used. Petrophysically significant facies and related pore types were identified through core analysis. Key facies were made into thin sections and photomicrographs were imported into an image analysis program where pore abundance and geometries were determined. Facies and related pore geometries were compared to sonic velocity values to identify the relationship of velocity and pore architecture. Facies with greater rigidity contain more rounded pores and have higher velocities whereas facies with less rigidity contain more irregular shaped pores and have slower velocities. Permeability can then be determined by integrating the relationship between pore types and facies with the effect of pore geometry on rock acoustics. As a result, quantifying rock and well log data relationships allows for better prediction of reservoir quality with logs in the absence of rock data.

Selected References

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Quantifying Pore Architecture by Facies for Enhanced Prediction of Reservoir Distribution in Silurian Pinnacle Reefs of the Michigan Basin

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Outline

- Purpose
- Regional Setting
- Previous (initial) Studies
- Approach/Methods
- Well selection, facies identification, image analysis, sonic velocity
- Results and Interpretations
- Image analysis, sonic velocity, integration of velocity and I.A. data, reservoir/seal predictability
- Conclusions

Purpose

- Relate rock fabric to pore types by developing petrophysically significant facies
- Relate pore architecture to pore connectivity/permeability
- Use laboratory and log measured sonic velocity to establish a first order relationship between sonic velocity and pore type/pore network connectivity
- Develop a better understanding of the local vertical and regional lateral heterogeneity in the Niagaran reef reservoirs

Application

- Develop a better understanding of the local vertical and regional lateral heterogeneity in the Niagaran reef reservoirs – apply methods to other reservoirs
- Increase predictability from logs
- Potential tie (porosity and permeability) to seismic data

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Niagaran Reefs

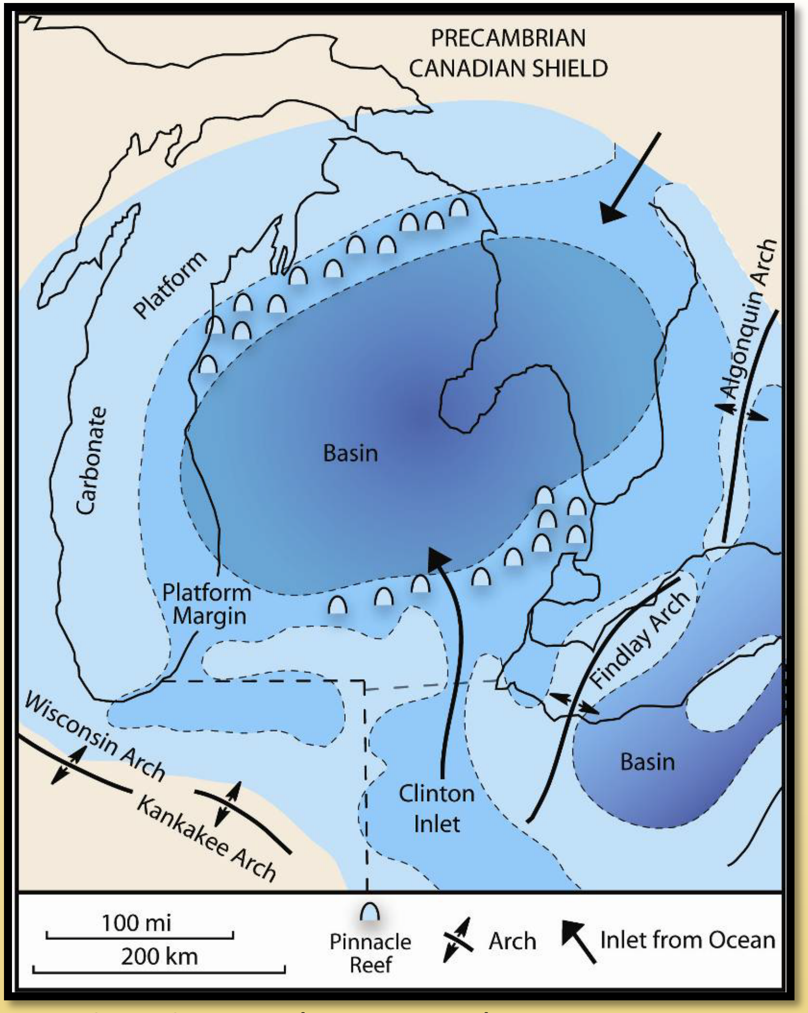
- **Good porosity and permeability in various facies but significant reservoir heterogeneity**
- **Regional Seal (A-2 Evaporite)**
- **The reef play is the most successful play in Michigan**
  - production of 475 MMBO and 2.8 TCF of gas
- **Ultimate recovery**
  - 1 billion BOE from over 1,000 pinnacle reefs
- **Undiscovered resources**
  - 211 MMBO and 434 BCFG (USGS, 2005)
- **Gas storage**

Presenter's Notes:

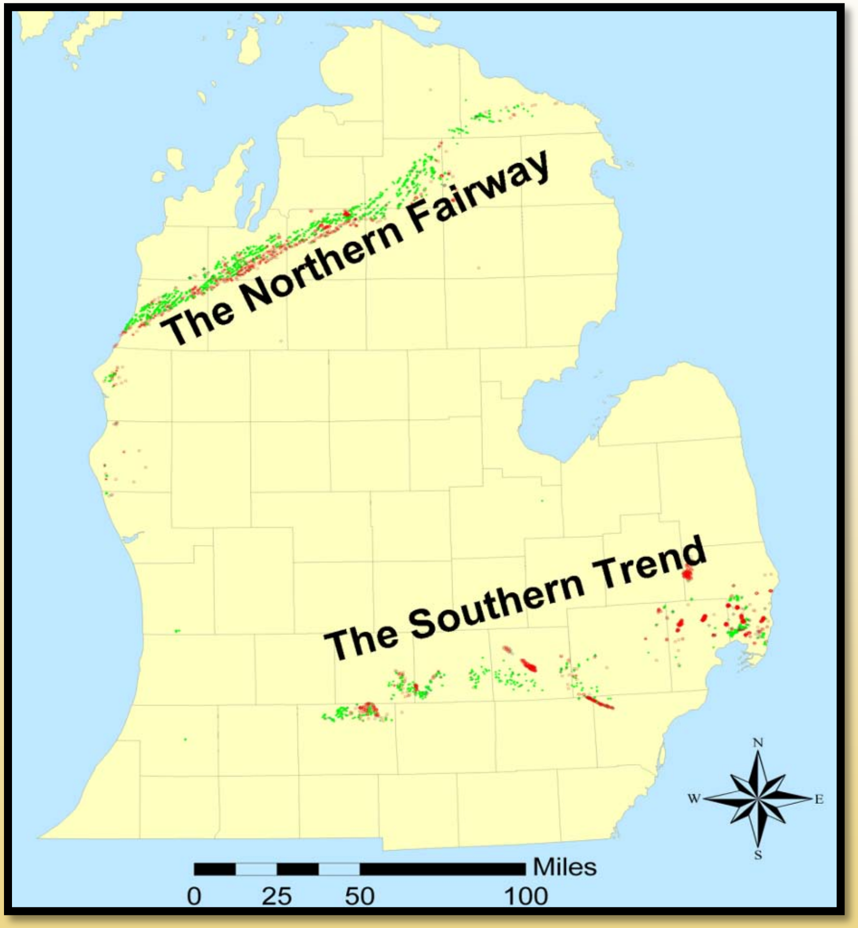
The pinnacle reefs occur in the stratigraphic unit known as the Brown Niagaran. They are of particular interest because of their good porosity and permeability.

Also, the A-1 Evaporite drapes over the reefs, providing an excellent seal. The Niagaran reef play is known as the most important and successful play in Michigan with a large production of oil and gas. The ultimate recovery is 1 billion barrels of oil equivalent from over 1,000 pinnacle reefs. There are still a lot of undiscovered resources that exist in the Niagaran reef play that can be extracted by combining new ideas and technology with the old fashioned. In addition, many reefs have been converted to gas storage, so it is important to understand the reservoir qualities of the reef facies even for that reason

Regional Setting

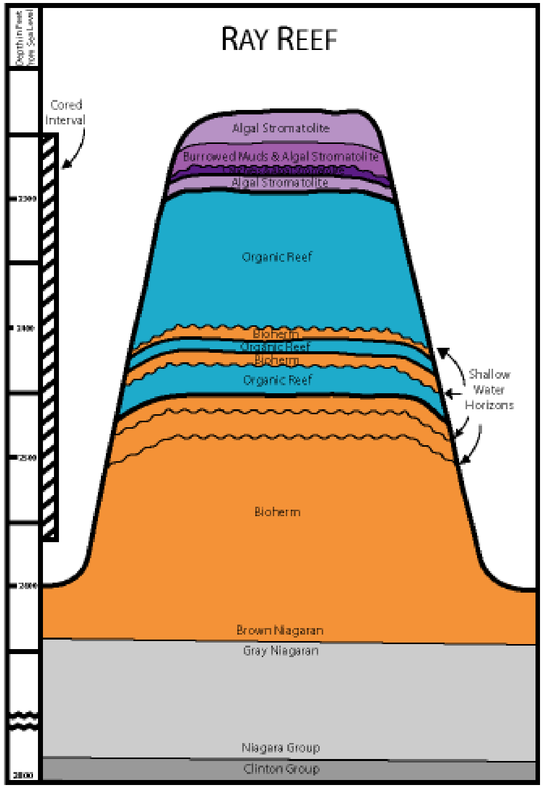


Middle Silurian (Niagaran) environments in the Michigan Basin (modified from Briggs et al., 1980)

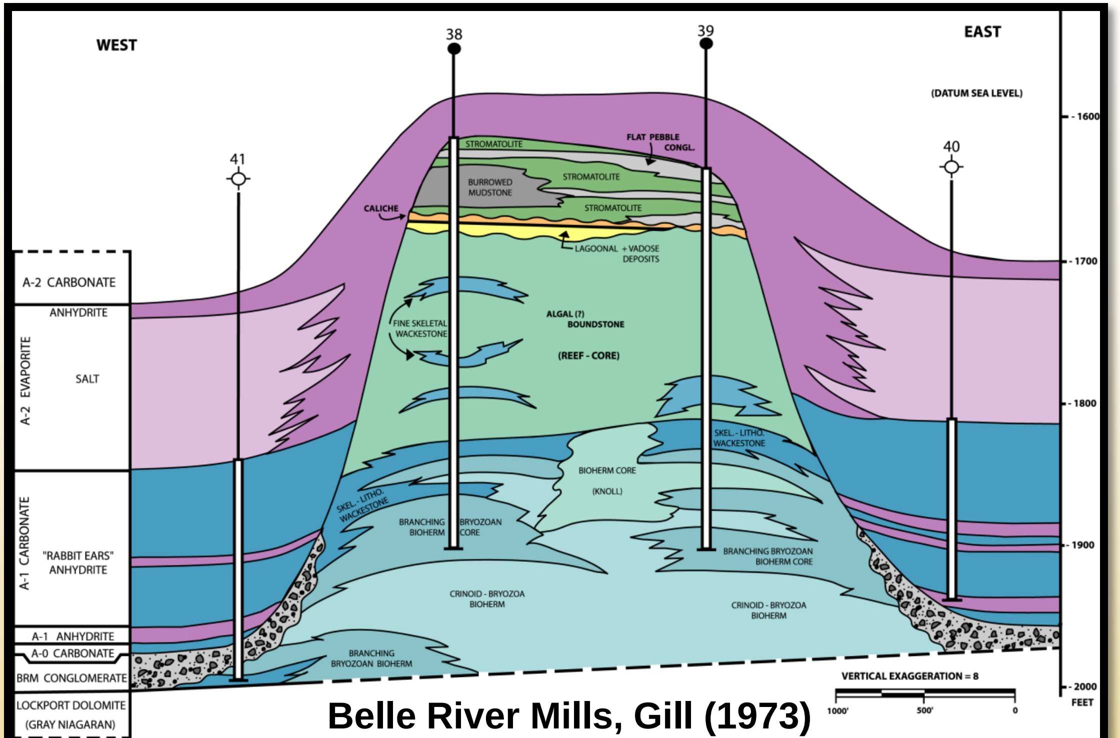


Northern and Southern Reef Trend Oil (green) and Gas (red) Producers (Michigan DNR ESRI ArcMap, 2006)

Initial Niagaran Reef Models



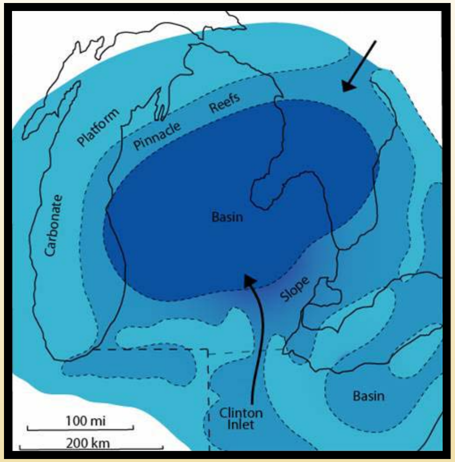
Balogh (1981)



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 wasn't focus of earlier studies

Location of Wells



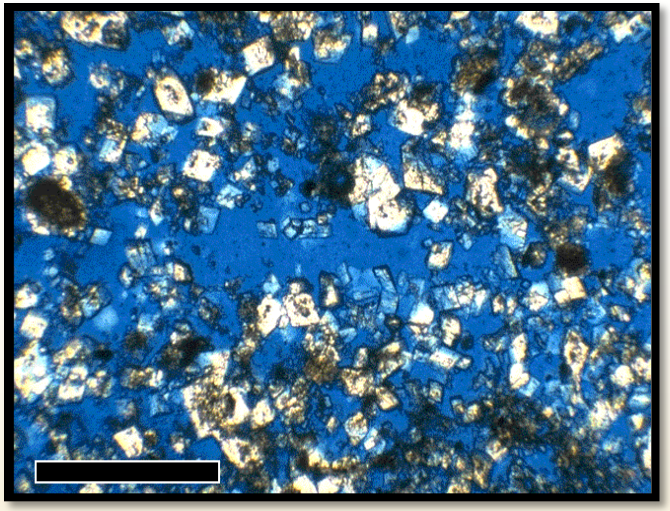
Middle Silurian (Niagaran) environments in the Michigan Basin (modified from Briggs et al., 1980)

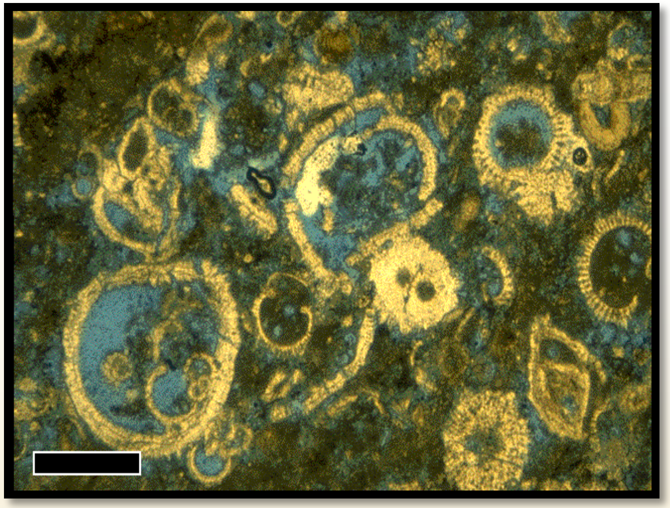
Niagaran cores chosen for this study

Facies Pore Architecture

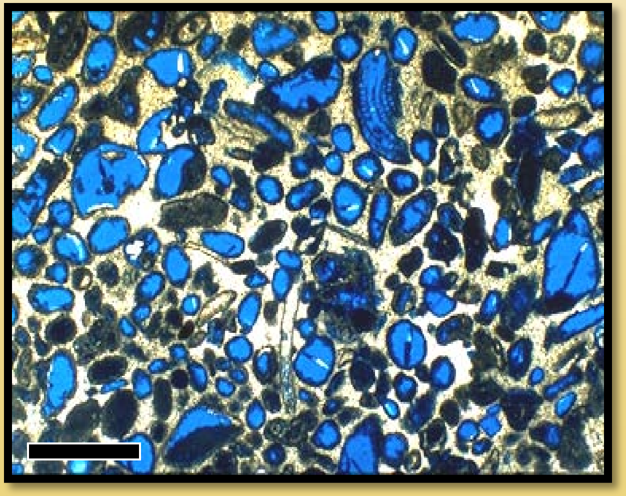
-Image Analysis

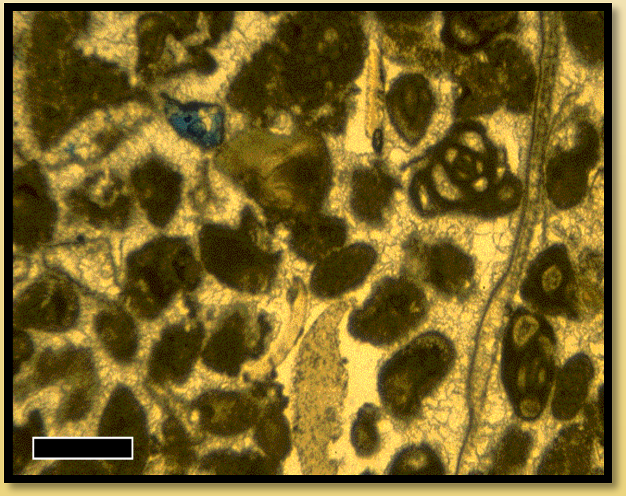
-Sonic Velocity

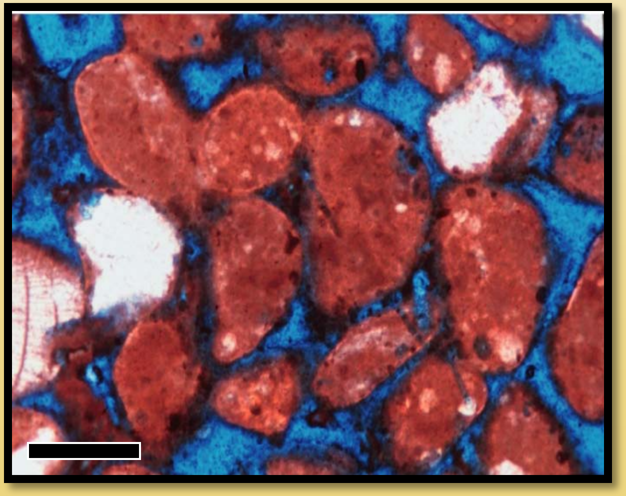




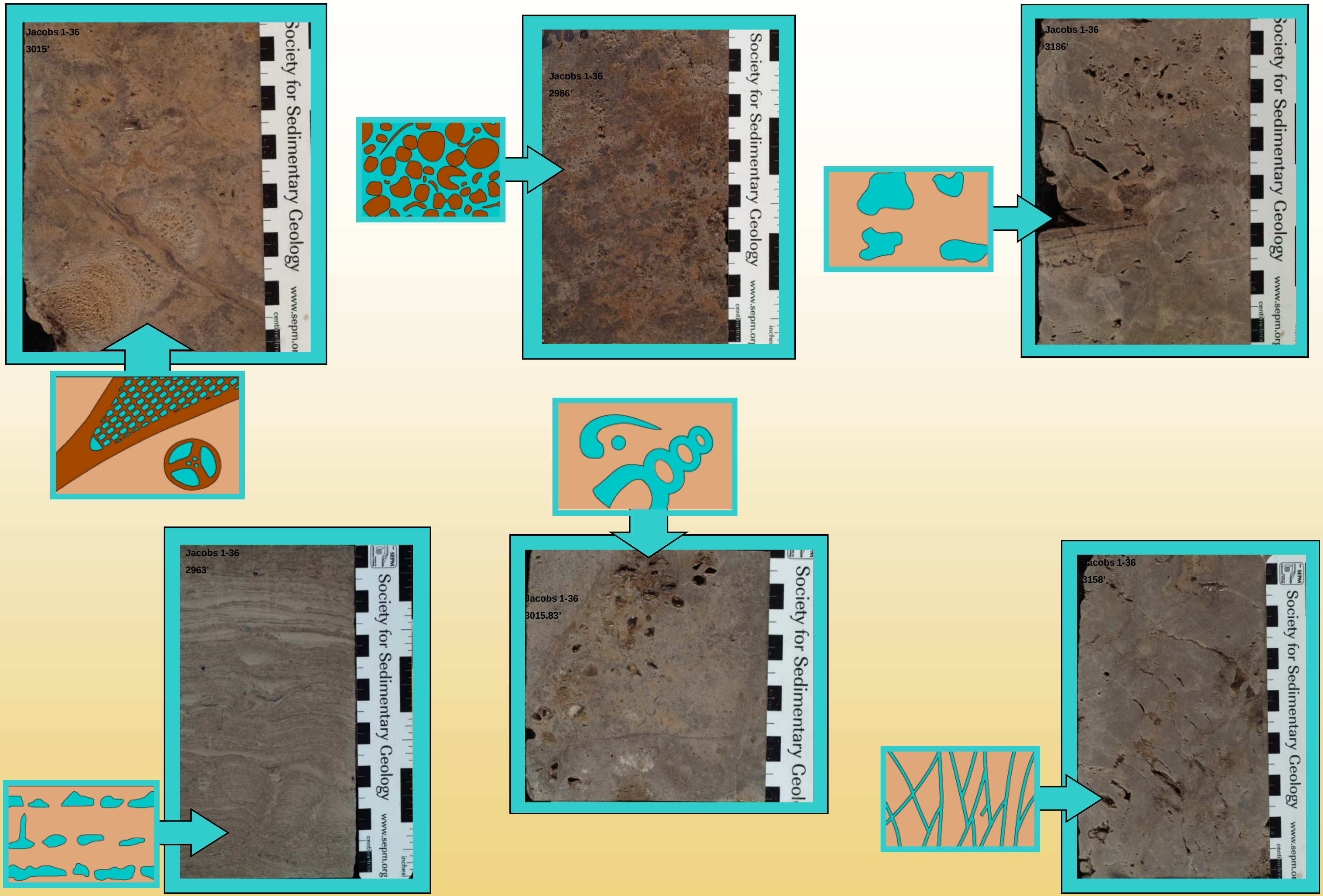
Carbonates have varying pore types that influence permeability







Eberli, 2000



Pore types from Scholle and Ulmer-Scholle (2003)
modified from Choquette and Pray (1970)

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

Petrophysically Significant Facies

1) Muddy Bioherm

 -Moldic/vuggy, intercrystalline

2) Framework Reef

 -Moldic/vuggy, fracture, intraparticle, intercrystalline

3) Framework Reef with Detritus

 -Moldic/vuggy, fracture, intraparticle, interparticle, intercrystalline

4) Capping Wackestone, Packstone, and Grainstone

 -Moldic/vuggy OR interparticle, intercrystalline

5) Laminated Mudstone

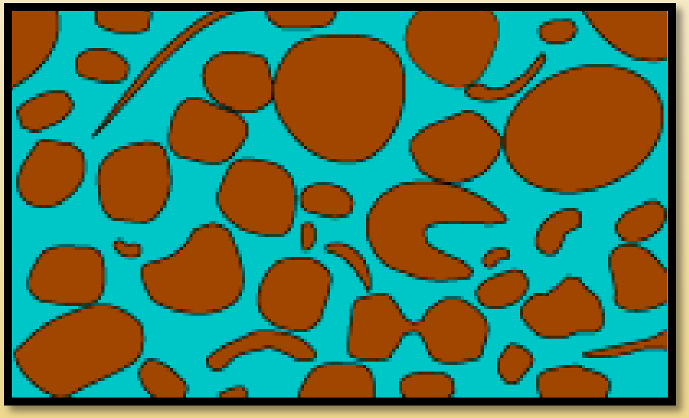
 -Microporosity, intercrystalline

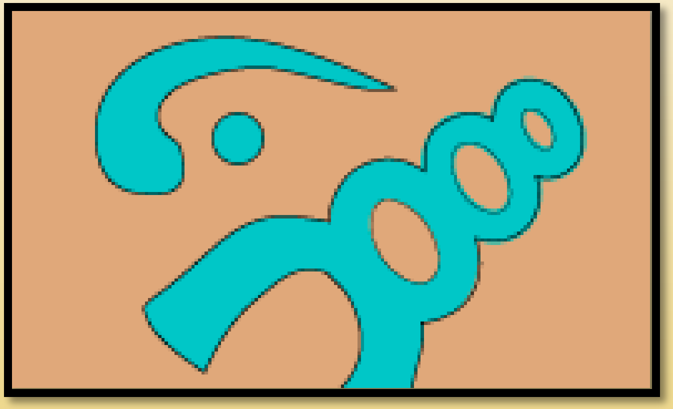
6) Cyanobacterial Mat

 -Fenestral, interparticle, intercrystalline

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

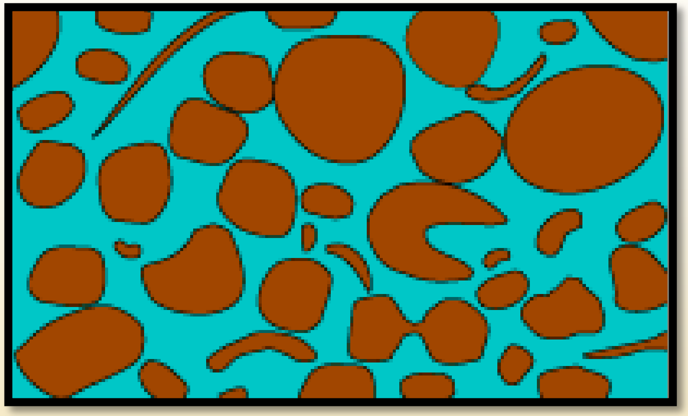
•The roundness/sphericity parameter from the image analysis program is a ratio of the pore perimeter to the pore area

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

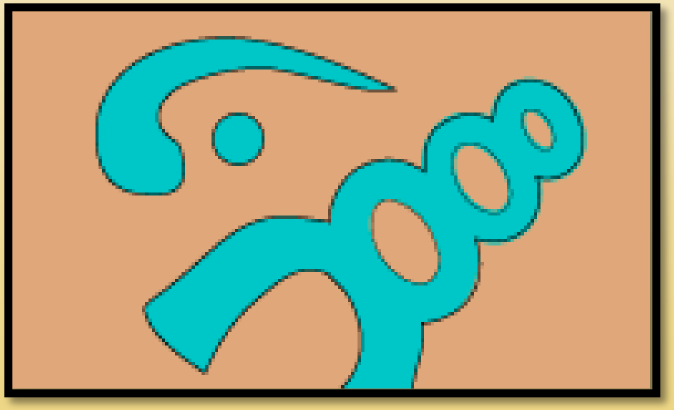
•However, another study by Anselmetti et al. (1998) suggests a similar roundness/"sphericity"/shape parameter

γ= Perimeter / (2 * √(π* Area))

ϕ ~ 20%
γ ~ 2.40

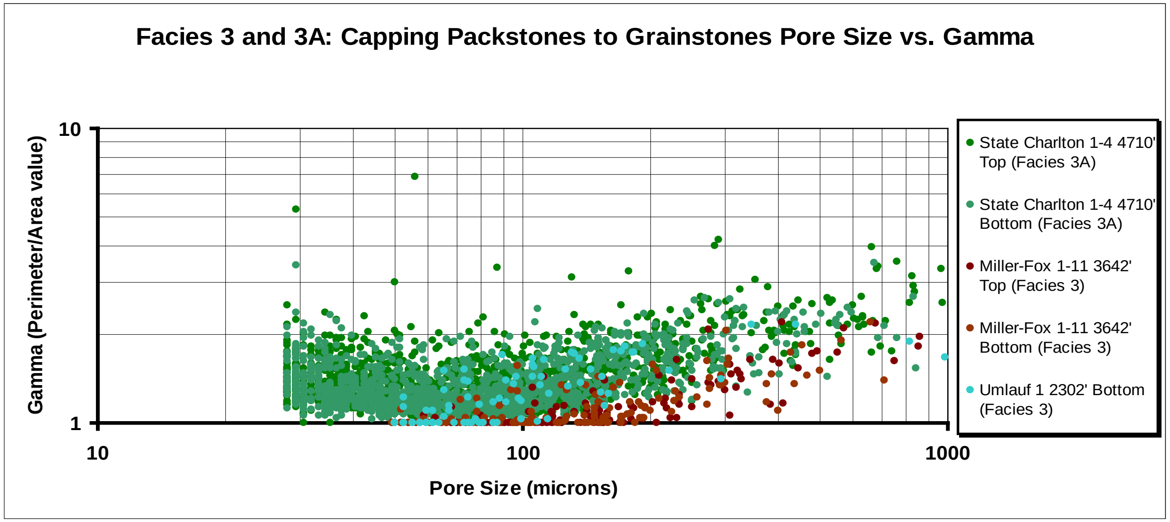


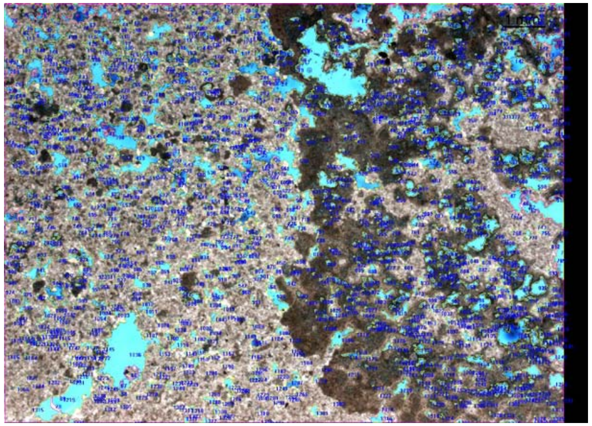
ϕ ~ 20%
γ ~ 1.06



Scholle and Ulmer-Scholle, 2003

Click to view Presenter's Notes

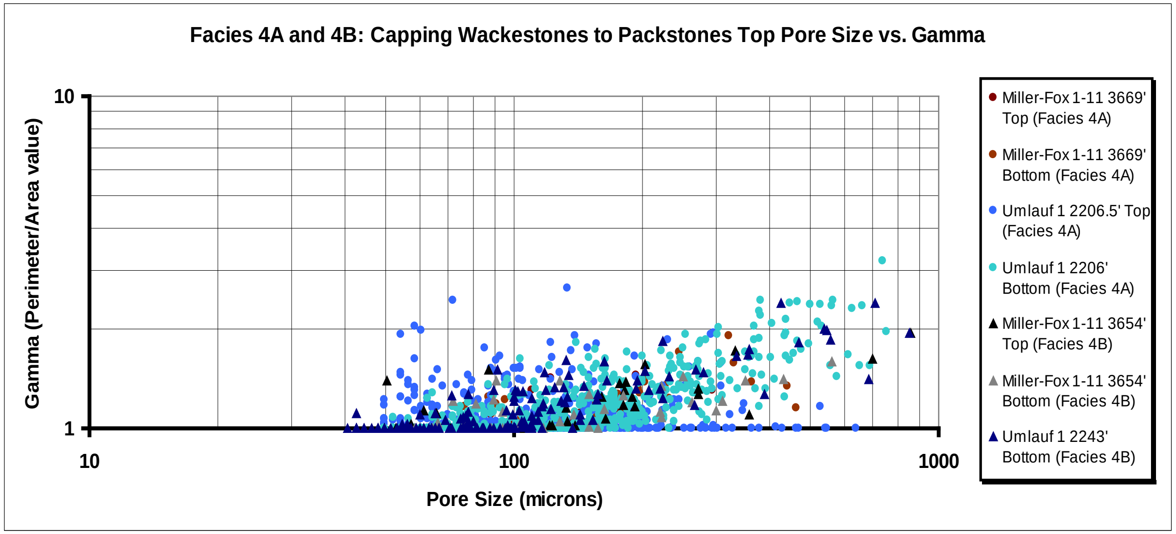


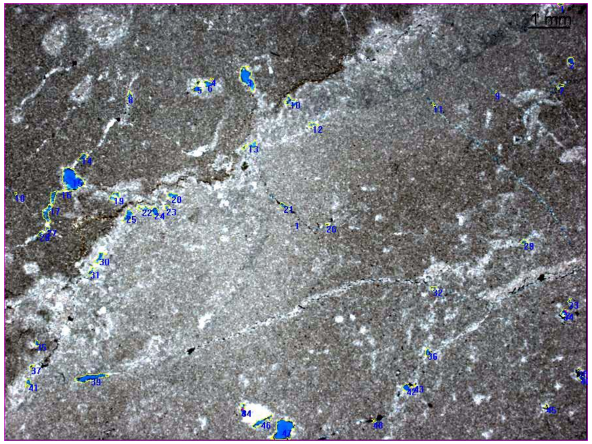


Charlton 4710' Top

Porosity: 29%

Gamma: 1.5





Miller-Fox 3669' Porosity (mud-rich):

Bottom: 2%

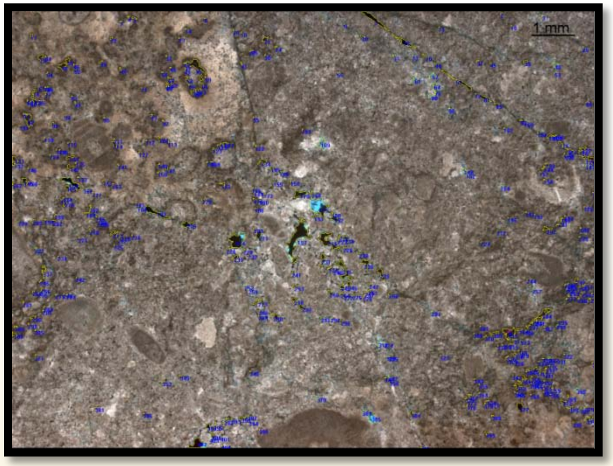
Gamma: 1.14

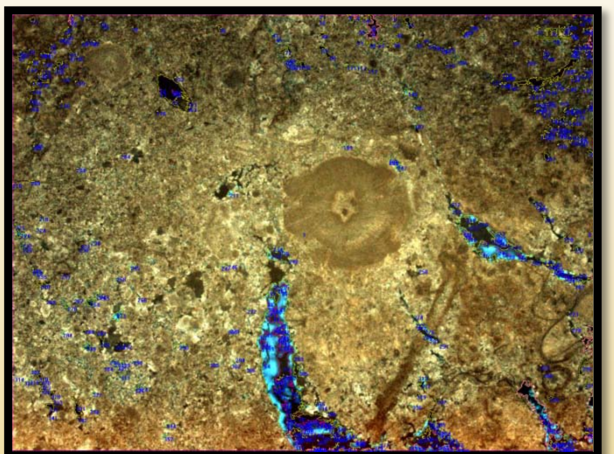
Presenter's Notes:

Here is an overall comparison between rock fabric, pore type, and pore connectivity (also known as the permeability) determining the ultimate pore network's ability to allow for fluid movement. The capping packstone to grainstone and the capping wackestone to packstone are used as a comparison due to the abundance of multiple pore types. On the X-axis is the pore size that is defined as the square root of the pore area, which gives average pore diameter. On the Y-axis is the aforementioned gamma (or the roundness) value of the pores.

The pore size distribution for the capping packstones to grainstones is from about 30 microns to 1,000 microns. From 30 to about 50 microns, the pores have a more irregular shape (meaning the pores are not completely rounded with values higher than 1. Perfect interparticle pores between spherical grains have a value of 1.9 and intercrystalline pores have around that same value. These smaller pores are therefore inferred to be interparticle or intercrystalline pore space, with some of the more rounded values being moldic pore space. From 50 – 100 (even up to 200) microns, the pores have gamma values approaching 1, thus being well rounded. We infer the pores formed by the dissolution of grains, leaving behind nicely rounded, smoothed, and isolated moldic porosity. From 100 microns and larger, the pores become highly irregular (values approaching 2 or higher). These pores are usually irregular vuggy porosity or moldic.

While the capping packstone to grainstone can have a variety of pore shapes and sizes, the capping wackestone to packstone has two to three different predominant pore types: intercrystalline, moldic, and isolated vugs. From all the wells, the overall trend is with the majority of the pores in the 50 – 300 micron range, with rounded shape values. These pores are predominantly moldic. The anomalous irregular shaped pores in the 50 – 100 microns range are intercrystalline pores and the pores in the 300 – 1,000 micron range with irregular shapes are usually the solution enhanced vuggy or moldic porosity resulting in the irregular shaped pores.



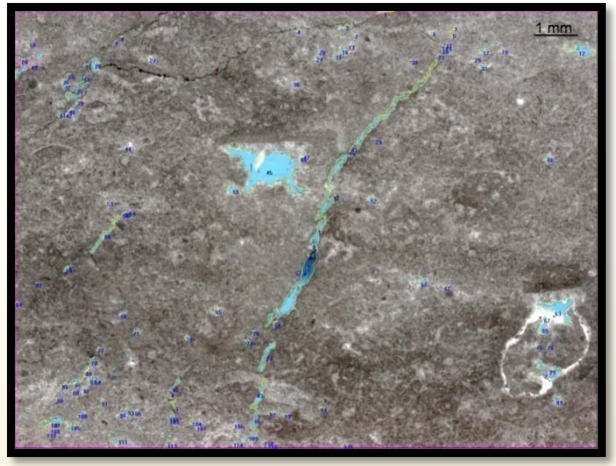


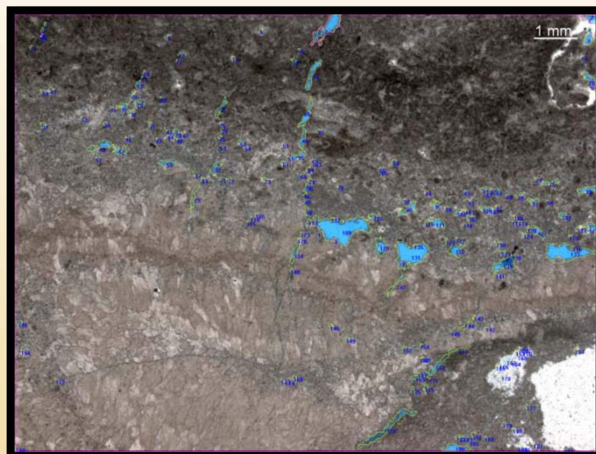
Charlton 4921' IA Porosity:

Top: 1.8%

Bottom: 4.2%

Roundness: 1.7



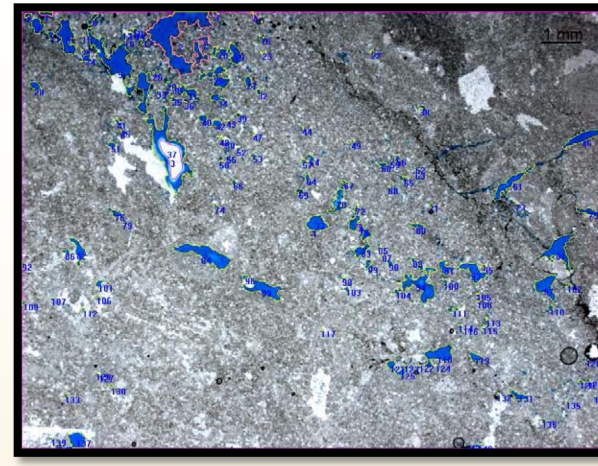


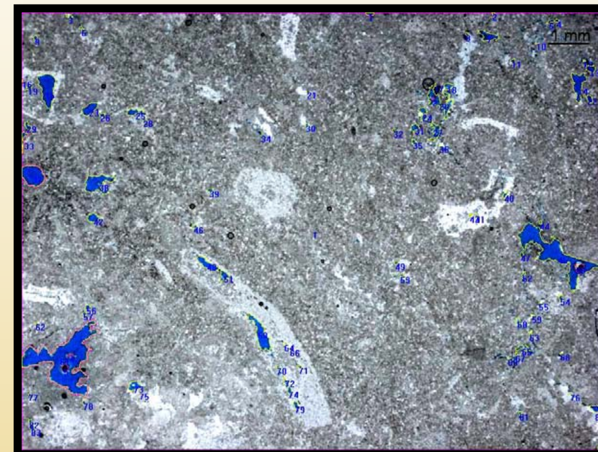
Fugere 4335' IA Porosity:

Top: 2.7%

Bottom: 2.75%

Roundness: 1.5



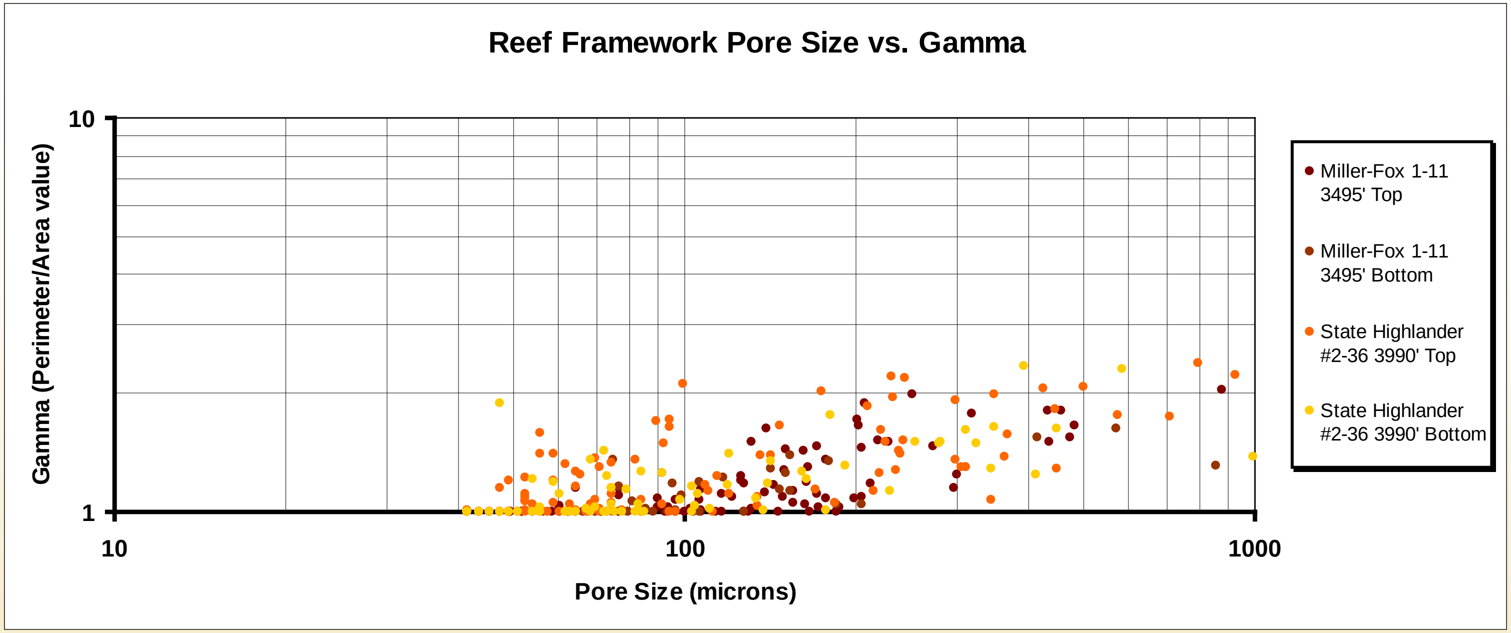


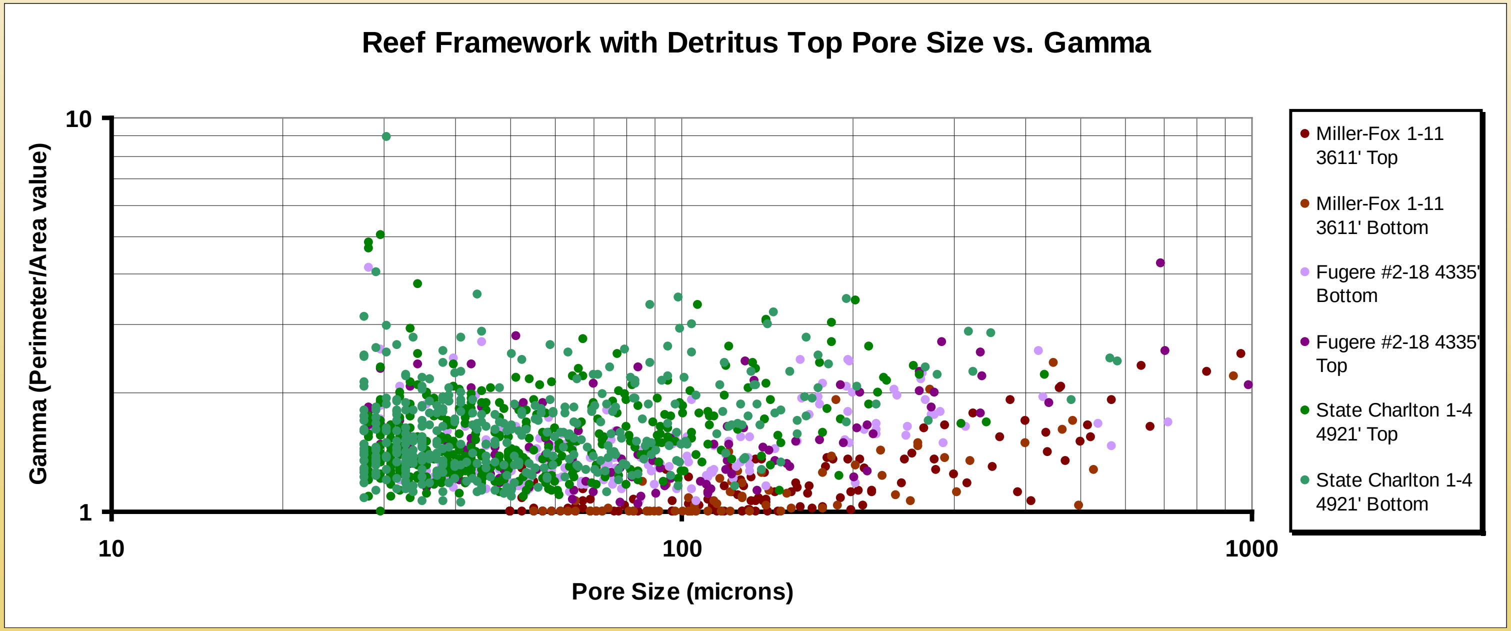
Miller-Fox 3611' IA Porosity:

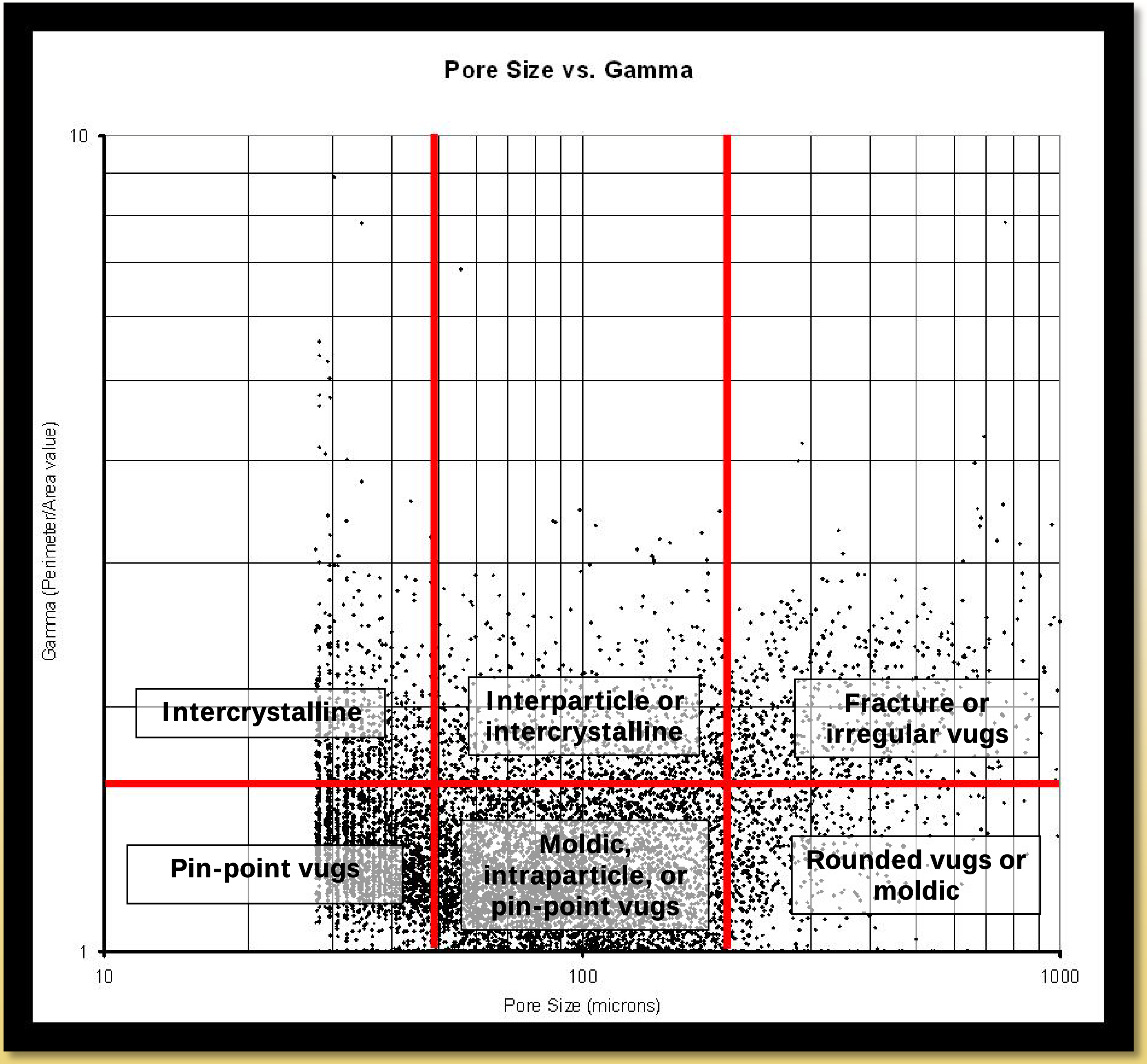
Top: 5.6%

Bottom: 3.2%

Roundness: 1.2


Reef Framework Pore Size vs. Gamma
Gamma (Perimeter/Area value)
10
1
10
100
1000
Pore Size (microns)
Miller-Fox 1-11 3495' Top
Miller-Fox 1-11 3495' Bottom
State Highlander #2-36 3990' Top
State Highlander #2-36 3990' Bottom


Reef Framework with Detritus Top Pore Size vs. Gamma
Gamma (Perimeter/Area value)
10
1
10
100
1000
Pore Size (microns)
Miller-Fox 1-11 3611' Top
Miller-Fox 1-11 3611' Bottom
Fugere #2-18 4335' Bottom
Fugere #2-18 4335' Top
State Charlton 1-4 4921' Top
State Charlton 1-4 4921' Bottom

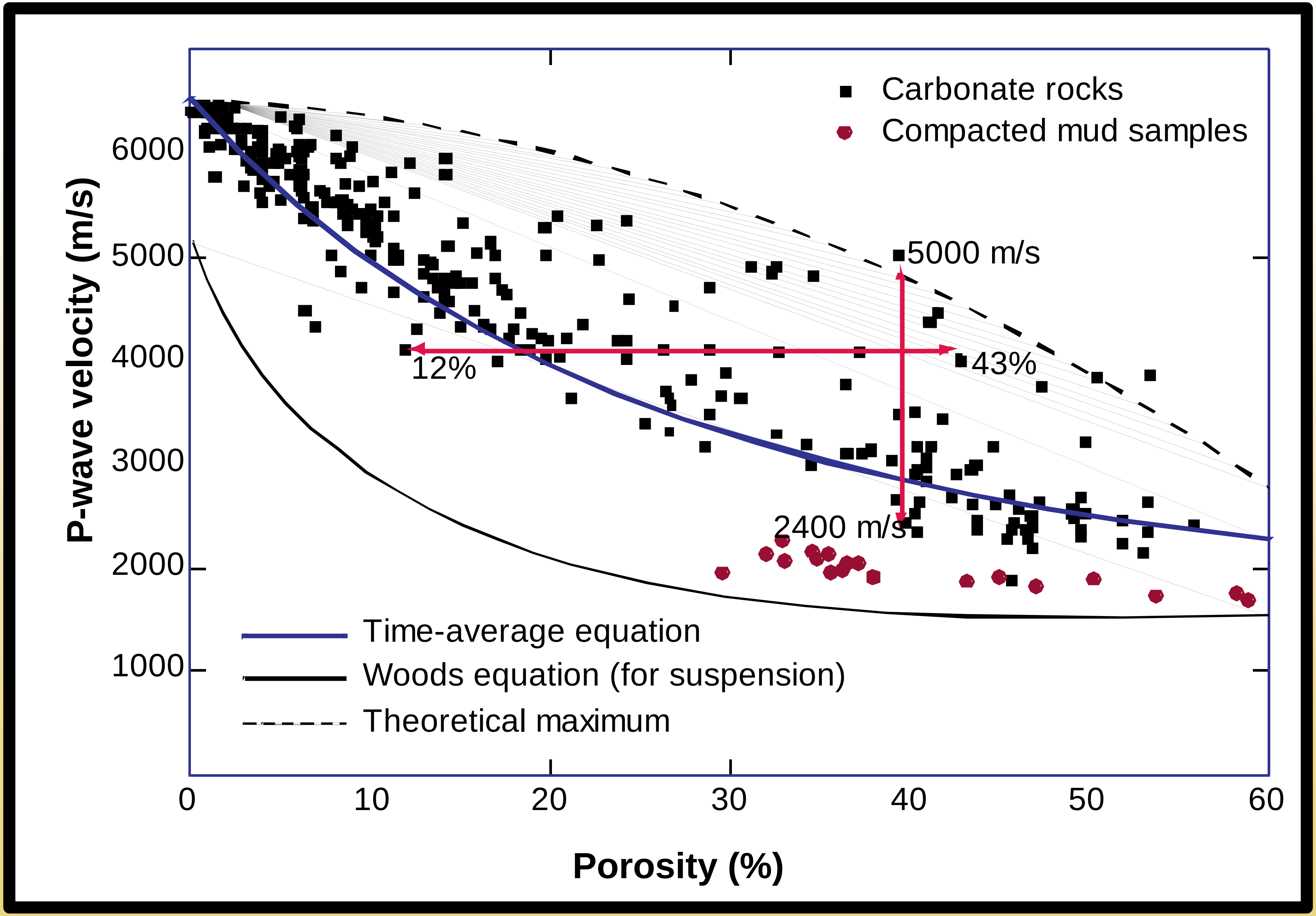

Pore Size vs. Gamma
10
1
Gamma (Perimeter/Area value)
10
100
1000
Pore Size (microns)
Intercrystalline
Interparticle or intercrystalline
Fracture or irregular vugs
Pin-point vugs
Moldic, intraparticle, or pin-point vugs
Rounded vugs or moldic

Noack (2008)

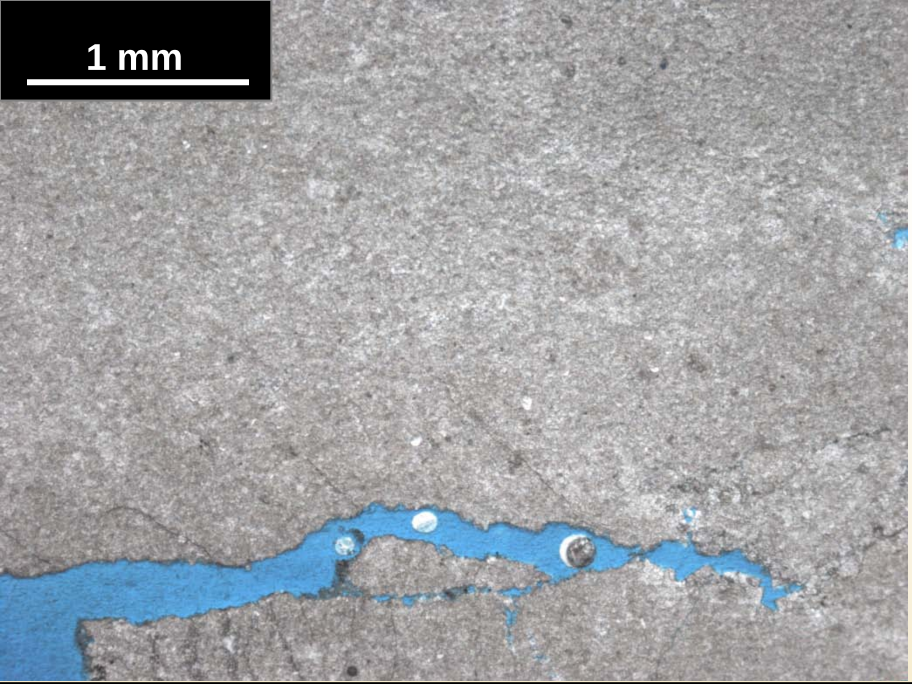
Sonic Velocity Results

- Higher velocity values = pores isolated and spherical
- Low velocity values = pores irregular shaped and connected

Velocity versus Porosity in Carbonates



Anselmetti and Eberli (1999)



Isolated vugs and local fractures with no matrix ϕ/K

3572 ft.

ϕ = 5.0%

K = .05 mD

Vp = 6480m/s

Small (pin-point) vugs with minor matrix ϕ/K

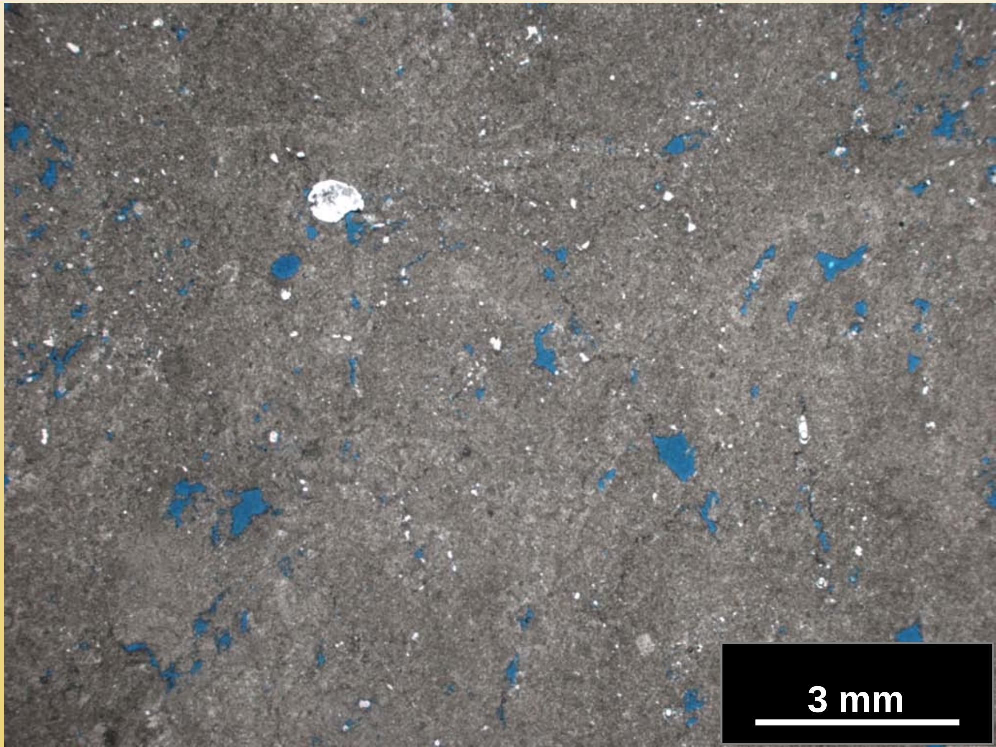
3430 ft.

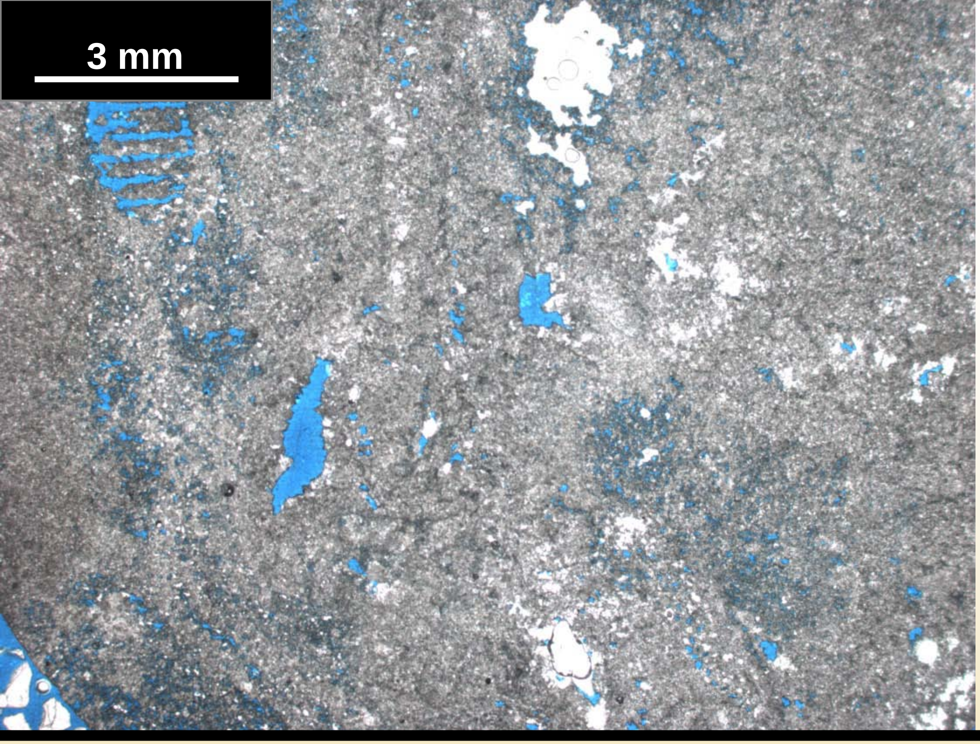
ϕ = 8.9%

K = .12 mD

Vp = 6400m/s

Grammer, 2006





Large vugs + IX matrix

3480 ft.

ϕ = 18%

K = 17.8 mD

Vp = 5900m/s

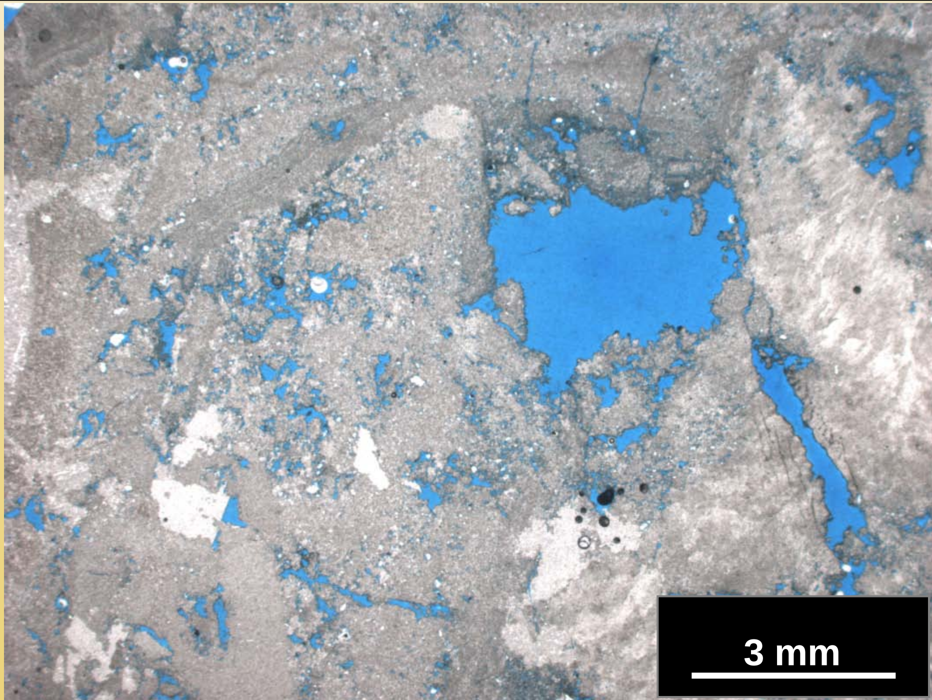
Large vugs + IX matrix

3631 ft.

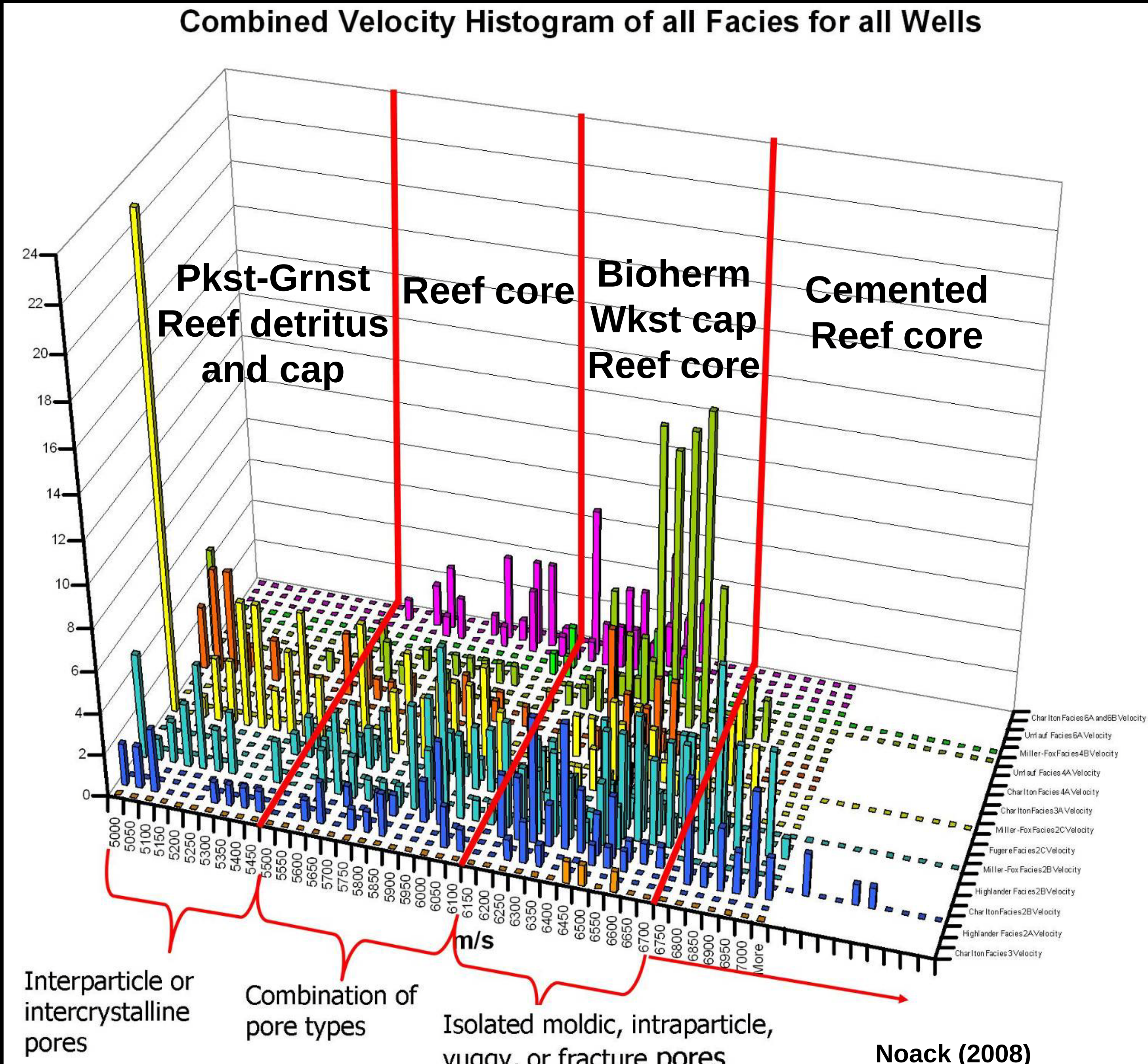
ϕ = 13%

K = 17.3 mD

Vp = 5630m/s



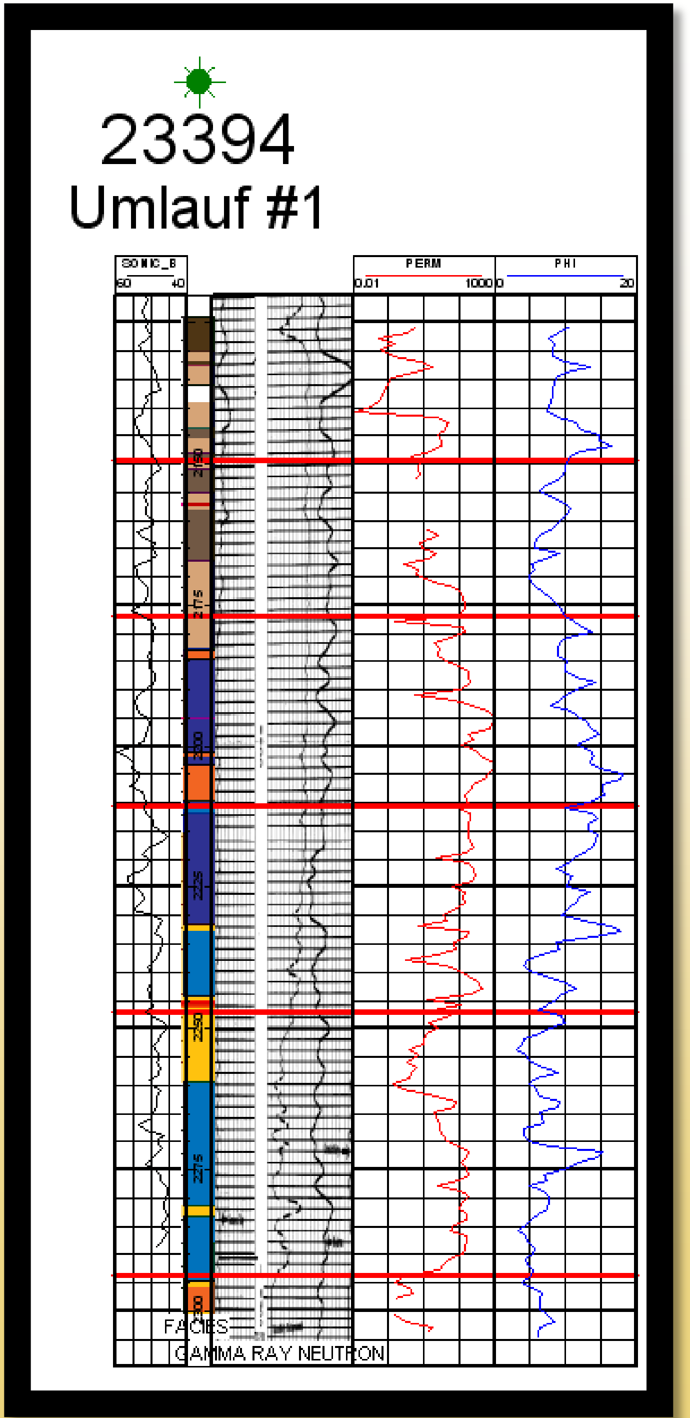
Grammer, 2006



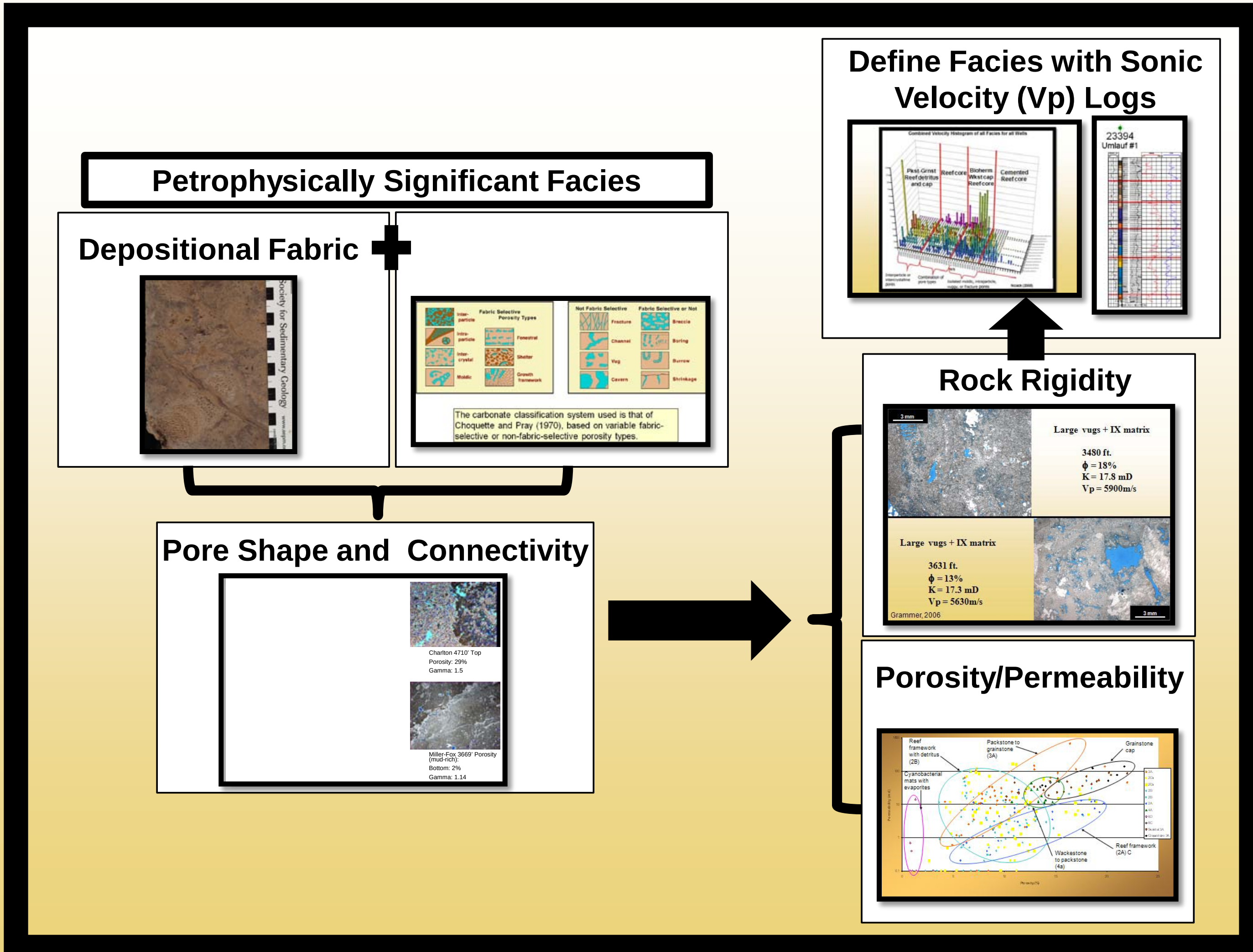
Combined Velocity Histogram of all Facies for all Wells
Pkst-Grnst Reef detritus and cap
Reef core
Bioherm Wkst cap Reef core
Cemented Reef core
24
22
20
18
16
14
12
10
8
6
4
2
0
5000 5050 5100 5150 5200 5250 5300 5350 5400 5450 5500 5550 5600 5650 5700 5750 5800 5850 5900 5950 6000 6050 6100 6150 6200 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
Umlauf Facies 6A Velocity
Miller-Fox Facies 4B Velocity
Umlauf 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



Summary


Petrophysically Significant Facies
Depositional Fabric
Pore Shape and Connectivity
Rock Rigidity
Porosity/Permeability
Define Facies with Sonic Velocity (Vp) Logs
The carbonate classification system used is that of Choquette and Pray (1970), based on variable fabric-selective or non-fabric-selective porosity types.
Large vugs + IX matrix
3480 ft.
ϕ = 18%
K = 17.8 mD
Vp = 5900m/s
Large vugs + IX matrix
3631 ft.
ϕ = 13%
K = 17.3 mD
Vp = 5630m/s
Grammer, 2006
23394
Umlauf #1

Conclusions

- Porosity and related permeability in carbonates is highly heterogeneous, even within the same facies
- Primary depositional fabric controls pore architecture
- Pore architecture affects pore connectivity, thus affecting permeability
- Macropore shape (γ value) is the controlling factor of permeability

Conclusions (continued)

- Acoustic properties of carbonate rocks are controlled by the depositional fabric, diagenetic fabric, and their related pore types and architecture
- The pore architecture and related sonic velocity values can be recognized within a sequence stratigraphic framework
- By correlation of logs to sonic velocity values porosity and permeability zones can be better predicted
- Apply to other reefs without core that have sonic logs
- **Apply method to other types of reservoirs**

Thank You!

Western Michigan University:

-Dr. G. Michael Grammer

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University of Colorado:

-Dr. Matthew Pranter

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-Jennifer Schulz

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-Amanda Wahr

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-Kalamazoo Gem and Mineral Society

-Graduate Student Research Fund