Characterization of a Carbonate Mudrock Reservoir by Integrating Sequence Stratigraphy, Sonic Velocity, and Characterization of the Macro- to Micropore Architecture *

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Abstract

The Mid-Continent Mississippian age limestone is a proven and valuable carbonate mudstone reservoir in Oklahoma and Kansas. Vertical wells have been producing oil and gas for over 50 years, but recent horizontal activity has highlighted the need to understand and predict the internal reservoir architecture. Using the high-resolution sequence stratigraphic framework as the foundation, laboratory measured sonic velocity response, porosity, and permeability, coupled with characterization of the macro- to nanopore architecture using 2-D and 3-D image data are integrated to enhance the predictability of key reservoir facies with similar petrophysical properties within the same paleo-basin. Detailed facies analysis from five cores located in north-central Oklahoma and southern Kansas indicate deposition occurred on a regionally pervasive, distally steepened carbonate ramp with variable siliciclastic input. Facies stack into shoaling upward packages of weakly calcareous mudstones to wackestones overlain by progressively higher energy skeletal packstone to grainstone facies capped, in some areas, by tidal flat facies. Enhanced porosity or permeability due to significant alterations resulting from subaerial exposure and hydrothermal dolomitization are also incorporated into the analysis as applicable. The span of facies and depositional environments results in a wide range of porosity (<1% to >40%), permeability (<0.001md to >170md), and sonic velocity response (6500-2000m/sec (Vp)). Observed pores are mostly oblong to oval, and include intercrystalline, interparticle, intraparticle, vuggy/moldic, and matrix pores. Pores and pore throats span from meso- (4mm-62.5 µm) to nanopore (1µm-1nm) size. Acoustic response data show an inverse relationship with porosity and a distinct pattern specific to the Mid-Continent basin that can be used as the foundation for predicting porosity in other Mid-Continent Mississippian age carbonates. The sequence stratigraphic hierarchy of shoaling upward packages observed in core at the 3rd, 4th, and 5th order scale are roughly correlated to wireline logs at the third and fourth order with the 5th order being used to assist in predicting facies with enhanced porosity and permeability. Deviations from basin trends are explained by the pore architecture and differences in diagenetic alterations. Interpreting the data set using an integrated, holistic approach, allows for enhanced predictability of facies and development intervals.

Selected References

Eberli, G.P., G.T., Baechle, F.S. Anselmetti, and M.L. Incze, 2003, Factors controlling elastic properties in carbonate sediments and rocks: The

Leading Edge, v. 22, p. 654-660.

Harris, S.A., 1975, Hydrocarbon accumulation in "Meramec-Osage" (Mississippian) rocks, Sooner Trend, northwest-central Oklahoma: AAPG Bulletin, v. 59, p. 633-664.

Characterization of a carbonate mudrock reservoir by integrating sequence stratigraphy, sonic velocity, and characterization of the macro- to micropore architecture

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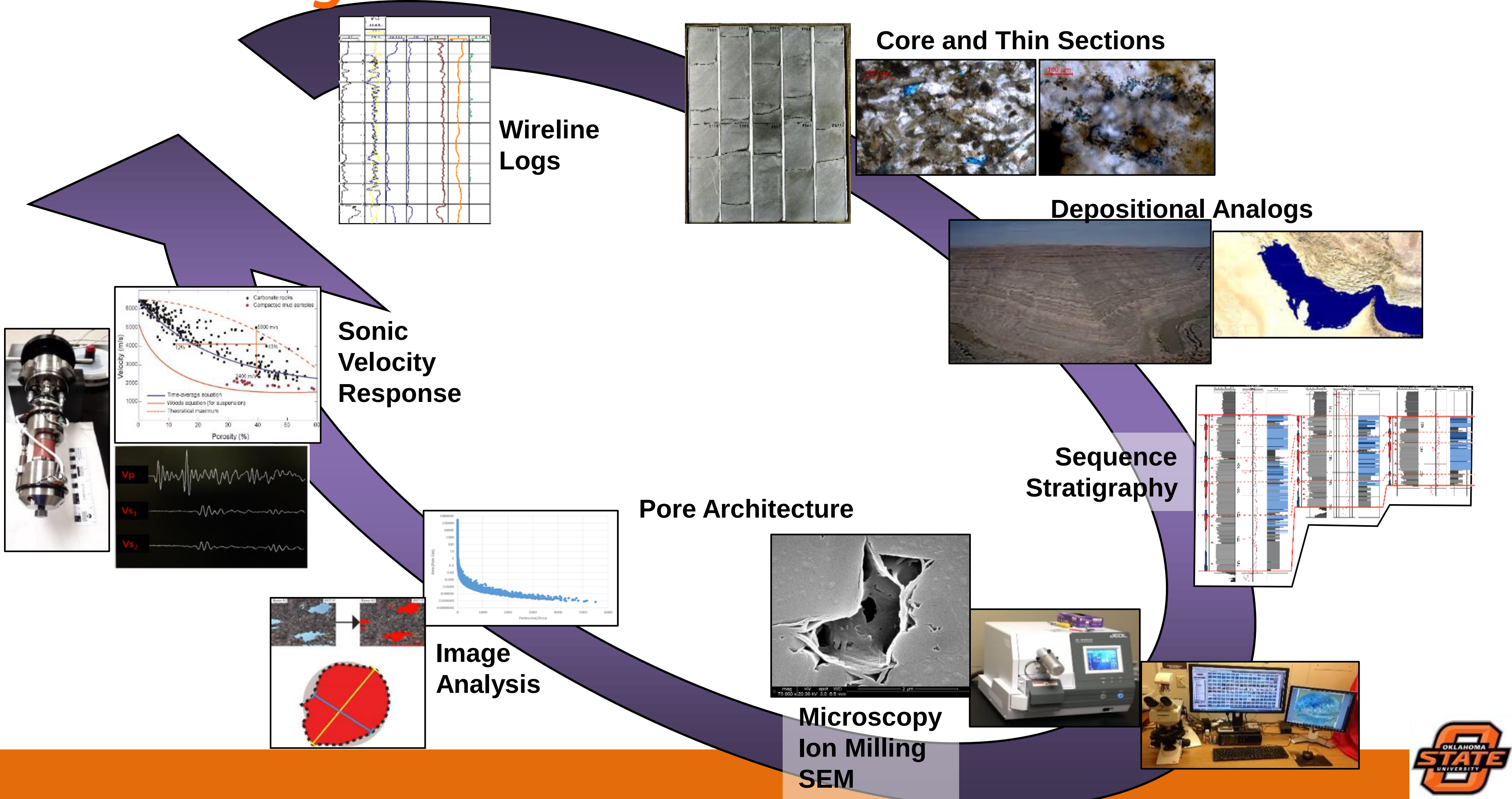
Integrated Reservoir Characterization



Mid-Continent "Mississippi Limestone" Play Potential

- Revitalized play with advancements in drilling technology
- Several reported lithologic classifications with potential oil and gas production
- Continued insight into reservoir architecture and production potential are necessary for continued successful development of the play

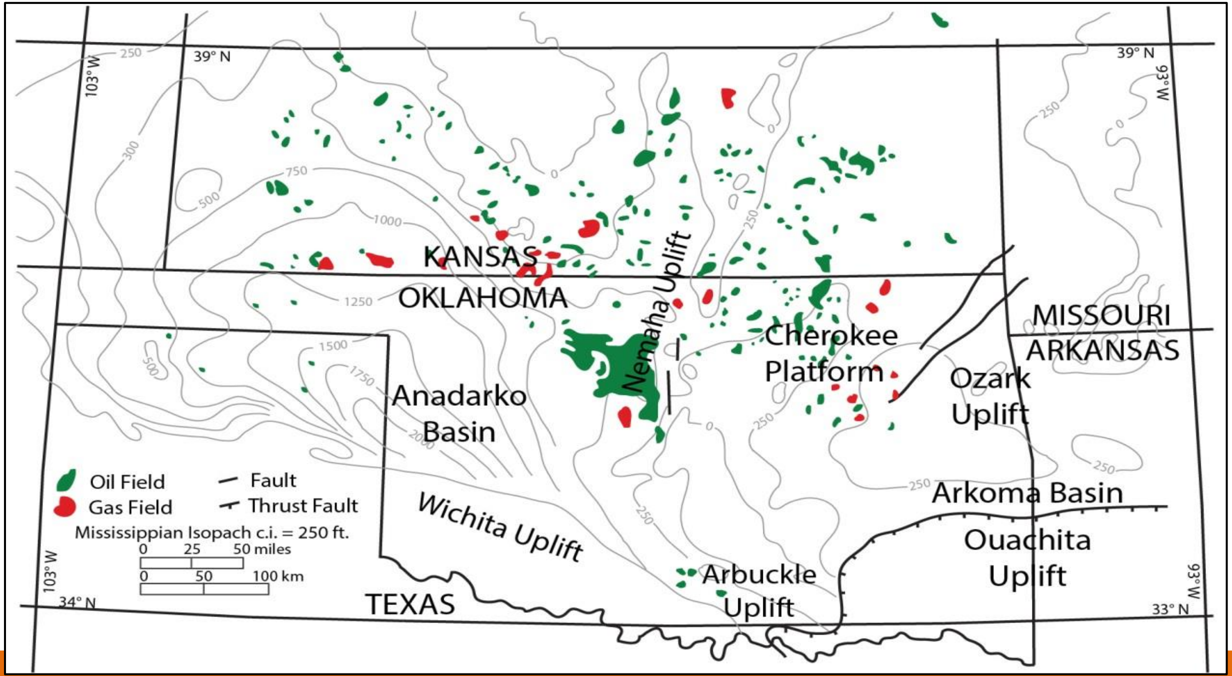


Figure modified from Harris (1975)

Lower Carboniferous - Mississippian Paleogeography

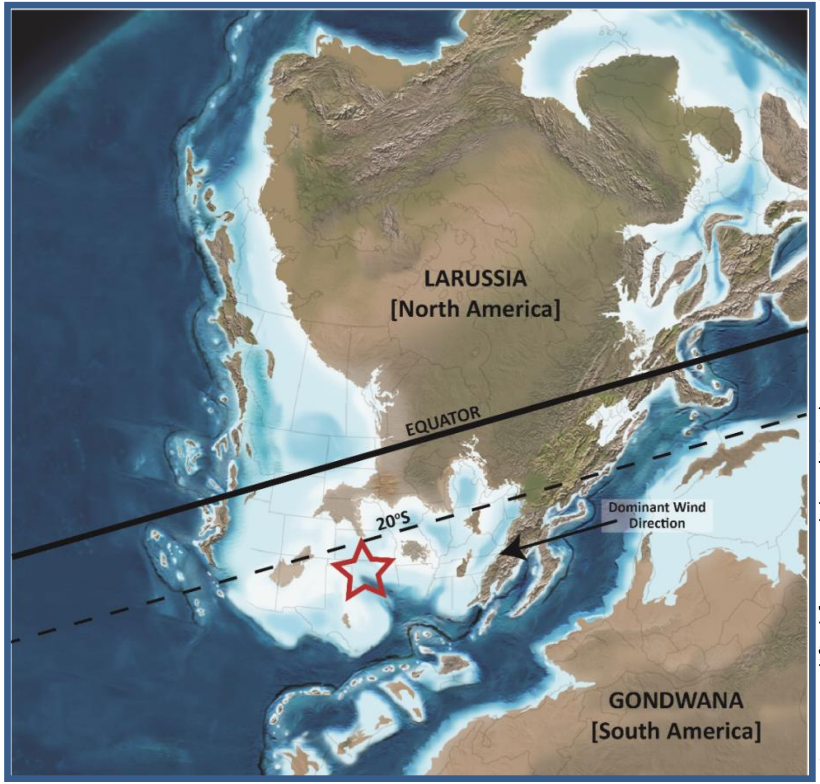


Figure modified from R. Blakey (2011)

Early Mississippian (~345 Ma)

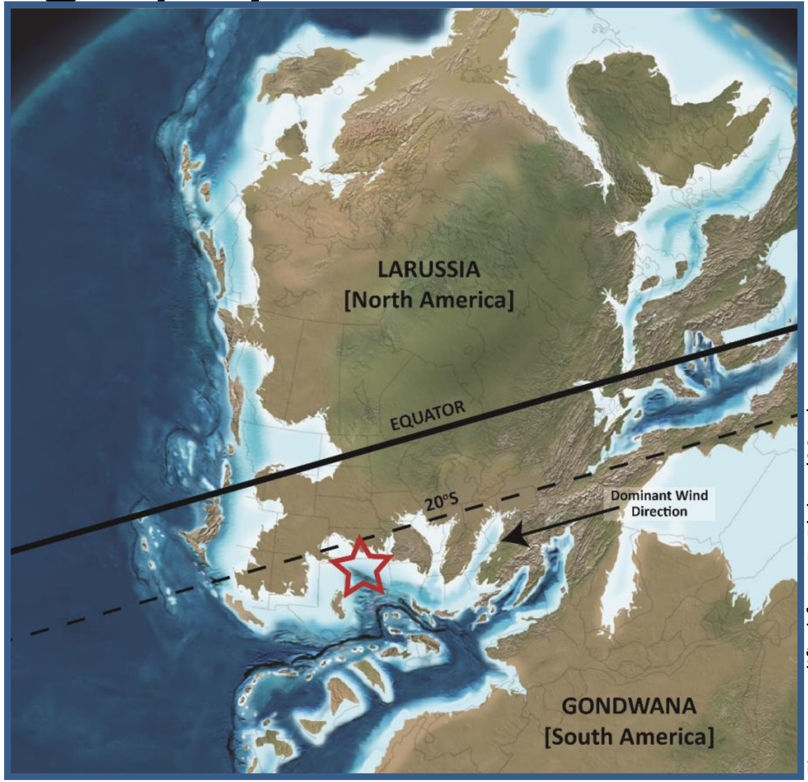
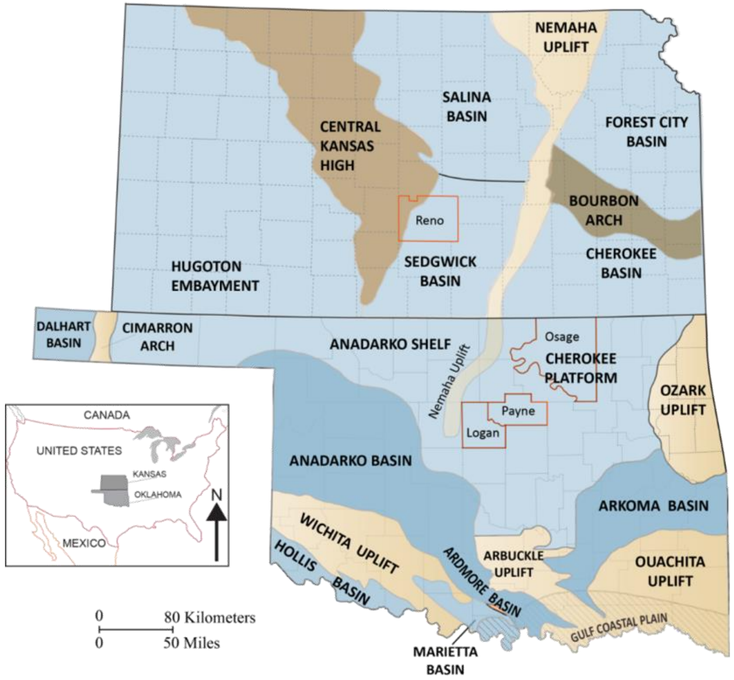


Figure modified from R. Blakey (2011)

Late Mississippian (~325 Ma)

Core Locations and Data Set



Five (5) cores:

- Logan, Payne County, OK
- Osage County, OK
- Reno County, KS

Available Data:

- Wireline logs
- Conventional lab measured porosity
- Conventional lab measured permeability
- Thin sections
- SEM images from argon milled samples
- Core plug sonic velocity response
- High resolution sequence stratigraphic framework

Location (Well Name)	Cored Mississippian Interval (356m, 1165ft.)	Thin Sections (322)	SEM Samples (208)	Velocity Response (181 dry, 115 saturated in 35ppt NaCl brine)
Reno County, KS (Bartel)	70m (230ft.)	87	30	39, 34
Osage County, OK (Orion)	85m (278 ft.)	50	67	93, 34
Payne County, OK (Elinore)	44m (143.2ft.)	22	37	14, 14
Payne County, OK (Winney)	58m (189.6 ft.)	69	38	16, 14
Logan County, OK (Adkisson)	99m (323.7ft.)	94	36	19, 19

Depositional Environments & Facies Analysis

- Wide variation in depositional environments
  - Localized influences relative to basin topography and continental (siliciclastic) influences
- Pore sizes: meso-scale pores to nano-scale pores and nano-scale to picopore scale pore throats
- Pore types: interparticle, intergranular, dissolution enhanced moldic and vuggy, fracture, intraparticle, organic
- Potentially different time periods captured

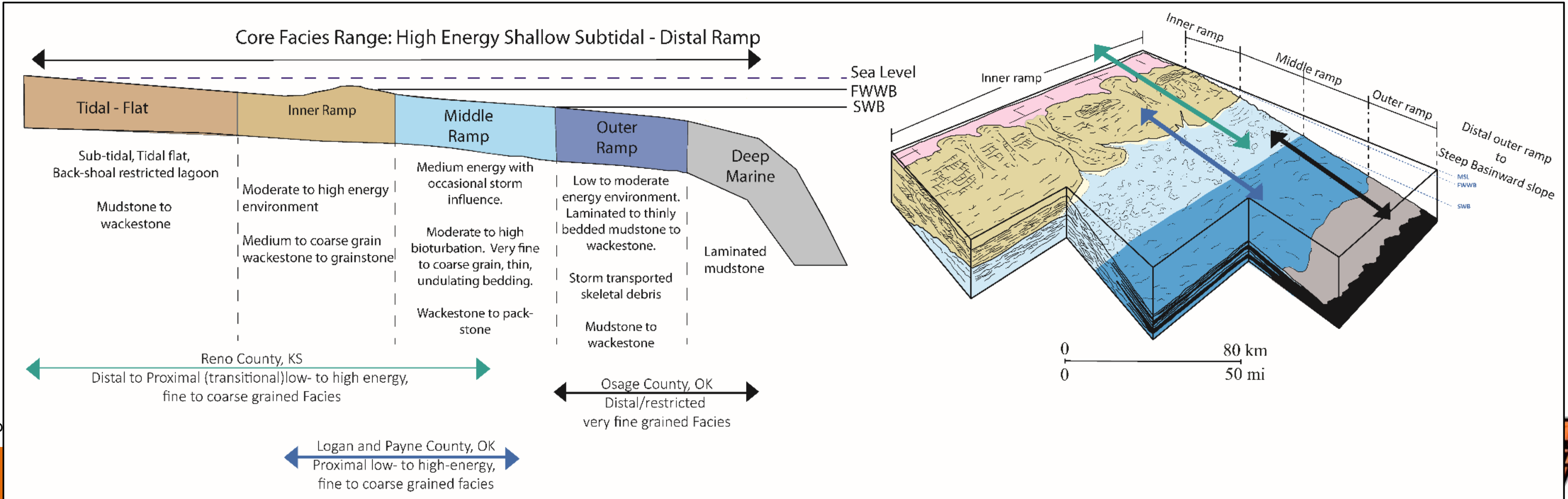
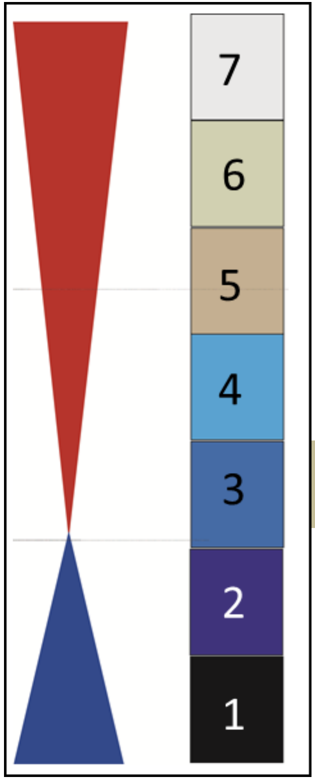
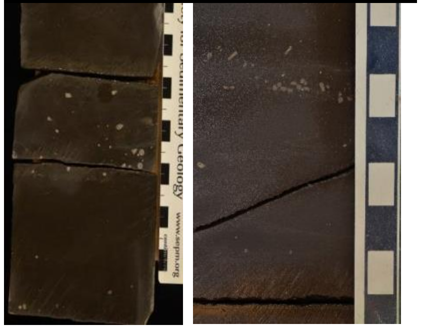


Figure modified from Handford 1986

Distal outer ramp, low energy environment facies



Facies 1
Spiculitic Mudstone to Wackestone



Facies 2
Bioturbated Mudstone to Skeletal Wackestone

Facies 3
Peloidal-Skeletal-Ooid-Wackestone to Packstone

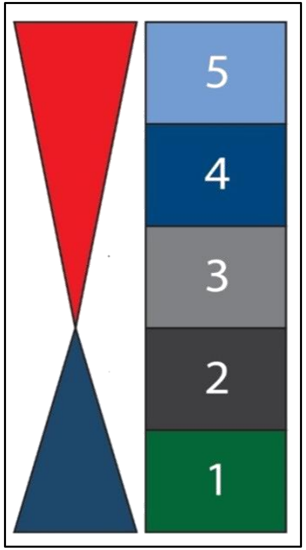
Facies 4
Bioturbated Skeletal-Peloidal Wackestone

Facies 5
Bioturbated Wackestone

Facies 6
Bioturbated Skeletal-Peloidal Wackestone

Facies 7
Bioturbated Mudstone to Skeletal Wackestone

Proximal to middle ramp, low to moderate energy environment facies



Facies 1
Glauconitic
Sandstone

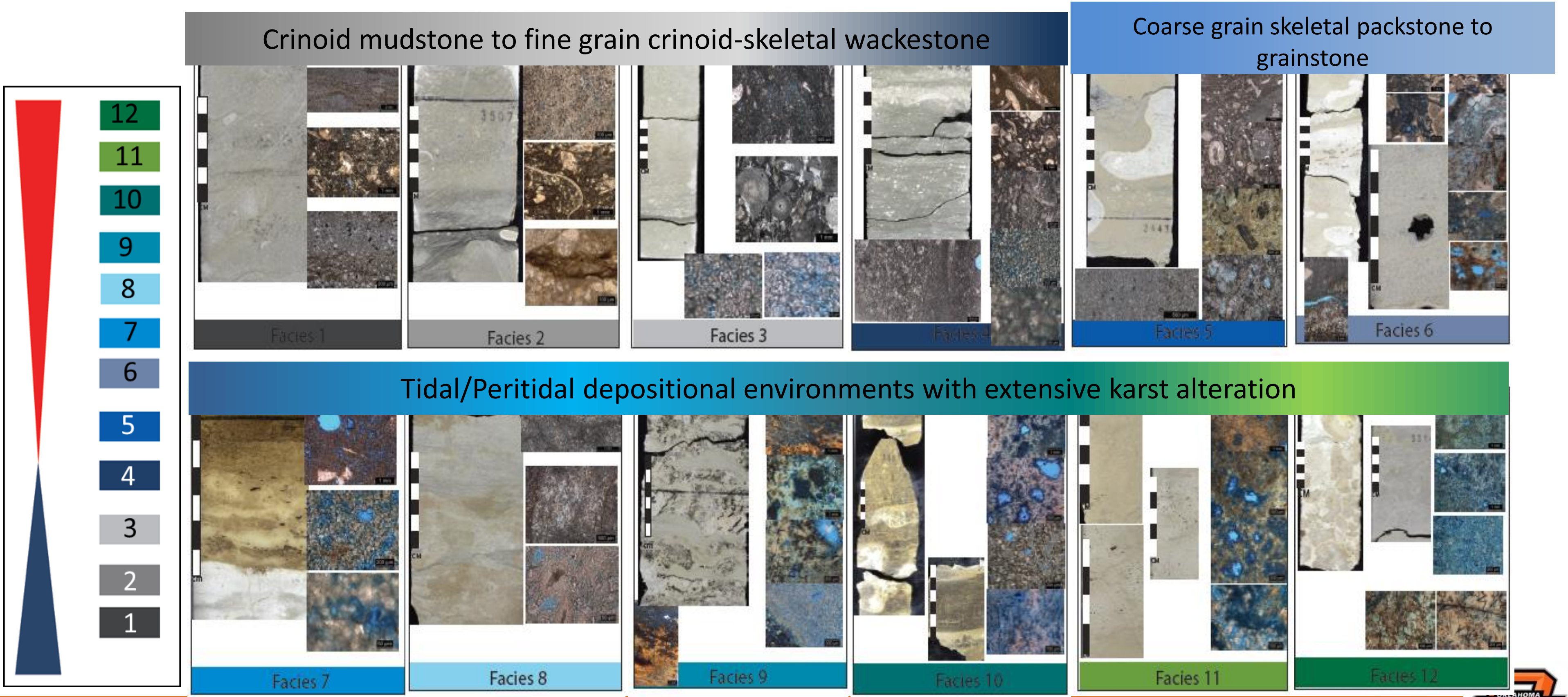
Facies 2
Burrowed Calcareous
Mudstone-
Wackestone

Facies 3
Bioturbated
Wackestone -
Packstone

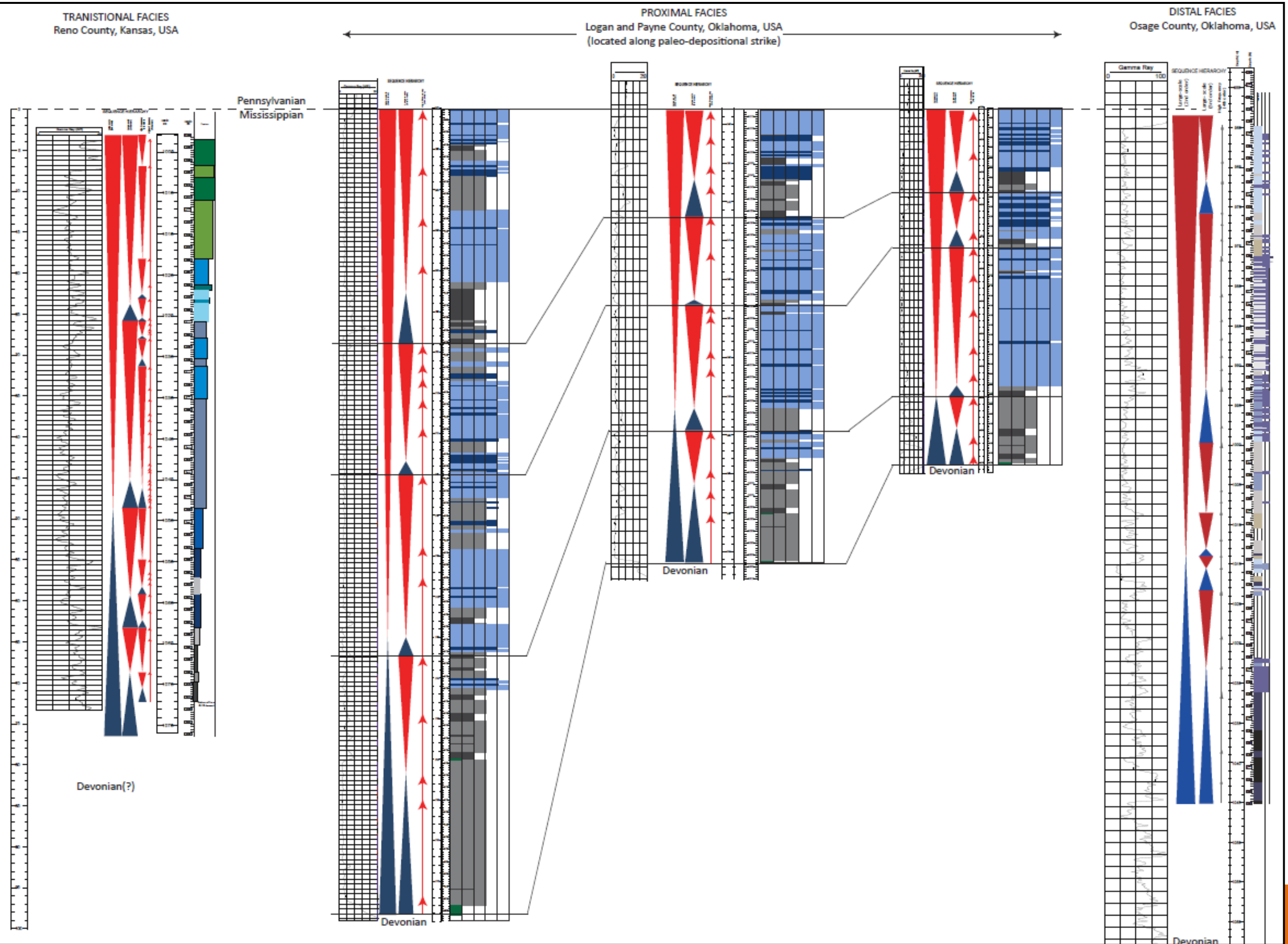
Facies 4
Peloidal Packstone -
Grainstone

Facies 5 Skeletal
Packstone -
Grainstone

Distal/middle ramp to shoreline and peritidal, low to high energy environment facies

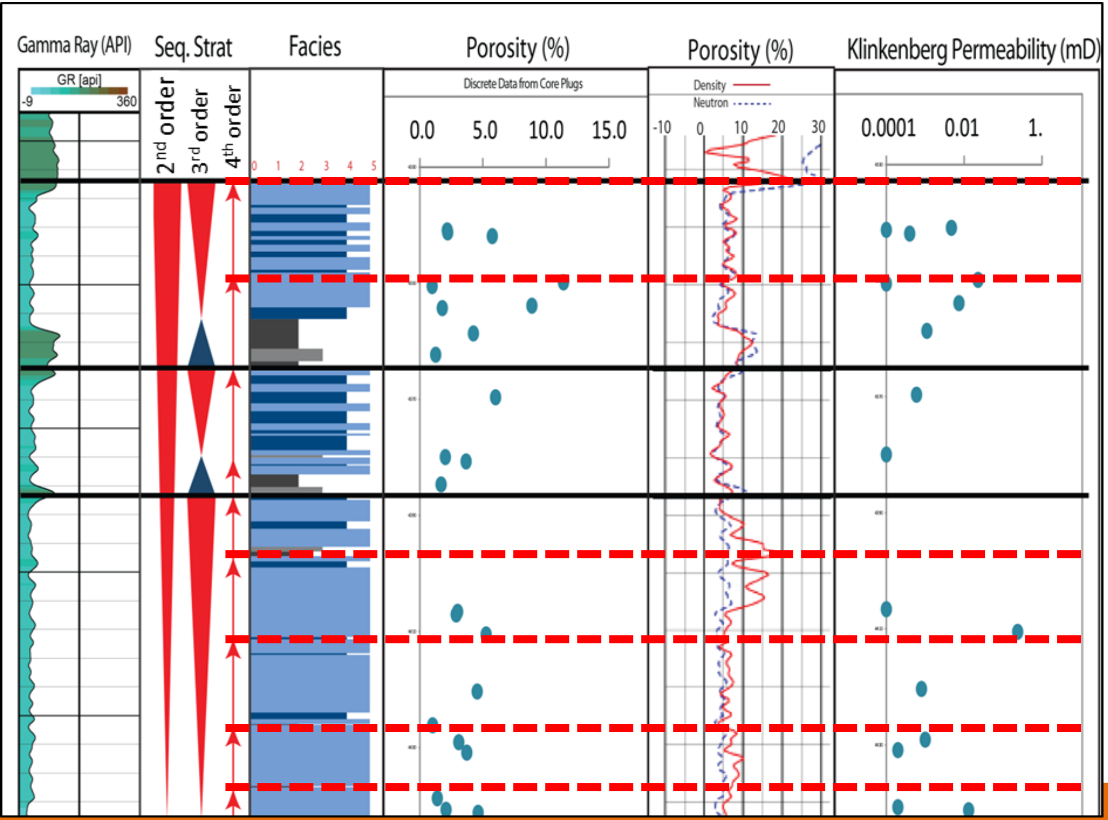


Similar Sequence Stratigraphic Framework



- Single 2nd order sequence
- Similar number of 3rd order sequences that can be used for correlation within a single region
- 4th order cycles often correlate with high porosity and high permeability zones

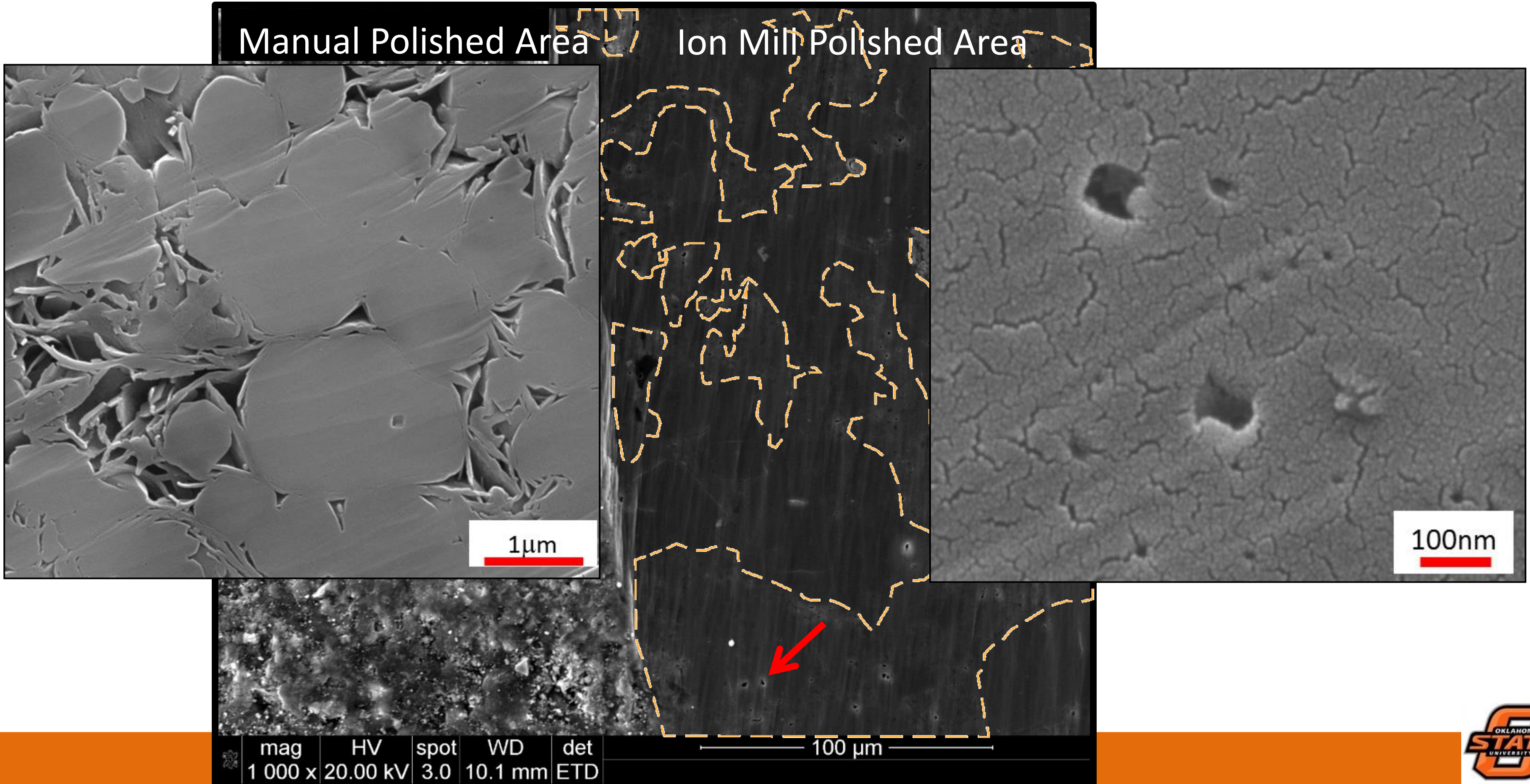
Sequence stratigraphic framework correlation with wireline logs, and increased porosity and permeability



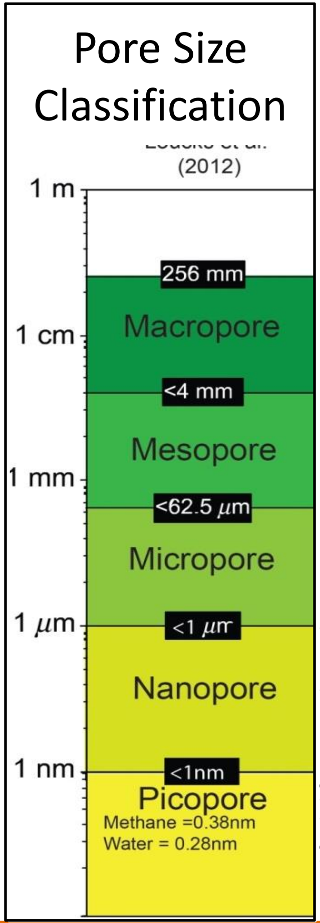
Modified from LeBlanc 2015

- Predictable correlation between sequence stratigraphic framework, porosity, and permeability
- Wireline logs (GR) correlate to 3rd order sequences
- Porosity and permeability correlate with top of 4th order cycles within 2nd and 3rd order regressive phase
- *No predictable correlation between facies, porosity, and permeability*

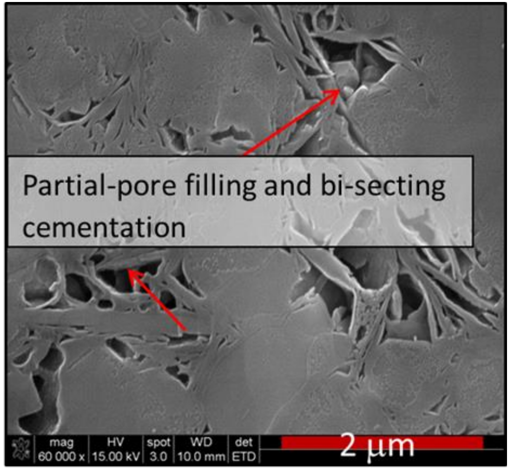
Ion mill polished samples

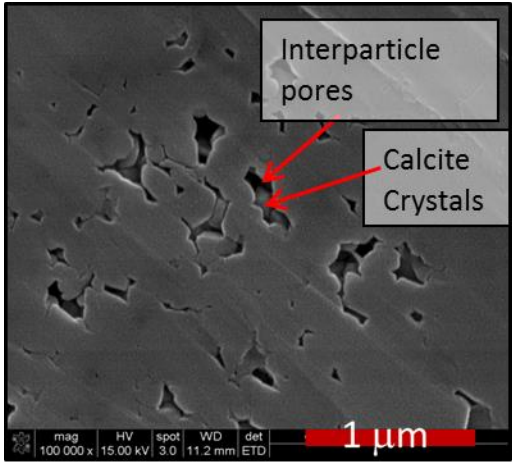


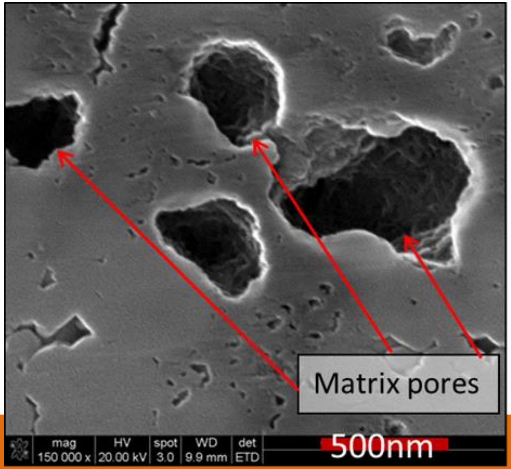
SEM analysis: pore types and sizes

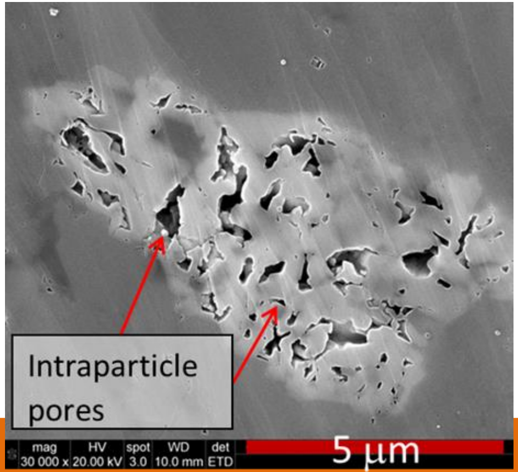


Modified d from Loucks et al., 2012

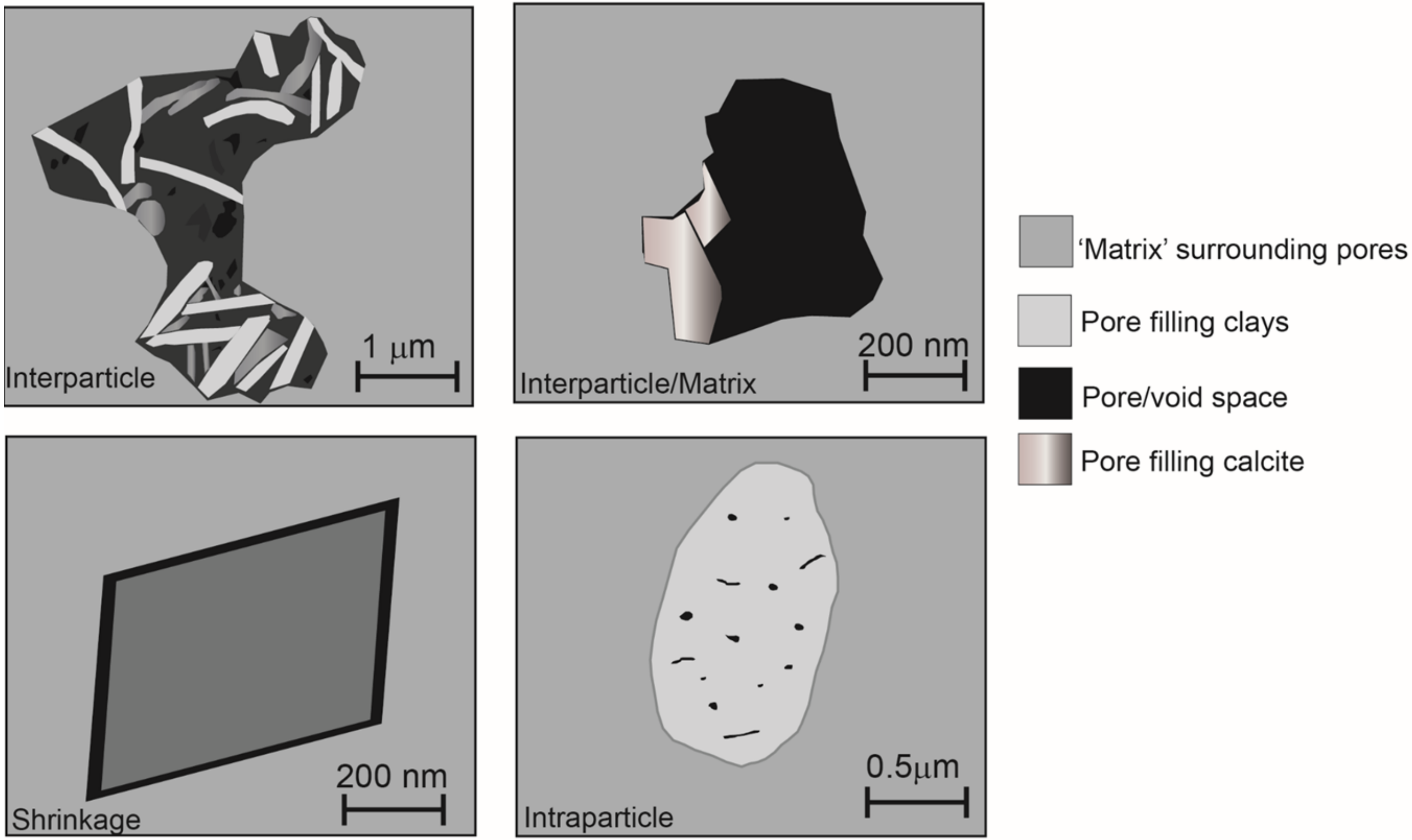




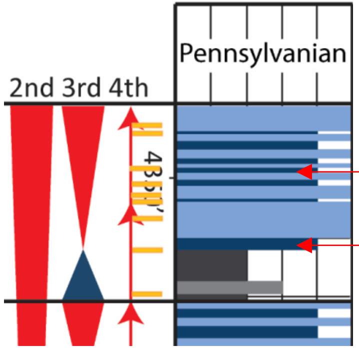




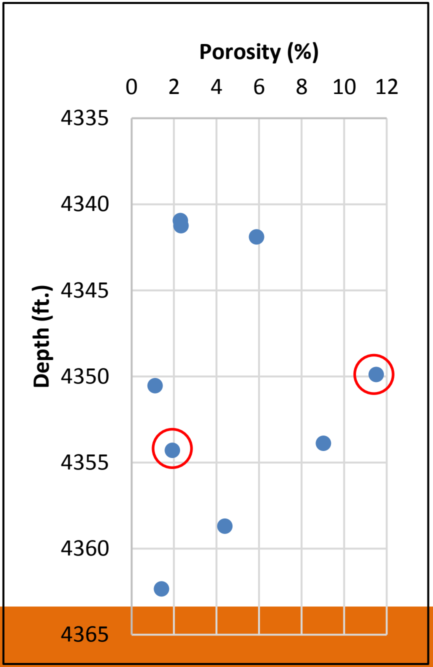
Common pore types

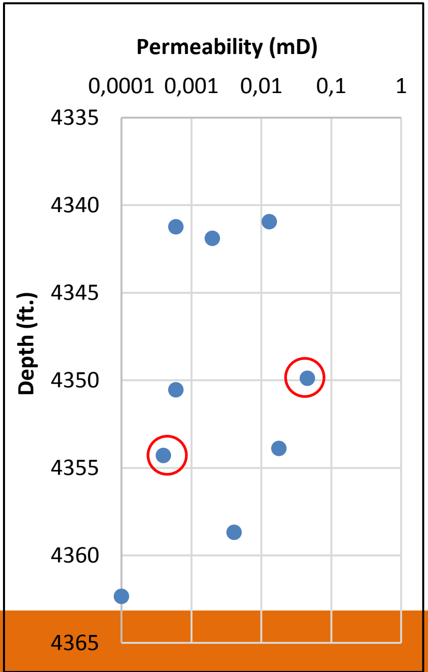


Sequence Stratigraphic Controls on Pore Type, Porosity, and Permeability



- Targeted intervals for milling, ESEM, and DIA analysis
- Relate to the high resolution sequence stratigraphic framework
- Relate to laboratory measured porosity and permeability intervals

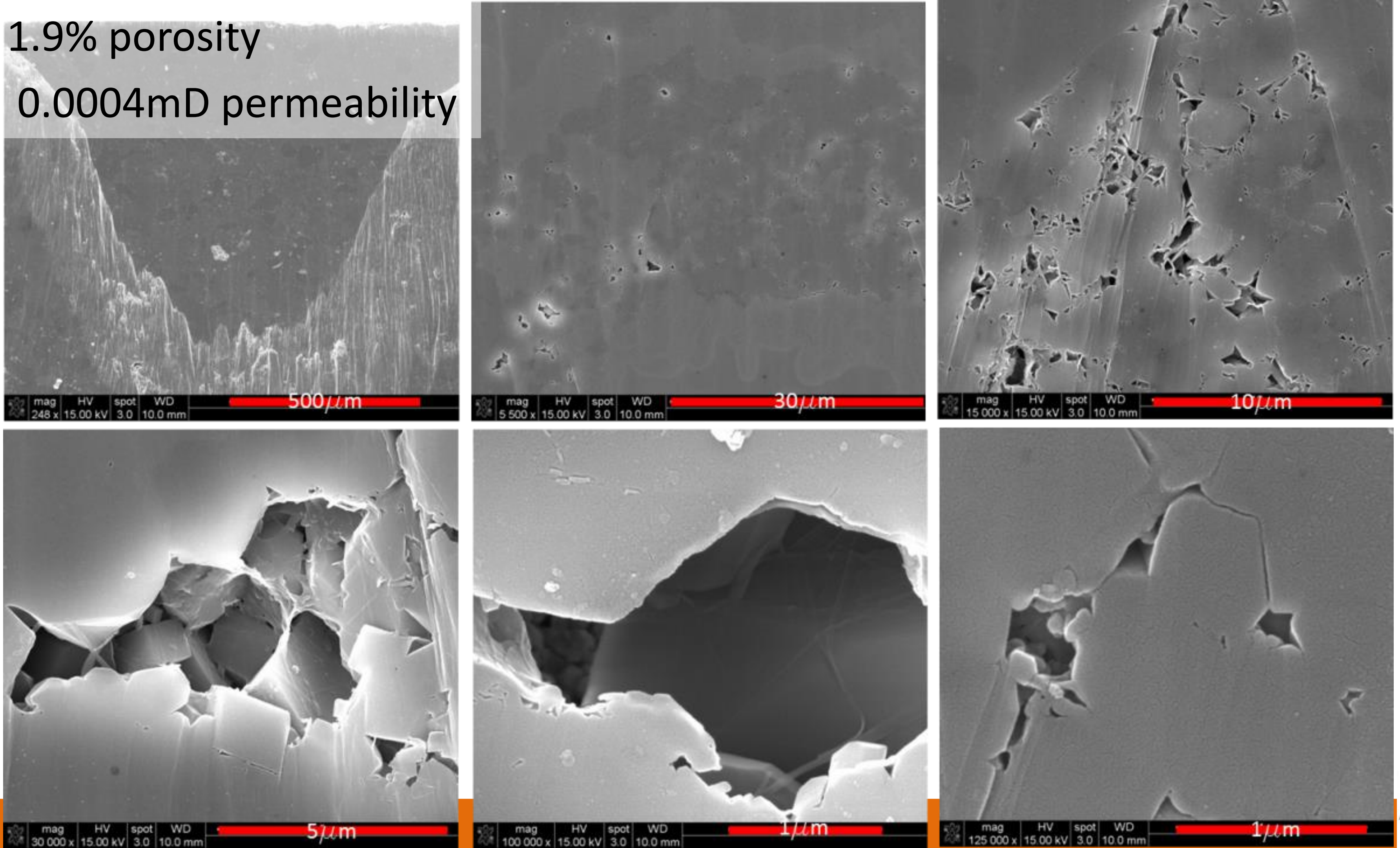


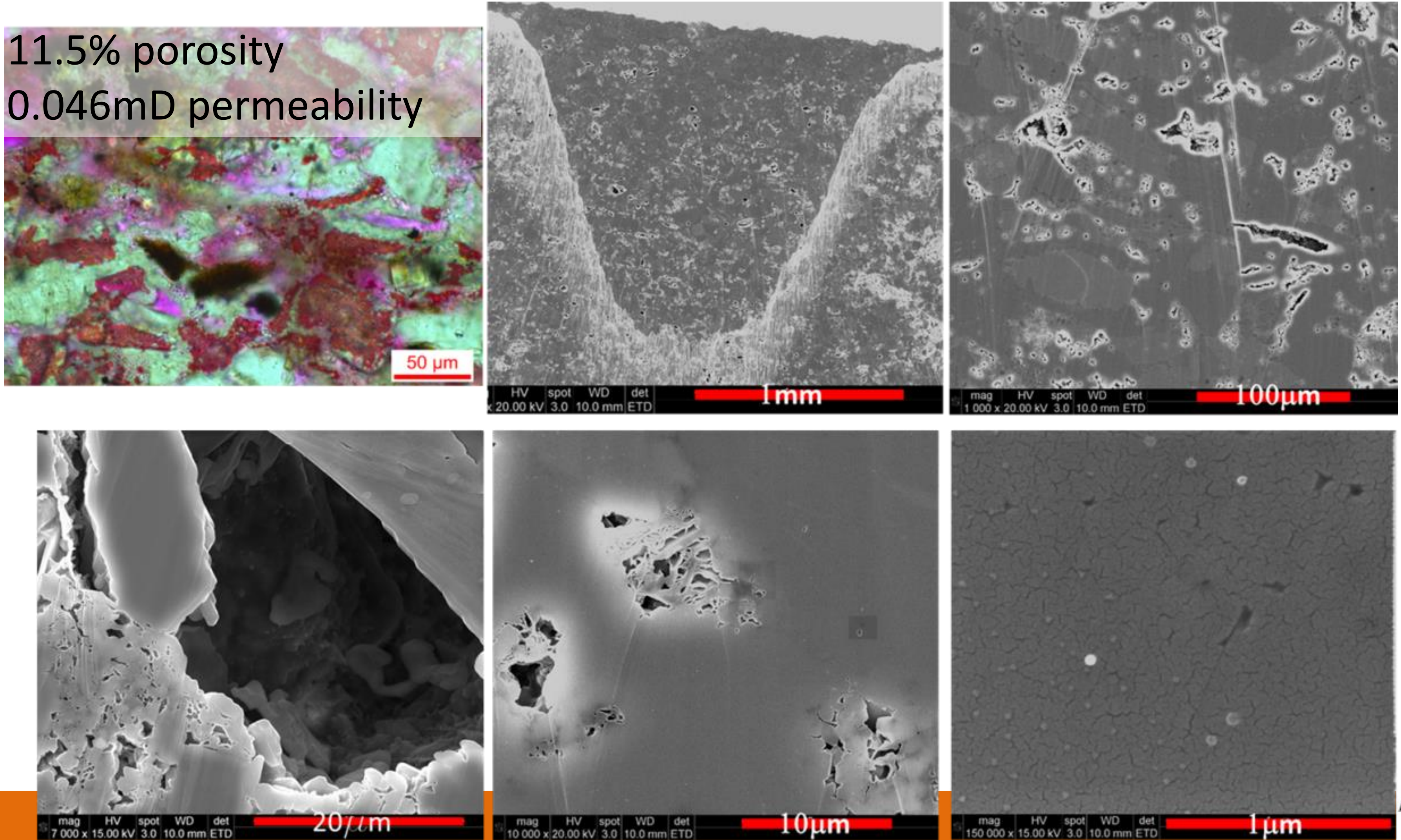


Sample I.D.	Depth	Porosity (%)	Permeability (mD)	Thin Section	Facies
2.10	4340.95	2.3	0.013	4340.25	5
2.11.1	4341.9	5.9	0.0020	4341.9	5
2.19	**4349.9**	**11.5**	**0.046**	**4349.9**	**4**
2.20	4350.55	1.1	0.0006	4350.55	5
2.23	4353.9	9.0	0.018	4353.9	5
2.24	**4354.3**	**1.9**	**0.0004**	**4354.3**	**4**
2.28	4358.7	4.4	0.0041	n/a	5
2.32	4362.35	1.4	0.0001	4362.35	2
2.39	4369.7	6.1	0.0026	n/a	3

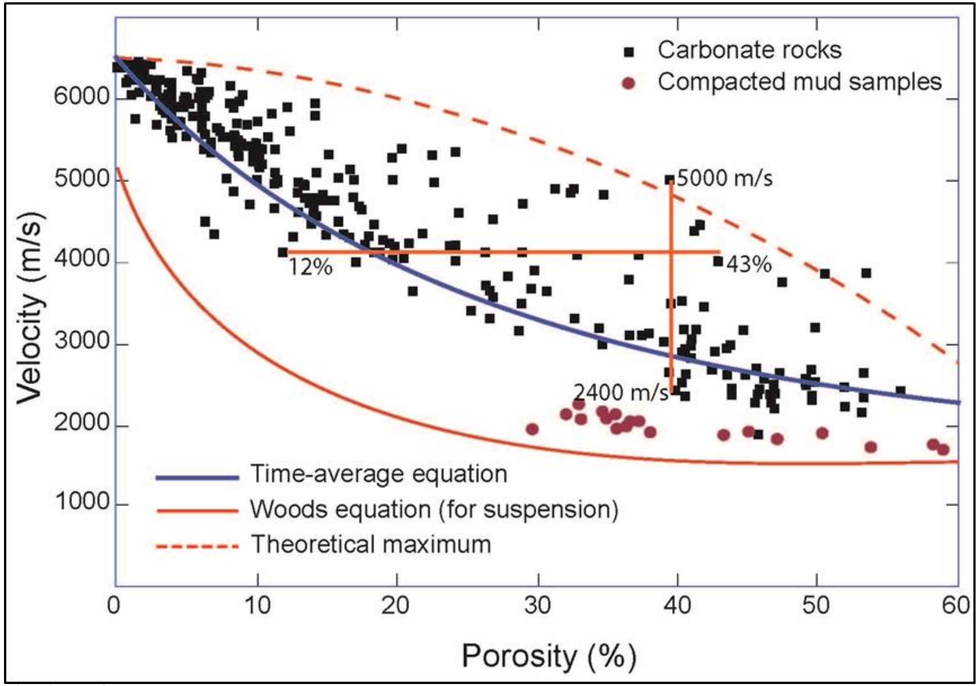
1.9% porosity

0.0004mD permeability




11.5% porosity
0.046mD permeability
50 μm
HV spot WD det
20.00 kV 3.0 10.0 mm ETD
1mm
mag HV spot WD det
1 000 x 20.00 kV 3.0 10.0 mm ETD
100μm
mag HV spot WD det
7 000 x 15.00 kV 3.0 10.0 mm ETD
20μm
mag HV spot WD det
10 000 x 20.00 kV 3.0 10.0 mm ETD
10μm
mag HV spot WD det
150 000 x 15.00 kV 3.0 10.0 mm ETD
1μm

Acoustic Response in pure carbonates



Eberli et al. 2003

- Vp – Φ approximated by the WTA eqn.
- Scatter correlates to dominant pore type
- Pore type related to permeability
- Pore architecture related to permeability
- Qualitative perm ('Vp-deviation log')
- Quantitative perm w/ pore architecture

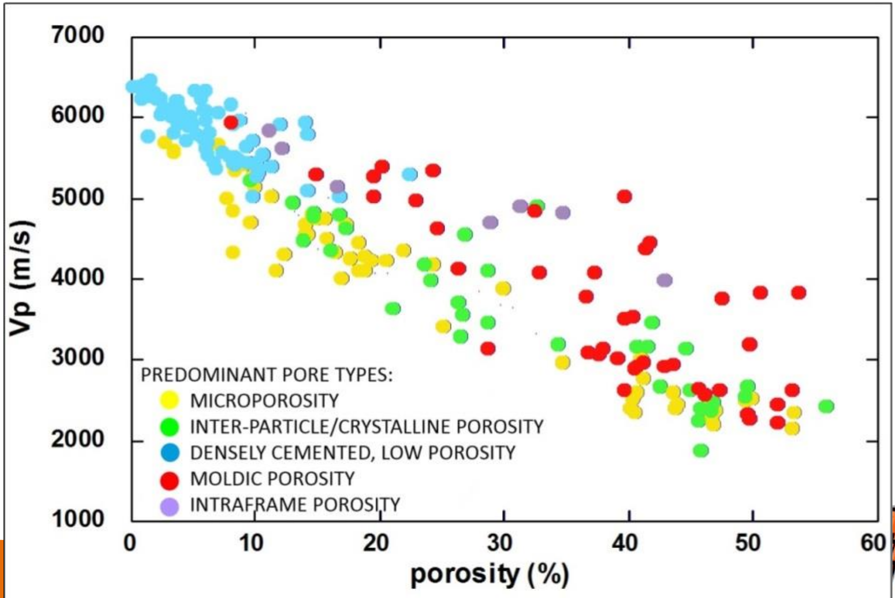
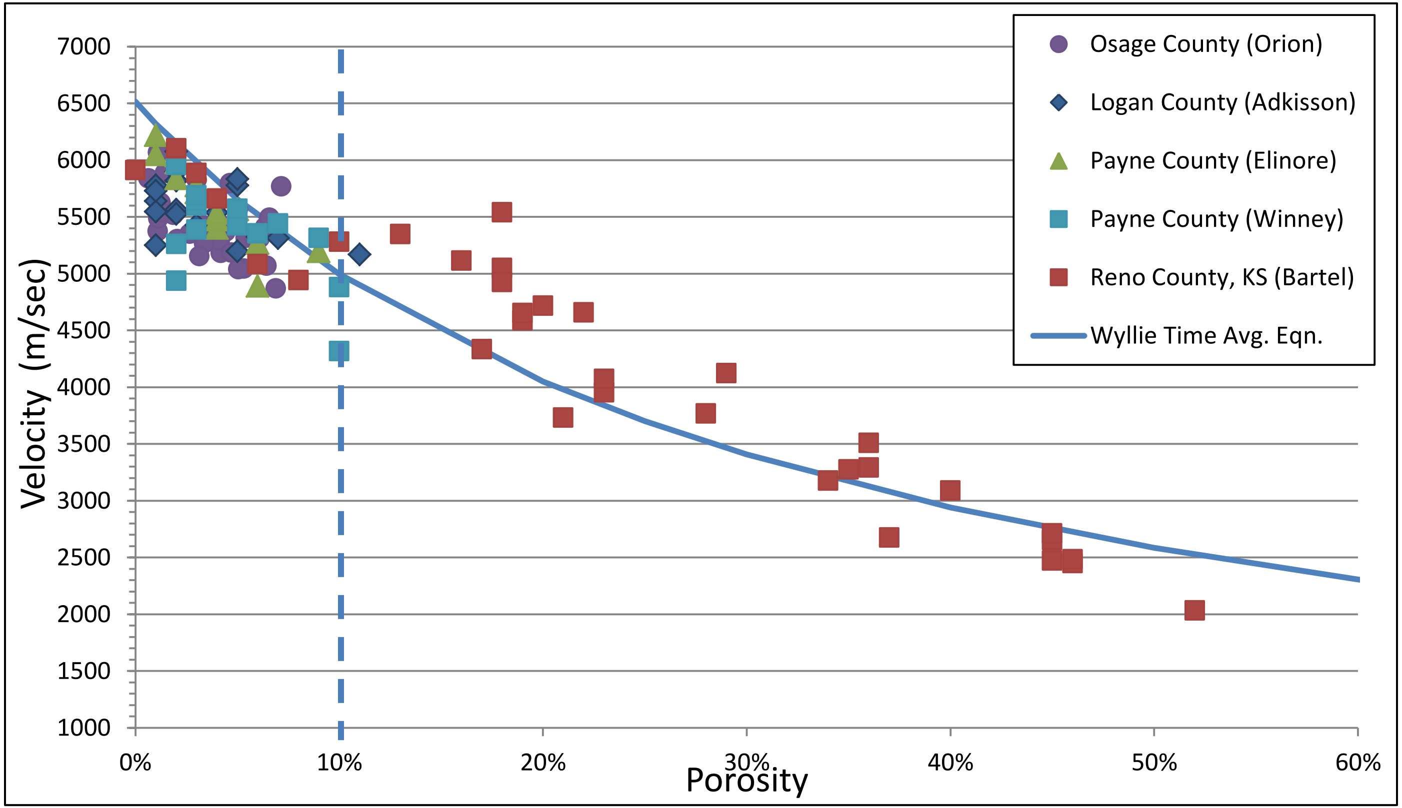


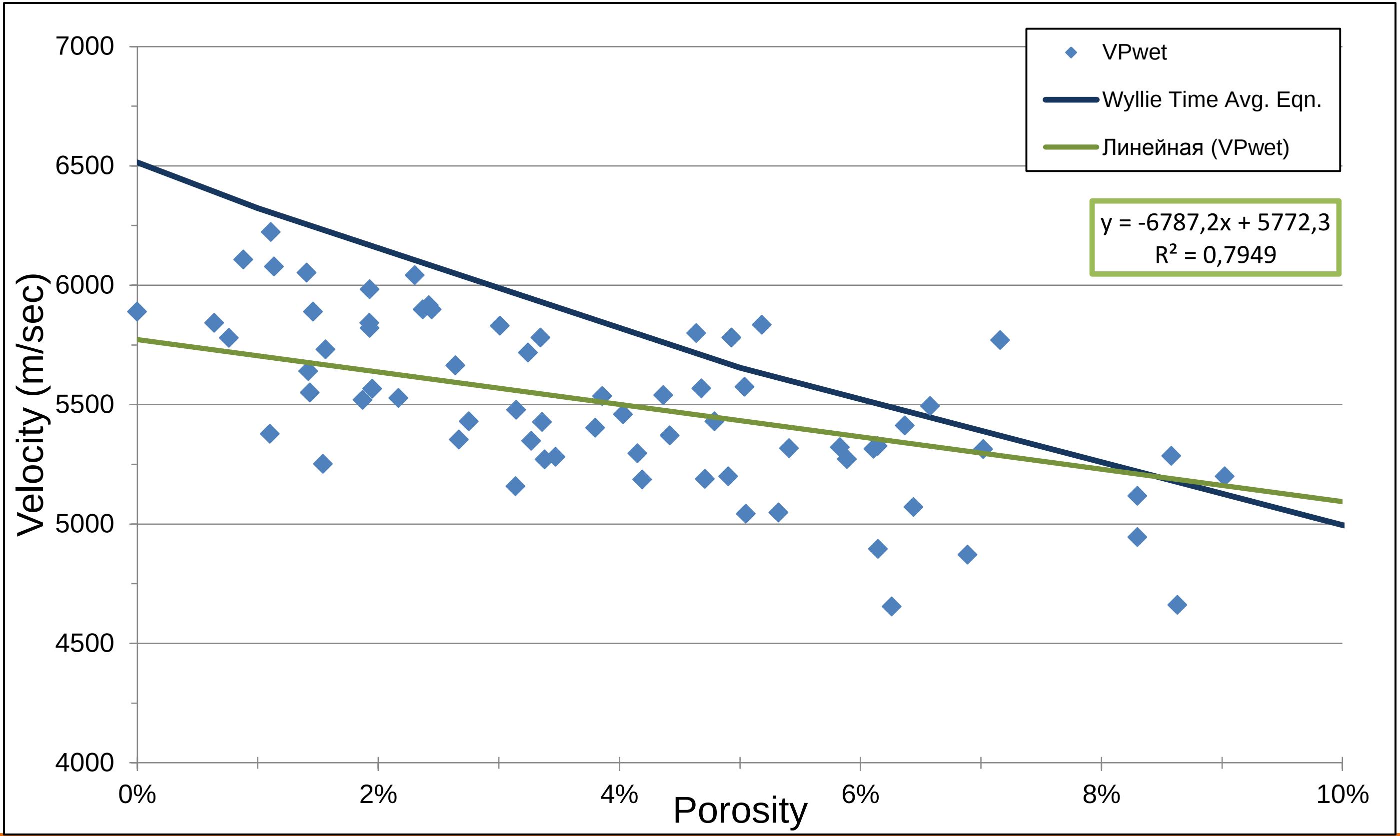
Figure Modified from Eberli et al. 2003

Mississippian N.A. Mid-Continent
Vp- Φ



Vanden Berg, 2016

Mississippian N.A. Mid-Continent
Vp-Φ (micro- to nano-scale pore samples)

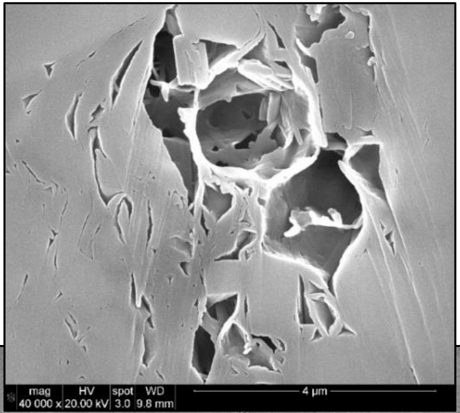


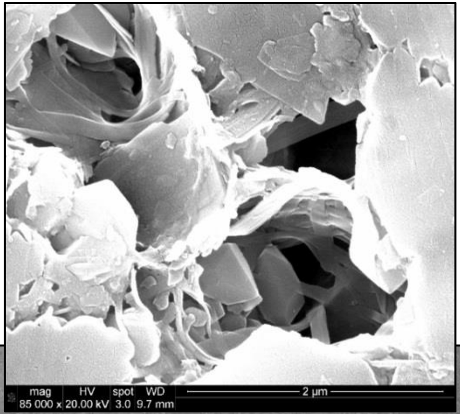
Primary Conclusions from this study

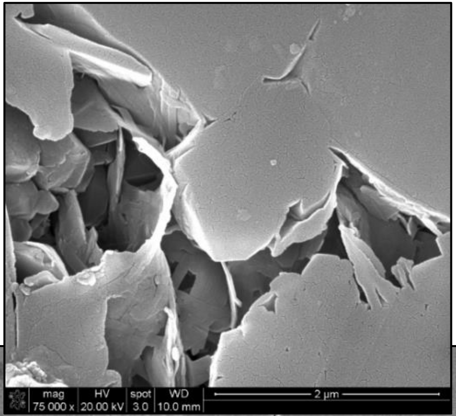
- There is a high degree of similarity in the depositional architecture within the Mississippian N.A. Mid-Continent stratigraphic interval
  - Predictive correlation between the sequence stratigraphic framework, and intervals with high porosity and permeability
- A relatively defined sequence stratigraphic hierarchy can provide predictive value within a reservoir system
- Characterization of a (carbonate) mudrock is most accurately achieved with the integration of qualitative and quantitative analysis

Primary Conclusions from this study

- Porosity and Permeability are best predicted in relation to the sequence stratigraphic framework
  - Intervals with a significant amount of clay precipitated in the pore space correlates to low porosity, low permeability
  - Intervals with a significant amount of quart or calcite *only* precipitated in the pore space correlates to relatively high porosity and permeability
- The micro- to nano-scale pore architecture within a mixed carbonate-siliciclastic system is significantly more complex than carbonates with predominately macro- to meso-scale porosity
  - Affects the velocity response and relationship to pore type, porosity, and permeability


mag HV spot WD
40 000 x 20.00 kV 3.0 9.8 mm
4 µm


mag HV spot WD
85 000 x 20.00 kV 3.0 9.7 mm
2 µm


mag HV spot WD
75 000 x 20.00 kV 3.0 10.0 mm
2 µm

Thank you!