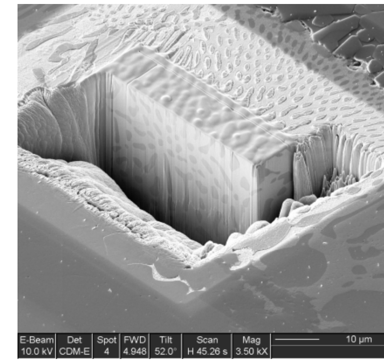
SAND2010-1464C

Pore-Scale Transport Properties of Mudrocks



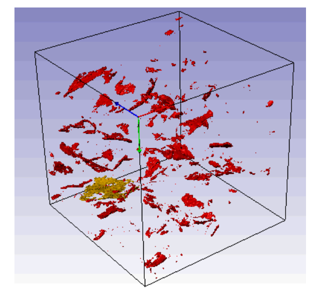
Geosciences Research Program in the Department of Energy's Office of Basic Energy Sciences

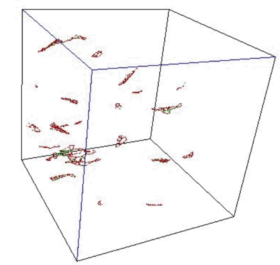
Research Symposia on Geophysics and Fluid Flow

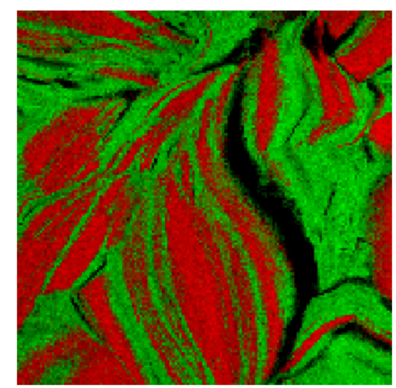
March 12, 2010

Thomas Dewers[1] and Jason Heath[2]

Sandia National Laboratories, Departments of [1]Geomechanics and [2]Geophysics, Albuquerque, NM







Funding for this research is from U.S. Department of Energy Basic Energy Sciences/Office of Science

Outline and Acknowledgements

Pore networks in mudrocks from five depositional settings

- Geology Overview
- FIB/SEM and Pore Network Construction
- Pore Statistics from Imaging and Porosimetry
- CFD Modeling of Flow in Shale Pores
- Shale Nano-Mechanics
- Summary and Conclusions
- Path Forward

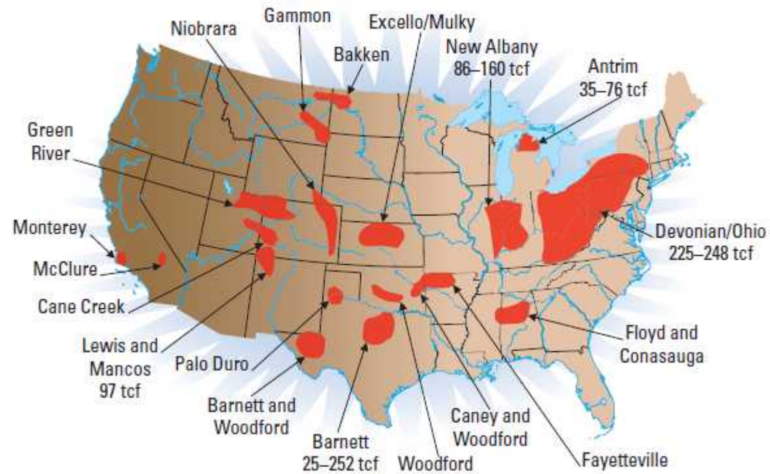
Funding for this study is from Department of Energy Basic Energy Sciences/Office of Science. Thanks also to programs from DOE-NETL's SWP and SEACARB, ARI and The Southern Company, Terra Tek/Schlumberger, OMNI/Weatherford, PoroTek, and to the UGS Shale Gas Project

Thanks to:

Tom Chidsey, UGS
Robin Petrusak, ARI
Michael Rye, SNL
Scott Cooper and Randy Everett, SNL
Brian McPherson, UU
Alexis Navarre-Stitchler, CSM

Mudstones are…..

Shale Gas Reservoirs



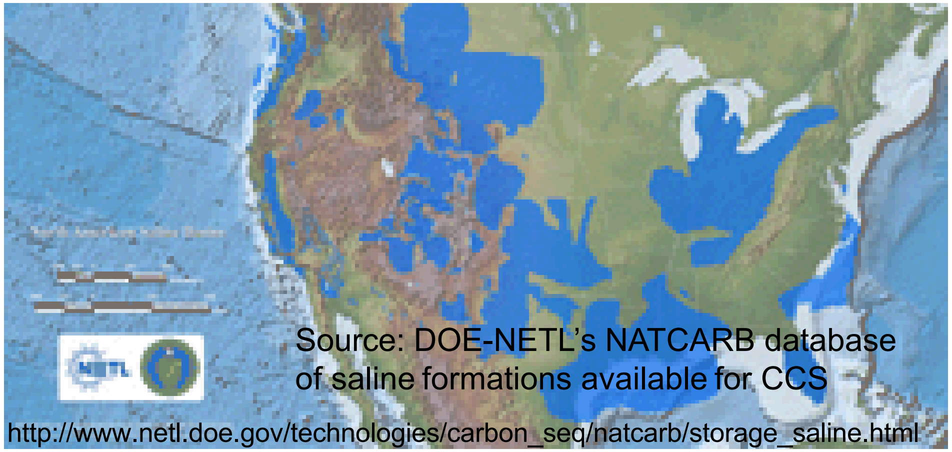
Major shale gas basins in the United States with total resource potential of 500 to 1,000 tcf.

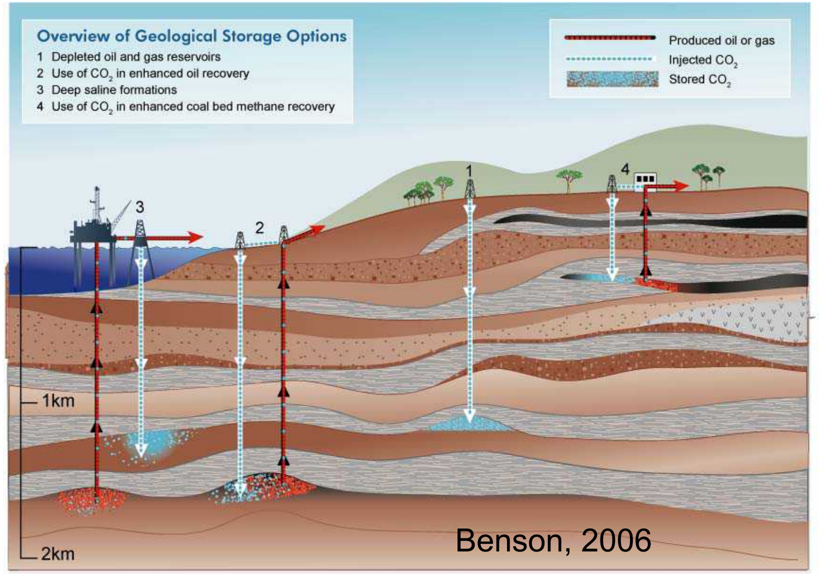
Source:Schlumberger, Shale Gas, 2005

Cook (1999) defines “shale” as a rock with over 50% by wt. clay minerals, and with a continuous network of clay, i.e. clay matrix is load supporting. Other workers use the term “mudrock” with this definition, wherein “shales” are mudrocks with well developed fissility or bedding plane partings.

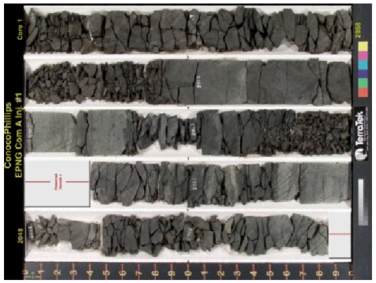
Schlumberger Oil-Field Glossary defines shale more generally as a “fine-grained, fissile, detrital sedimentary rock formed by consolidation of clay- and silt-sized particles into thin, relatively impermeable layers” (<62 microns)

Seals/Caprocks for CCS





Workflow: Characterization and simulation of pore scale transport properties



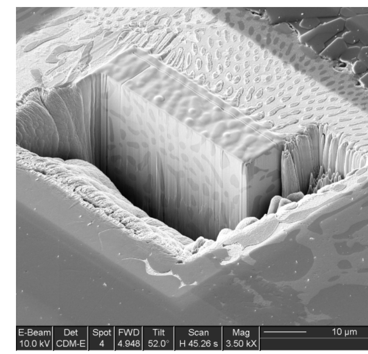
Sample Selection

Thin Sectioning and plug coring

Gas absorption perm measurements, other properties

3D Laser Scanning Confocal Microscopy and 2D SEM

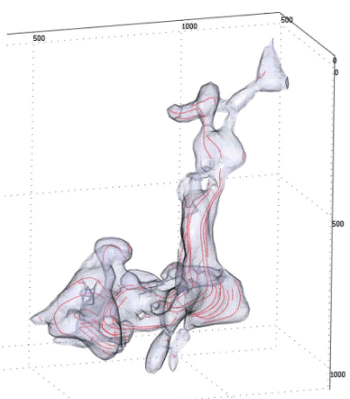
FIB/SEM/TEM Imaging



Mercury Porosimetry

Pore Statistics

Image Analysis, 3DMA, ScanIP etc.



CFD, Lattice-Boltzmann, FEM Simulations

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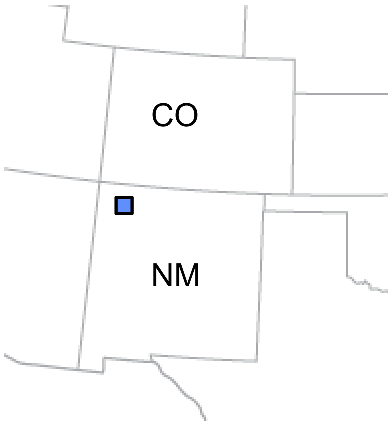
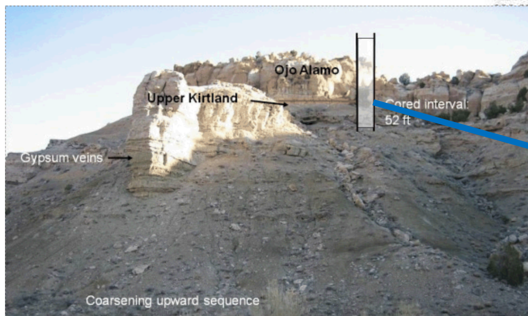
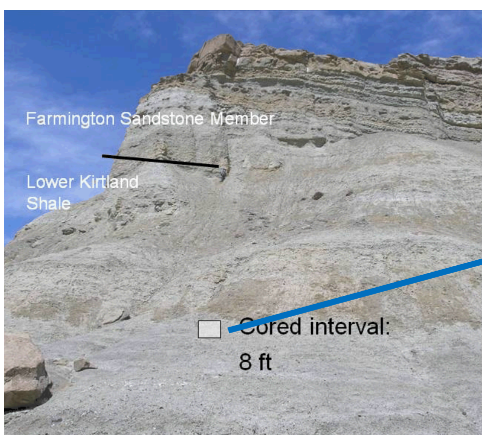
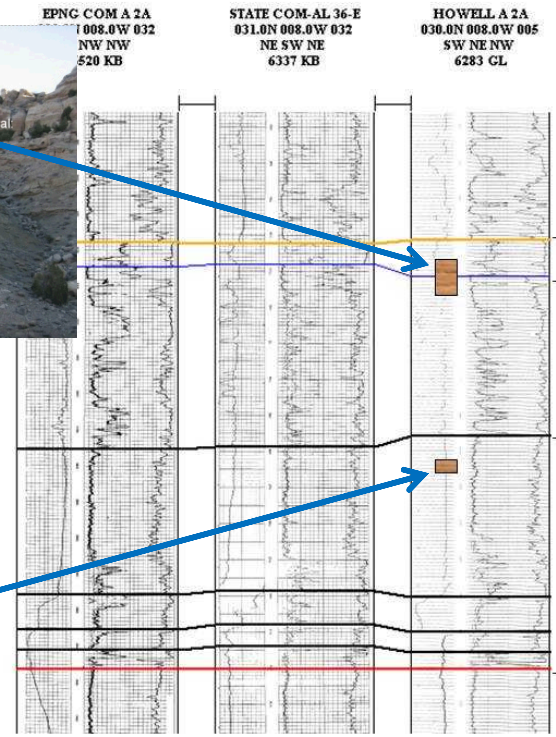
Upper and Lower Kirtland Shale, Cretaceous, San Juan Basin, NM









(Well logs from ConocoPhillips)

Core Points

Goal: 120 ft total

Reality: 60 ft total

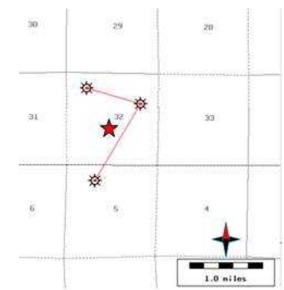
Ojo Alamo

Upper Kirtland and Farmington Sandstone Member

Lower Kirtland Shale

Fruitland

Pictured Cliffs



Samples from preserved core, drilled as part of the Pump Canyon Pilot Project, Phase 2 of DOE-NETL's SWP

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Gothic Shale, Pennsylvanian,Paradox Basin, Utah

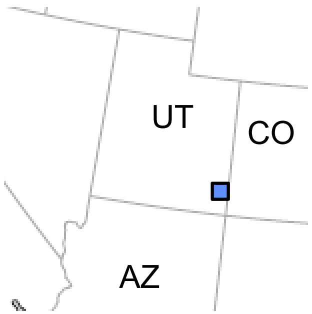
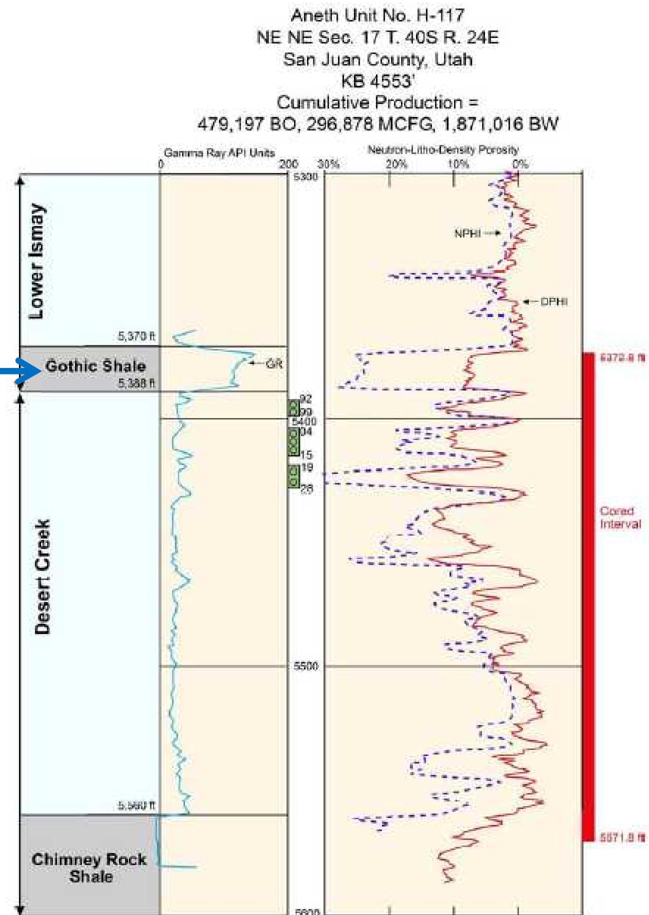


Figure 7-2. Gothic shale in the Pennsylvanian Paradox Formation exposed along the Honaker Trail, San Juan River Canyon, Utah.



Core sampling performed in conjunction with Utah Geological Survey Shale Gas Project and the Phase II Aneth Project of the DOE-NETL SWP

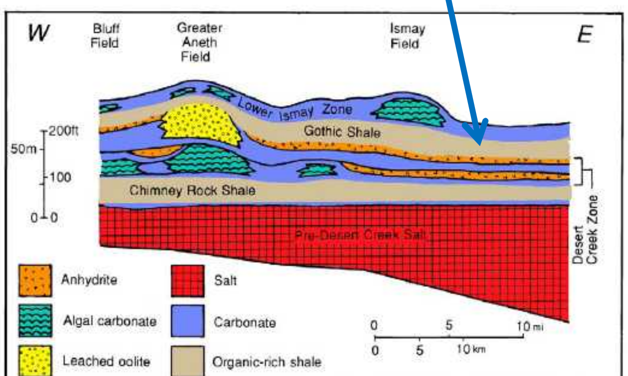


Figure 7-1. Diagrammatic lithofacies east-west cross section across Greater Aneth and Ismay fields, San Juan County, Utah. Modified from Peterson (1992).

Figure 7-3. Interpreted geophysical log from the Aneth Unit No. H-117 well, NENE section 17, T. 40 S., R. 24 E., SLBL&M. Cored interval of the Desert Creek zone and Gothic shale shown in red.

Source: Chidsey et al., 2009

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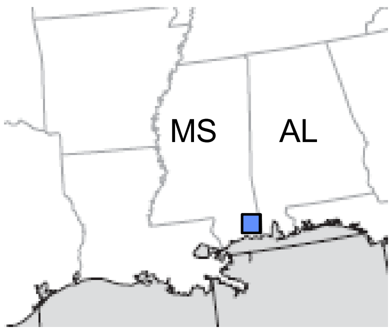
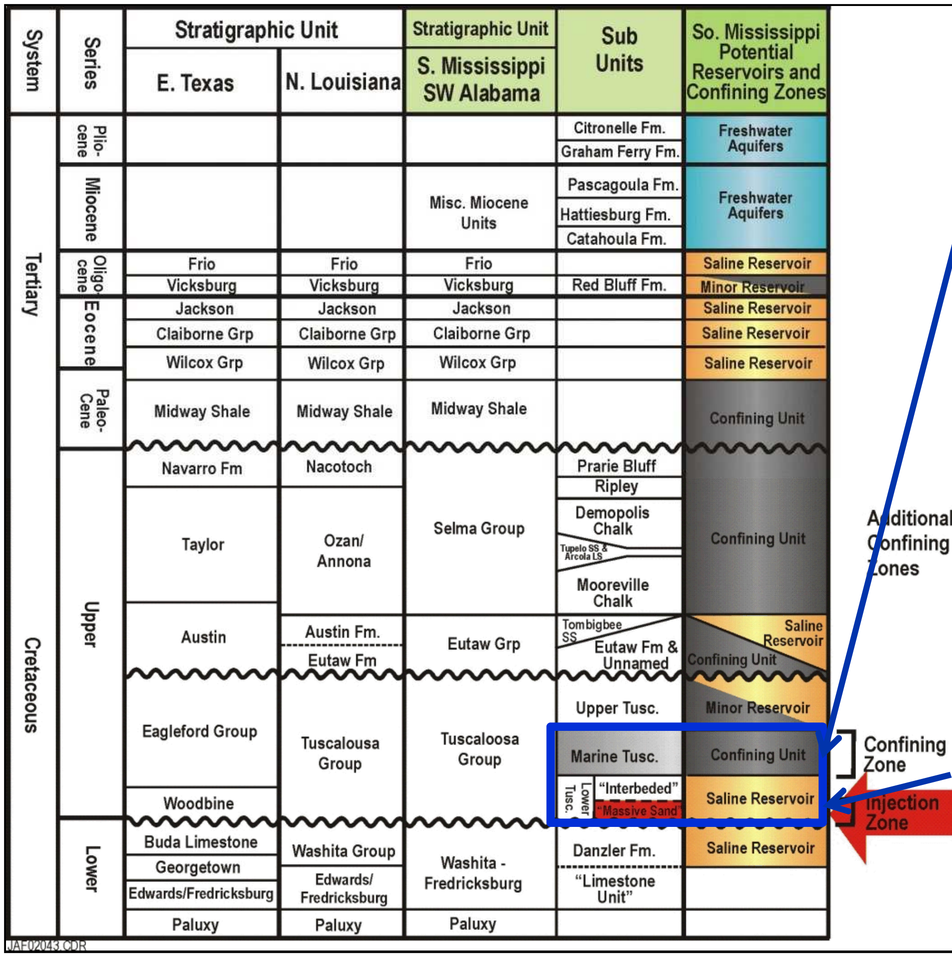
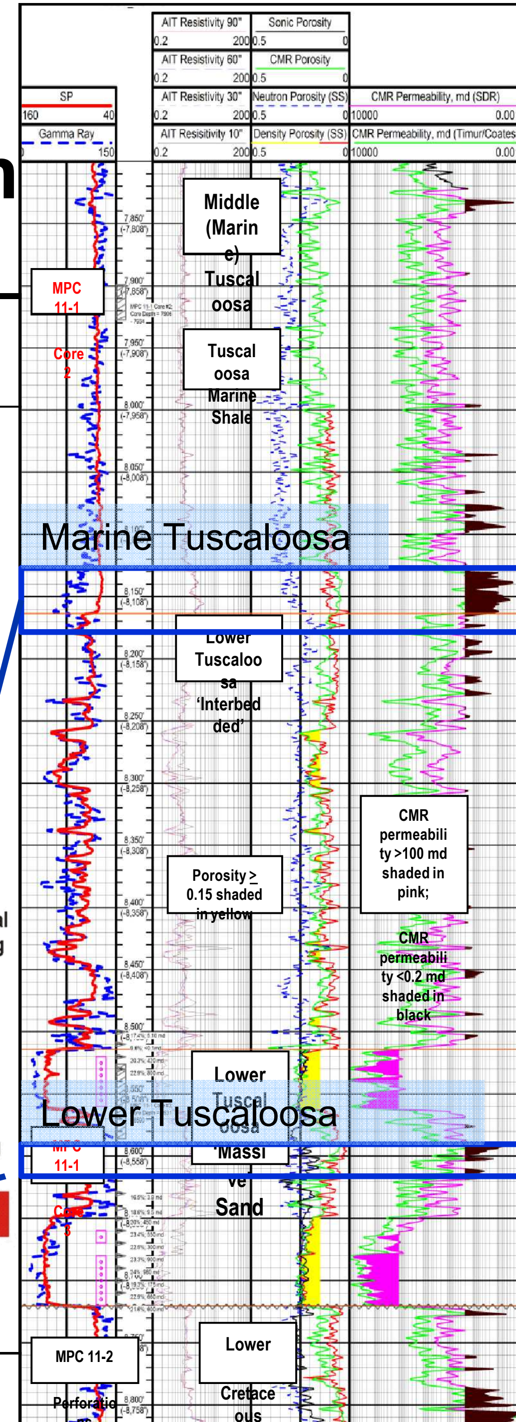
Marine and Lower Tuscaloosa Fm Cretaceous, US Gulf Coast



Samples from Mississippi Power Company Well #11-2, DOE-NETL's SEACARB Phase II Demonstration Site



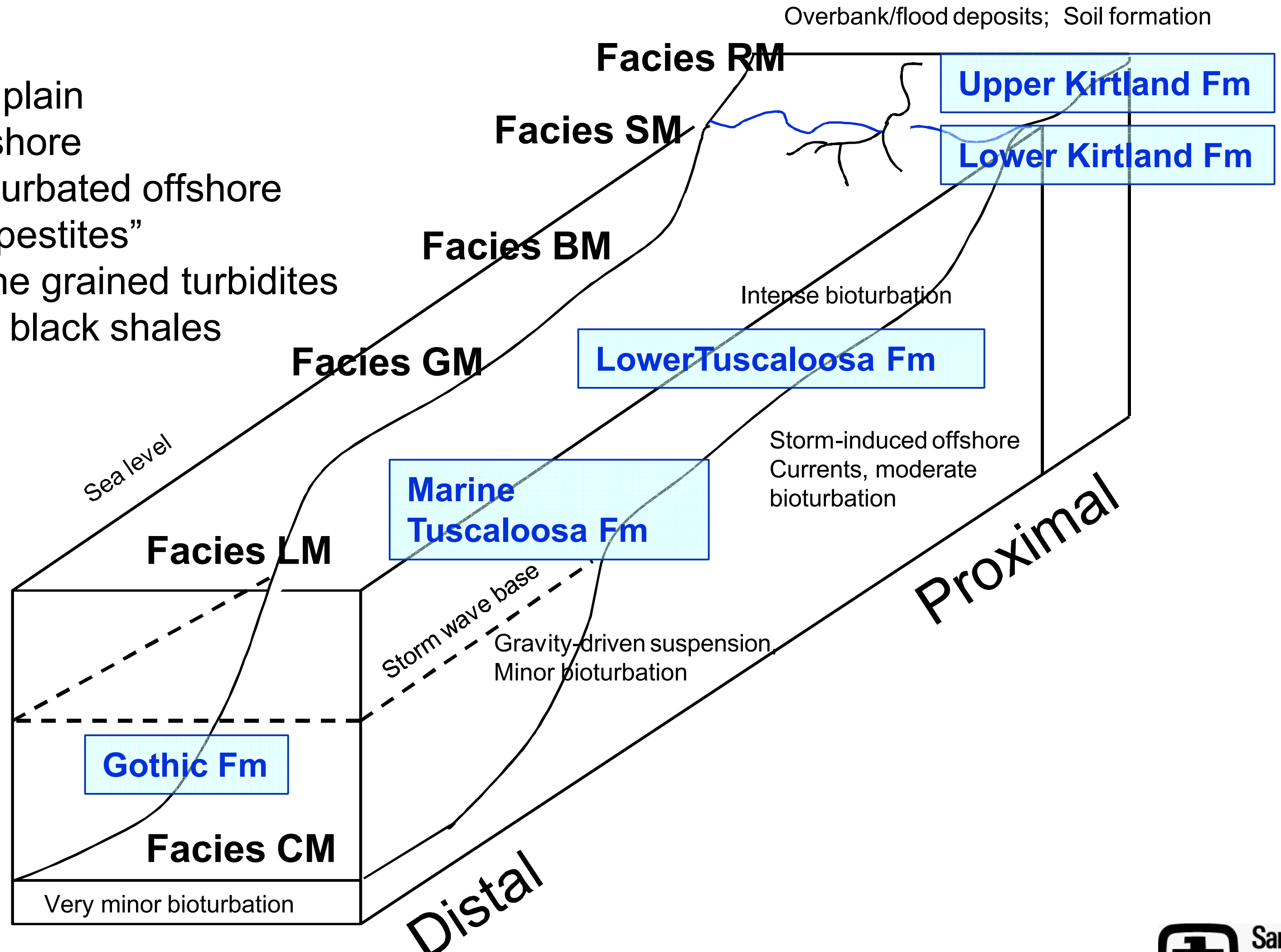


Source: Petrusak et al., 2009

A Word on Mud Depositional Environments & Facies

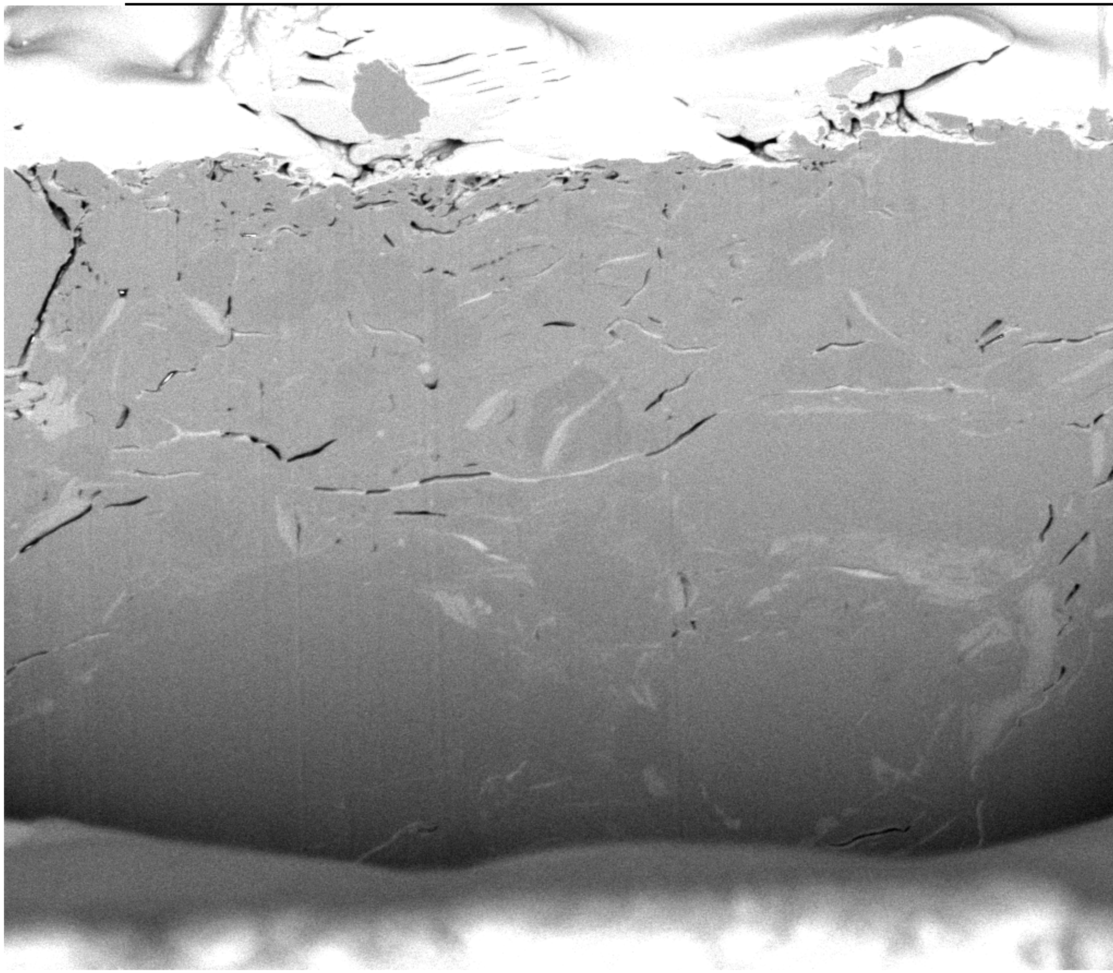
Facies

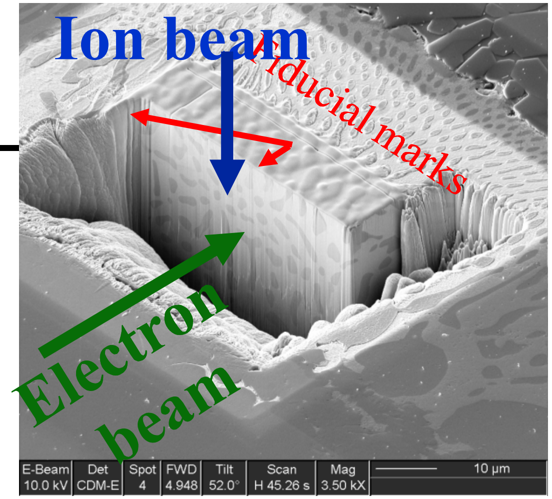
- **RM** – grey coastal plain
- **SM** – sandy near-shore
- **BM** - intensely bioturbated offshore
- **GM** – graded "tempestites"
- **LM** – laminated, fine grained turbidites
- **CM** – deep marine black shales

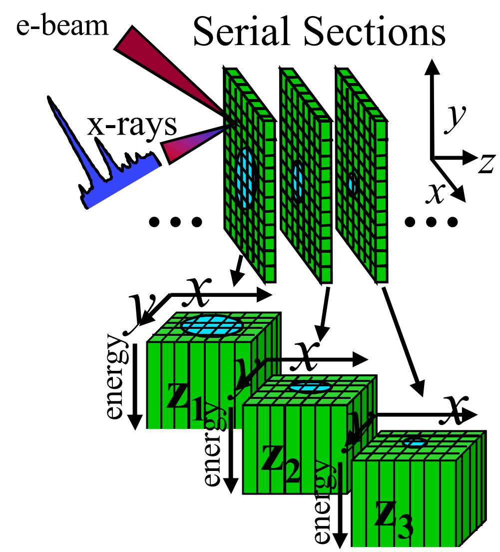


Simplified from Schieber, 1998

FIB/SEM Animation



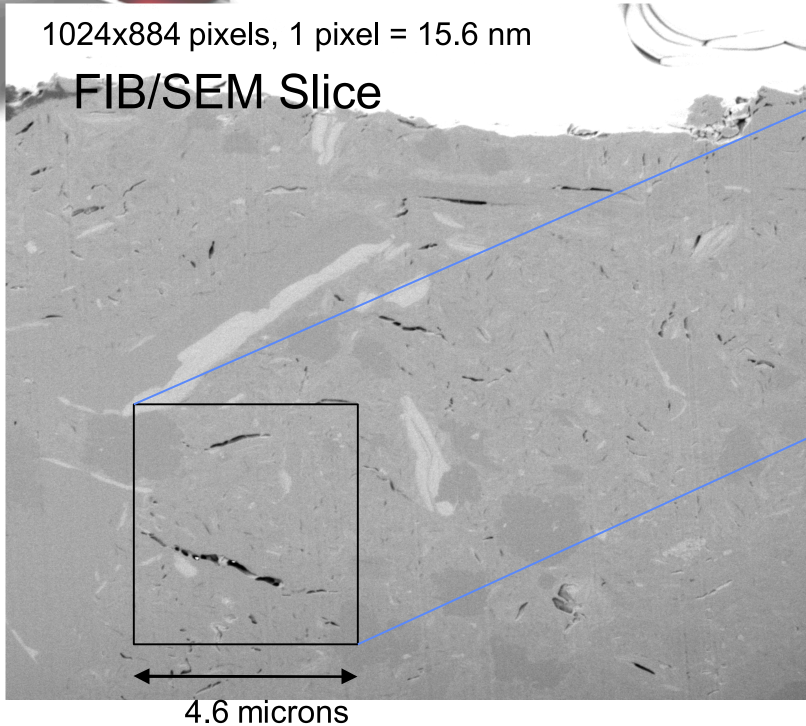


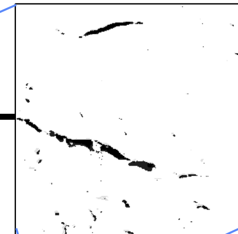


1024x884 pixels, 1 pixel = 15.6 nm, 400 slices at 25 nm per slice

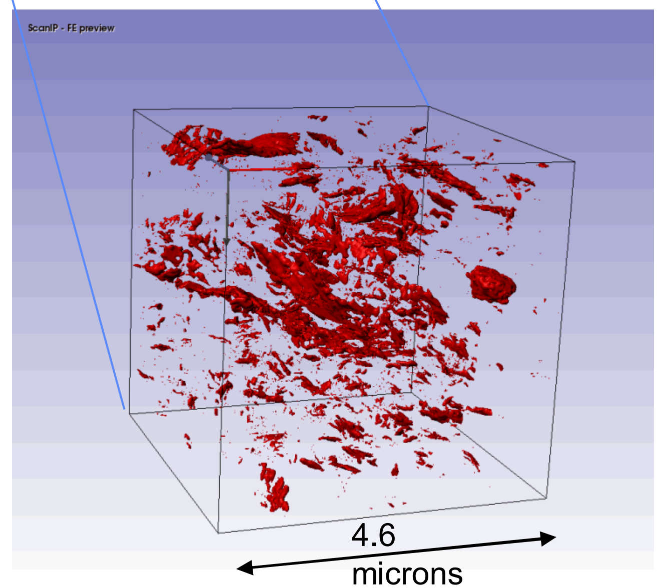
Lower Kirtland Shale, 2692 ft bgs

Upper Kirtland Shale @ 2049 ft bgs



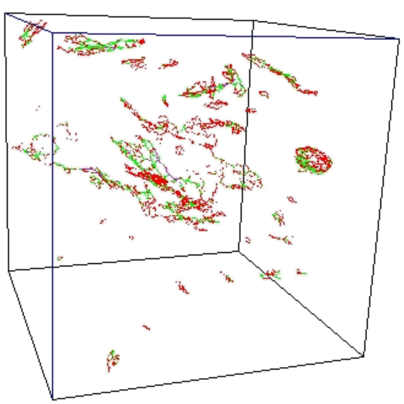


Registered, cropped, and thresholded slice (299x299 pixels)

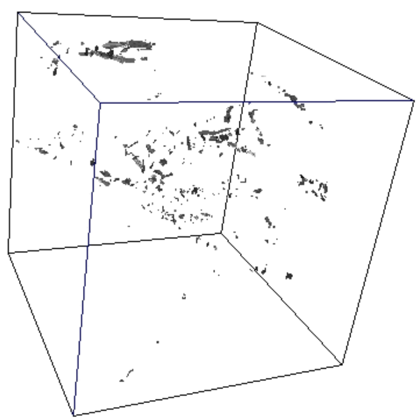


3D reconstructed pores

1.04% porosity
37% connected



Medial Axes of Pore Networks



Pore throats

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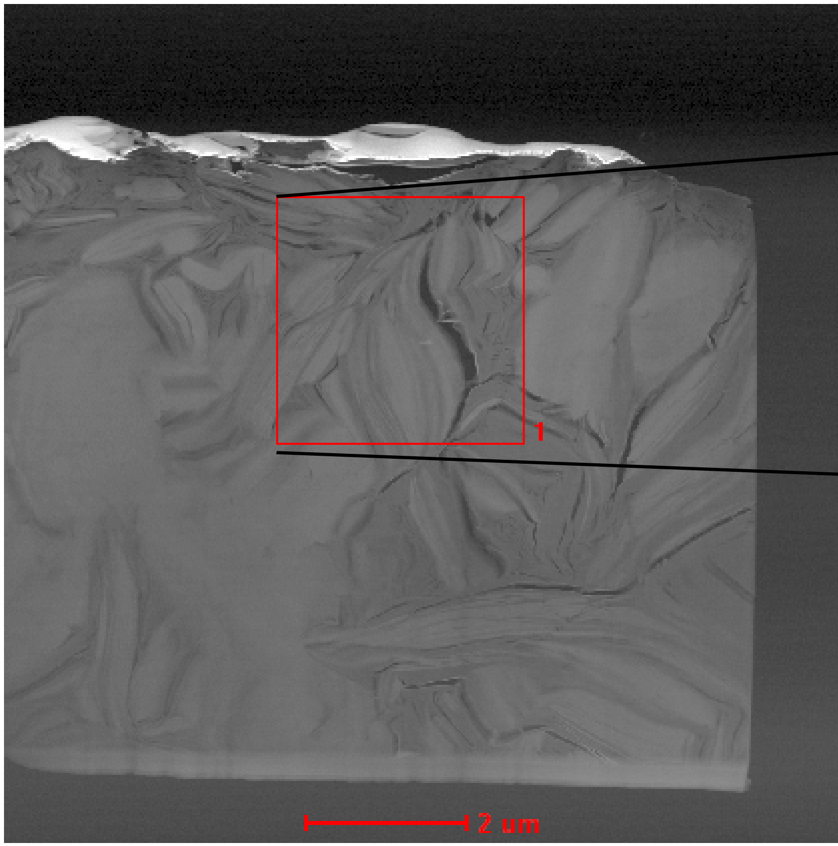
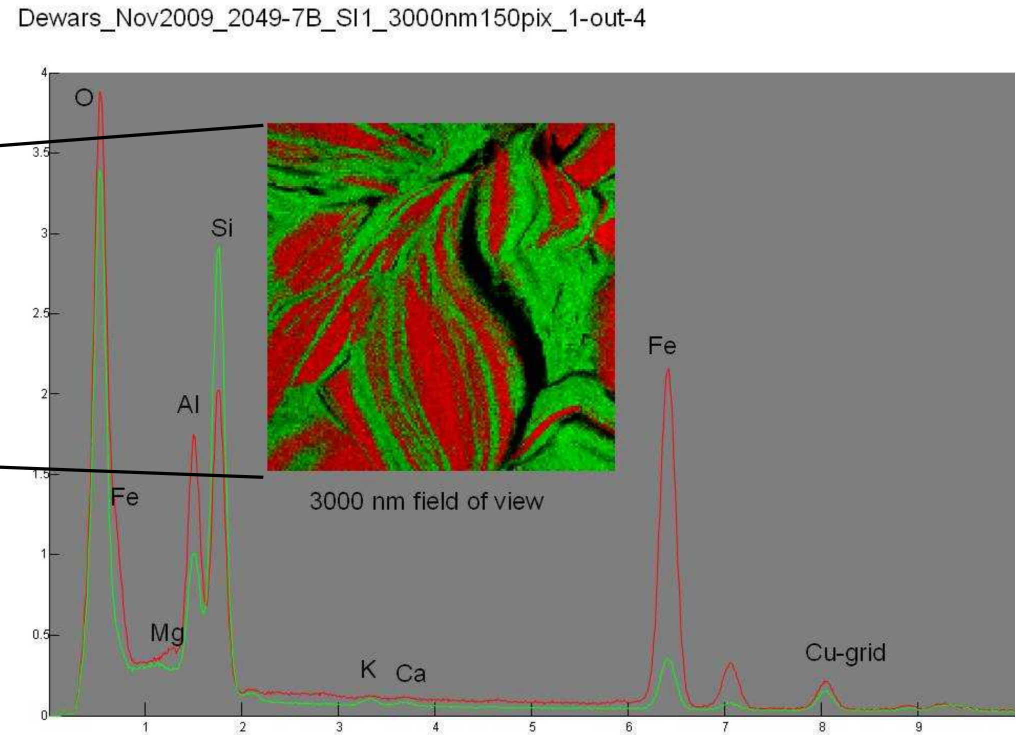
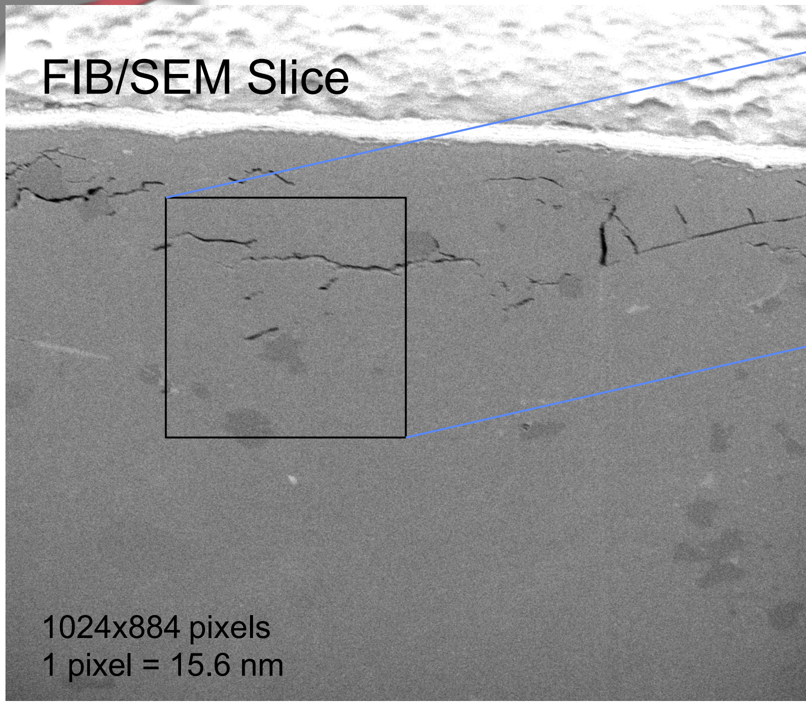
Upper Kirtland Shale TEM-EDS

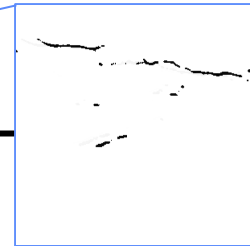




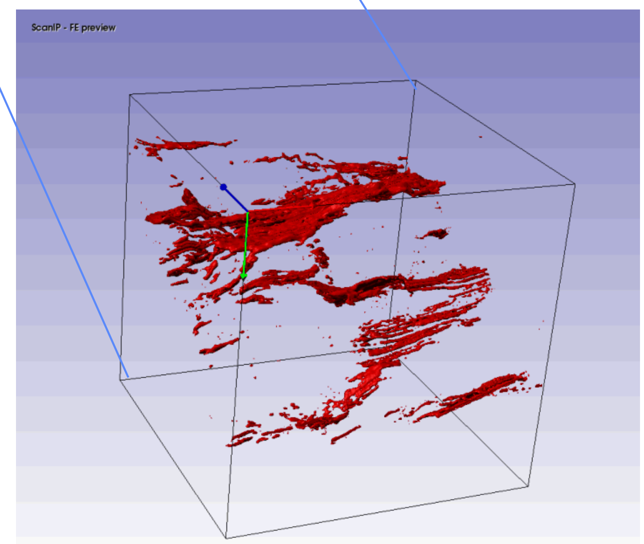
Compacted clay floccules
of Scheiber and ???

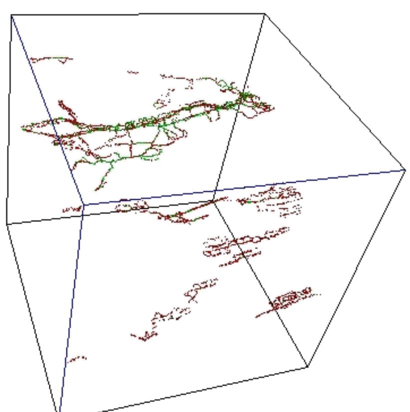
Lower Kirtland Shale @ 2692 ft bgs



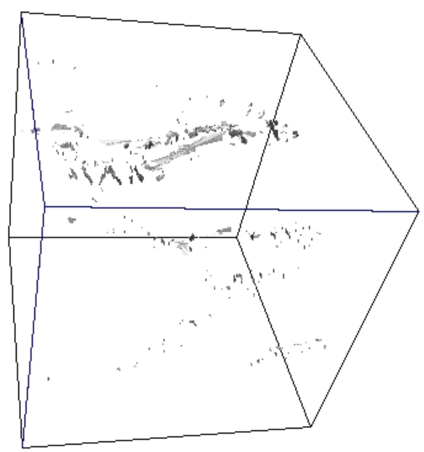


Registered, cropped, and thresholded slice (299x299 pixels)





Medial Axes of Pore Networks



Pore throats

Porosity = 0.722%
Connectivity = 28%

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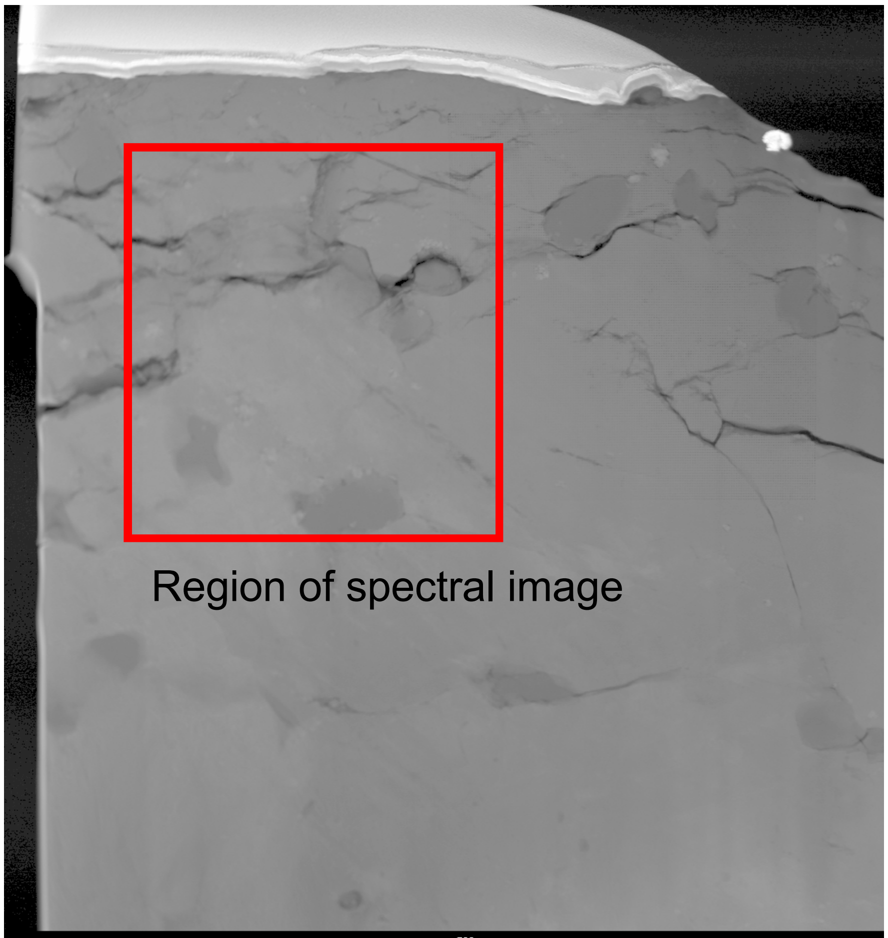
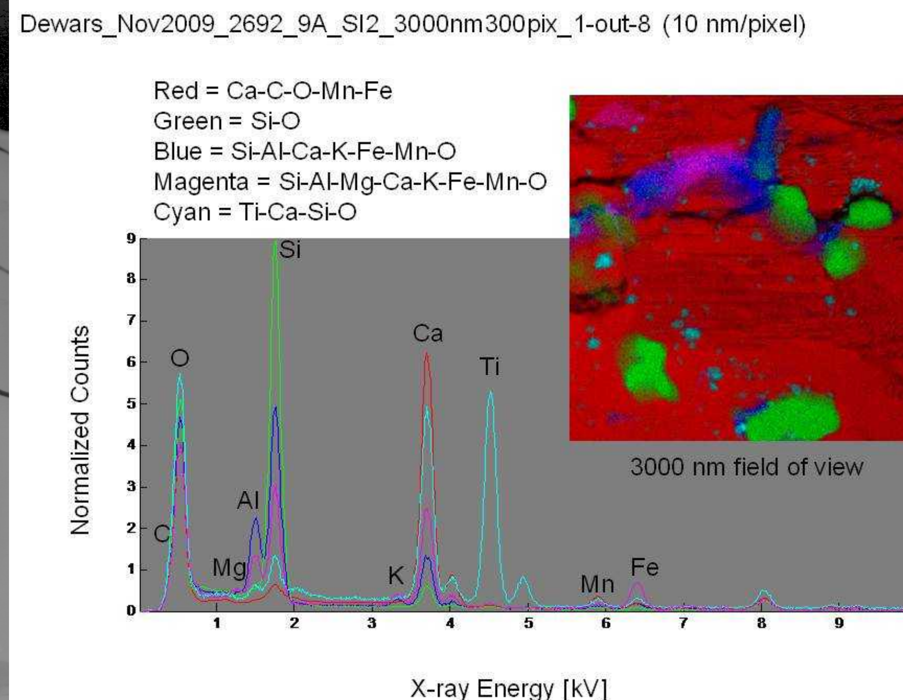
Lower Kirtland Shale @ 2692 ft bgs





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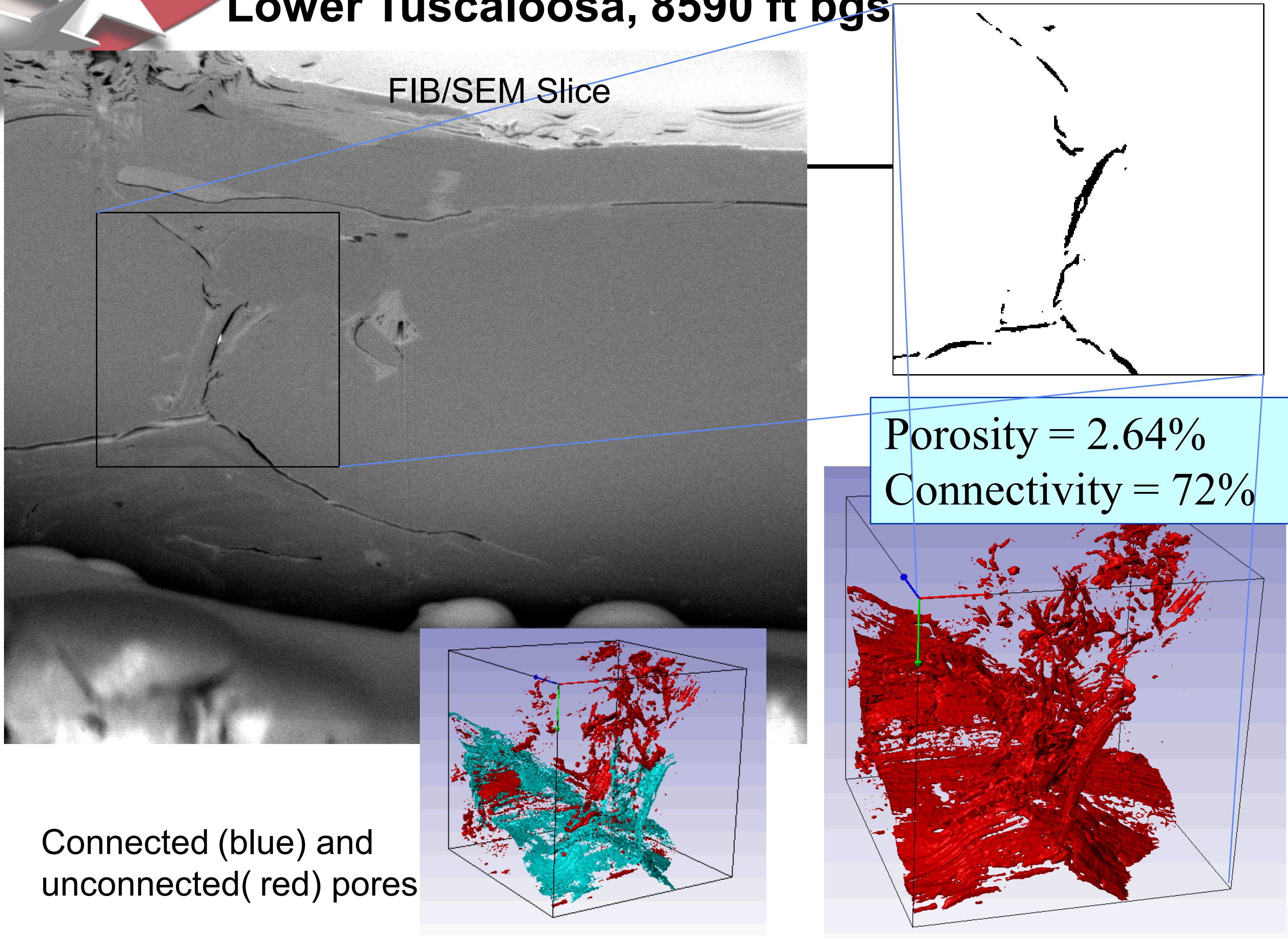
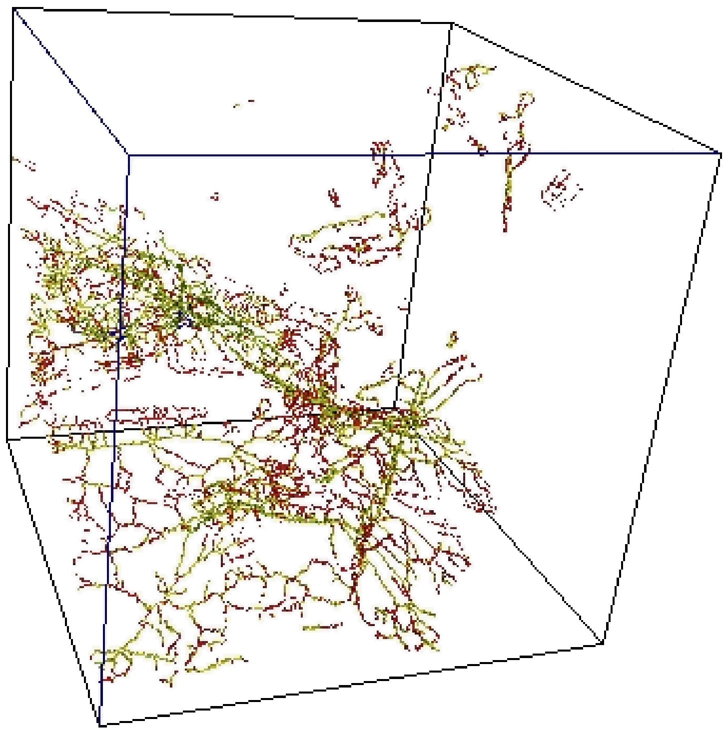
Lower Tuscaloosa, 8590 ft bgs



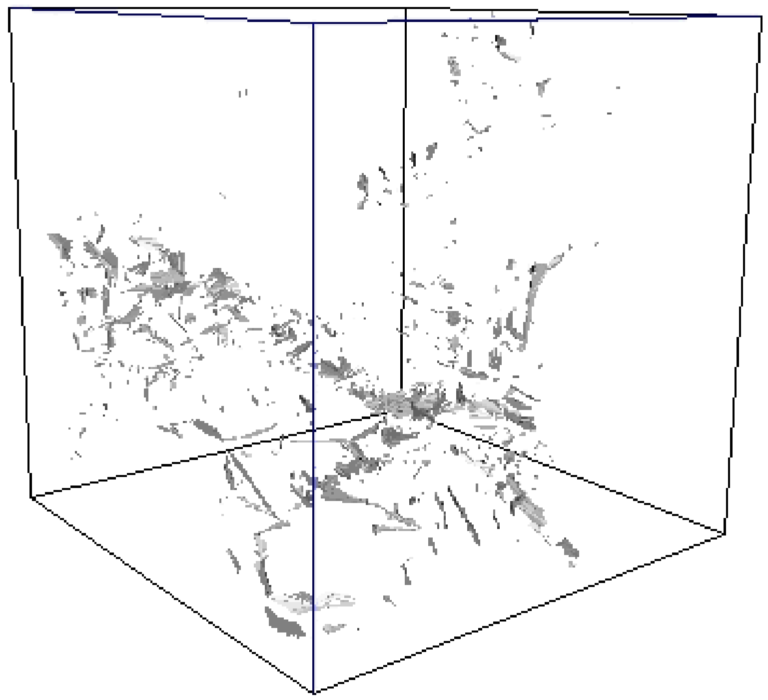
Porosity = 2.64%
Connectivity = 72%

Connected (blue) and unconnected(red) pores

Lower Tuscaloosa, 8590 ft bgs

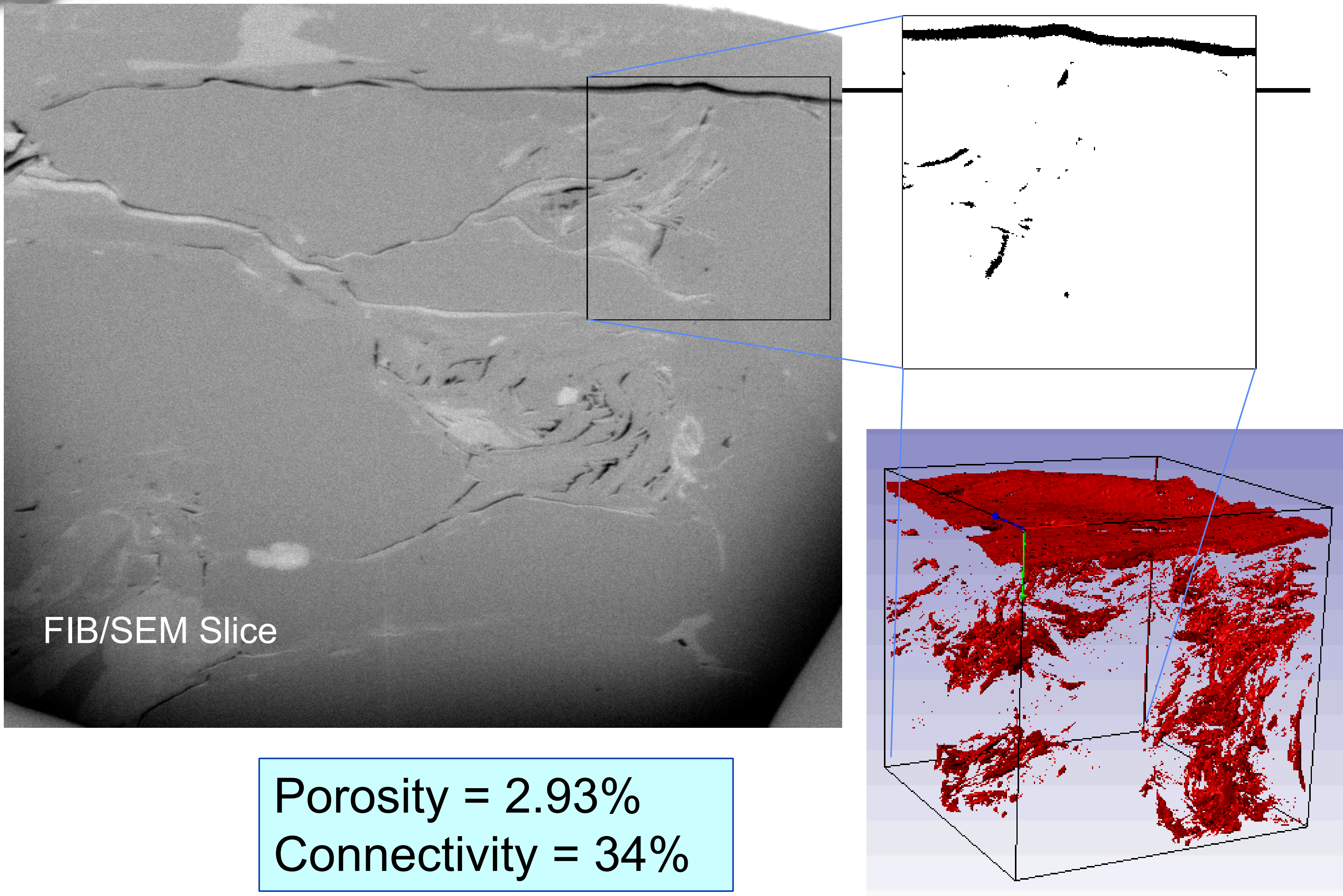


Medial Axes of Pore Networks



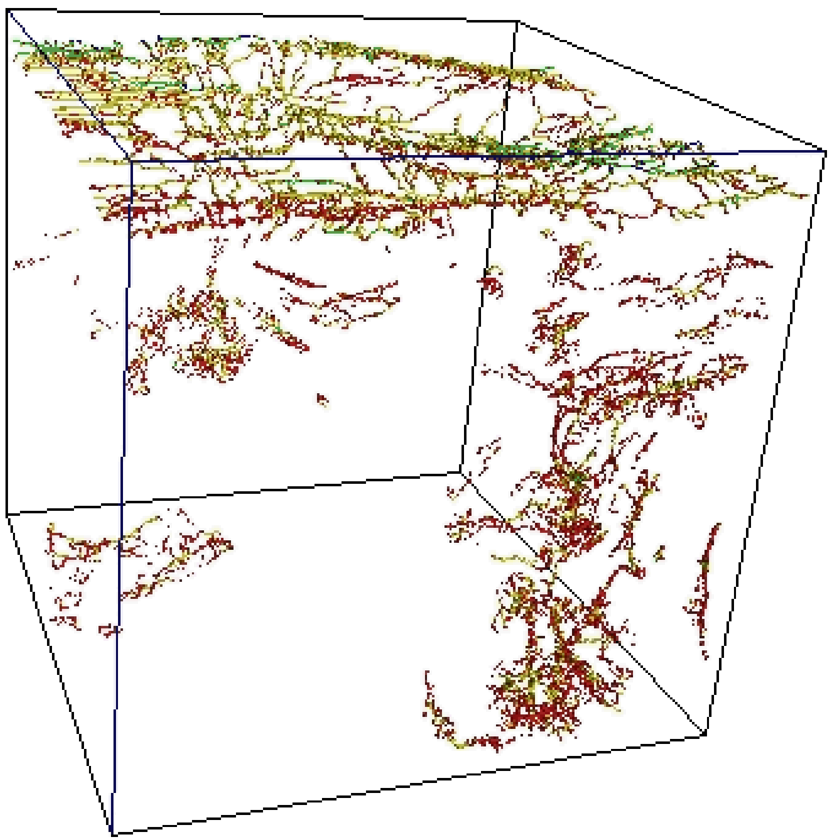
Pore throats

Lower Tuscaloosa @ 8590 ft bgs

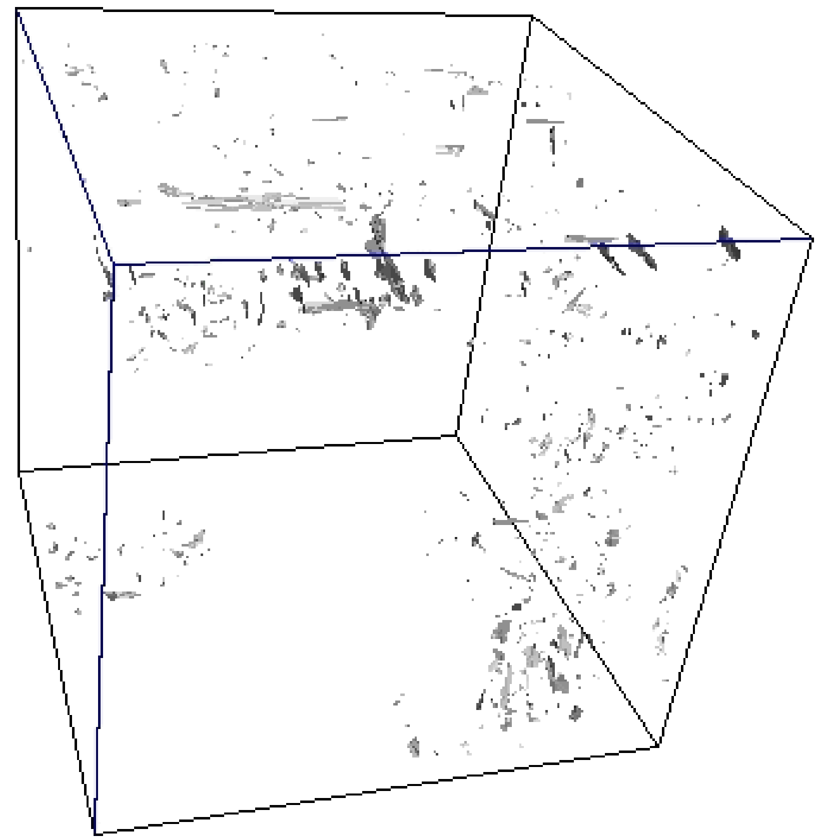


Porosity = 2.93%
Connectivity = 34%

Lower Tuscaloosa @ 8590 ft bgs



Medial Axes of Pore Networks



Pore throats

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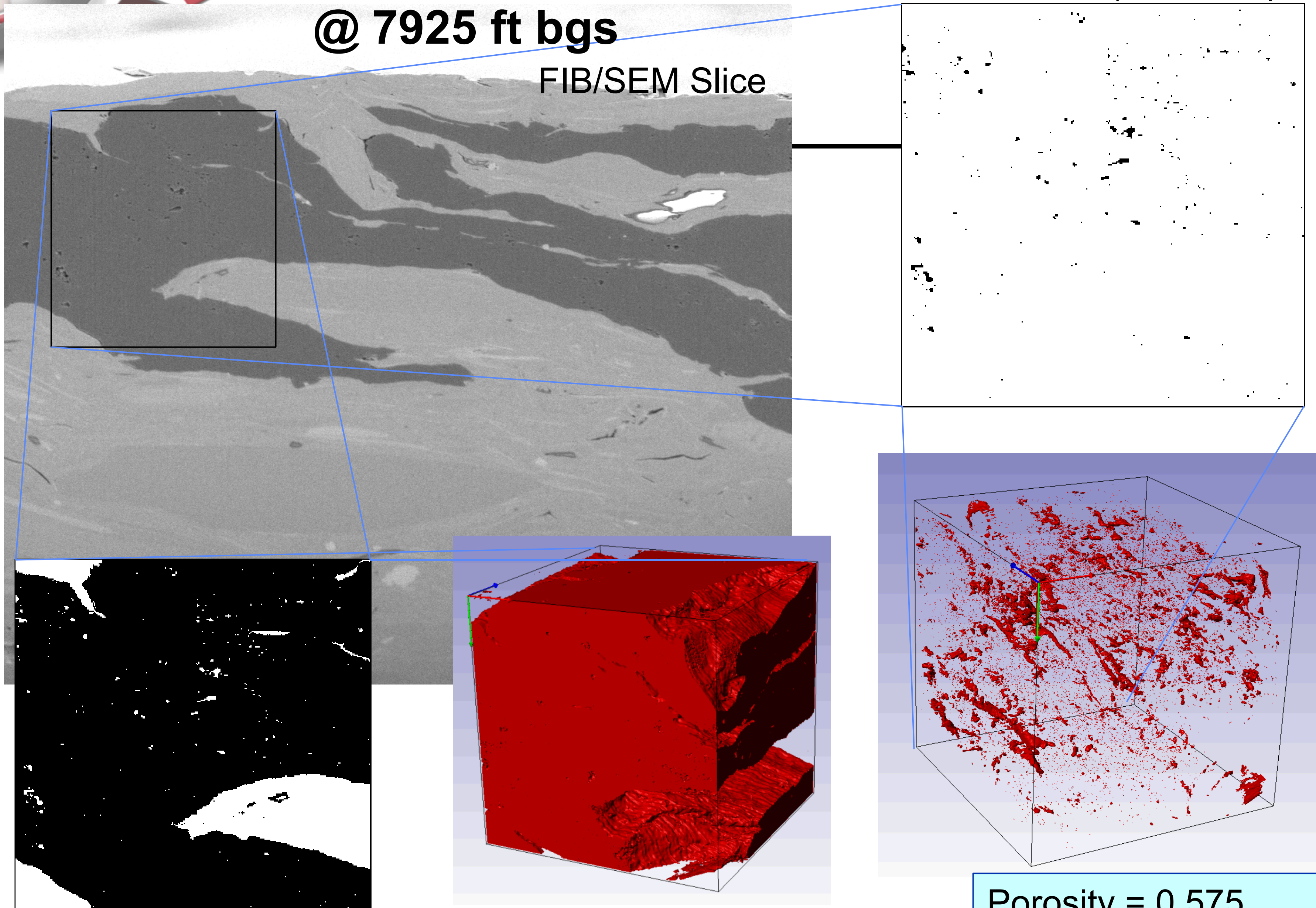
Marine Tuscaloosa @ 7925 ft bgs

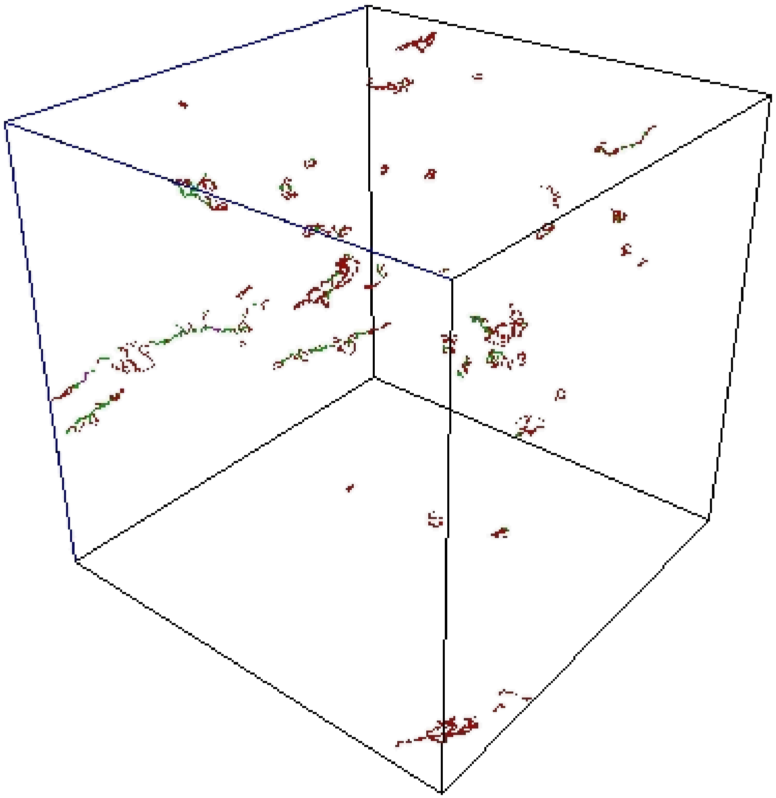
Registered, cropped, and thresholded slice (299x299 pixels)



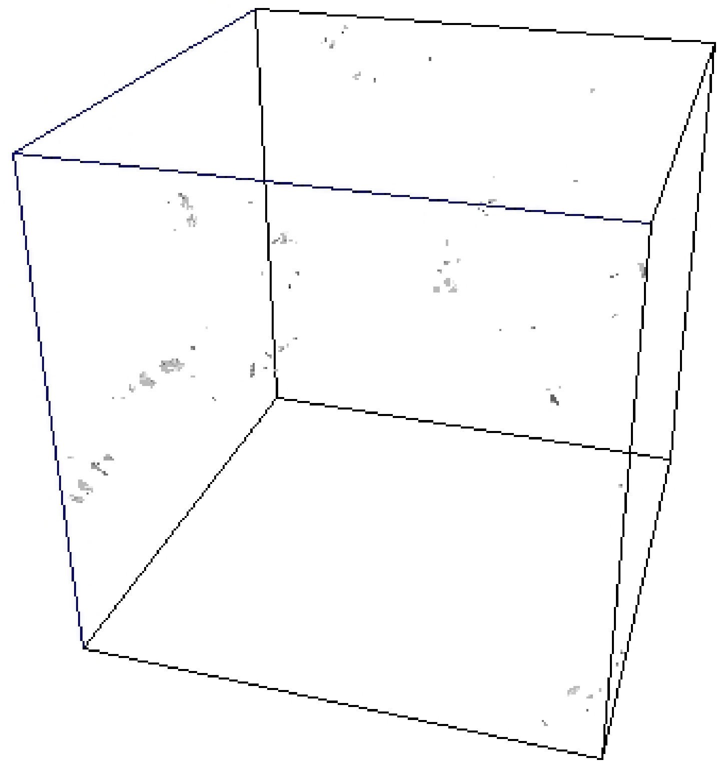
Organic phase vol. fraction = 85.01%

Porosity = 0.575
Connectivity = 62%

Marine Tuscaloosa @ 7925 ft bgs

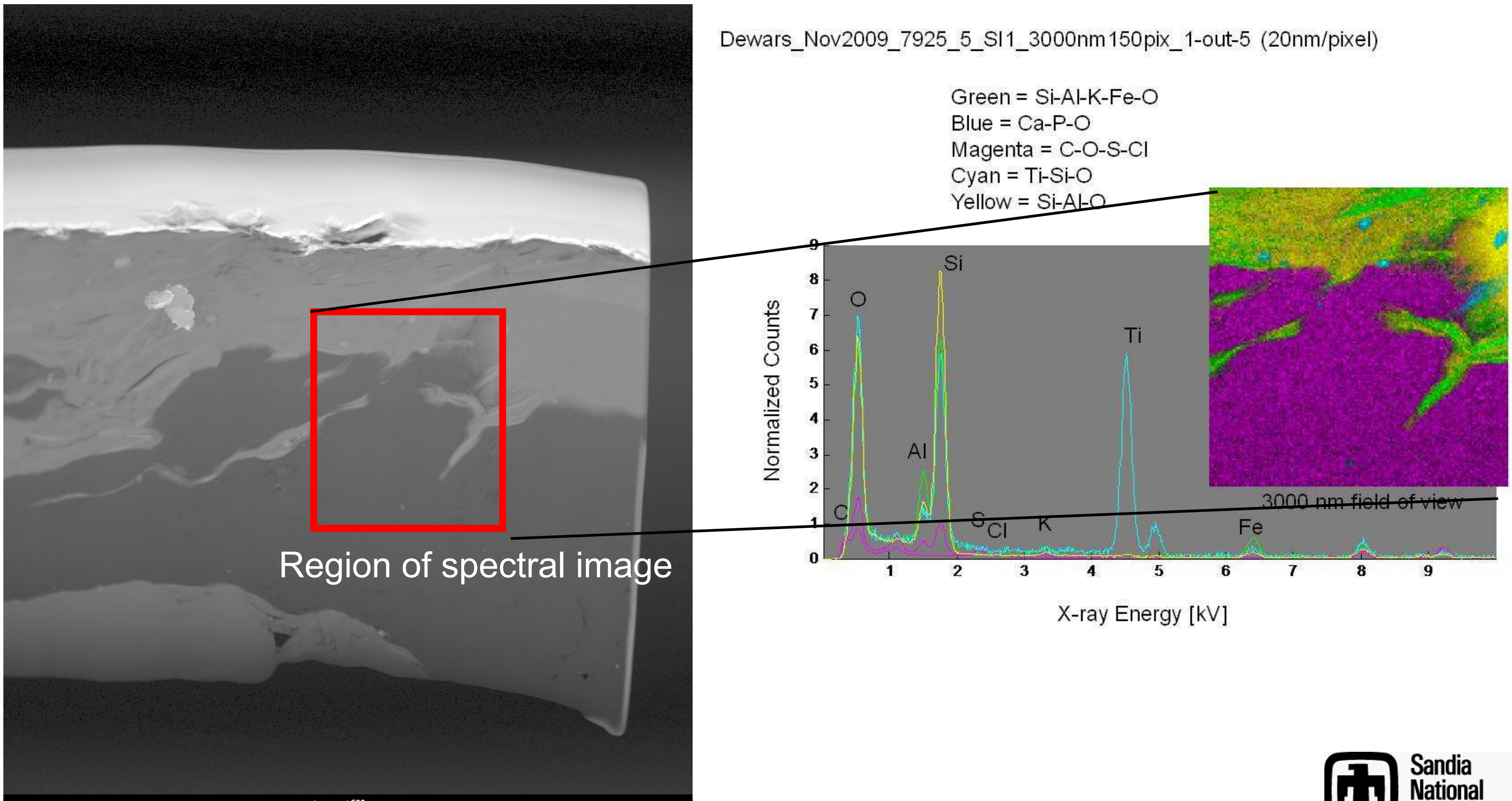


Medial Axes of Pore Networks

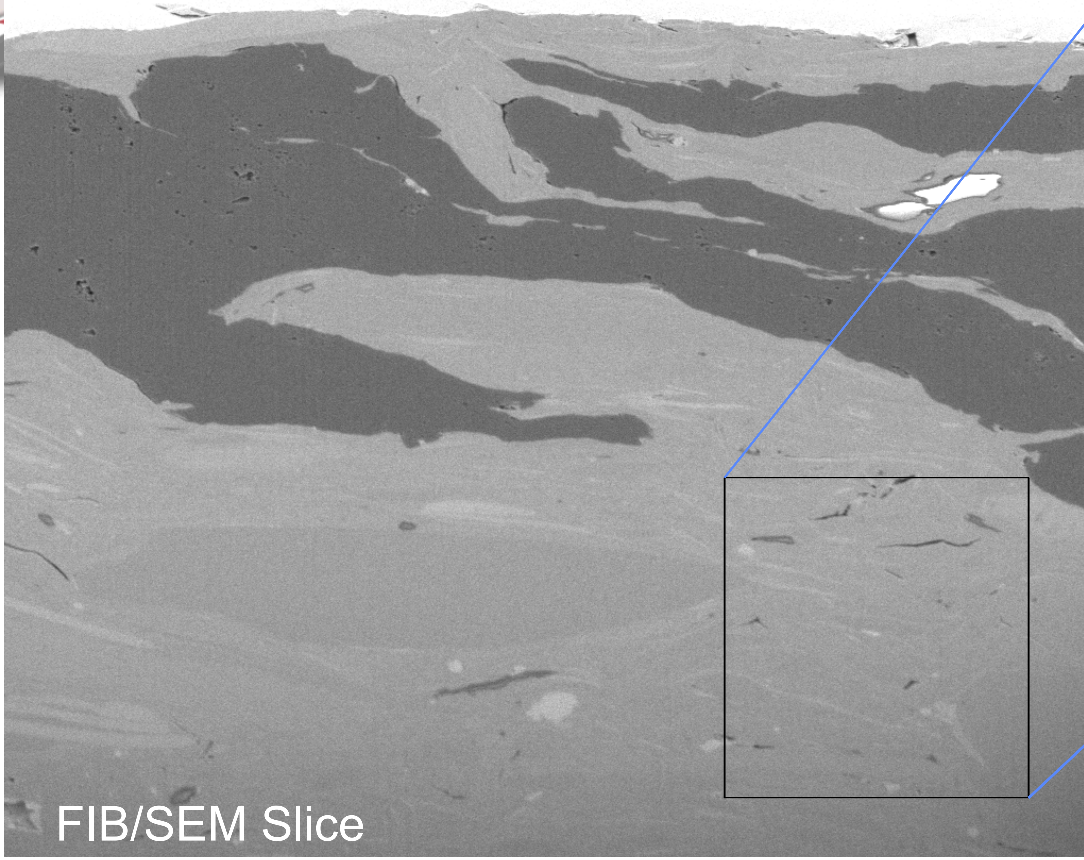


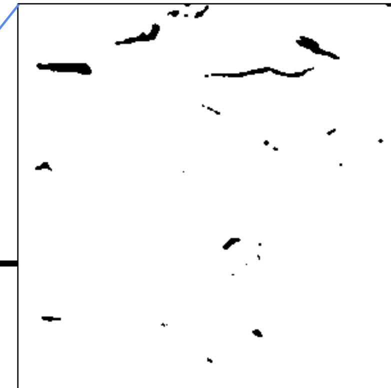
Pore throats

Marine Tuscaloosa @ 7925 ft bgs

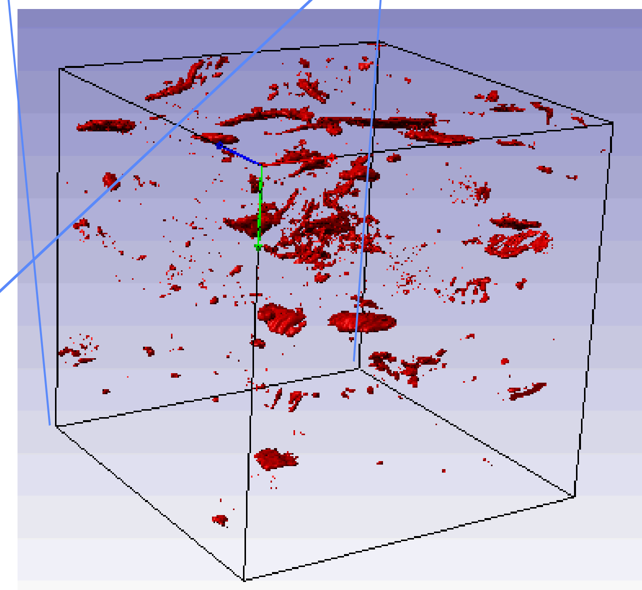


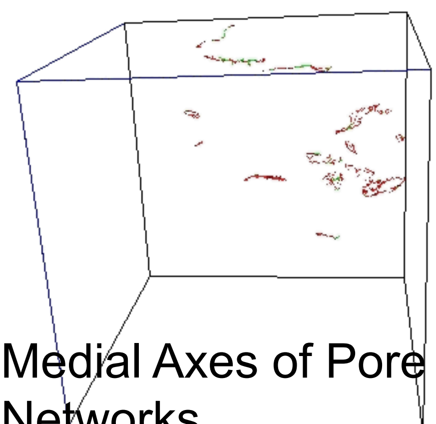
Marine Tuscaloosa @ 7925 ft bgs

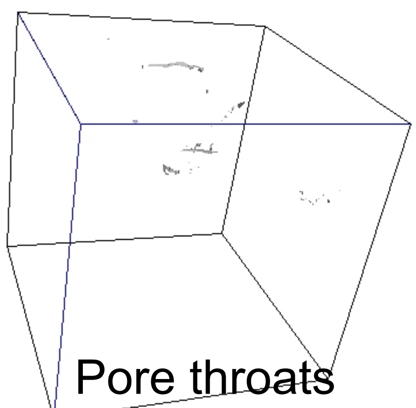




Registered, cropped, and thresholded slice (299x299 pixels)







Porosity = 0.47%
Connectivity = 52%

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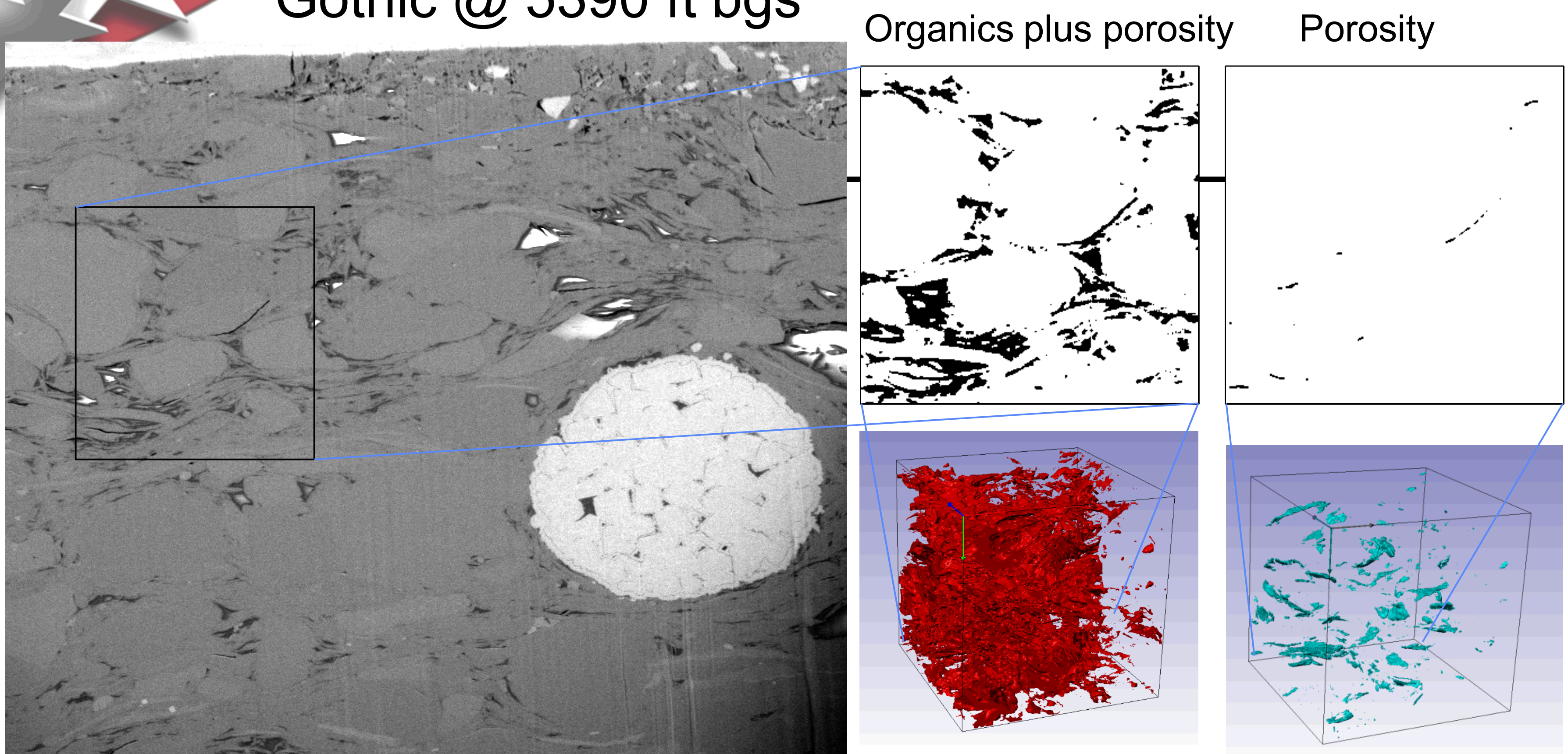
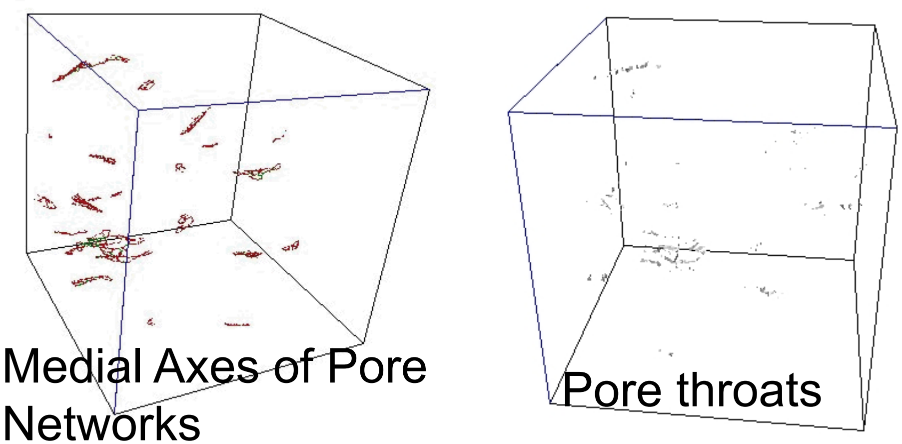
Gothic @ 5390 ft bgs

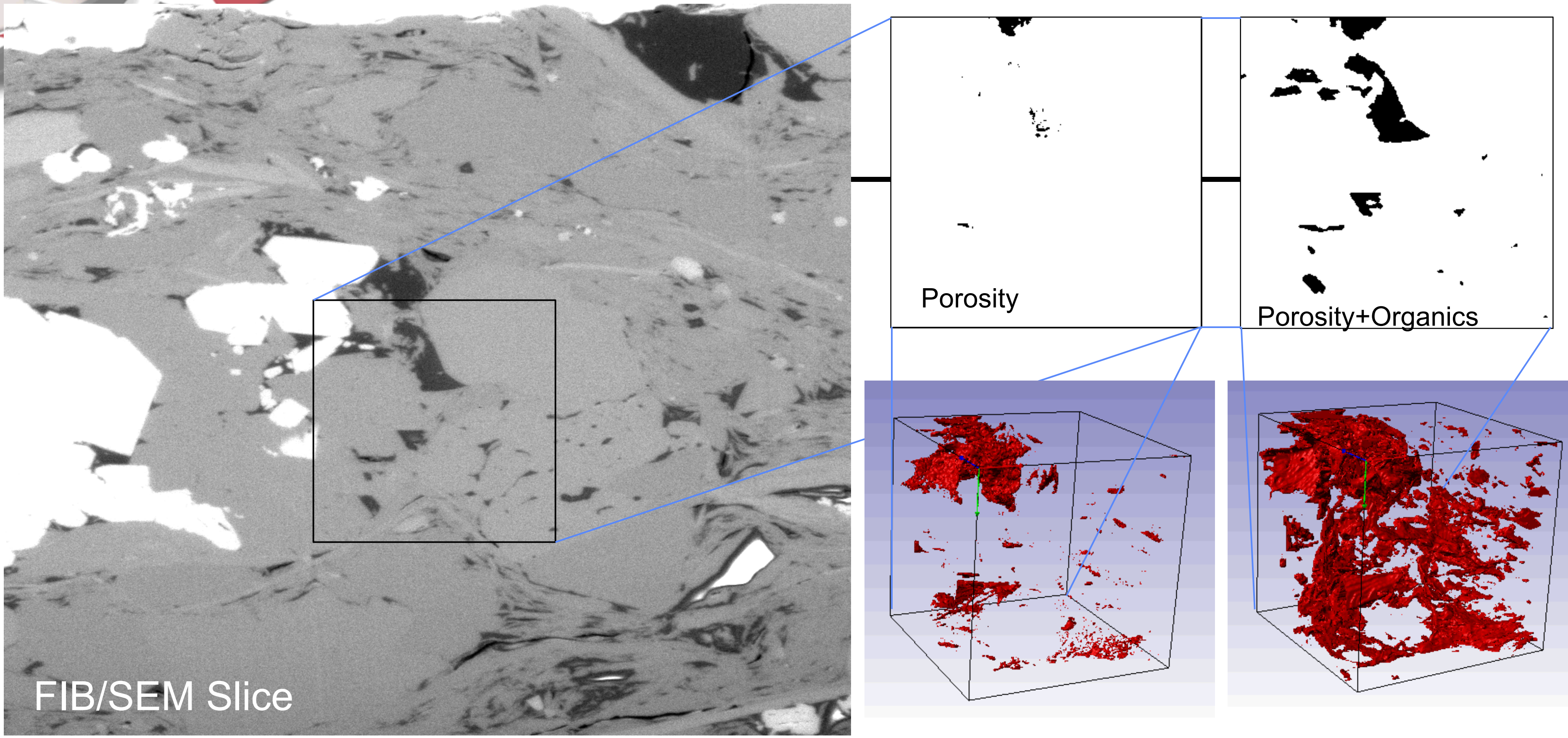


15.2% Vol. Fraction

0.42 % Porosity
Connectivity = 44%

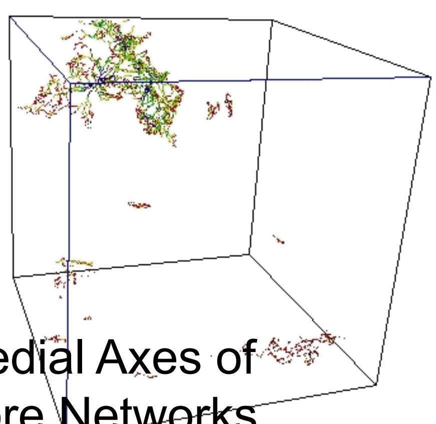


Gothic @ 5390 ft bgs

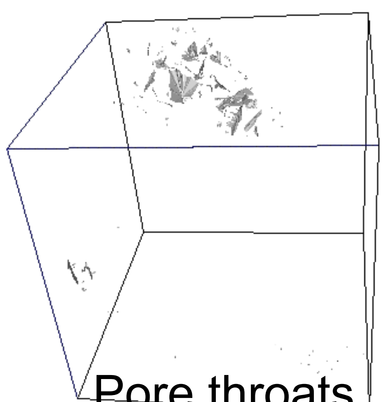


Porosity = 1.33%

Vol. % = 5.59



Medial Axes of Pore Networks



Pore throats

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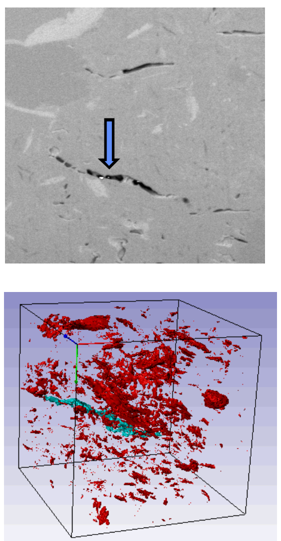
Shale “Nano” Pore Networks

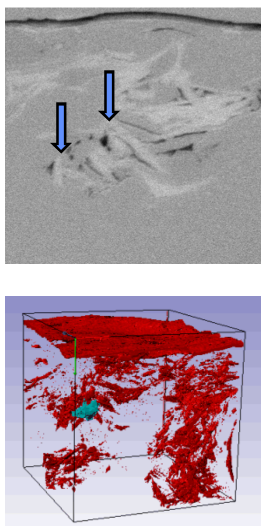
*Type I**

Elongated pores between similarly oriented clay sheets1



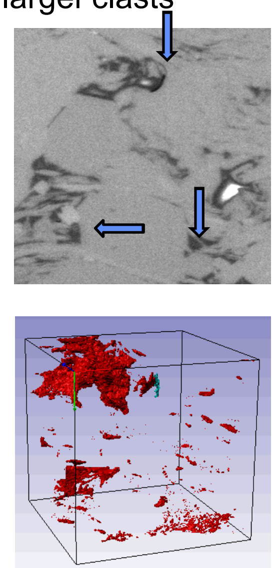
*Type II**

Crescent-shaped pores in “saddle reefs” of folded clay sheets



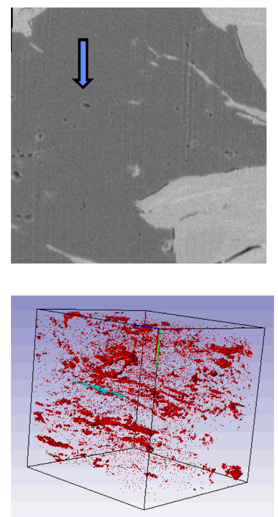
*Type III**

“Jagged” pores in compaction shadows around larger clasts



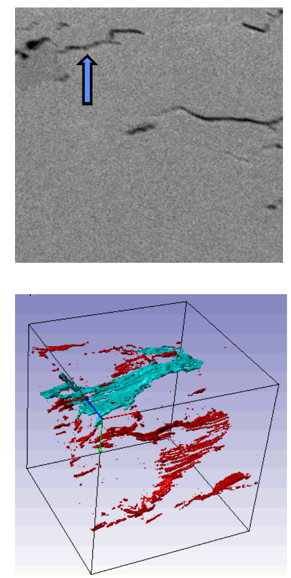
Type IV

Tubular pores in “foamy” organics



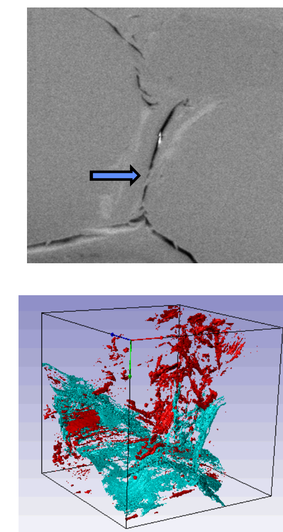
Type V

Diagenetic; clay seams or micro-stylolitic; grain dissolution, etc.



Type VI

Microfracture related; may or may not be induced



← Remnant Pore Types →

← Secondary Pore Types →

*As proposed by Desbois et al., 2009

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Pore Statistics: Lower Tuscaloosa

Mercury Porosimetry: D = 2.86

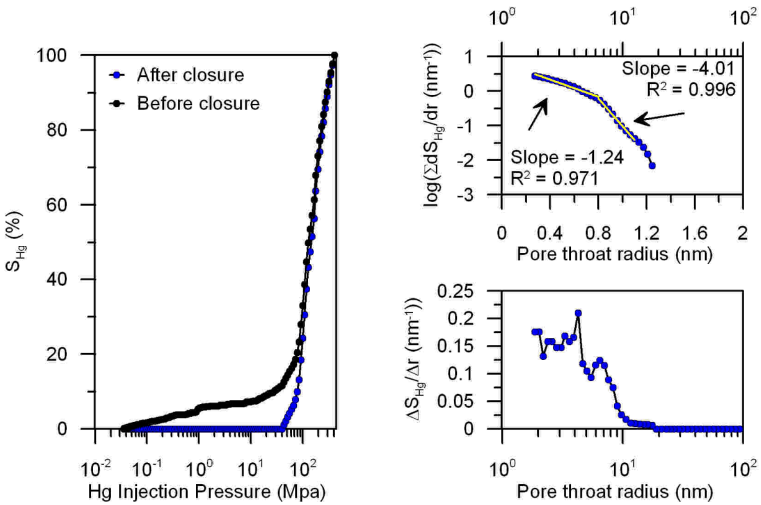
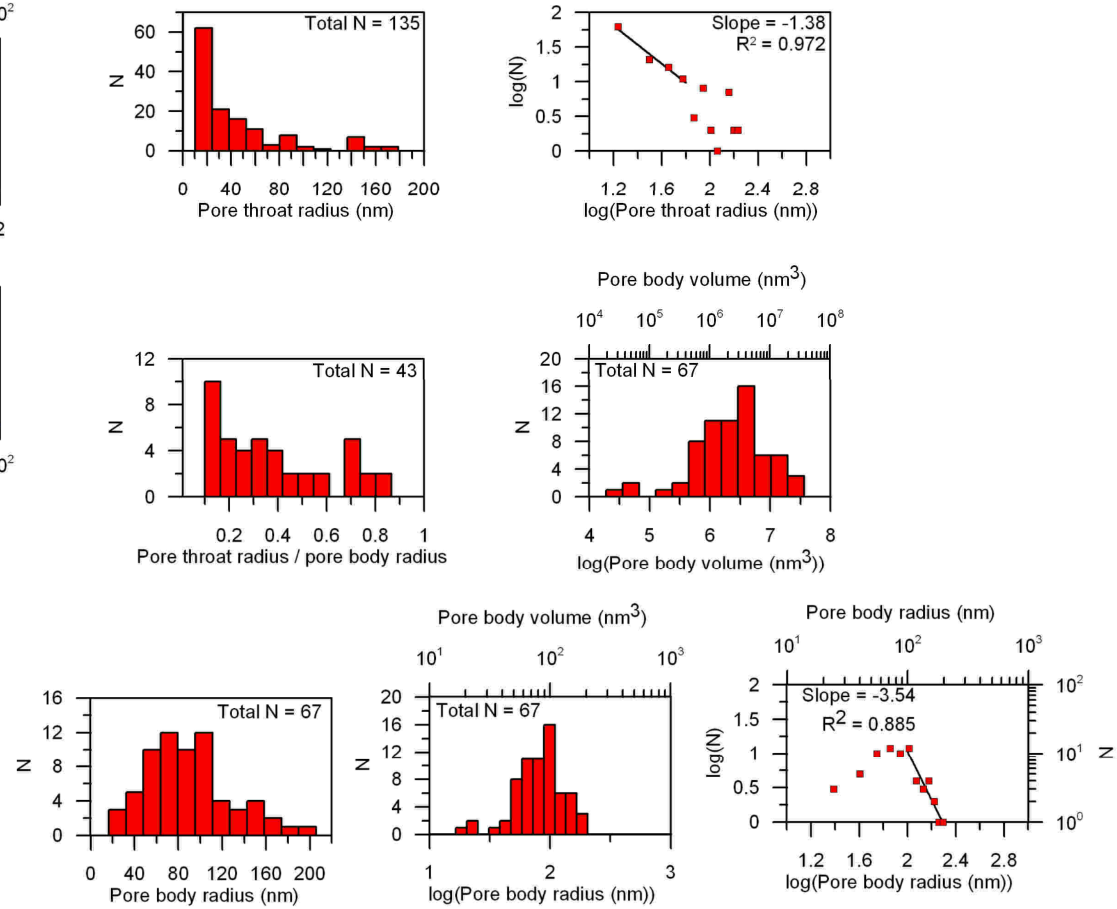


Image-based pore distributions: D = 2.54



Number Distribution

$$\text{Log } f(r) = -(D+1)\text{ Log } r_{\text{pore volume}}$$

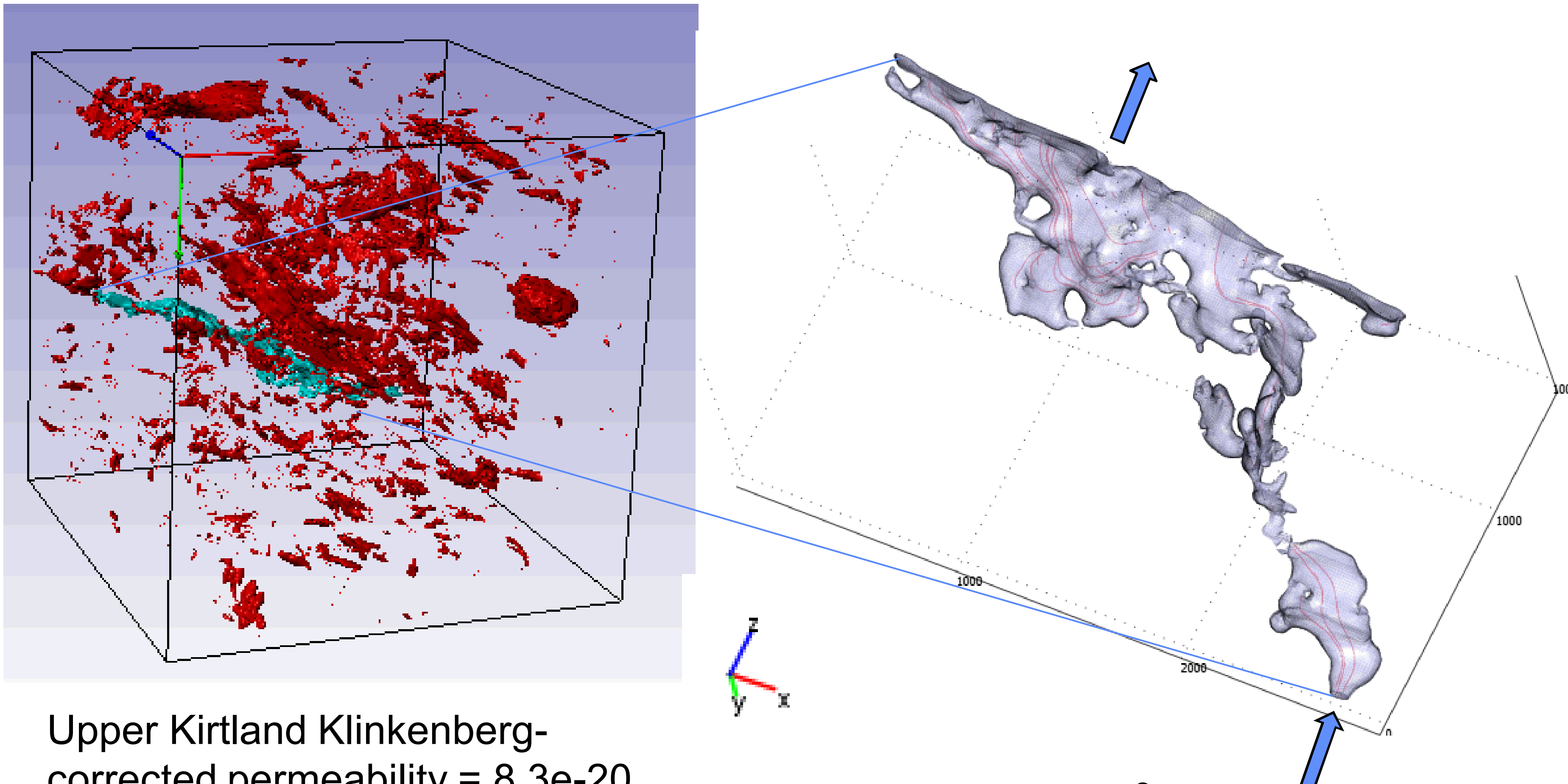
Mercury Intrusion Volume

$$\text{Log } V_{Hg}(r) = (3-D)\text{ Log } r_{\text{pore throat}}$$

Bartoli et al., 1990; Han et al., 2006

CFD Simulations

Type I Pore; Upper Kirtland Shale @ 2049 ft bgs



Upper Kirtland Klinkenberg-corrected permeability = 8.3e-20 from 5 measurements from 2048 – 2067 feet bgs

$k_{pore} = 1.0\text{e-}19\ m^2$

$k_{meas} = 7.2\text{e-}20\ m^2$

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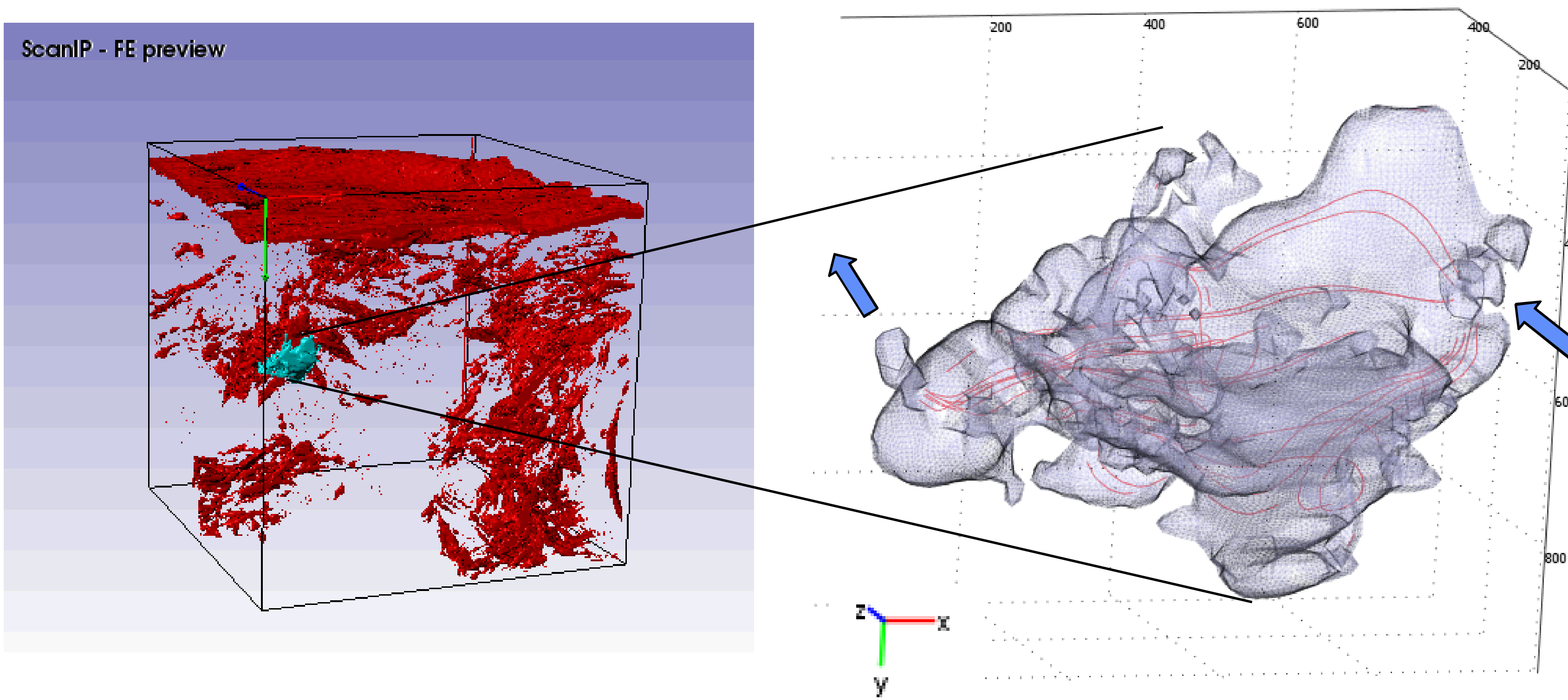
CFD Simulations

Type II Pore: Lower Tuscaloosa @ 8590 ft bgs



Lower Tuscaloosa Klinkenberg-corrected permeability = 2.8e-17 from 3 measurements from 8584 to 8590 feet bgs

k_{pore} = 8.7e-17 m^2

k_{meas} =6.8e-17 m^2

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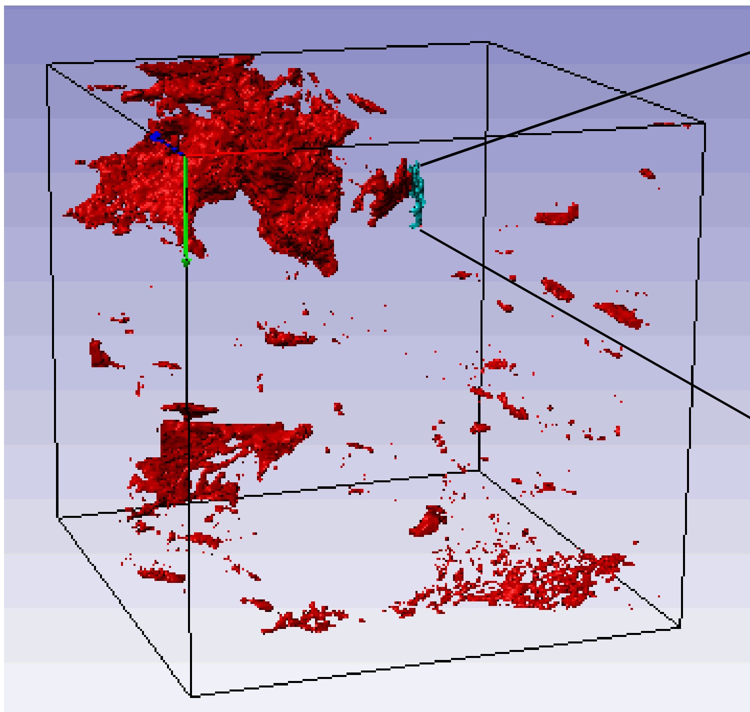
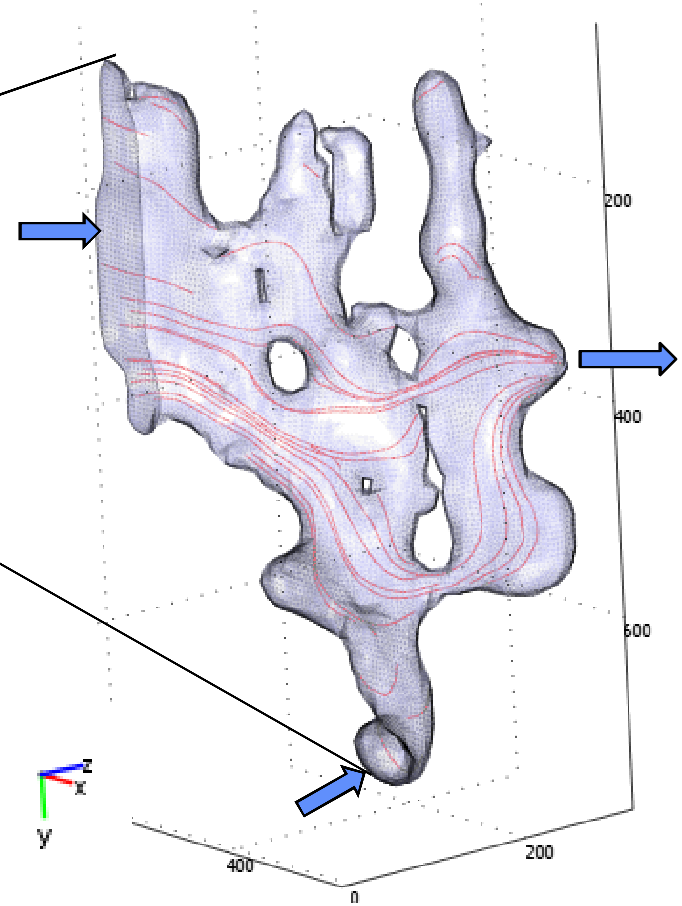
CFD Simulations

Type III Pore: Gothic Shale @ 5390 ft bgs



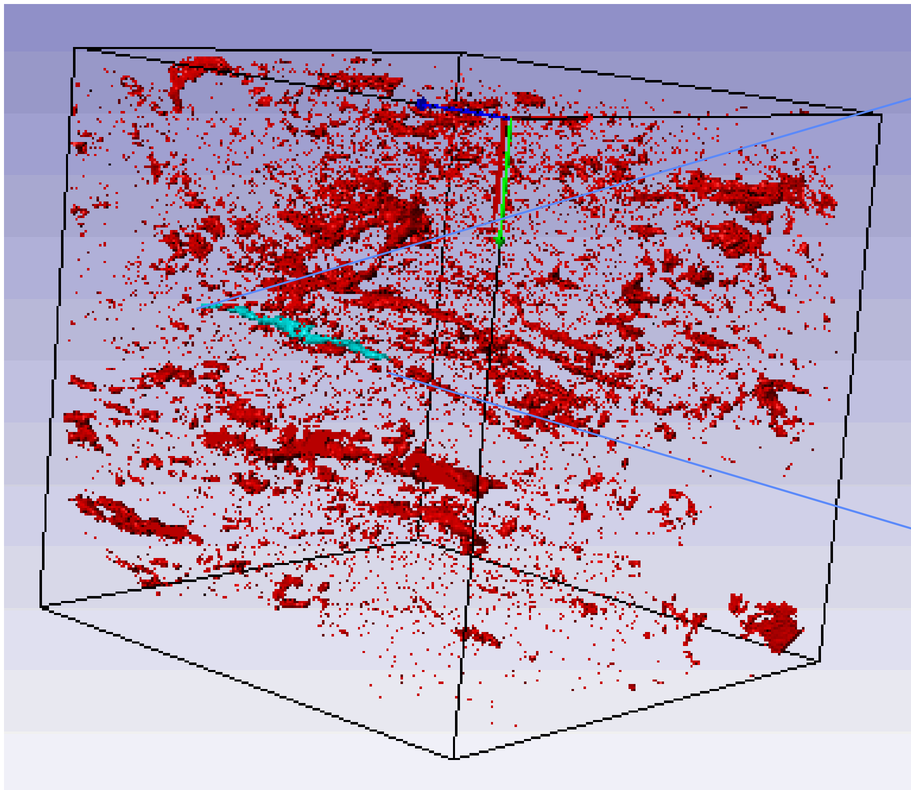


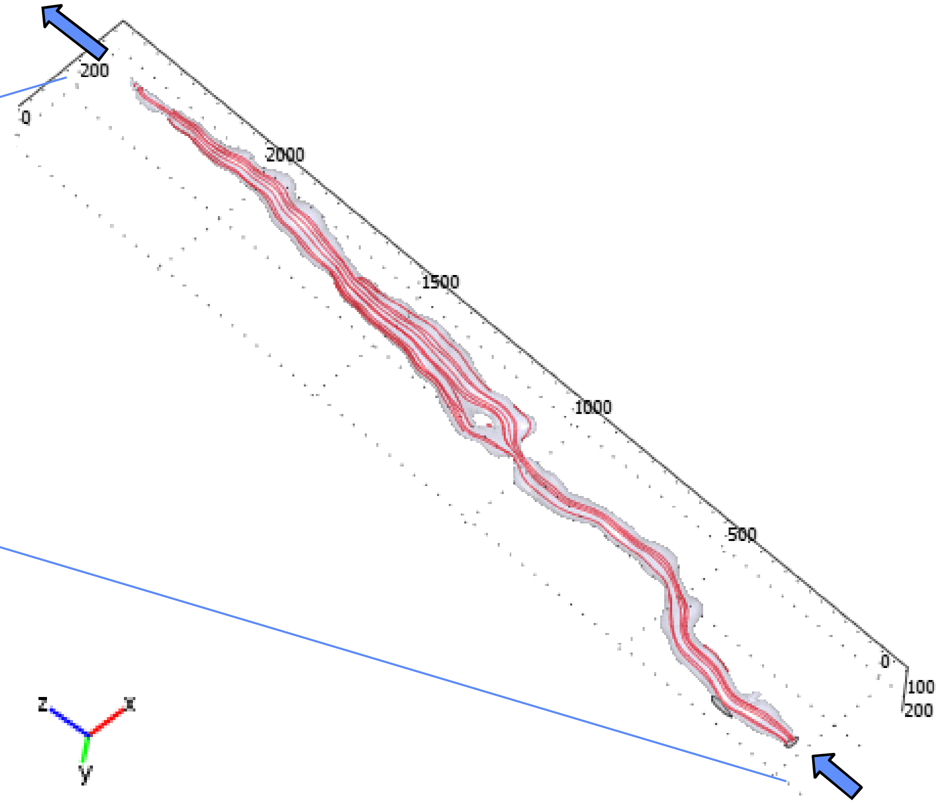
Gothic Klinkenberg-corrected permeability = 1.4e-19 from 4 measurements from 5379 to 5391 feet bgs

k_{pore} = 2.1e-17 m^2

k_{meas} =1.3e-19 m^2

Type IV Pore: Marine Tuscaloosa @ 7925 ft bgs





Marine Tuscaloosa horizontal Klinkenberg-corrected permeability = 1.5e-18 m^2 from 6 measurements from 7818 to 7934 feet bsg

k_{pore} = 4.5e-18 m^2

k_{meas} =9.9e-20 m^2

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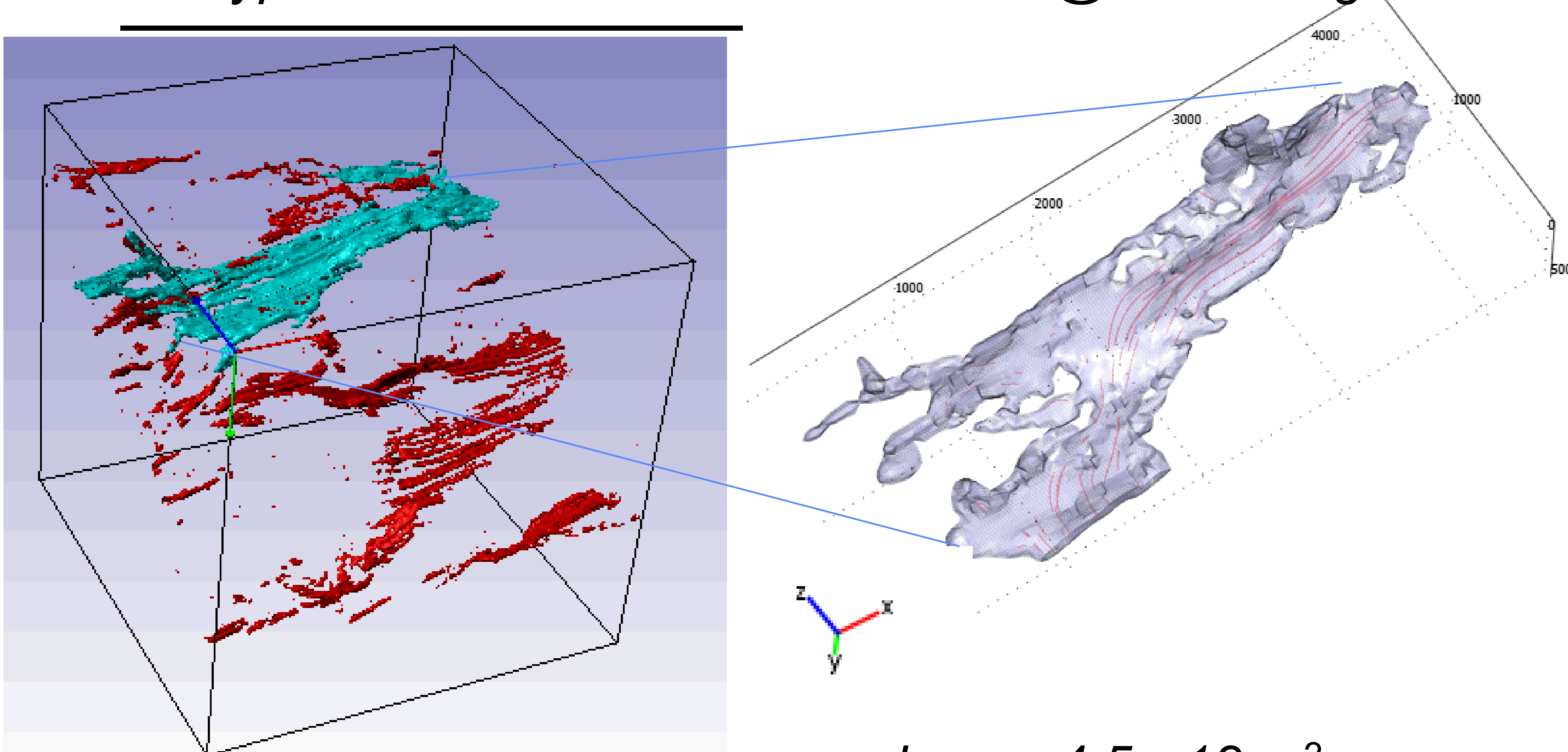
CFD Simulations

Type V Pore: Lower Kirtland Shale @ 2692 ft bgs



Lower Kirtland horizontal Klinkenberg-corrected permeability = 8.1e-20 m^2 from 2 measurements from 2692 to 2697 feet bgs

k_{pore} = 4.5e-18 m^2

k_{meas} =7.9e-20 m^2

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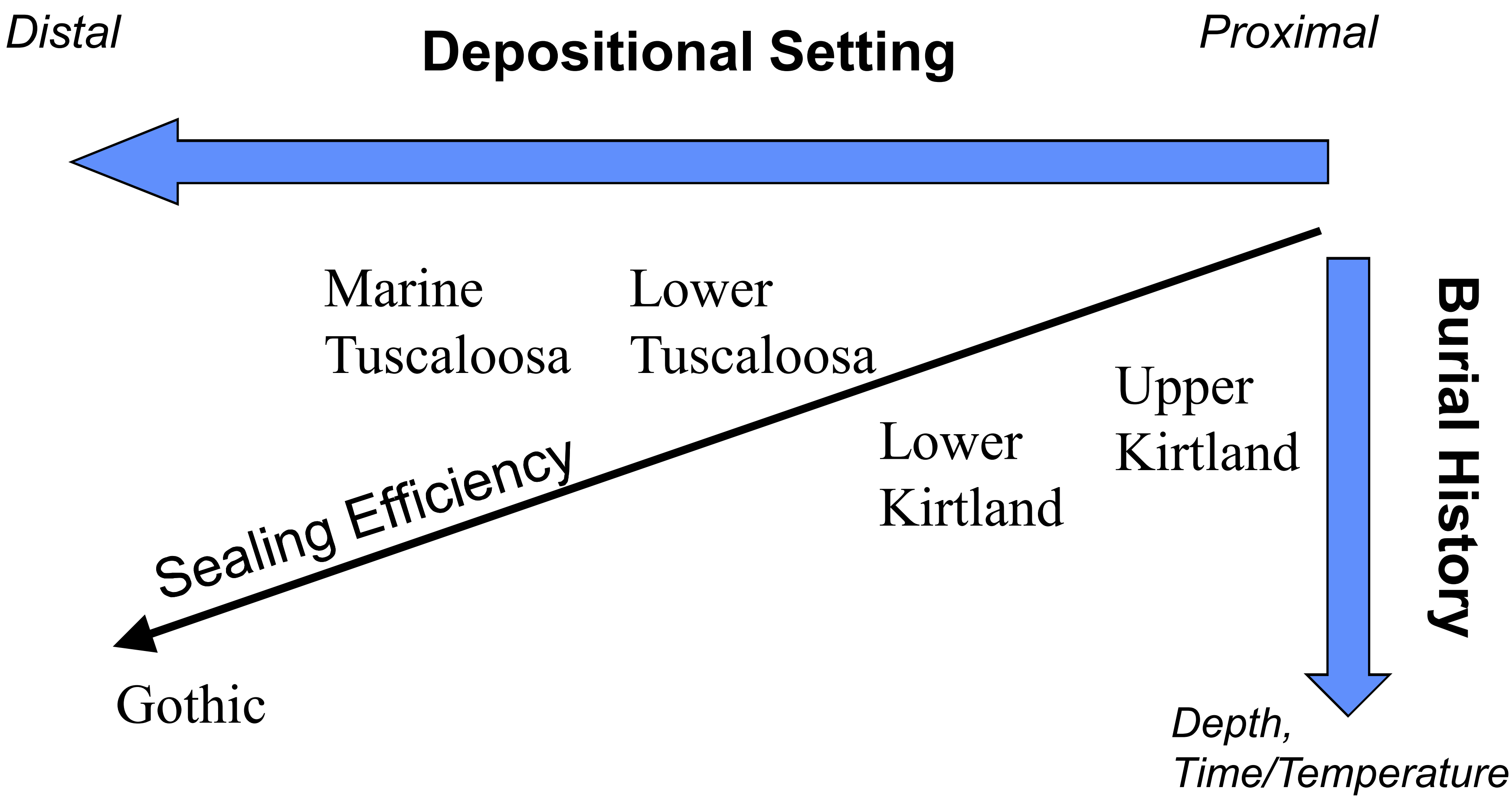
Summary: Sealing Types



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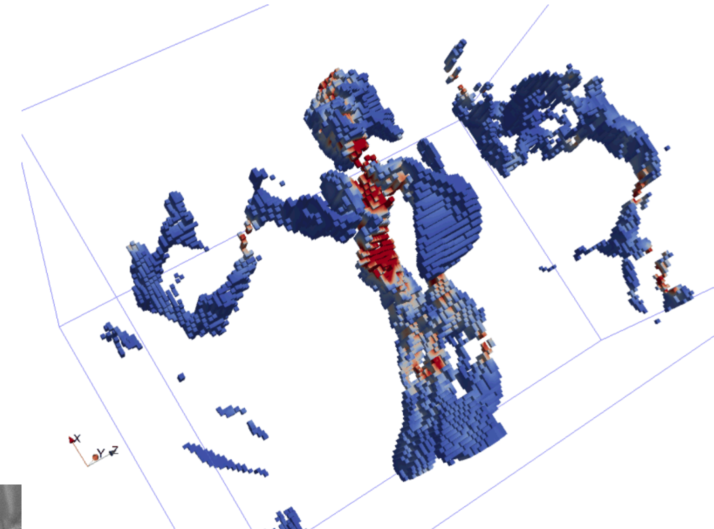
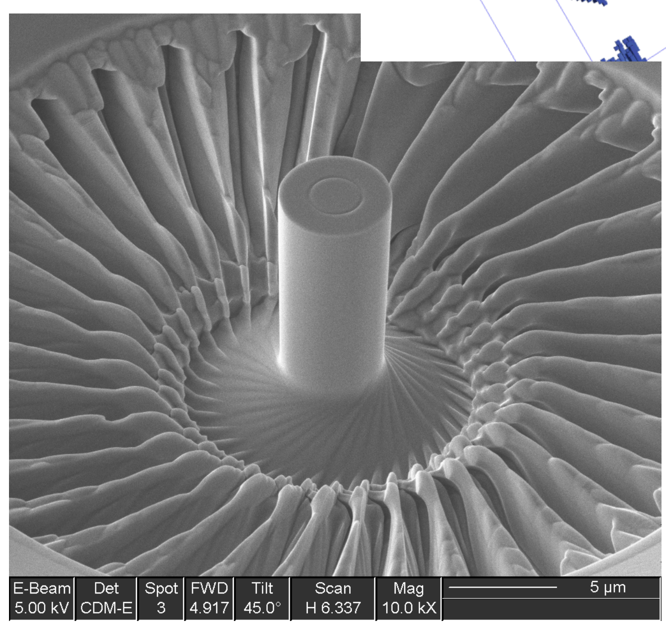
Path Forward

- **SANS (with Alexis Navarre-Stitchler) at ORNL**
- **3DTEM (with Paul Kotula)**
- **Acoustic Emissions/Mancos Shale (with David Holcomb)**
- **Cryo-FIB, FIB/e-SEM, eSEM with loading frame, nano-indenter**
- **Confocal work with re-hydration/swelling**
- **Membrane Efficiency**

Lattice-Boltzmann simulation of flow through type 3 pore network





5 micron diameter by 10 micron long ion milled column of Gothic Shale

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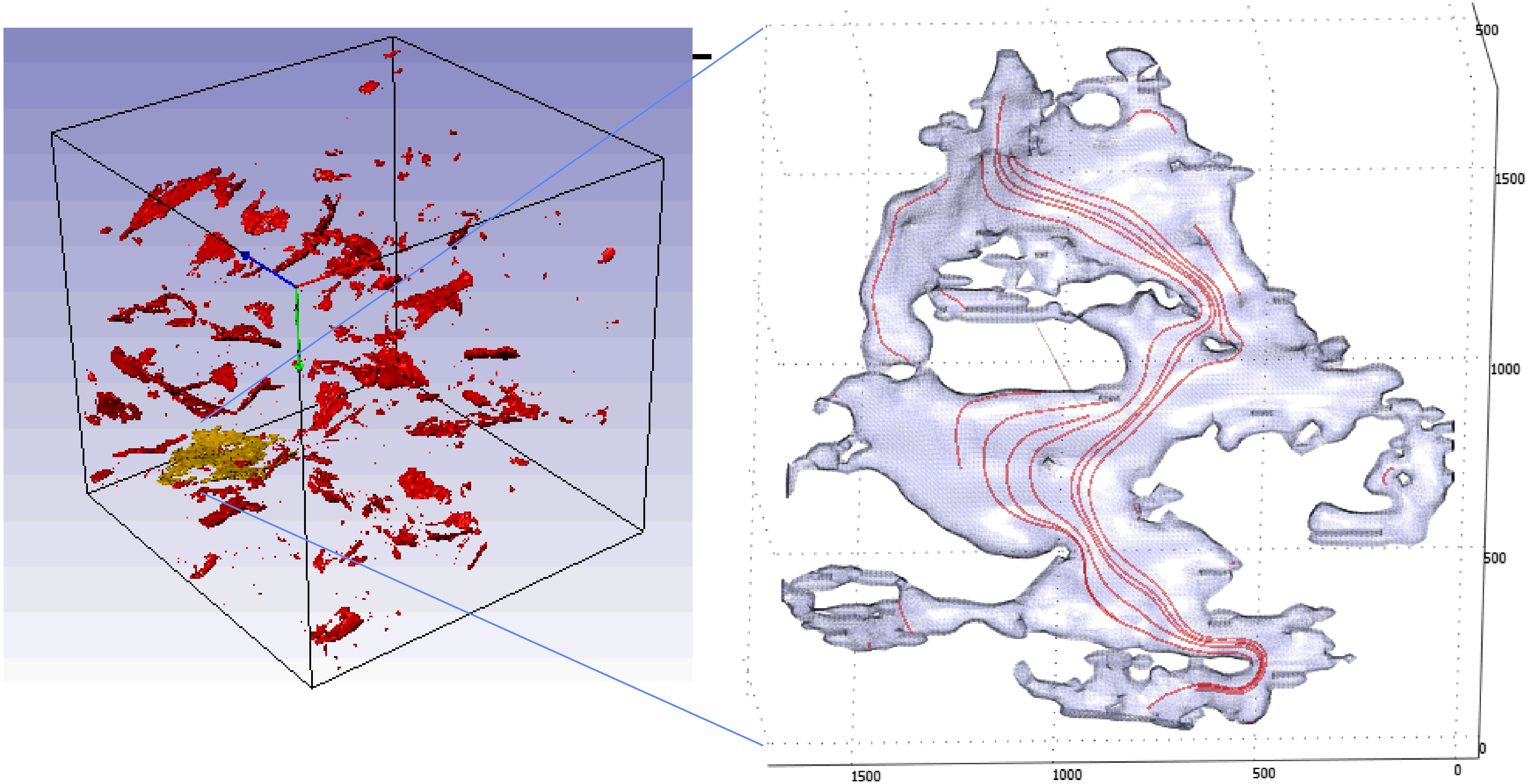
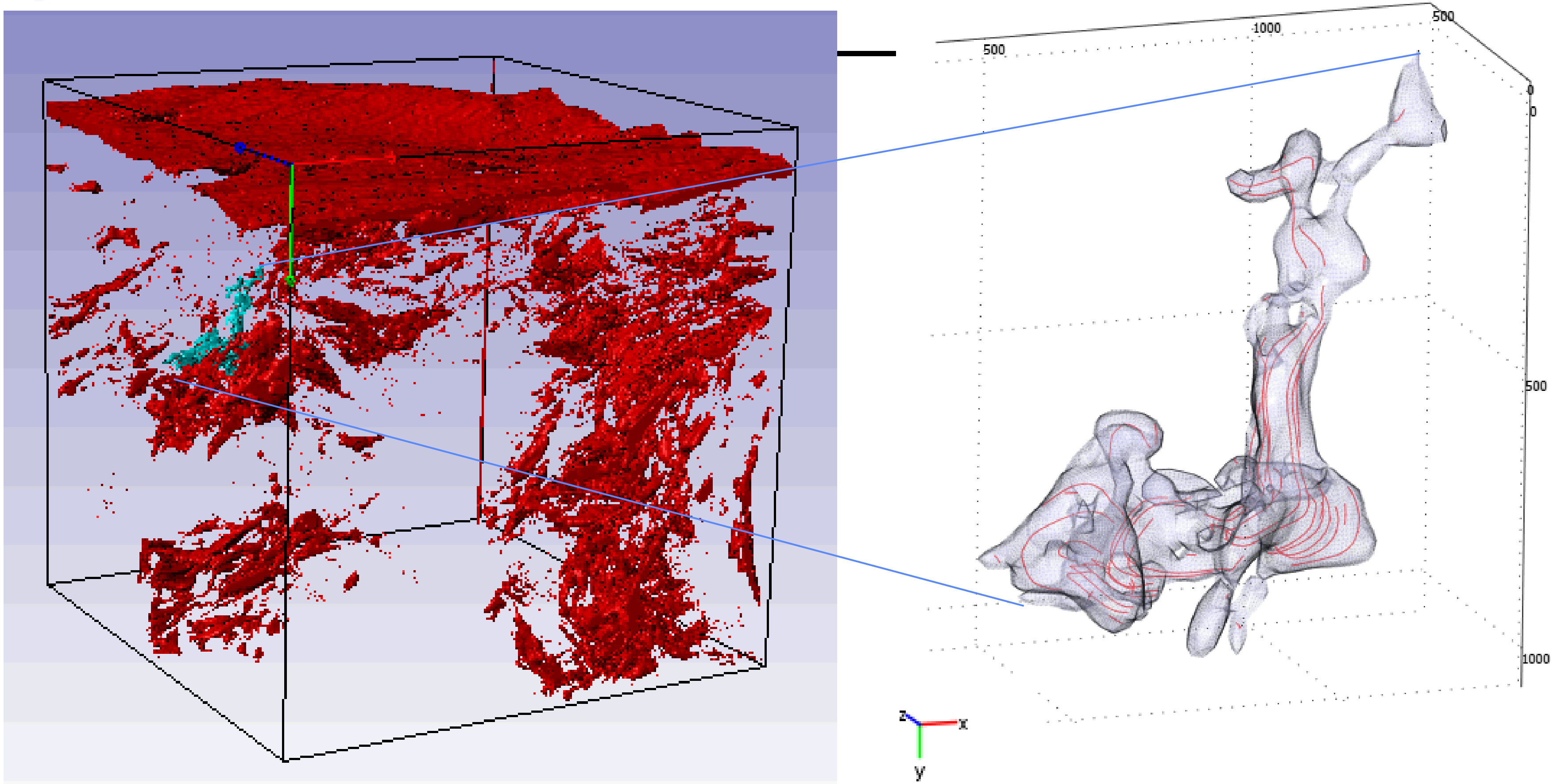
Summary: Shale Transport Properties

- **What can we know?** By examining a variety of shale types from distinct depositional environments and burial history, we can infer generalizations about pore types and connectivity, and effect of pore topology on single and multiphase transport and sealing behavior.
- **How can we know it/study it/model it?** Combination of old and new technology (i.e. MICP with FIB/SEM, NANS) allows fundamental assessment of pore types and influence on flow behavior.
- **What do the fundamental observations mean to broader problems?** Can justify application of certain model methodology in making predictions on e.g. shale gas, CCS, waste disposal PA, etc.

Extra slides

5390-8-A




500
1000
500
0
0
500
1000
z
x
y

Shale Macro Pore Types

- **Fracture and fracture-fill porosity**
- **Pedogenic**
- **Diagenetic, associated with concretions/nodules**

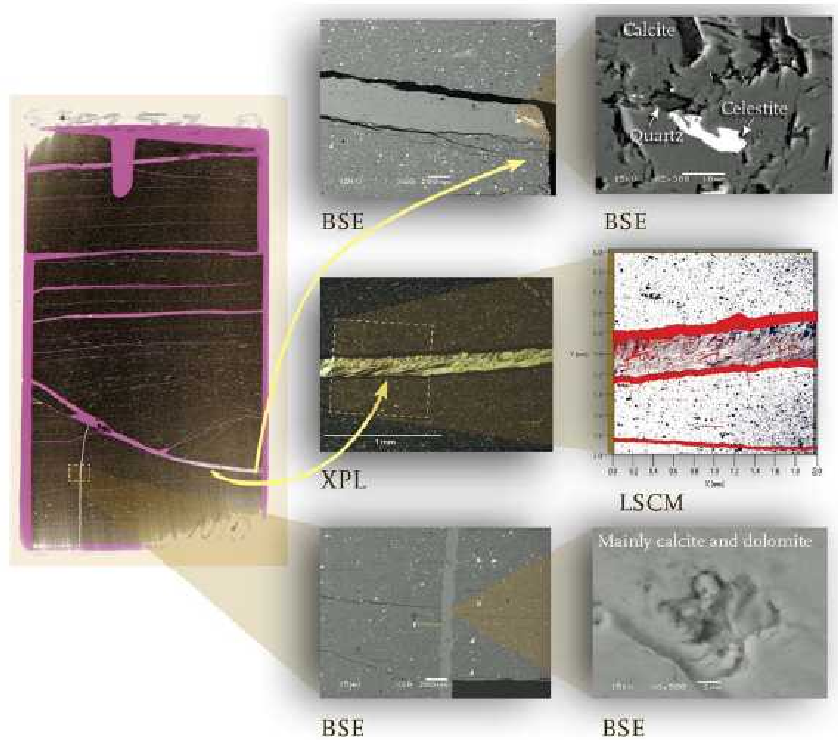


Figure 7-25. Additional views of the inclined shear fracture zone from 5392.30 to 5392.5 feet (core shown on figure 7-23) displayed on various BSE, XPL, and LSCM images at different magnifications derived from the thin section shown on the left.

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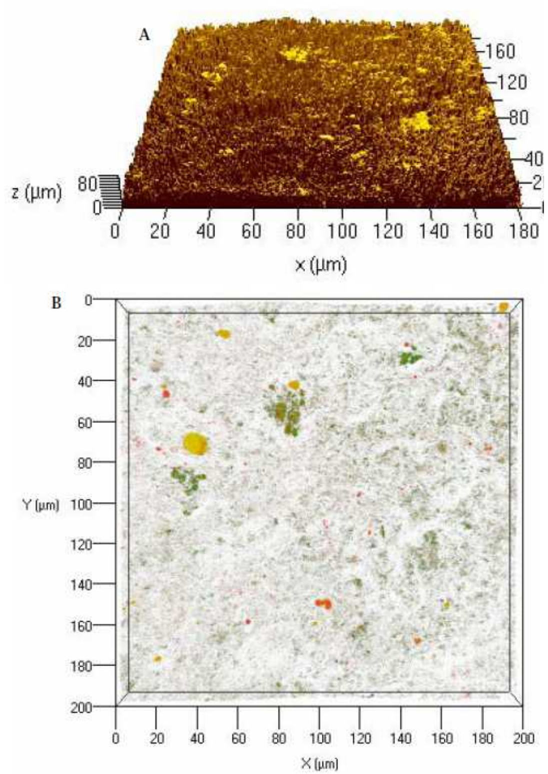

Figure 7-12. Low magnification of corresponding LSCM images of a bedding Gothic shale from 5380.0 feet. A – Image showing topography in an oblique Image shows green, yellow-orange, and red fluorescing material.

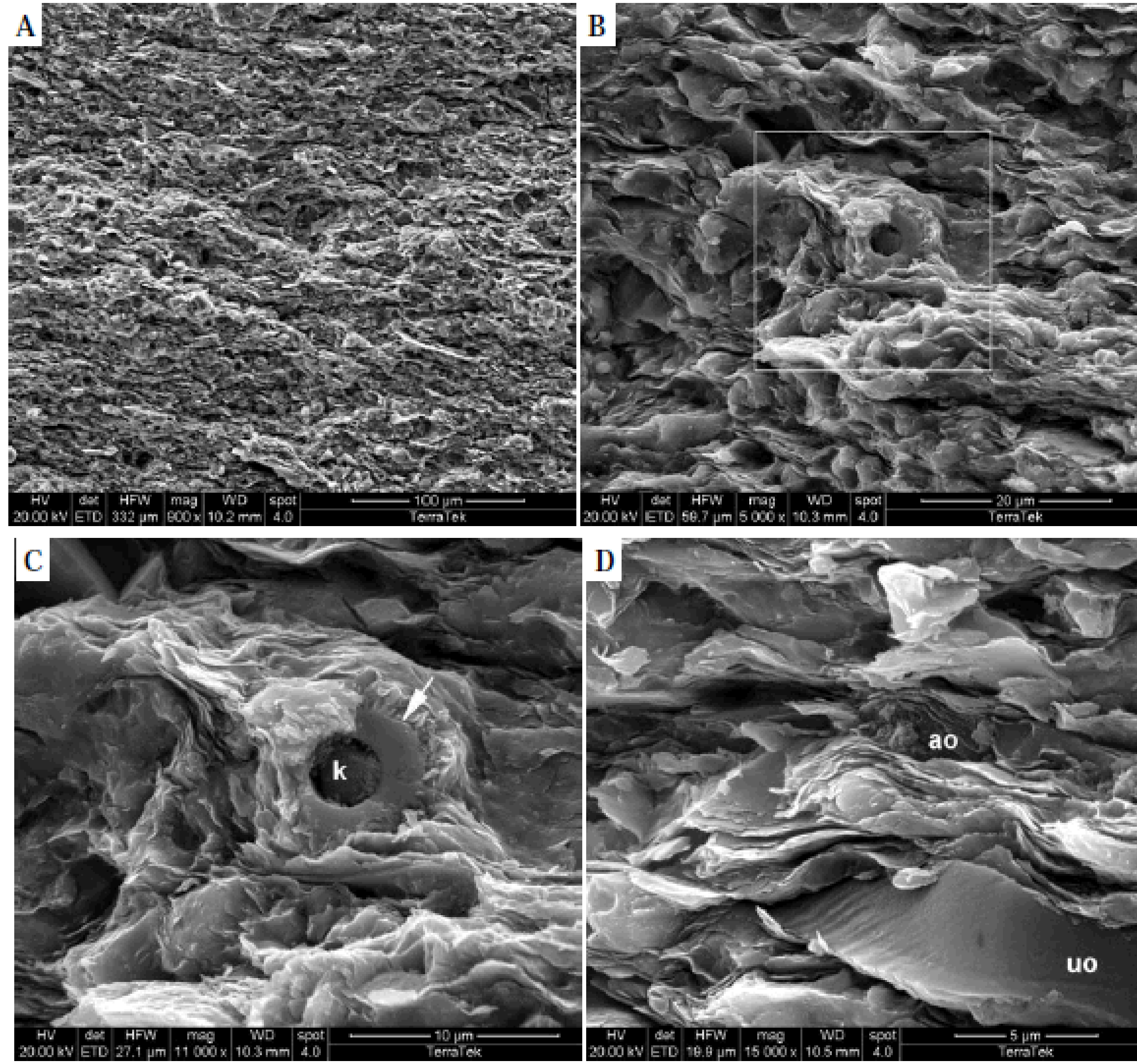

Figure 7-17. Scanning electron images of argillaceous mudstone in Gothic shale from 5382.8 feet. A – Overview of argillaceous mudstone highlighting distinct grain orientation. B – Closer view of mudstone matrix showing wavy parting planes between clay packets. The tube at center (box) is enlarged in the next image (7-17C). C – Detail of pyrite tube (arrow) shown in the previous image. The form represents a replaced microfossil, and is lined with scruffy kerogen residue (k). Note the flakey matrix clays, likely illite and/or mixed layer illite-smectite. D – Matrix detail showing unaltered and altered carbonaceous material. The smooth particle at lower right (uo) represents a discrete carbonaceous grain with little alteration. At top center, a particle representing a different class of organics, embedded