Digital Rock Physics Reveals Link between Reservoir Quality and Pore Type in Eagle Ford Shale*

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Search and Discovery Article #40785 (2011)
Posted August 8, 2011

*Adapted from oral presentation at AAPG Southwest Section meeting, Ruidoso, New Mexico, USA, June 5-7, 2011

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Abstract

Hydrocarbon production from source rocks is dependent on the type, quantity, and connectivity of the pore space within the rock matrix. Loucks (2010) has identified three main pore types in mudstones; kerogen, intragranular, and intergranular. The objective of this work was to observe and quantify how the predominant pore types affect porosity and permeability and how they vary with facies and depositional sequences. The work was conducted on a whole core from the Eagle Ford Formation of South Texas.

The work was conducted using high-resolution focused ion beam scanning-electron microscopy (FIB-SEM) and 3D X-ray CT scanning. The whole core was X-ray CT scanned in such a way that bulk density (RhoB) and effective atomic number (Zeff) could be separately quantified. This is a new method that substantially increases the value and information content of X-ray CT data versus older methods that just produce images of X-ray attenuation. Samples used for matrix permeability tests were selected based on the core RhoB and Zeff data. The FIB-SEM method was used to create 3D volumes of pores, kerogen, and solid grains. Digital rock physics (DRP) technology was used to segment these volumes into different pore types and compute connectivity and matrix permeability directly. Density is an indicator of porosity plus kerogen and Zeff is a lithology indicator (similar to the photoelectric or PE log). As with most mudstone formations, Eagle Ford has a distinct pattern of repeating facies and sequences that can be detected in whole core by the combination of RhoB and ZefJ. These changes are caused by depositional trends in quartz, clay, kerogen, and calcite content. Because the resolution is many times finer than open-hole logs (about 0.5 millimeter), these sequences can be

accurately defined. The porosity versus matrix permeability behavior is related to the pore types, and the pore types vary depending on their location relative to depositional sequences.

Observations and Conclusions: Fine-scale depositional sequences in Eagle Ford shale were detected using a new X-ray CT method that quantifies both bulk density and effective atomic number. This data helps identify the most porous and organic-rich zones as opposed to the calcareous, harder streaks. Digital rock physics technology showed that the porosity-permeability trends in these samples are controlled by pore type, with kerogen porosity being critical to good reservoir properties.

References

Loucks, R.G., R.M. Reed, S.C. Ruppel, and U. Hammes, 2010, Preliminary classification of matrix pores in Mudrocks: GCAGS, Transactions, v. 60, p. 435-441.

Tolke, J., C. Baldwin, Y. Mu, N. Derzhi, Q. Fian, A. Grader, and J. Dvorkin, 2010, Computer simulations of fluid flow in sediment; from images to permeability: The Leading Edge, v. 29/1, p.68-74.

Eagle Ford Shale Characterization by Digital Rock Physics (DRP)

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AAPG Southwestern Section Meeting

Ruidoso, NM
June 6, 2011

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Digital Rock Physics Lab

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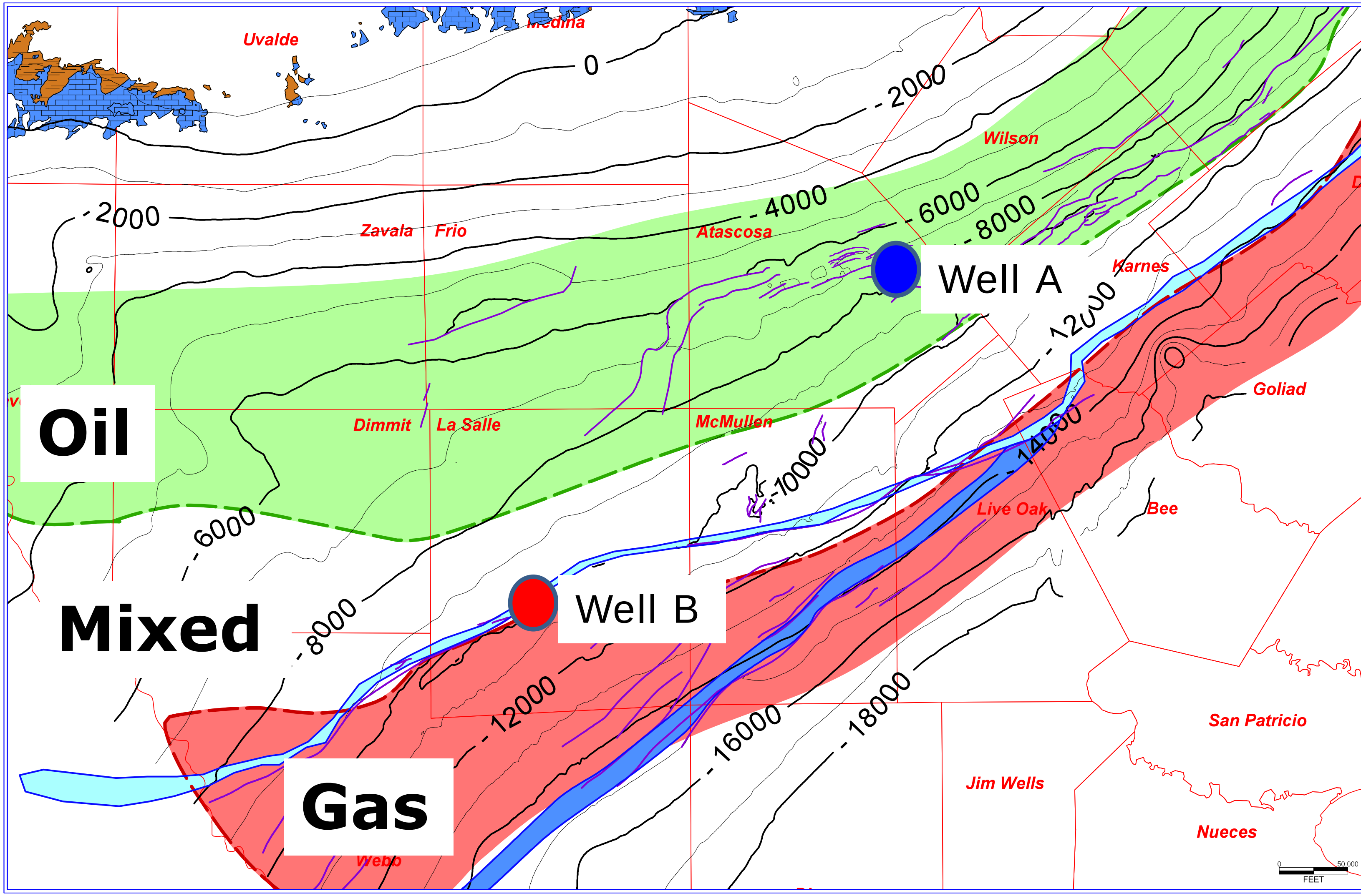
Overview

- Eagle Ford map and well locations
- Basics of digital rock physics (DRP) in shale
  - Integrated shale workflow
  - 3D whole core imaging and facies analysis: Eagle Ford shale
  - Organic content and mineralogy
  - 3D pore scale imaging and computation
- Porosity-perm trends
- Pore types and organic matter classification
- Observations

Digital Rock Physics Workflow

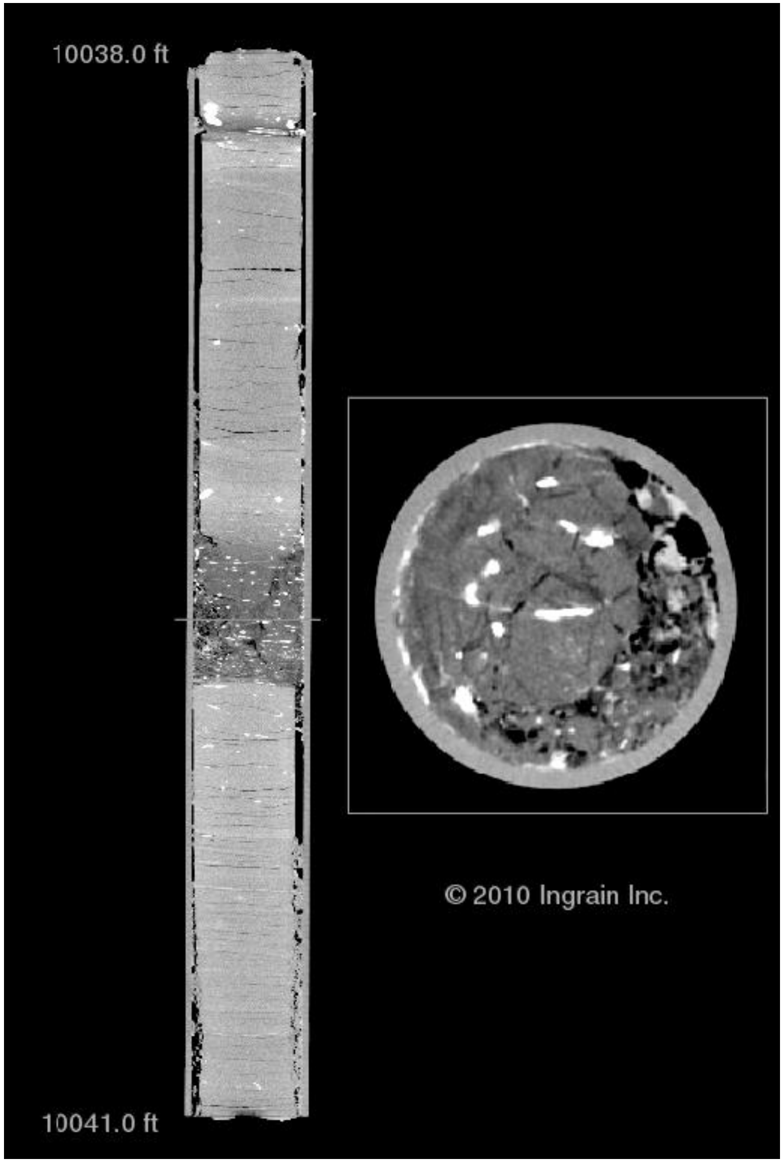
- Stage 1: Whole core X-ray CT Imaging and Analysis (CoreHD)
  - 3D imaging of core, ideally preserved, unslabbed
  - Visual display of bedding, fractures, fossils, burrows, parasequences, etc.
  - Computation of bulk density (RhoB) and effective atomic number (Zeff)
  - Classification of facies from RohB-Zeff crossplot
- Stage 2: Plug-size sample analysis
  - 3D Micro CT imaging for small scale bedding, fractures, etc.
  - SEM images of multiple ion-beam polished surfaces
  - SEM image analysis for porosity, organic content
  - EDX analysis for detailed mineralogy
- Stage 3: SCAL: 3D Focused Ion Beam SEM analysis
  - Create FIB-SEM volume
  - 3D image processing and analysis
  - Porosity, organics, and pore size analysis
  - Fluid flow, cap pressure computations (Lattice-Boltzmann)
  - Elastic properties

Eagle Ford Maturity Window



Base of Eagle Ford contours

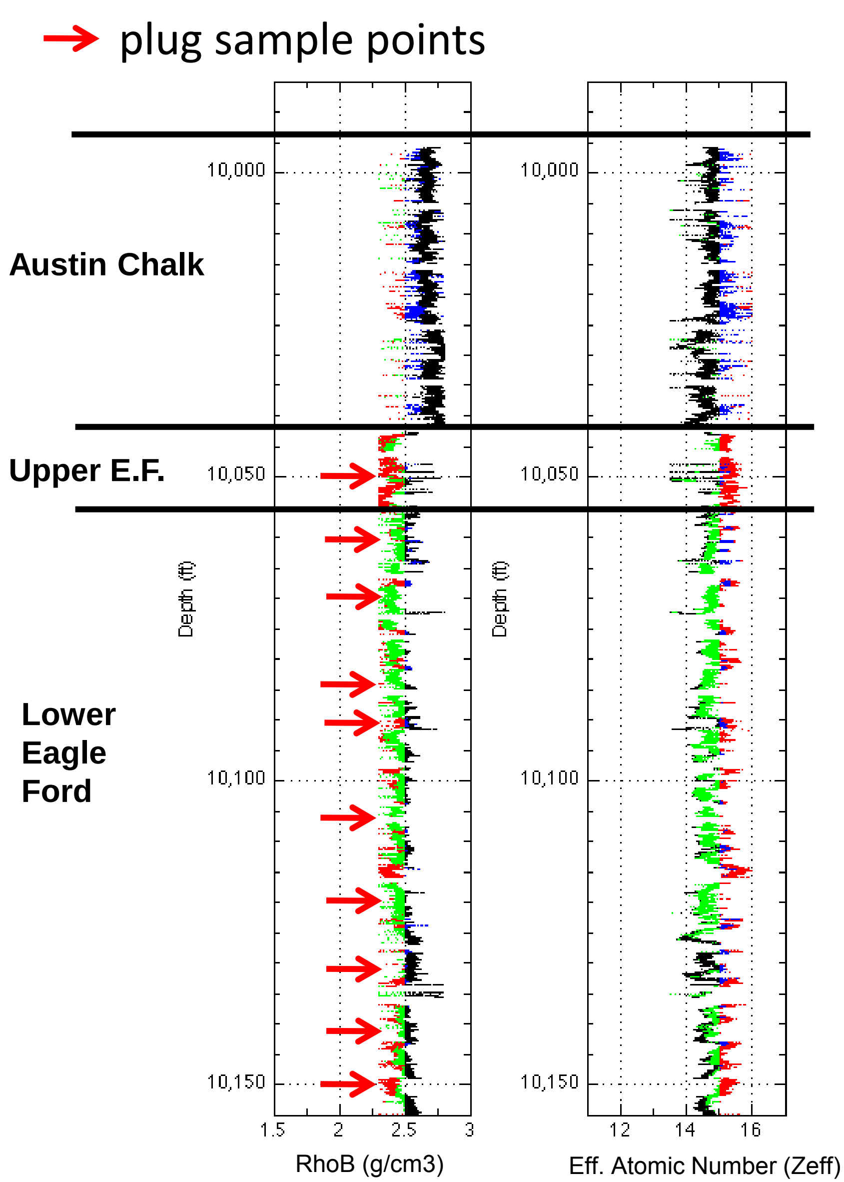
Stage 1: CT imaging provides structural and stratigraphic insight (Well B)



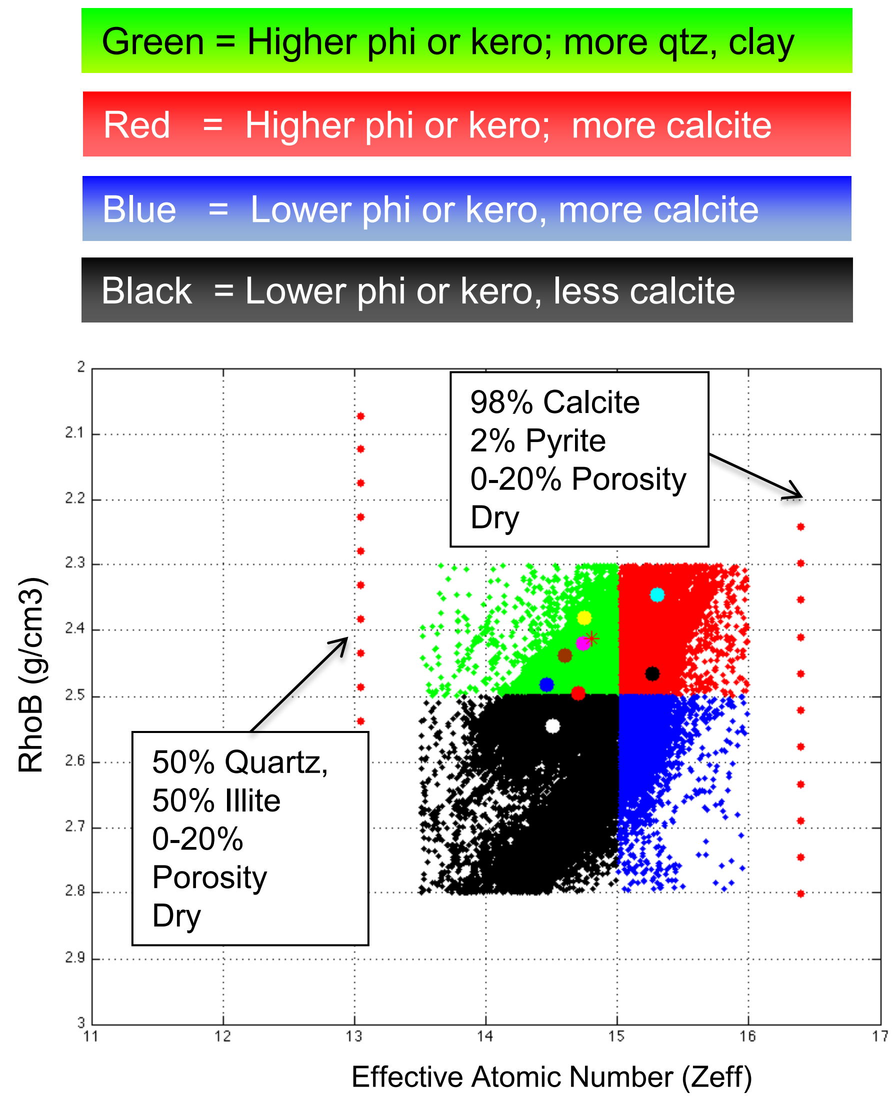
Upper Eagle Ford; burrowed, calcareous, pyritic

Core is preserved in original aluminum sleeve with rubber end caps.
About 500 CT slices/ft

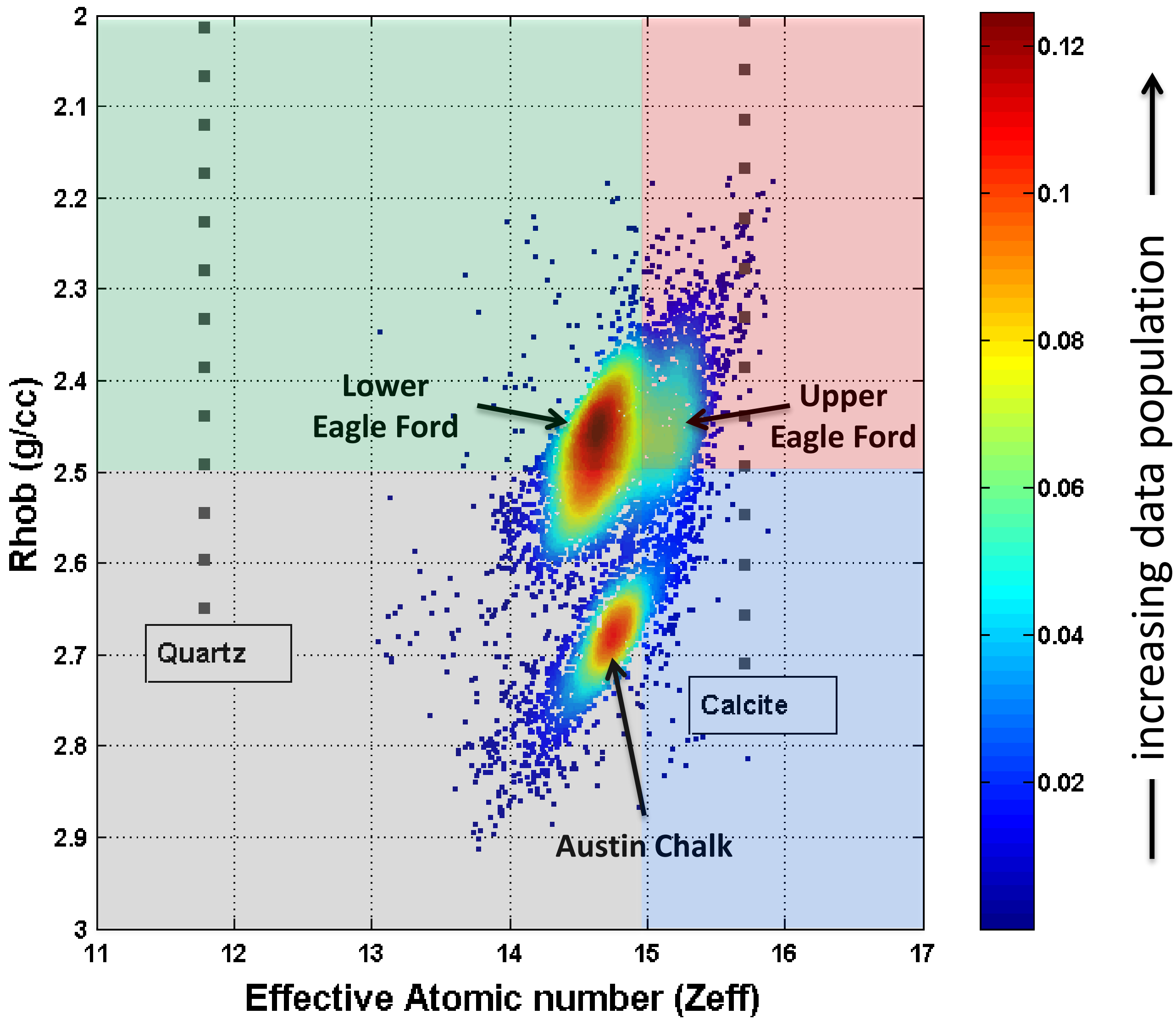
Stage 1: Whole core density and effective atomic number (Zeff) for facies identification (Well B, +11 ft depth shift)



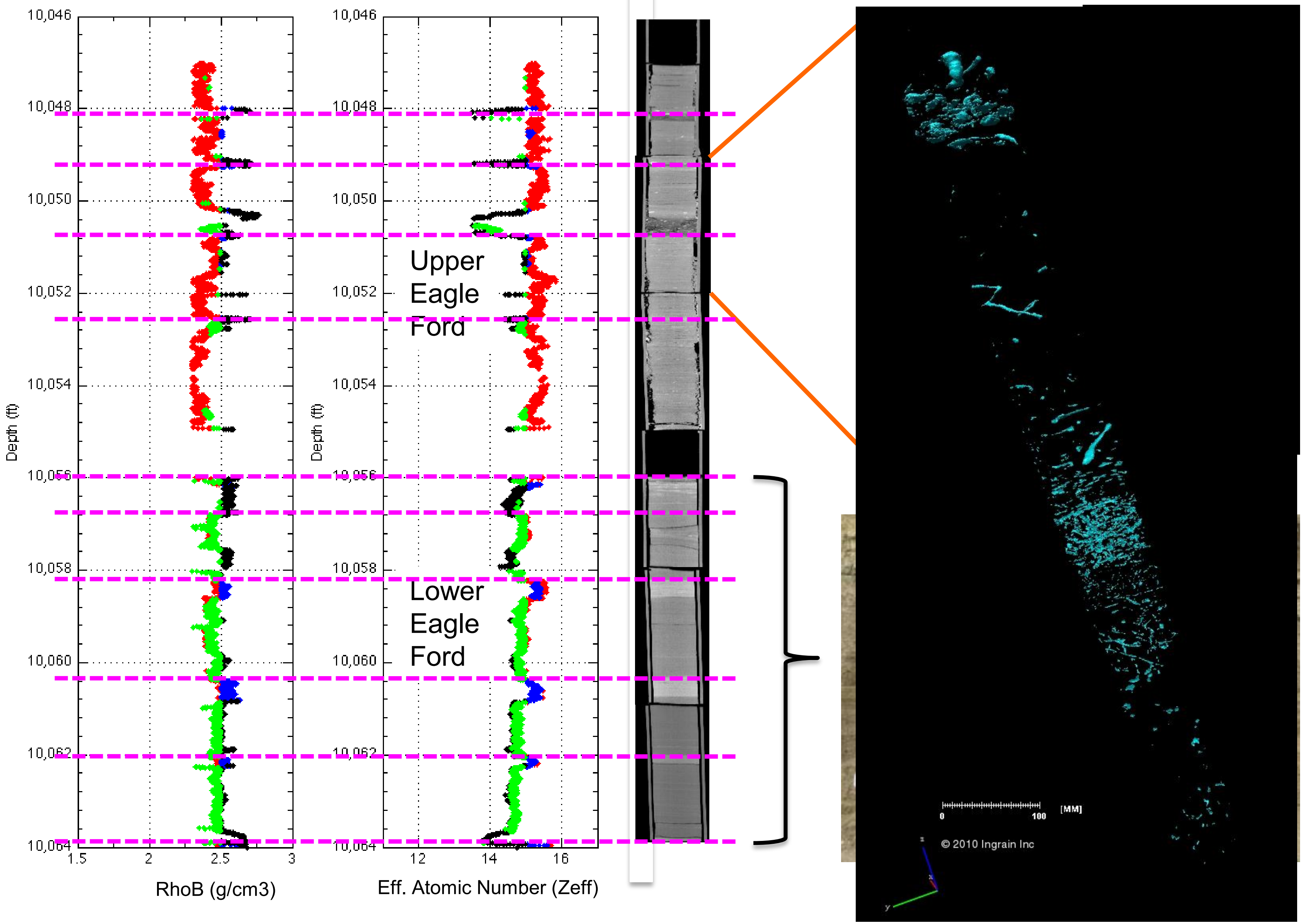
Zeff = 10 * (PE)^(1/3.6)



Whole core bulk density and effective atomic number (Zeff) for facies identification

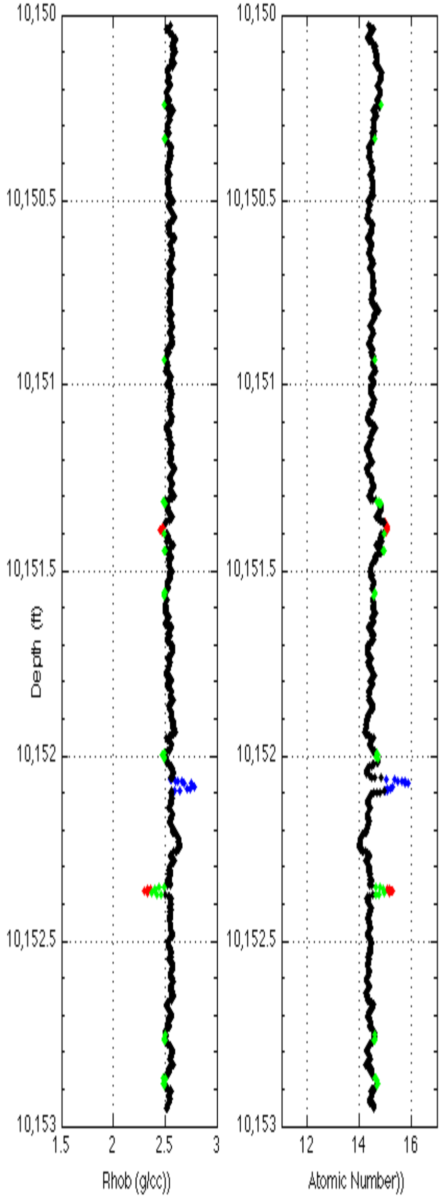


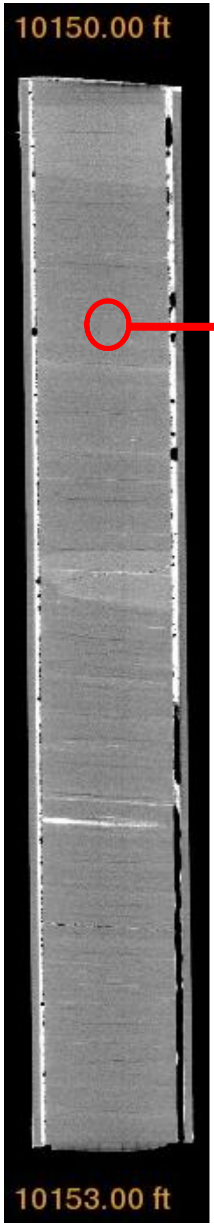
Stage 1: Density and effective atomic number (Zeff) from whole core X-ray CT analysis reveals facies and depositional sequences (Well B, +11 ft depth shift)



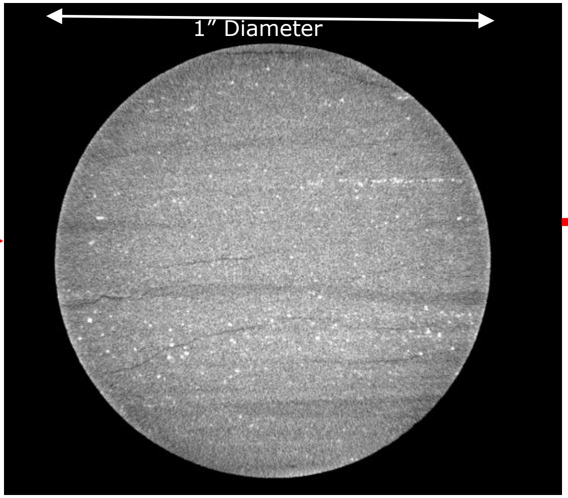
Stage 2: Well B, Plug sample analysis

CoreHD

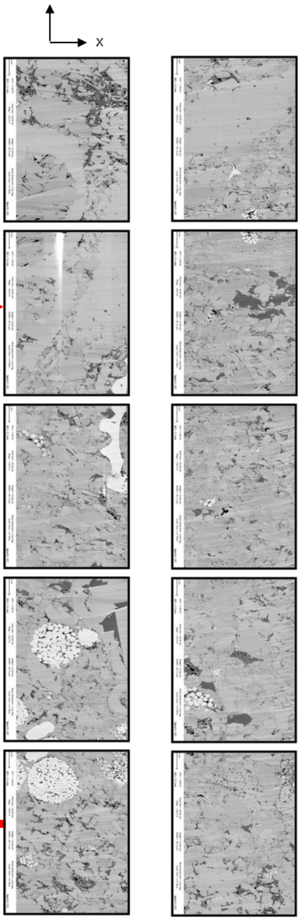


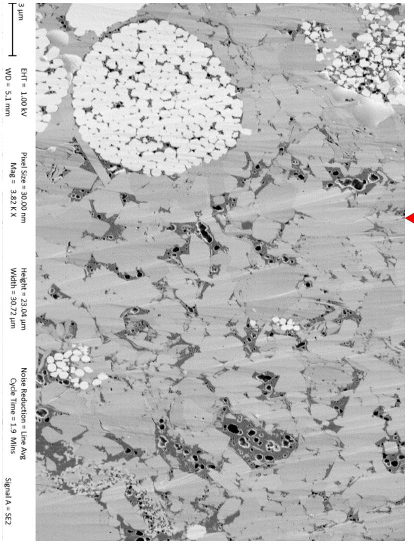


Micro CT

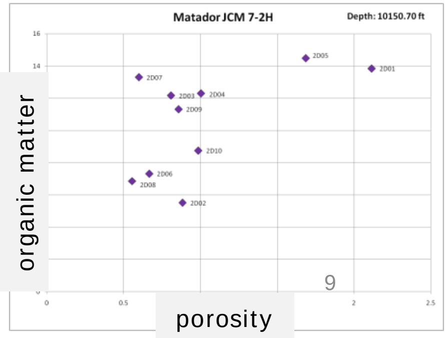


Ion Milled SEM



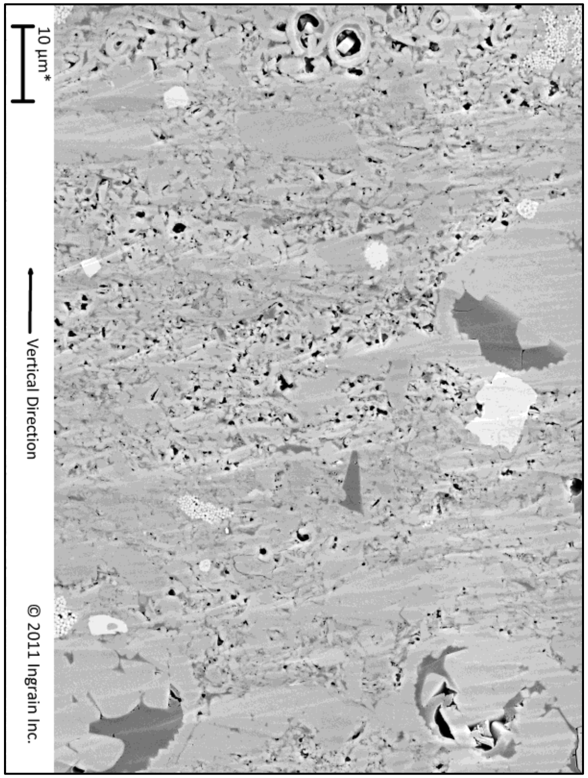


Region selected for vRock 3D volume

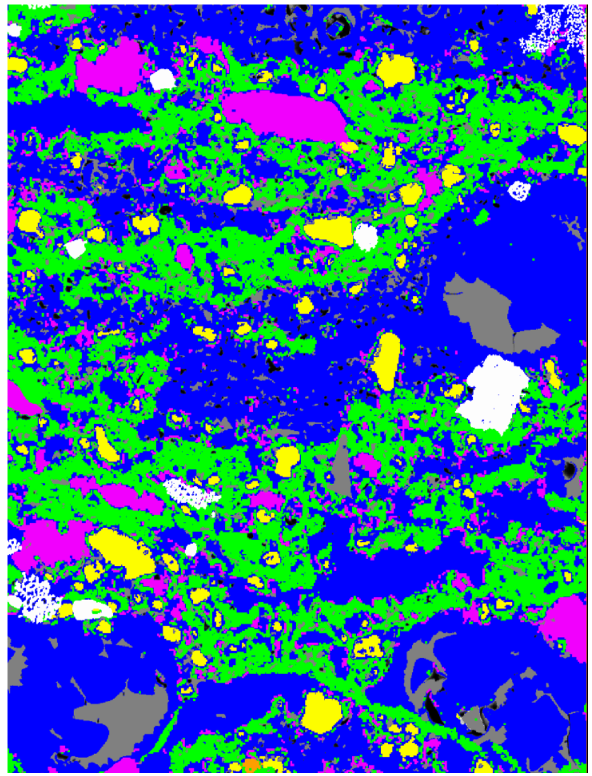


Mineralogy by Energy Dispersive Spectral Analysis (EDS)

a) SEM Image



b) X-ray Spectral Map



c) Mineral Distribution (% by vol)

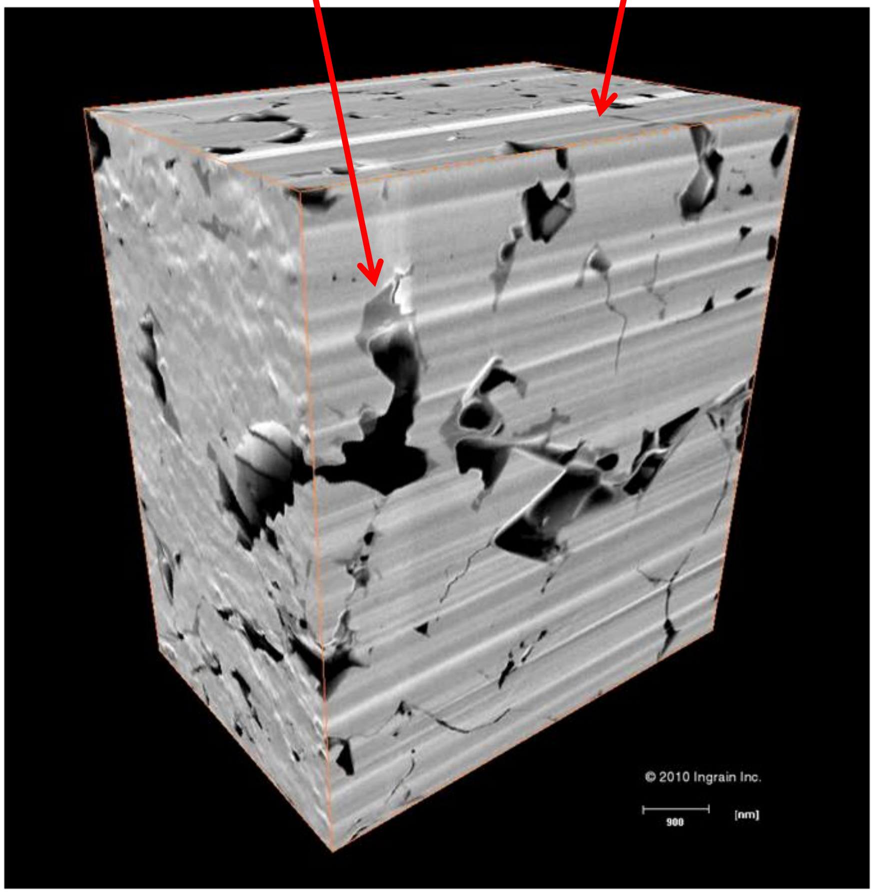
clay	27.7
pore	1.7
organic	7.2
calcite	48.7
qtz	4.3
plagioclase	8.1
pyrite	2.2
TiO2	0.1
Total	**100**

a) **SEM (Scanning Electron Microscope) picture of a sample from the Eagle Ford shale. The arrow on the left illustrates the orientation of the sample relative to the bedding plane.**

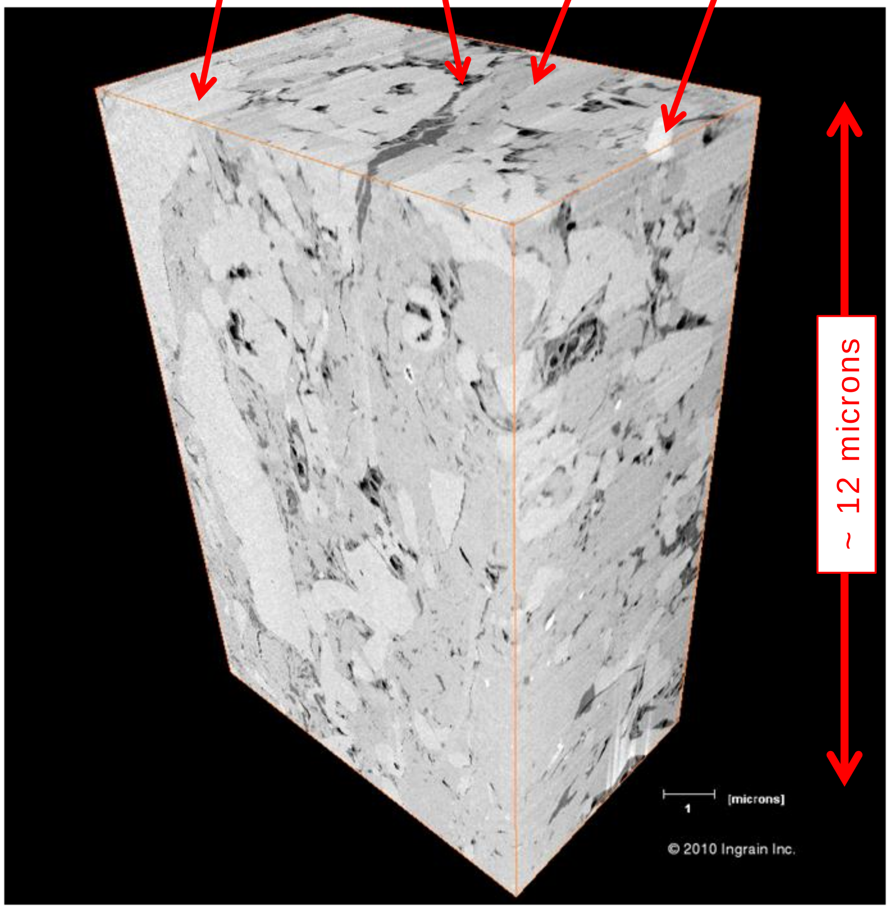
b) **X-ray spectral map showing different colors, which correspond to different minerals present in the rocks. Notice how the green color (clay) highlights the horizontal distribution of clay minerals between the framework calcite grains.**

c) **Mineral volume fractions in sample**

Stage 3: SCAL – Pores, organic matter, and minerals are imaged in 3D with focused ion beam scanning electron microscopy (FIB SEM)

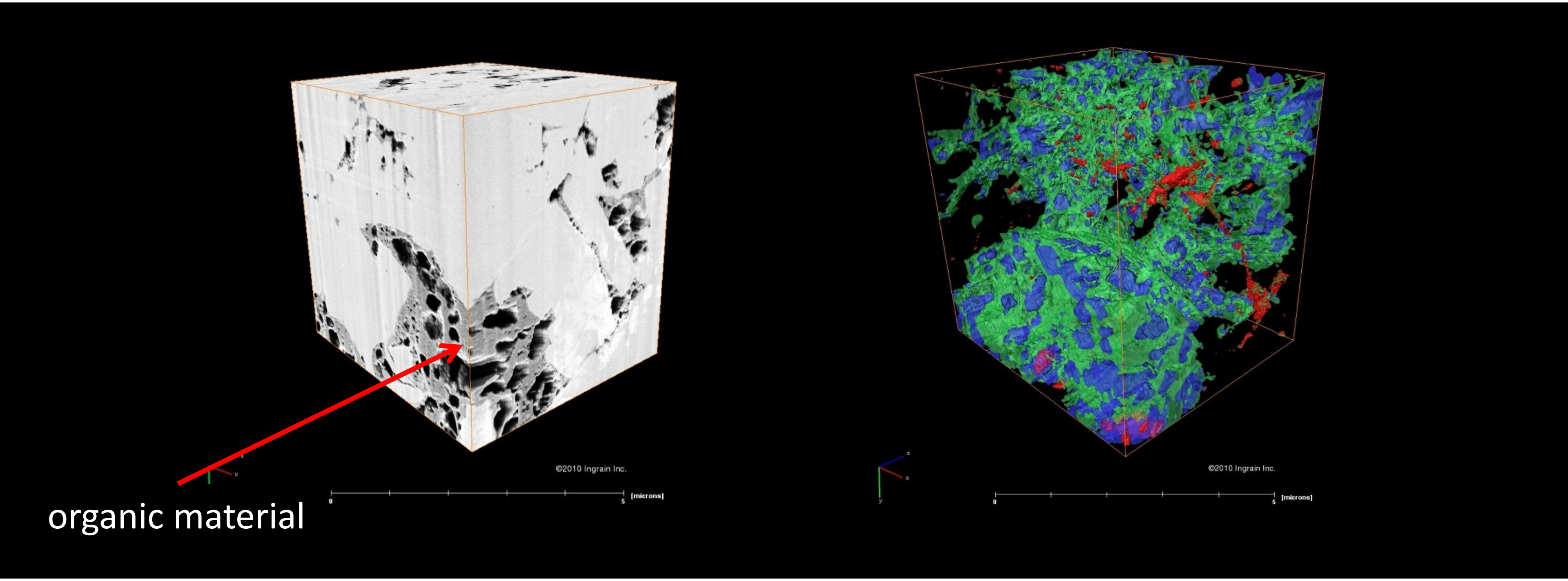


Well A, oil window
7854 ft



Well B, mixed gas-liquid
10151 ft

Stage 3: SCAL - Shale 3D vRocks are used for porosity and permeability analysis



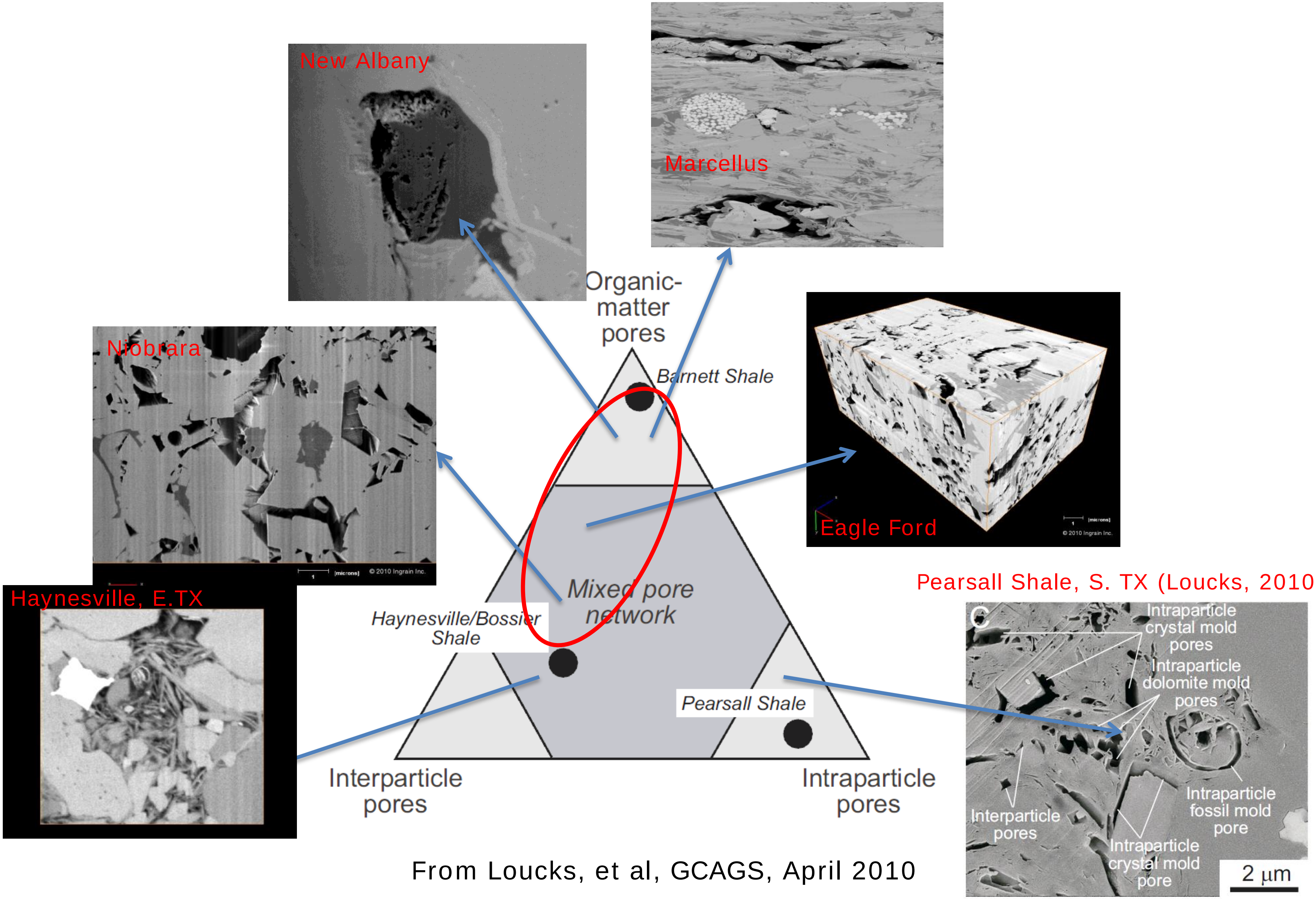
- OM porosity is about 75% of total in lower Eagle Ford
- Likely oil wet

Red: isolated pores
Blue: connected pores
Green: organic material

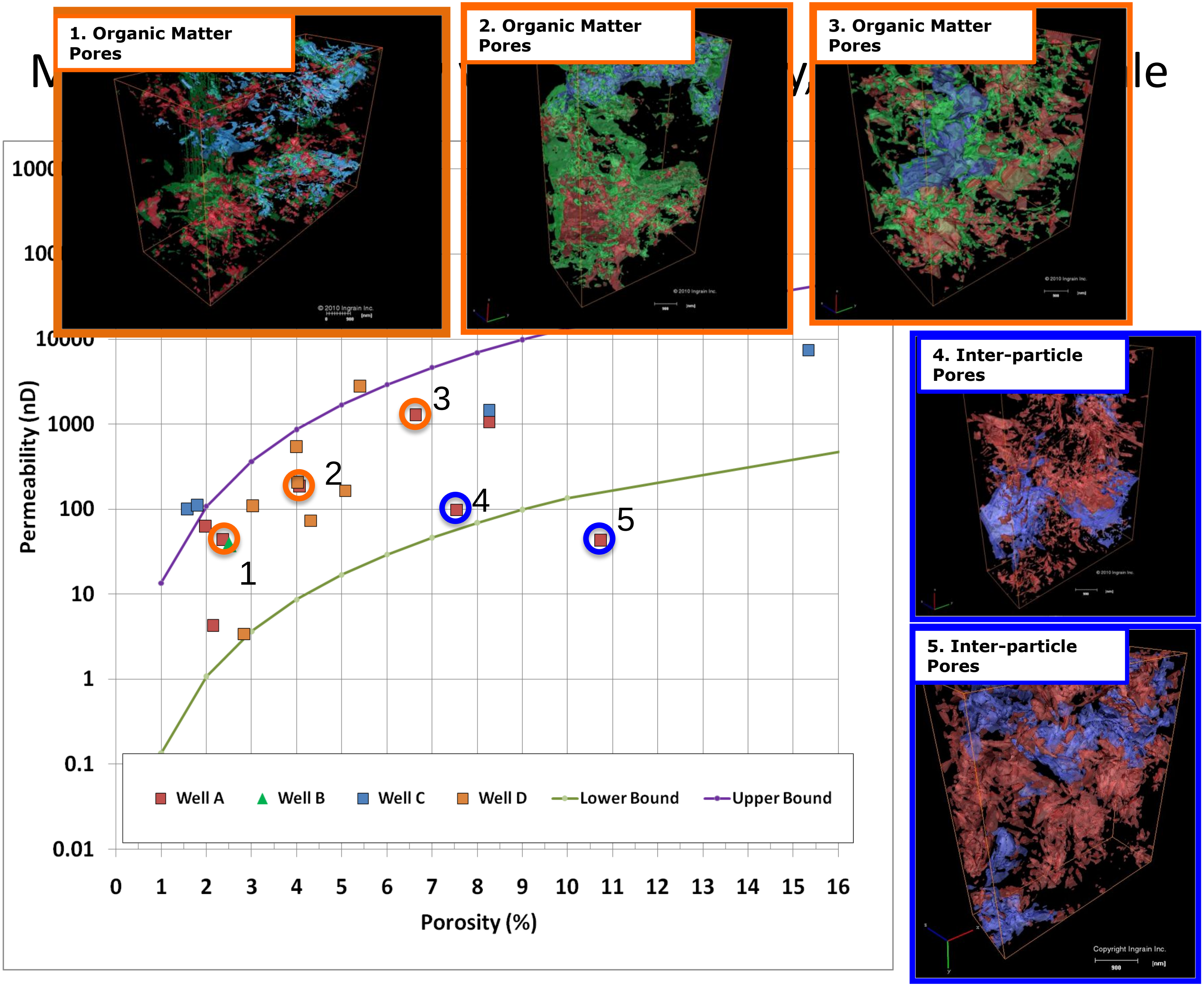
Organic material	12.2 %
Porosity	6.9%
Connected Porosity	6.2 %
Isolated Porosity	0.7 %
Organic Matter Porosity	4.5%
Permeability (nD)	
Kx	850
Ky	630
Kz	< 10

Permeability is computed through the pore system using Lattice-Boltzmann method (Tolke, et al, 2010)

Shale Pore Types (after Loucks, et al, 2010)



From Loucks, et al, GCAGS, April 2010


1. Organic Matter Pores
2. Organic Matter Pores
3. Organic Matter Pores
4. Inter-particle Pores
5. Inter-particle Pores
Permeability (nD)
10000
1000
100
10
1
0.1
0.01
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Porosity (%)
Well A
Well B
Well C
Well D
Lower Bound
Upper Bound
1
2
3
4
5
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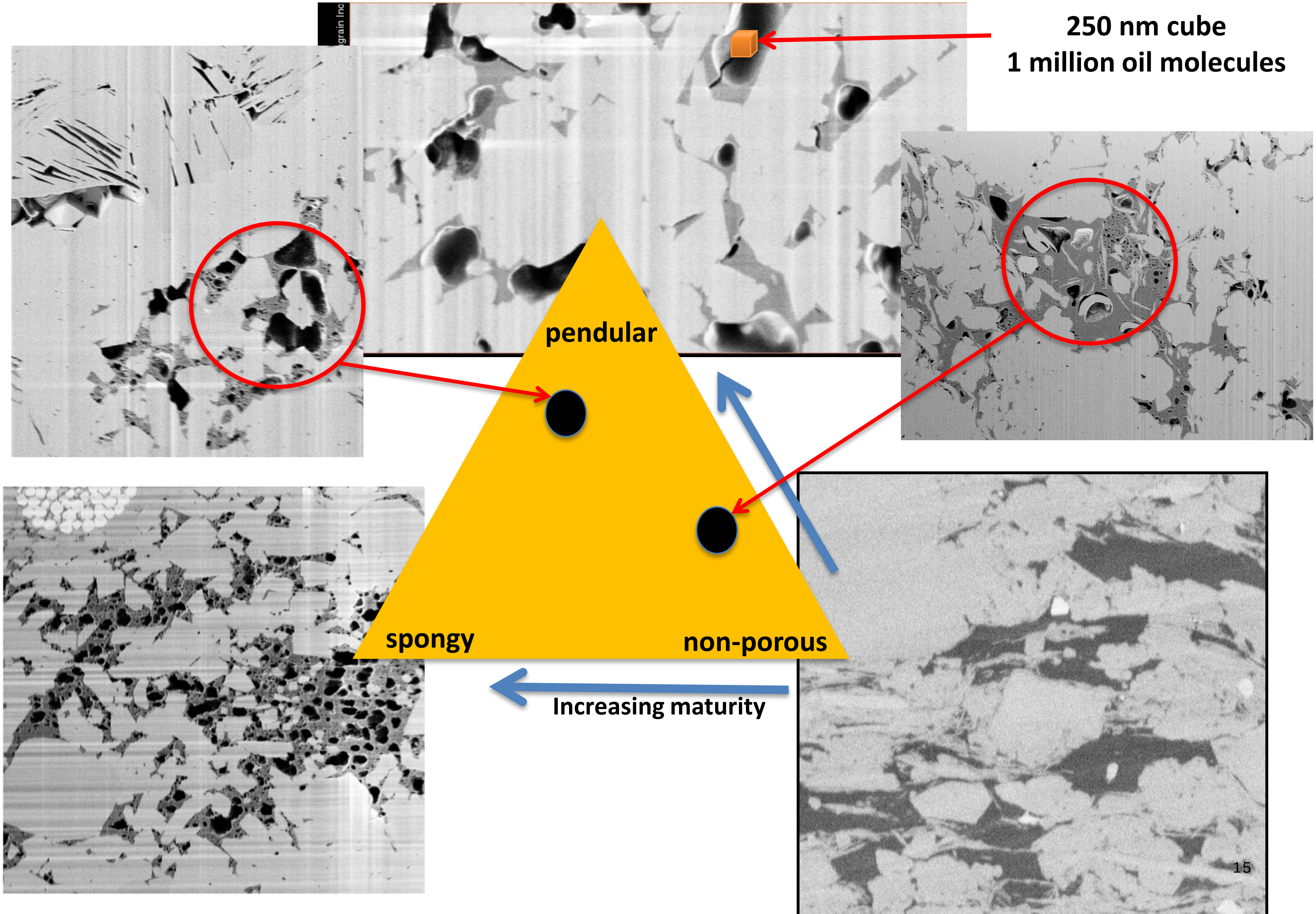
Three Classes of Organic Matter Morphology



Observations

- Density (RhoB) and effective atomic number (Zeff) from CoreHD X-ray CT scan provide detailed information on layering and facies in the Eagle Ford shale.
- Key facies changes can be readily observed from the CT data, while the core is preserved in the sealed aluminum tubes.
- Three organic matter forms; non-porous, spongy, pendular
- Some organic material could be mobile at reservoir conditions. If so, then ambient condition lab perms are too low.
- Lower Eagle Ford has mainly organic matter porosity, likely oil-wet, larger pores, and higher permeability
- Upper Eagle Ford has less organic matter porosity, smaller pores, and lower permeability (but can also make good wells).