Seeing Reservoir Quality at the Appropriate Scale: A Look at Tools for High-resolution Imaging and Our Evolving Understanding of Pore-Scale Processes in Fine-grained Systems

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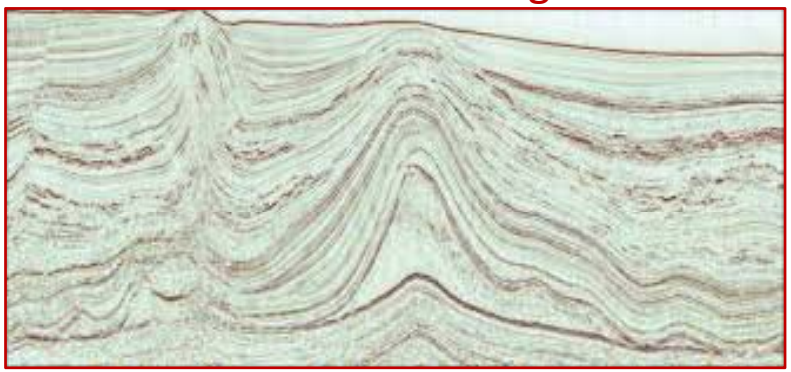
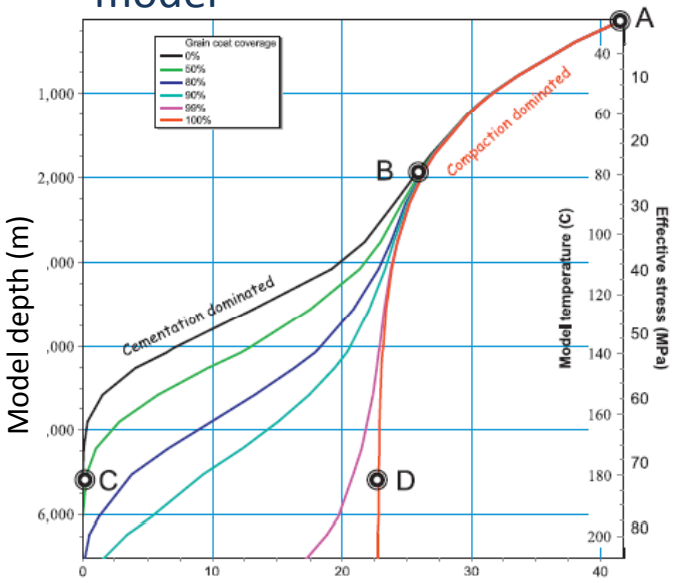
Exploration for conventional hydrocarbon reservoirs (sandstones and limestones) is a refined scientific endeavor that reduces economic risk.

Large-scale data

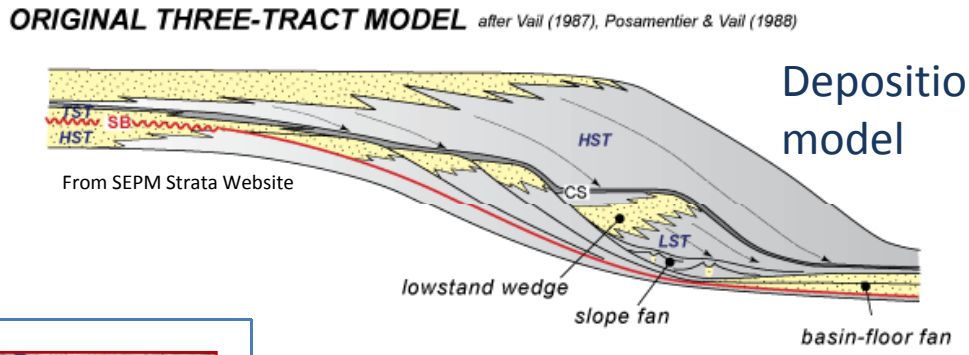


Porosity model

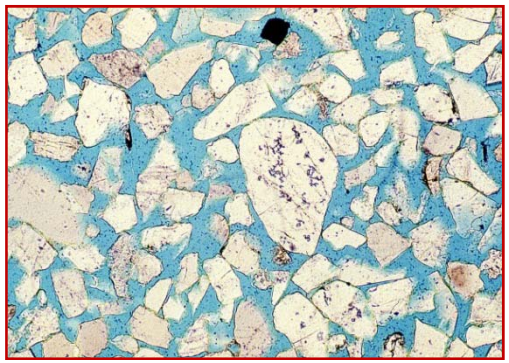
Ajdukiewicz & Lander, 2010

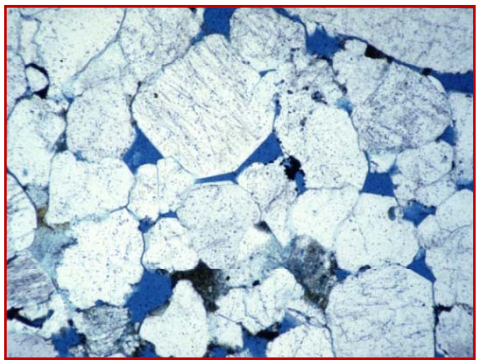


Depositional model

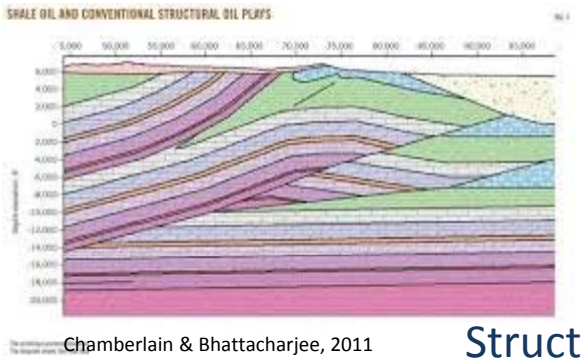


From SEPM Strata Website





Small-scale data



Chamberlain & Bhattacharjee, 2011

Structural model

Barnett Shale core.

Shale – Mudrock – Mudstone: Fine-grained Sedimentary Rocks

- A major type of sedimentary rock
- The most abundant type of sedimentary rock: 2/3 of the sedimentary record on Earth.
- Fine-grained: "clay-rich"

"We prefer the straightforward use of mudrock color for classification." Prothero & Schwab, 2003; p. 108.

Munsell color system.

Henry Clifton Sorby
"father of petrographic microscopy"

- Made first preparation of a rock for microscopic study.
- Published first paper on microscopic examination of rocks (1850s).

Possibly many may think that the deposition and consolidation of fine-grained mud must be a very simple matter, and the results of little interest. However, when carefully studied experimentally, it is soon found to be so complex a question, and the results dependent on so many variable conditions, that one might be inclined to abandon the enquiry, were it not that so much of the history of our rocks appears to be written in this language.

Sorby, 1908, Quarterly Jour. Geol. Soc. London, v. 64, p. 190-191.

EARLY 1960s

"In a way, shales are the last frontier of sedimentary petrology. . . . ."
Folk, 1962, JSP, v. 32, p. 539-537.

EARLY 1970s

"….very little is known about the relative abundances of microcline, orthoclase, and plagioclase in sandstones. ***Nothing is known*** concerning these species in mudrocks." Blatt, Middleton, and Murray, 1972, *Origin of Sedimentary Rocks*: Prentice Hall, NJ, 634 p.

EARLY 1980s

"Although they form approximately two-thirds of the stratigraphic column, mudrocks are poorly understood and inadequately studied. Few sedimentary geologists have chosen to study mudrocks……"
Ehlers and Blatt, 1982, *Petrology, Igneous, Metamorphic, and Sedimentary*: Freeman & Co., NY, 732 p.

EARLY 1990s

"Although shales constitute the bulk of the Earth's clastic sedimentary rocks, relatively little is known about……." Issler, 1992, AAPG Bull., v. 76, p. 1170-1189

Late 1990s

"….fine-grained terrigenous clastics (mudstones, shales), the dominant sedimentary rock type, are still "*terra incognita*" for most geologists."
Schieber et al. (eds), 1998, *Shales and Mudstones I*: E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart

Why was the science of mudrocks less advanced than the science of coarser grained systems at the end of the 20th Century?

- Mudrocks are challenging to study because the fundamental components (grains, pores) are so small they cannot be readily observed.
- The occurrence of extractable resources within mudrocks was not expected.
- The more obvious economic importance of sandstones and limestones attracted most of the research interest and funding for study.
- Little funding was directed to mudrocks and few people chose to study mudrocks.

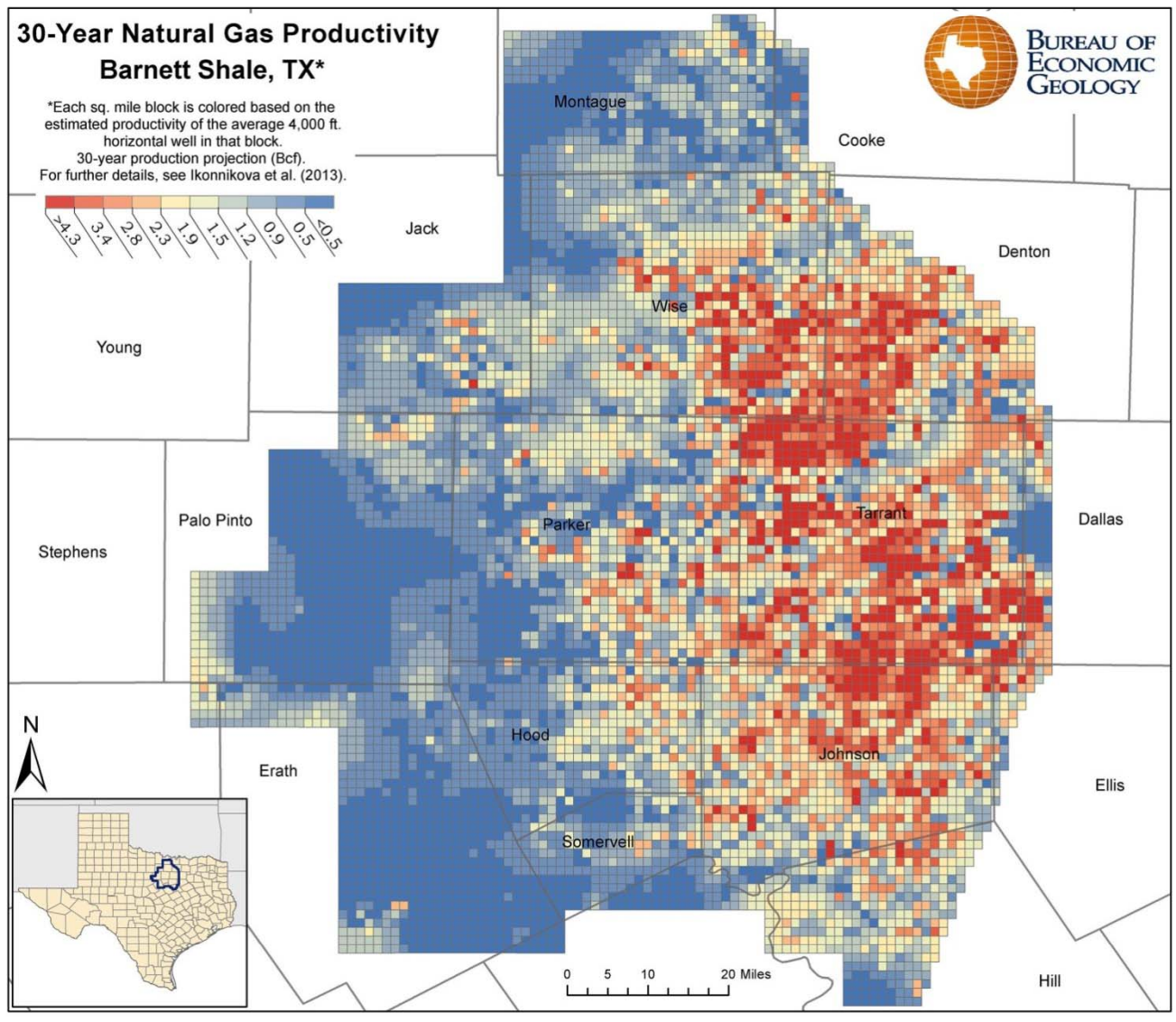
Mudrocks are no longer ignored!

And it's probably fair to say that we are in the *middle of a scientific revolution* in our understanding of the most common type of sedimentary rock.

We now know that mudrocks:

- Are a complex class of rocks that displays heterogeneity greater than that of sandstones and limestones.
- Contain abundant clay-size *crystals*, but are not necessarily dominated by clay *minerals* nor by clay-size *grains*.
- As "source, seal, and reservoir" for oil and gas, should be thought of as hosting *exploration targets,* because assessing mudrock heterogeneity is a solvable problem……

Productivity Tiers of the Barnett Shale; Browning et al., 2013.



"Sweet spots" : suggest potential for significant gains in efficiency by application of exploration models that address depositional environments, grain source mixing, and other basic causes of shale heterogeneity.

http://www.beg.utexas.edu/info/sloan_barnett.php

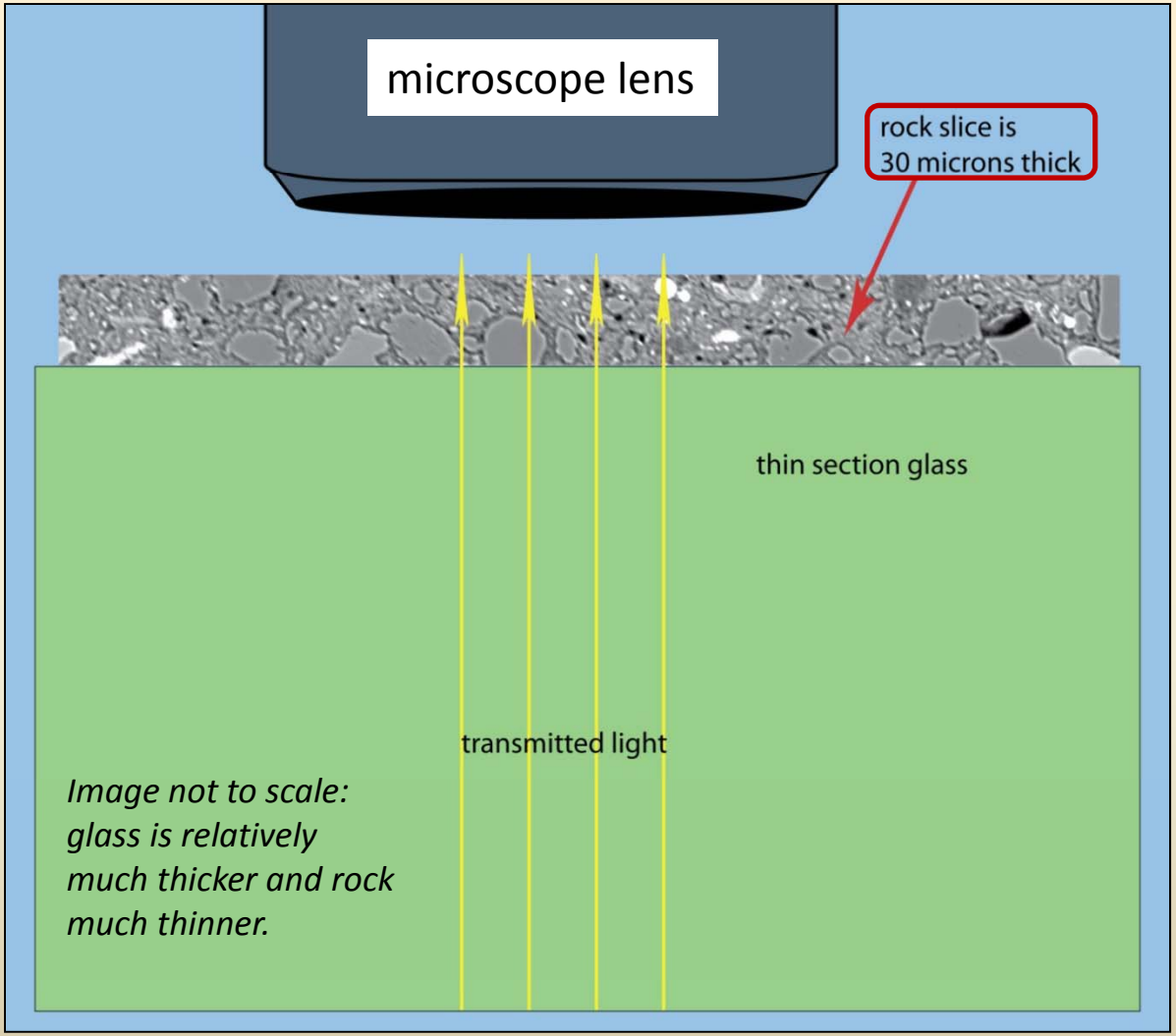
The Mudrock Problem in Light Microscopy:

Henry Clifton Sorby
"father of petrographic microscopy"

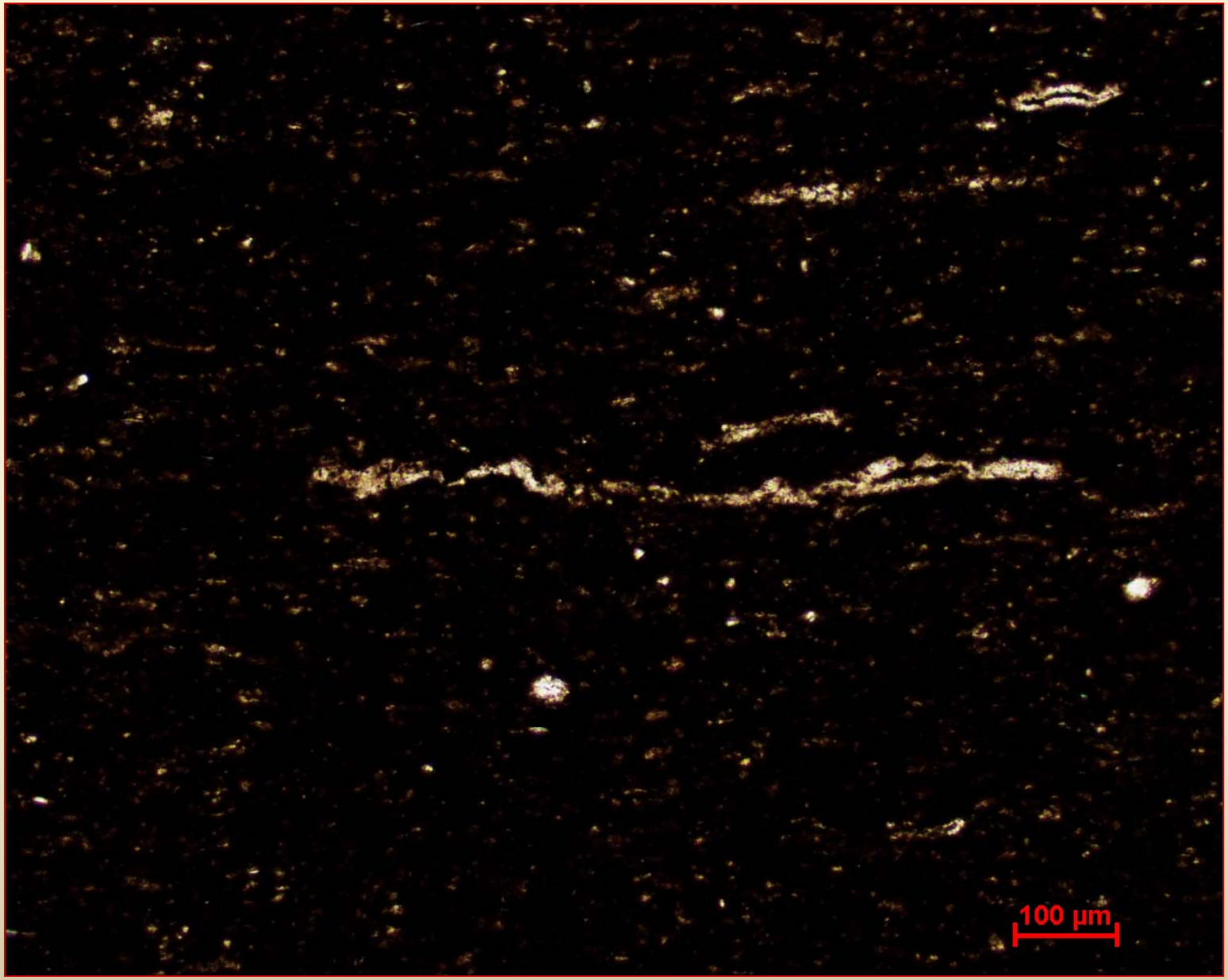
The challenge of mudrocks (shales) in the 19th century and today:

Components in mudrocks (grains, pores) are generally smaller than the thickness of the standard thin section (30 μm) used for light microscopy.

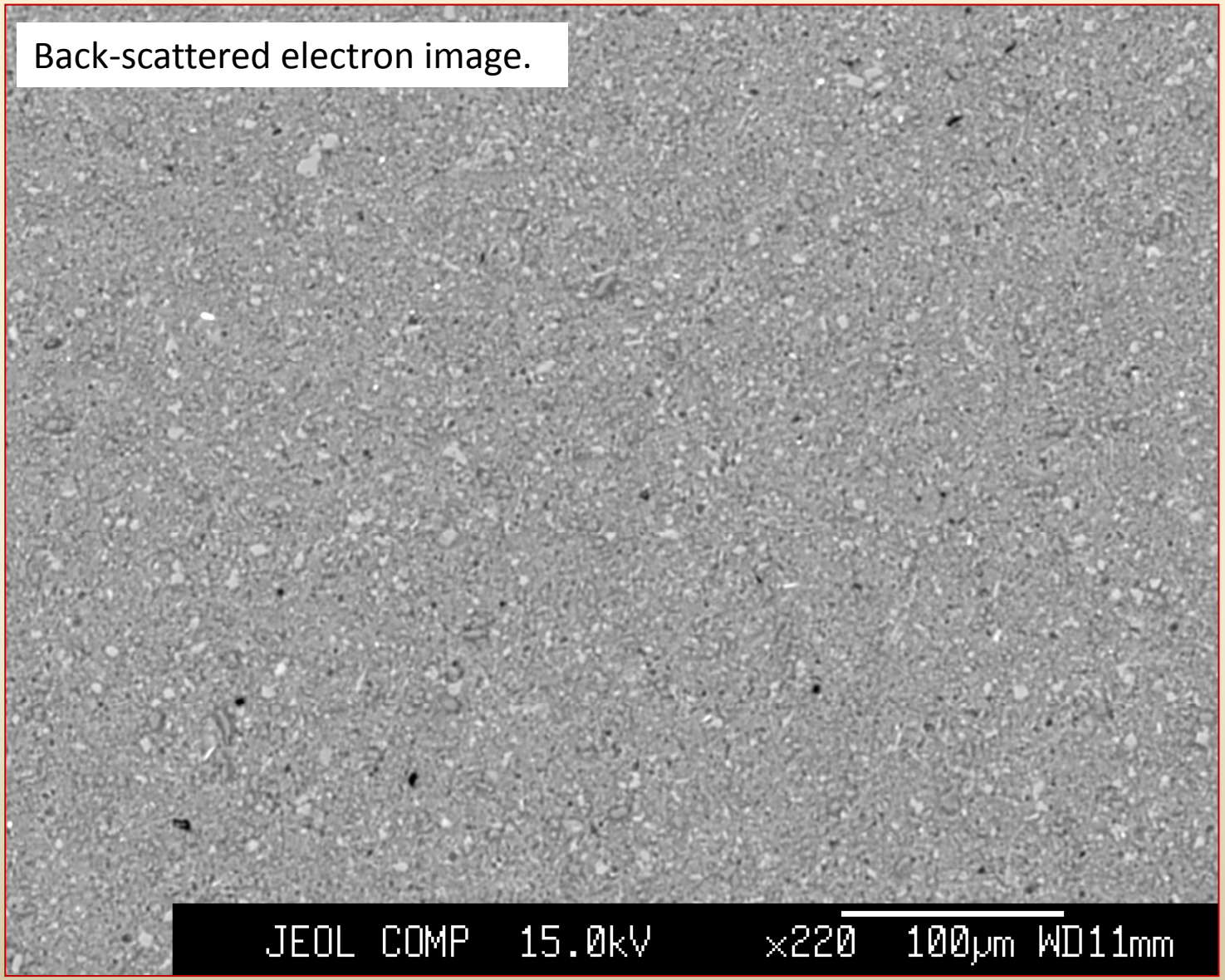
30 microns = 30,000 nm!



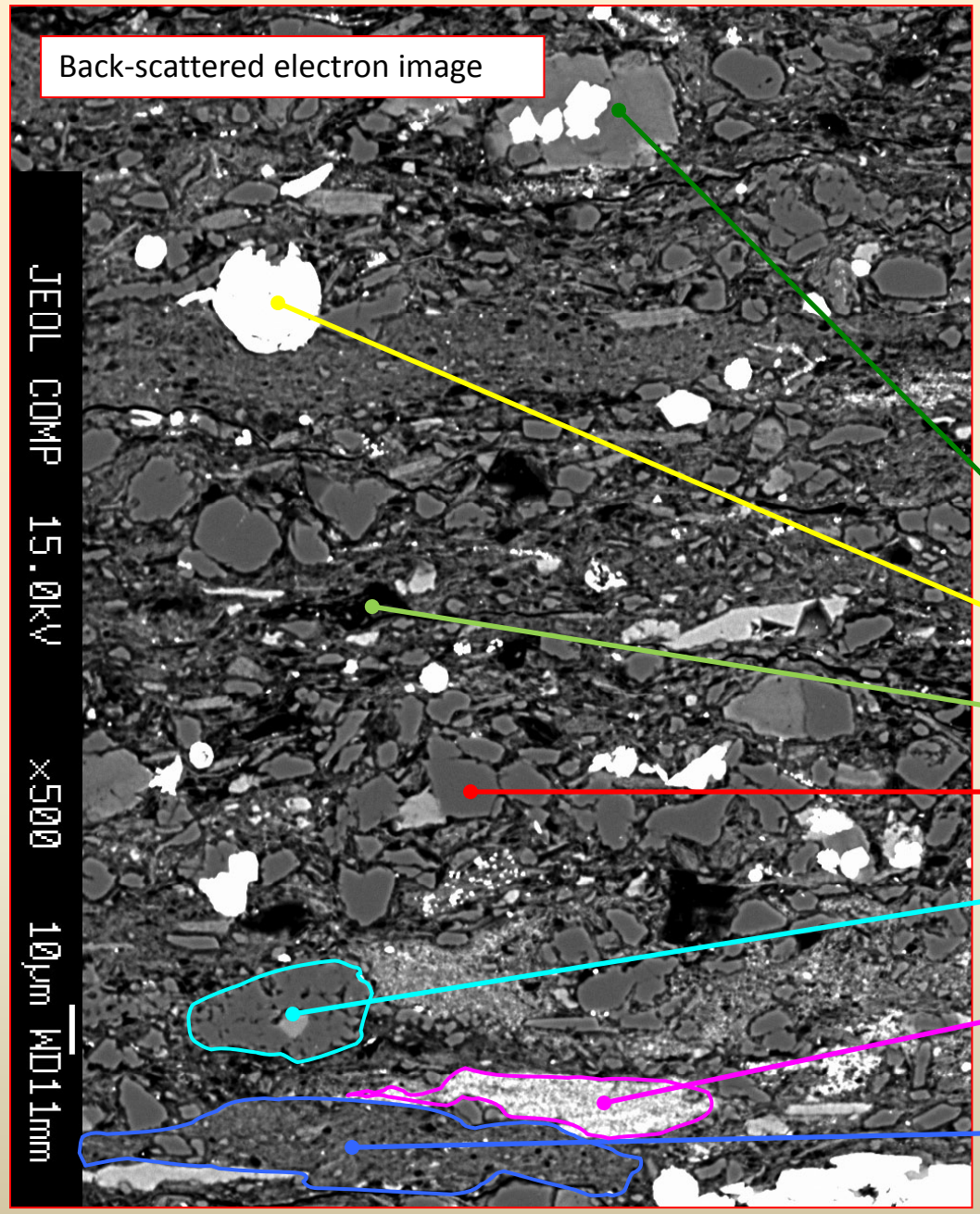
Barnett Shale seen in transmitted polarized light microscopy.



Claystones exist but are NOT the most common type of mudrock.



Oligocene Frio Formation, South Texas, USA.



Mudstones (mudrocks, shales) contain abundant:

- silt-size and sand-size grains
- non-clay minerals
- detrital and authigenic components
- fossils

Dolomite (authigenic?)

Pyrite (authigenic)

Organic matter

Quartz or feldspar (detrital)

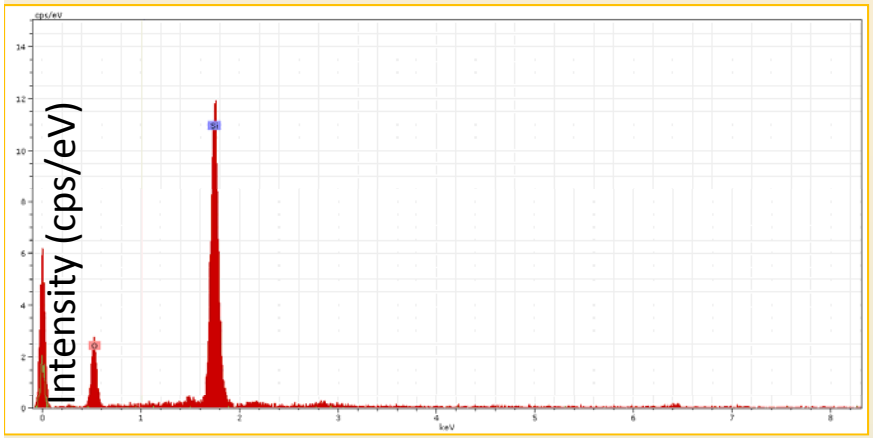
Agglutinated foraminifer

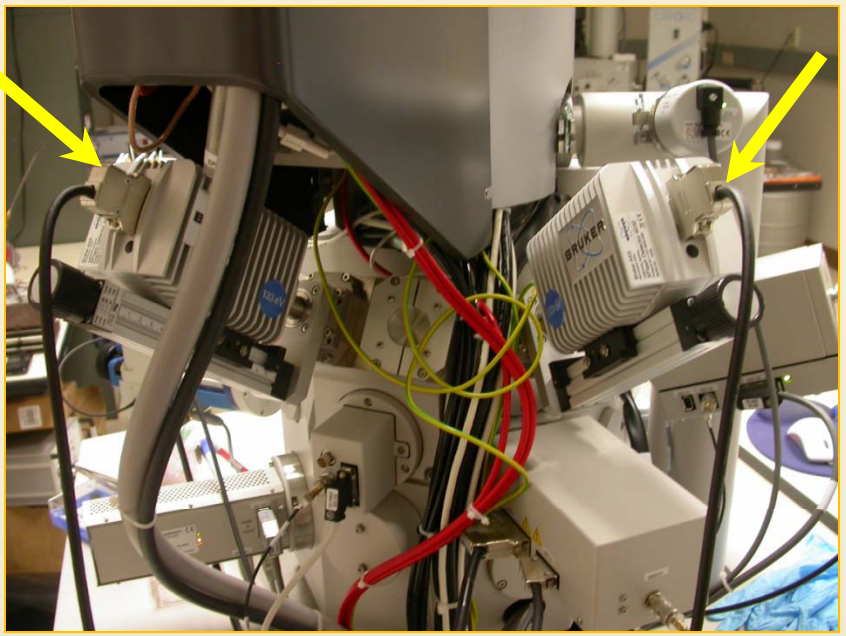
Phosphate clast

Clay aggregate

Barnett Shale, Wise County, Texas, USA

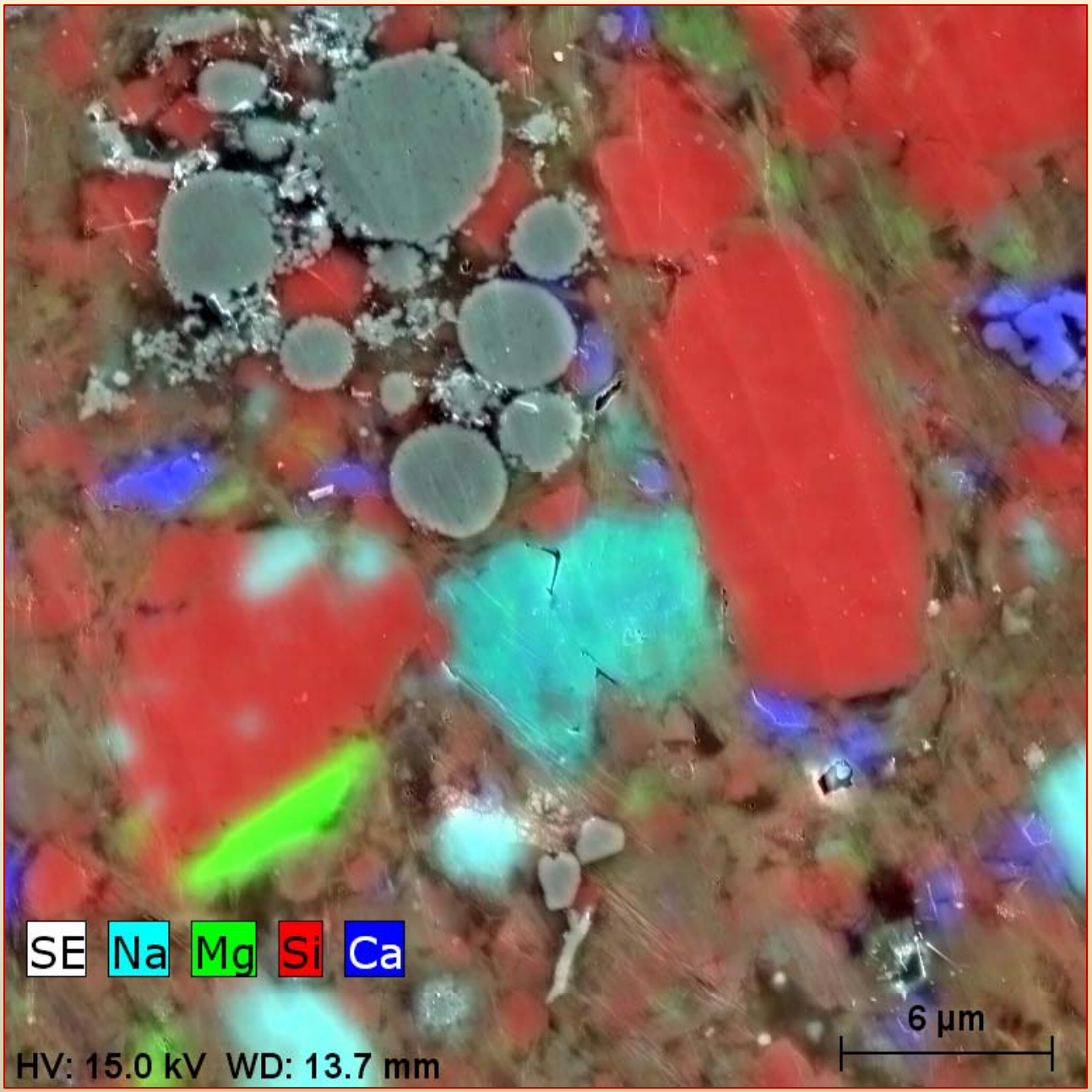
X-ray mapping by Energy-Dispersive Spectroscopy (EDS)





Twin 30 mm^2 EDS detectors: sum the signals

X-ray signal can be used qualitatively for element ID or mapping, or quantitatively for analysis.



Marcellus Formation, Pennsylvania

Multi-element map:

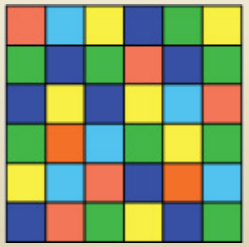
Nova NanoSEM 430

<5 nA

15 KV

10 minutes

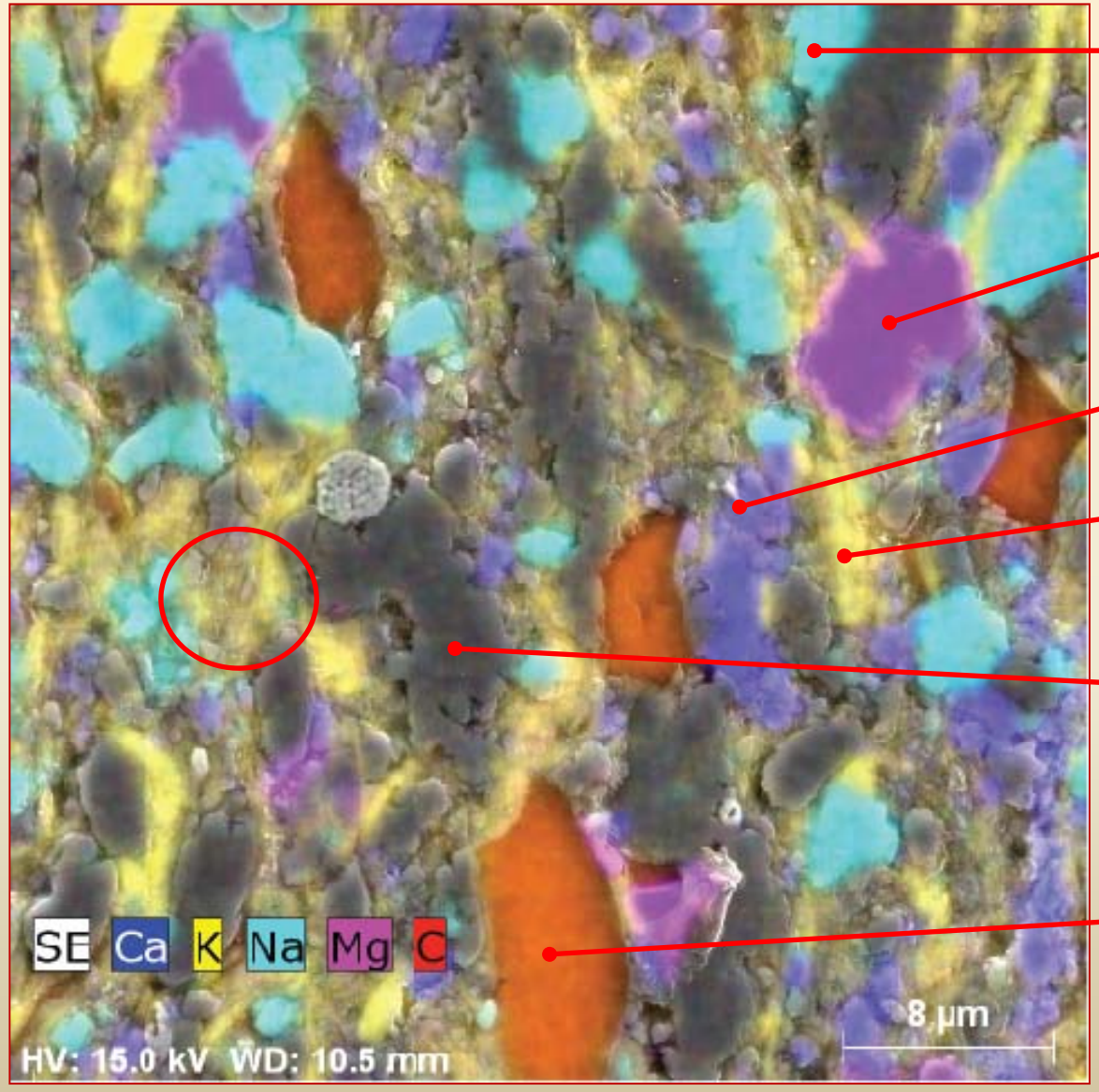
0.05 micron/pixel (approx)



1-micron pixel resolution

Mudrocks contain complex grain assemblages.

DETRITAL, mostly extrabasinal grains:



Barnett Shale, Ellis County, Texas, USA

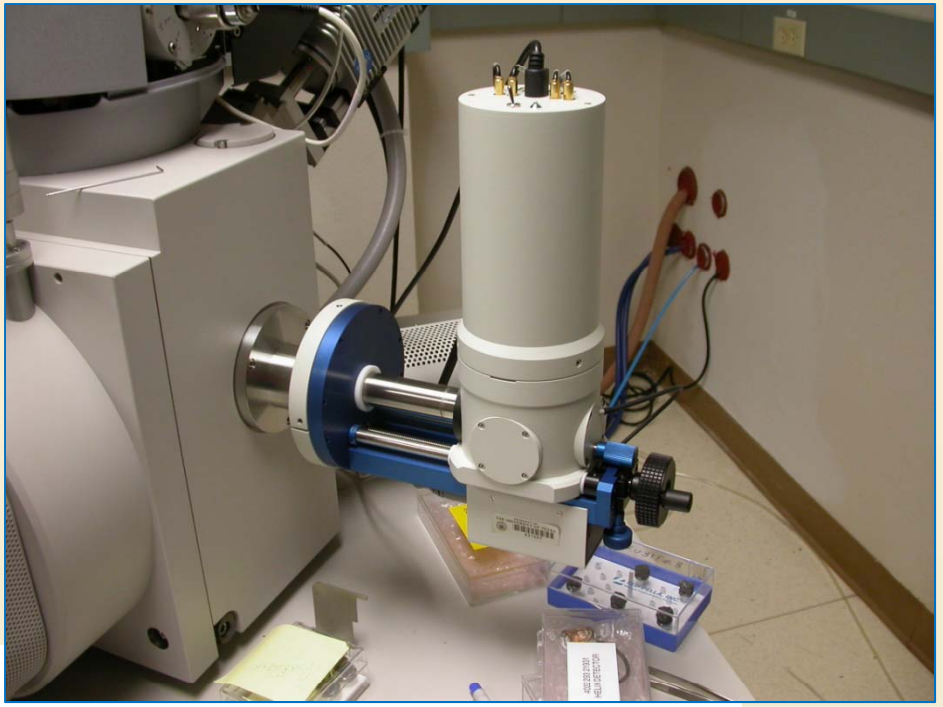
X-ray map

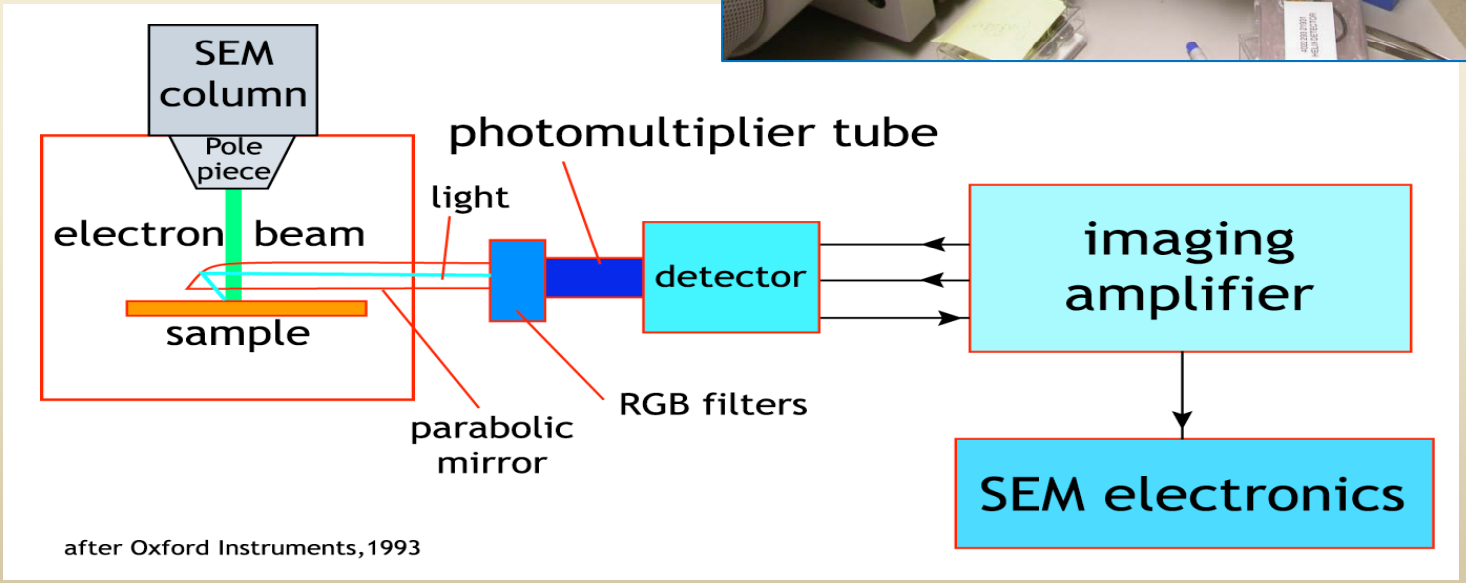
Scanned Cathodoluminescence Imaging

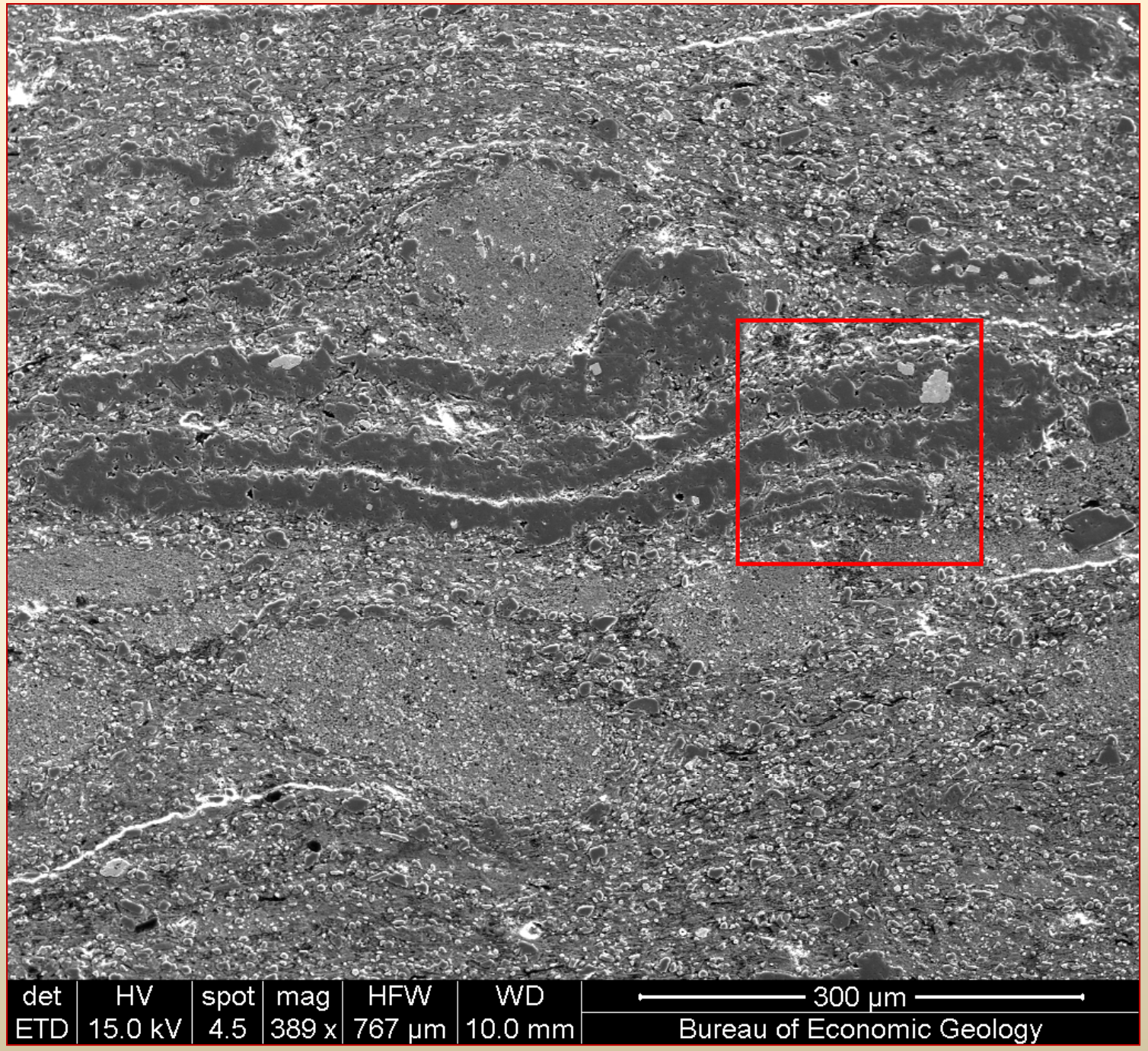
Visible light emitted in response to electron beam excitation.

Sensitive to trace element and defect variations.

Images subtle chemical differences that are invisible in other techniques.

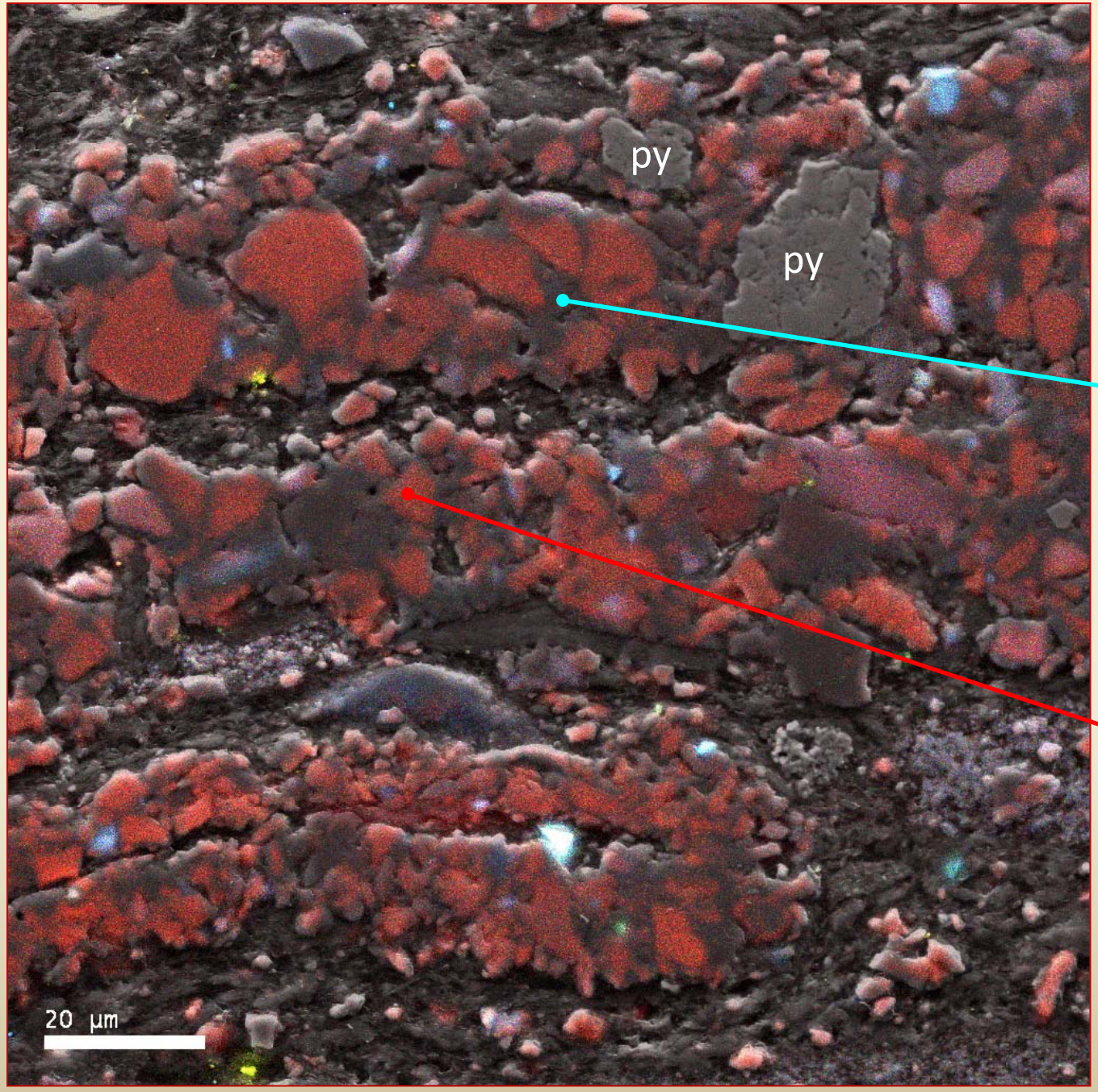






SE/BSE image

Barnett Shale, Wise County, Texas

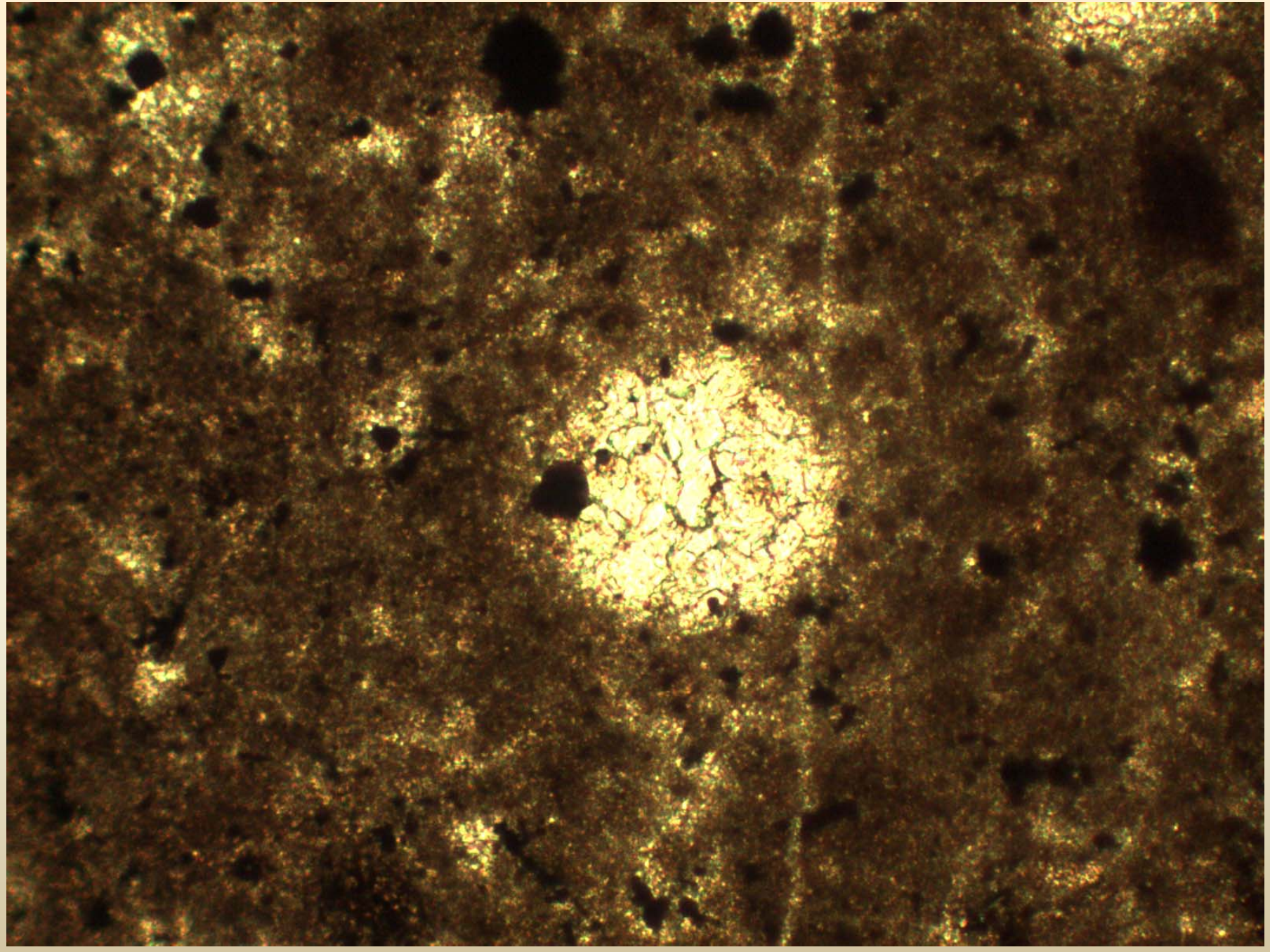


“matrix” quartz with dark CL:
- former opal?
- former organic matter?

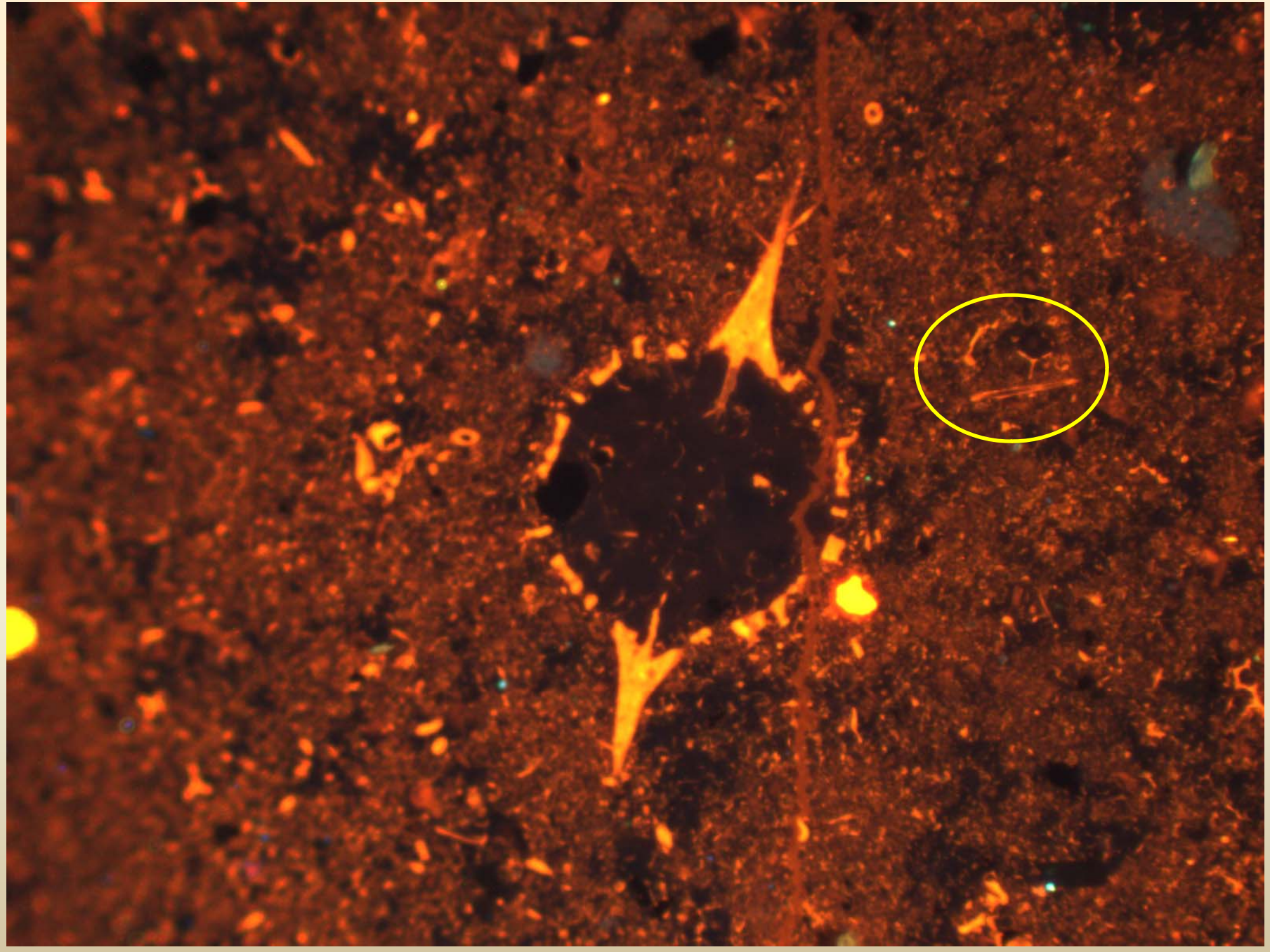
Angular silt with variable CL color & brightness

SE/BSE image

Barnett Shale, Wise County, Texas

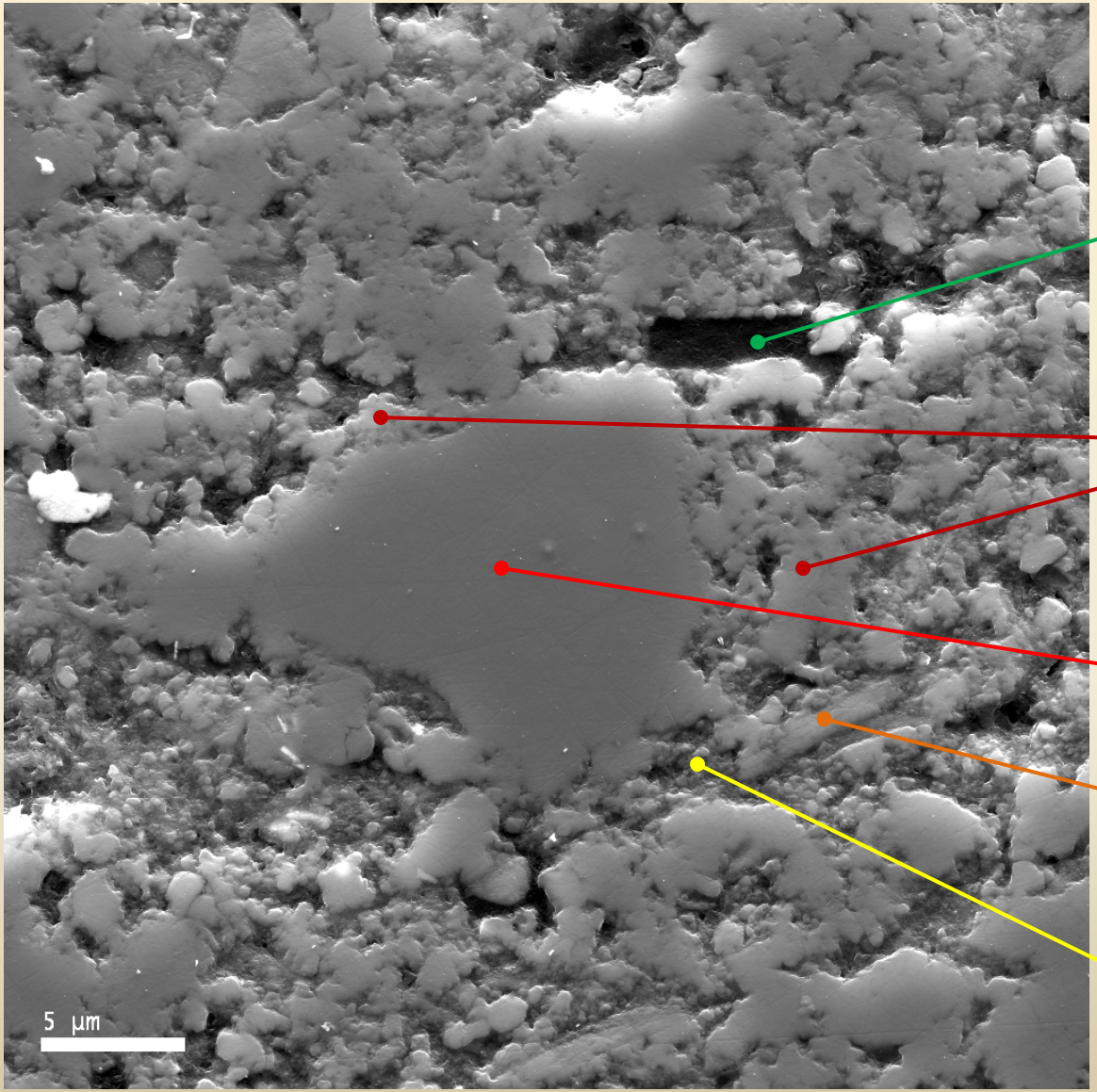


Barnett Shale, Wise County, Texas



Barnett Shale, Wise County, Texas

Barnett Shale: siliceous lithology



organic matter

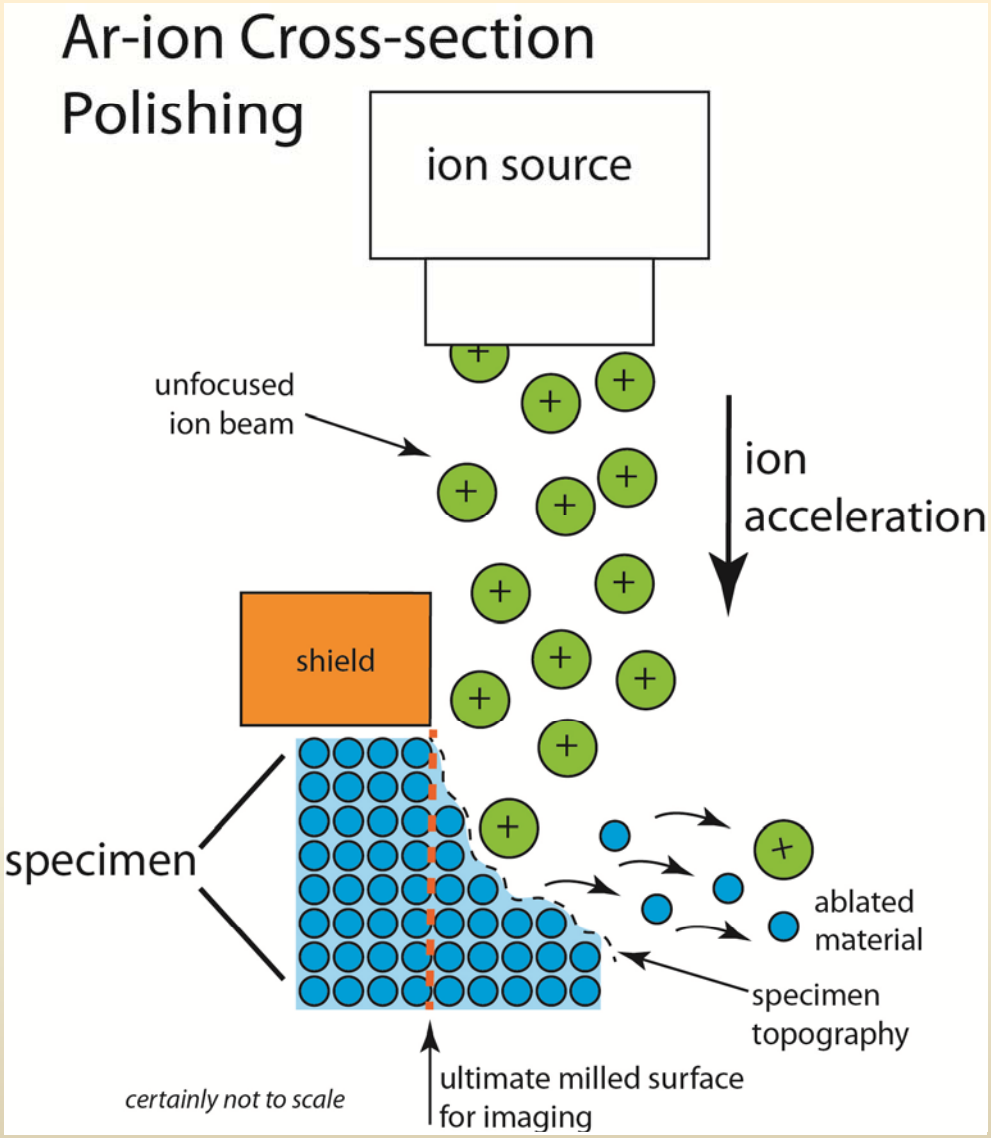
microquartz cement

extrabasinal quartz grain

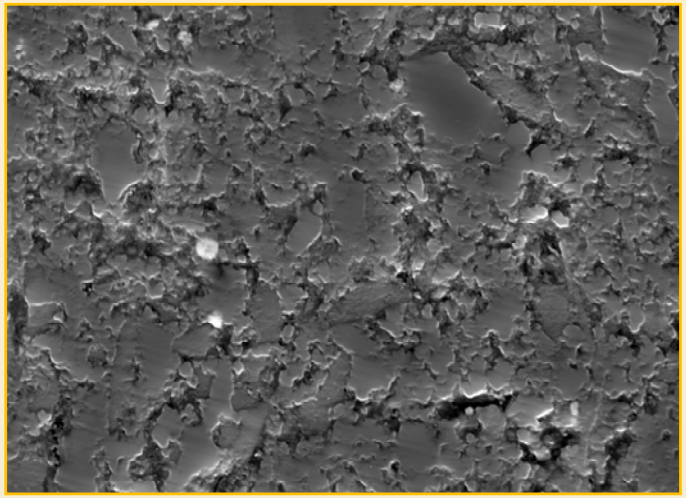
mica

clay mineral matrix

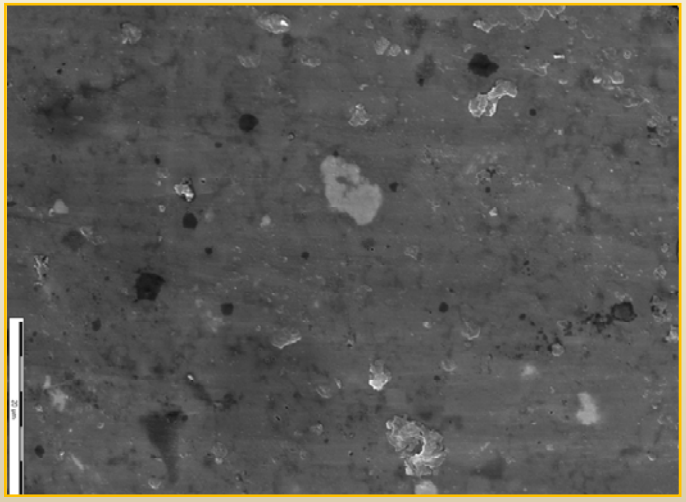
Barnett Shale, Ellis County, Texas



Barnett Shale sample:

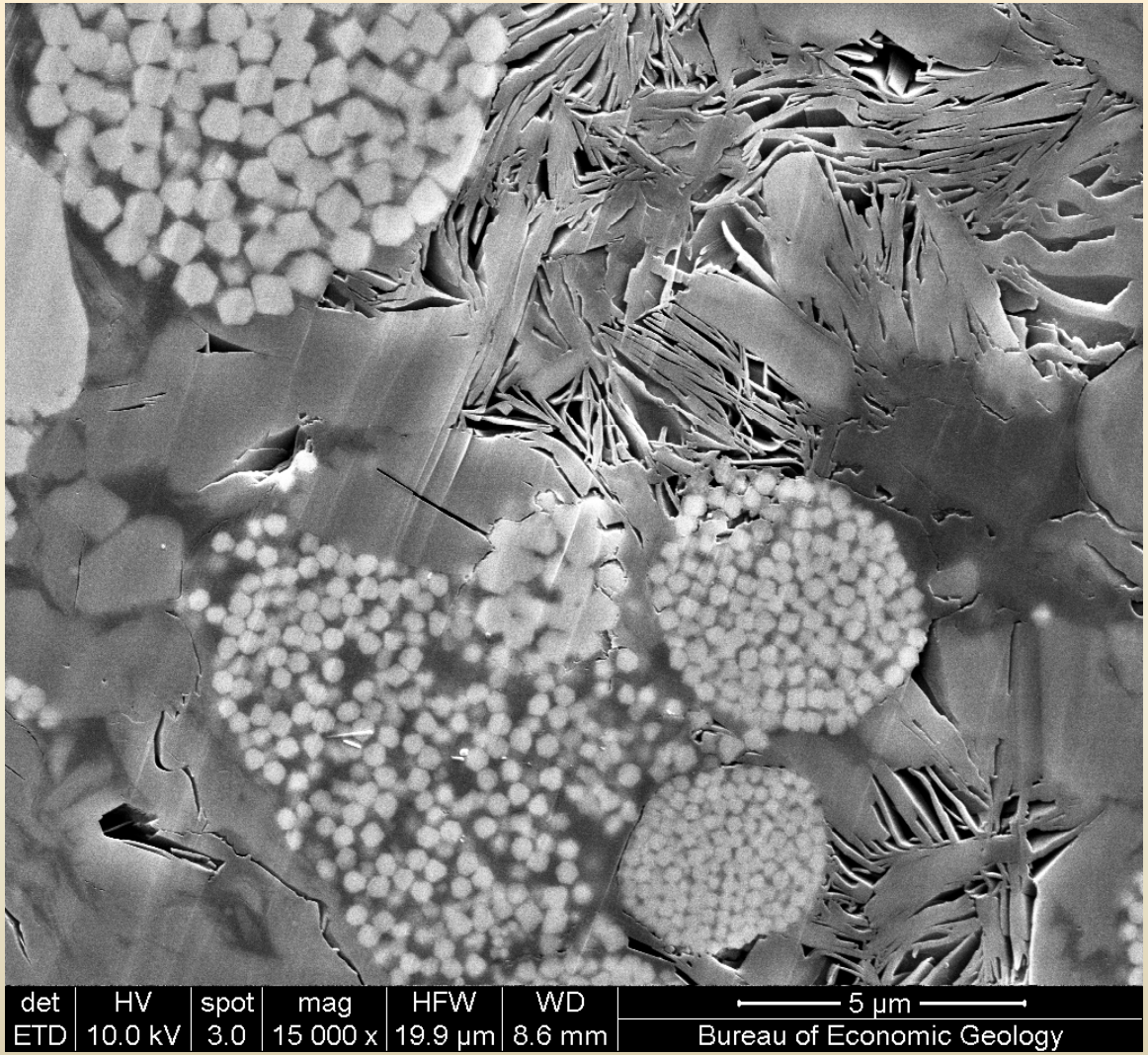


Polished thin section



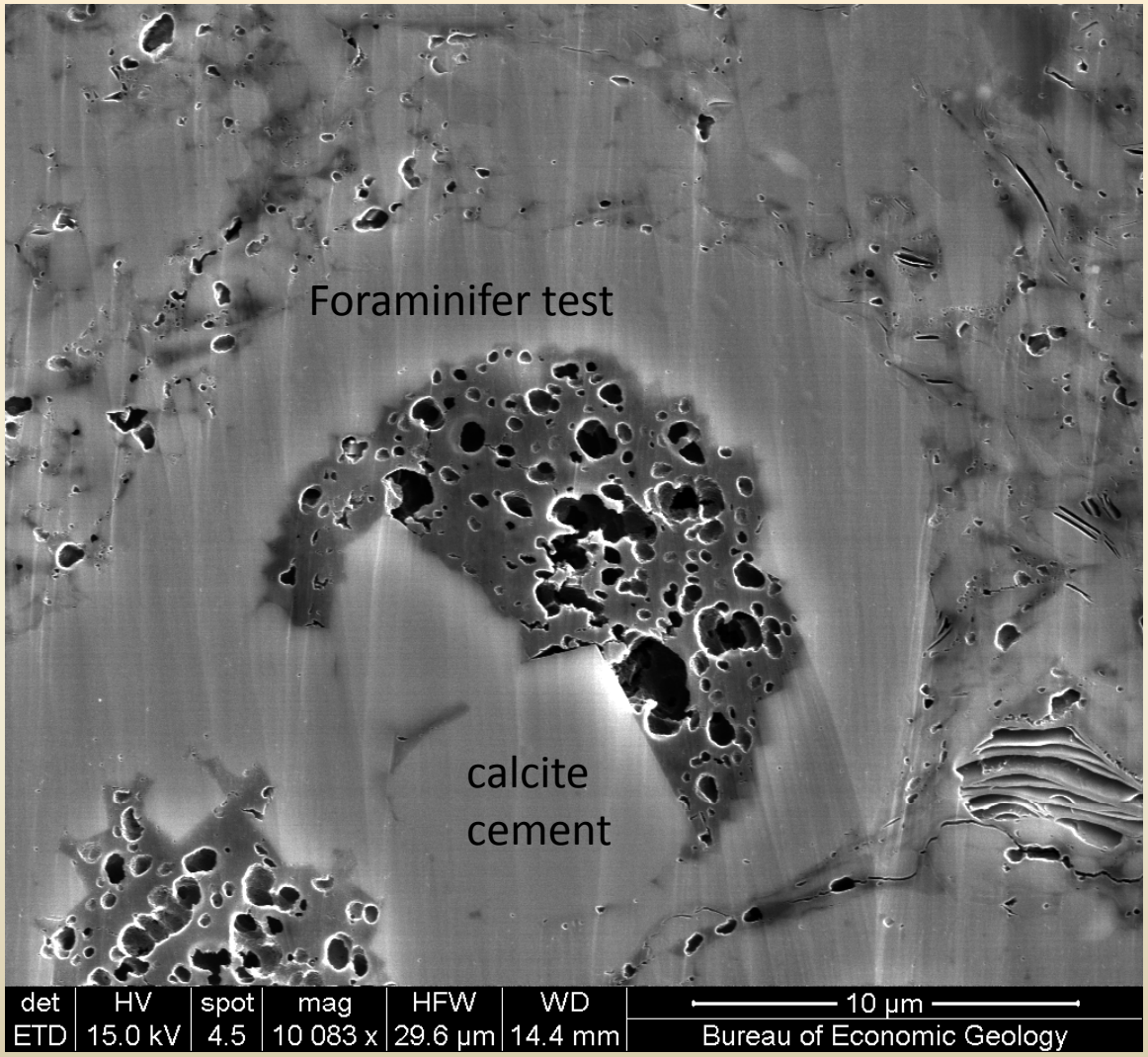
Ion-milled surface.

Mineral-hosted pores



Eagle Ford Formation, South Texas.

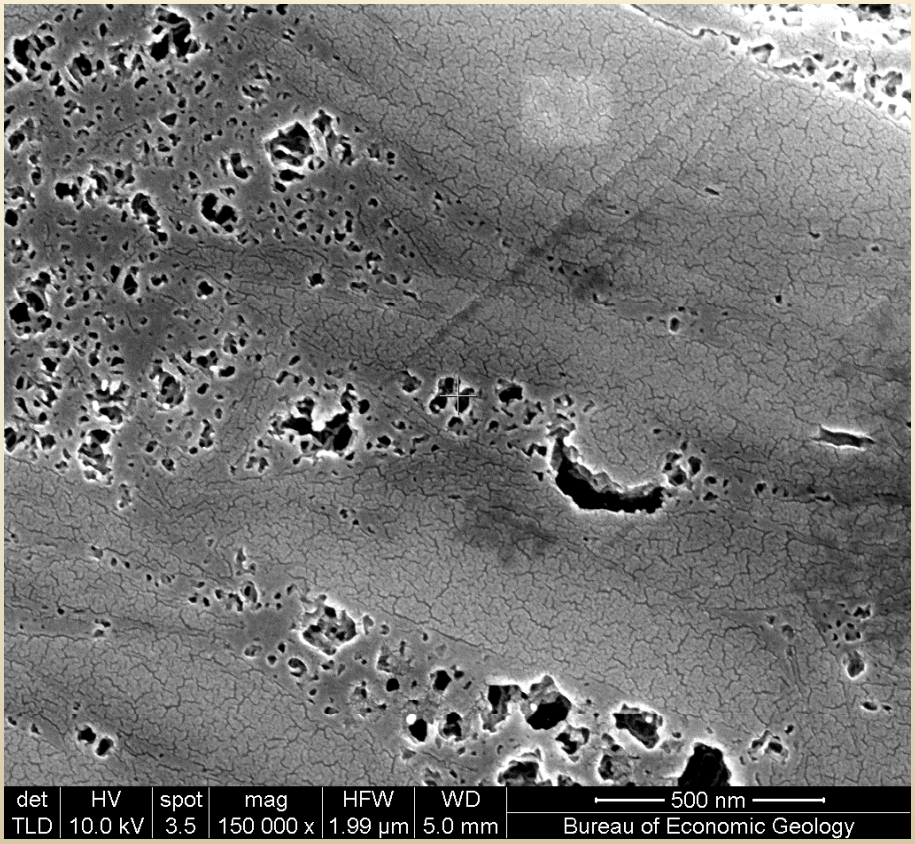
Secondary pores within pore-filling residual hydrocarbon.

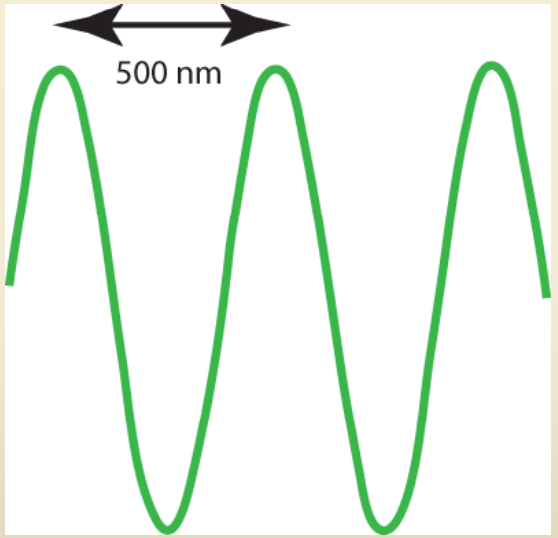


Eagle Ford Formation, South Texas

Something to think about:

Pores in mudrocks are generally smaller than the wavelength of light. Mudrocks are *natural nanomaterials*.





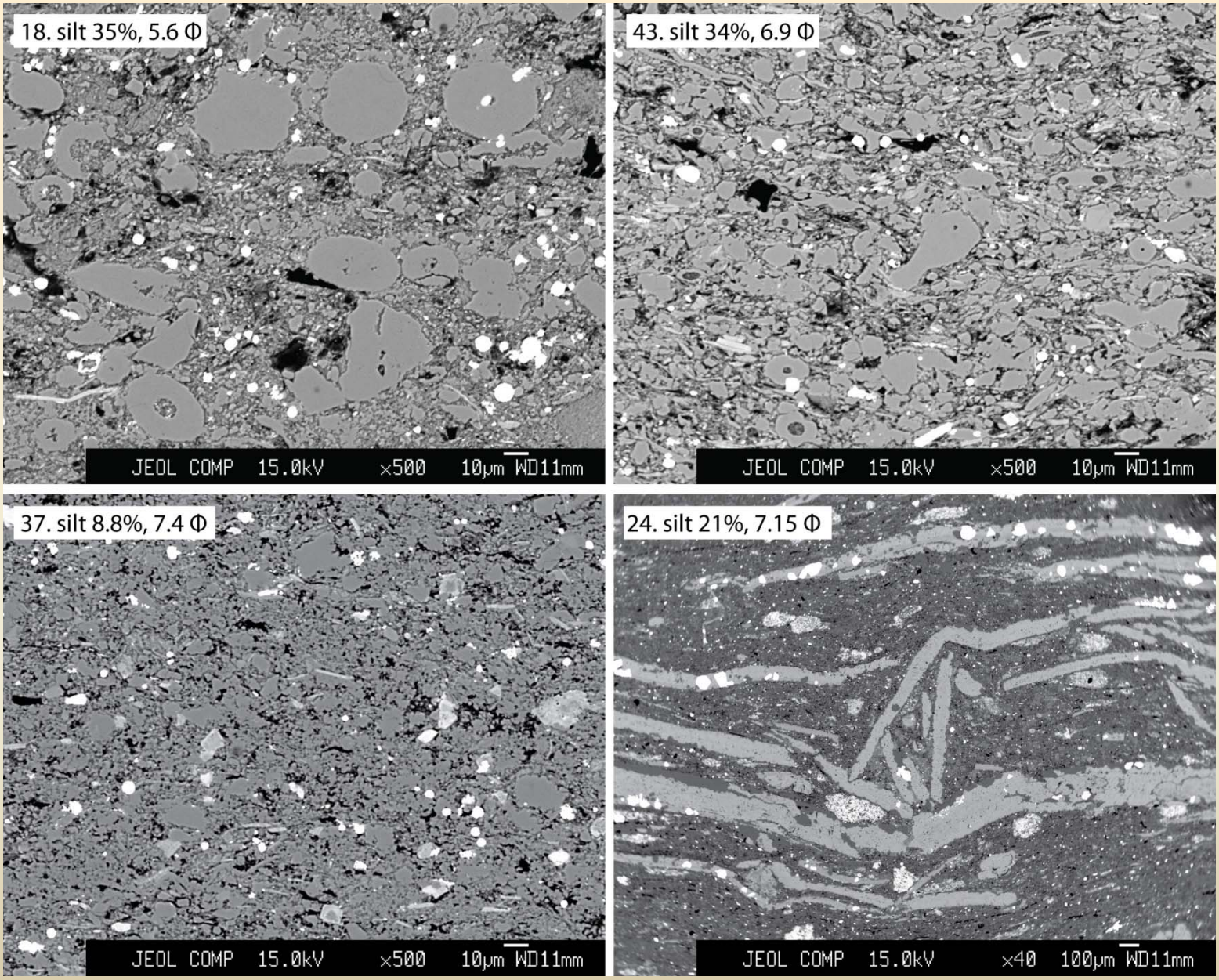
green light

If we had exploration models for fine-grained systems what would we want them to predict ?

Bulk properties:

- Porosity (storage)
- Permeability (flow)
- Organic content (source)
- Mechanical moduli (“frackability”)

Back-scattered electron images.

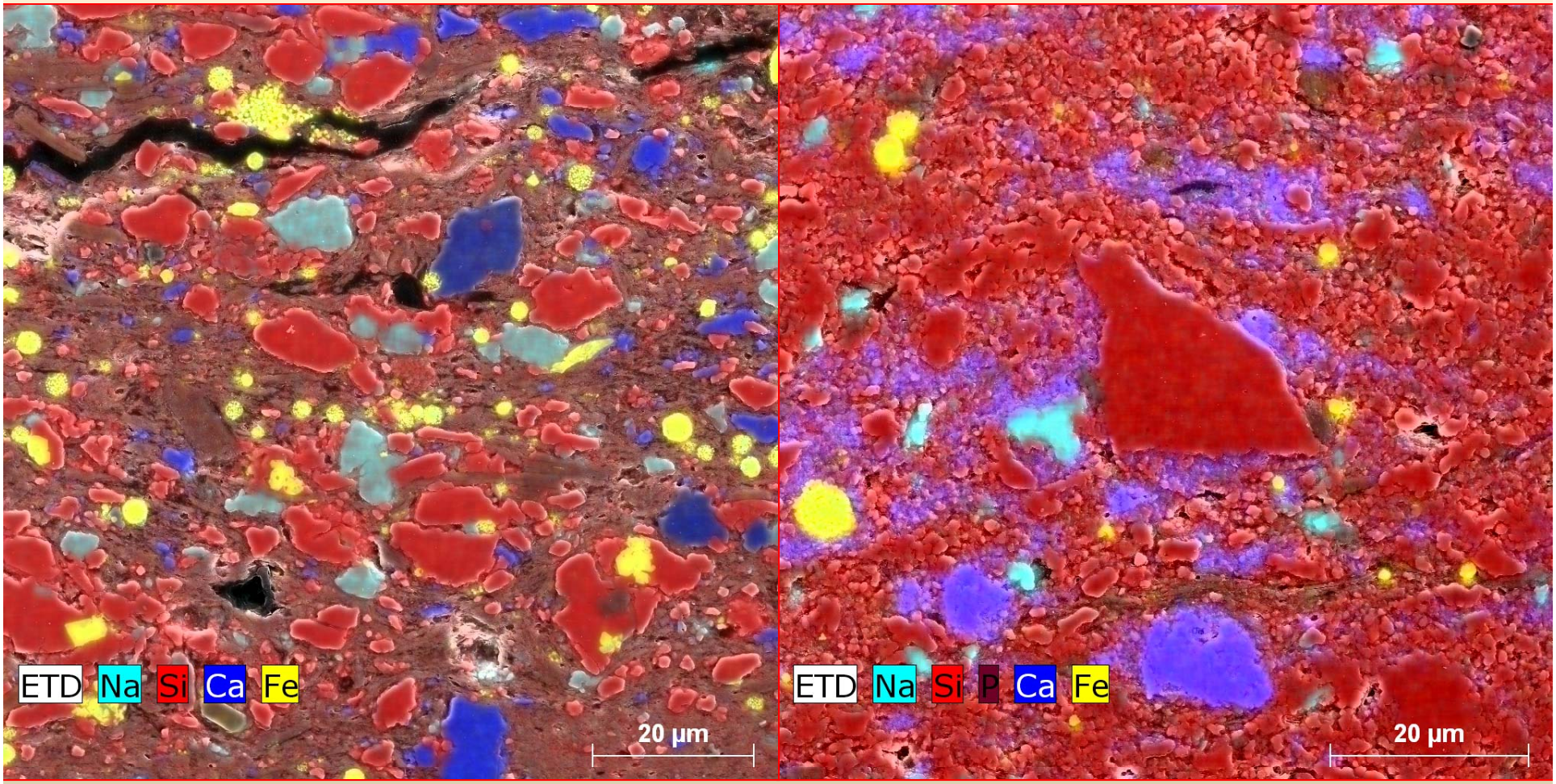


Textural heterogeneity: silt content, silt size

Barnett Shale, Ellis County, Texas, USA

Variations in grain assemblages can be assessed by CL and X-ray mapping.

X-ray maps



Silt-bearing mudstone

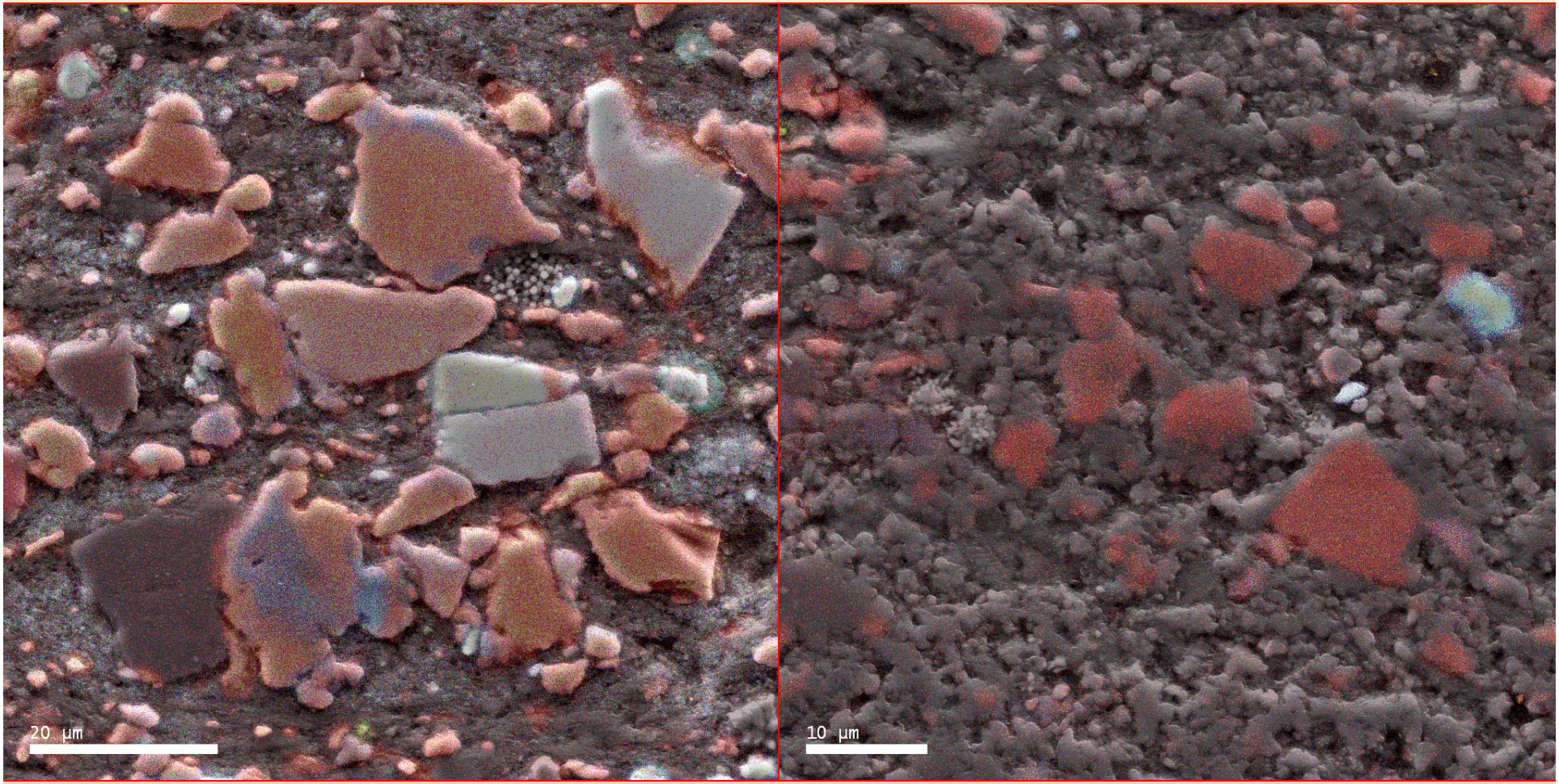
Chert-cemented mudstone

Barnett Shale

Milliken, 2013

Variations in grain assemblages can be assessed by CL and X-ray mapping.

CL maps



Silt-bearing mudstone

Barnett Shale

Cathodoluminescence images

Chert-cemented mudstone

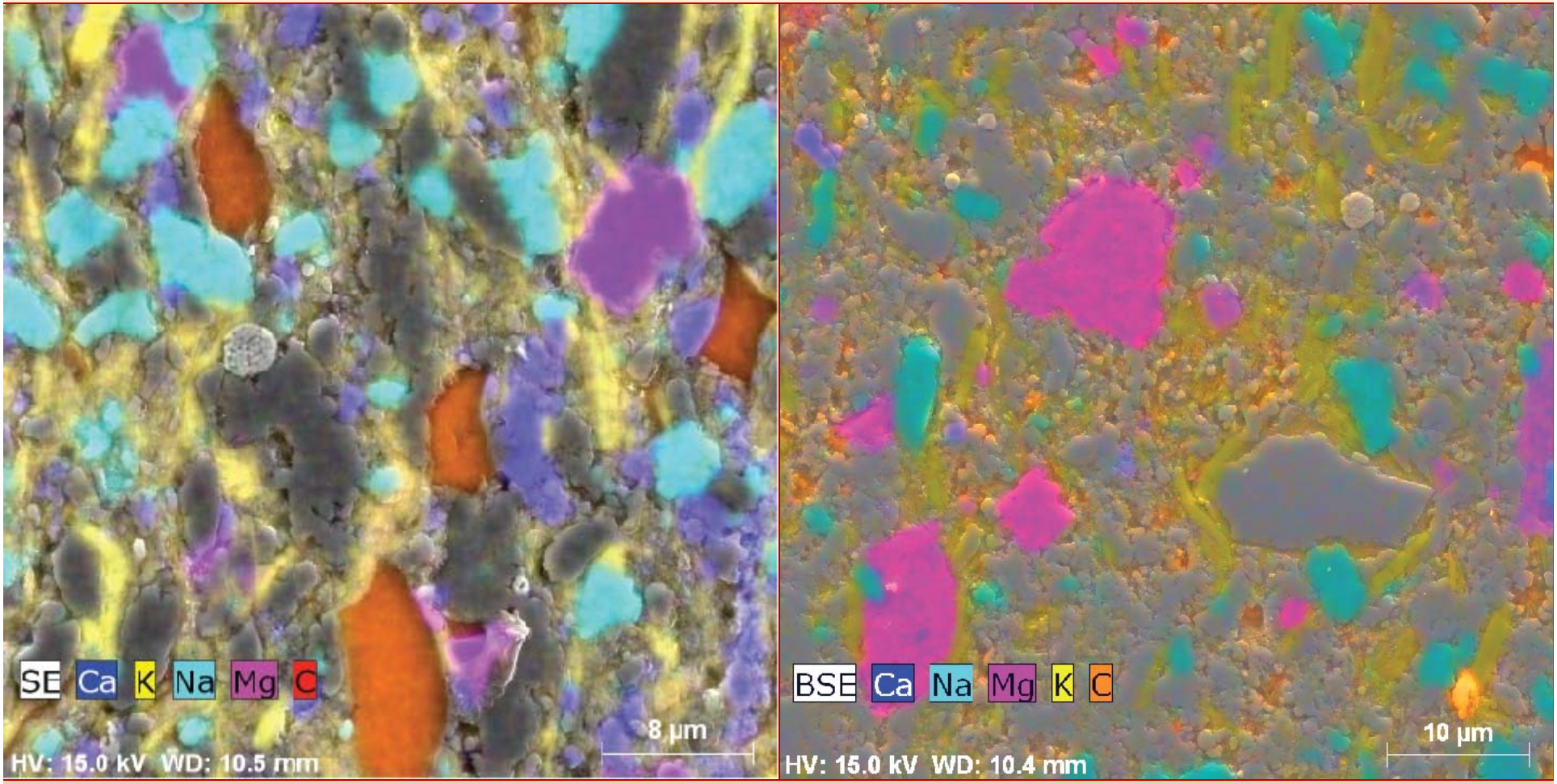
"matrix-dispersed authigenic microquartz"

Milliken, 2013

Variations in grain assemblages can be assessed by CL and X-ray mapping.

X-ray maps

Organic matter: terrigenous vs marine vs residual hydrocarbon.

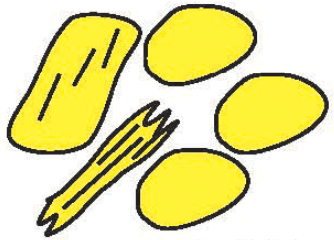
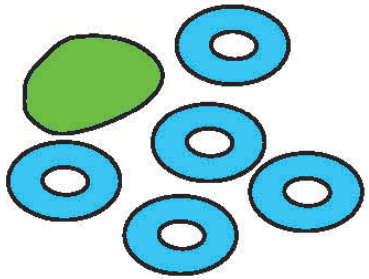
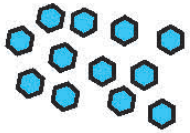


Silt-bearing mudstone

Chert-cemented mudstone

Milliken et al., 2012

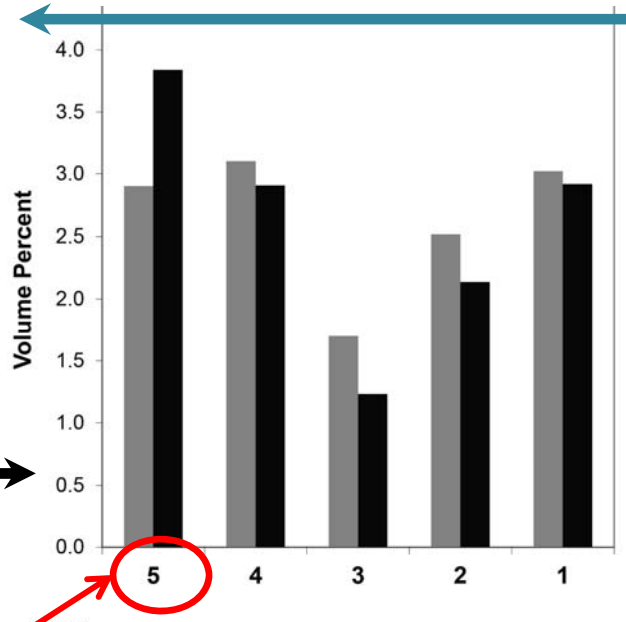
Four-component mixing system for sediments in the Barnett Shale

	Silt-size components	Clay-size components
Extrabasinal debris	 quartz, feldpar, mica	 clay, quartz, feldspar
Intrabasinal particles	 bio-siliceous allochems, glauconite	 bio-siliceous allochems

Quartz may dominate in 3 of these, even in a single sample.

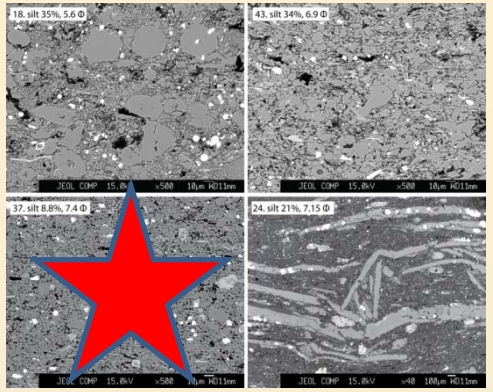
Milliken et al., 2012

Declining extrabasinal content



TOC

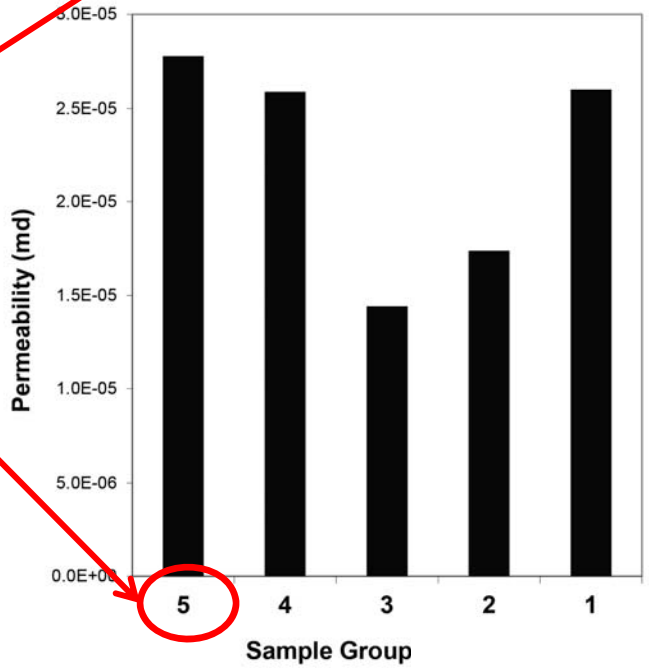
Porosity



Chert-cemented mudstone

Silt-bearing mudstone

Porous
Permeable
Brittle
Oil-prone



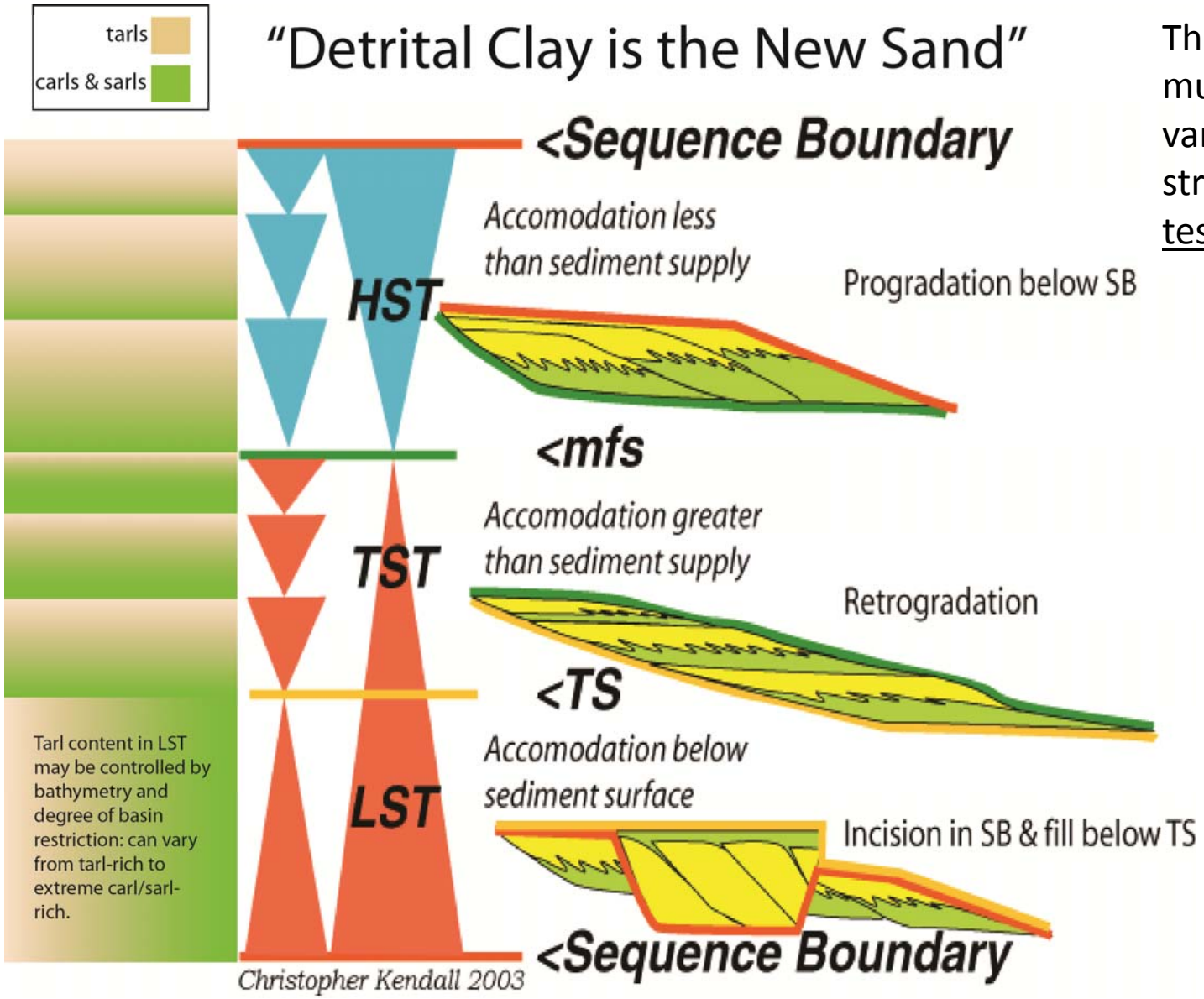
MODEL

best reservoir quality where:

- extrabasinal influx is minimal
- marine OM is highest
- siliceous fossils react to form brittle mudstones.

Milliken et al., 2012

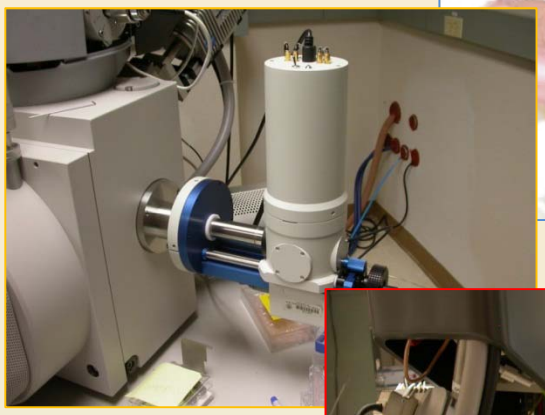
Future Exploration Model?

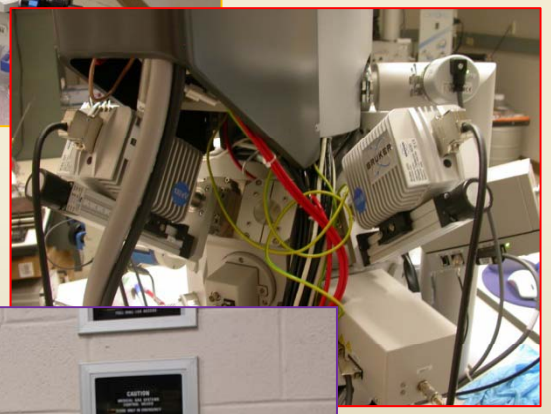


Theoretical idea for mudrock compositional variation across stratigraphy needs to be tested.

Transformative Technologies for Micro-Imaging:

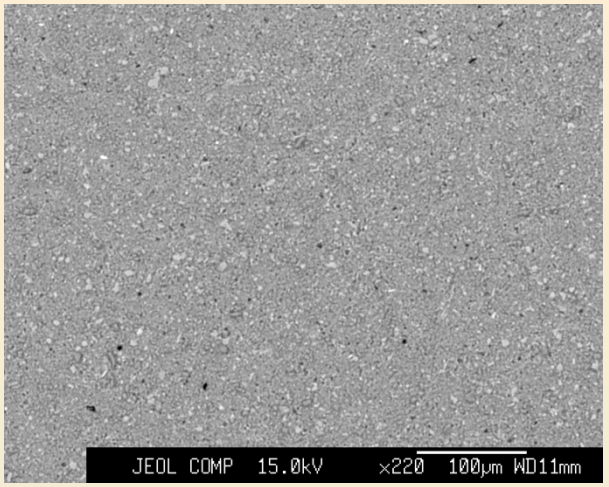
- Light microscopy
- X-ray mapping & CL imaging
  - Grain assemblages in mudrocks
- CL-imaging
  - Integrated chemical-mechanical history
- FE-SEM
  - *Ar-ion cross-section polishing*
  - Pore systems in mudrocks: correlating pore evolution to thermal maturity





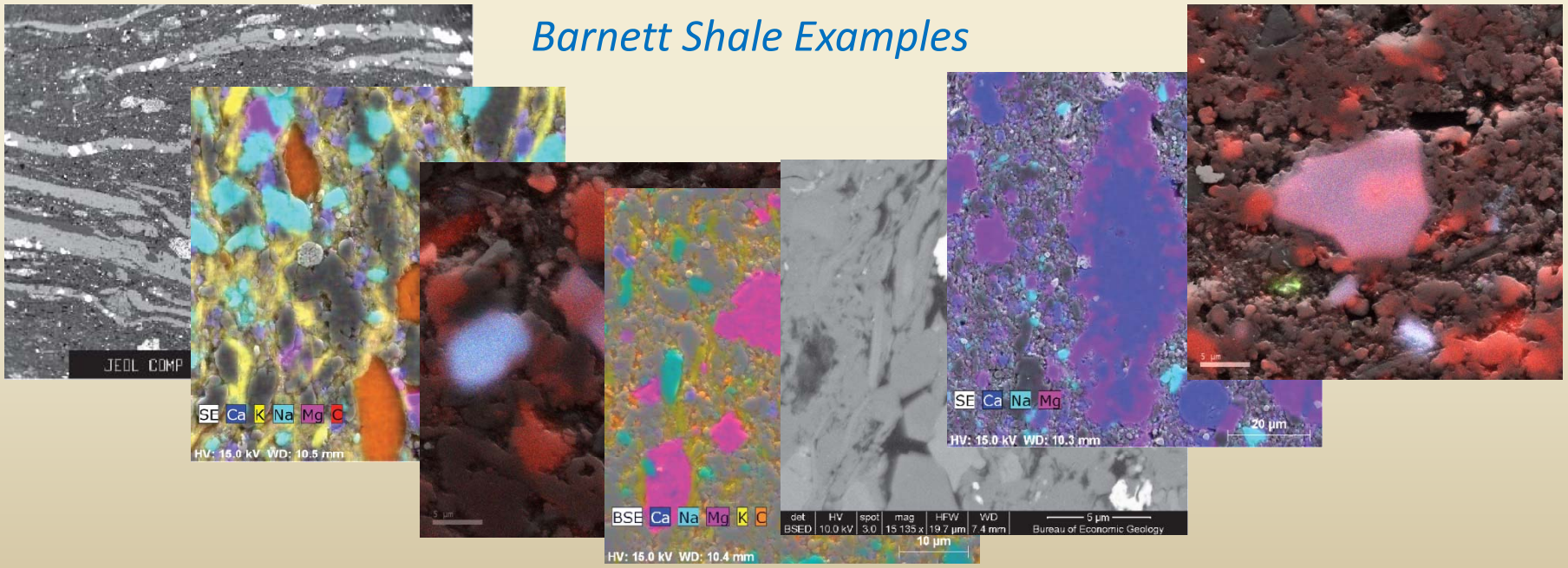
Apparent homogeneity of shales as seen by visual inspection is misleading……

At high magnifications, we learn that most shales don't look like this:



But rather, like:

Barnett Shale Examples



Building exploration models for fine-grained depositional systems: What does it take?

integration

integration

integration

- Training (undergraduate and graduate levels)
  - Basic chemistry, physics, biology, mathematics
  - Basic geoscience
  - Sedimentology and stratigraphy
  - Mineralogy and geochemistry
  - Petrology
  - Paleontology
- Working environment
  - Interdisciplinary
  - Multi-scale: basinal to nanometer
- Tools
  - High-quality log suites
  - Core descriptions
  - Micro-imaging
    - Light microscope
    - X-ray mapping
    - CL imaging
    - High-resolution pore imaging
    - Many affiliated techniques

http://www.fei.com/natural-resources/oil-gas/

Drivers:

- Economic motivations
- Technologies
- Scientific understanding

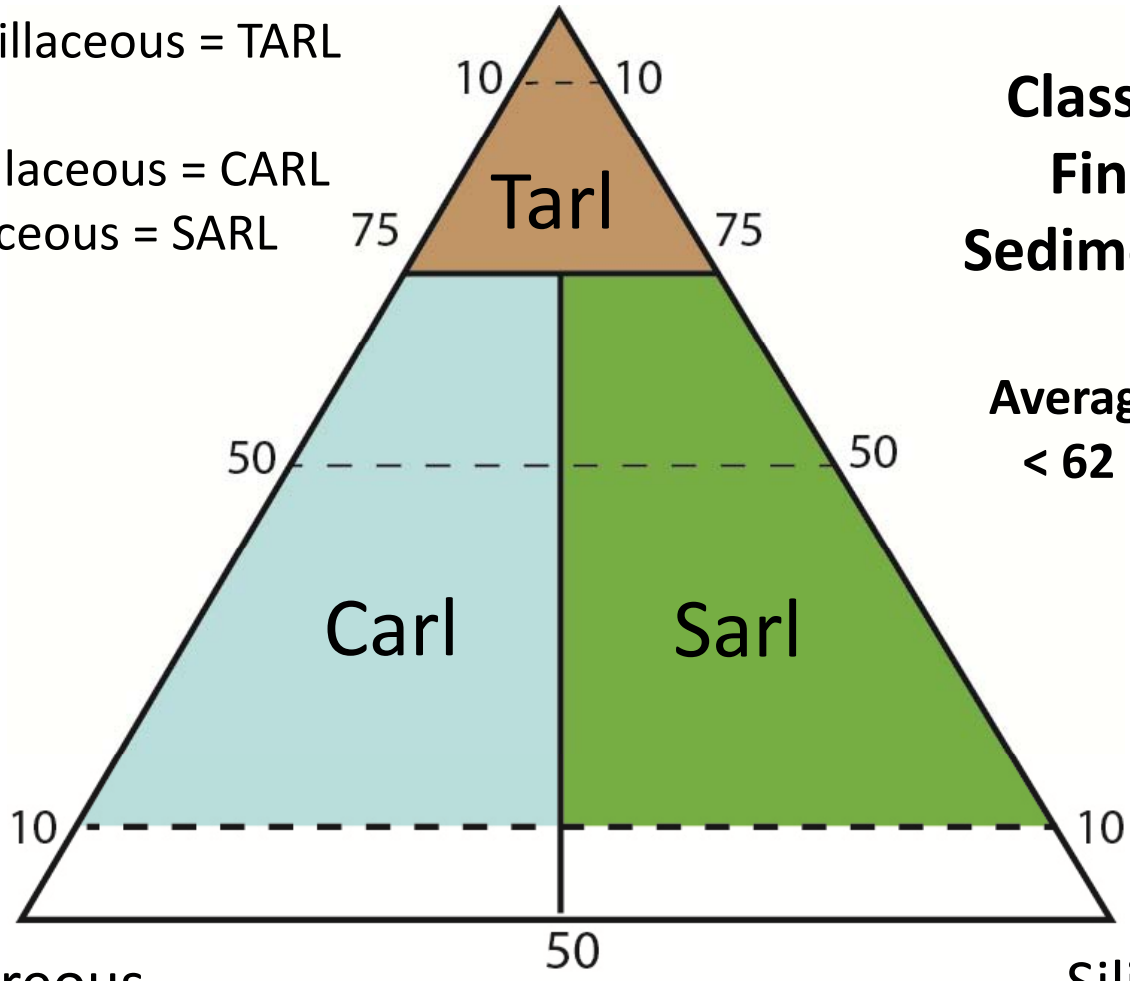
Needs:

- Education in rock-based studies
- Integration across disciplines and scales
- Cores (please share!)
- Time (Research takes time…..)

THE UNIVERSITY OF TEXAS AT AUSTIN
JACKSON SCHOOL OF GEOSCIENCES

BUREAU OF ECONOMIC GEOLOGY

EXTRABASINAL:
Terrigenous-argillaceous = TARL
INTRABASINAL:
Calcareous-argillaceous = CARL
Siliceous-argillaceous = SARL



Classification of Fine-grained Sedimentary Rocks

Average particle size < 62 micrometers

From Milliken, in press, JSR.