Multiscale characteristics of anisotropic, heterogeneous pore structures and compositions and its impact on mechanical properties of shale

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Sandia National Laboratories

Exceptional service in the national interest

SEPM 2016 Mudstone Diagenesis

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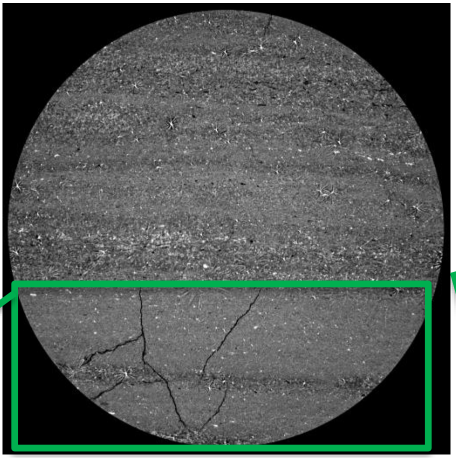
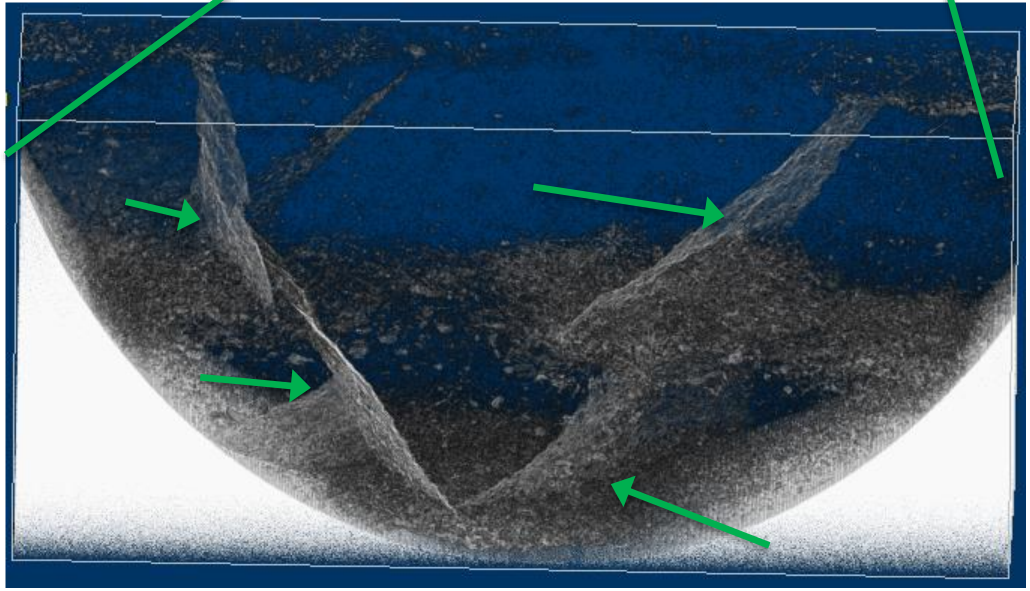
Shale Poromechanics: Multiscale Heterogeneity in Compositions, Pore structure, and Mechanical Properties

► Understand how heterogeneity, pores, cracks, flaws etc. contribute to shale poromechanics over scales and provide physical basis for core-scale measured deformational and transport constitutive behavior

► Develop novel and cutting edge techniques and workflow for a linked imaging, experimental, and modeling-based advancement of shale poromechanics

MicroCT Image of 1" core Mancos shale (17 microns resolution)



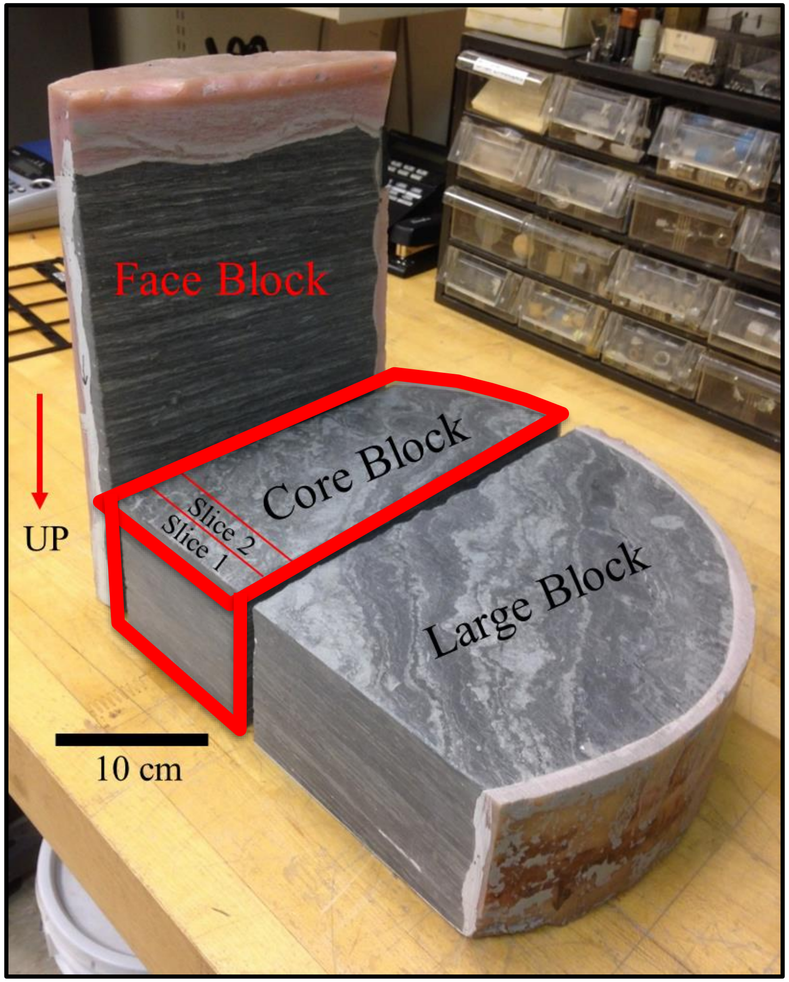


Courtesy: *N. Chakraborty on PSU's GEv|tome|x L300 multi-scale nano/ microCT system at the Center for Quantitative Imaging*

Mancos Shale

- Dark gray to black calcareous and noncalcareous shale
- Offshore and open-shallow marine Environments
- Late Cretaceous Interior Seaway

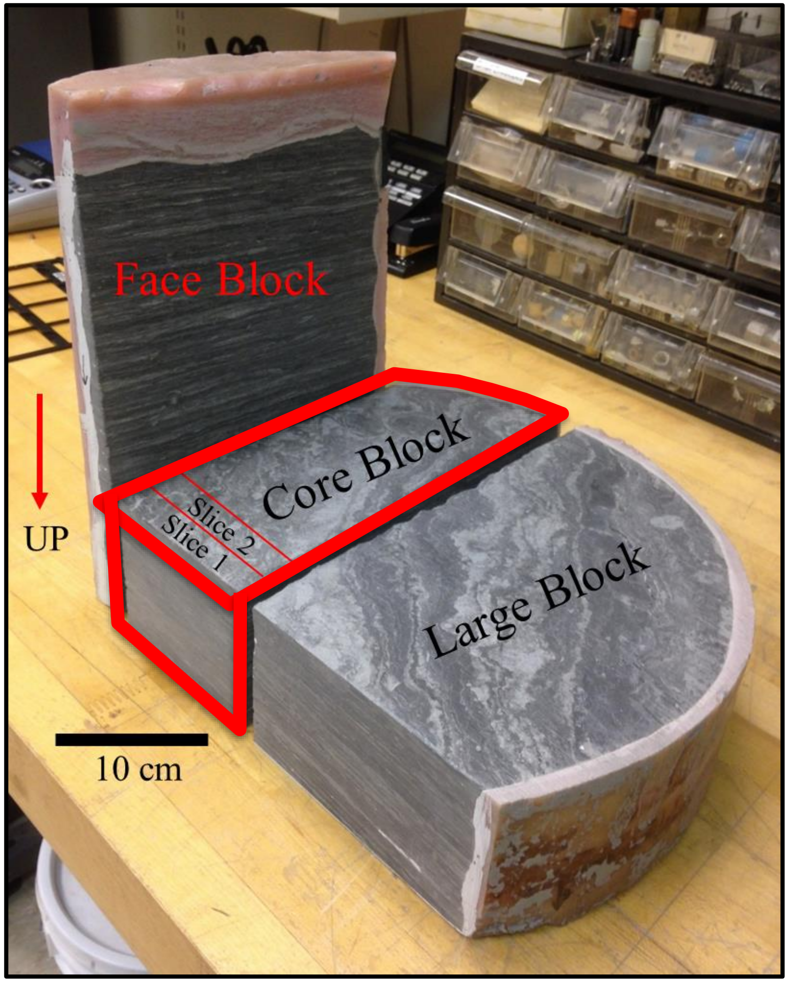
- Cheese Wheel
  - Interlaminated fine mud, medium/ coarse mud, and very fine sand
  - 1-3 mm laminae
  - Parallel lamina, wavy-lenticular lamina, ripple forms, and bioturbation sandy medium mudstone (smM)



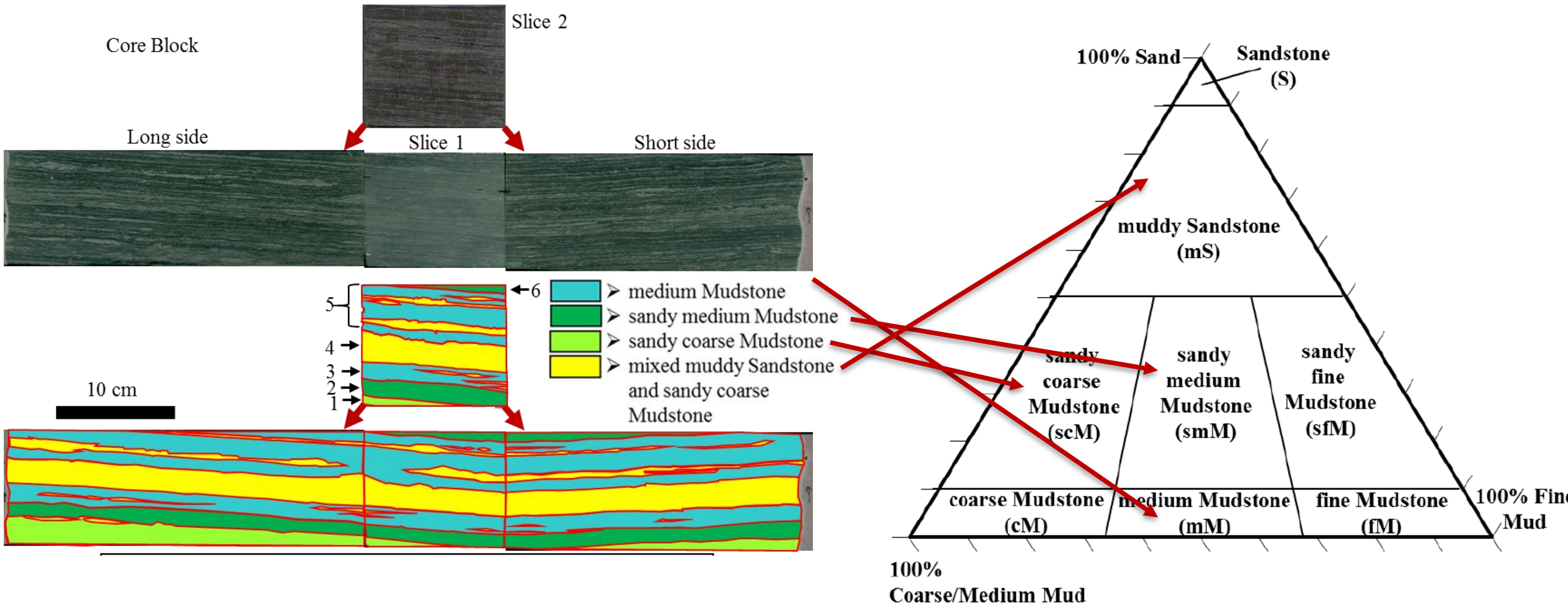
The Cheese Wheel

Multiscale Approach

- 40 cm diameter core of Mancos Shale
- Mineralogical and textural characterization
  - Macroscopic
  - Optical petrography/microscopy
  - Micro-CT
  - FIB-SEM
  - BSE, X-ray mapping
  - MAPS Mineralogy
- Mechanical tests
  - Uni-/Tri-axial compression (1x2")
  - Brazilian Test (1x0.5")
  - Nano-indentation
- Mechanical modeling



Cretaceous Mancos Shale (Macro-lithofacies)

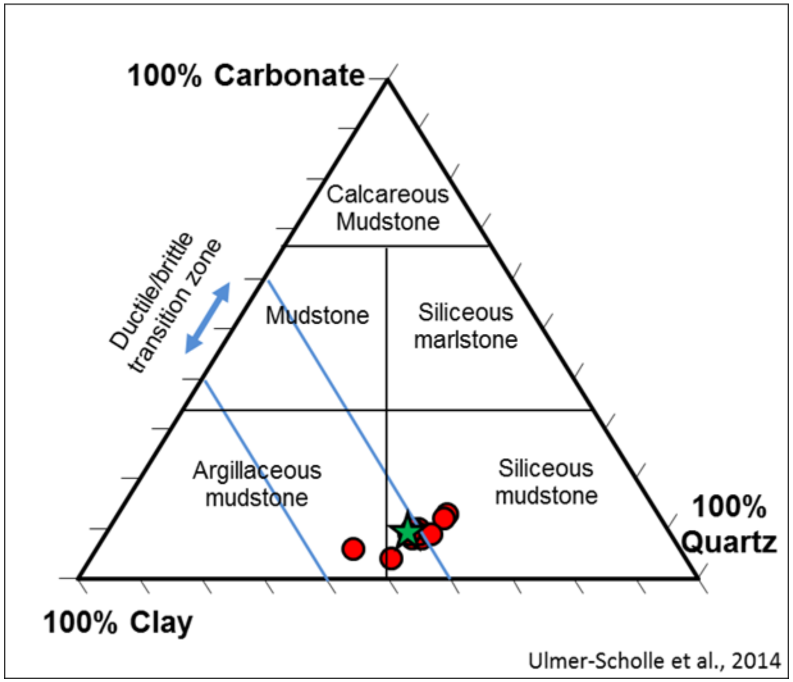


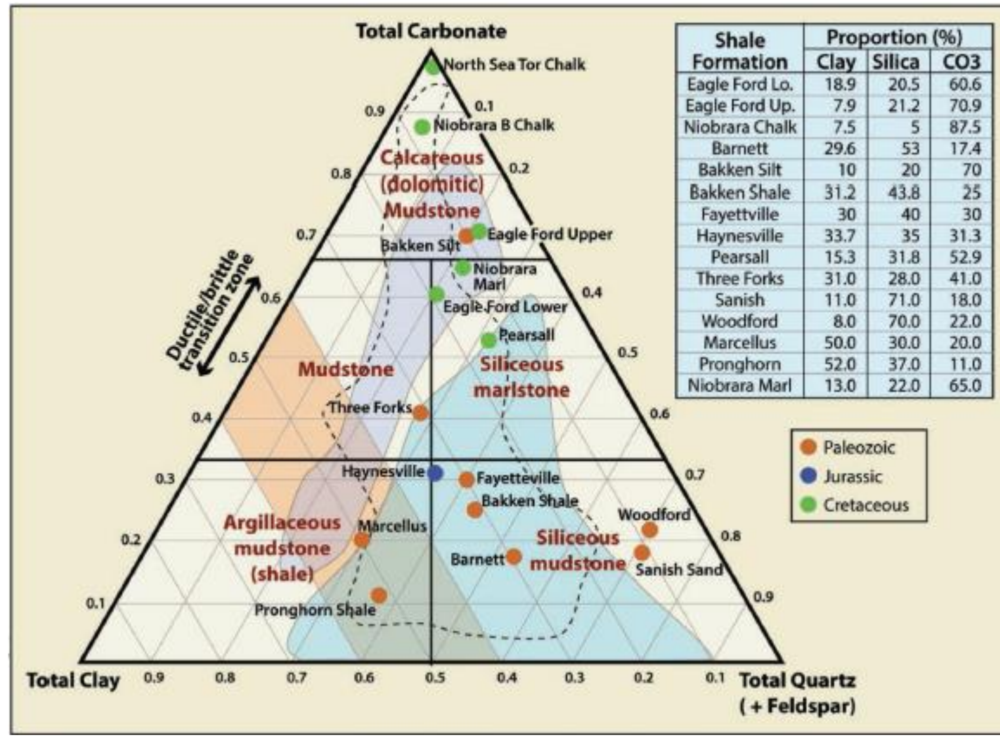
Lazar et al. (2015)

► Color-coded map of macro-lithofacies superimposed onto the scans of the Core Block as listed above

► Four macro-lithofacies are identified as above and numbered on the Slice 2 scan

Macro-lithofacies Composition



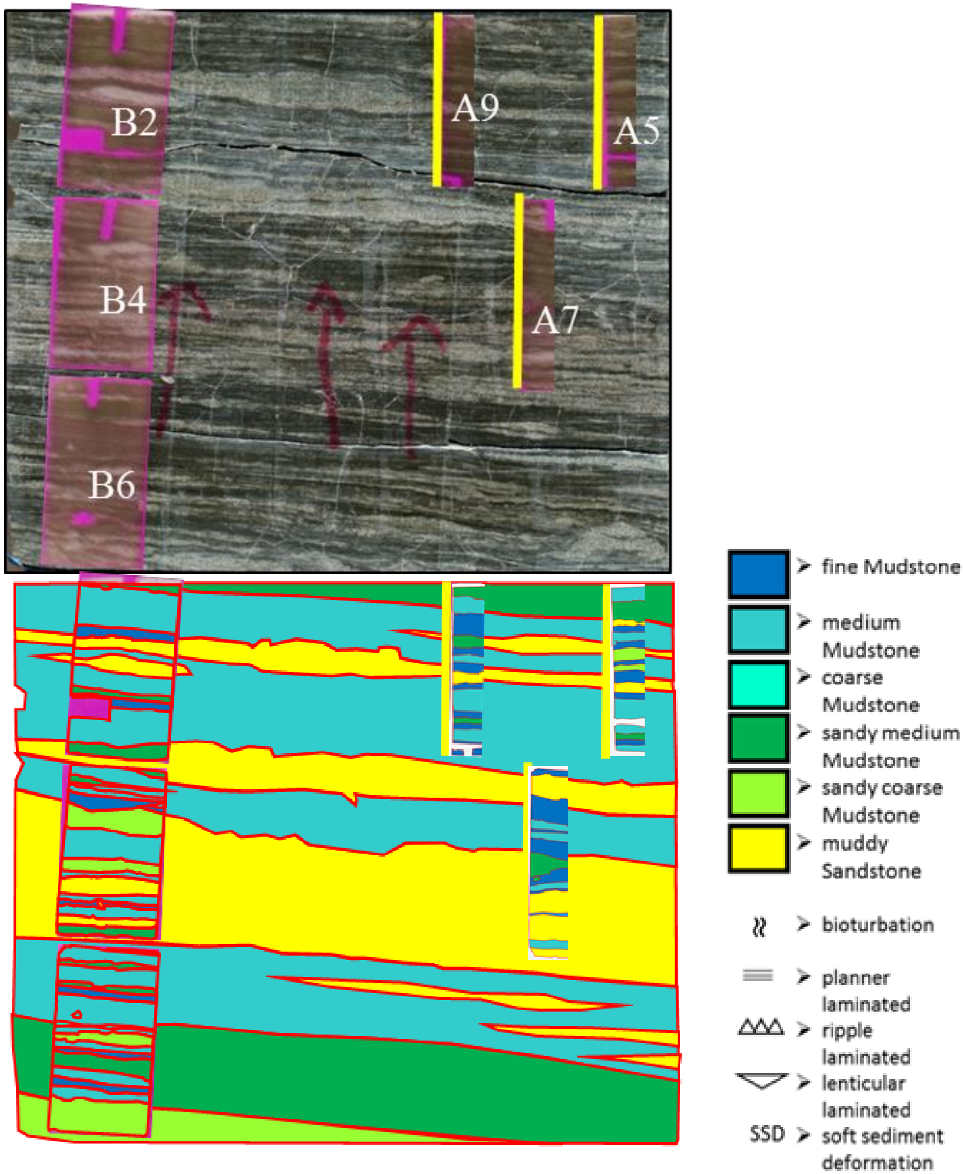


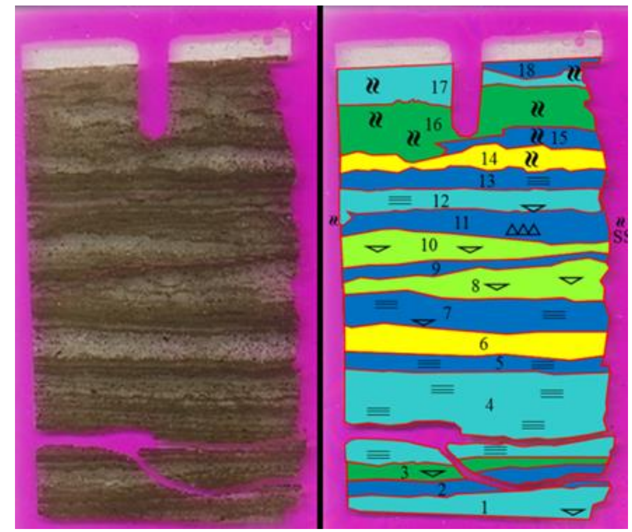
Shale Formation	Proportion (%)		
	Clay	Silica	CO3
Eagle Ford Lo.	18.9	20.5	60.6
Eagle Ford Up.	7.9	21.2	70.9
Niobrara Chalk	7.5	5	87.5
Barnett	29.6	53	17.4
Bakken Silt	10	20	70
Bakken Shale	31.2	43.8	25
Fayettville	30	40	30
Haynesville	33.7	35	31.3
Pearsall	15.3	31.8	52.9
Three Forks	31.0	28.0	41.0
Sanish	11.0	71.0	18.0
Woodford	8.0	70.0	22.0
Marcellus	50.0	30.0	20.0
Pronghorn	52.0	37.0	11.0
Niobrara Marl	13.0	22.0	65.0

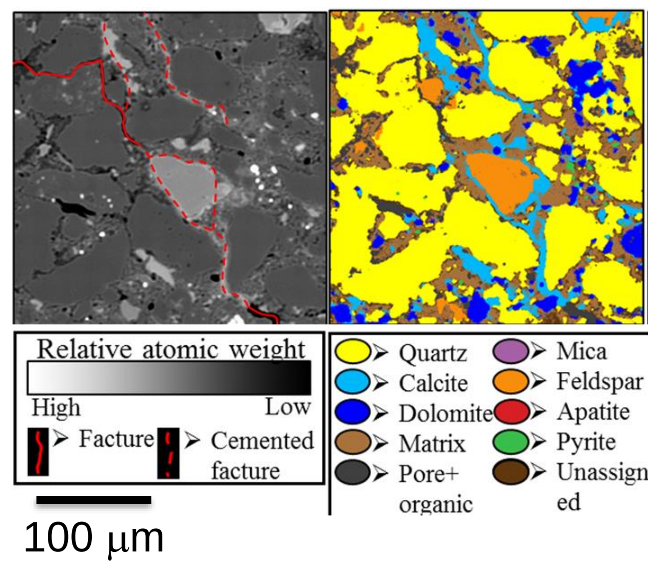
Ulmer-Scholle et al. (2014)

Heterolithic facies are mechanically homogeneous

“Micro-lithofacies” Interpretation: Optical Petrography

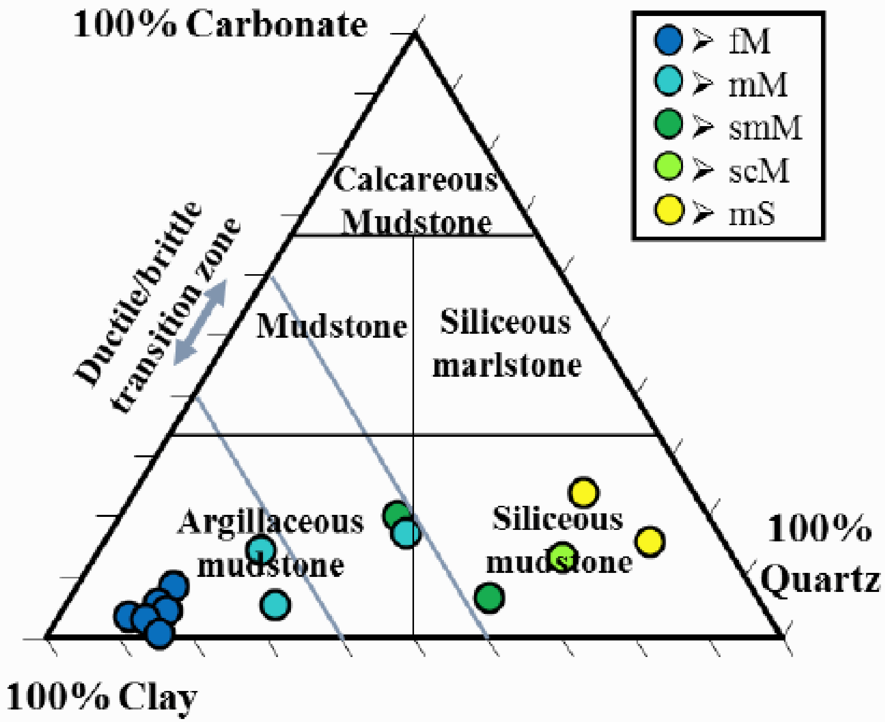




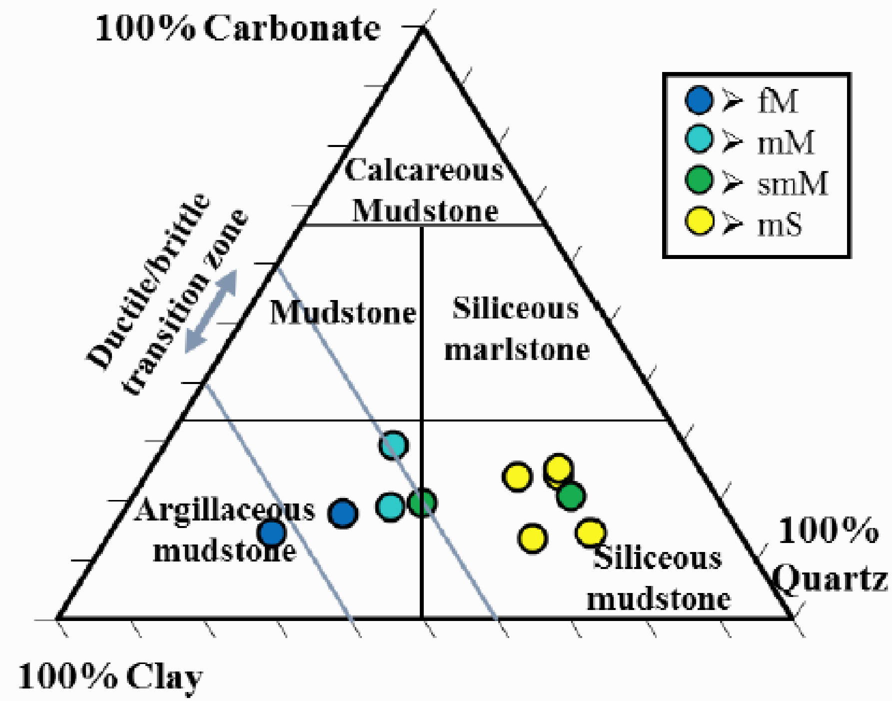


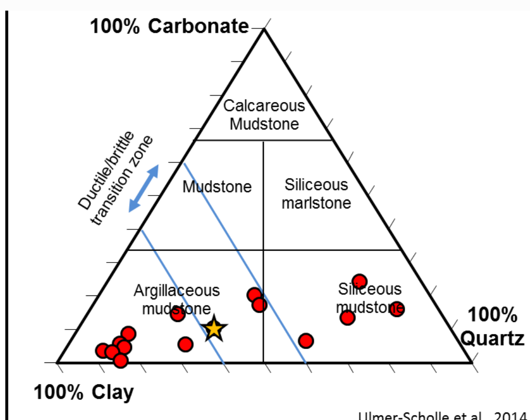
Compositional Heterogeneity

Point Counting (Micro)



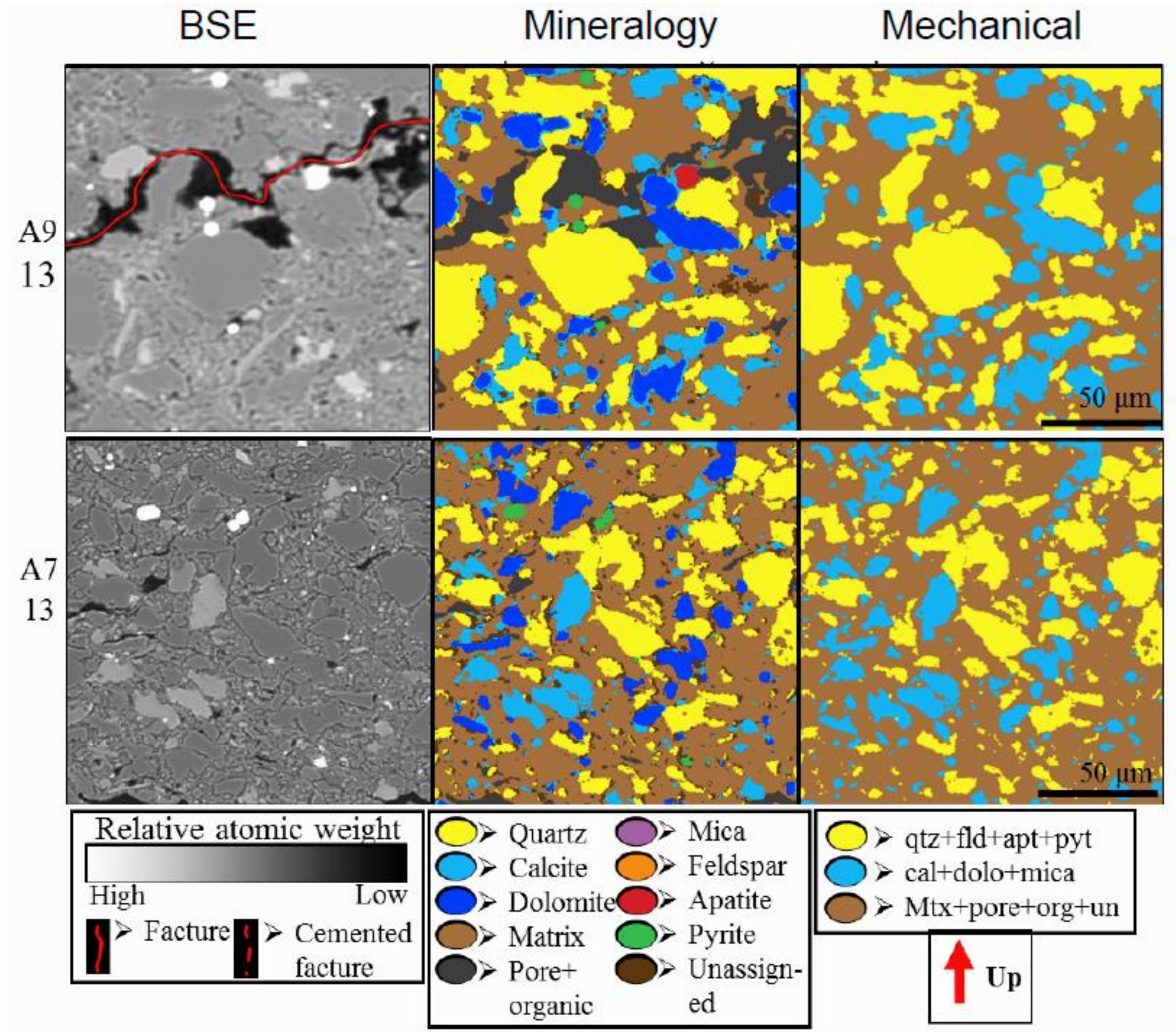
X-Ray Mapping (Micro)



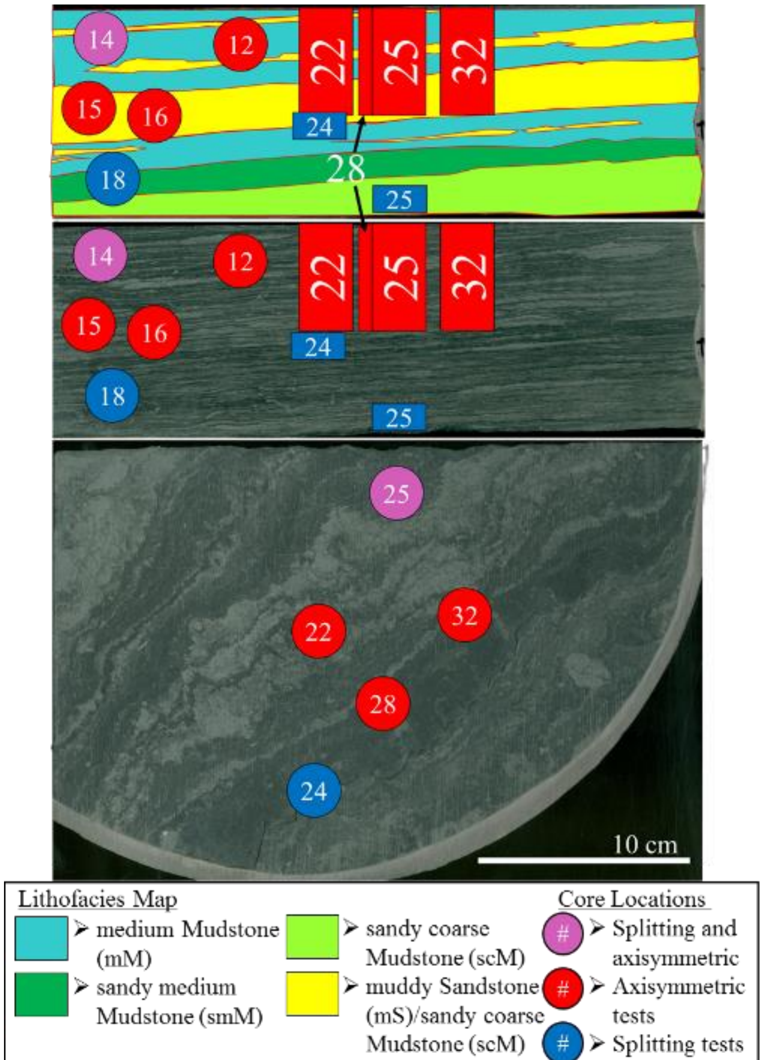


XRD (Macro)

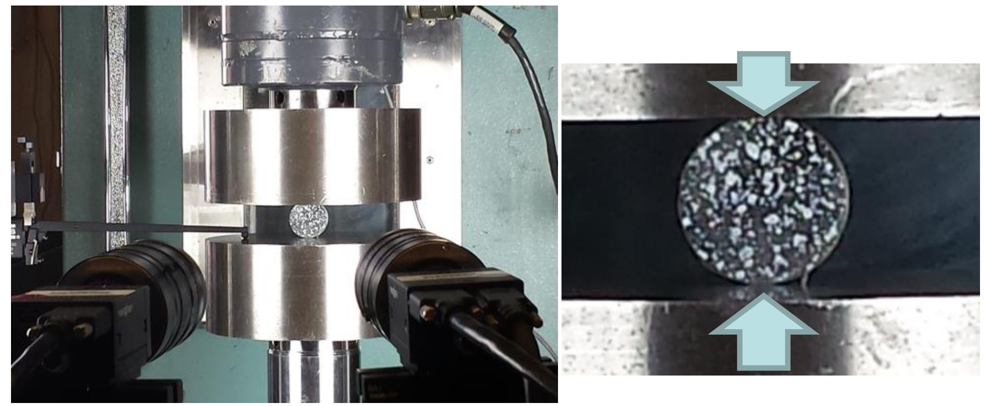
Compositional and Mechanical Heterogeneity



Mechanical Testing: Brazil or Cylinder Splitting Tests with Phase Field Model



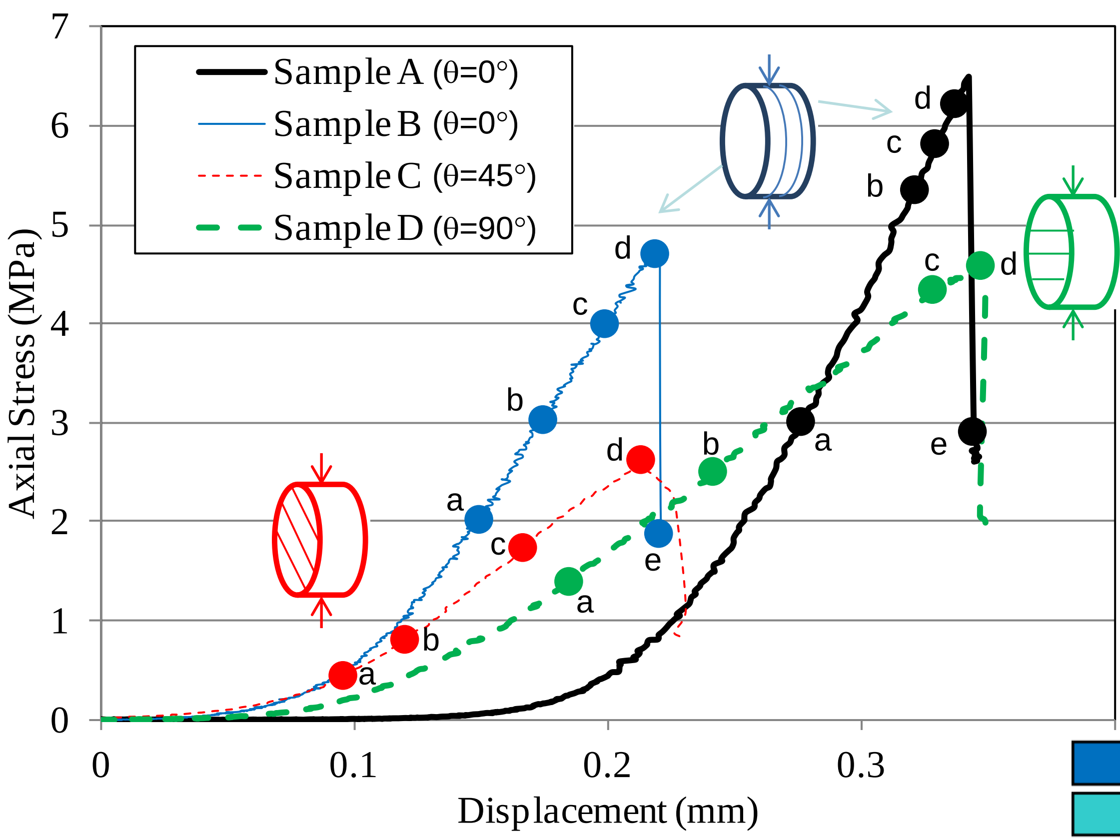
Indirect Tensile (Brazilian) Test



Paint markers: Digital Image Correlation to estimate 2D strain on the surface

Na et al. (2016, JGR under review)

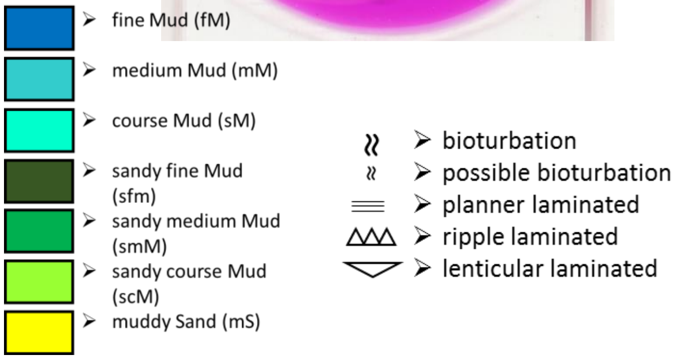
Indirect Tension Results



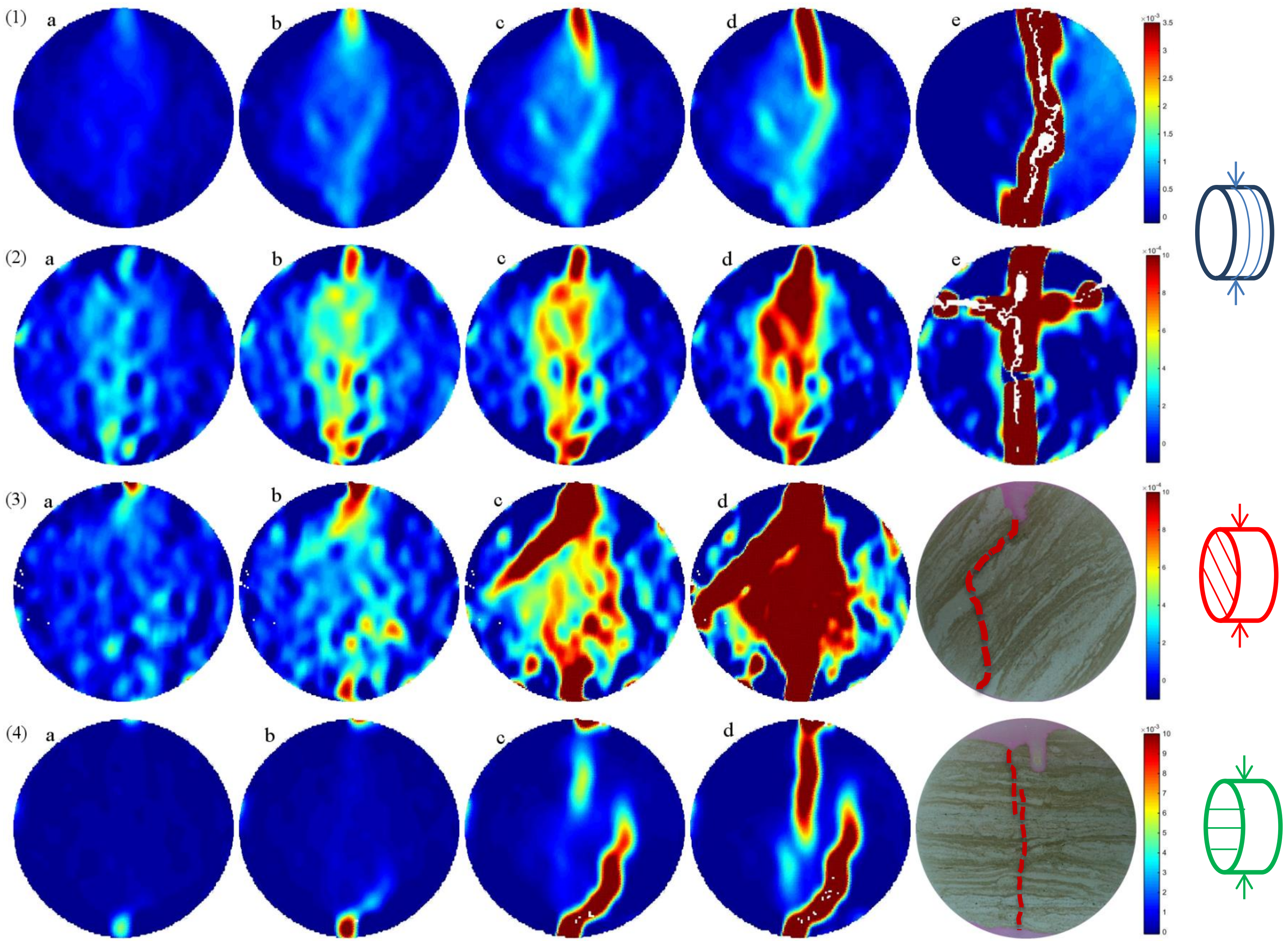
$$\sigma_t = \frac{2P}{\pi D t}$$

P: Loading

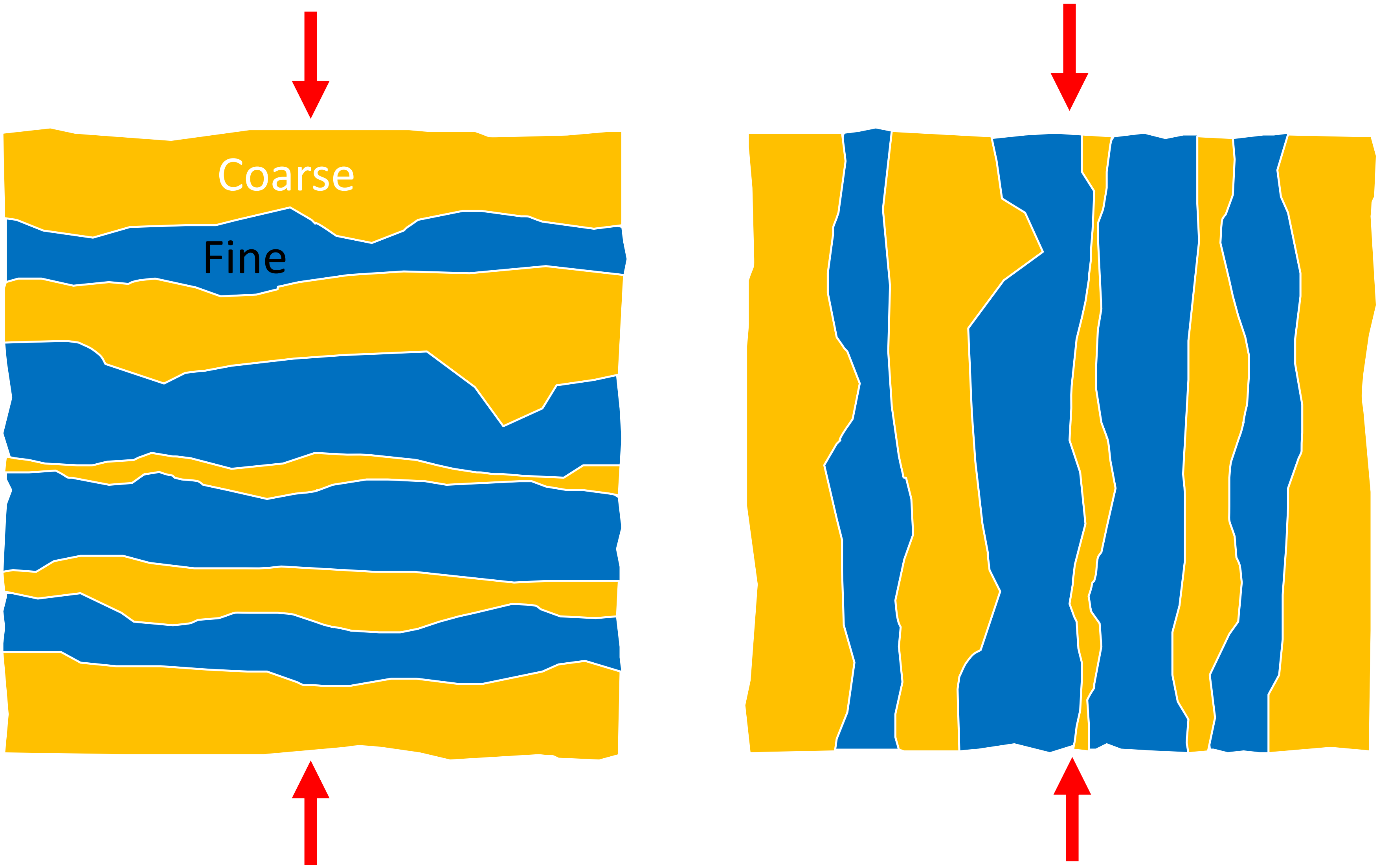
D: Diameter
t: thickness



Tensile Strain Distribution
(Digital Image Correlation)



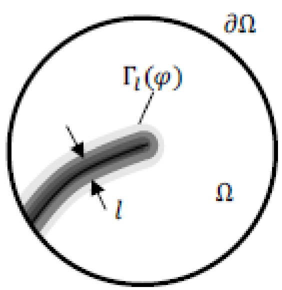
Conceptual Model of Layered System



Numerical Simulations of Brittle Fracturing

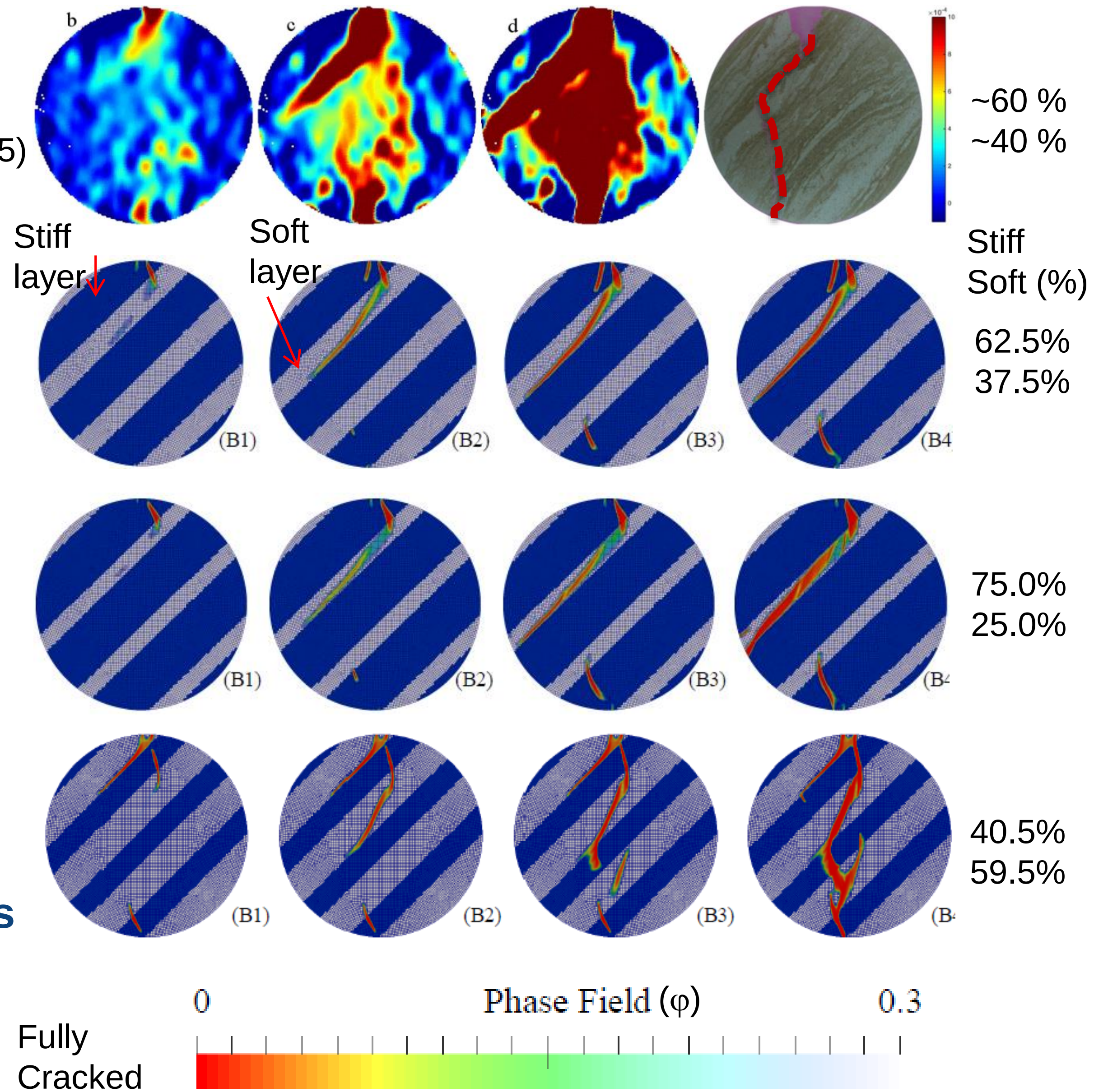
- Phase field model for crack representation (Heister et al,2015)
- Shale is modeled as two-constituent brittle materials with stiff and soft layers:
  - Young’s Modulus
  - (Pore pressure)
  - (Chemo-mechanical coupling)

Crack phase field (φ)

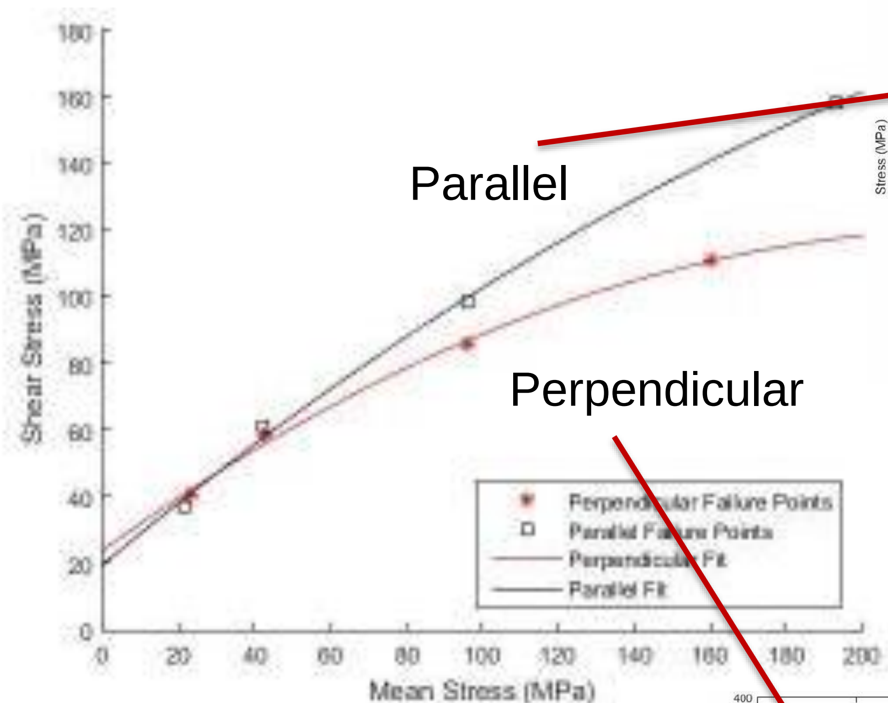


Differential Equations Analysis Library.II (Bangerth et al., 2007; 2013)

DEAL.II Open Source Finite Element Library

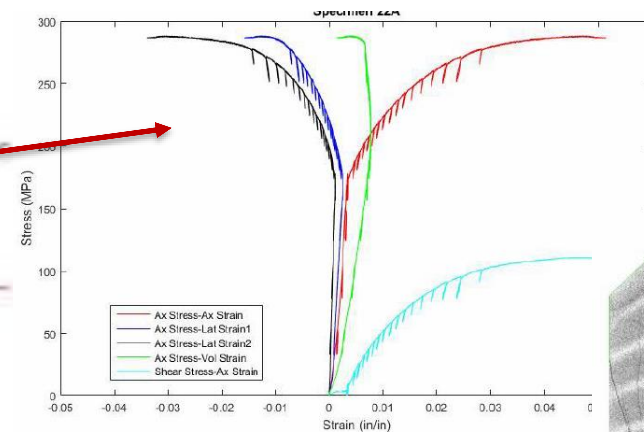


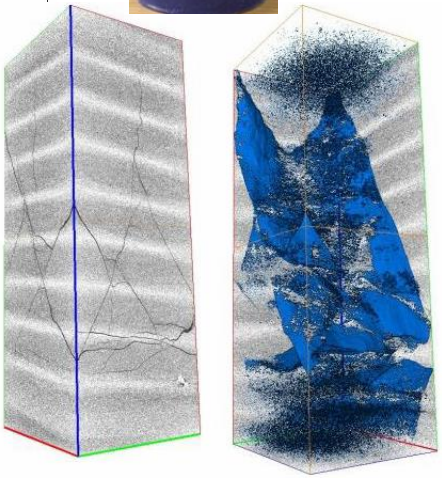
Axisymmetric Testing Results



Parallel

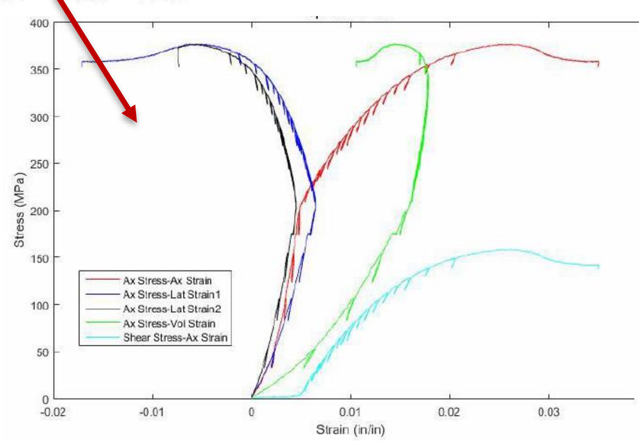
Perpendicular

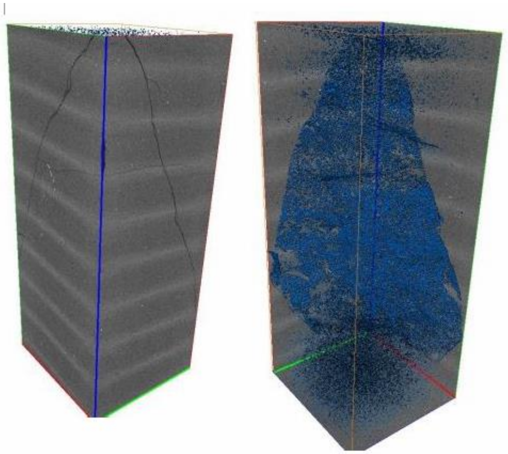




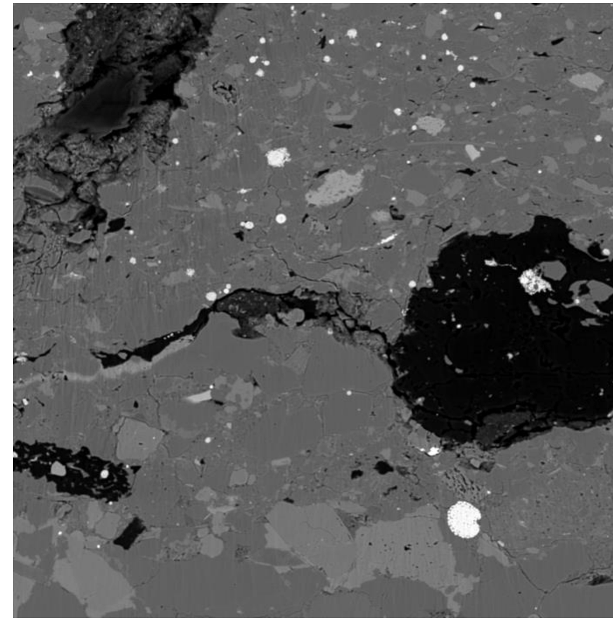
Loaded parallel to bedding

Loaded perpendicular to bedding

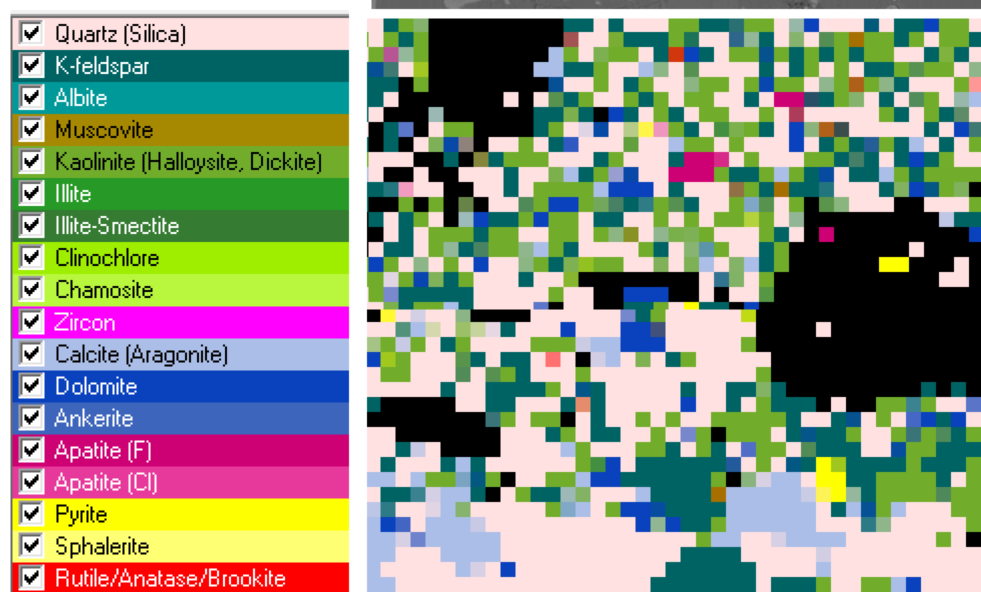




MAPS Mineralogy

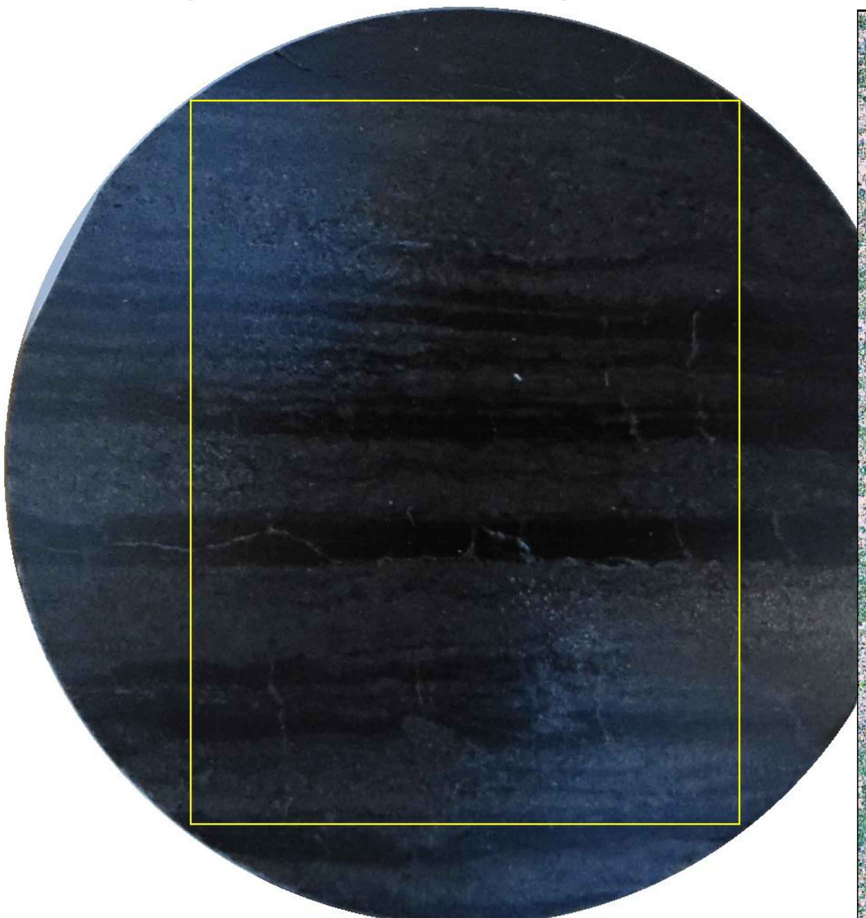


- FEI developed a new spatial mineralogy platform
- SEM-based automated mineralogical measurement, analysis, interpretation, data integration
  - – Collection, overlay and re-registration of multiple images from different modalities
  - – SEM, SEM-EDS, optical, CL, EBSD
  - – QEMSCAN measurement algorithms
- Mineral identification
  - – Spectral matching
  - – Each pixel can be a single mineral or multiple minerals
  - – Ideal for minerals that show elemental substitutions
  - – Simultaneous mineral, element and count maps

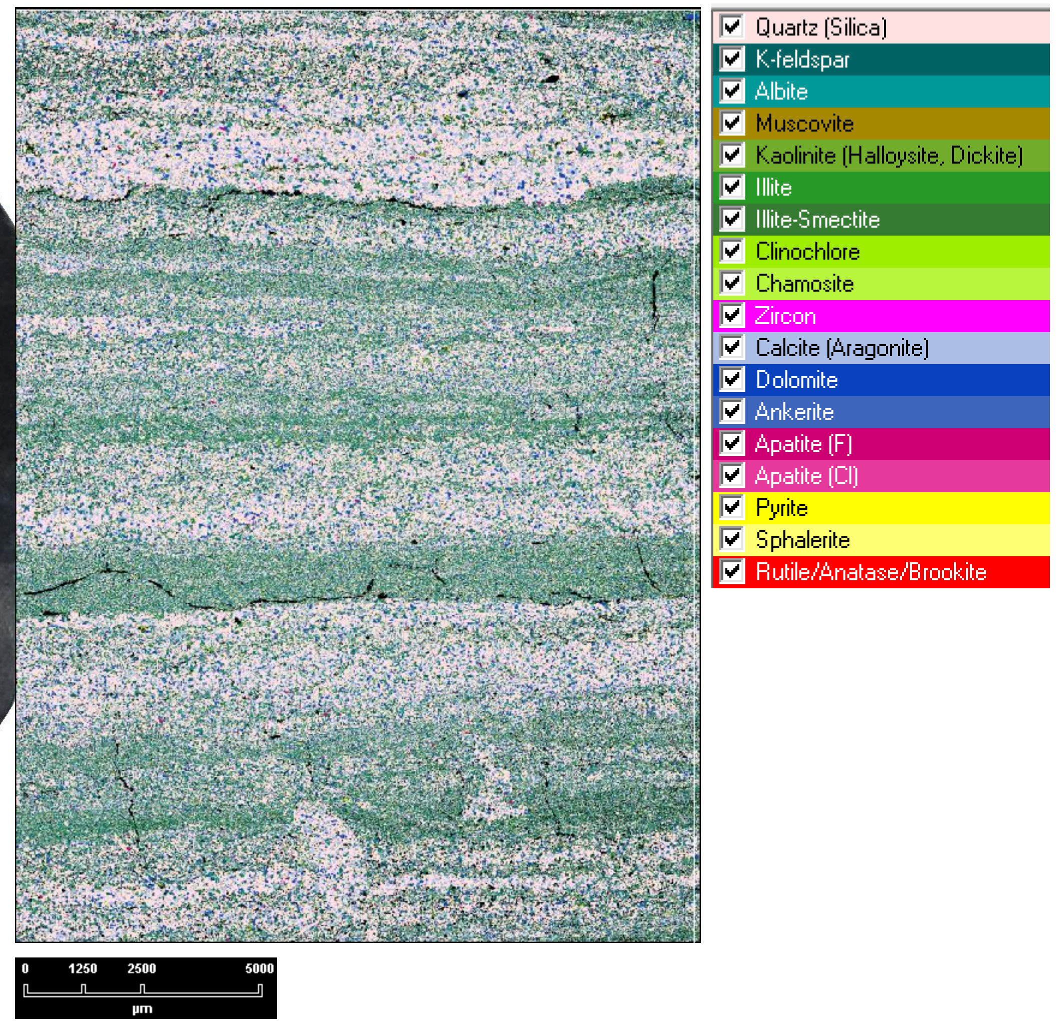


Mineralogy Mapping & Nanoindentation

Ion-milling polished Mancos
(Fischione ion mill)

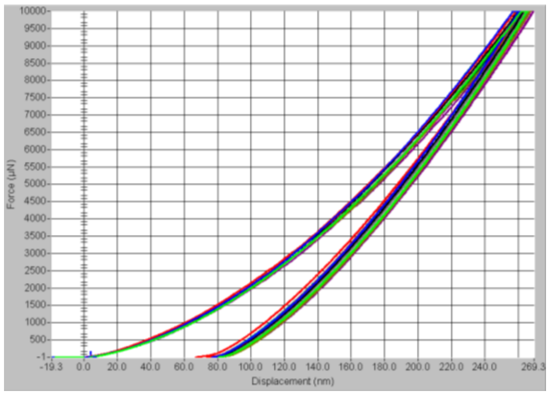


Yellow Box:
Mineral mapping area



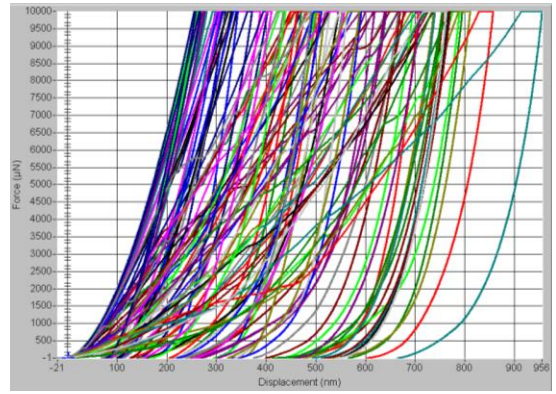
Nano-indentation Results

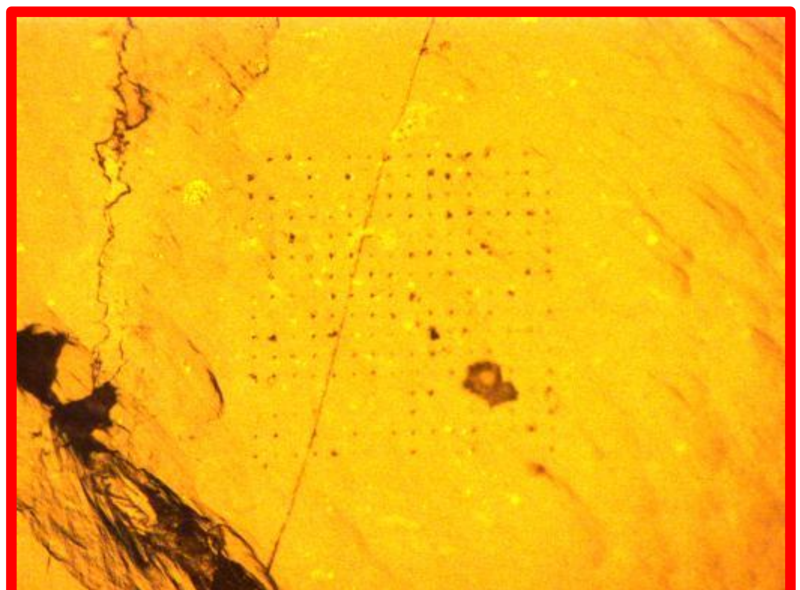
Polished quartz area, 20 indents



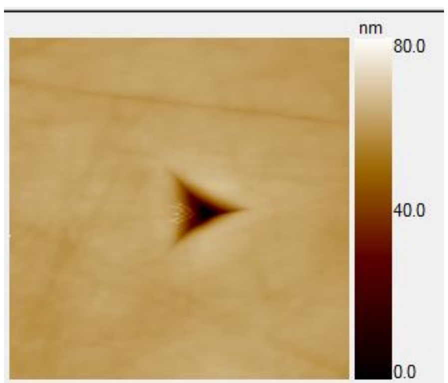
E (Gpa) = 80.8 ± 1.3

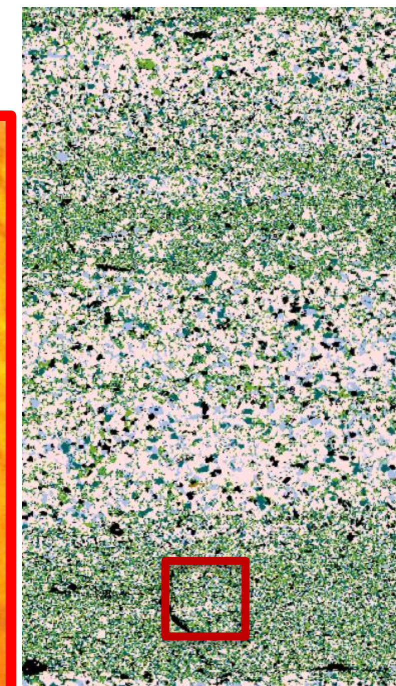
Polished Clay-rich area, 64 indents





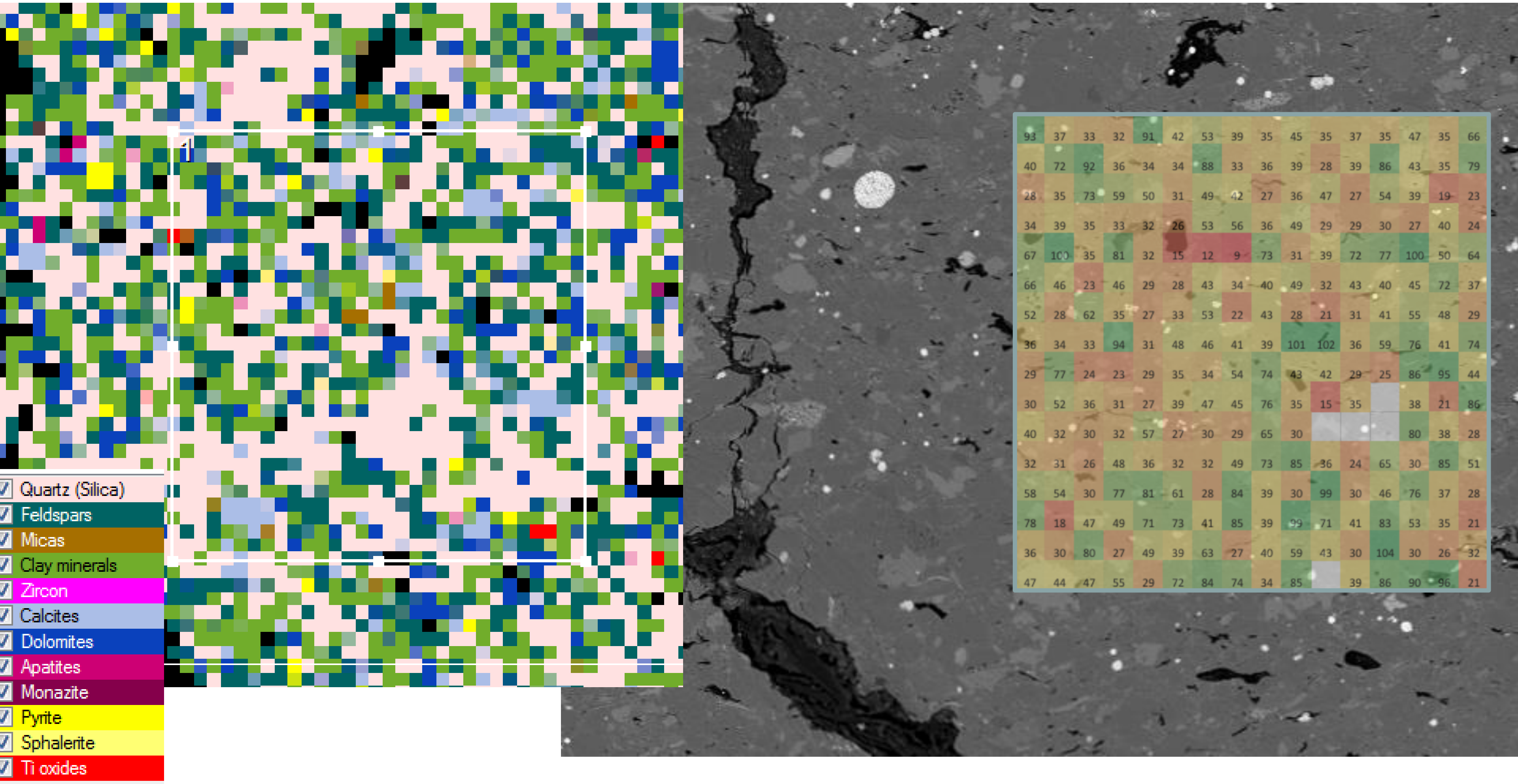
2 µm





Indentation strain rate = 0.1
Maximum load = 10 mN
Indentation array: 16 x 16, 20 um spacing

Nano-indentation Results



Summary

- Texture/mineralogical characterizations
  - – Considerable heterogeneity within macroscopic and sometimes microscopic facies
  - – Relationship with grain size: finer facies have more clay and less quartz, suggesting that coarser facies should be stronger than finer
- Mechanical tests
  - – Macroscopic and microscopic lithofacies have distinctively different mechanical properties
  - – Bulk properties may be misleading as they can represent averages of mechanically heterogeneous rock
  - – Microscopic heterogeneity controls the spatial distribution of fractures
  - – This heterogeneity should be taken into account for realistic mechanical modeling and can scale up by examining other common lithofacies
- Integrated multiscale imaging and mechanical testing with numerical simulation provides a robust approach to advancing our understanding of shale poro-mechanics

Thank You