

Multiscale characteristics of mechanical and compositional properties in Mancos shale



Hongkyu Yoon, Mathew Ingraham, Jason Heath, Thomas Dewers
(Sandia National Lab)

Joseph Grigg and Peter Mozley (New Mexico Tech)

Contributors: SeonHong Na, Steve WaiChing Sun (Columbia University)



*Exceptional
service
in the
national
interest*

GSA 2016 Annual Meeting

Acknowledgment: This work was funded by the U.S. Department of Energy, Office of Science, Basic Energy Sciences under Award Number DE-SC0006883.



Sandia National Laboratories is a multi-mission laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

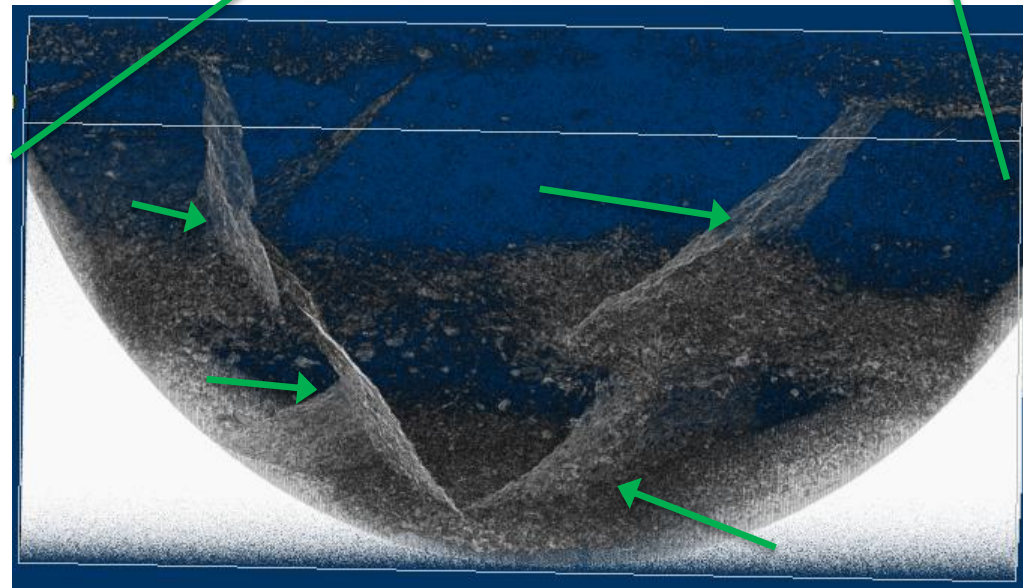
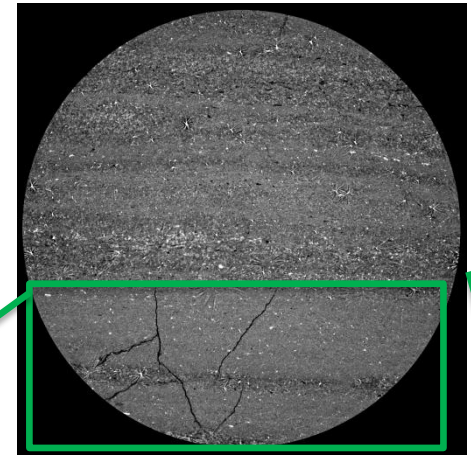
Shale Poromechanics: Multiscale Heterogeneity in Compositions, Pore structure, and Mechanical Properties

► 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

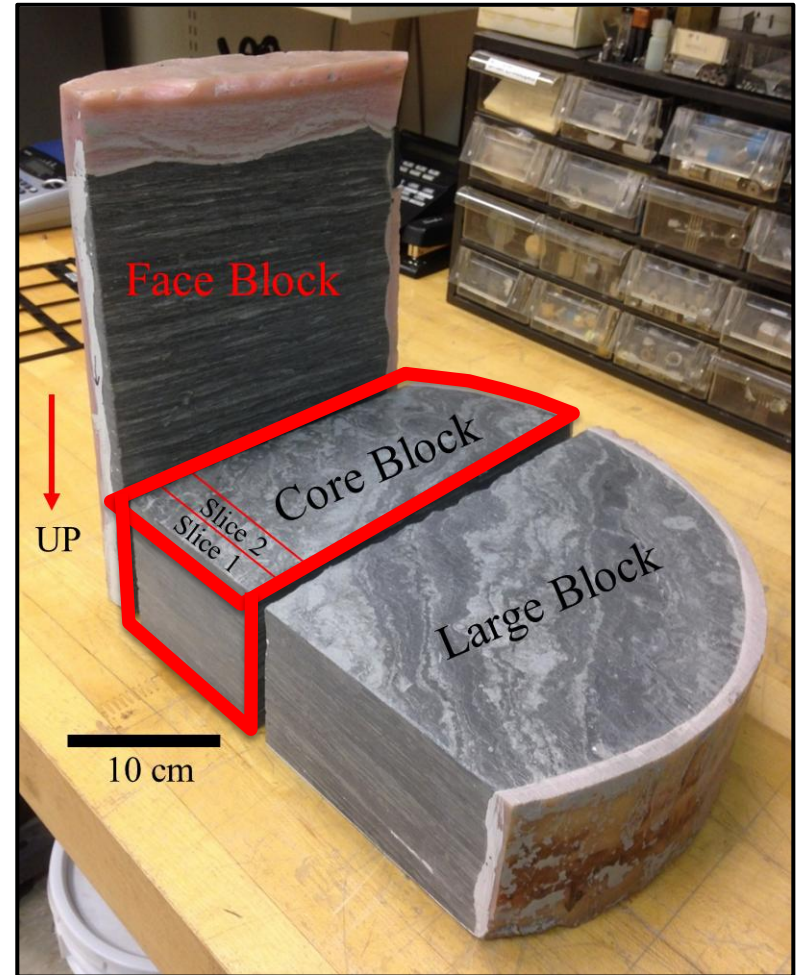
Courtesy: N. Chakraborty on PSU's GEv|tome|x L300 multi-scale nano/ microCT system at the Center for Quantitative Imaging

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



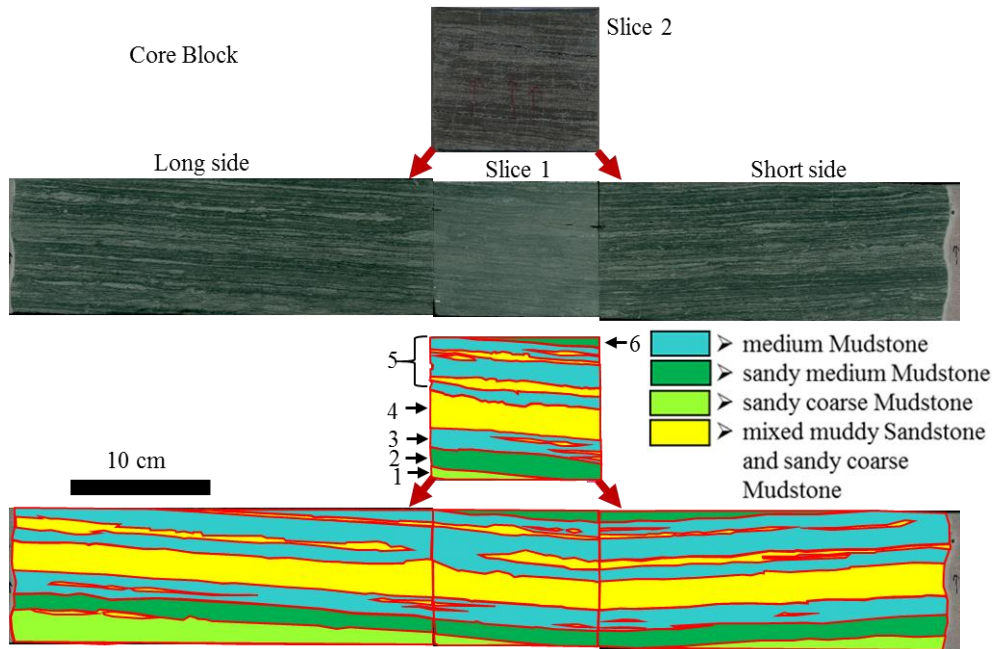
Multiscale Approach

- 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

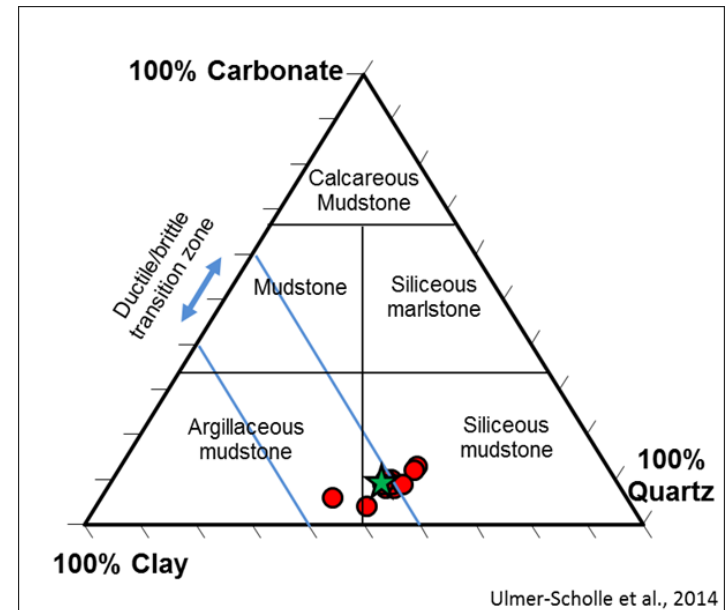


Cretaceous Mancos Shale (Macro-lithofacies)

- Heterolithic facies [Grigg, MS thesis, 2016]
 - Interlaminated fine mud, medium/coarse mud (Lazar et al., 2015), and very fine sand
 - 1-3 mm laminae
 - Parallel lamina, wavy lenticular lamina, ripple forms, and bioturbation

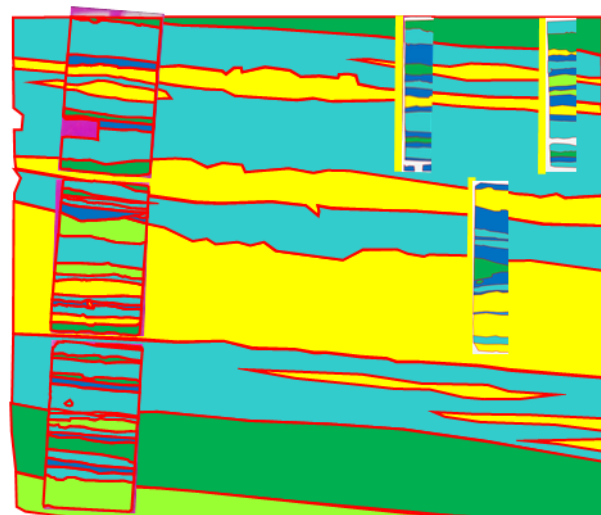
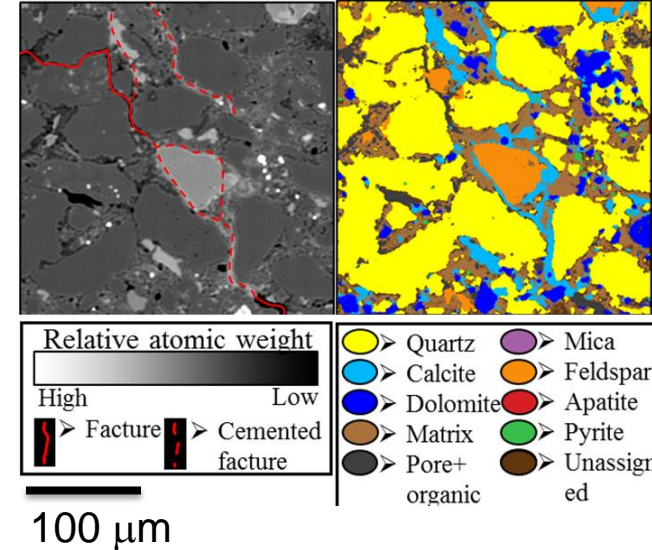
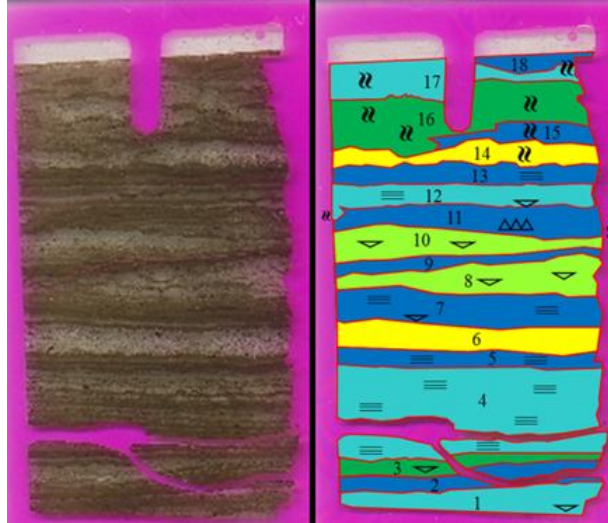
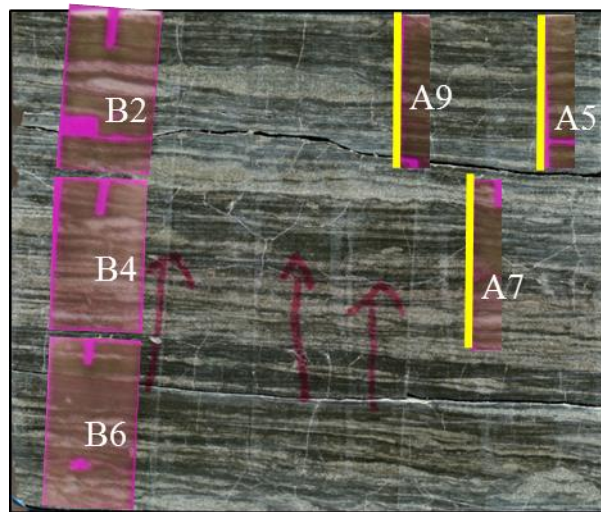


- Color-coded map of macro-lithofacies superimposed onto the scans of the Core Block as listed above
- Four macro-lithofacies are identified as above and numbered on the Slice 2 scan

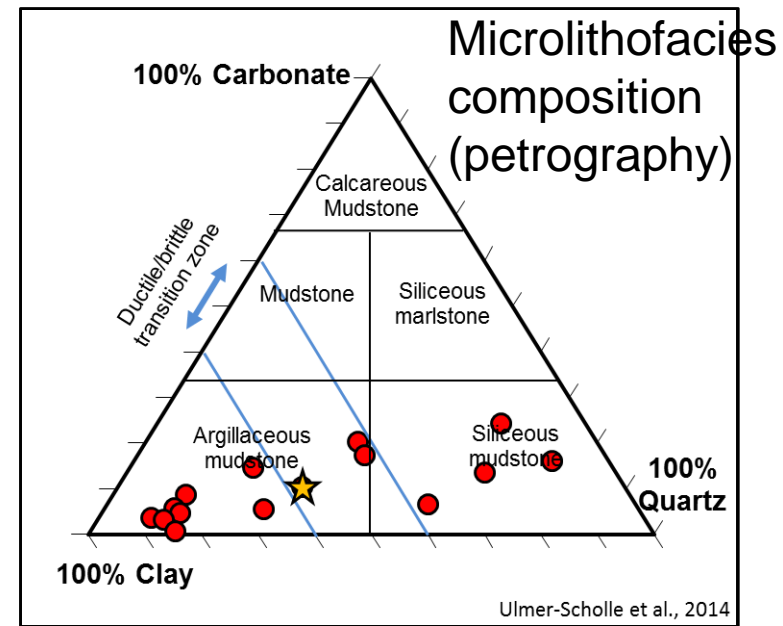


Macrolithofacies composition (XRD)

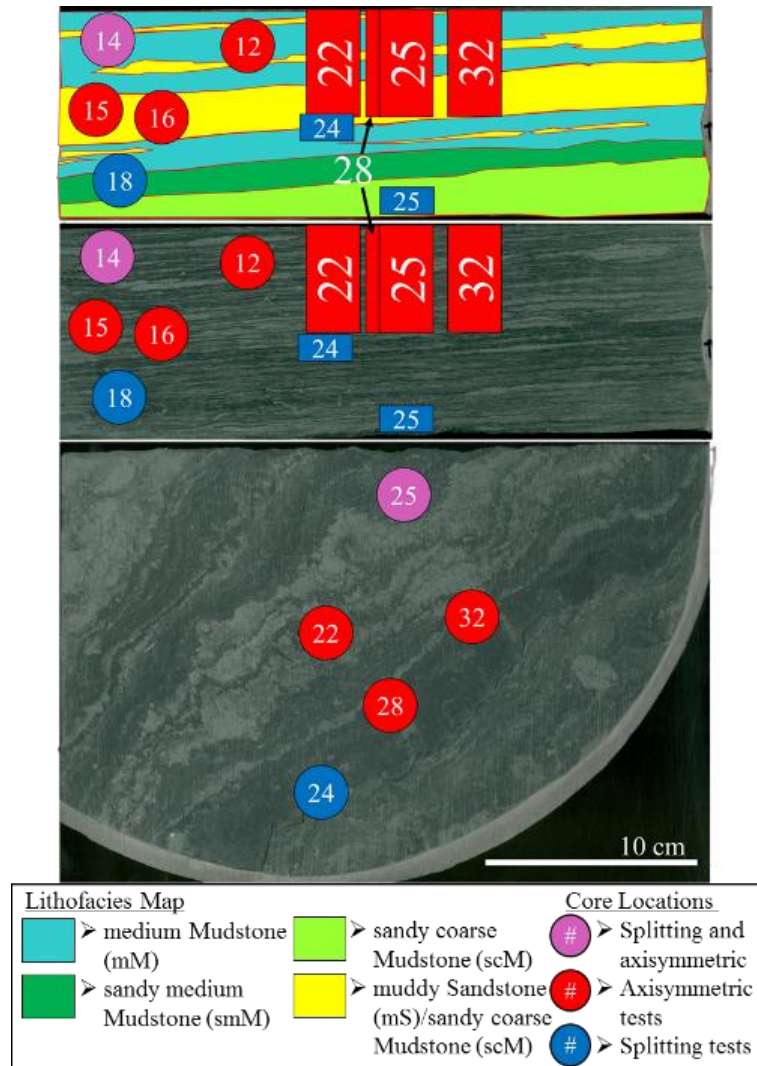
“Micro-lithofacies” Interpretation: Optical Petrography



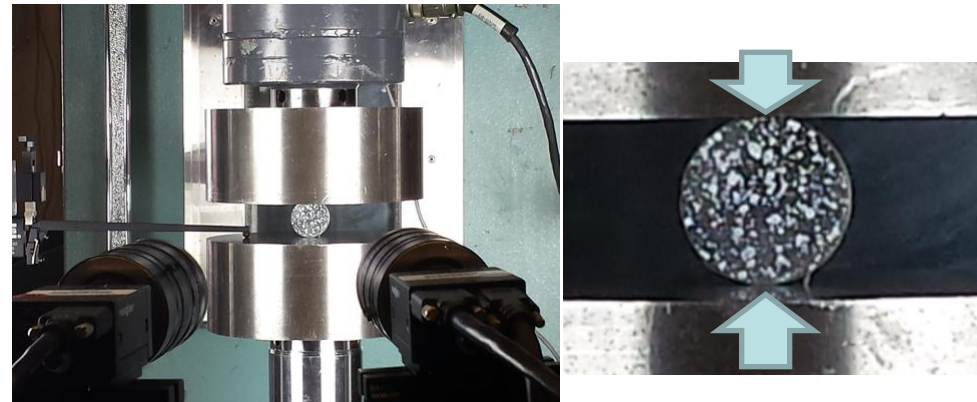
- fine Mudstone
- medium Mudstone
- coarse Mudstone
- sandy medium Mudstone
- sandy coarse Mudstone
- muddy Sandstone
- bioturbation
- planar laminated
- ripple laminated
- lenticular laminated
- SSD soft sediment deformation



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

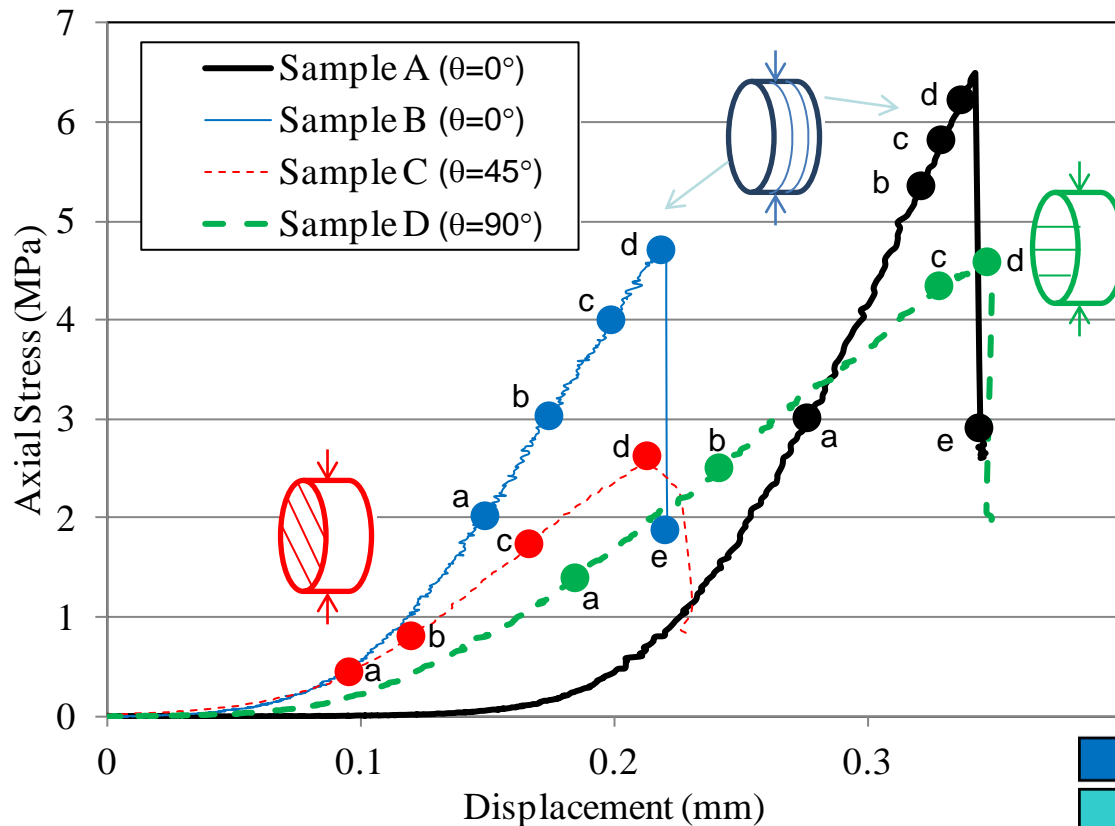


Indirect Tensile (Brazilian) Test



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

Indirect Tension Results



$$\sigma_t = \frac{2P}{\pi Dt}$$

P: Loading

D: Diameter

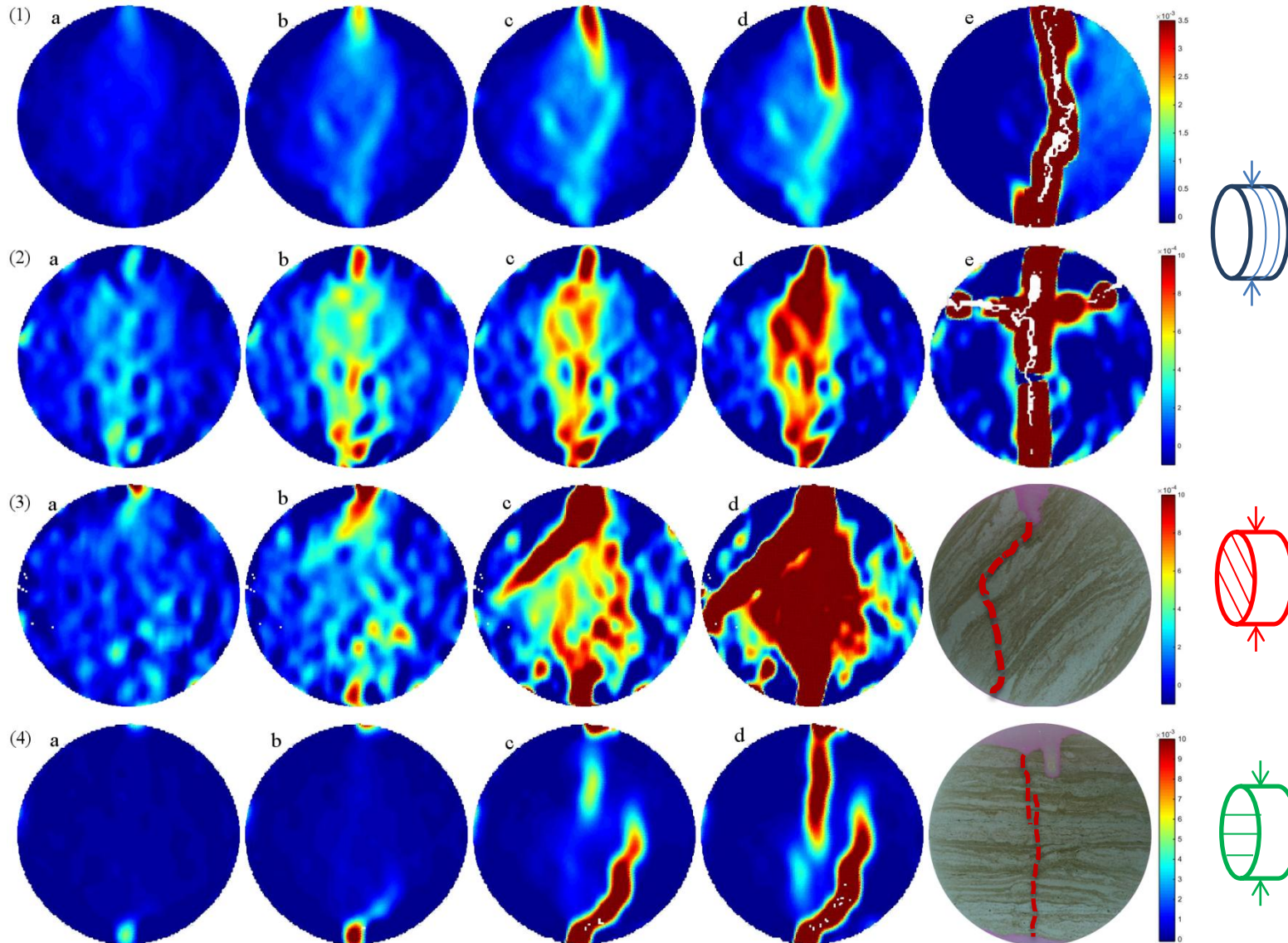
t: thickness

- fine Mud (fM)
- medium Mud (mM)
- course Mud (sM)
- sandy fine Mud (sfm)
- sandy medium Mud (smM)
- sandy course Mud (scM)
- muddy Sand (mS)

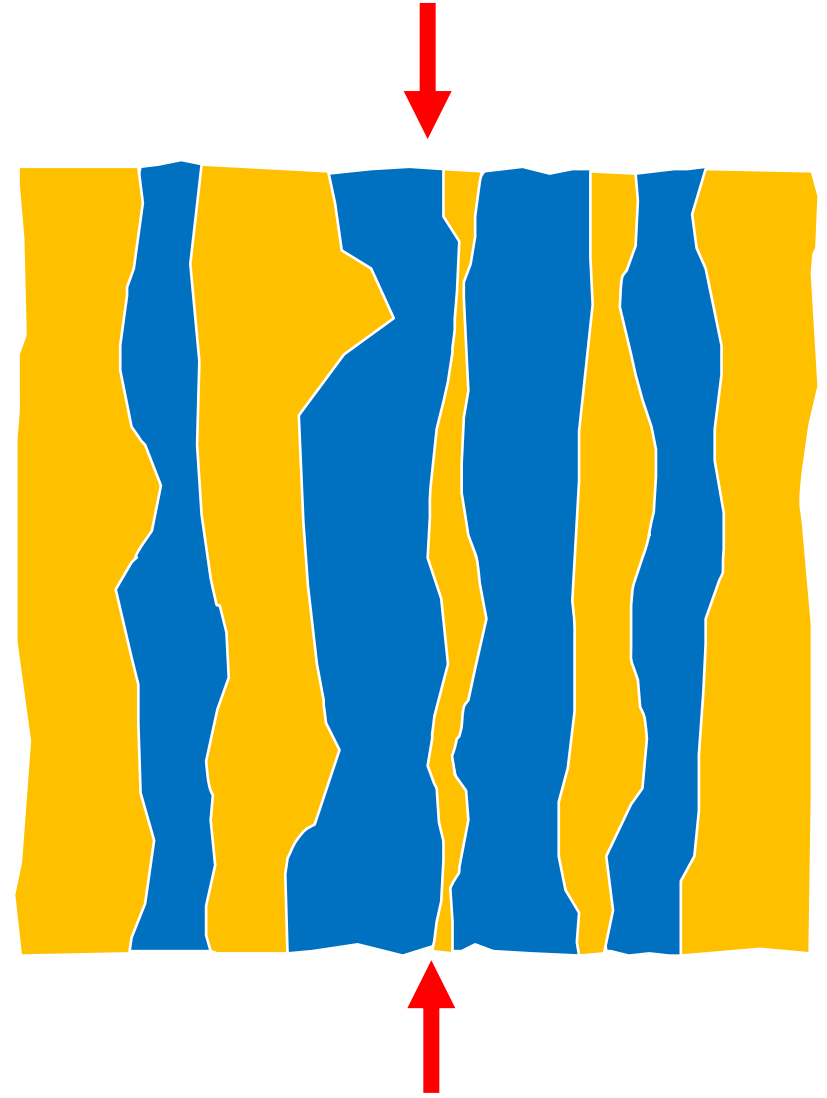
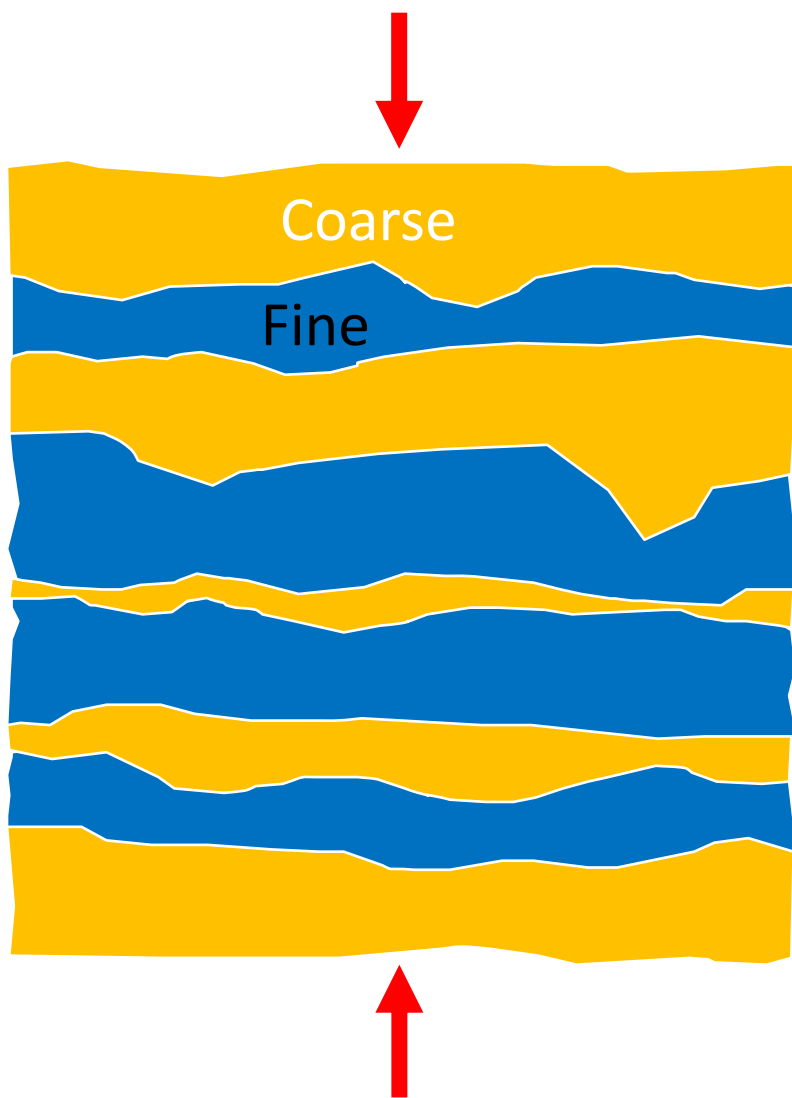
- ⋈ ➤ bioturbation
- ⋈ ➤ possible bioturbation
- ≡ ➤ planner laminated
- △△ ➤ ripple laminated
- ▽ ➤ lenticular laminated



Tensile Strain Distribution (Digital Image Correlation)



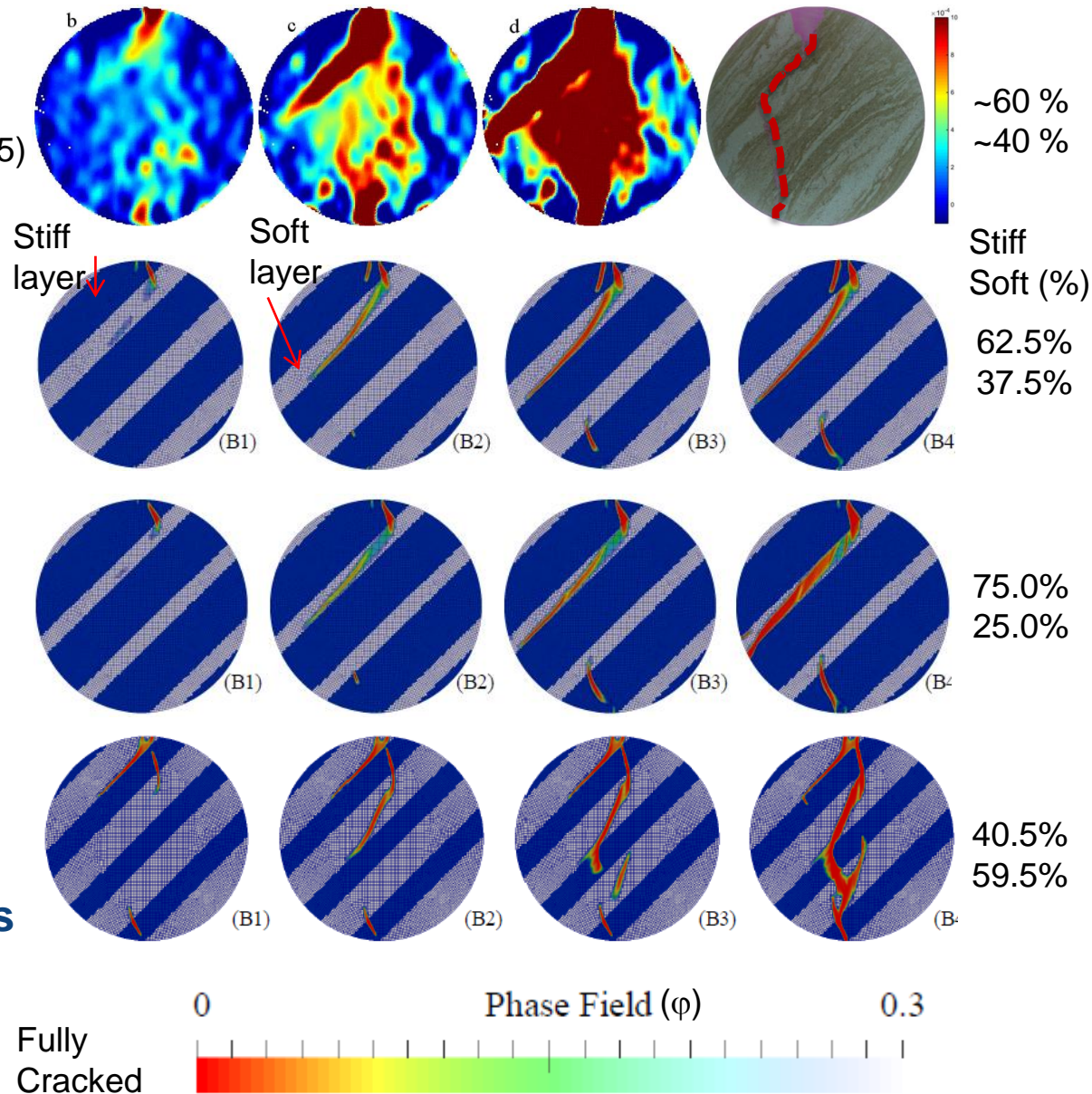
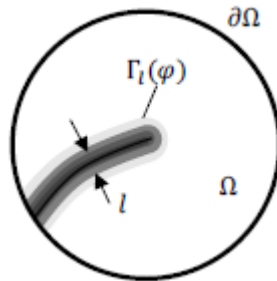
Conceptual Model of Layered System



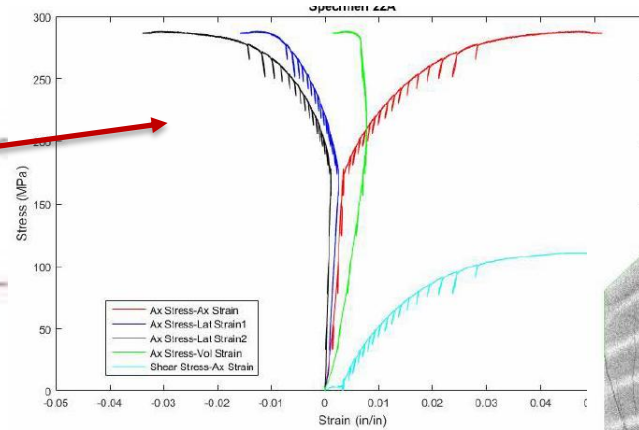
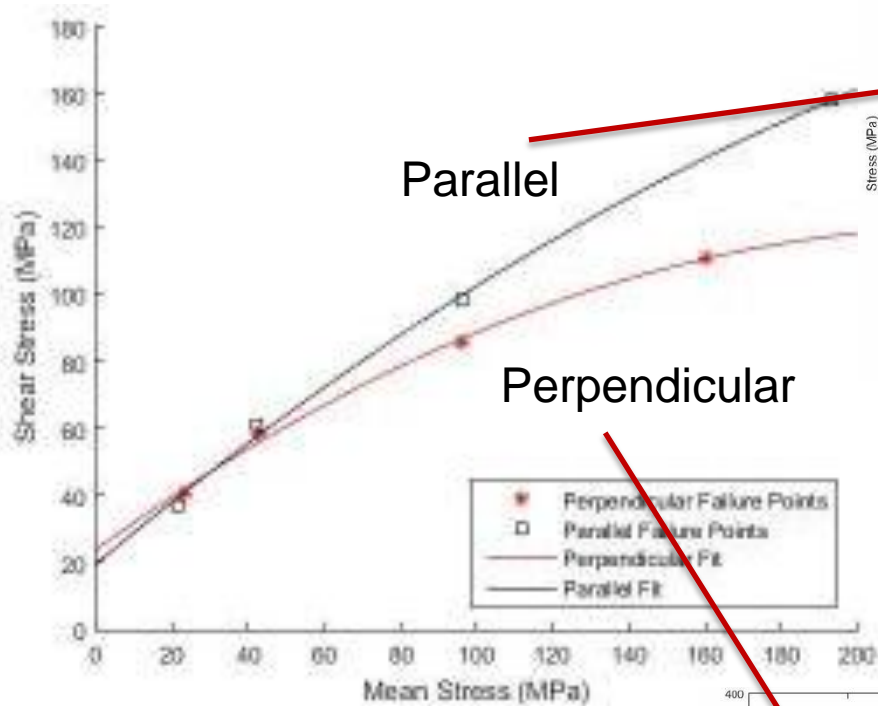
Numerical Simulations of Brittle Fracturing

- 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)

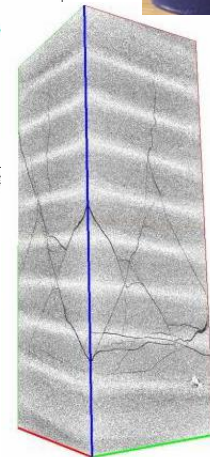
Crack phase field (ϕ)



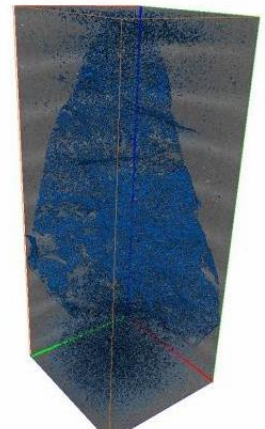
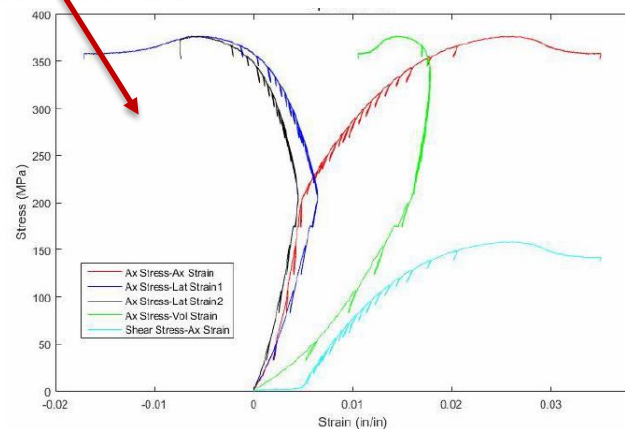
Axisymmetric Testing Results



Loaded parallel to bedding

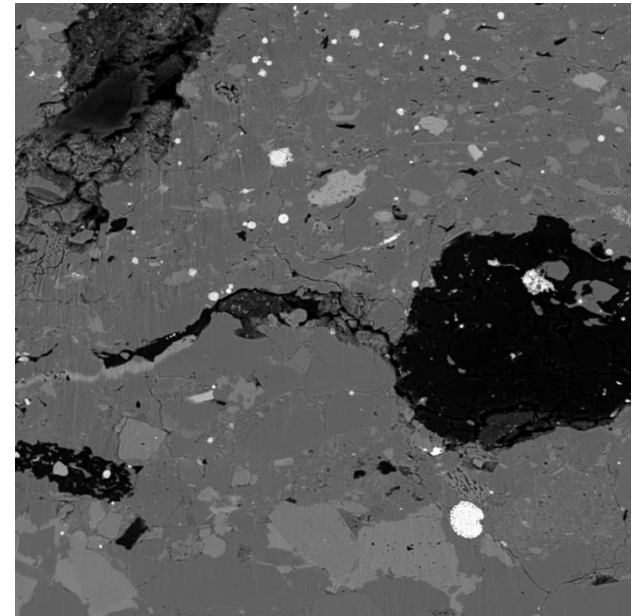


Loaded perpendicular to bedding



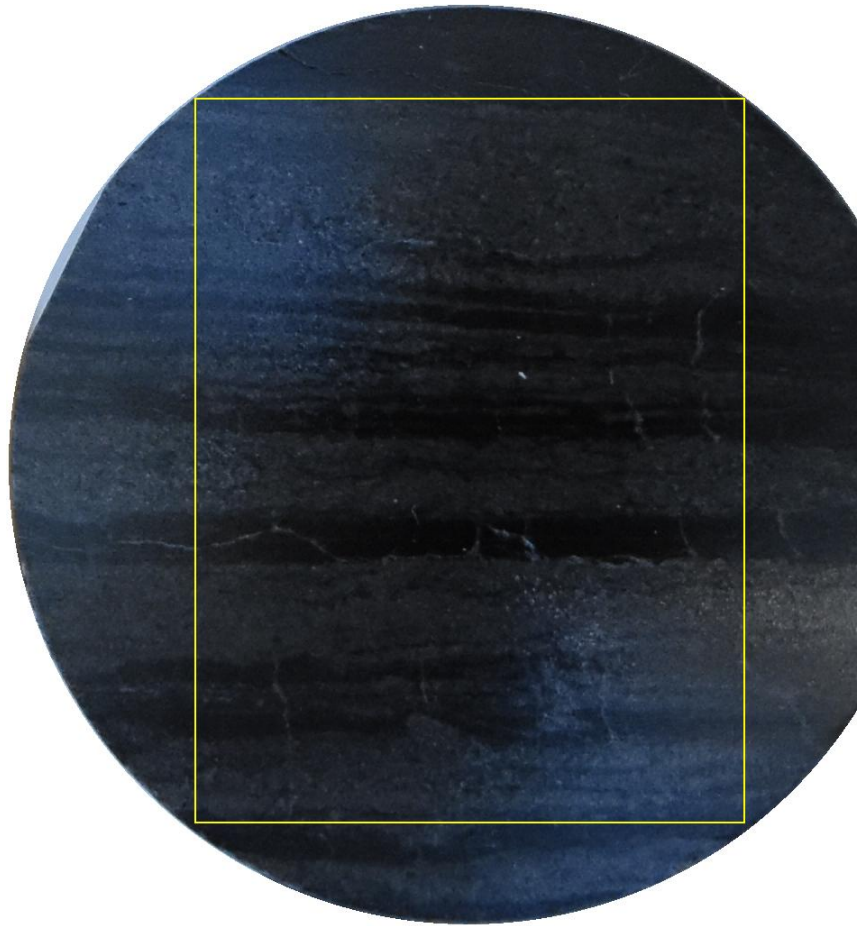
MAPS Mineralogy

- 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

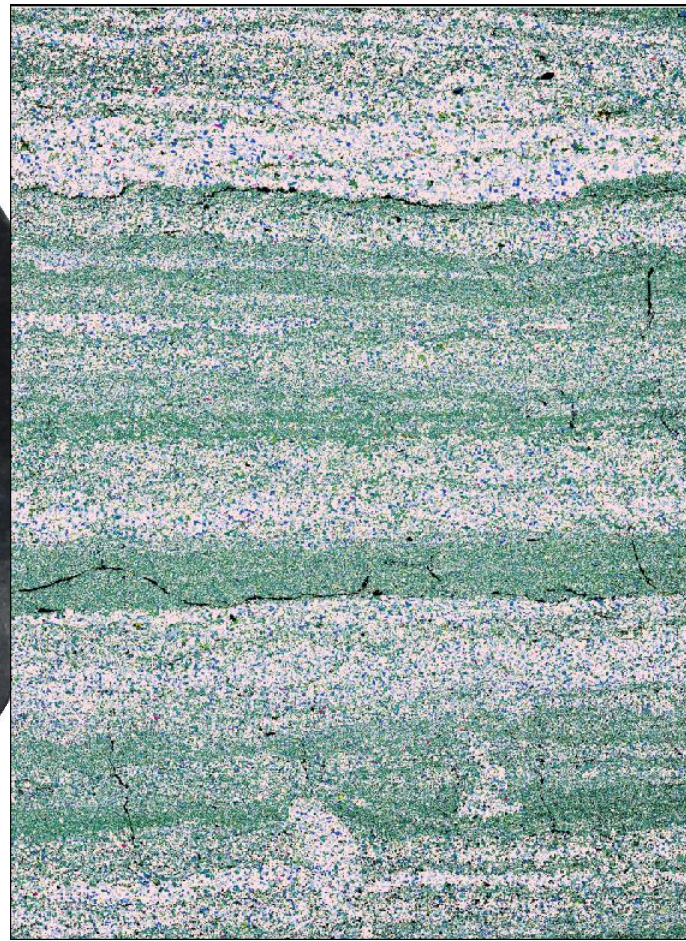


Mineralogy Mapping & Nanoindentation

Ion-milling polished Mancos



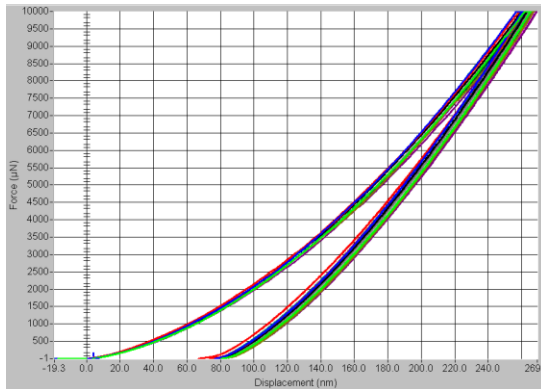
Yellow Box:
Mineral mapping area



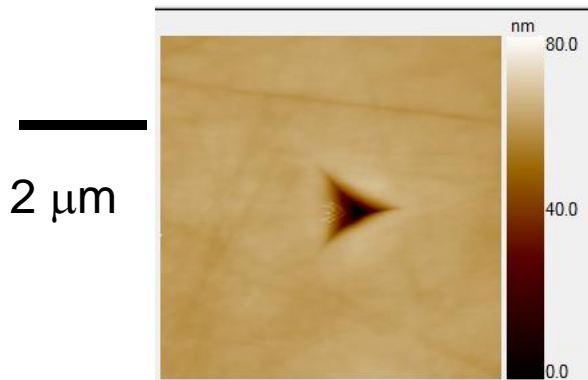
| | |
|-------------------------------------|---------------------------------|
| <input checked="" type="checkbox"/> | Quartz (Silica) |
| <input checked="" type="checkbox"/> | K-feldspar |
| <input checked="" type="checkbox"/> | Albite |
| <input checked="" type="checkbox"/> | Muscovite |
| <input checked="" type="checkbox"/> | Kaolinite (Halloysite, Dickite) |
| <input checked="" type="checkbox"/> | Illite |
| <input checked="" type="checkbox"/> | Illite-Smectite |
| <input checked="" type="checkbox"/> | Clinocllore |
| <input checked="" type="checkbox"/> | Chamosite |
| <input checked="" type="checkbox"/> | Zircon |
| <input checked="" type="checkbox"/> | Calcite (Aragonite) |
| <input checked="" type="checkbox"/> | Dolomite |
| <input checked="" type="checkbox"/> | Ankerite |
| <input checked="" type="checkbox"/> | Apatite (F) |
| <input checked="" type="checkbox"/> | Apatite (Cl) |
| <input checked="" type="checkbox"/> | Pyrite |
| <input checked="" type="checkbox"/> | Sphalerite |
| <input checked="" type="checkbox"/> | Rutile/Anatase/Brookite |

Nano-indentation Results

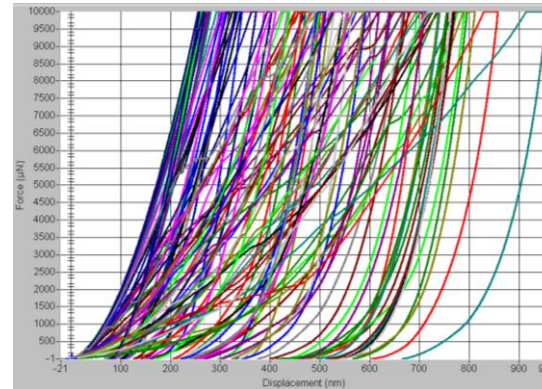
Polished quartz area, 20 indents



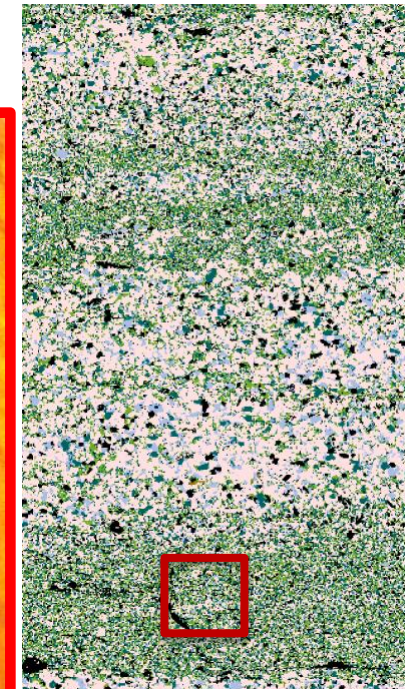
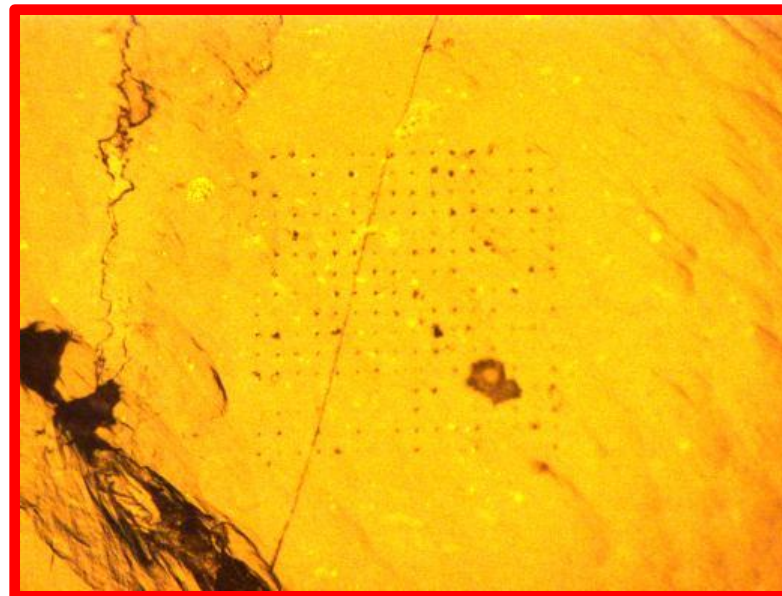
$$E \text{ (Gpa)} = 80.8 \pm 1.3$$



Polished Clay-rich area, 64 indents



- ☒ Quartz (Silica)
- ☒ Feldspars
- ☒ Micas
- ☒ Clay minerals
- ☒ Zircon
- ☒ Calcites
- ☐ Dolomites
- ☐ Apatites
- ☐ Monazite
- ☐ Pyrite
- ☐ Sphalerite
- ☐ Ti oxides

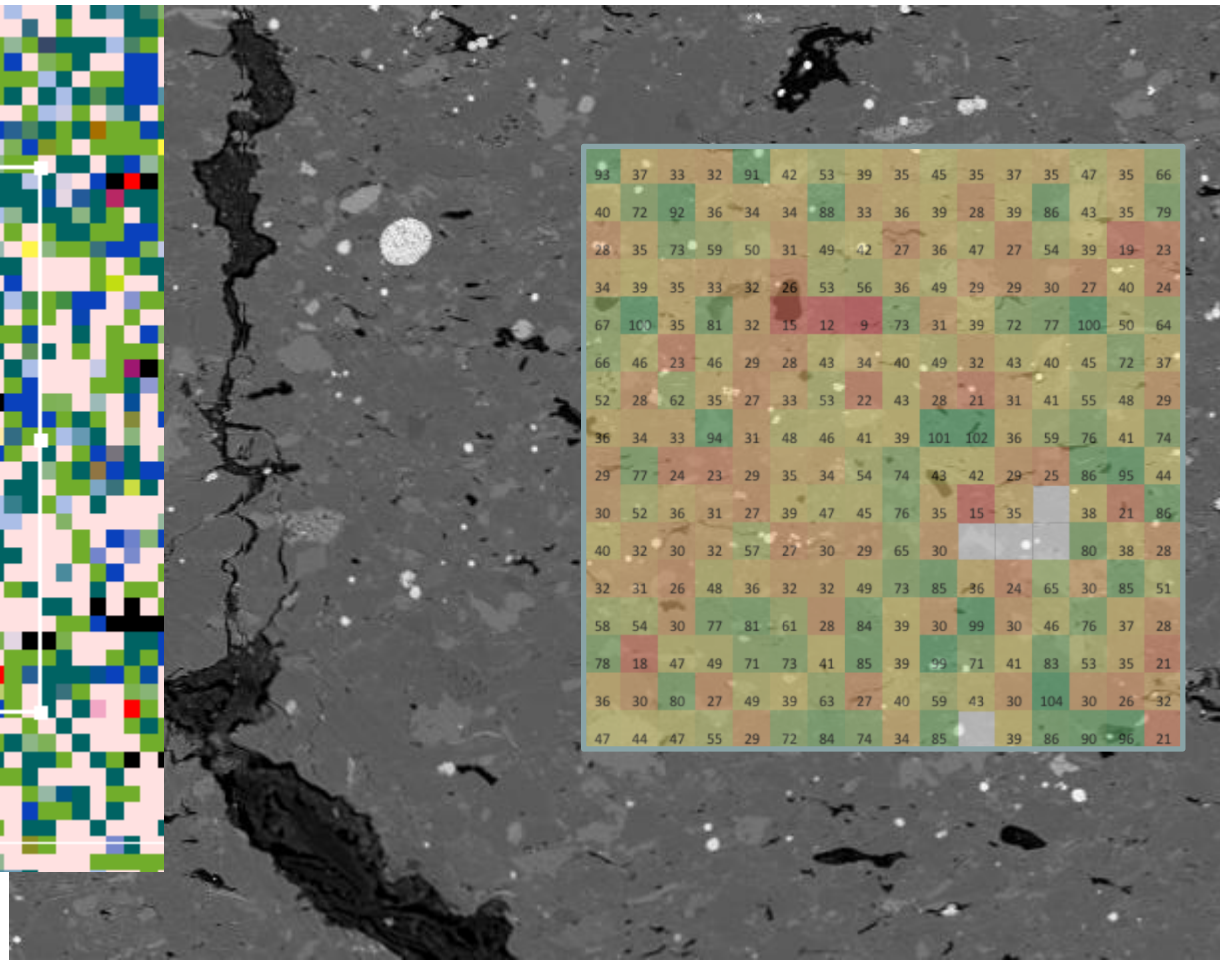
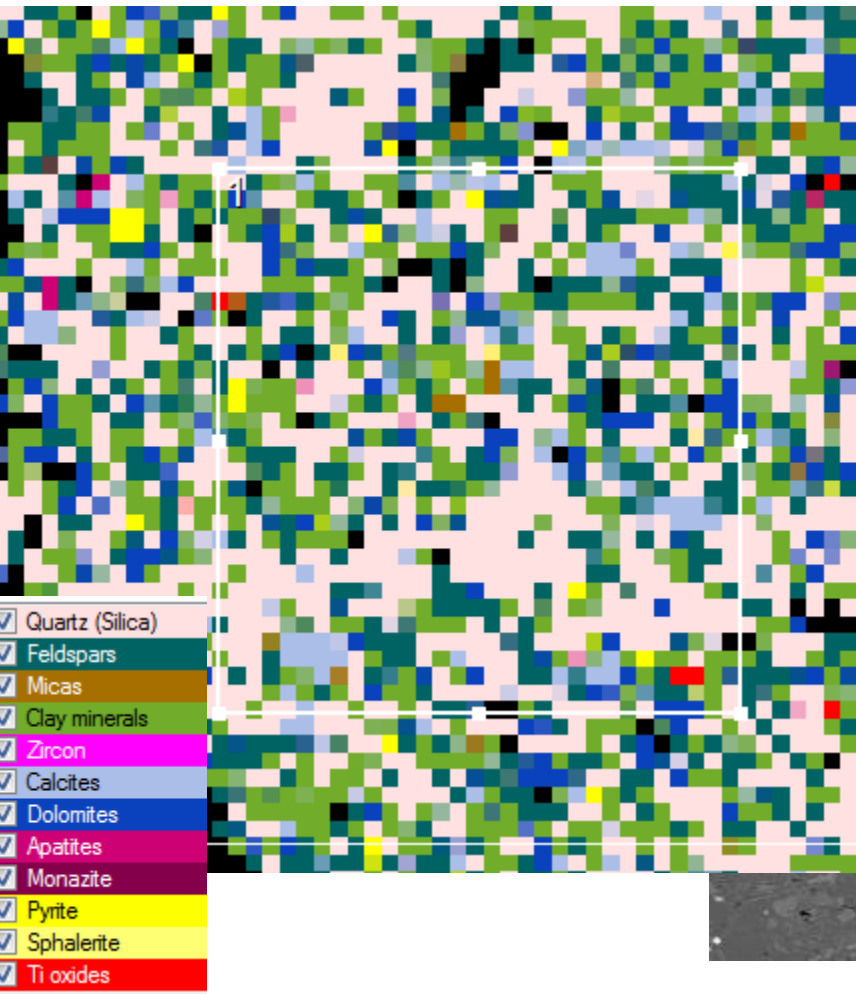


Indentation strain rate = 0.1

Maximum load = 10 mN

Indentation array: 16 x 16, 20 µm spacing

Nano-indentation Results



| | | | | | | | | | | | | | | | |
|----|-----|----|----|----|----|----|----|----|-----|-----|----|-----|-----|----|----|
| 93 | 37 | 33 | 32 | 91 | 42 | 53 | 39 | 35 | 45 | 35 | 37 | 35 | 47 | 35 | 66 |
| 40 | 72 | 92 | 36 | 34 | 34 | 88 | 33 | 36 | 39 | 28 | 39 | 86 | 43 | 35 | 79 |
| 28 | 35 | 73 | 59 | 50 | 31 | 49 | 42 | 27 | 36 | 47 | 27 | 54 | 39 | 19 | 23 |
| 34 | 39 | 35 | 33 | 32 | 26 | 53 | 56 | 36 | 49 | 29 | 29 | 30 | 27 | 40 | 24 |
| 67 | 100 | 35 | 81 | 32 | 15 | 12 | 9 | 73 | 31 | 39 | 72 | 77 | 100 | 50 | 64 |
| 66 | 46 | 23 | 46 | 29 | 28 | 43 | 34 | 40 | 49 | 32 | 43 | 40 | 45 | 72 | 37 |
| 52 | 28 | 62 | 35 | 27 | 33 | 53 | 22 | 43 | 28 | 21 | 31 | 41 | 55 | 48 | 29 |
| 36 | 34 | 33 | 94 | 31 | 48 | 46 | 41 | 39 | 101 | 102 | 36 | 59 | 76 | 41 | 74 |
| 29 | 77 | 24 | 23 | 29 | 35 | 34 | 54 | 74 | 43 | 42 | 29 | 25 | 86 | 95 | 44 |
| 30 | 52 | 36 | 31 | 27 | 39 | 47 | 45 | 76 | 35 | 15 | 35 | | 38 | 21 | 86 |
| 40 | 32 | 30 | 32 | 57 | 27 | 30 | 29 | 65 | 30 | | | | 80 | 38 | 28 |
| 32 | 31 | 26 | 48 | 36 | 32 | 32 | 49 | 73 | 85 | 36 | 24 | 65 | 30 | 85 | 51 |
| 58 | 54 | 30 | 77 | 81 | 61 | 28 | 84 | 39 | 30 | 99 | 30 | 46 | 76 | 37 | 28 |
| 78 | 18 | 47 | 49 | 71 | 73 | 41 | 85 | 39 | 99 | 71 | 41 | 83 | 53 | 35 | 21 |
| 36 | 30 | 80 | 27 | 49 | 39 | 63 | 27 | 40 | 59 | 43 | 30 | 104 | 30 | 26 | 32 |
| 47 | 44 | 47 | 55 | 29 | 72 | 84 | 74 | 34 | 85 | | 39 | 86 | 90 | 96 | 21 |

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