Impact of Multi-Scale Characteristics of Heterogeneous Pore Structure and Mineralogy on Mechanical Properties of Shale*

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Abstract

Because of the need to artificially enhance permeability through induced fracture of mudstones, internal variations in the strength, toughness and elasticity of mudstones have been linked to reservoir performance. Mudstone mechanical properties are geologically controlled through changes in detrital and authigenic mineralogy, organic content and porosity that can be linked to deposition and diagenesis. We are investigating the impact of these geologic controls on mechanical strength and compliance from 10 µm to 10 cm scales in the Mancos Shale. We have described the range of sample lithologic variations at the sub-cm scale using a combination of optical petrography, microbeam analysis and laser scanning confocal microscopy. The samples' lithologic variations have been subdivided into macroscopic and microscopic facies. The microfacies' porosity and mineralogy were determined using dual focused ion beam-scanning electron microscopy at 10s of nm resolution. Micropillar unconfined compression testing (10 µm diameter by 20 µm length) perpendicular and parallel to bedding determined each microfacies' unconfined strength and Young's modulus. Micropillars were created with focused Ga ion milling. Micropillar compression tests were performed with a nanoindenter and flat diamond indenter. Macro-scale mechanical testing was conducted both perpendicular and parallel to bedding on the core samples from the different macrofacies using unconfined and triaxial compression tests with traditional hydraulic presses and pressure vessels.

From the stress-strain paths of both micropillar and macro-scale mechanical testing, the anisotropy of elastoplastic deformation was determined. Comparison of multi-scale lithologic description and multi-scale anisotropic mechanical experiments is useful to directly evaluate the relationship between mechanical response and microscopic features across scales. This evaluation provides an example on how to develop multi-scale understanding of reservoir mudstones by correlating spatially extensible lithologic descriptions to multiple scales of deformation and failure.

Acknowledgement

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Lazar, O. Remus, Kevin M. Bohacs, Joe H.S. Macquacker, Juergen Schieber, and Timothy M. Demko, 2016, Capturing key attributes of fine-grained sedimentary rocks in outcrops, cores, and thin sections: Nomenclature and description guidelines: Jour. Sedimentary Research, v. 85, p. 230-246.

Ulmer-Scholle, Dana S., Peter A. Scholle, Jürgen Schieber, and Robert J. Raine, 2014, A color guide to the petrography of sandstones, siltstones, shales and associated rocks: AAPG, Tulsa, OK.

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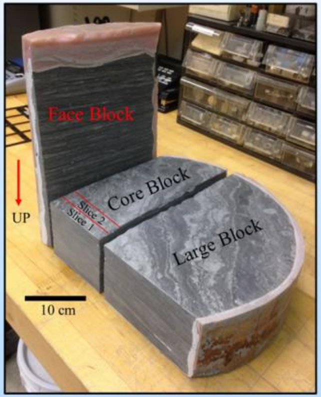
Introduction

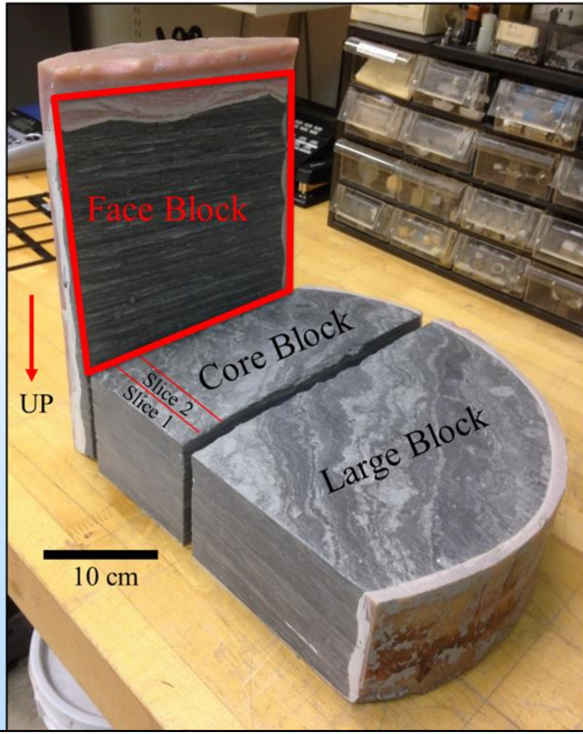
- Predicting mechanical characteristics of shale.
- Approach is to relate petrographic observations to mechanical properties at multiple scales.
- Use as data for mechanical modeling.
- This is a progress report.

Approach

- 40 cm diameter core of Mancos Shale
- Mineralogical and textural characterization
  - Macroscopic
  - Optical petrography
  - BSE, X-ray mapping
  - Micro-CT
- Mechanical tests
  - Triaxial compression (1x2")
  - Cylinder splitting (1x0.5")
  - Micropillar compression (nannoindentation)
- Mechanical modeling



Presenter's notes: Hard to get a large intact piece of shale (somewhere in UT)



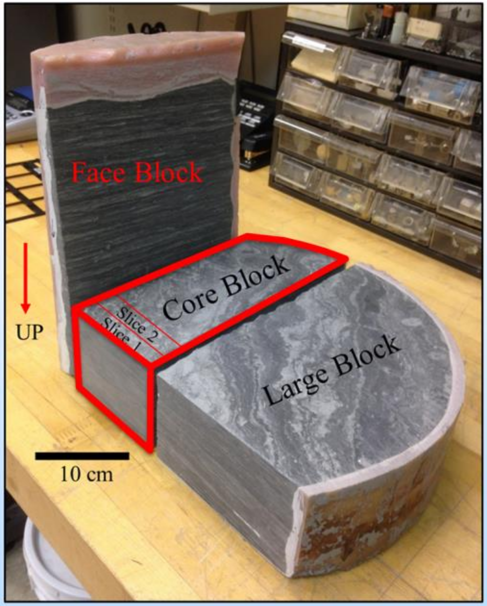
Presenter's notes: Common Bakken, Chattanooga, and Woodford Shales, USA; Monte Antola Formation, Italy; Mount Isa Group, Australia; and Eau Claire Formation

- Cretaceous Mancos Shale
- Heterolithic facies
  - 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

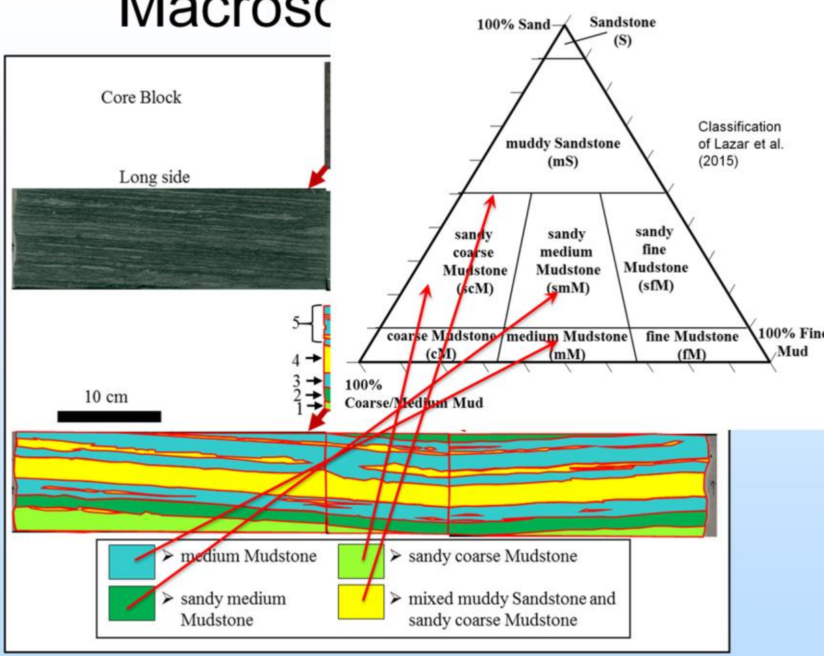
Facies description

- Macroscopic
  - Workflow of Lazar et al. (2015)
    - Hand lens, knife, spray bottle…
- Microscopic
  - Optical, BSE, X-ray mapping

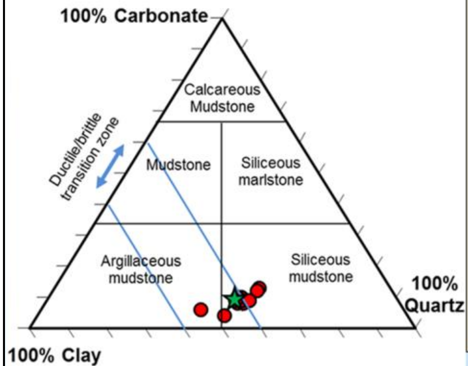
Presenter’s notes: What scale of description is necessary to capture mechanical behavior at larger scales?


Face Block
Core Block
Slice 2
Slice 1
Large Block
UP
10 cm

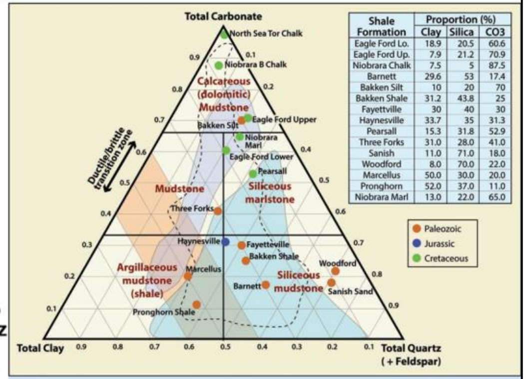
Macrosc


Core Block
Long side
10 cm
5
4
3
2
1
100% Sand
Sandstone (S)
muddy Sandstone (mS)
sandy coarse Mudstone (scM)
sandy medium Mudstone (smM)
sandy fine Mudstone (sfM)
coarse Mudstone (cM)
medium Mudstone (mM)
fine Mudstone (fM)
100% Fine Mud
100% Coarse/Medium Mud
Classification of Lazar et al. (2015)
medium Mudstone
sandy coarse Mudstone
sandy medium Mudstone
mixed muddy Sandstone and sandy coarse Mudstone

Macroscopic Facies - XRD



Mancos XRD Data



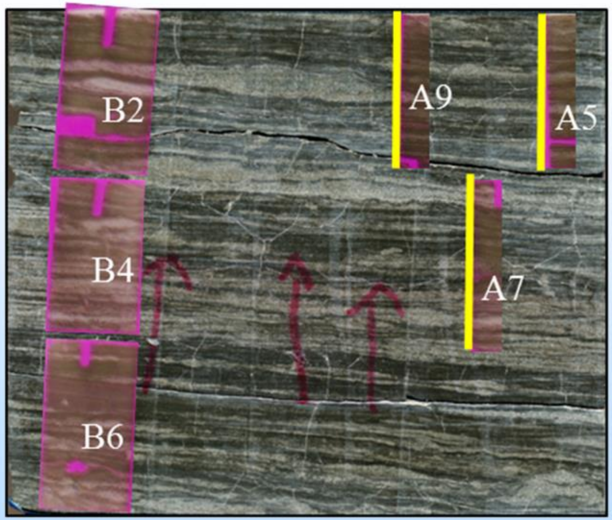
Shale Formation	Proportion (%)		
	Clay	Silica	CO3
Eagle Ford Lo.	18.9	20.5	60.6
Eagle Ford Up.	7.9	21.2	70.9
Niobrara Chalk	7.5	5	87.5
Barnett	29.6	53	17.4
Bakken Silt	10	20	70
Bakken Shale	31.2	43.8	25
Fayettville	30	40	30
Haynesville	33.7	35	31.3
Pearsall	15.3	31.8	52.9
Three Forks	31.0	28.0	41.0
Sanish	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

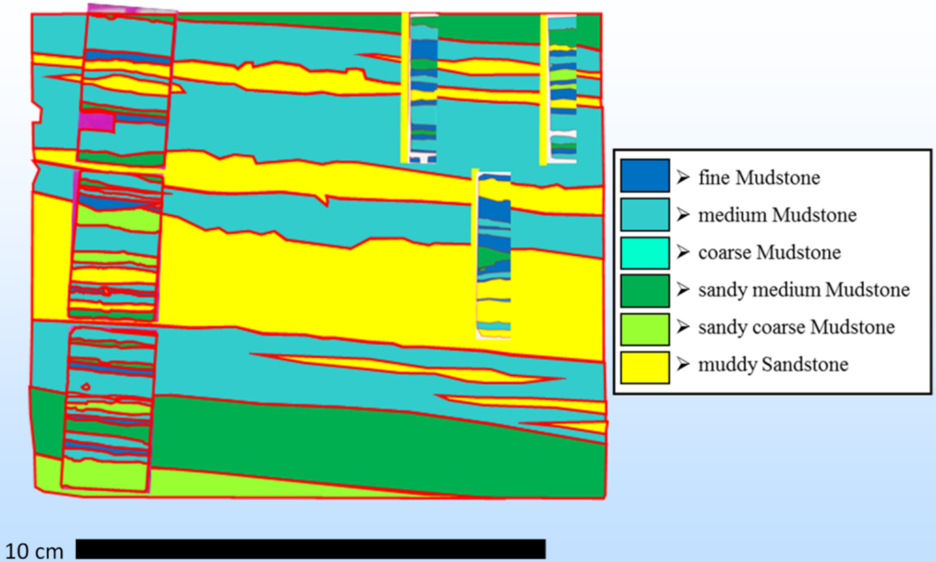
Ulmer-Scholle et al. (2014)

Prediction: Heterolithic facies are mechanically homogeneous.

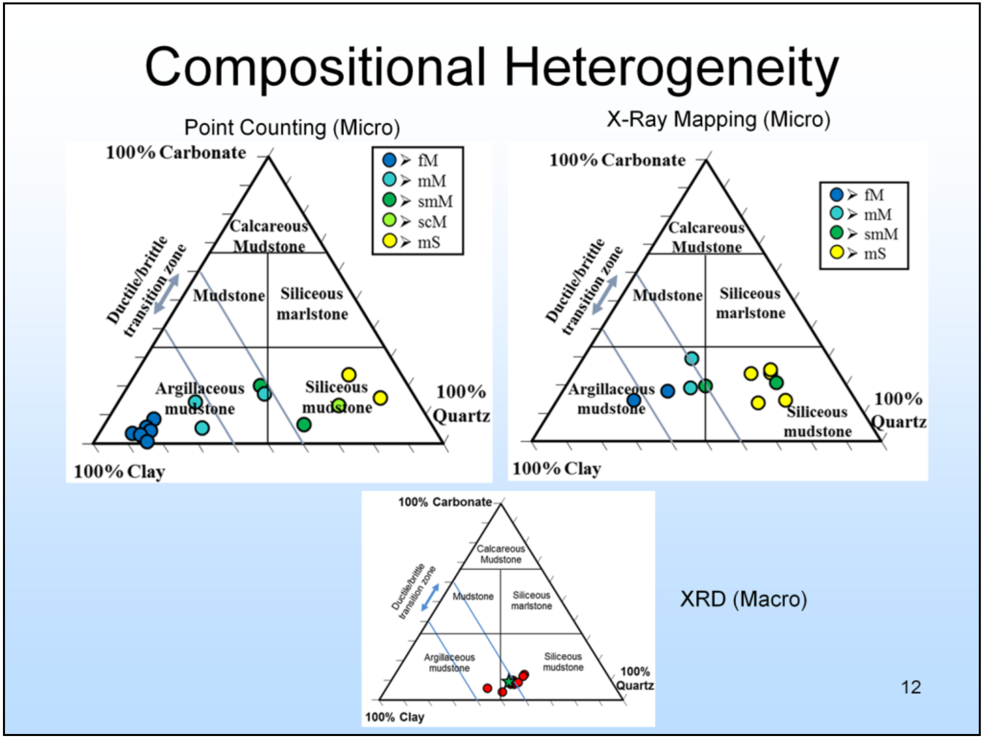
Presenter's notes: One might be tempted to predict that there will be only minor mechanical differences among the macro lithofacies based upon the XRD data. Check classification scheme

- Macro-lithofacies consist of several micro-lithofacies



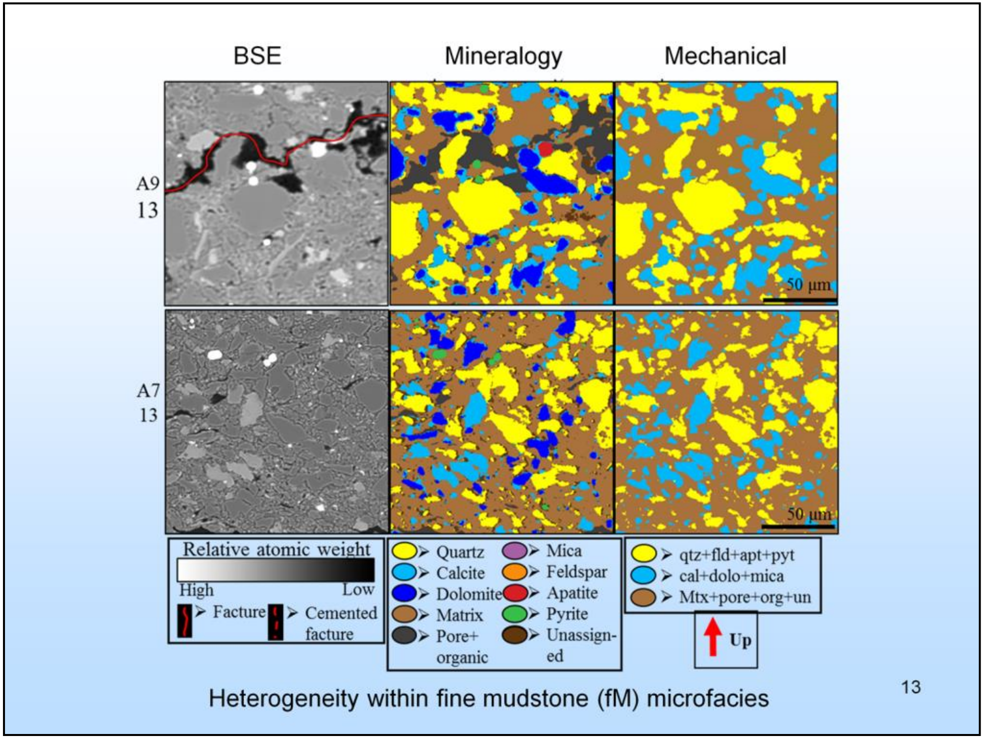


Presenter's notes: Macro-lithofacies consist of several micro-lithofacies. Used the same classification scheme as for macrolithofacies.



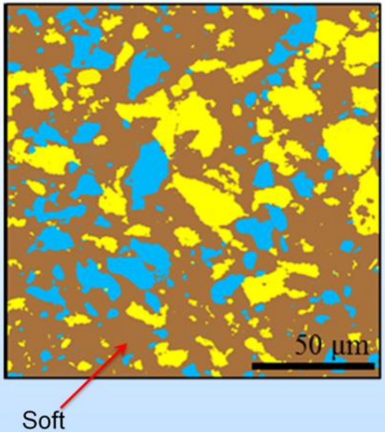
Presenter's notes: Suggests that the "prediction" from the macroscopic characterization is incorrect. It seems to be mechanically heterogeneous. However, there is heterogeneity within the microfacies… Coarser microfacies have more quartz and less clay.

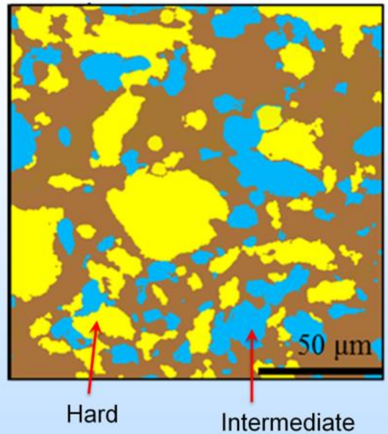
I imagine the geologist releaved to hear this!



Presenter's notes: Within microfacies heterogeneity. Some are relatively homogeneous

Mechanical Facies



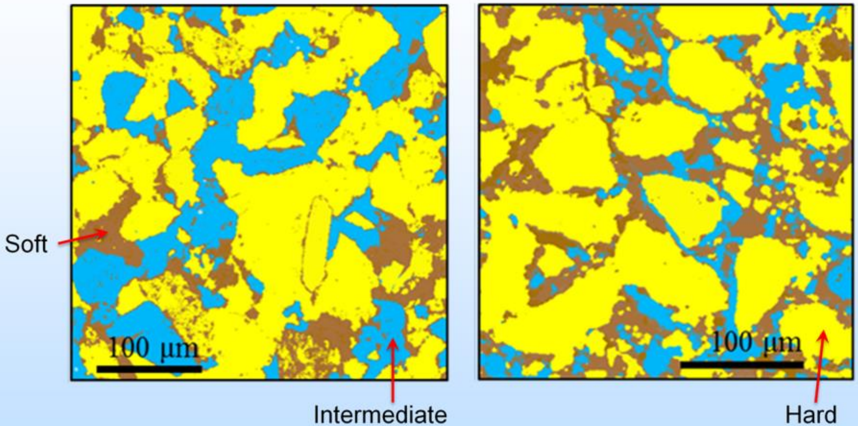


Hard 22%
Intermediate 15%
Soft 63%

Hard 30%
Intermediate 18%
Soft 52%

fine mudstone (fM) microfacies

Mechanical Facies



Hard 55%
Intermediate 26%
Soft 19%

Hard 58%
Intermediate 14%
Soft 28%

muddy Sandstone (mS) microfacies

Presenter's notes: Image on right has highest quartz %, but all surrounded by clays. Should have lower strength than zone to left.

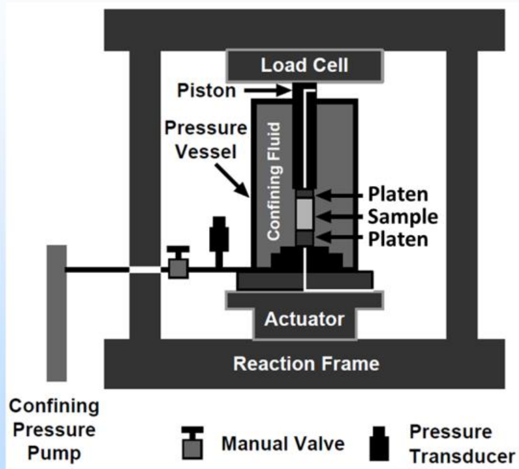
Textural/mineralogical conclusions

- Considerable heterogeneity within macroscopic and sometimes microscopic facies.
- Relationship with grain size: finer facies have more clay and less quartz.
- Suggests that coarser facies should be stronger than finer.

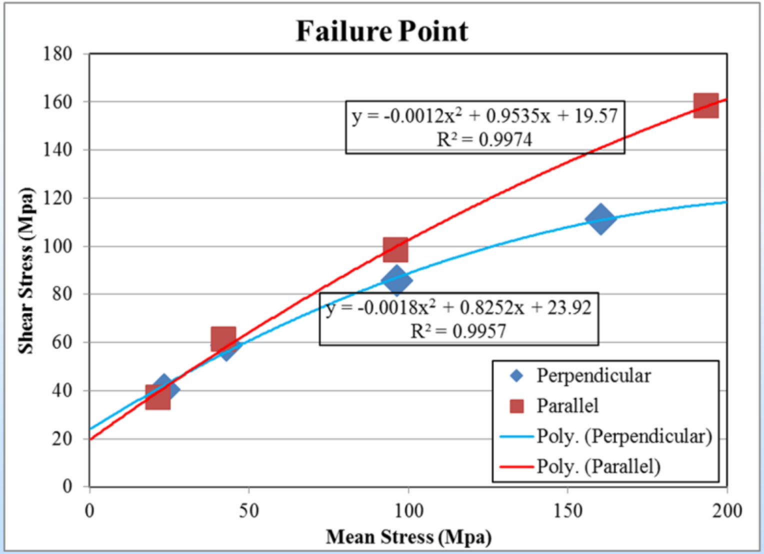
Presenter's notes: Compositional variation muted by averaging in larger samples.

Triaxial Compression Tests

- Bedding parallel and perpendicular 1 x 2 inch plugs
- Polyurethane jacketed
- LVDT's (linear variable differential transformers) record strain



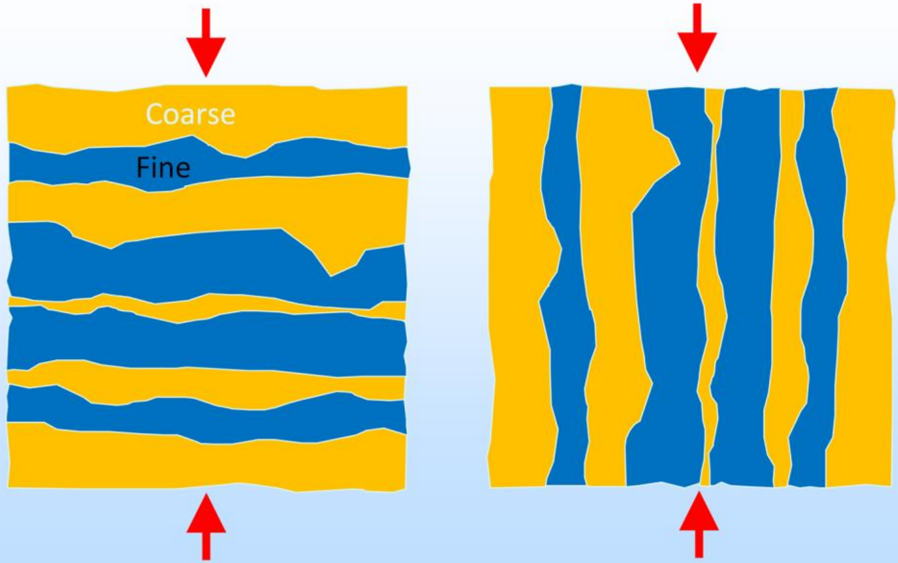
Presenter's notes: 1"x2" plugs

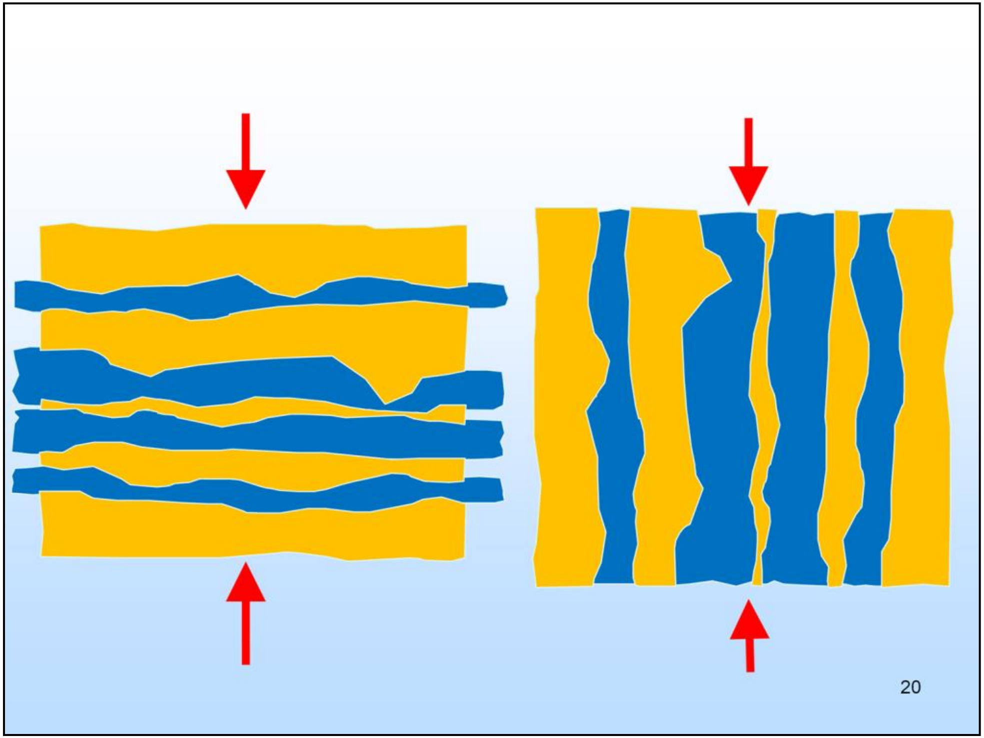


Greater shear stress needed for failure parallel to bedding

Presenter's notes: Triaxial Compression Tests

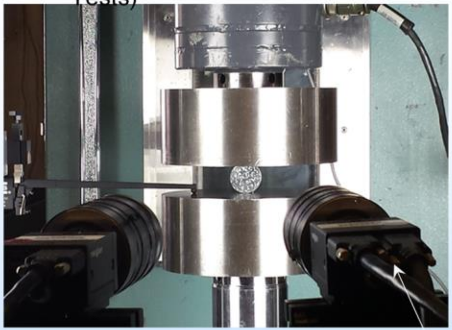
Geomechanics-Conceptual Model



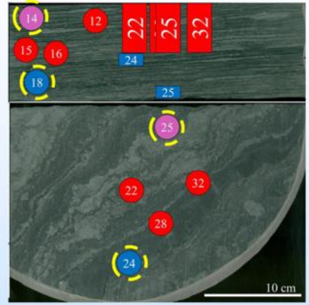


Presenter's notes: This is a hypothesis. Next we move to try to relate strain more directly to lithofacies…

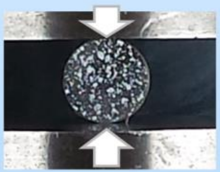
Indirect Tensile (Brazilian Tests)



High speed camera

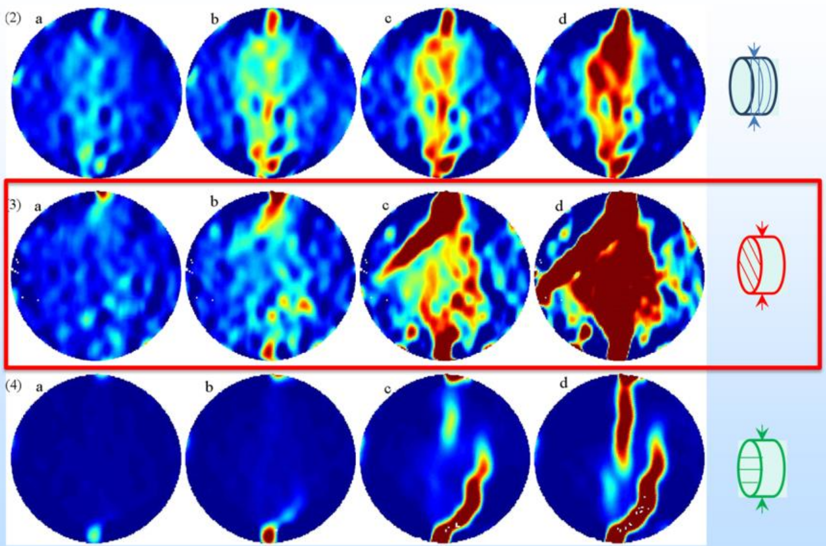


Two perpendicular and two parallel to bedding samples

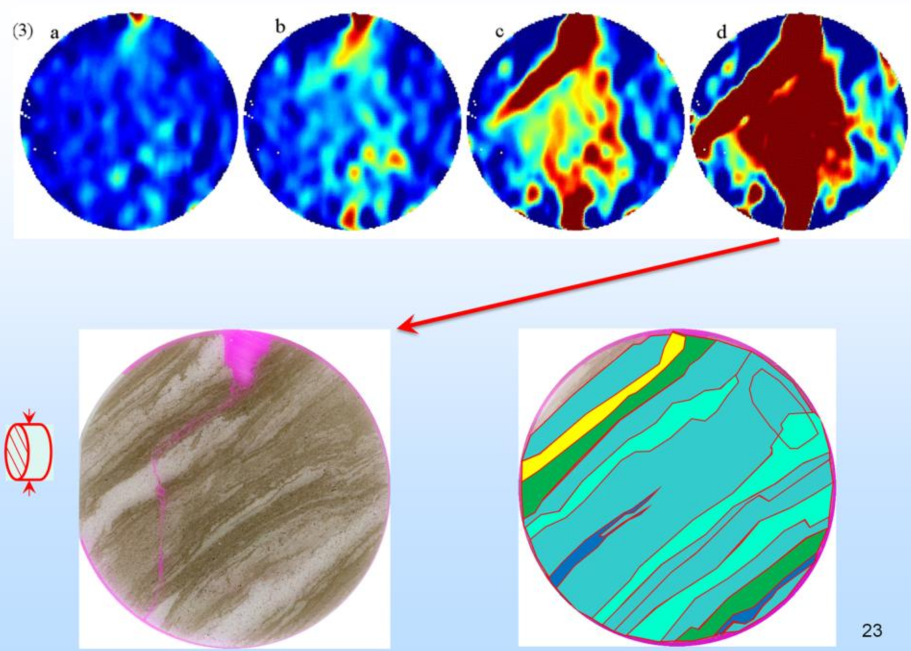


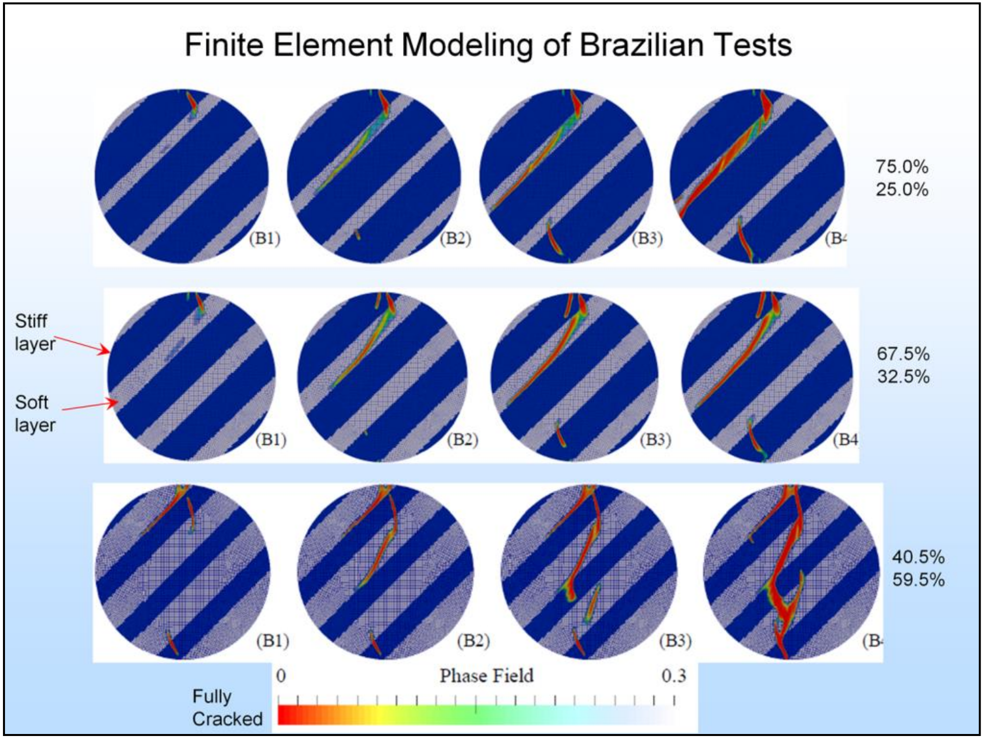
Paint markers: Digital Image Correlation to estimate 2D strain on the surface

Tensile Strain Distribution (Digital Image Correlation)



Presenter's notes: Stain strongly partitioned by microfacies


(3)
a
b
c
d



Presenter's notes: Phase field model for crack representation

Shale is modeled as two-constituent brittle materials with stiff and soft layers:

Young's Modulus of Stiff and soft layers are 70.0 and 5.6 GPa, respectively, and the Poisson's ratio of both layers are assumed to be 0.2

(Pore pressure)

(Chemo-mechanical coupling)

Differential Equations Analysis Library. II

DEAL.II Open Source Finite Element Library (Bangerth et al., 2013)

To simulate the crack propagation in shale in the brittle regime, a phase field fracture model based on generalized Griffin's theory is adopted.

The phase field fracture model allows one to treat a crack in a continuum media not as an embedded discontinuity but as an diffusive region with a given characteristic length. The phase field evolution can be therefore captured with continuous displacement field, and the governing equations can be obtained via the minimization of a free energy functional that combines the elastic strain energy which governs the reversible deformation, the fracture energy that responsible of the growth of fracture zone and the external work done on the body (Moelans et al., 2008). This diffusive-interface model can overcome some of the difficulties inherent to discrete fracture approaches that need sharp interfaces with complex evolving topologies and explicit heuristics to govern their propagation and interaction.

Conclusions

- 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.
- Can scale up by examining other common lithofacies.

Acknowledgements

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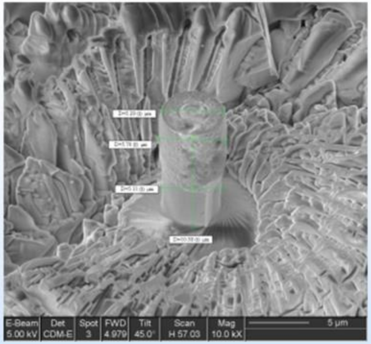
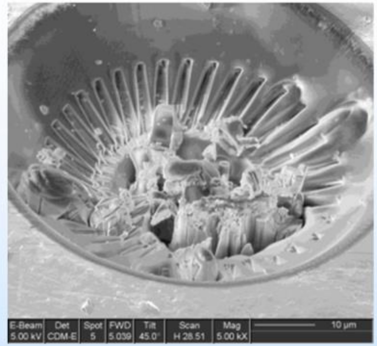
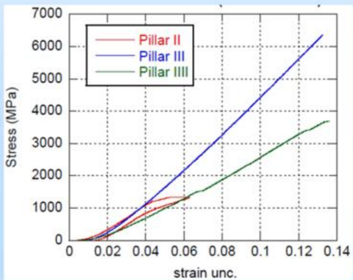
Coming Soon: Micropillar Compression Testing







- Focused Ga+ Ion Milling and SEM imaging
- Micropillar compression (load vs. displacement) performed with a nanoindenter and flat diamond indenter


Outdoor