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Impact of Multiscale Heterogeneity on Mechanical Behavior of Mancos Shale

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Sandia National Laboratories

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Exceptional service in the national interest

National Nuclear Security Administration

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Summary

The performance of unconventional resources reservoir is a function of the hydro, mechanical, and chemical properties of shale formations with compositional and textural heterogeneity across a range of scales. In particular, mechanical properties (elastic properties, fracture toughness, anisotropy, etc.) are controlled by a variety of geologic variables, including detrital and authigenic mineralogy, cements, and organic content, and the spatial distribution of these characteristics. In this work integrated approach of multiscale imaging, mineralogy distribution, nano-indentation, and numerical simulations is employed to investigate the impact of the micro-lithofacial heterogeneities on pore structure and mechanical properties for Cretaceous Mancos Shale, a thick mudstone with widespread occurrence across the western interior of the USA. Detailed petrographic analysis results are mapped to results from axisymmetric compression and indirect tensile strength testing of this facies at the core-plug scale, and nanoindentation measurements at the micron scale. As anticipated, there is a marked difference in elastic and failure response in axisymmetric and cylinder splitting tests relating to loading orientation with respect to bedding or lamination. Shear bands and Mode-I fractures display contrasting fabric when produced at low or high angles with respect to lamination. Nanoindentation, mineralogy distribution based on MAPS (Modular Automated Processing System) technique, and high resolution backscattered electron images show the effect of composition, texture phases, and interfaces of phases on mechanical properties. A range of Young's moduli from nanoindentation is generally larger by a factor of 1 to 4 compared to axisymmetric compression results, showing the important effect of pores, microcracks, and bedding boundaries on bulk elastic response. Together these data sets show the influence of cement distribution on mechanical response. Variations in micro-lithofacies are first-order factors in determining the mechanical response of this important Mancos constituent, and are likely responsible for its success in hydrofracture-based recovery operations as compared to other Mancos lithofacies types. This work allows us to make more accurate prediction of reservoir performance by developing a multi-scale understanding of mudstone response to reservoir stimulation efforts.

Acknowledgments

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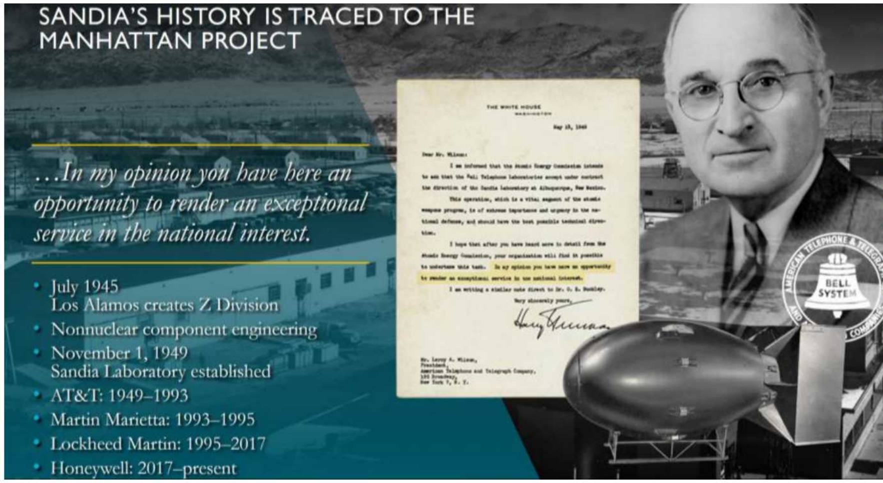
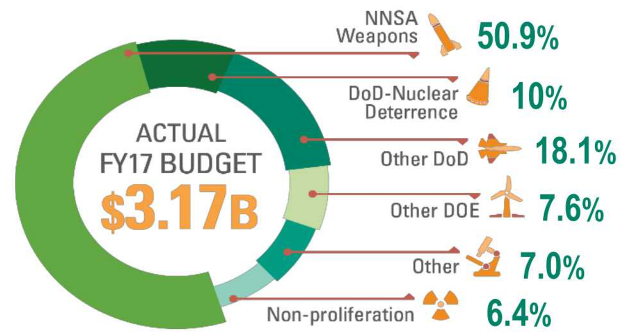
- Peter Mozley, Oh-Tark Kwon (NMT)

SANDIA NATIONAL LABORATORIES OVERVIEW



SANDIA ADDRESSES NATIONAL SECURITY CHALLENGES

SANDIA'S BUDGET and WORKFORCE



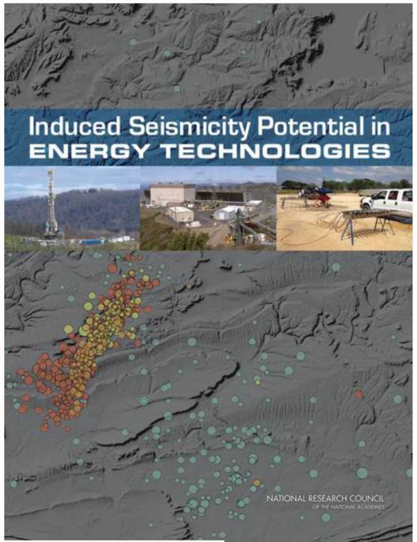
12,256 EMPLOYEES

10,940 New Mexico

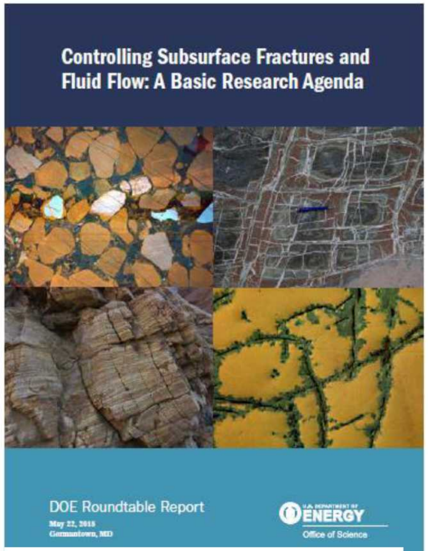
1,316 California

Subsurface Energy Activities

- Subsurface energy technologies typically involve the change of fluid flow, stress, thermal, chemical (aka THMC) status in fractured and porous media
  - Unconventional resources recovery
  - Disposal of wastewater and nuclear waste
  - Subsurface carbon and compressed gas storage
- To improve modern energy activities and reduce adverse risks (e.g., induced seismicity and environmental impact), current understanding of poromechanics, averaging conceptual models (e.g., cubic law and biot effective stress), and coupled effects on flow paths needs to be improved
- Mesoscale analysis – linking discrete and complex pore-scale behavior to continuum (macroscale) reservoir response – is key, yet remains elusive as a result of the extreme heterogeneity and resulting scale dependence.



NRC, 2013



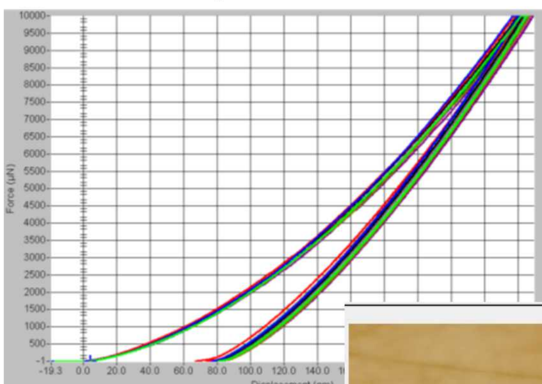
DOE BES Report, 2015

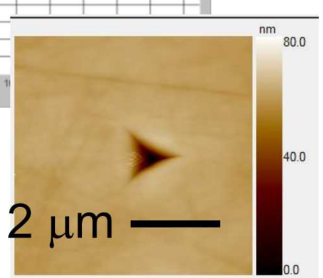
Multiscale Heterogeneity in Compositions, Pore structure, and Mechanical Properties

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

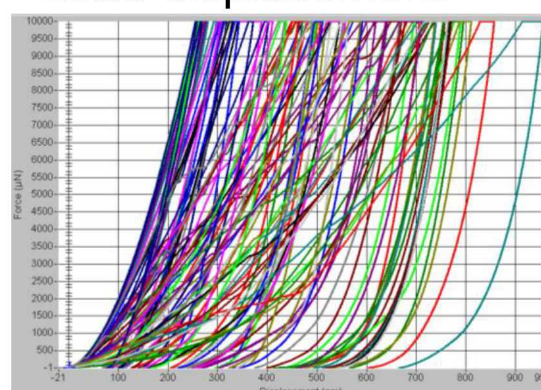
Quartz area, 20 indents
Load-displacement

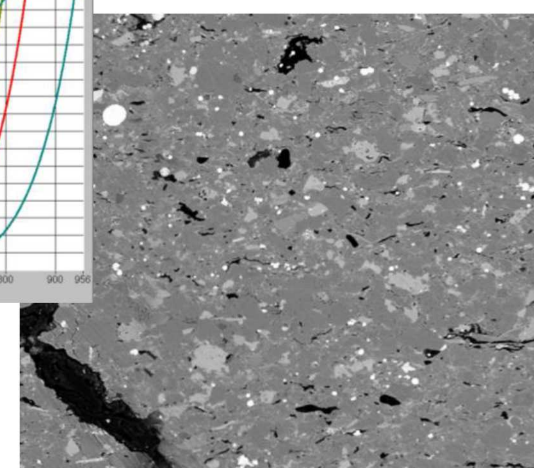




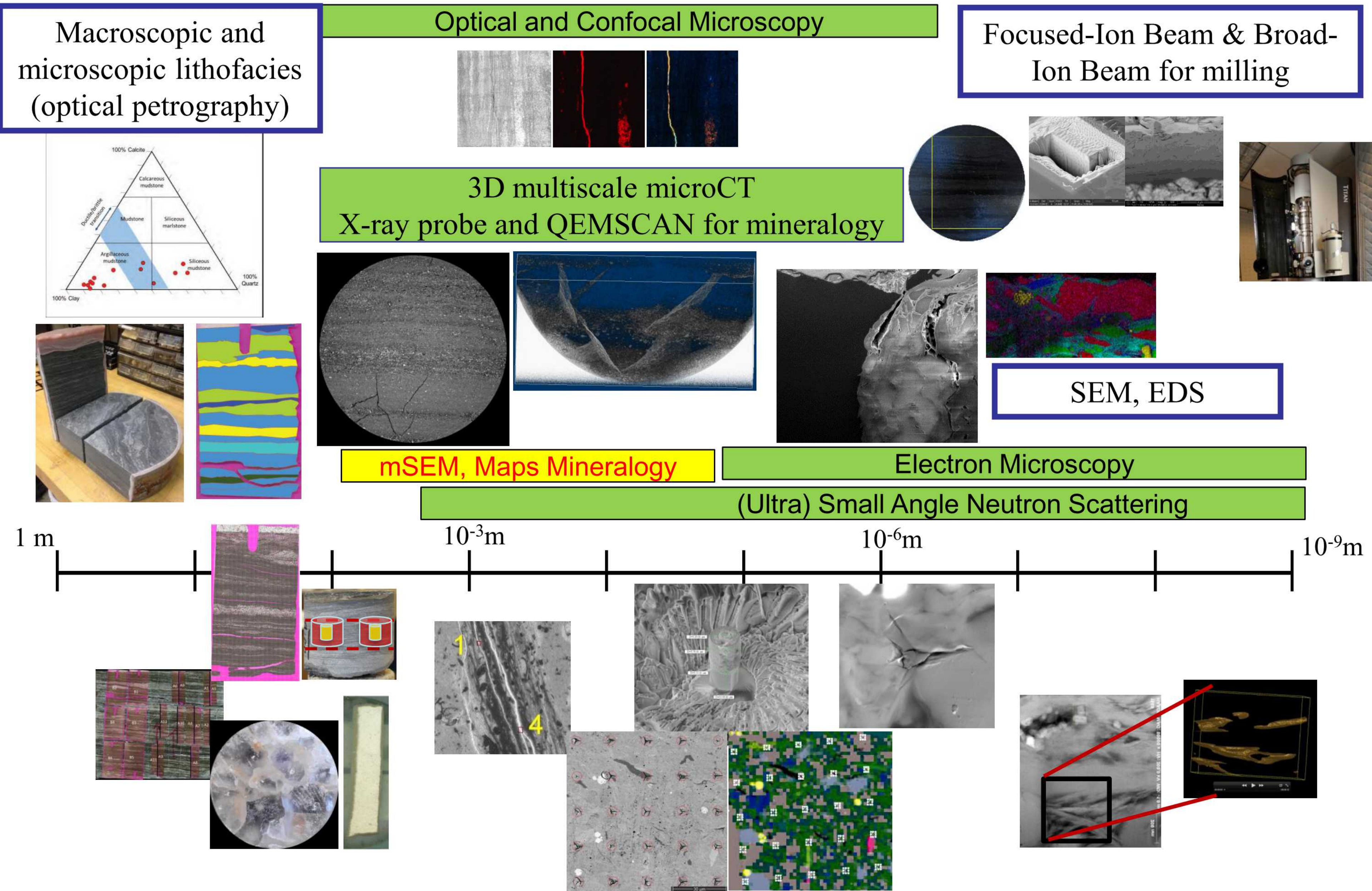
Er (Gpa) =
80.8 ± 1.3

Clay-rich area, 64 indents
Load-displacement



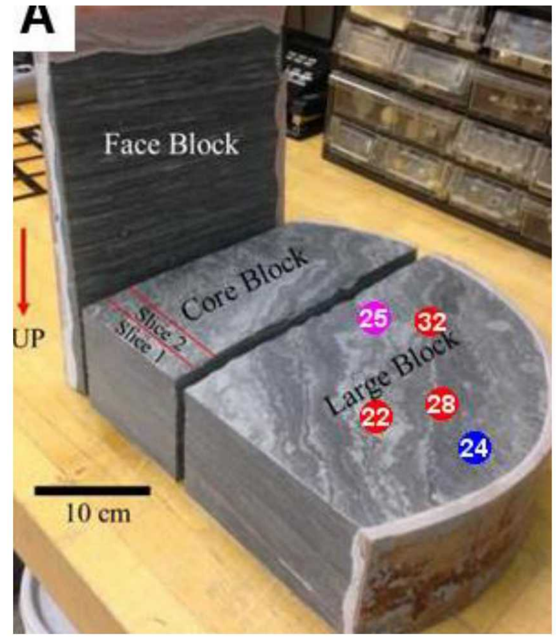


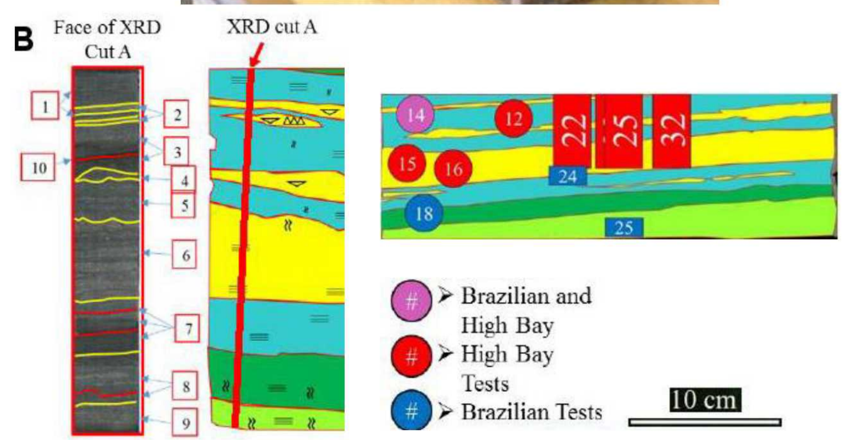
Multiscale characterization of physical, chemical, and mechanical heterogeneity of nano-porous geomaterials



Approach

- **40 cm diameter core of Mancos Shale**
  - Interlaminated fine mud, medium/ coarse mud, and very fine sand
  - 1-3 mm laminae
  - Parallel lamina, wavy lenticular lamina, ripple forms, and bioturbation
- **Mineralogical and textural characterization**
  - Macroscopic
  - Optical petrography/microscopy
  - Micro-CT
  - FIB-SEM
  - BSE
  - MAPS Mineralogy
- **Mechanical tests**
  - Uni-/Tri-axial compression (1x2”)
  - Brazilian Test (1x0.5”)
  - Nanoindentation
- **Computational modeling**

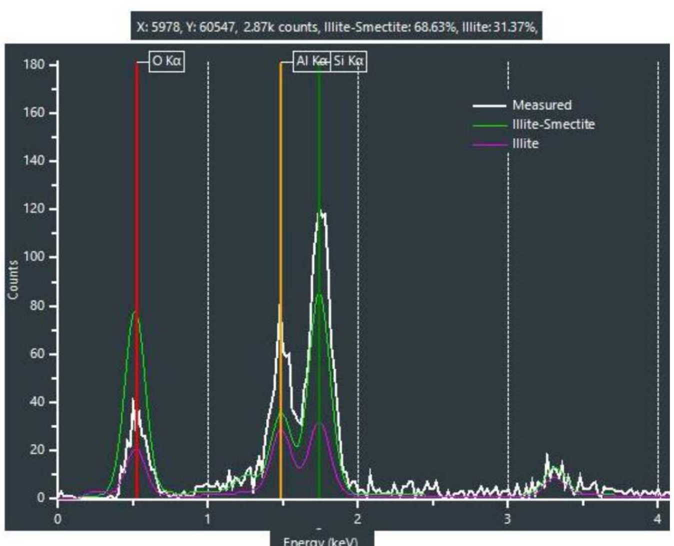


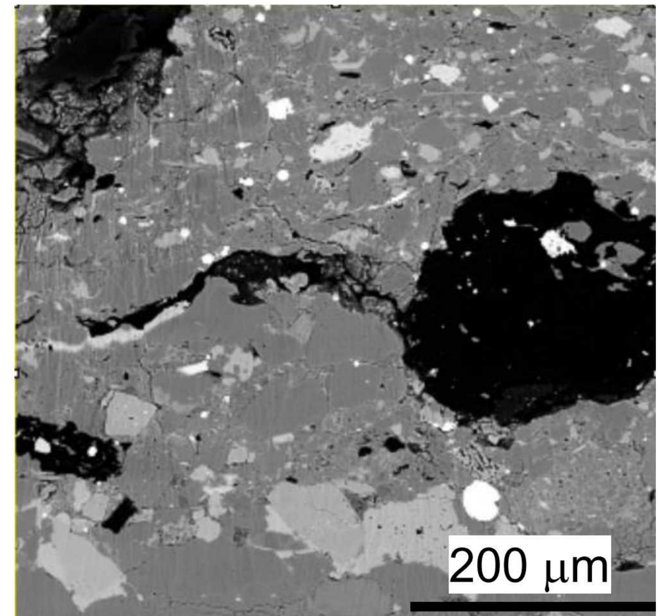


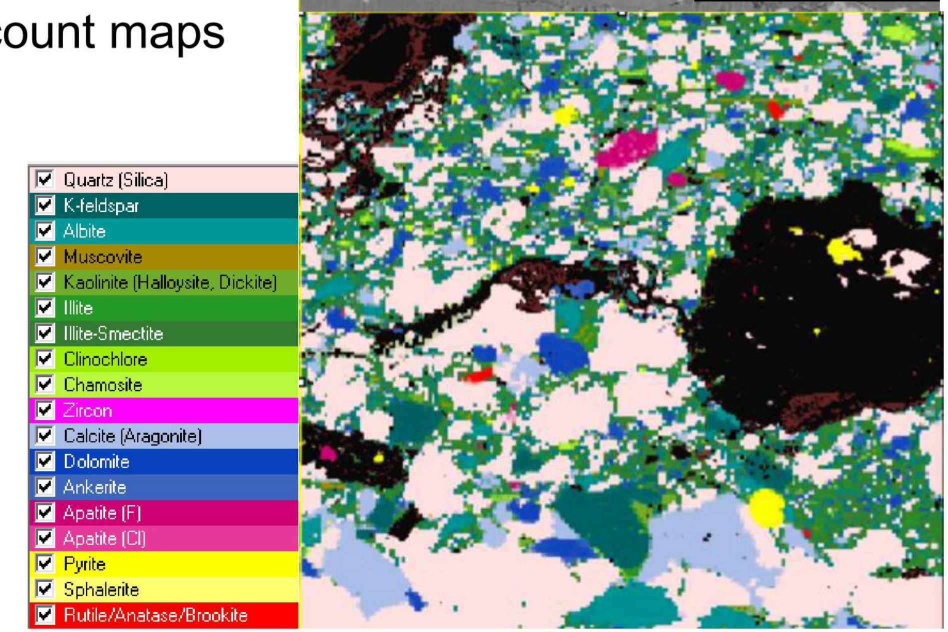
Yoon et al. (AAPG, Memoir 2019, in press)
Dewers et al. (AGU, Monograph, 2019, in press)

MAPS Mineralogy

- **SEM-based automated mineralogical measurement, analysis, 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 – single/multiple minerals
  - Elemental substitutions
  - Simultaneous mineral element and count maps

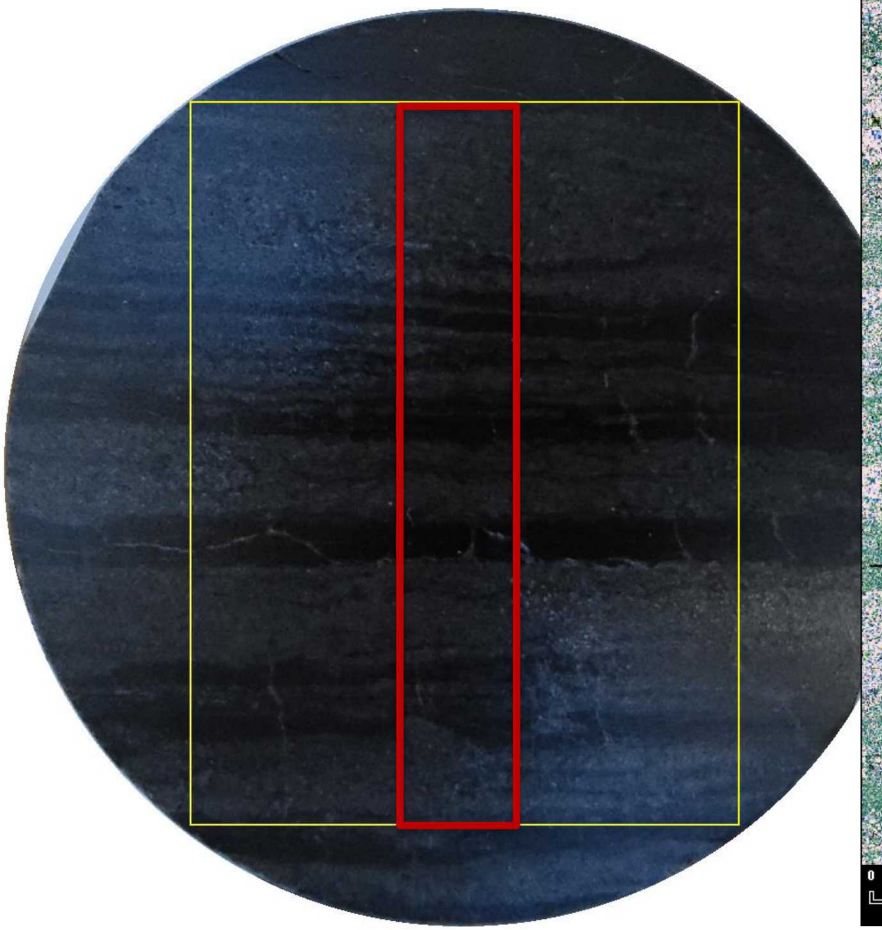


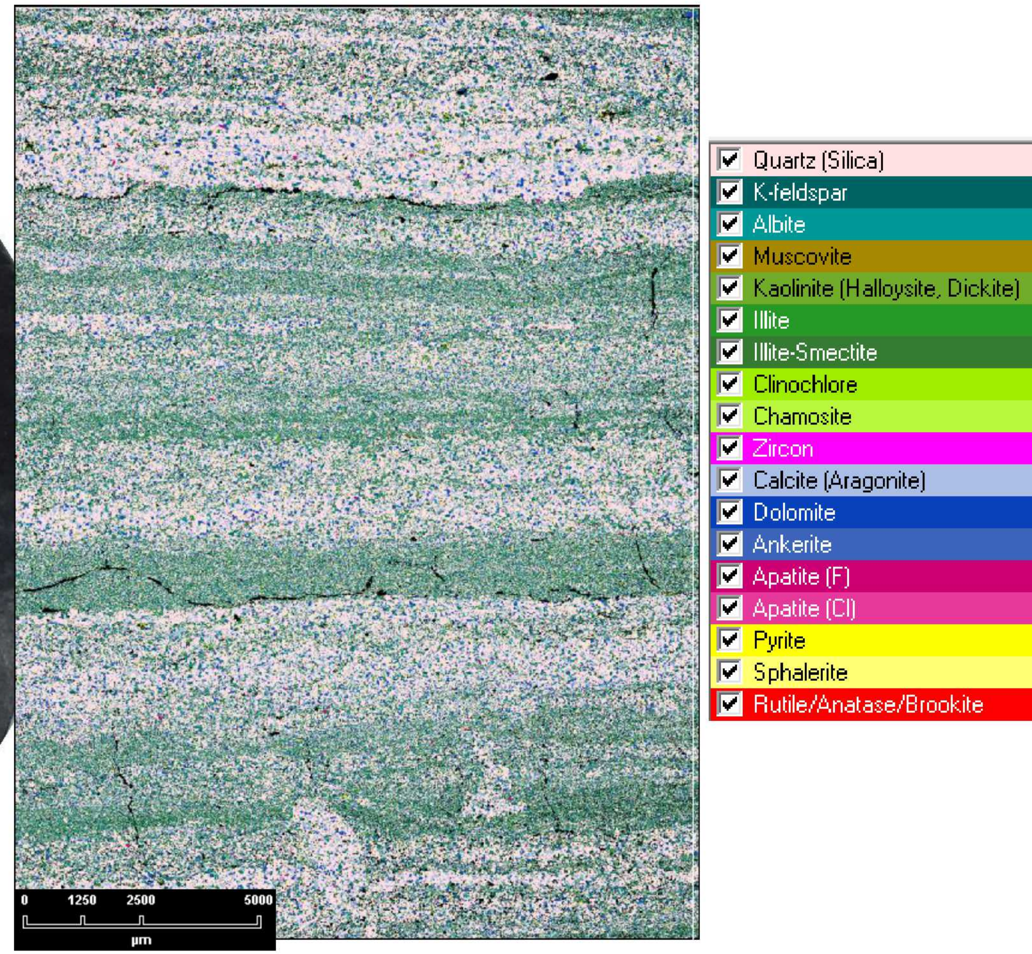




Mineralogy Mapping

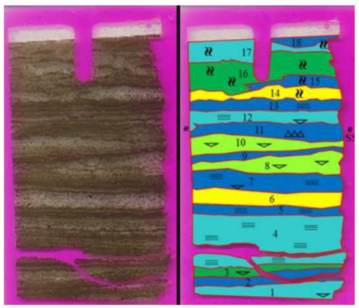
Ion-milling polished Mancos
(1 inch diameter)

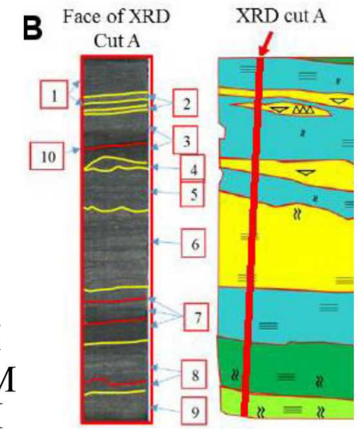


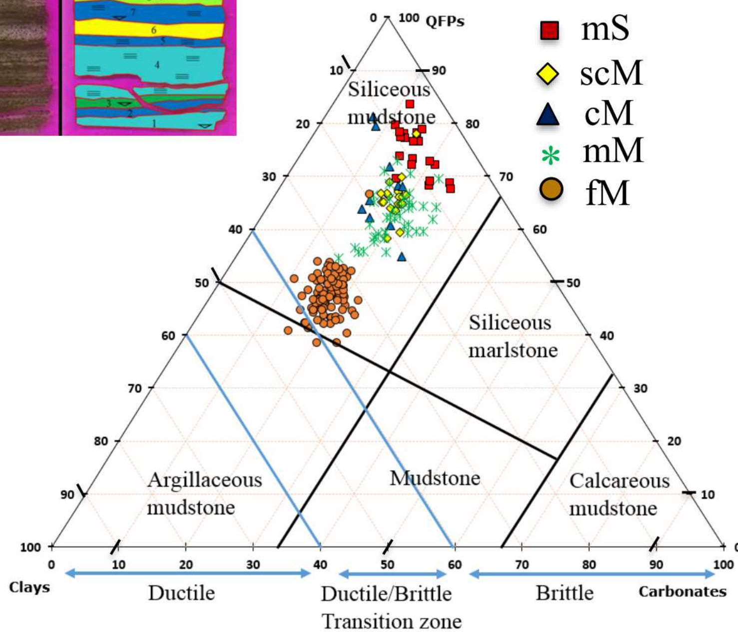


Yellow Box (1.45 x 1.98 cm): BSE @ 1µm & MAPS @ 10µm
Red box (0.18 x 1.98 cm): BSE @ 0.2µm & MAPS @ 2µm

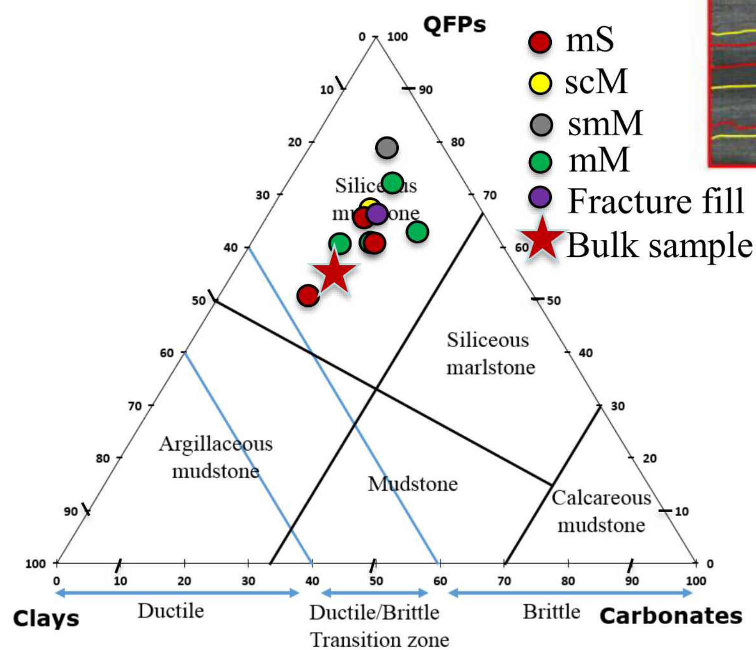
Mineralogy Mapping: Scale/methods dependent







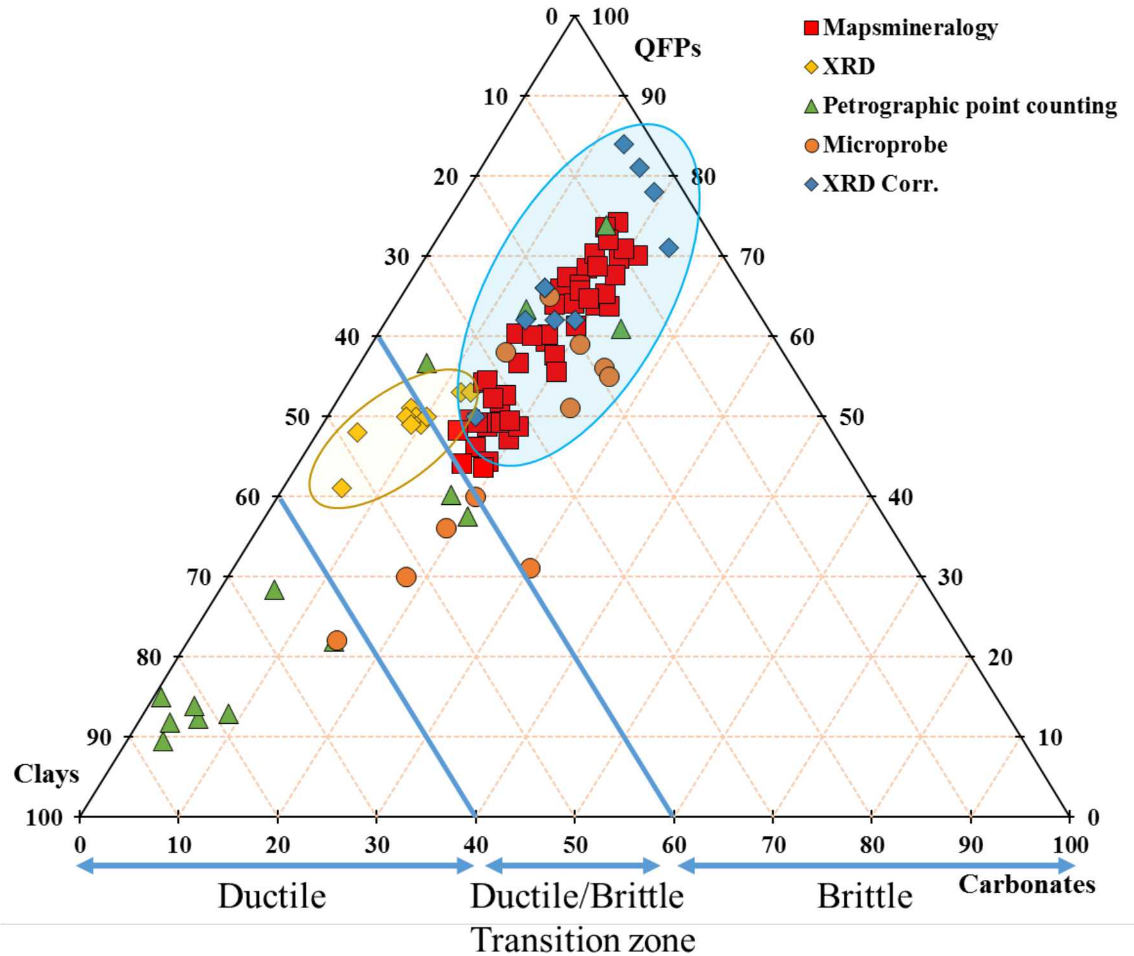
MAPS



XRD

Yoon et al. (AAPG, Memoir 2019, in press)

Mineralogy Mapping: Scale/methods dependent



Kwon (@NMT, MS work, 2018)

Influence of geological attributes on mechanical properties

Micro-lithofacies

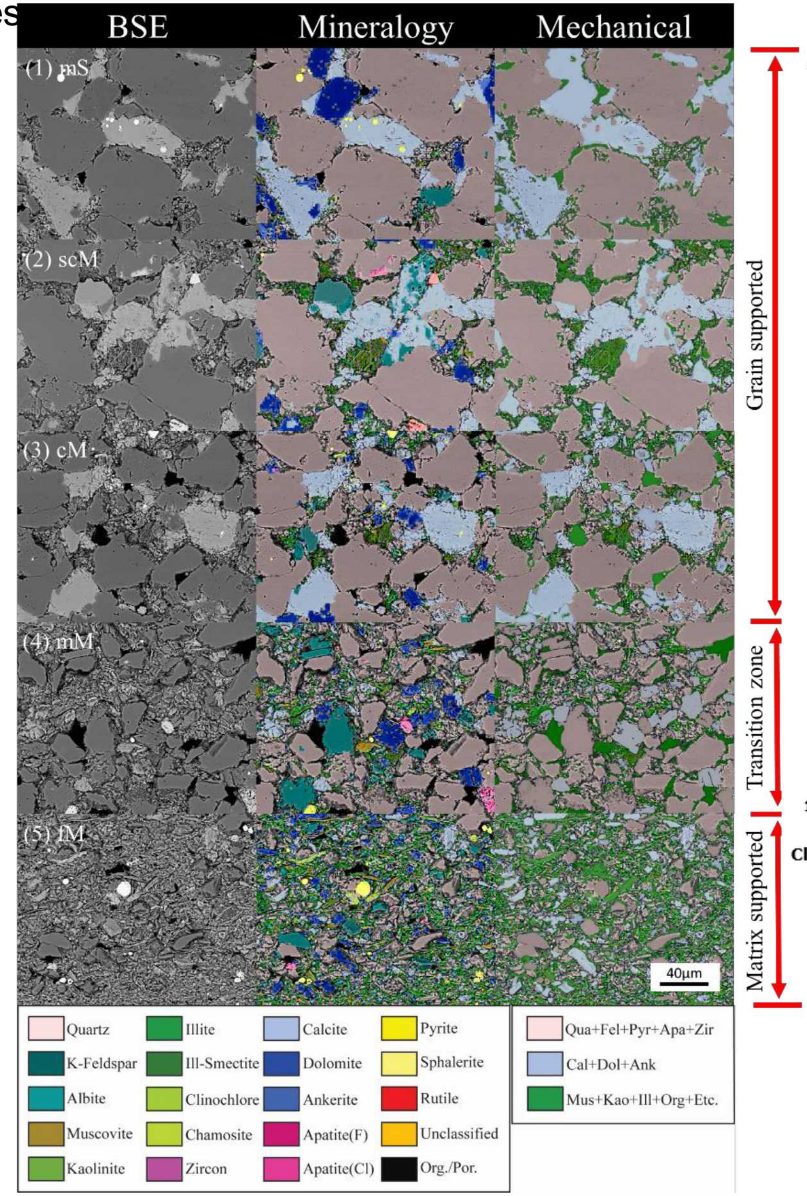
mS

scM

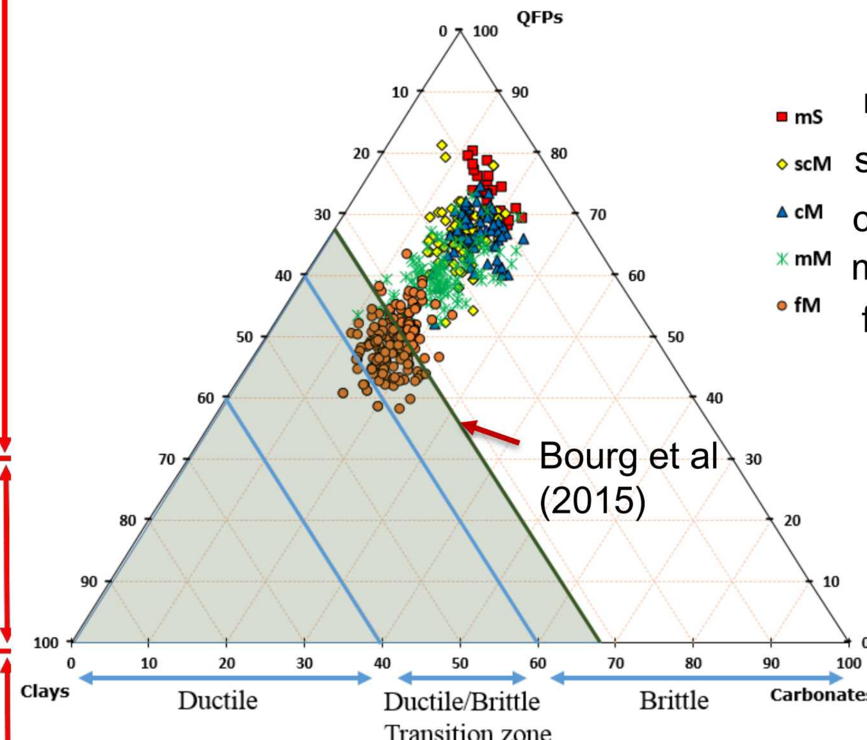
cM

mM

fM



Mineral Assemblages



mS

scM

cM

mM

fM

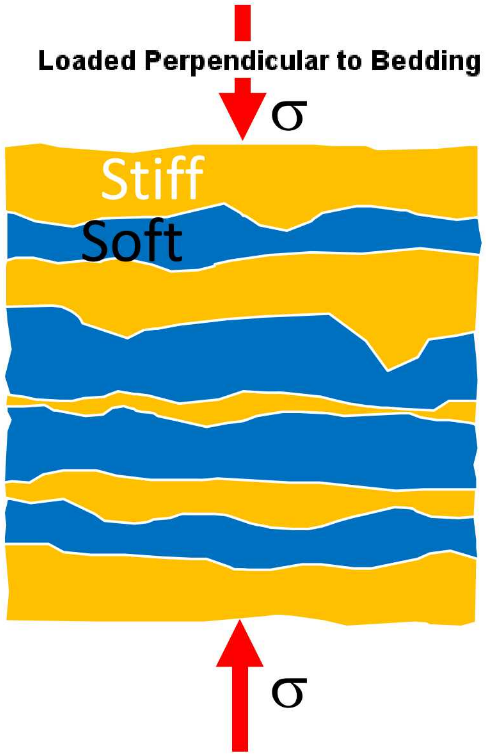
Ulmer-Scholle et al. (2014)

Kwon (@NMT, MS work, 2018)

Conceptual Model of Anisotropic Layered System

QFPs
Carbonate

Clay
Organics



$\sigma_{stiff} = \sigma_{soft} = \sigma$

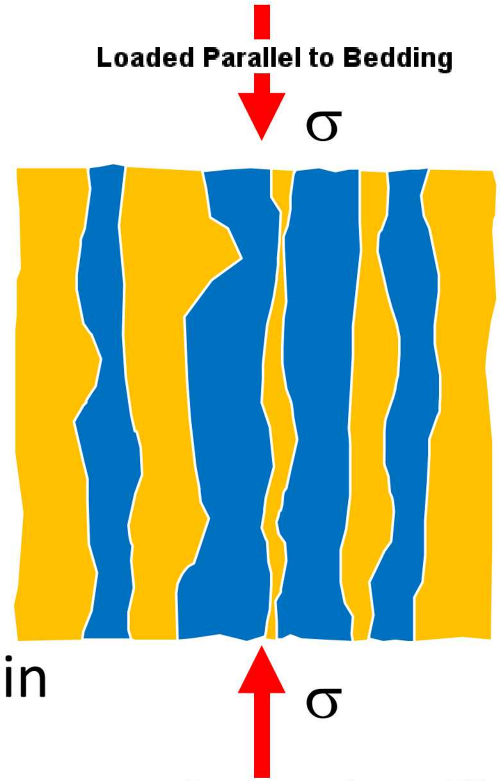
$\varepsilon_{stiff} < \varepsilon < \varepsilon_{soft}$

Overall strain

>

P wave velocity

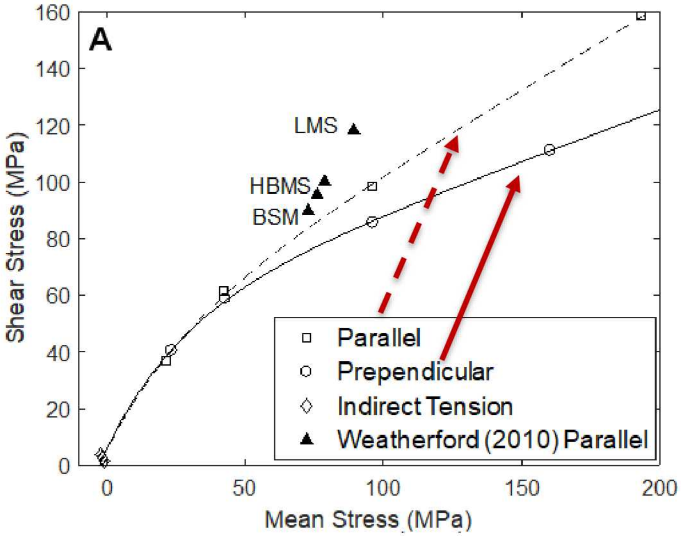
<

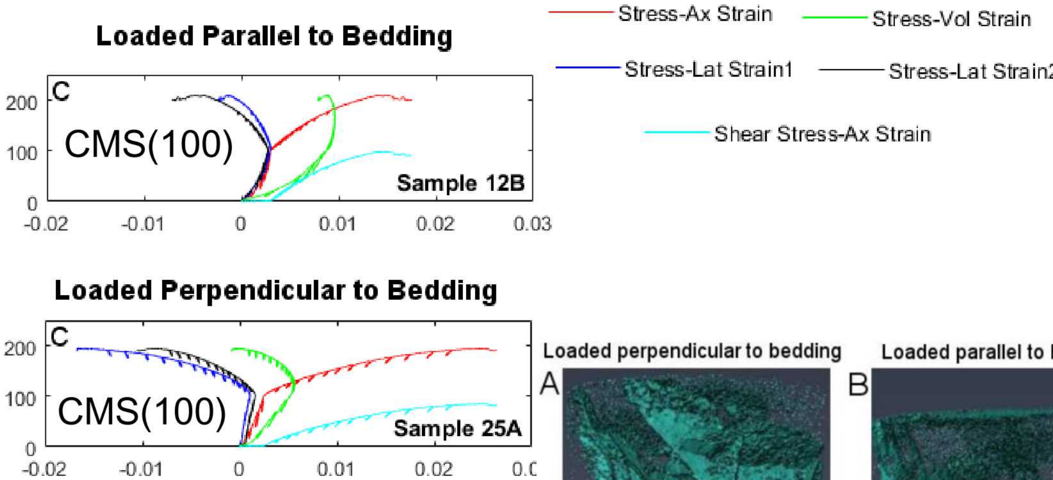


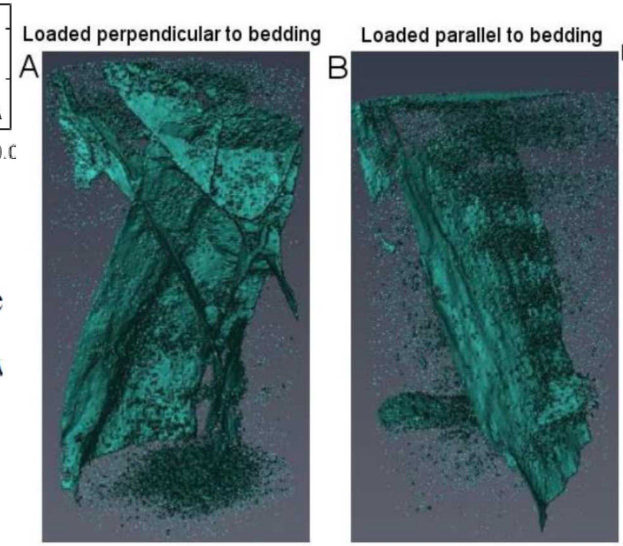
$\sigma_{soft} < \sigma < \sigma_{stiff}$

$\varepsilon_{stiff} = \varepsilon = \varepsilon_{soft}$

Axisymmetric Compression Testing







Segmented MicroCT images

	Confined (MPa)		Axial Stress	Mean Stress	Shear Stress	Fracture Angle (\
15B	CMS (50)	Parallel	113.00	42.20	61.31	13.5
28A	CMS (50)	Perpendicular	110.64	42.80	58.75	15.5
12B	CMS (100)	Parallel	209.59	96.09	98.30	23.5
25A	CMS (100)	Perpendicular	195.07	96.20	85.62	30
14B	CMS (200)	Parallel	376.37	193.42	158.44	27.5
22A	CMS (160)	Perpendicular	288.64	160.31	111.14	35.5

CMS: Constant Mean Stress

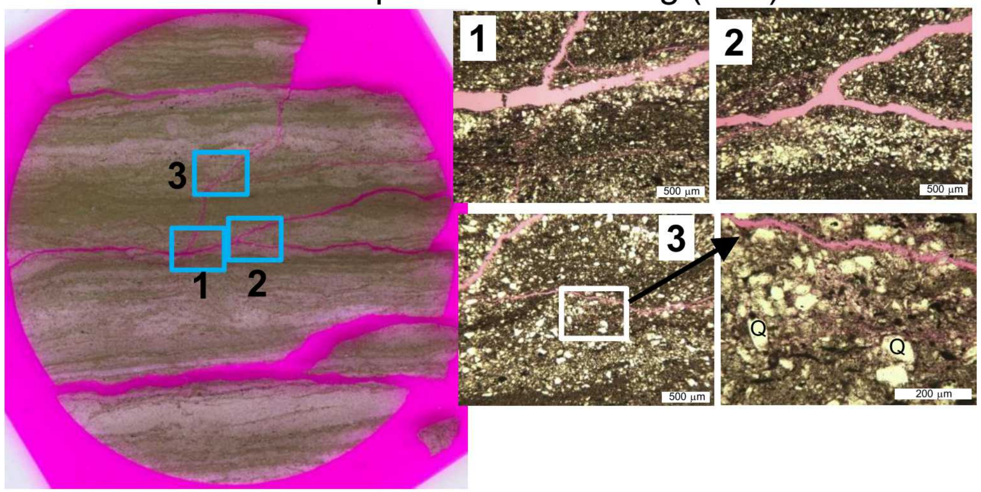
Yoon et al. (AAPG, Memoir 2019, in press)

Axisymmetric Compression Testing

Horizontal slice through the central part of sample

A. Loaded parallel to bedding (15B)

One primary & two secondary fractures

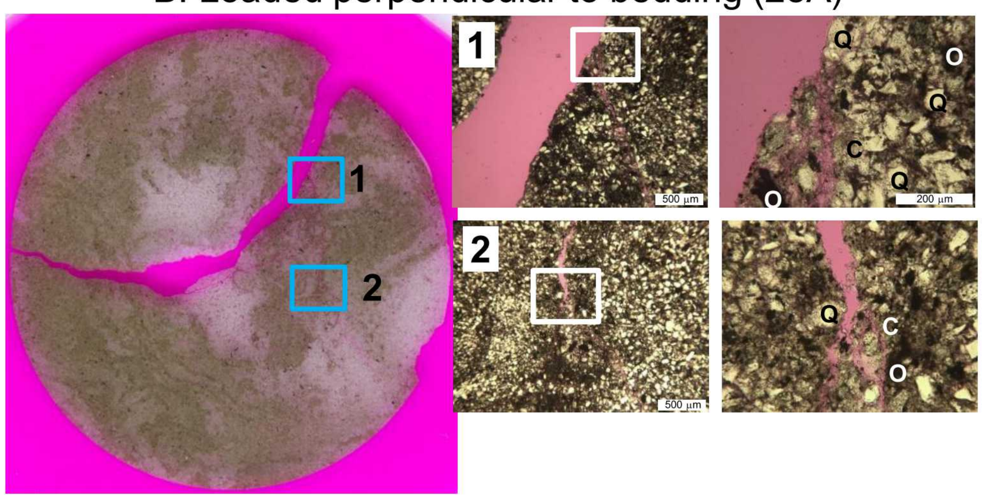


Fracture intersection & bifurcation with small aperture microfractures

Microfracture propagation in between quartz grains

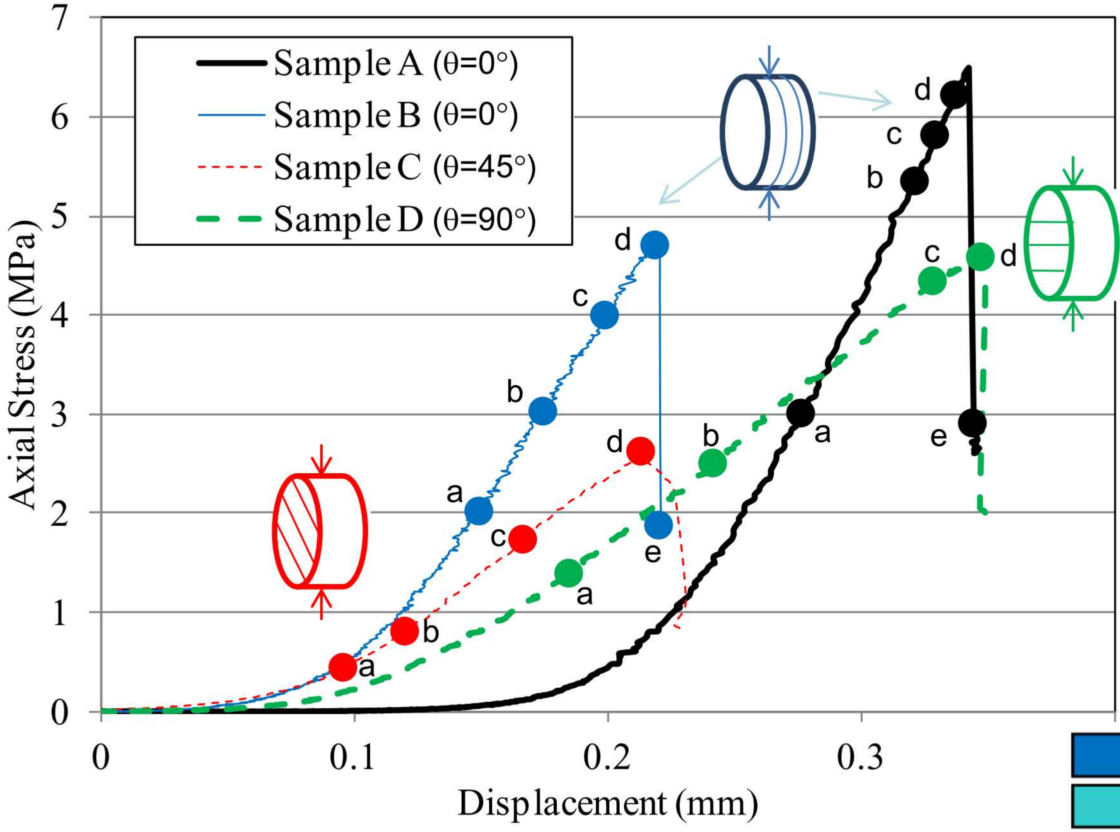
B. Loaded perpendicular to bedding (28A)

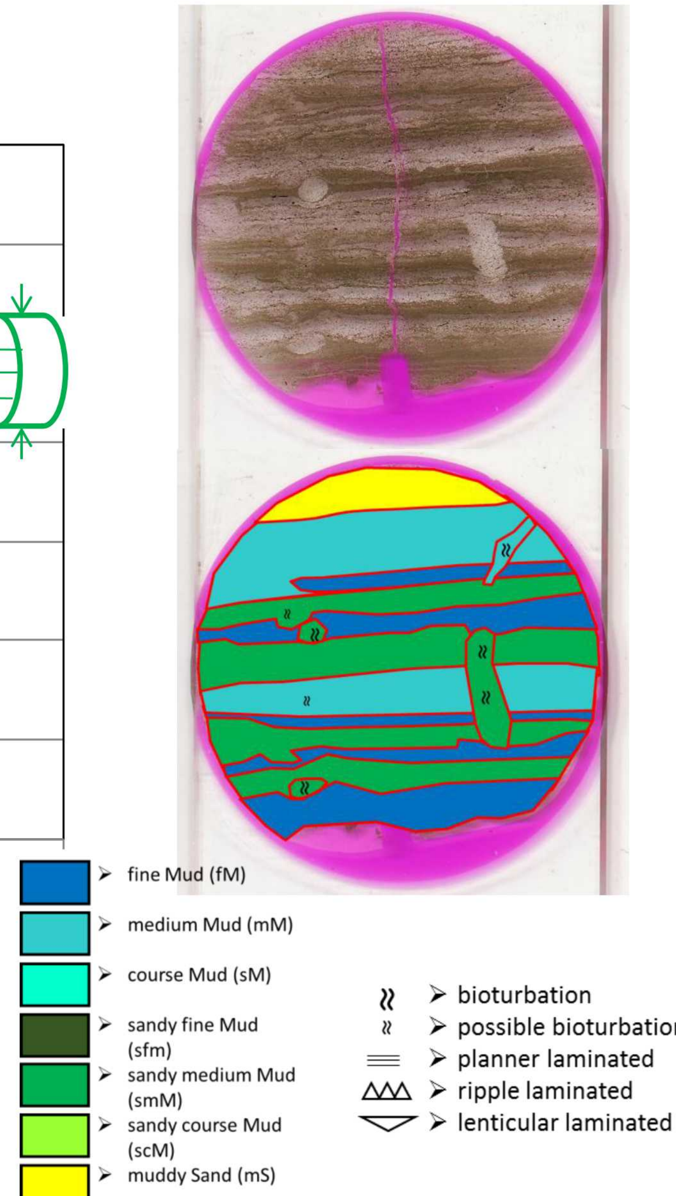
Curved main fracture



Microfracture patterns in between quartz grains

Indirect Tension Results





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

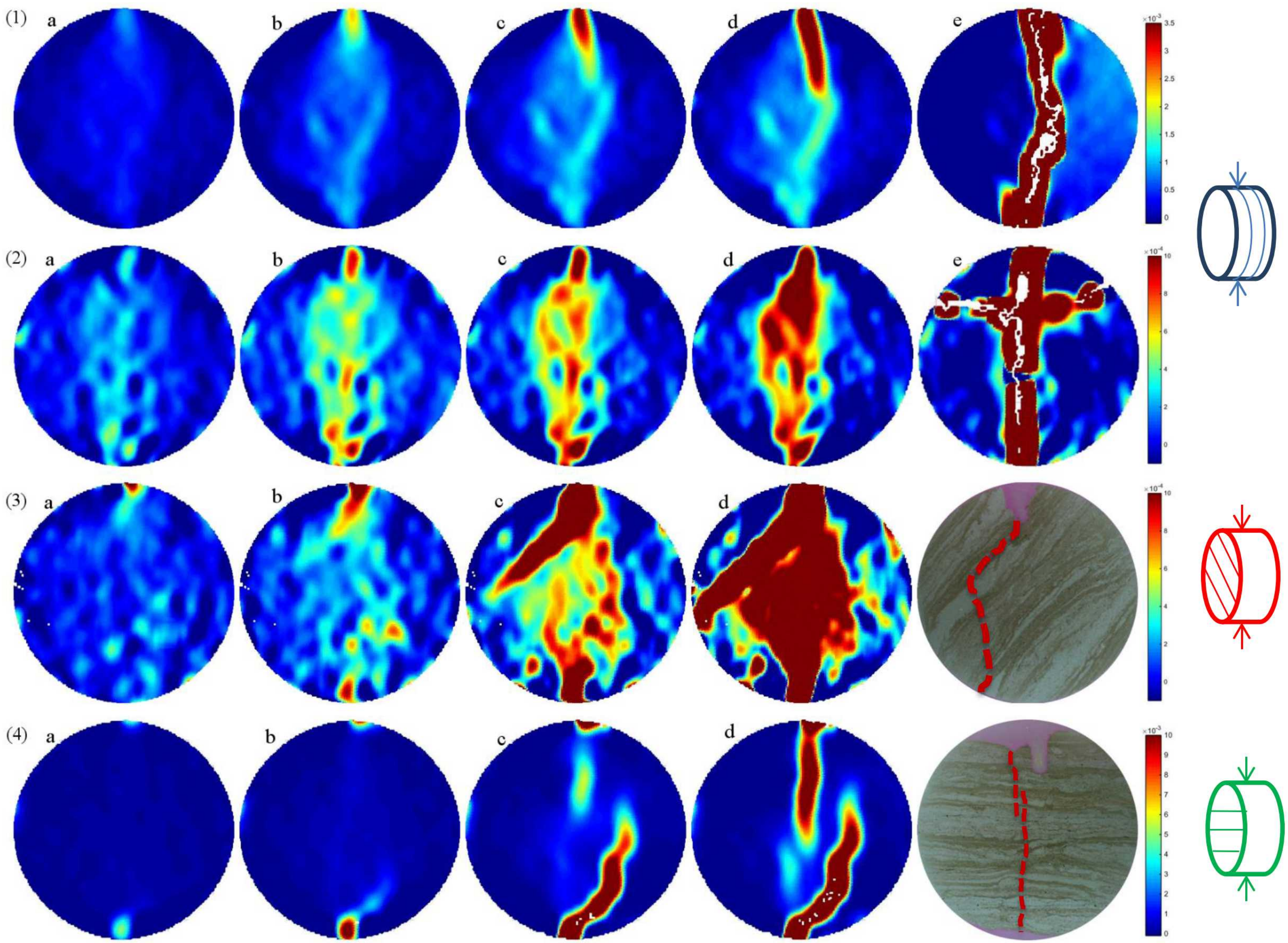
P: Loading

D: Diameter

t: thickness

Na et al. (JGR 2017)

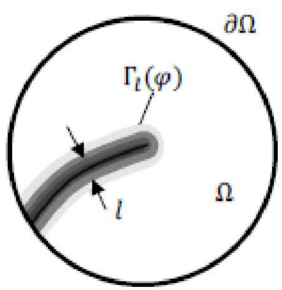
Tensile Strain Distribution (Digital Image Correlation)

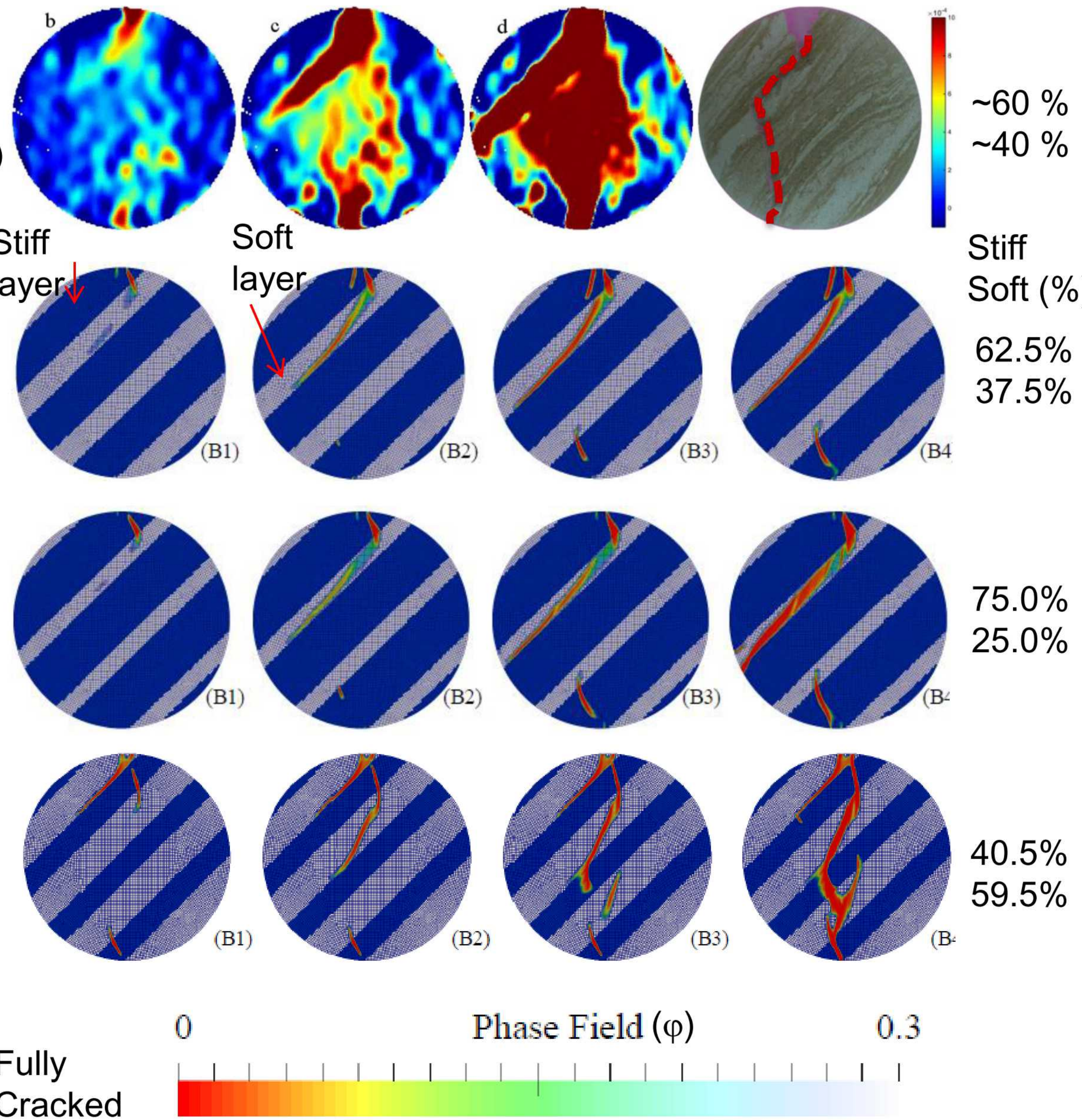


Numerical Simulations of Brittle Fracturing

- 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)



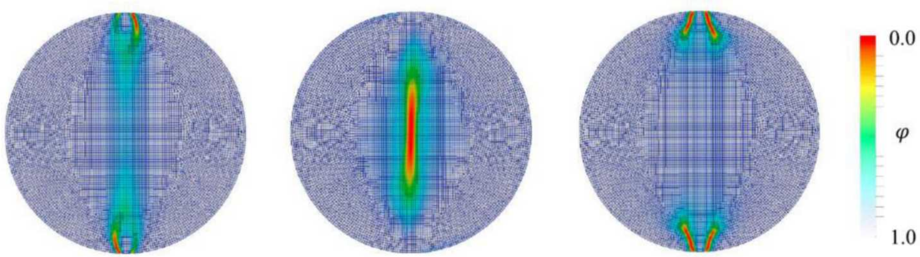


Differential Equations Analysis Library.II (Bangerth et al., 2007; 2013)

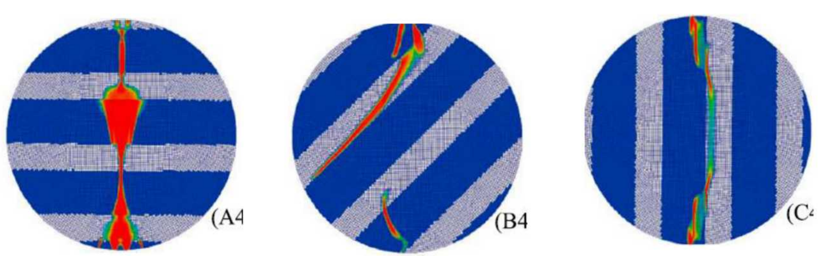
DEAL.II Open Source Finite Element Library

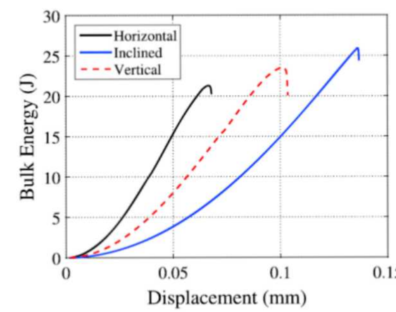
Effective Properties of Heterogeneous Materials

- Transversely isotropic effective medium for elastic parameters (Berryman, 1998)
  - Spatial homogenization procedure leads to much simpler crack patterns than those from the layered isotropic materials
  - Crack paths in the effective medium are less tortuous due to (probably) filtering out mesoscopic information via homogenization
  - Smaller surface area created by the fracture process yields the reduced tortuous crack paths with a diminished amount of energy dissipation (much higher effective fracture toughness)

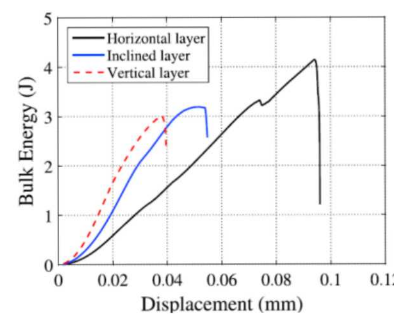


(a) Transversely isotropic (horizontal) (b) Transversely isotropic (inclined) (c) Transversely isotropic (vertical)





Transversely Isotropic



Layered Isotropic

Na et al. (JGR 2017)

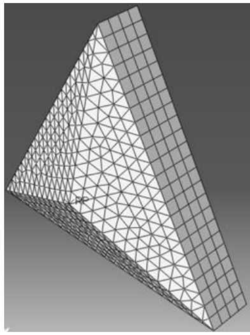
NanoIndentation

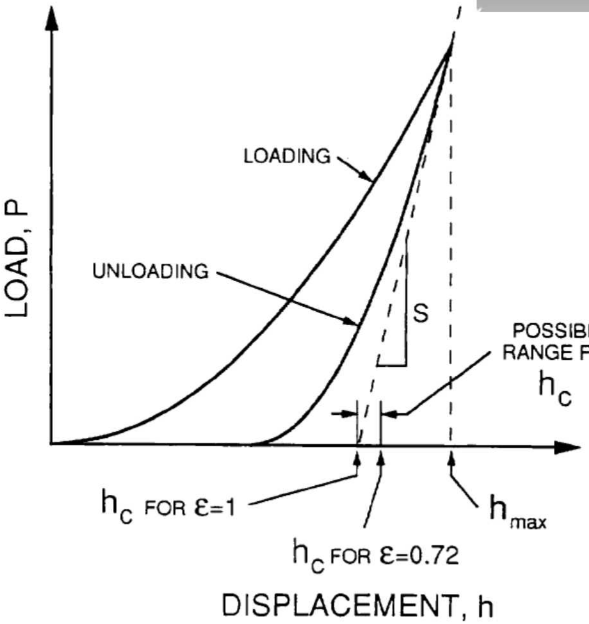
- **Depth sensing/instrumented indentation**
  - highly accurate load-displacement record
  - Analytical models to determine modulus, hardness and other mechanical properties using the load-displacement data

- **Analytical concept**
  - Purely elastic deformation upon initial unloading
  - Contact between a rigid indenter and homogeneous isotropic elastic half spacing
  - Compliance of the sample and indenter tip – springs in series
  - Hardness = load/contact area
  - Elastic modulus determined by stiffness (S)

- **Dynamic Modulus Analysis at nm scale**

Berkovich indenter

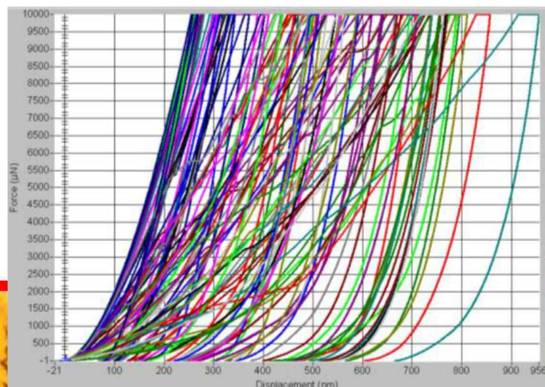


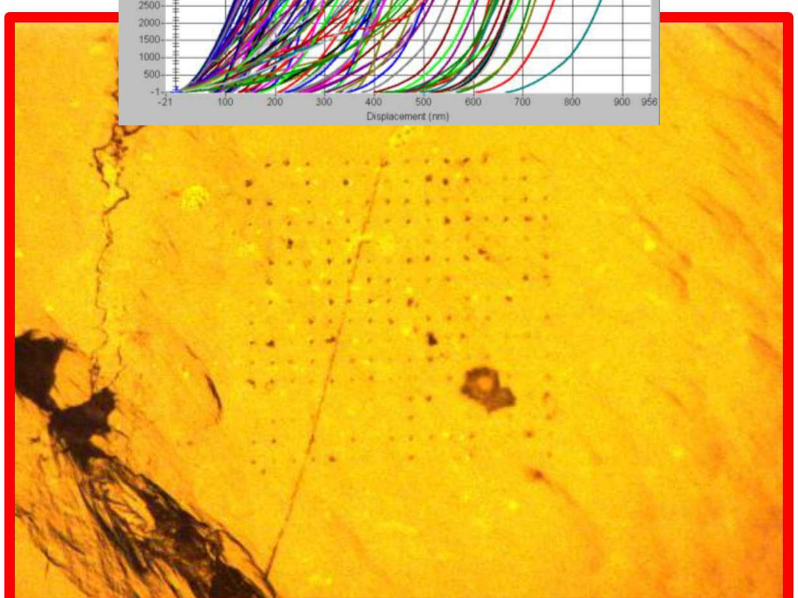


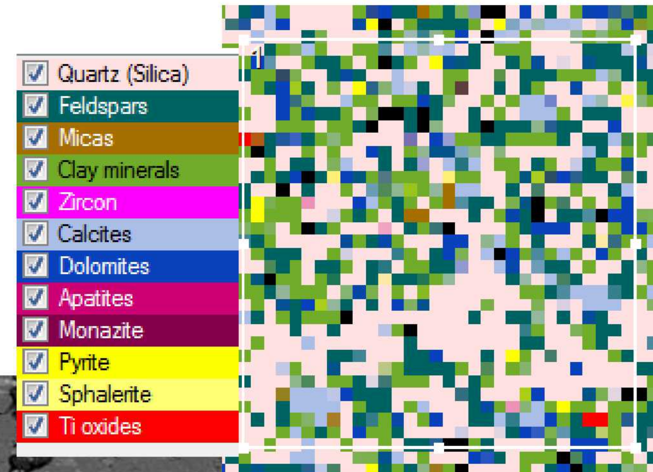
Oliver & Pharr (1992)

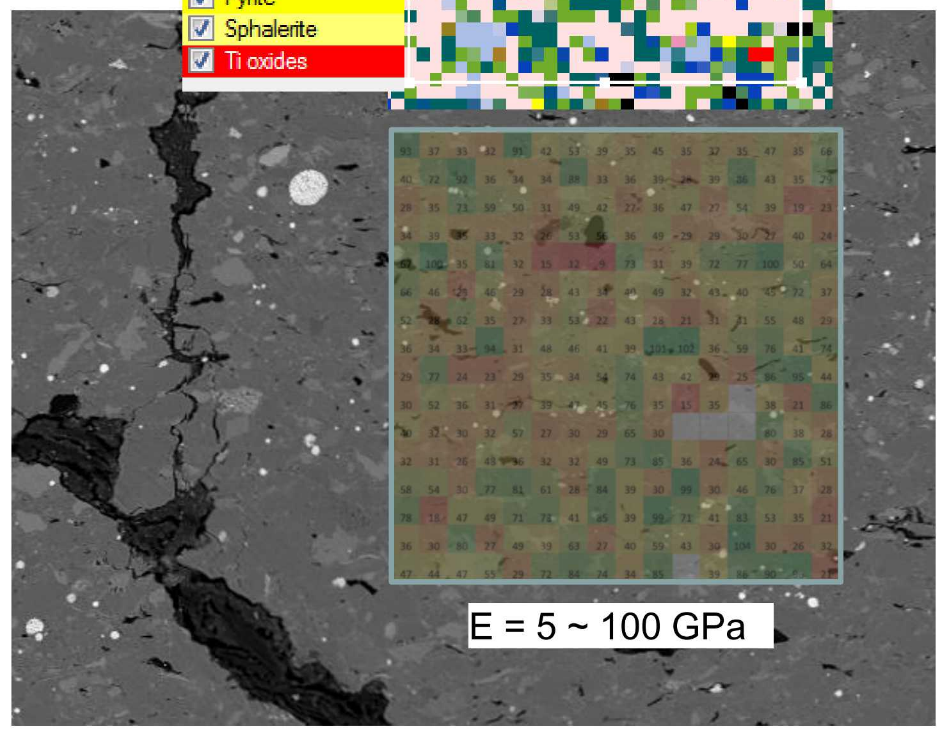
Initial Indentation Results

Indentation array: 16 x 16, 20 um spacing
[Hysitron TriboIndenter 900]
Indentation strain rate = 0.1 (Oliver et al., 1997)
(current change in displacement/current total disp.)
Maximum load = 10 mN



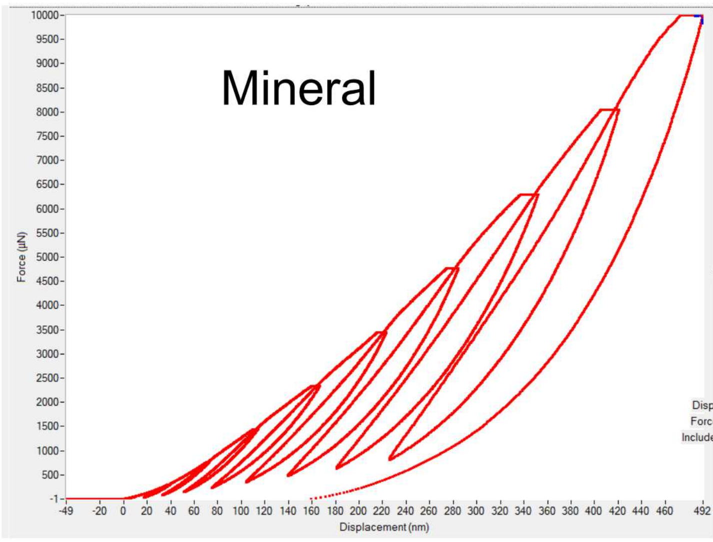


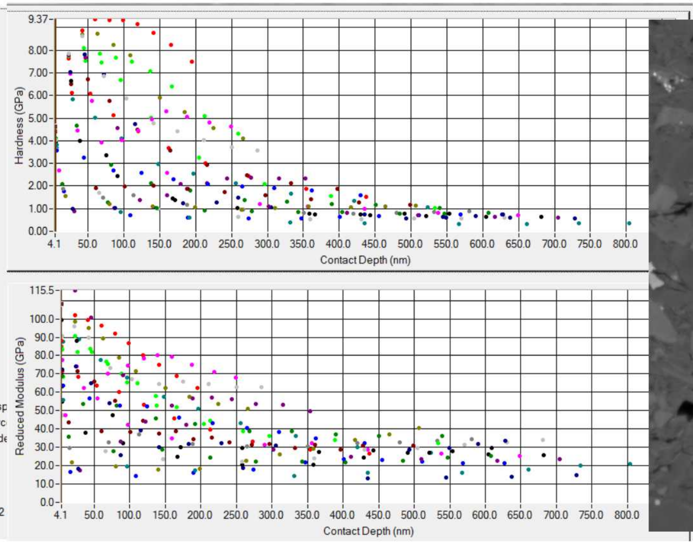


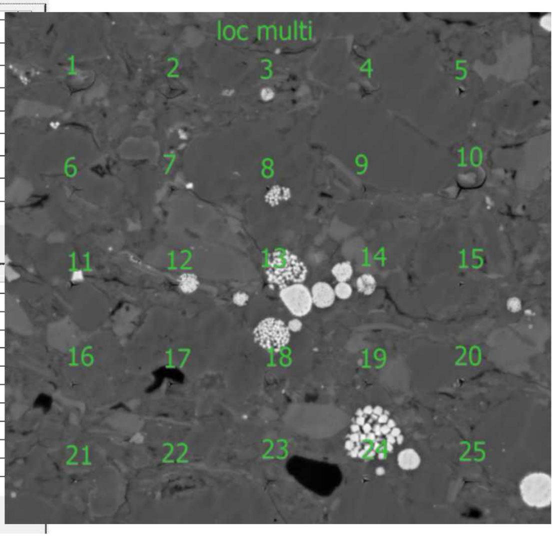


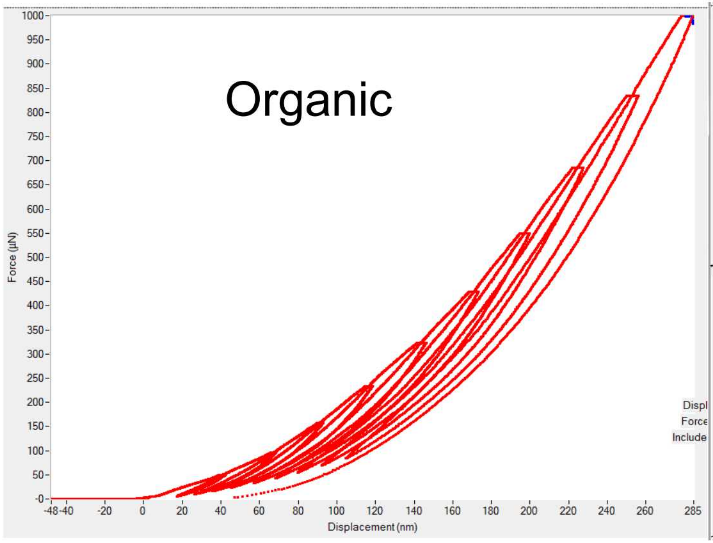
Multiscale Indentation Testing

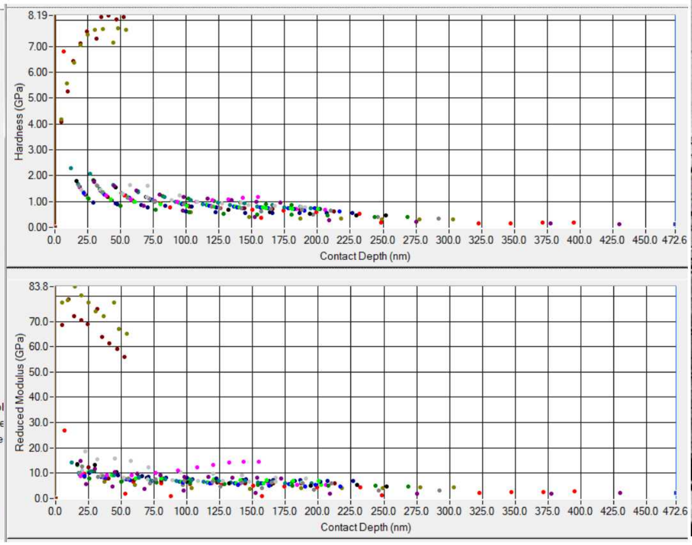
Loading-unloading cycle

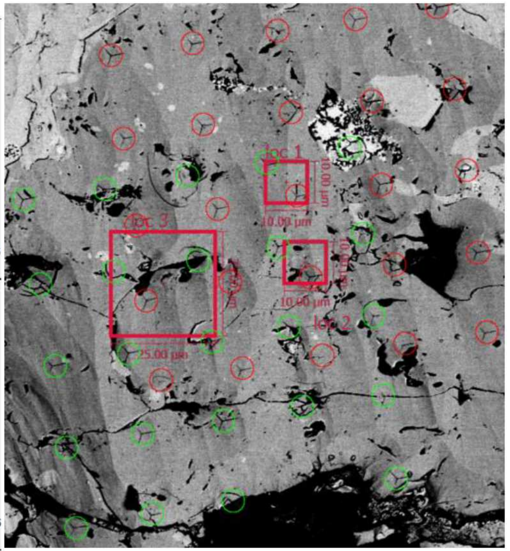




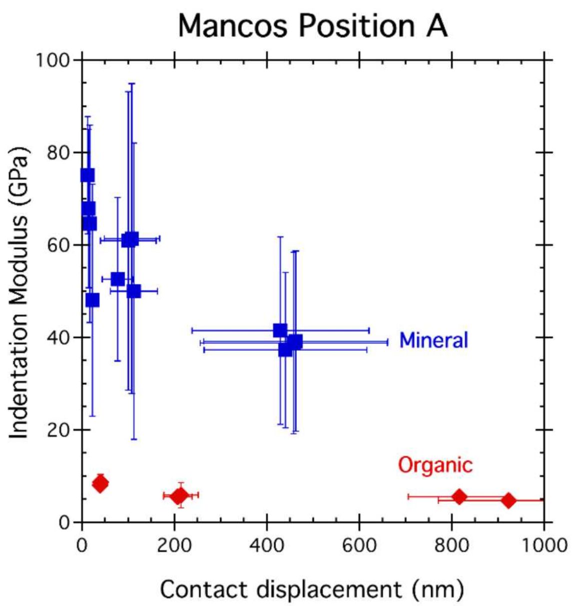


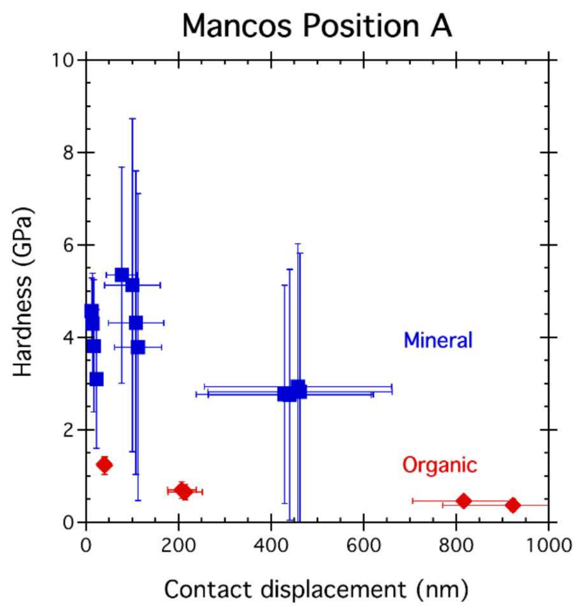


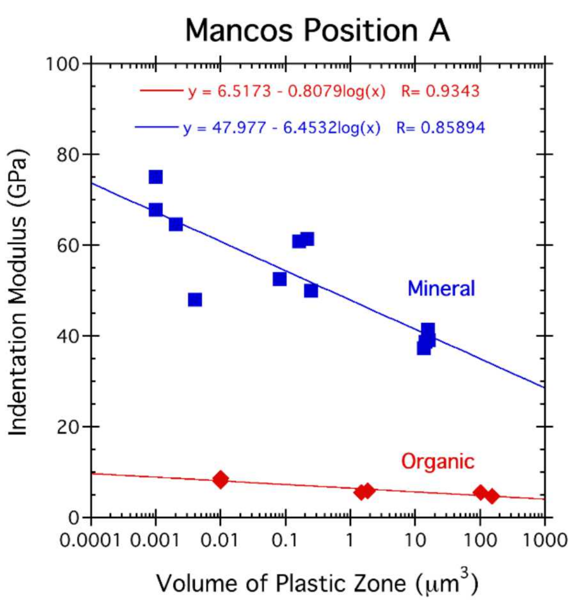


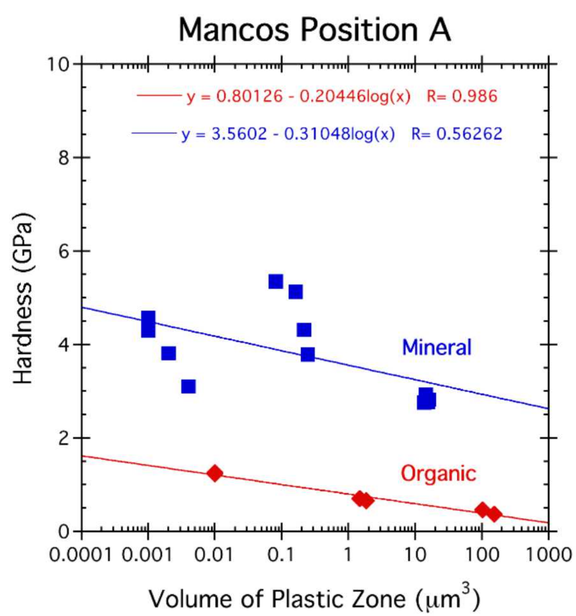


Multiscale Indentation Testing

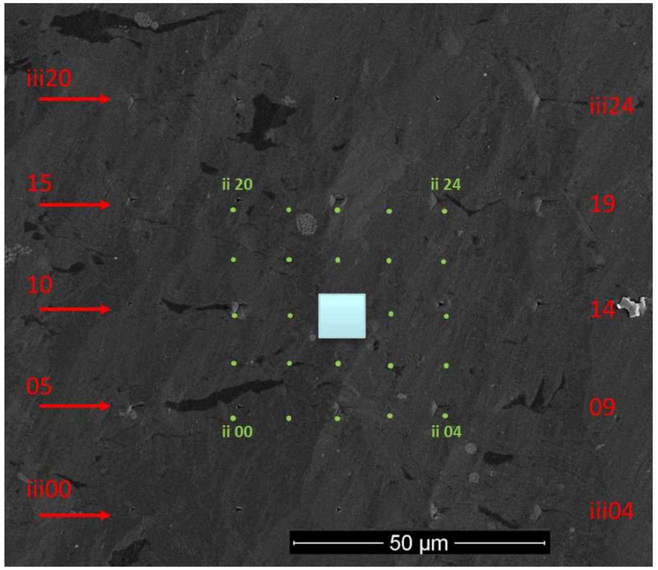








Distributed arrays



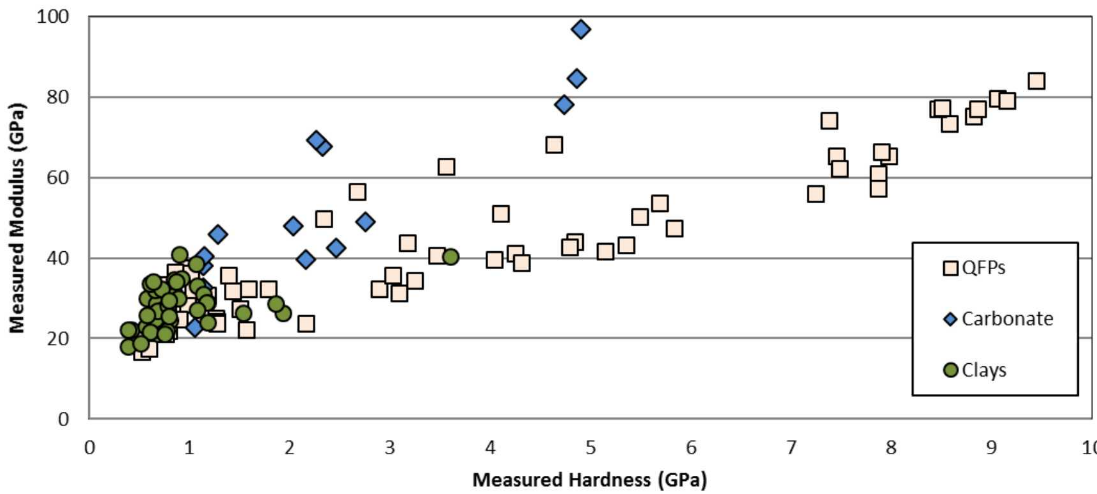
Indentation key	Array dimension	indent spacing	Max Load
i	8x8 um	2 um	0.1 mN
ii	40x40 um	10 um	1 mN
iii	80x80 um	20 um	10 mN

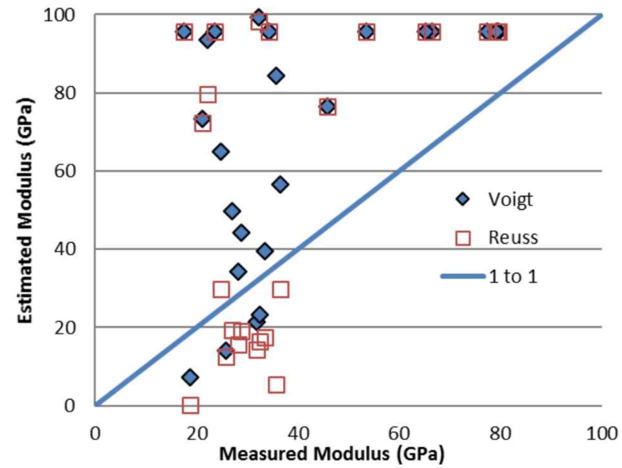
Estimate plastic zone radius

$$\frac{R_p}{\delta_m} = -12.907\frac{H}{E_r} + 4.5451 \qquad \frac{H}{E_r} < 0.35$$

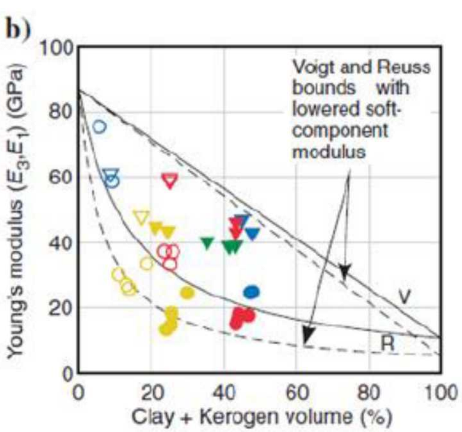
Chen & Bull, Surface & Coatings Technology (2006) 4289–4293.

Effect of Mineralogy on Mechanical Properties

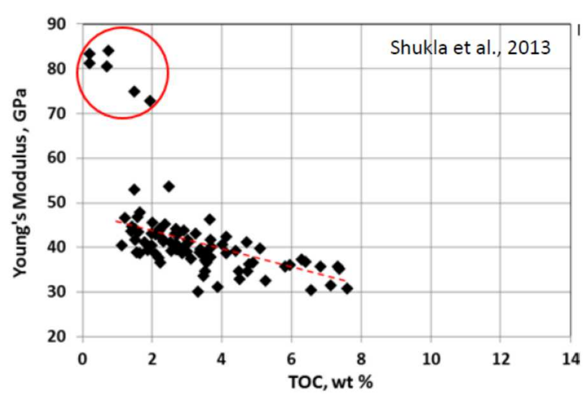




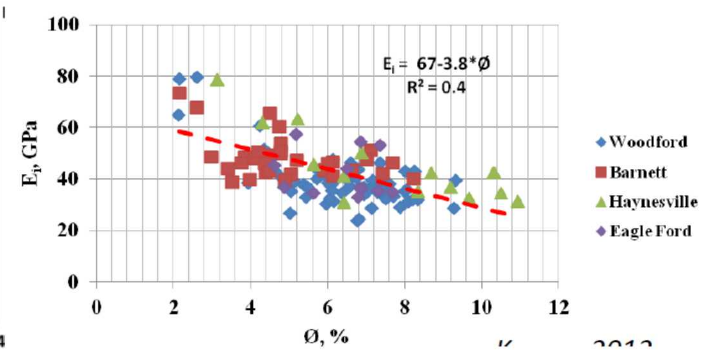
Sone & Zoback (2013)



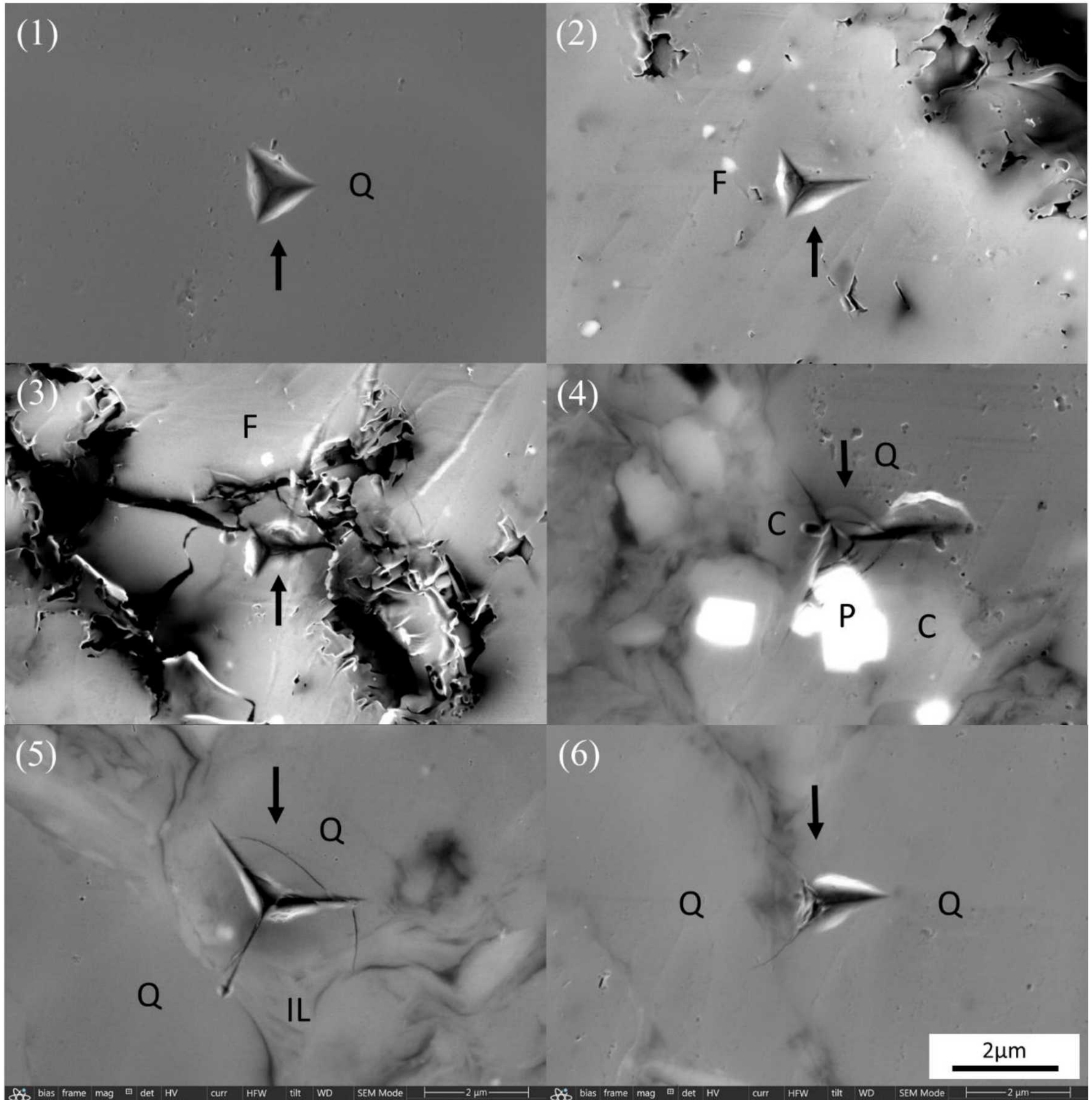
Shulka et al. (2013)



Kumar et al. (2012)



Nanoindentation Impressions



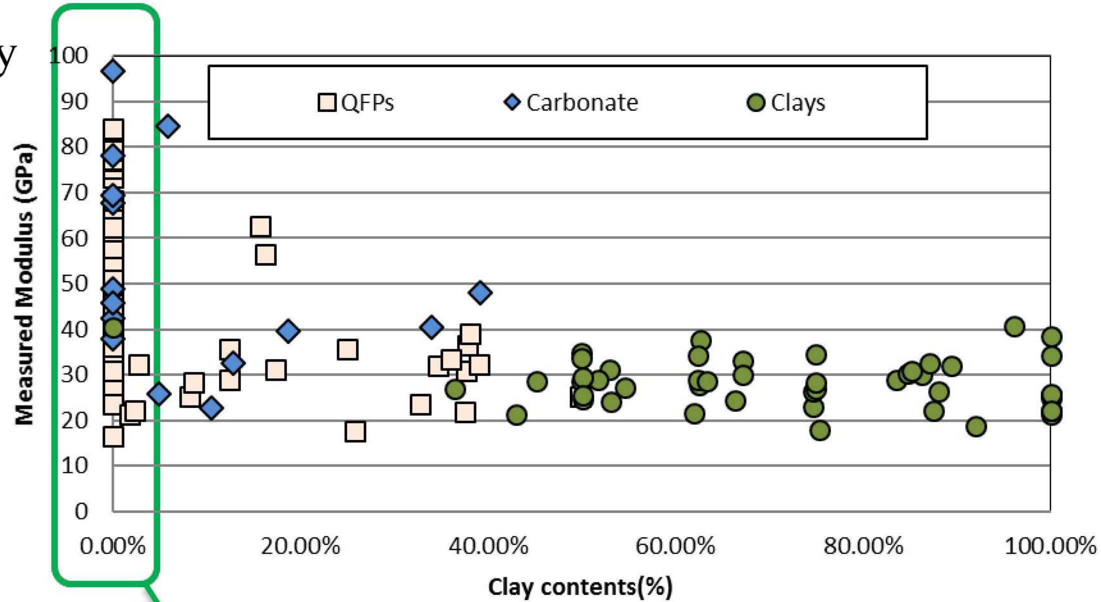
Low-clay percentage samples.
(1&2): surface of pure quartz and feldspar having higher values of mechanical properties such as elastic modulus and hardness.
(3): dissolution surface of feldspar
(4-6): grain-to-grain boundary and edge-of-grain, which have lower mechanical properties values.

NOTE: Q=quartz, P=pyrite, C=carbonate, F=feldspar, and IL=illite)

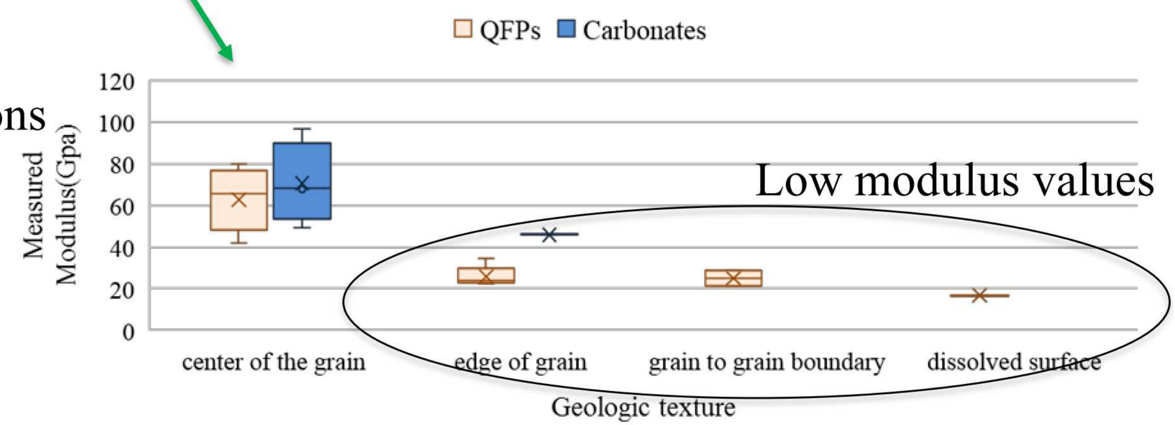
Yoon et al. (in prep)

Effect of Compositions and textures on Mechanical Properties

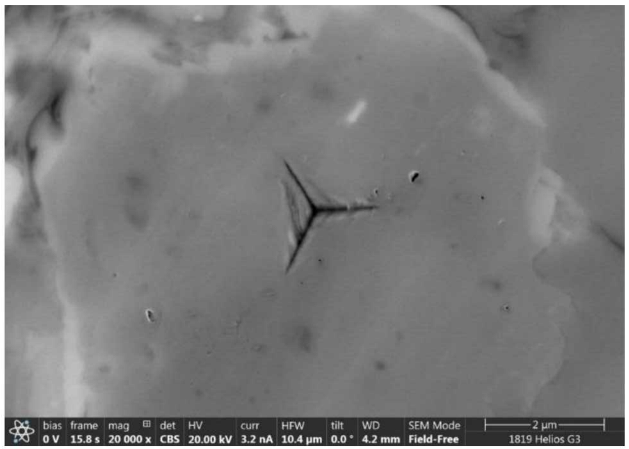
High variability

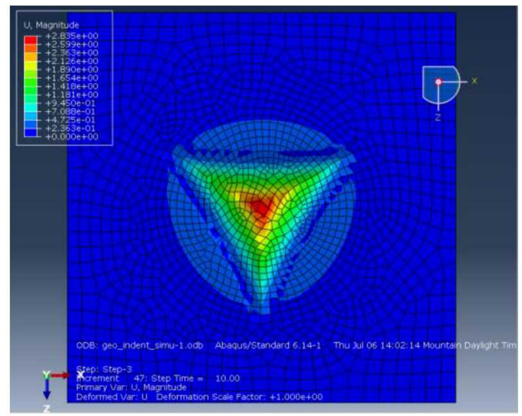


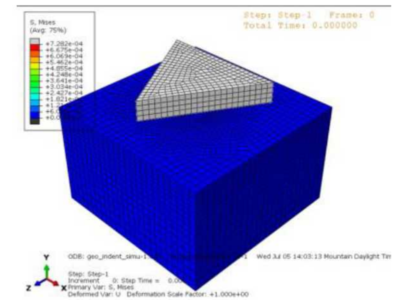
Analysis of SEM image on indentation impressions



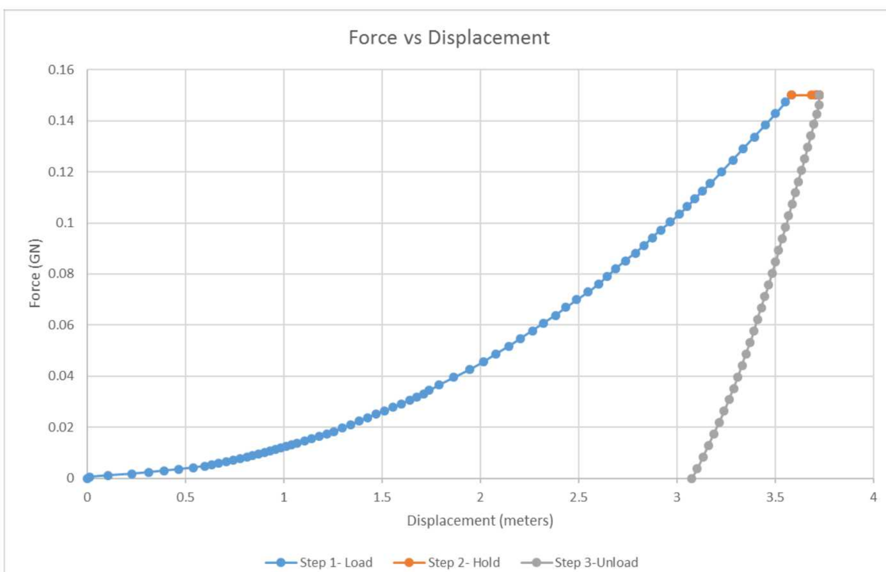
3D Mechanistic Modeling

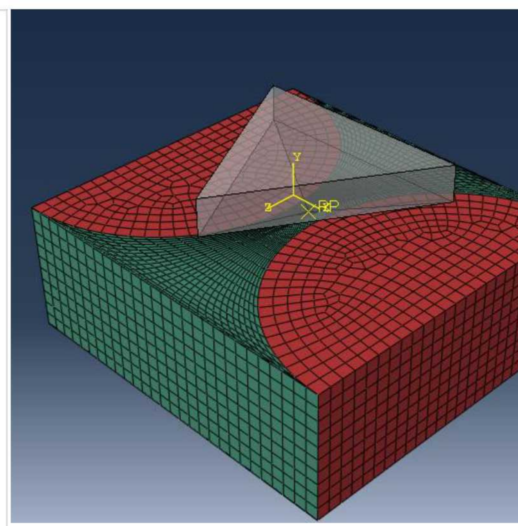


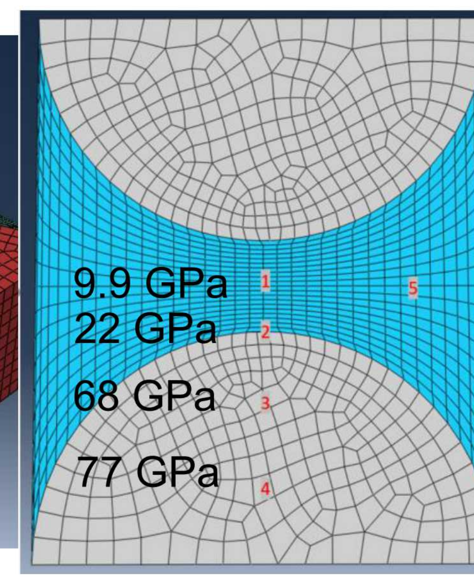




ABAQUS FEA



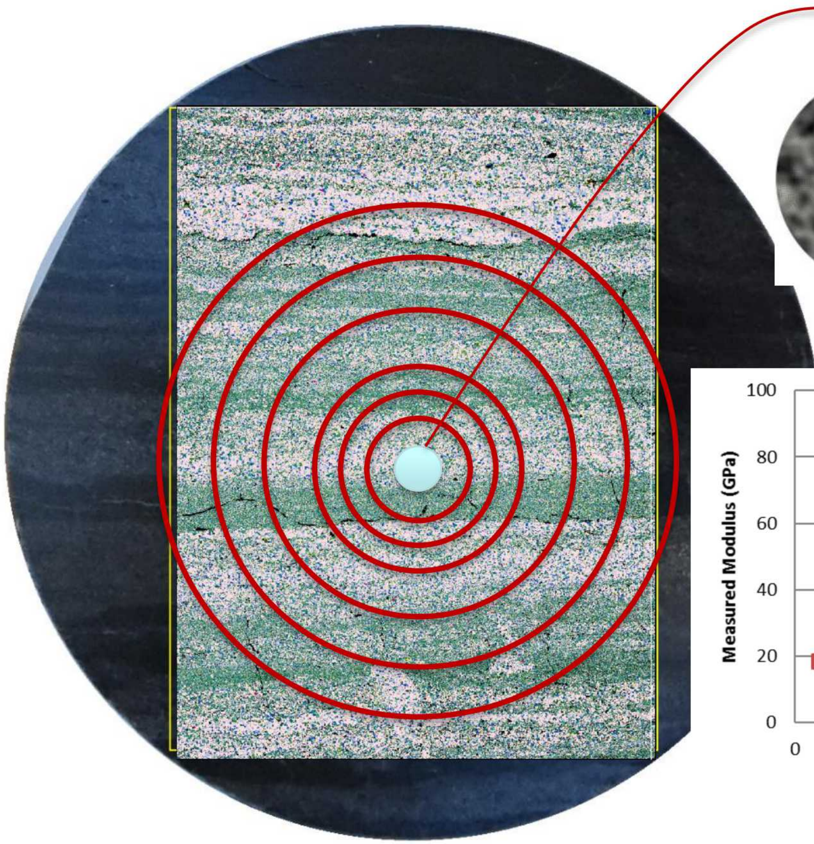


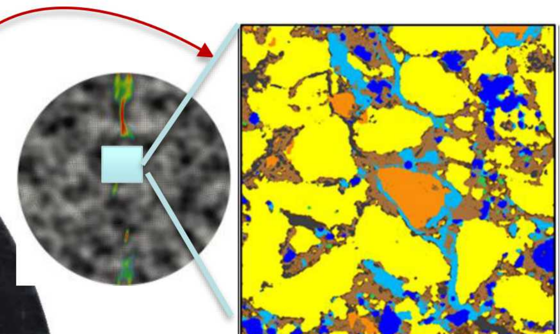


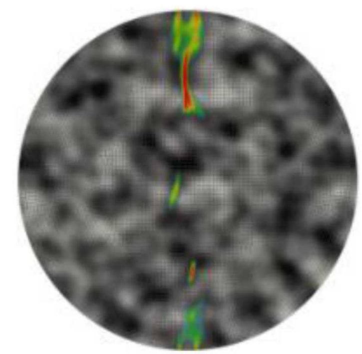
Elastic Modulus

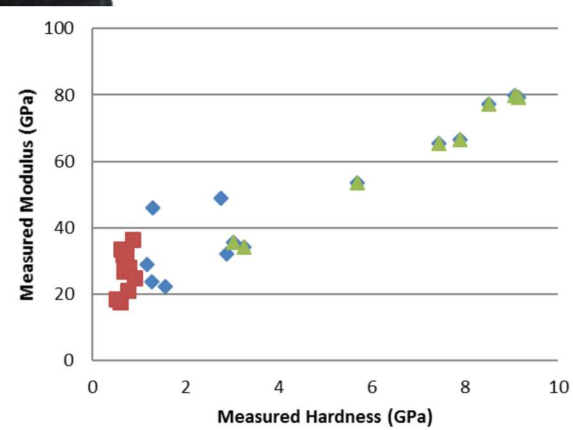
Upscaling for Mechanical Properties

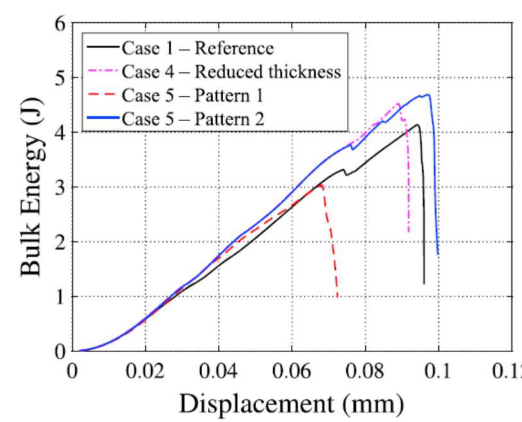
- Phase field modeling for averaging mechanical properties
  - Spatial mineralogical mapping with compositional heterogeneity
  - Development of correlation with nanoindentation results
  - Evaluation of soft cement or multi-mineral regions on mechanical responses with various conditions (e.g., defects, layering, anisotropy)





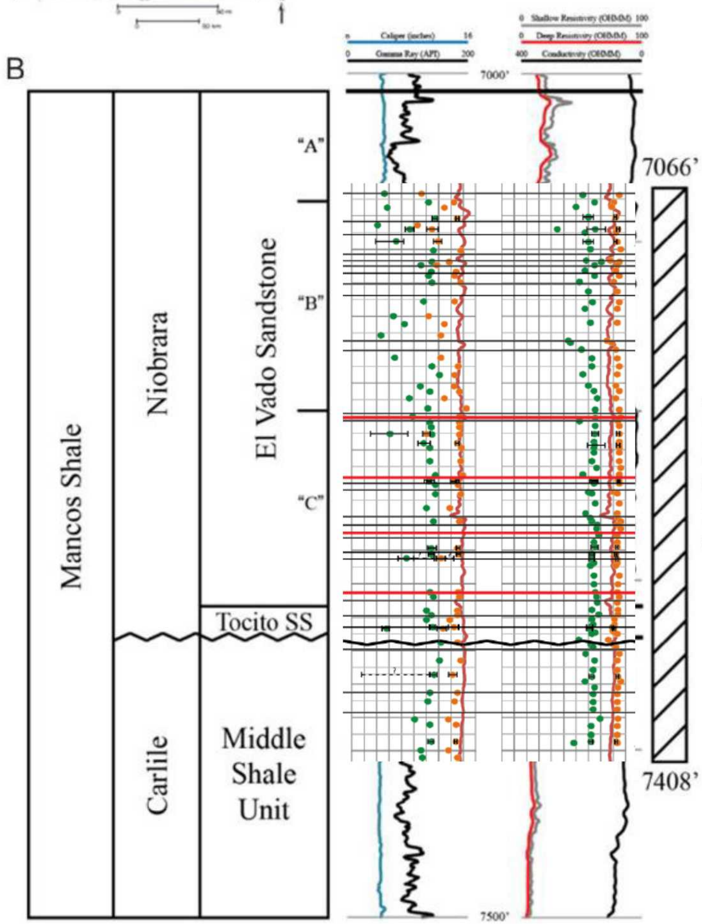


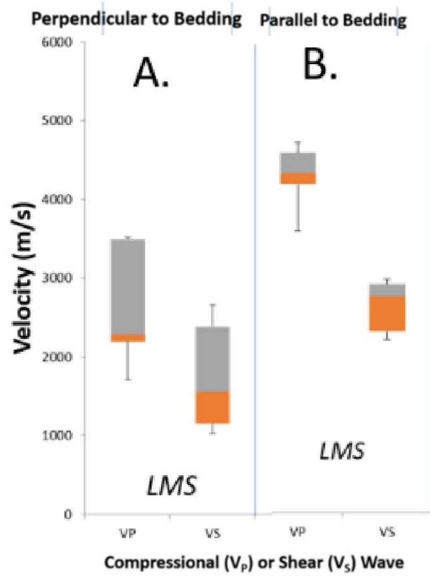


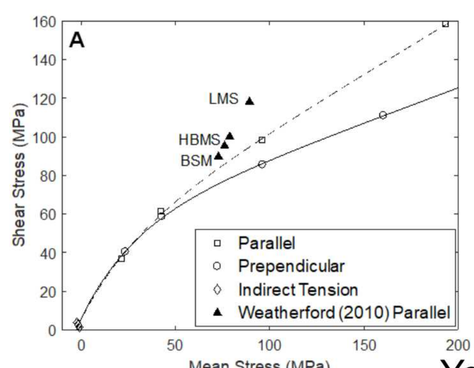


Velocities of Mancos Shale lithofacies

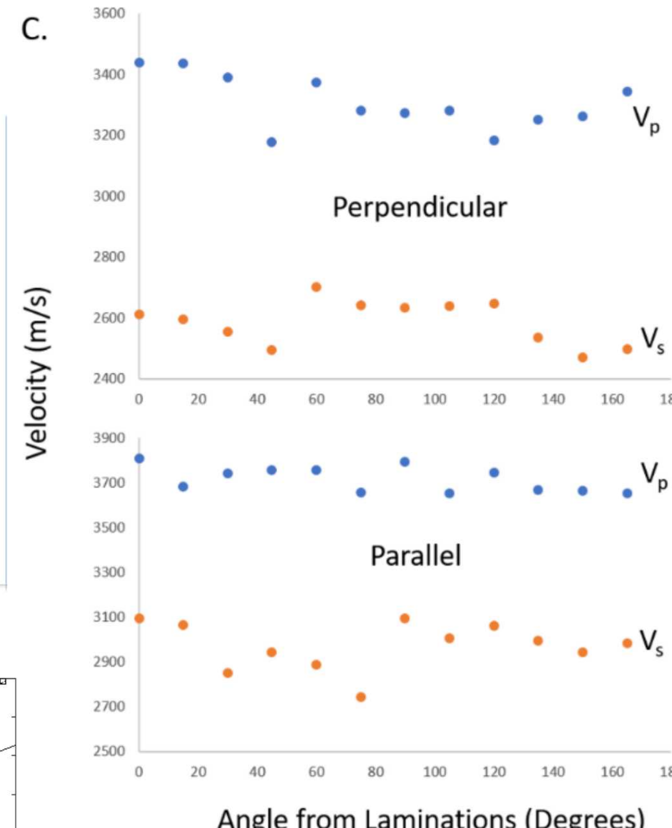
Drilled Core Samples







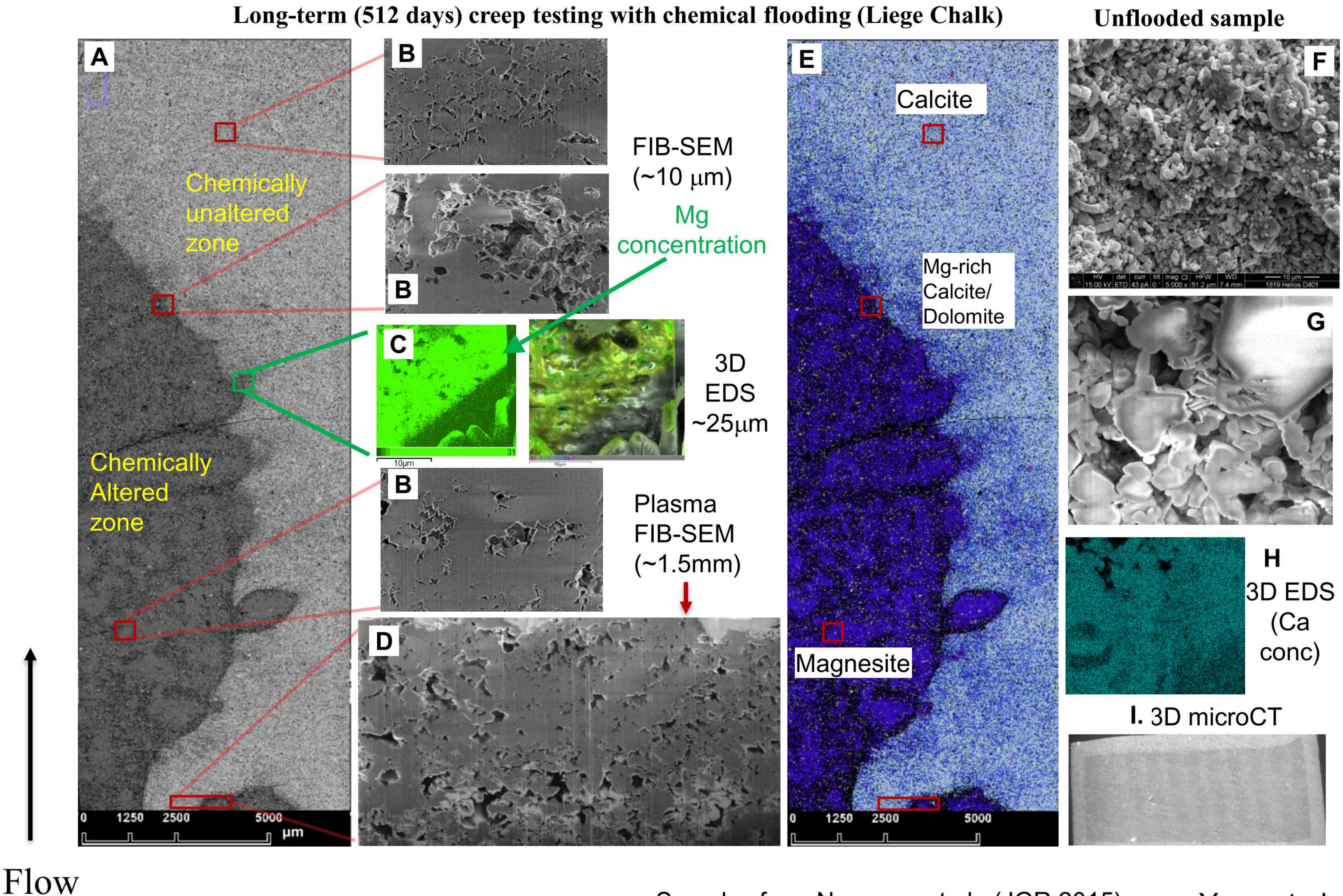
Lab Block Samples



Yoon et al. (AAPG, Memoir 2019, in press)

Other Ongoing Works

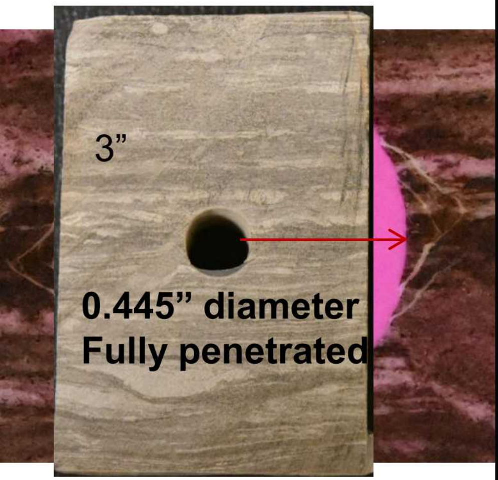
Chemo-mechanical Processes: Chemical Flooding in Nano-porous Chalk



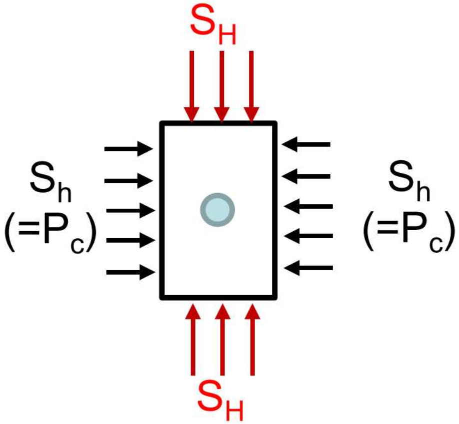
Samples from Nermoen et al., (JGR,2015)

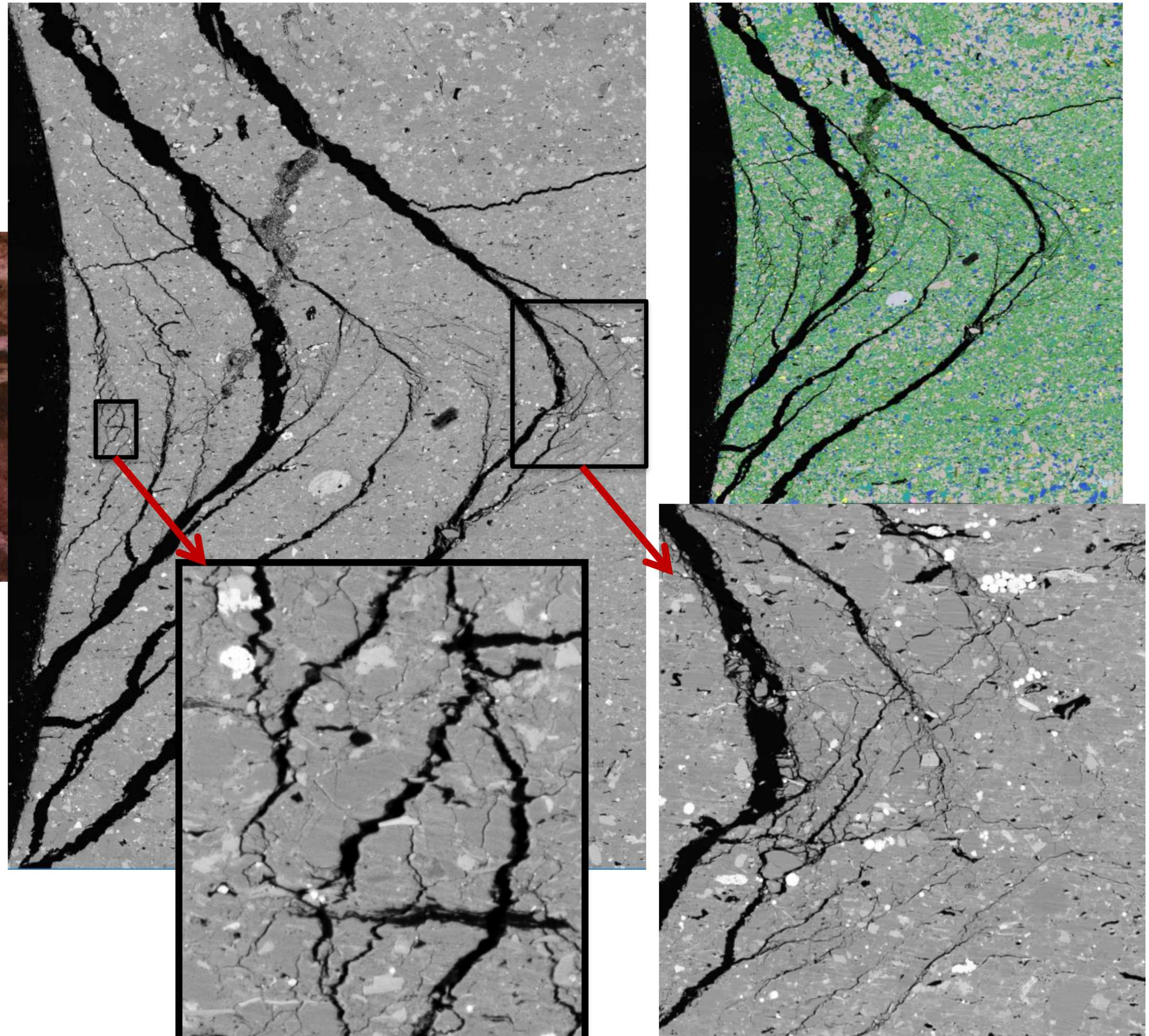
Yoon et al. (In prep)

Fracture Patterns: Borehole Breakout Test

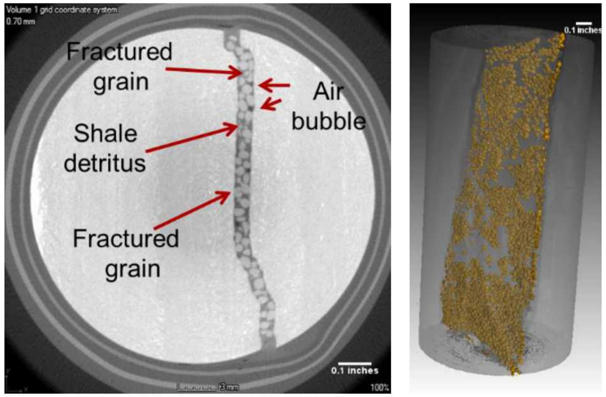


2” diameter

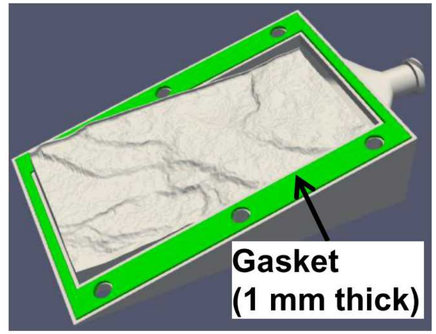


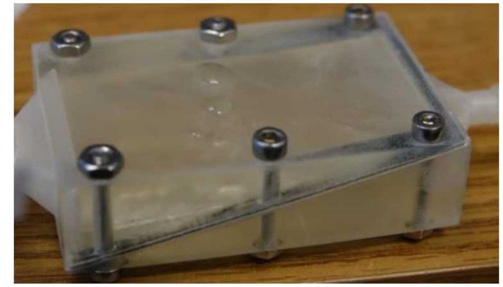


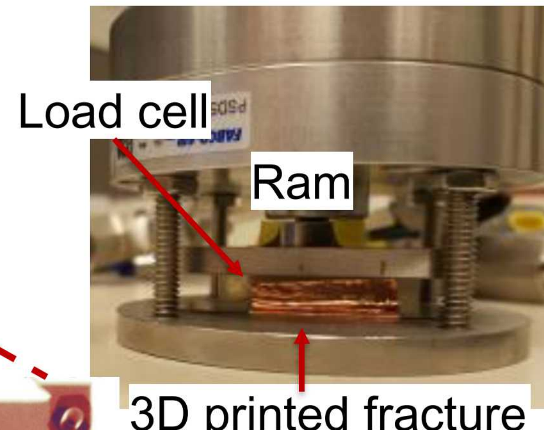
Permeability Control and Proppants' Behavior in Fractures



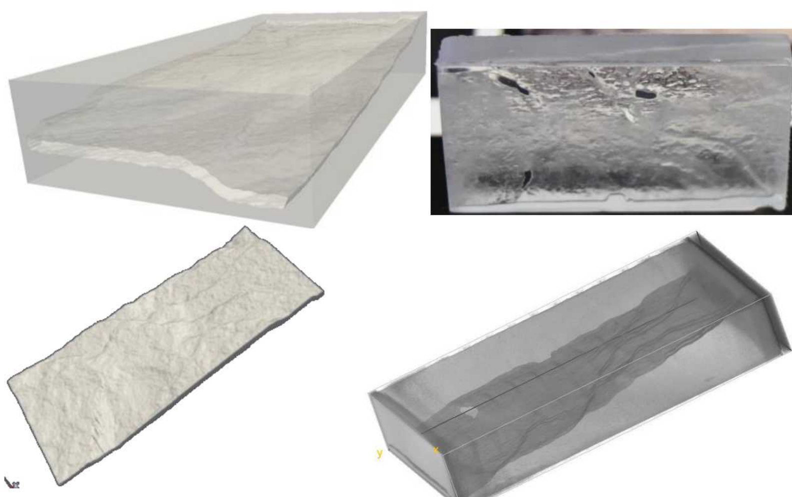
Micro-CT image with proppants in a fracture

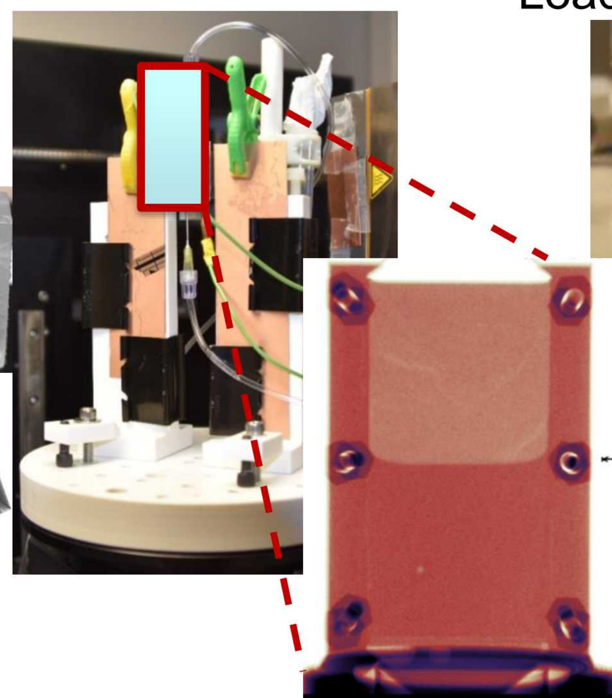


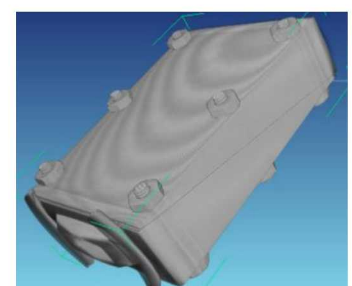




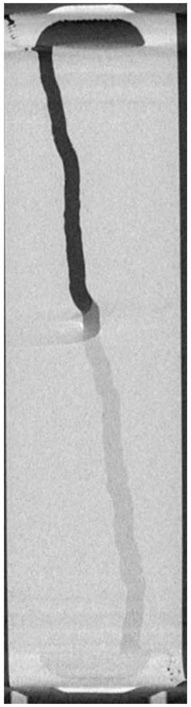
3D printing applications

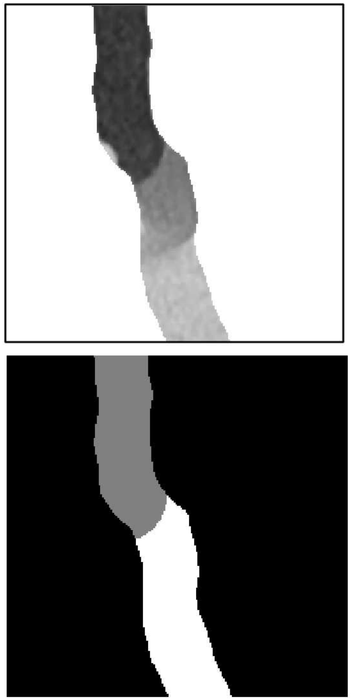


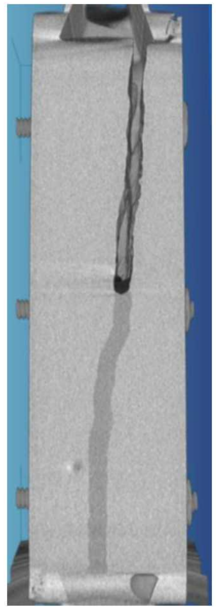


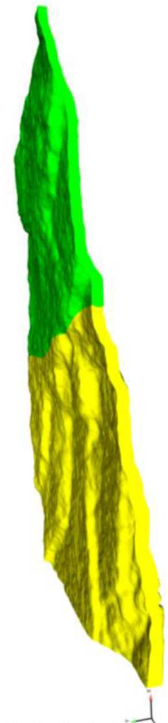


Multiphysics Simulations

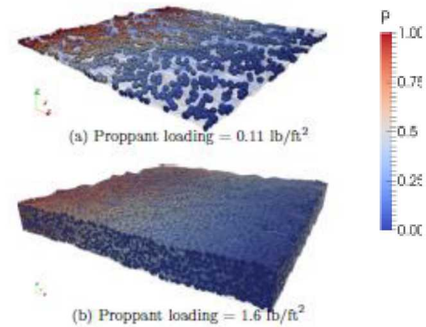


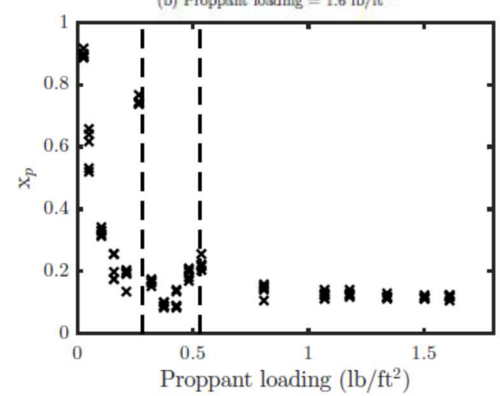




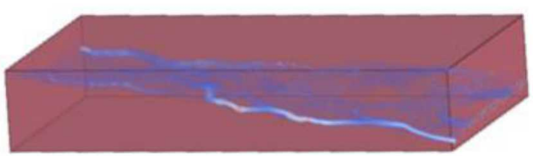


Multiphase flow

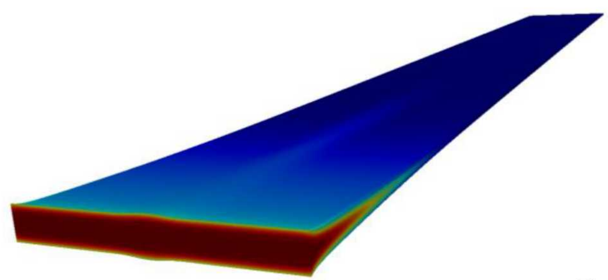


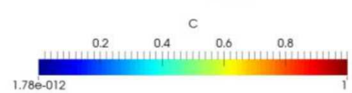


Proppants' behavior



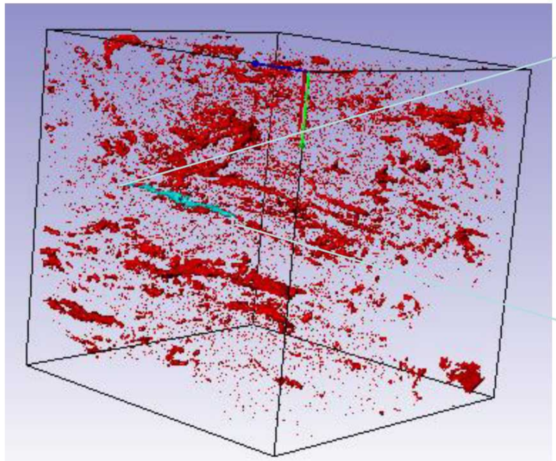
CFD simulation flow field

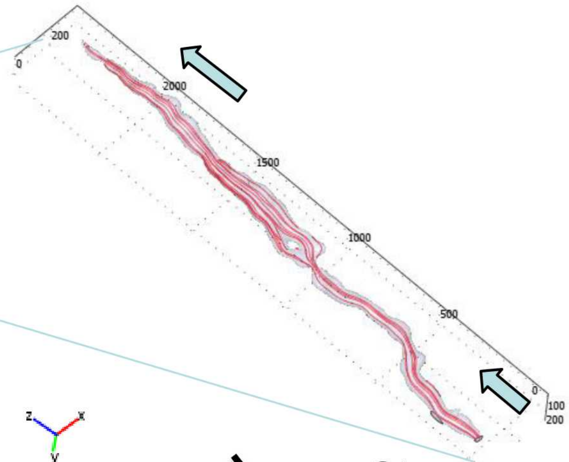


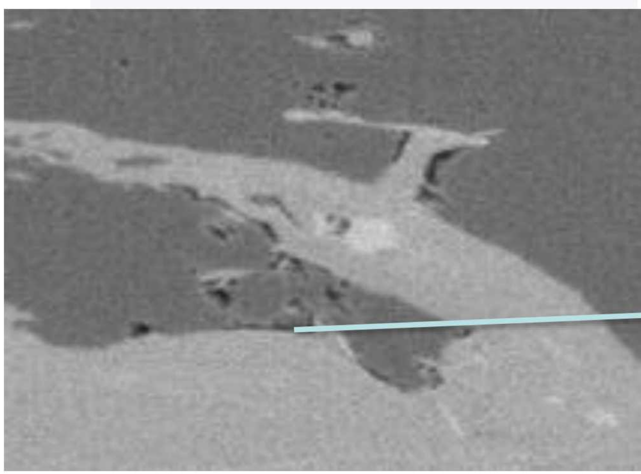


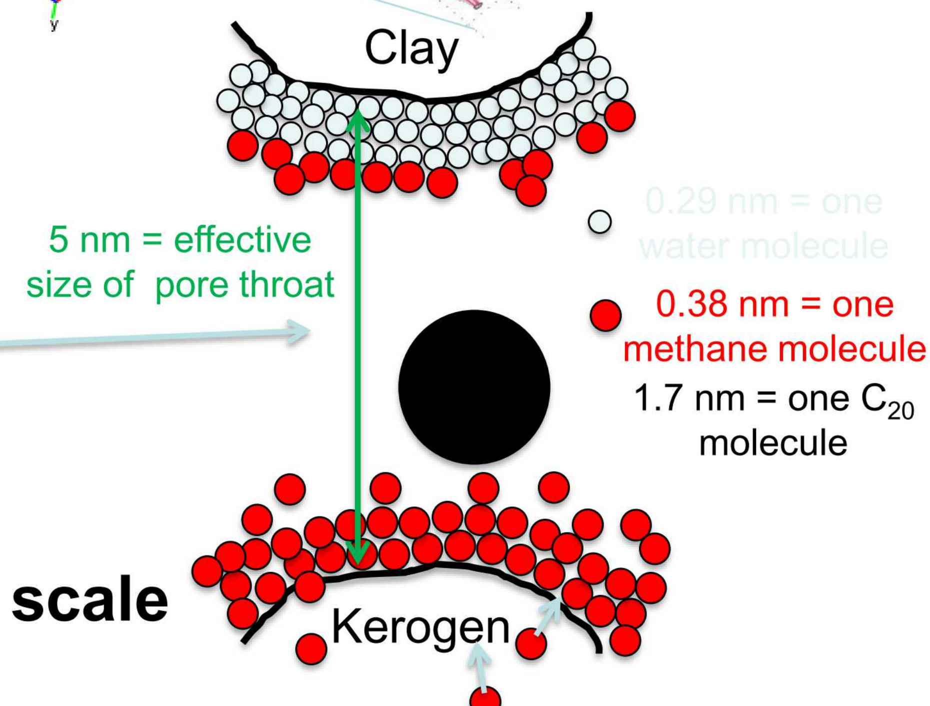
Reactive Transport

Methane flow in kerogen “tubule”





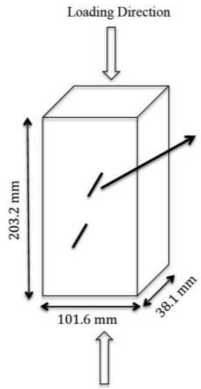


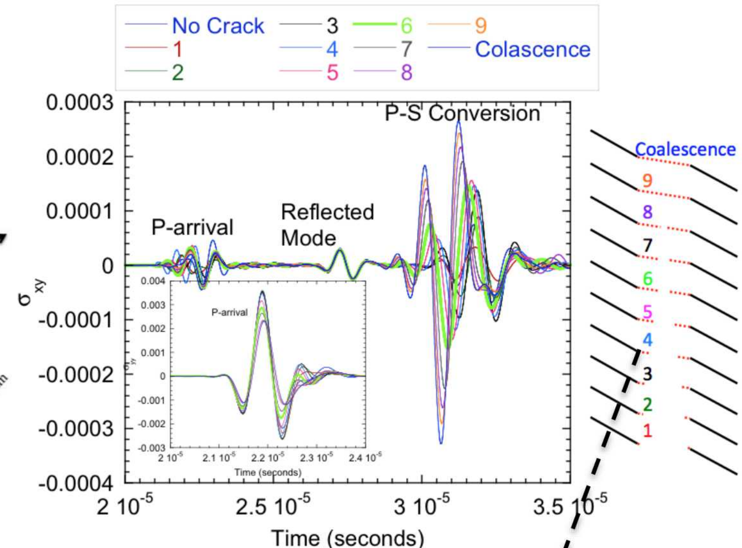


Pore throats are at molecular scale

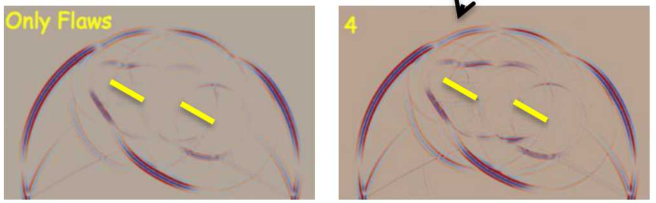
Seismic Signal Acquisition and Analysis

- Full waveform measurements with AE and seismic wave transmission/reflection:
  - Delineate the stages of crack initiation and propagation
  - Use bi-& tri-axial loading conditions and crack orientations to achieve mixed-mode I-II-III loading with and without pore pressure
- Experimental data will be analyzed in conjunction with computer simulations:
  - Identify all possible components of the signals (body wave, converted modes, guided modes, etc.)
  - Interpret the hydraulic properties of fractures
  - Develop the relationship between the interpreted stiffness of the fractures and fluid flow (w/ micro-CT images)

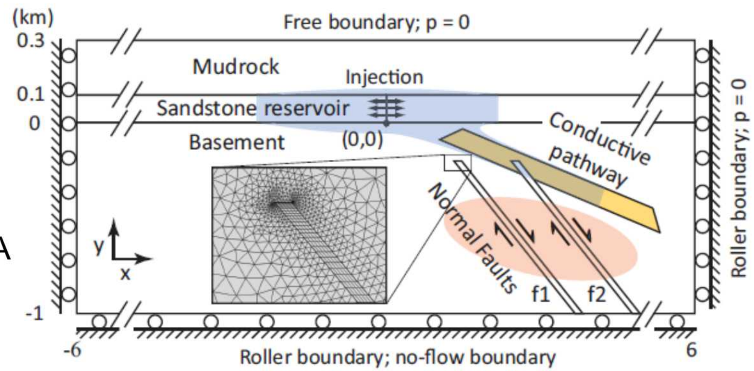




Simulated shear stress wavefront propagating from bottom to top (Pyrak-Nolte at Purude)



Fully coupled poroelastic simulation of fluid-injection scenarios (Chang et al., BSSA 2018, JGR & GRL (under review)



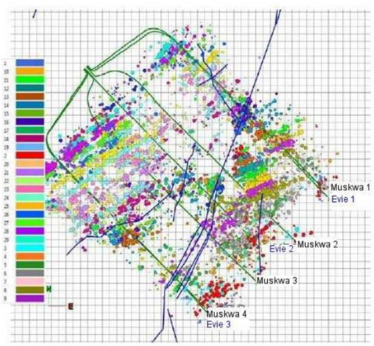
Multiscale network and flows with ROMs + ML

Horn River Shale Gas (CA)

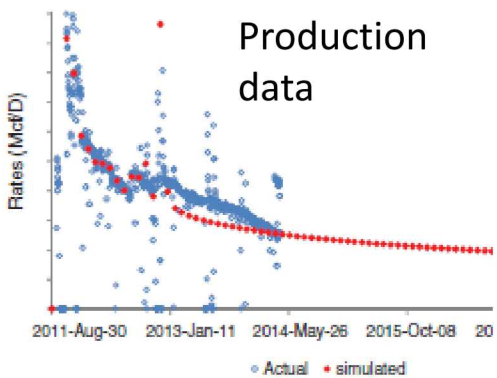
- International collaboration with Korea Gas Corporation (KOGAS)
- Extensive Reservoir characteristics (3D seismic data & microseismic data, well logs (gamma ray, resistivity, sonic, porosity, etc), core sample analysis)
- Integrated 3D reservoir model & geomechanical and geophysical model
- Dynamic production data

U.S. Major Shale Plays (with UT-BEG)

- Can we explain and predict future technology shifts and well performance?
- How large is the uncertainty around well performance?
- How should ML algorithms be trained (supervised, un-(or semi-)supervised)?



Microseismic data
(courtesy from KOGAS)



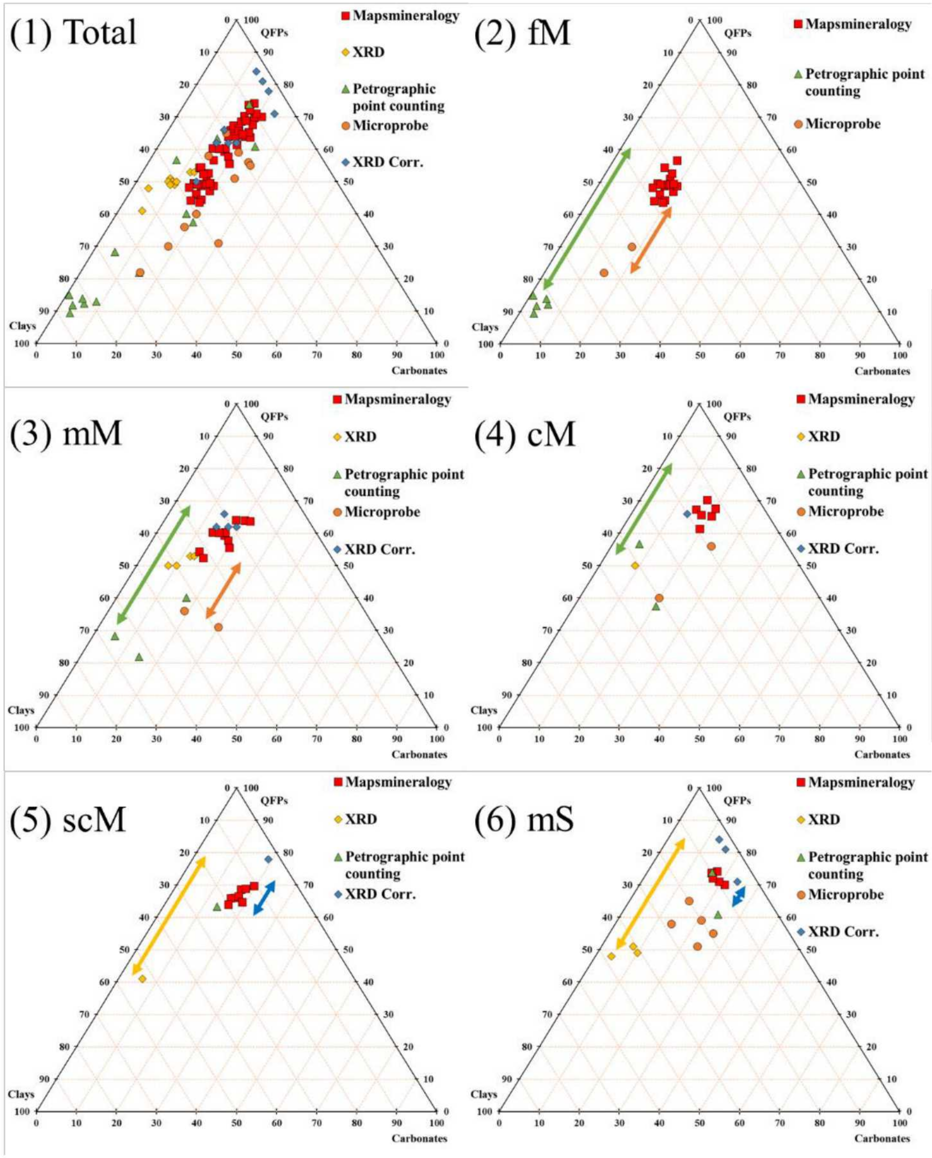
Ref: Kam et al. (2015, SPE-171611-PA)

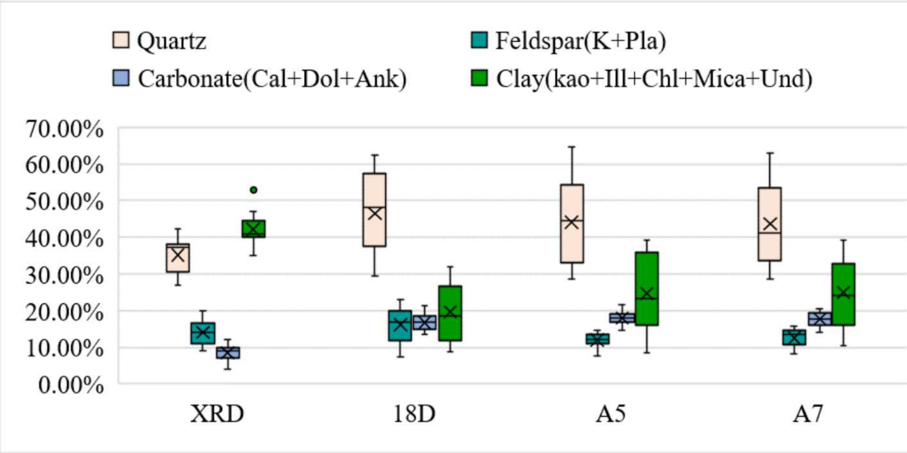
Summary

- Integrated multiscale imaging and mechanical testing with numerical simulation provides a robust approach to advancing our understanding of shale (poro-) mechanical behaviors
- Texture/mineralogical characterization
  - – Recent advances in mineralogical mapping with high resolution imaging over the large area
  - – Multiscale mineralogical and geologic features lead to considerable heterogeneity of mechanical properties
- Mechanical tests
  - – Macroscopic and microscopic lithofacies have distinctively different mechanical properties
  - – Bulk properties/averaging theory may be misleading as they can represent averages of mechanically heterogeneous rock
  - – Microscopic heterogeneity of mechanical properties can control the spatial distribution of fractures
  - – This heterogeneity should be taken into account for realistic mechanical modeling and can scale up by rigorous theoretical and numerical modeling

Thank You!!!

XRD vs. MAPS Mineralogy





FIB-SEM images