Additive Manufacturing and Digital Rock Physics for Geoscience Applications

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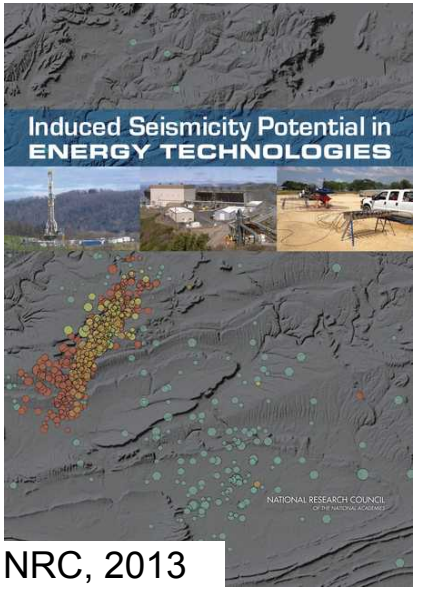
Subsurface Energy Activities

- Subsurface energy technologies correspond to >75% US Energy production
- These activities typically involve the change of fluid flow, stress, thermal, chemical (aka THMC) status in fractured and porous media
  - Energy production (Oil, Gas, Geothermal)
  - Disposal of wastewater and nuclear waste
  - Subsurface carbon and compressed gas storage
- To reduce adverse risks (e.g., induced seismicity and environmental impact) and improve modern energy activities, 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

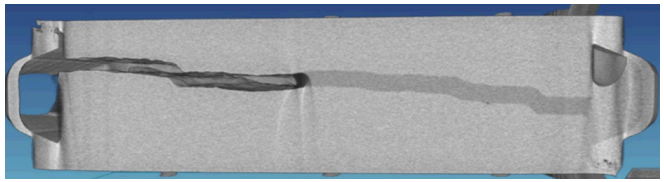
DOE BES Report, 2015

3D Printing for Geoscience Applications

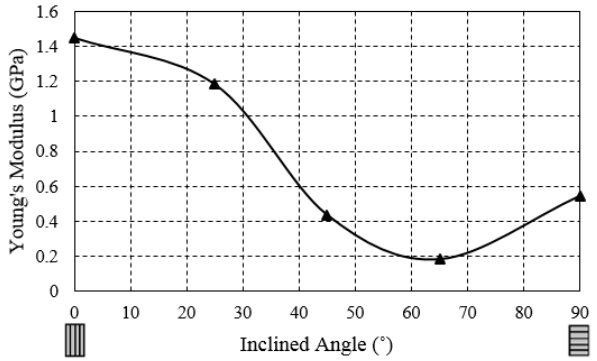
- Why is 3D printing?
  - Develop methodology for additive manufacturing of synthetic media that mimics natural media and enables creation of custom/functional porous material
  - Overcome sample-to-sample variability for testing material response
  - Connect controllable pore/fracture structure to macro-scale behavior to advance constitutive models for poro-hydro-mechanics of fractured rock
- Fracture structure features for this work:
  - 100+ micron single fractures over a range of angles, aperture distributions, the length and number of cracks (~10-20 cm scale in each dimension)
- 3D printing with granular materials (e.g., gypsum) and various bonding chemicals
- Inverse printing of enclosed and/or fracture network:
  - Fractures printed with burnable, castable resin are molded with ceramic, silica gels to create fracture network and/or enclosed fractures

Gypsum-based sample

ProJet CJP 360/460



MicroCT image of 3D printed fracture with water

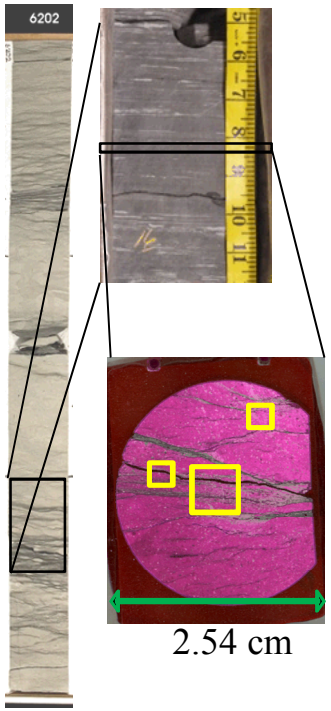


Effect of printing direction: Young's modulus

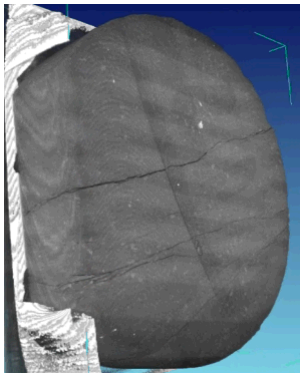
Workflow for Digital Rock Physics (DRP)

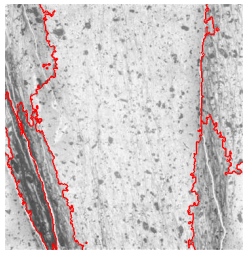
Rock Sample	Multiscale imaging	Image Process	Flow and Transport Properties	Static Effective Elastic Properties	Wave Propagation

Core (~1m)

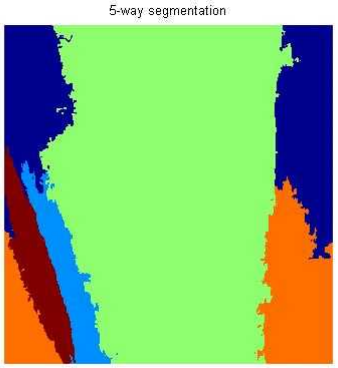


- DRP can help us characterize and understand the role of heterogeneity and multiscale aspects of fractured and porous media
- Multiscale imaging can support upscaling

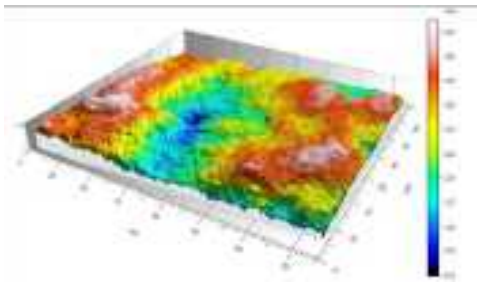




Multiscale Imaging

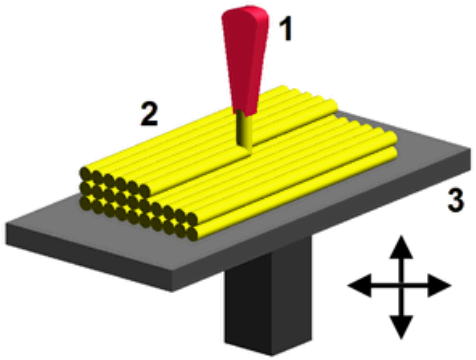


Multiscale Features

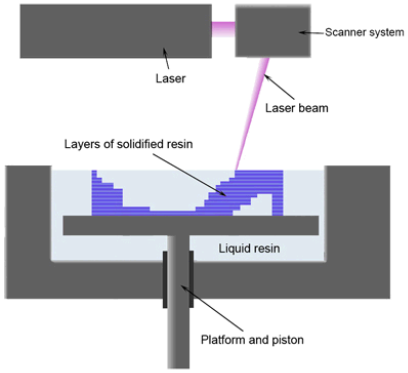


Topological Analysis

Representative 3D Printing Process Categories

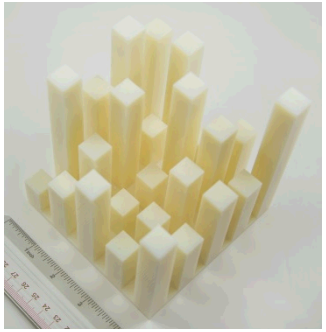


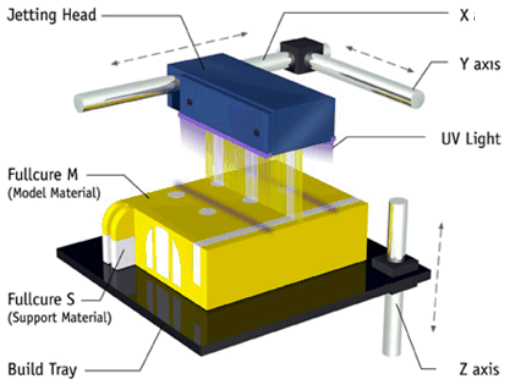
"Fused deposition modelling", Wikipedia



"Stereolithography", Wikipedia

Formlabs Form 1+ & 2





Objet material jetting, www.me.vt.edu

- Why 3D printing?
  - ability to design & realize complex geometries
  - engineered material control at new regimes
- Porous structure features for this work:
  - Real pore structure on specimens greater than 1 REV
  - 25-100 micron pores, 100+ micron fractures

3D Printing for Geoscience Applications

- Single Fracture Network

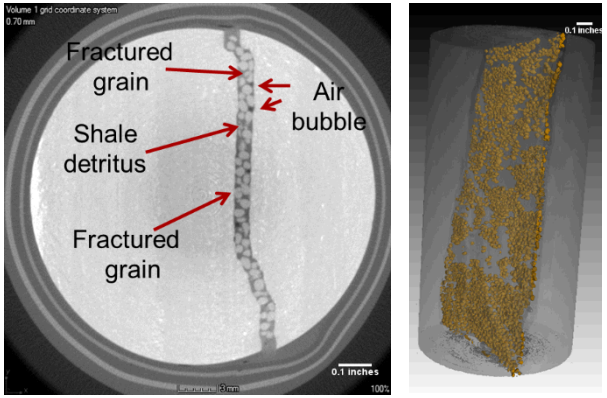
- Geomechanical testing with acoustic emission

(1) determine the mechanical failure mechanisms that lead to induced seismicity from crack propagation
(2) delineate crack initiation, propagation and failure using both active and passive seismic/ultrasonic monitoring techniques

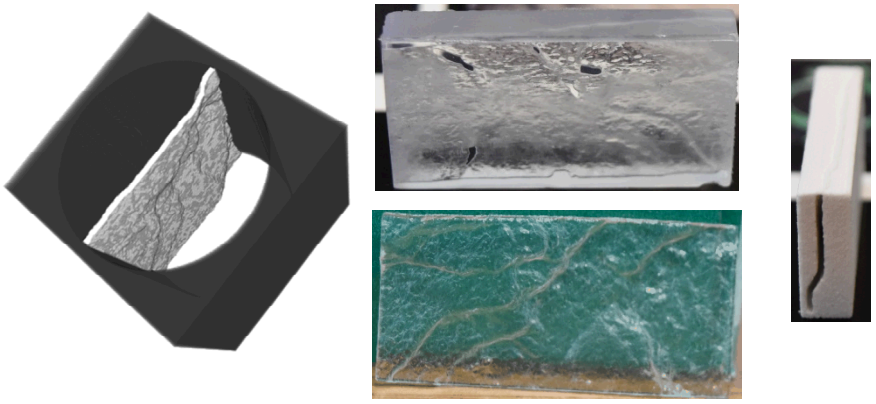
► *Experimental setup under in-situ conditions (P & T) with advanced monitoring techniques is key to identifying precursor(s) to the induced seismicity (IS) from existing fracture systems*

Printing Single Fracture Network

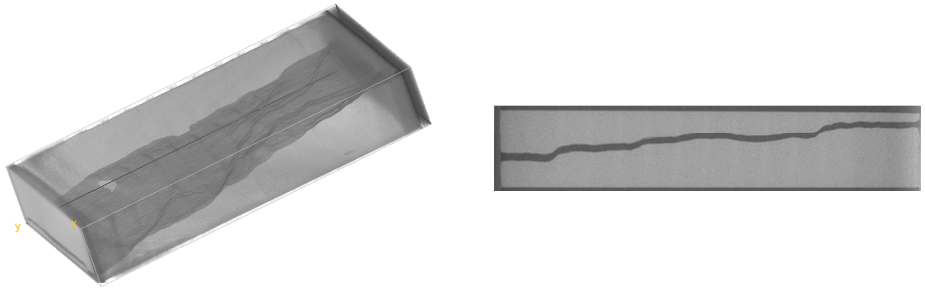
- MicroCT image of a single fracture system (100 to 1000 microns aperture)
- Fracture printed with clear resin (SLA)
- Printed fracture network was scanned using microCT (12 microns resolution)



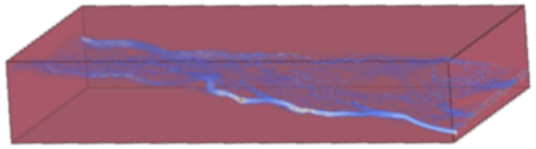
Micro-CT image with proppants in a fracture



Single fracture network (left), printed fracture network and aperture (middle), printed with gypsum (right)



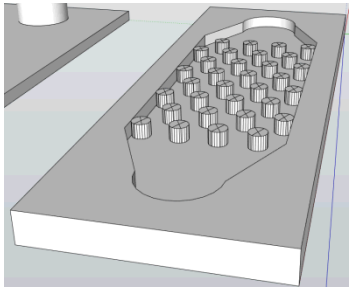
microCT image of printed fracture (@12 μm)

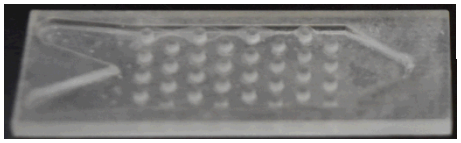


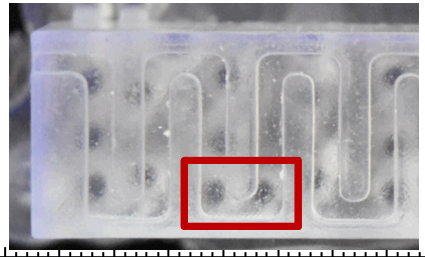
Lattice Boltzmann simulation flow field

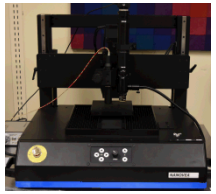
Micro Pattern Designs and Printing

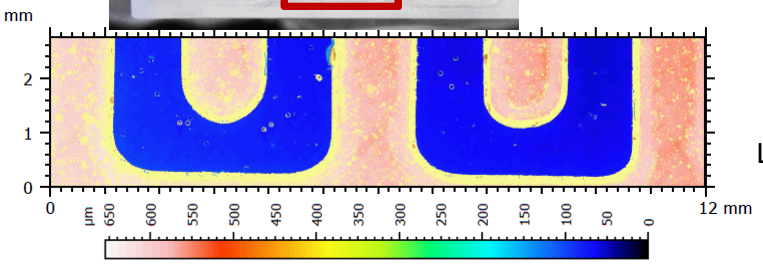
- Design of various pore structure and capillarity patterns
- Flexible printing options with luer lock ports for inlet and outlet
- Printed parts are assembled with plasma or corona bonding
- Embedded sensors can be printed
- Some natural materials will be filled with patterns for reactive transport experiments
- Wettability and surface roughness of printed products will be evaluated thoroughly



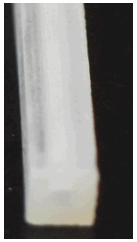


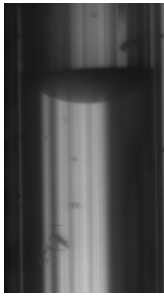






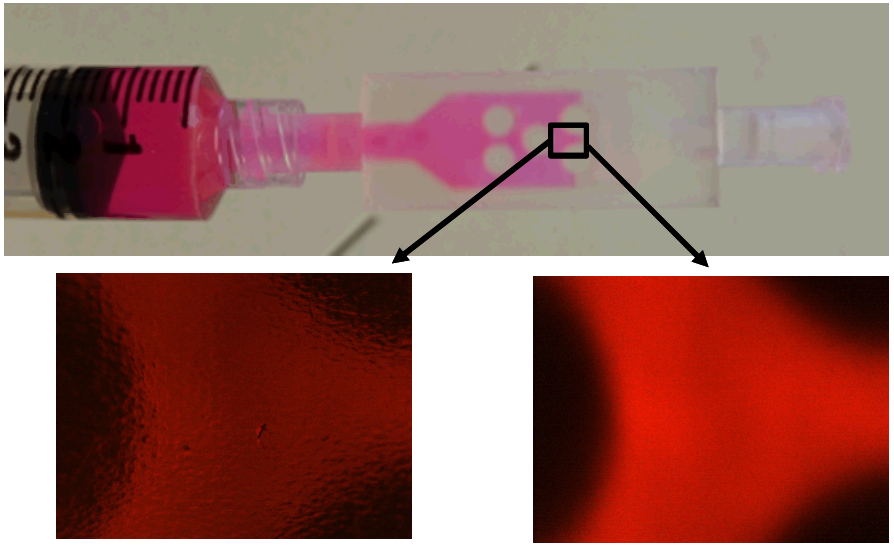
Surface roughness image
of printed square channel with 1 mm square shape



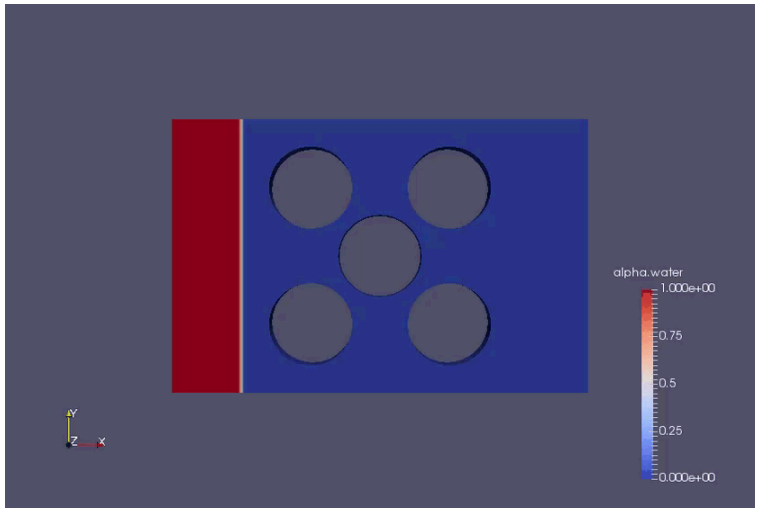


Contact angle measurement
Left: non-wetting on printed channel (middle), and wetting contact angle on glass capillary

Multiphase Flow Testing & Simulation

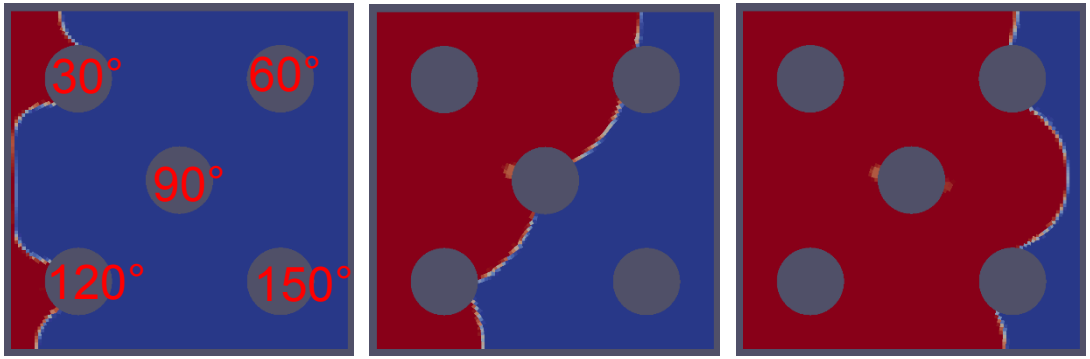


Confocal microscope image of 5 cylinder channel
(Left: bottom surface, Right: middle in the channel)



Multiphsae flow simulation with CA=45°

Multiphase flow simulation with CA=90° on the wall

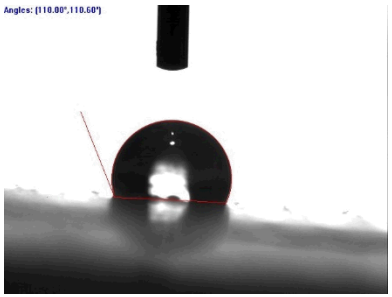


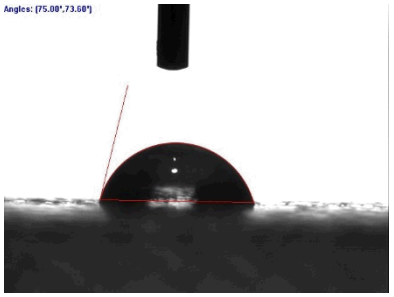
Multiphase flow with multiple wetting angles on the surface of cylinder (30, 60, 90, 120, and 150°) The left boundary has a constant velocity condition of 0.01 m/s.

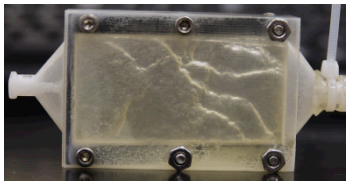
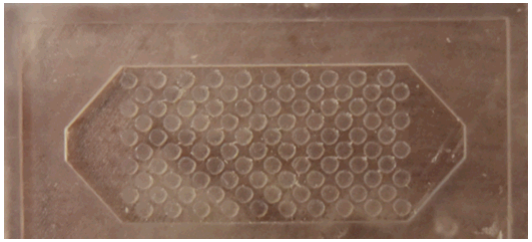
Wettability manipulation and bonding

- Contact angle measurement after plasma treating on printed materials

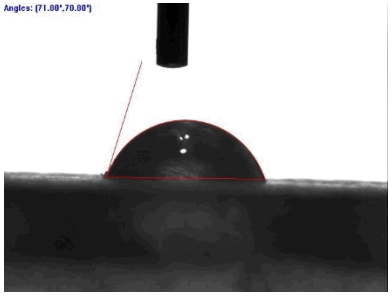
Fracture surface (110 to 75)

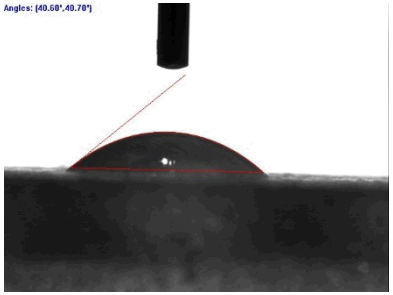




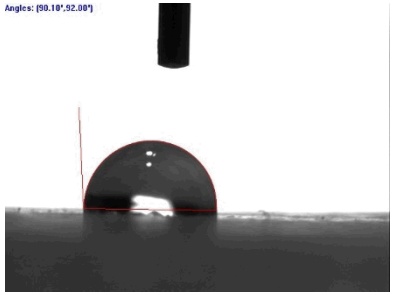



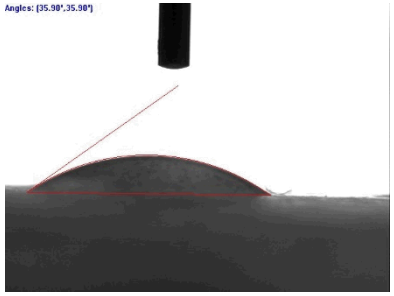
Milli-fluidic channel (71 to 41)



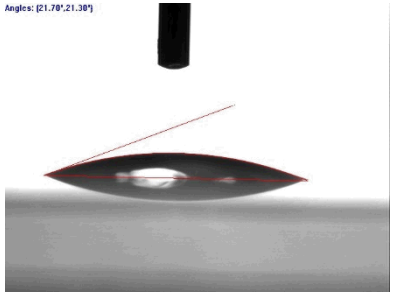


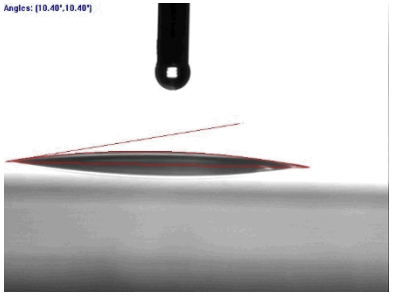
Milli-fluidic cover (90 to 36)



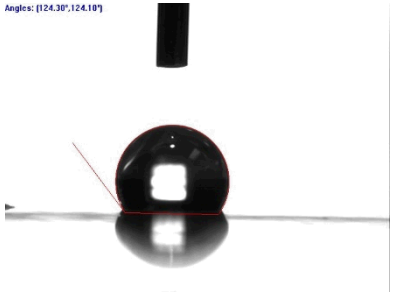


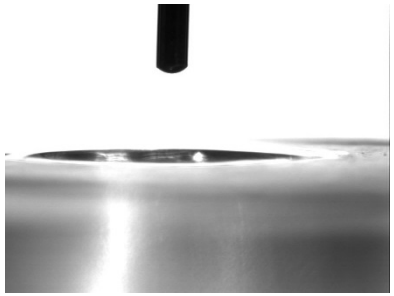
Glass (21 to 10)



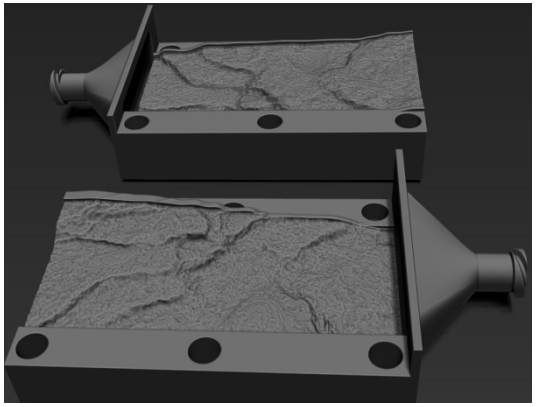


PDMS (124 to <10)

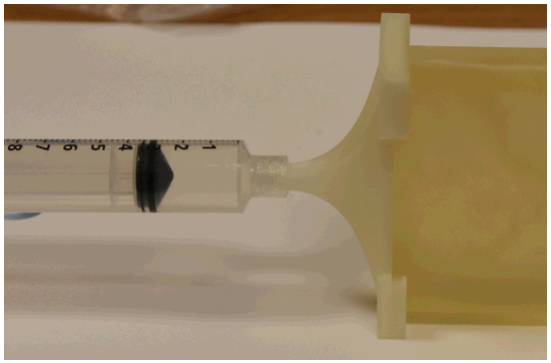




Single fracture design, printing, and testing



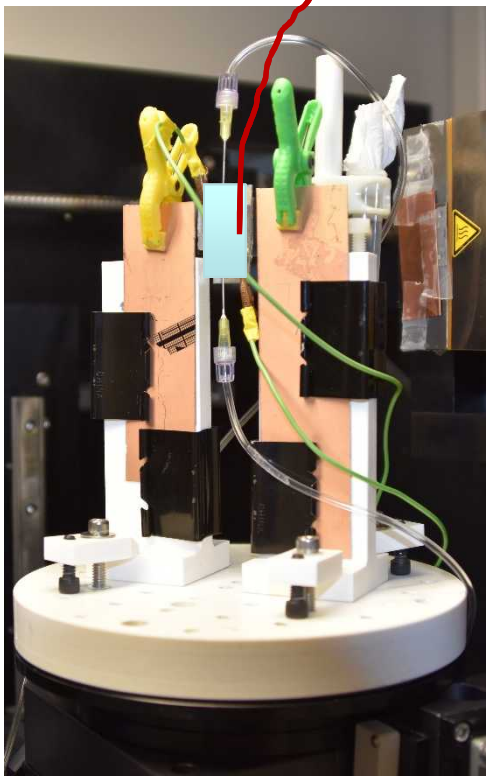
3D printing design (STL)



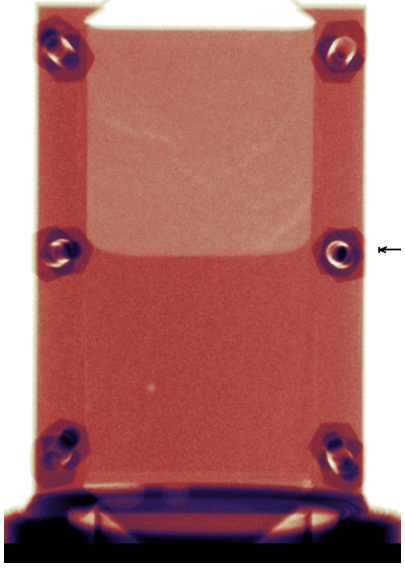
3D printed sample of single fracture (sealing unit is also printed)

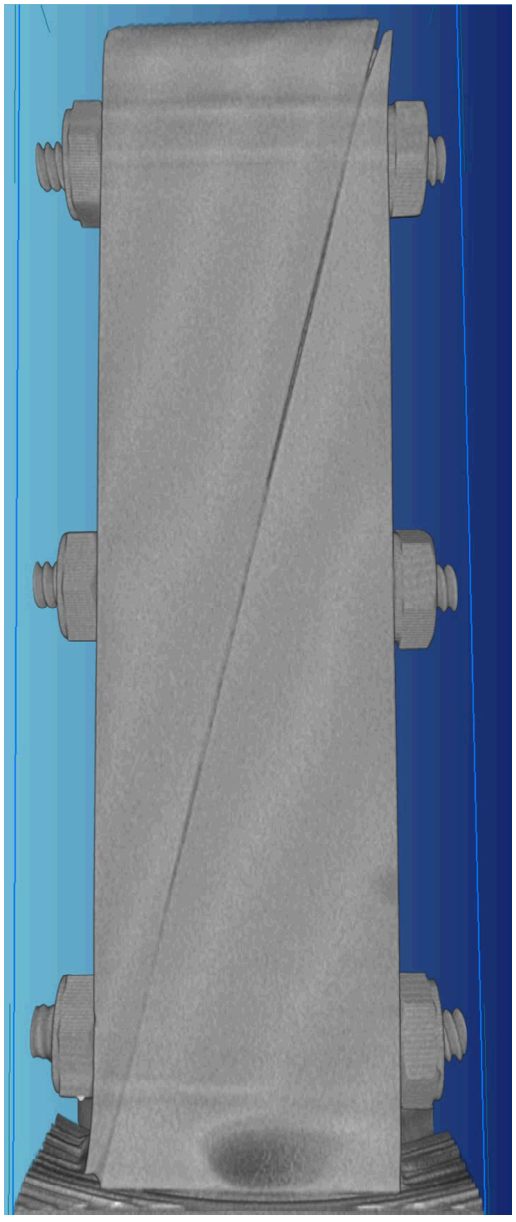
- Developed multiple printing designs of single fracture system with plastic materials
- Comparison of microCT images of printed fracture with original microCT images
- Permeability measurement
- 3D curvature of advancing and receeding interface (e.g., air-water or two liquid phase) as a function of surface roughness and aperture distribution
- Single fracture system will be tested for coupled hydro-mechanical relations

Flow Testing in Single Fracture Network



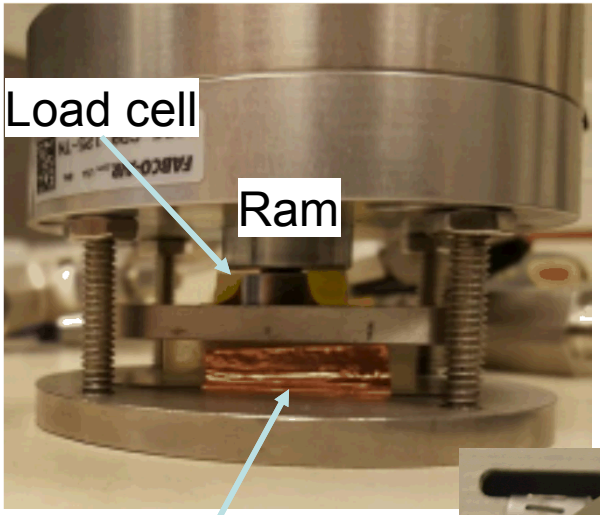
MicroCT setup

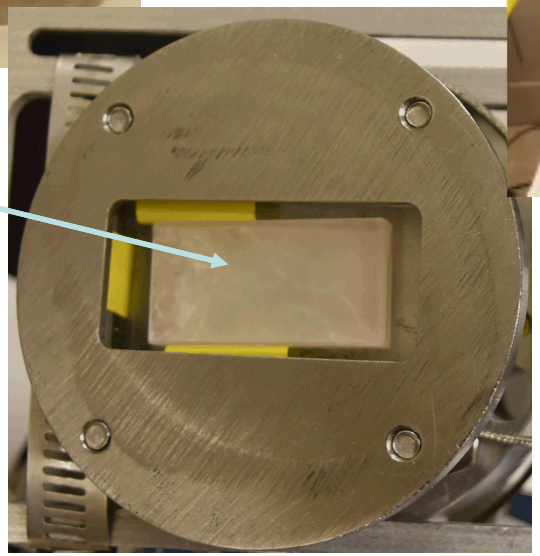




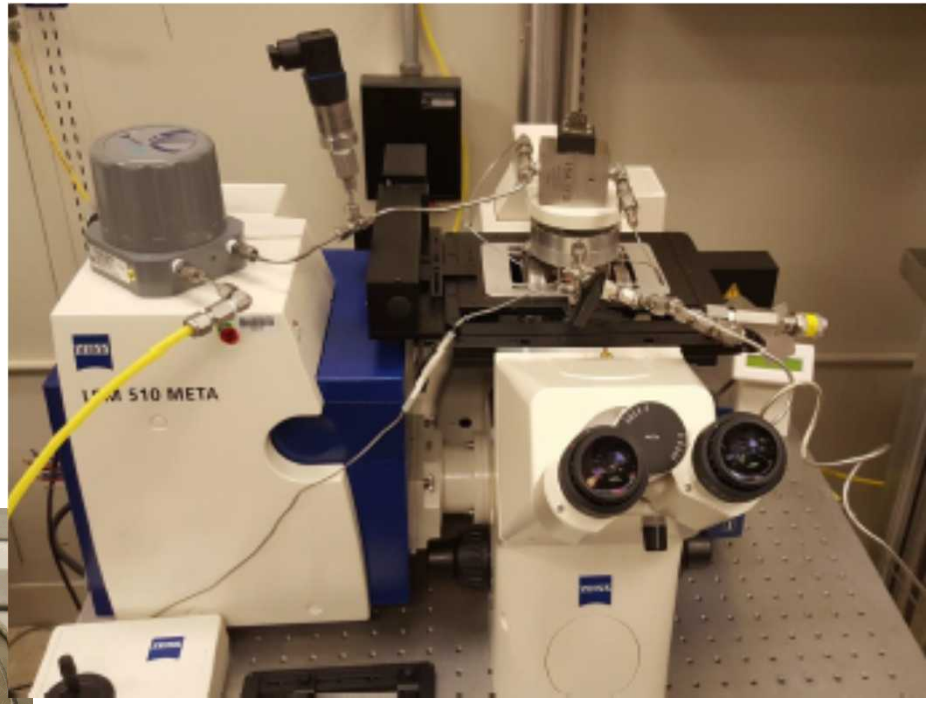
Microscopic measurement of 3D printed fracture constitutive behavior

Can subject AM sample fractures to 100 psi load with flow through and laser scanning imaging





3D printed fracture



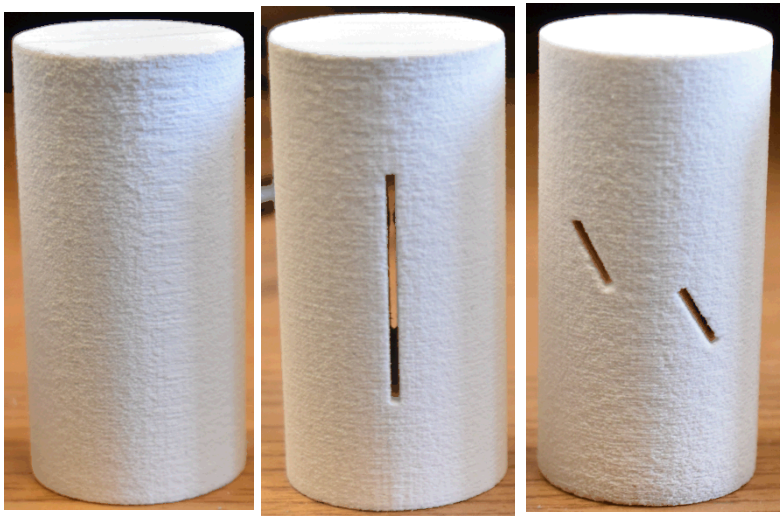
Laser Scanning Confocal Microscope

Loaded sample fitted into laser confocal microscope with TESCOM pressure controller/permeability system

Printing with Gypsum Powder

- A thin layer of gypsum ($CaSO_4 \bullet 0.5H_2O$) power is deposited onto build chamber
- A print head with binder jets dispenses a binder material where binding is required
- The build chamber is lowered and then repeated
- The dimension of the build bed is ~20-30 cm and the resolution of inkjet print heads is 300-500 dots per inch (~100 micron thick layer)
- Cracks or flaws can be printed at ~1mm feature resolution

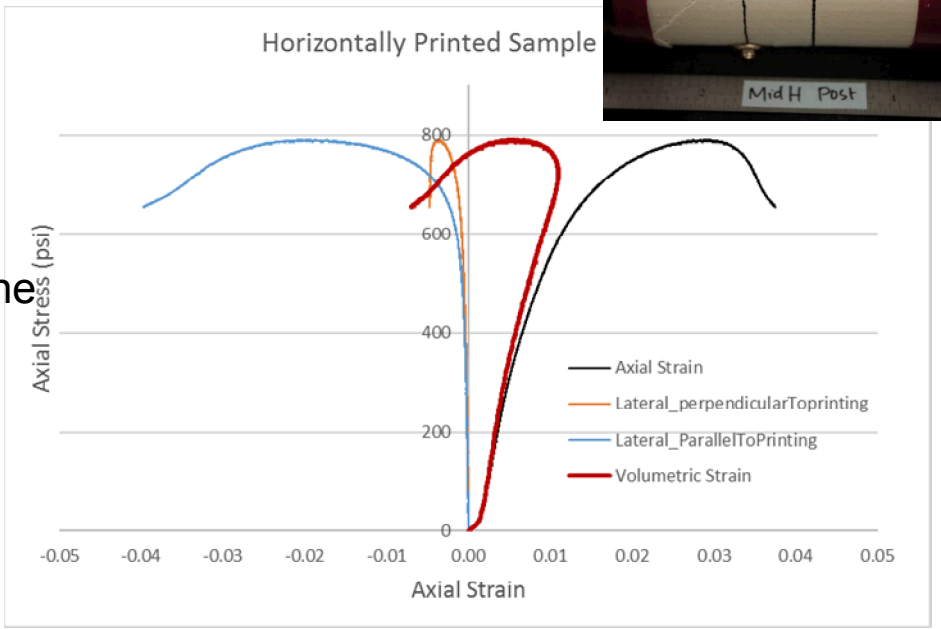
3D systems ProJet 360/460

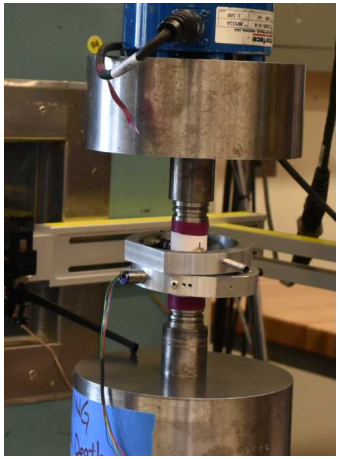


Compression Testing

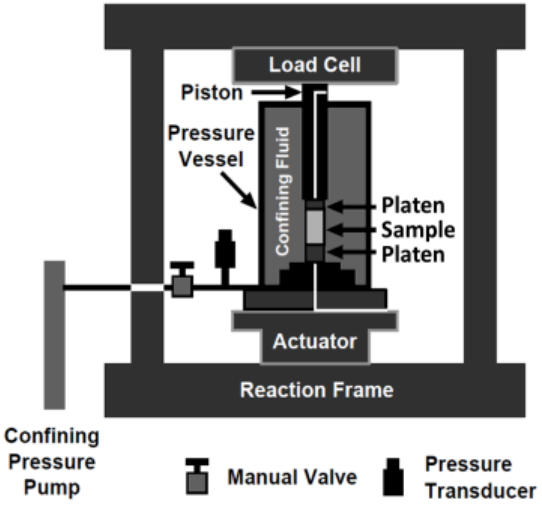
3D printed core sample (Gypsum+Binder) like geomaterials

- Axisymmetric (triaxial) testing of 3D printed cylinder of gypsum behaves like weak sandstone (Mt Simon Sandstone, Dewers et al., 2014)
- Similarities include initial elastic behavior, yielding, and failure
- Note compaction-to-dilation “turn around”

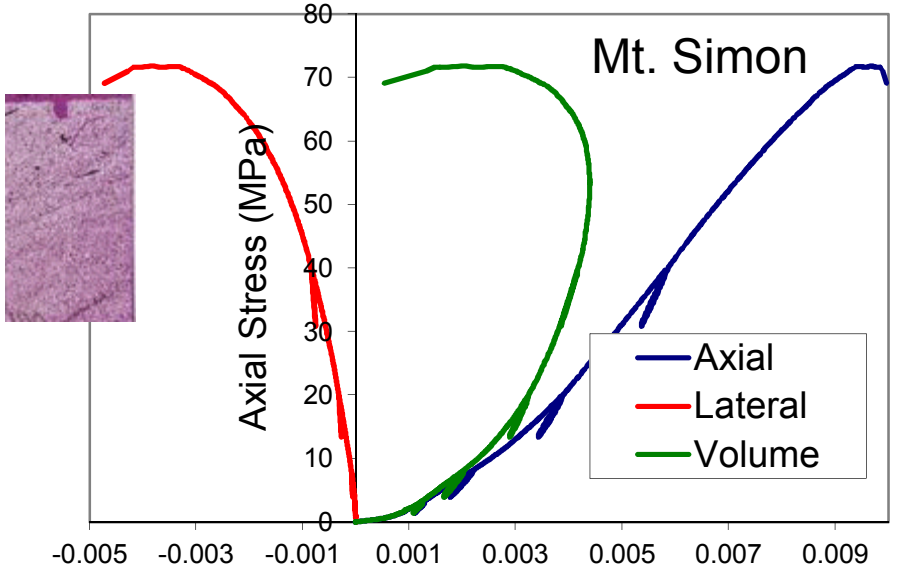




UCS setup

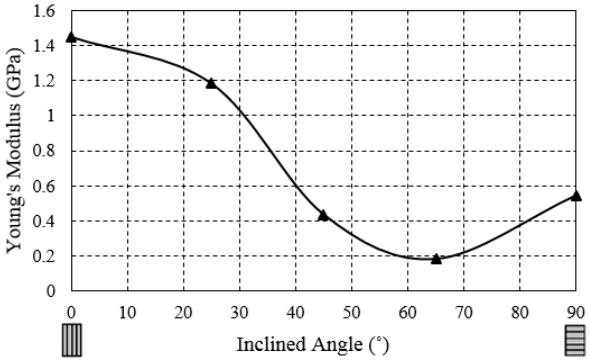


Triaxial setup

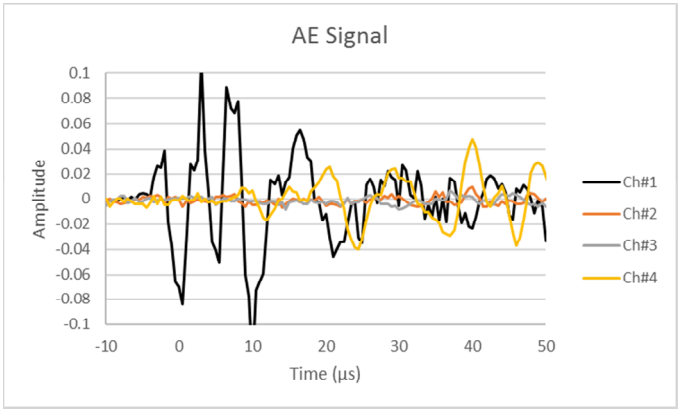


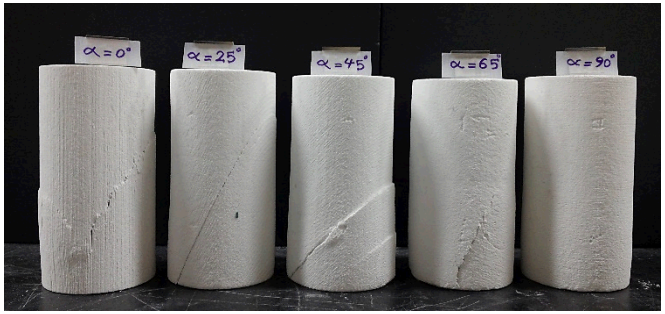
3D printed gypsum columns

- Printing artifacts or limitations (?)
  - Impact of printing direction on strength/failure patterns/ductile behavior/wave velocity
  - Non-uniform binder distribution

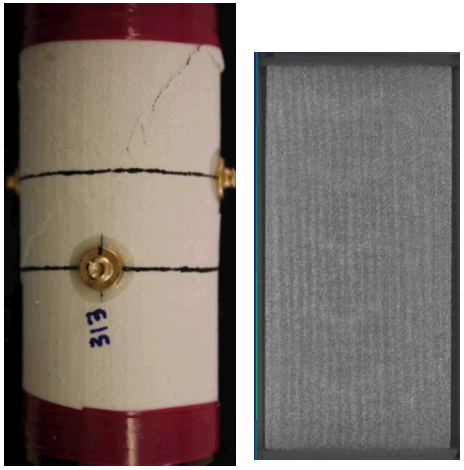


Effect of printing direction: Young's modulus

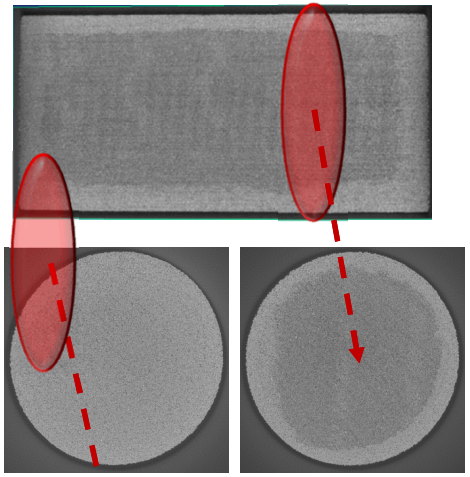




Failure pattern of 3D printed gypsum specimens with different printing directions after UCS test

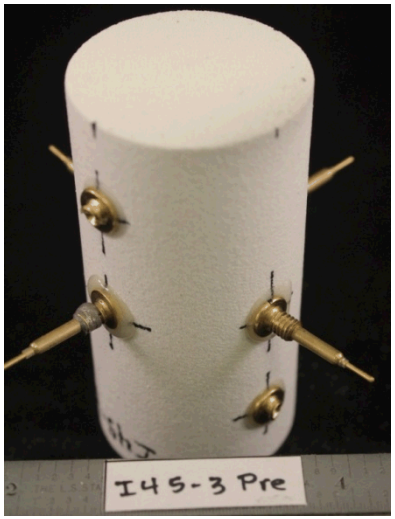


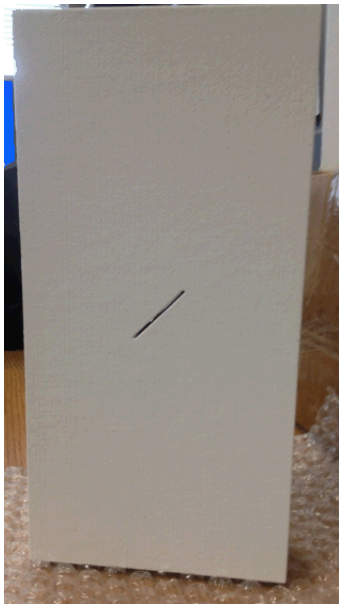
3D printed core & microCT image



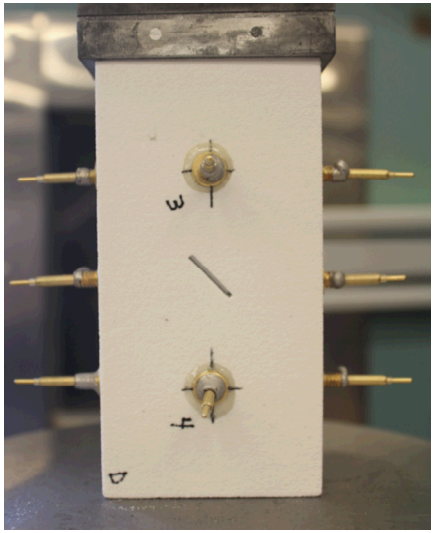
MicroCT image with CA adhesive

Mechanical Testing Samples

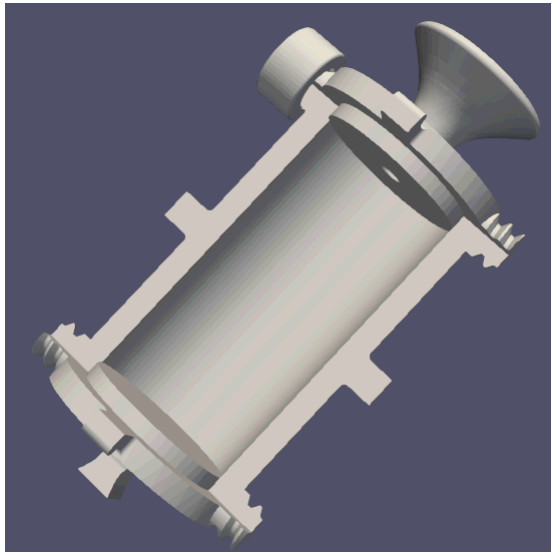




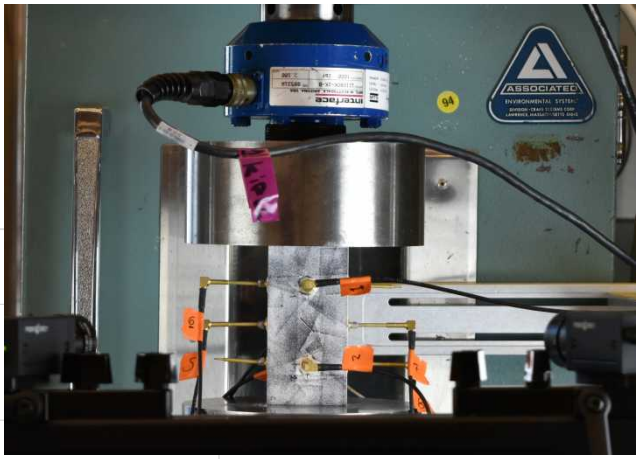
3D printed samples with gypsum

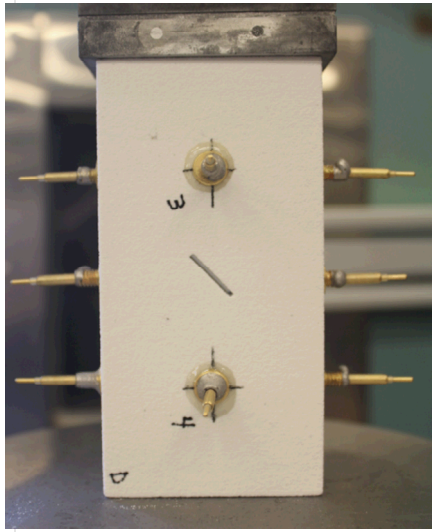


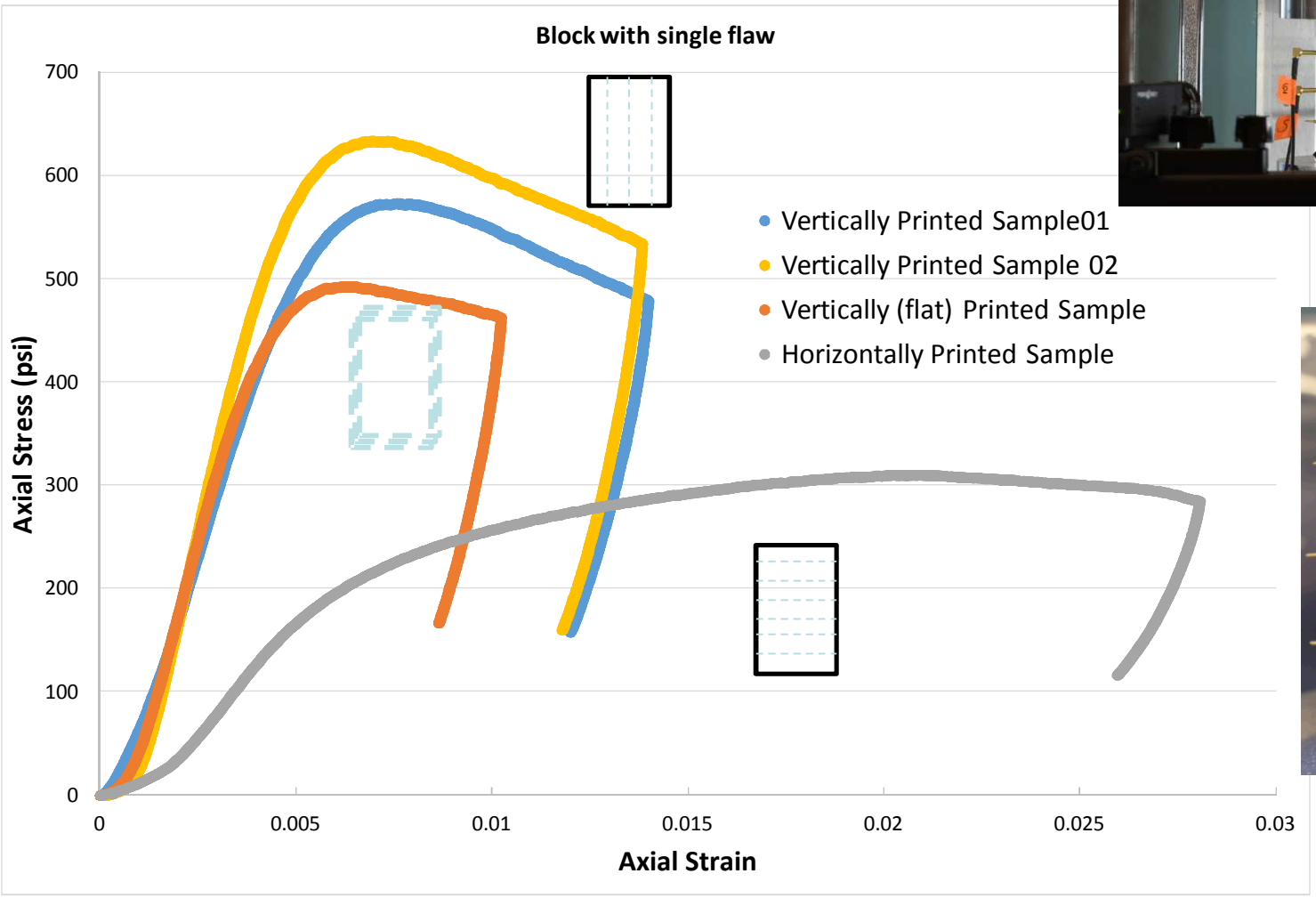
3D printed molding setup



Mechanical Testing

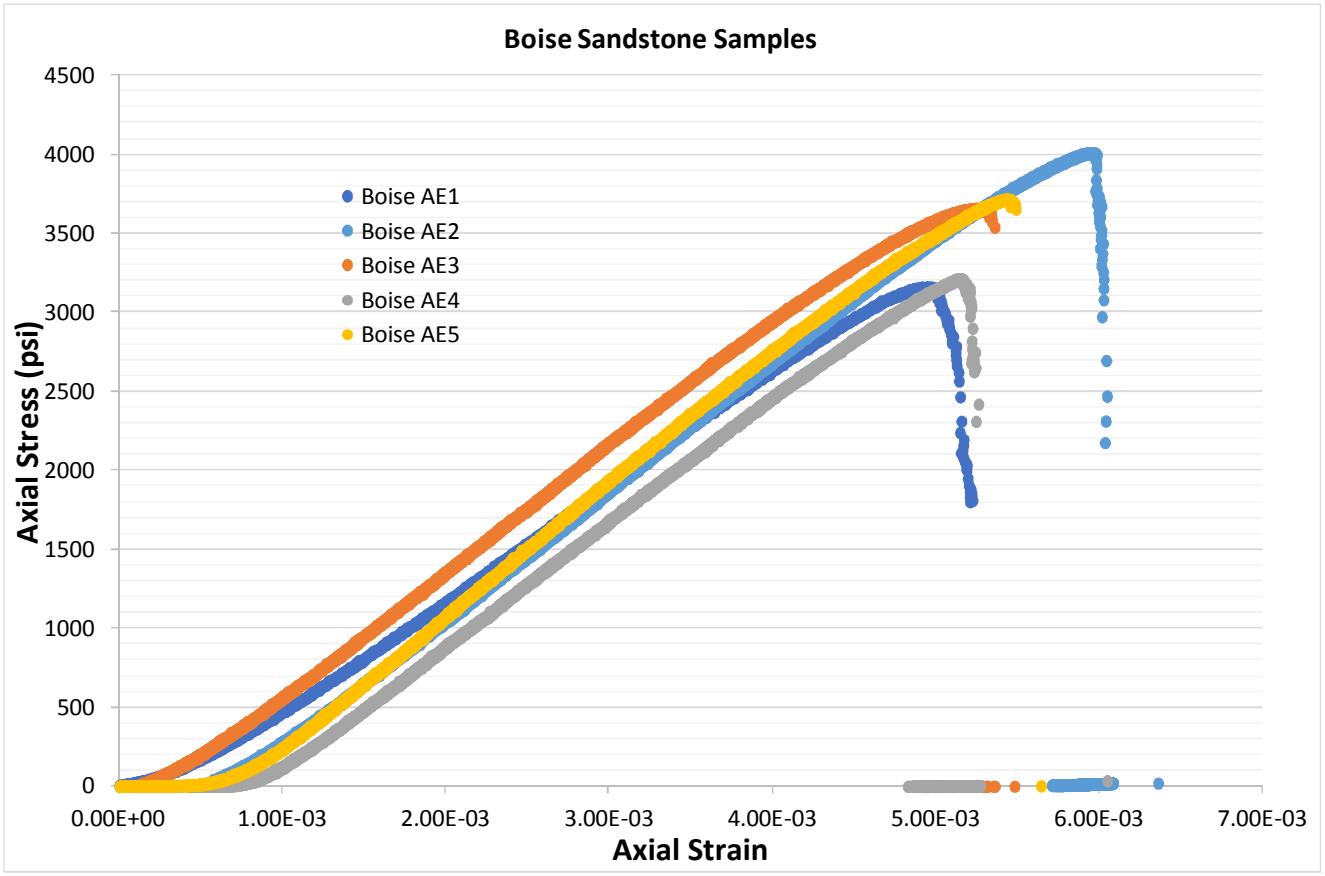




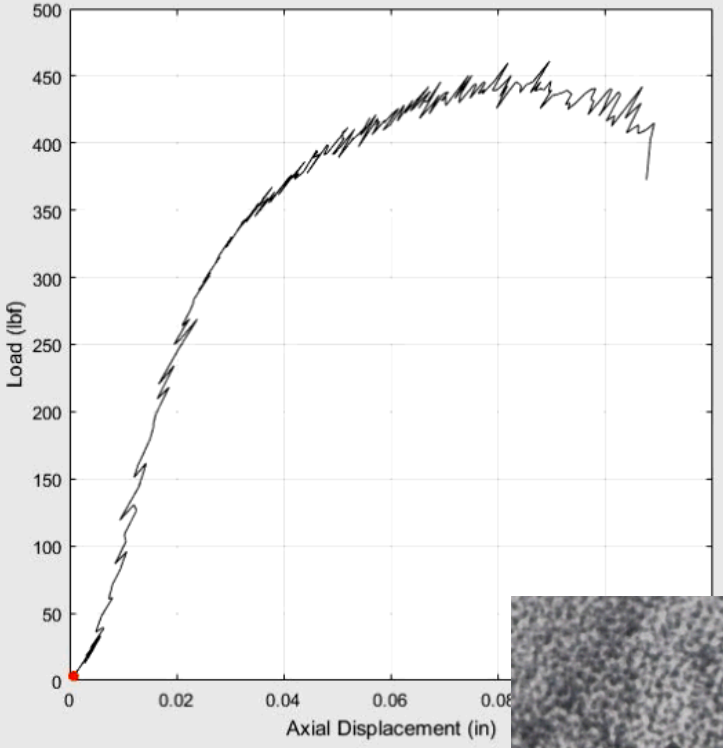


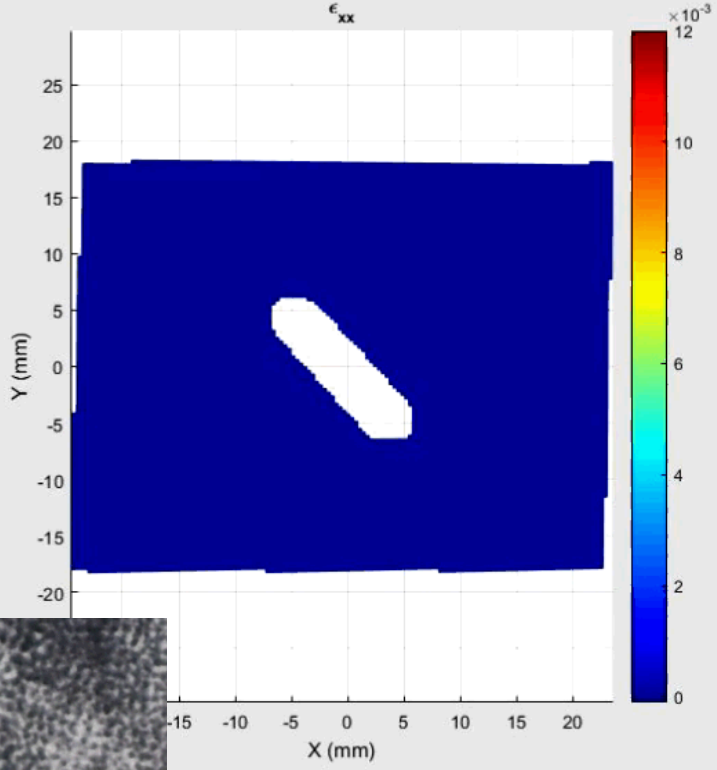
Mechanical Testing

Natural Sandstone



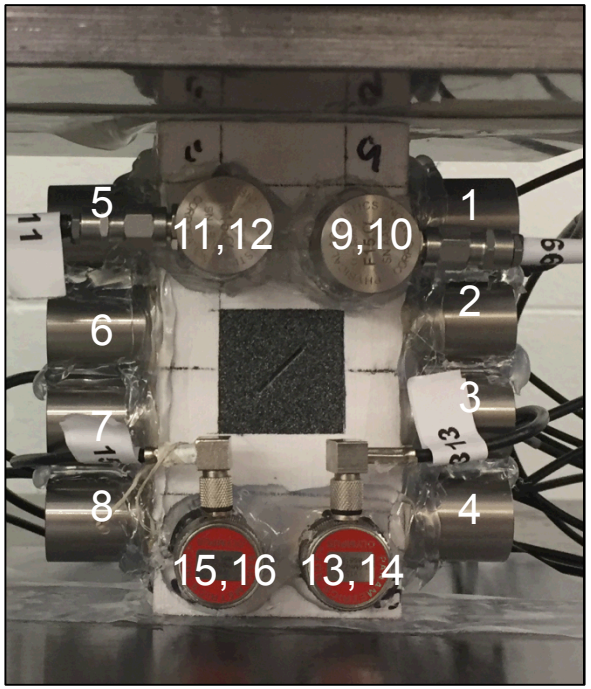
Mechanical Testing

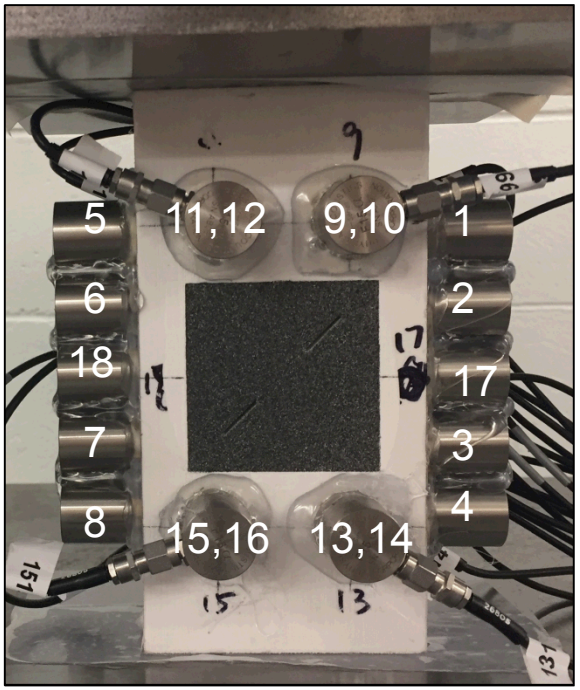




Testing Samples and AE systems

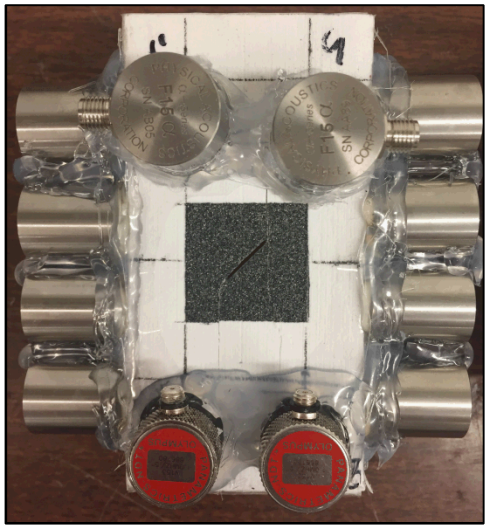
Sample	*Layering*	*Density Kg/m3*	*Flaw Length mm*	*Continuity mm*	*Flaw Aperture mm*
3DP1-V-one flaw	Vertical	1229.0	12.7	-	1.27
3DP2-H-one flaw	Horizontal	1291.5	12.7	-	1.27
3DP3-V-two flaws	Vertical	1263.5	12.7	19.05	1.27
3DP4-H-two flaws	Horizontal	1309.4	12.7	19.05	1.27



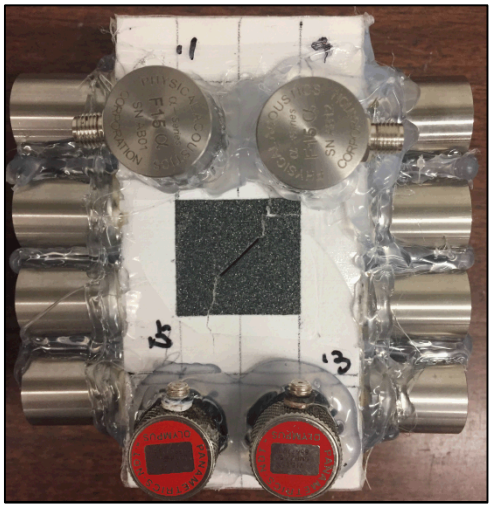


Sample Failure

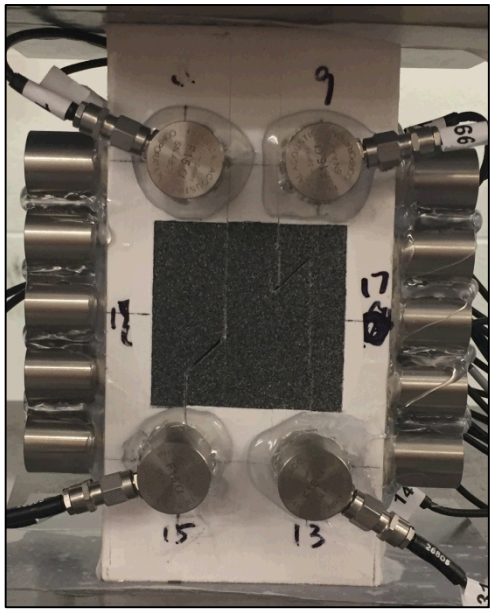
3DP1-V



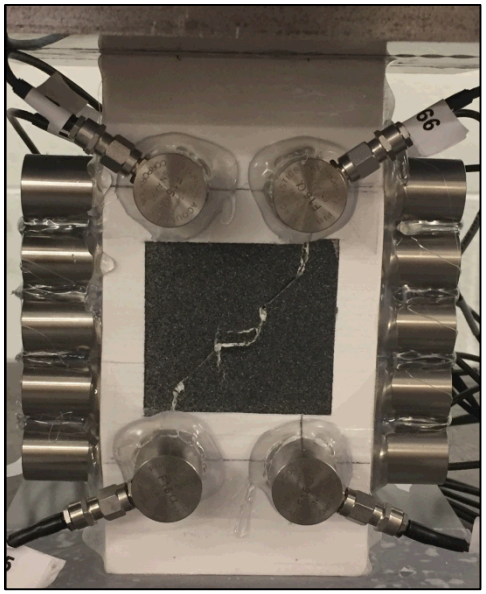
3DP2-H



3DP3-V

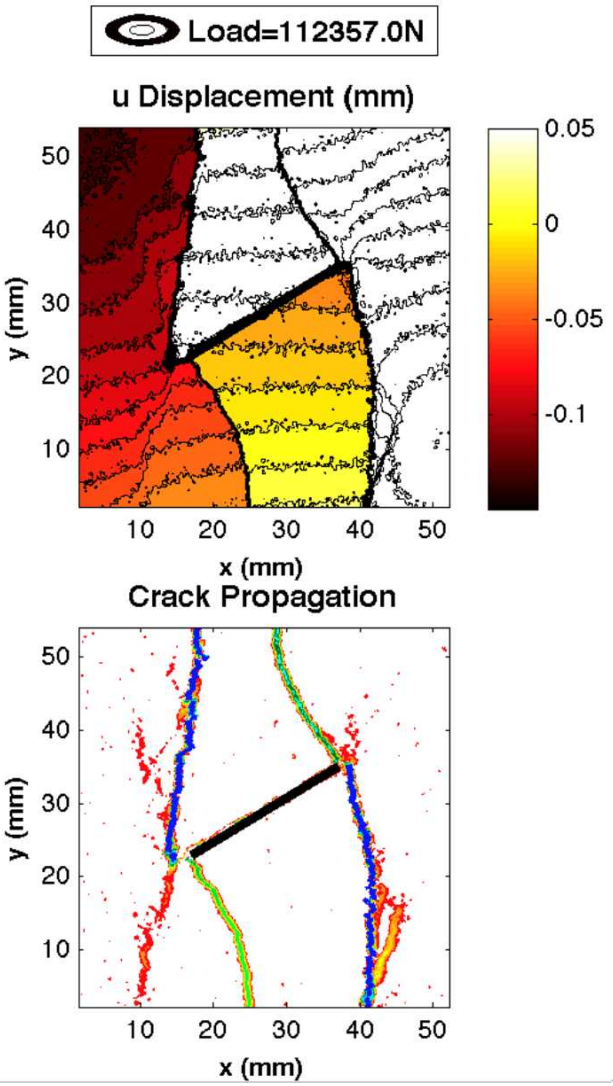


3DP4-H

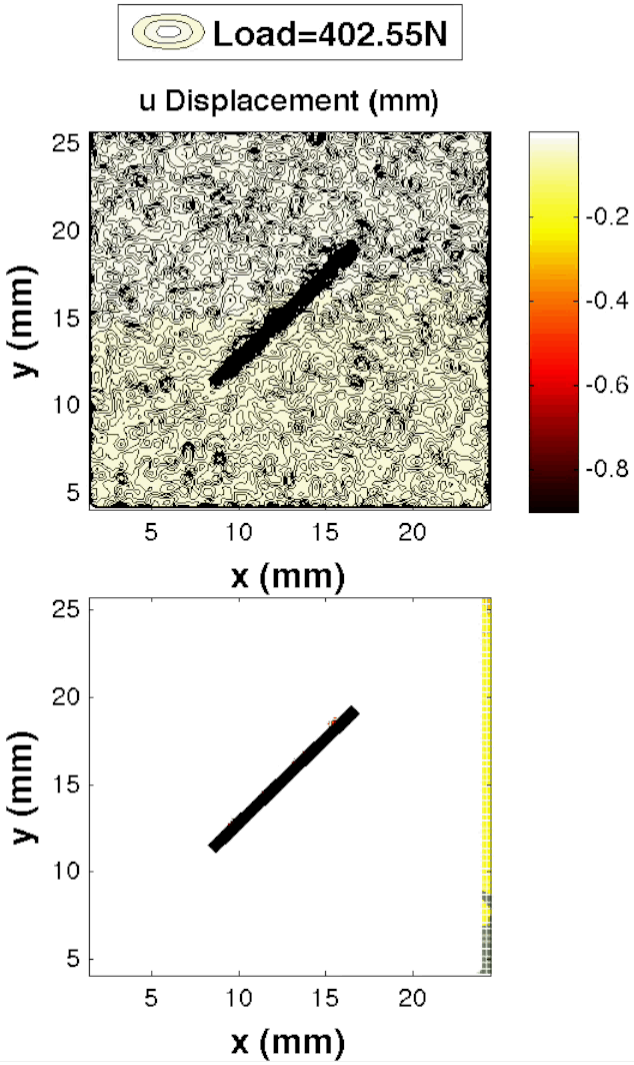


Mechanical Testing

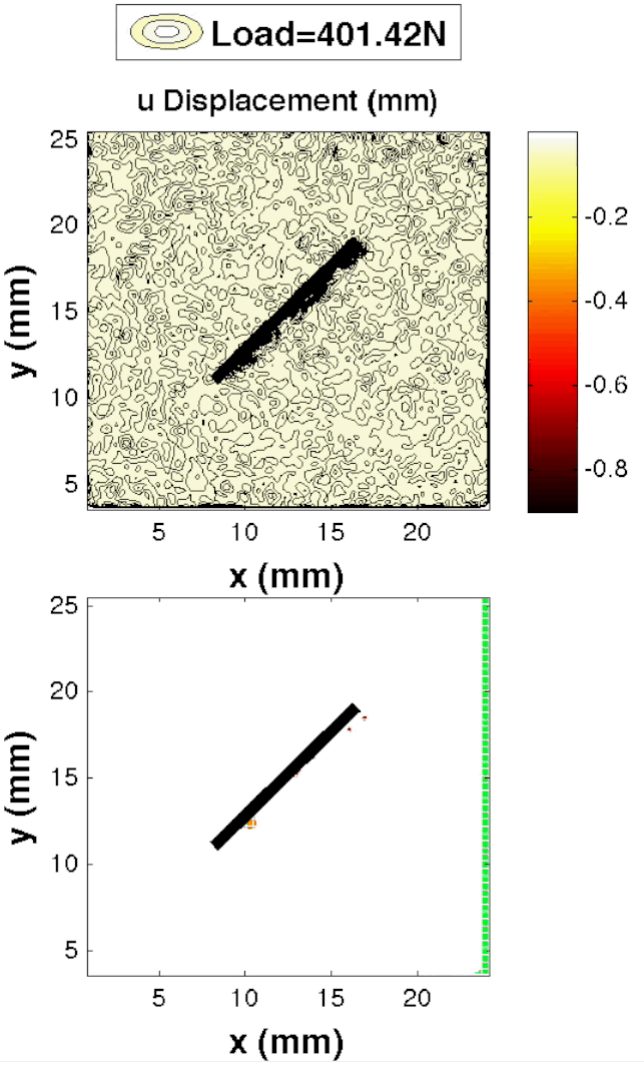
Limestone



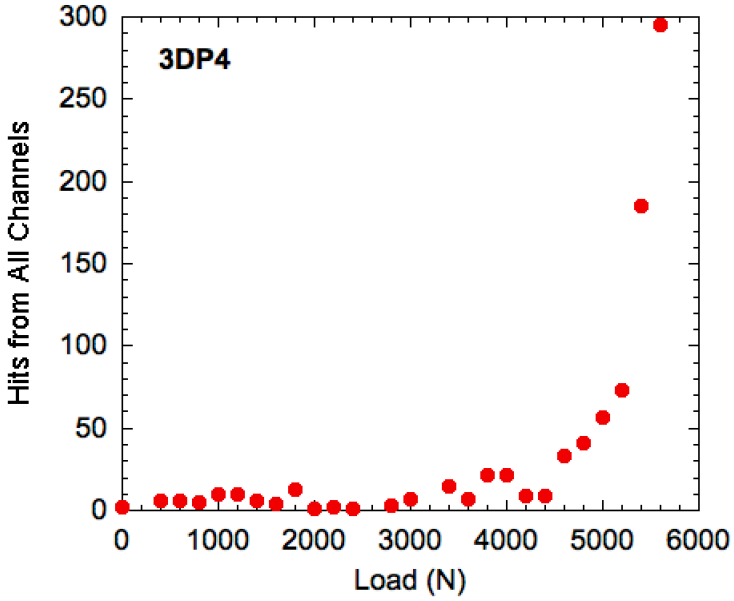
3DP1-V

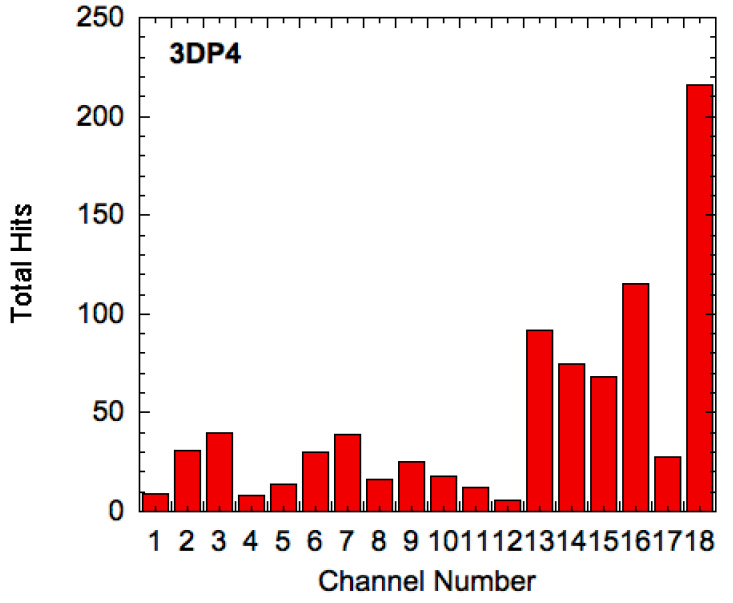


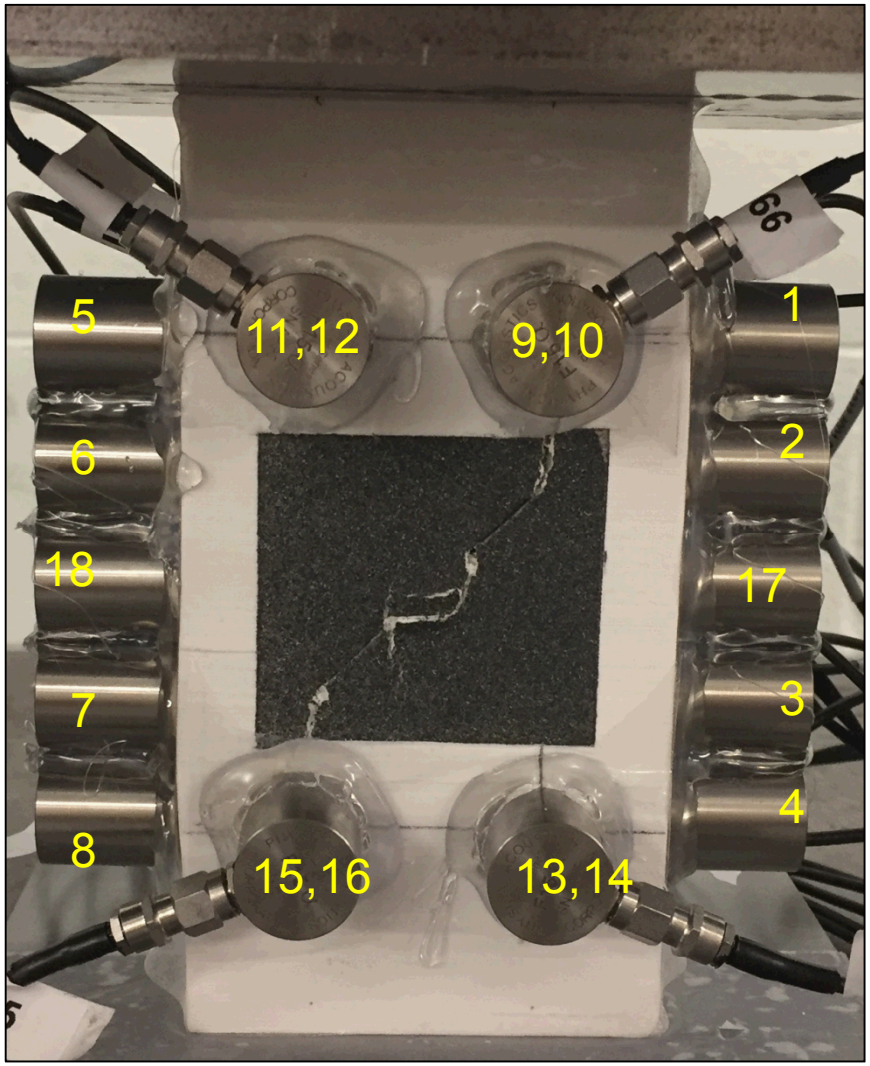
3DP2-H



Testing Single Fracture Network



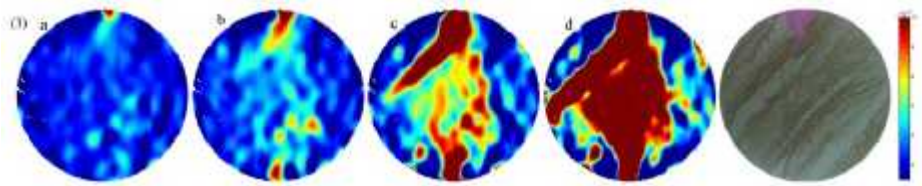




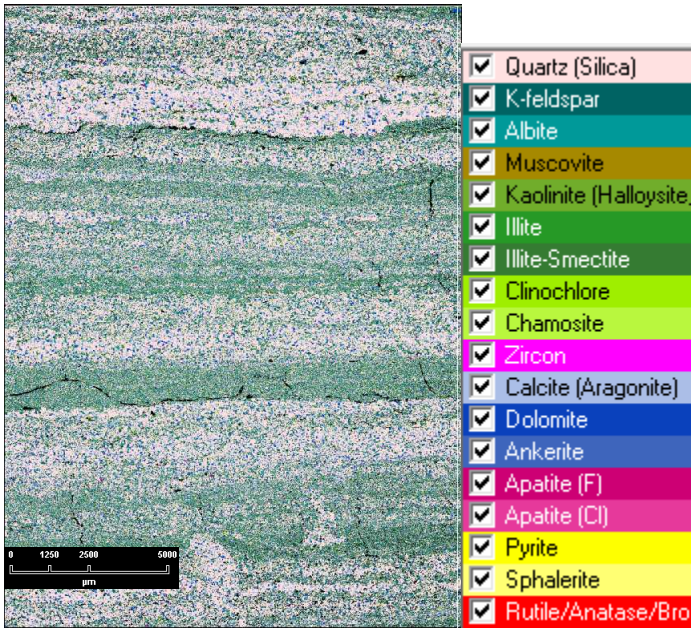
Simulations of Brittle Fracturing

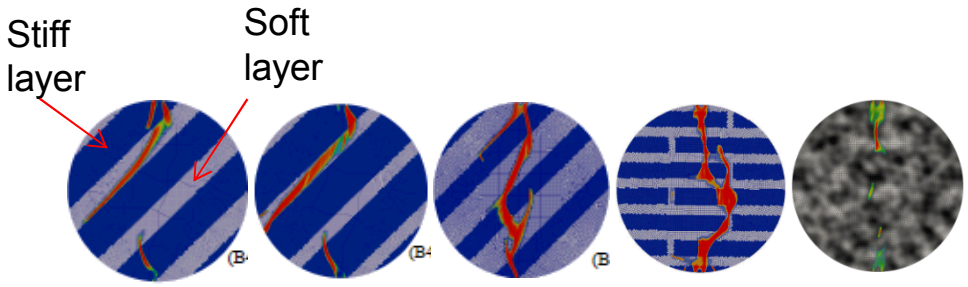
DEAL. Ⅱ Open Source Finite Element Library

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



Tensile strain based on DIC imaging during Brazilian test with Mancos Shale

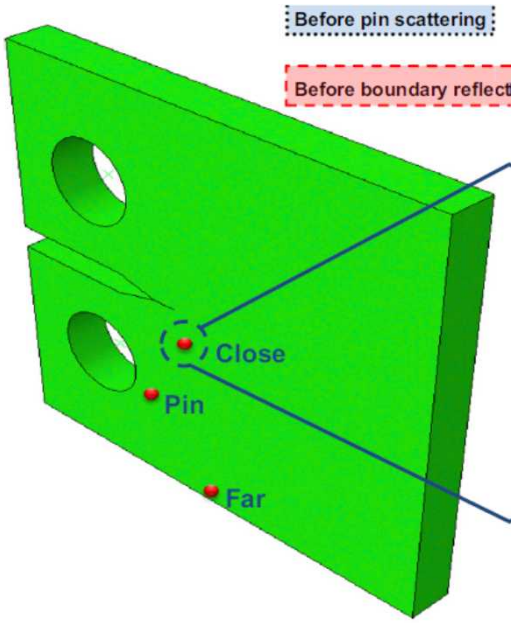


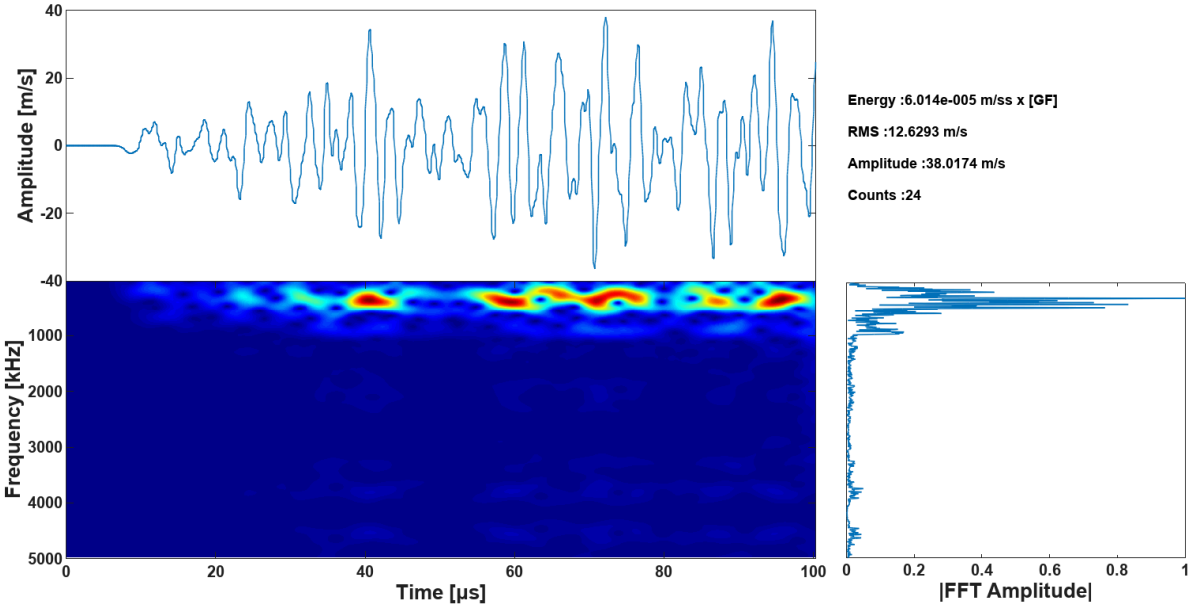


Phase field modeling of crack initiation and propagation under different conditions

Na et al. (JGR, 2017)

AE Simulations





Cuadra et al.
(2015, J. Sound and Vib.)

- Crack tip simulation: ABAQUS XFEM library for automated crack onset and growth
- FFT results of simulated waveforms and corresponding wavelet analysis

Summary

- Digital rock physics augmented with 3D printing of porous and fractured structures has a lot of potential to advance our understanding of poromechanics

  – Imaged & printed real fractured rock and microfluidic channels for poro-mechanical testing

  – Contact angle and wettability experiments

  – Mini load frame with laser imaging for in-situ testing

  – Gypsum power based samples with various post processing for mechanical testing with geophysical sensing

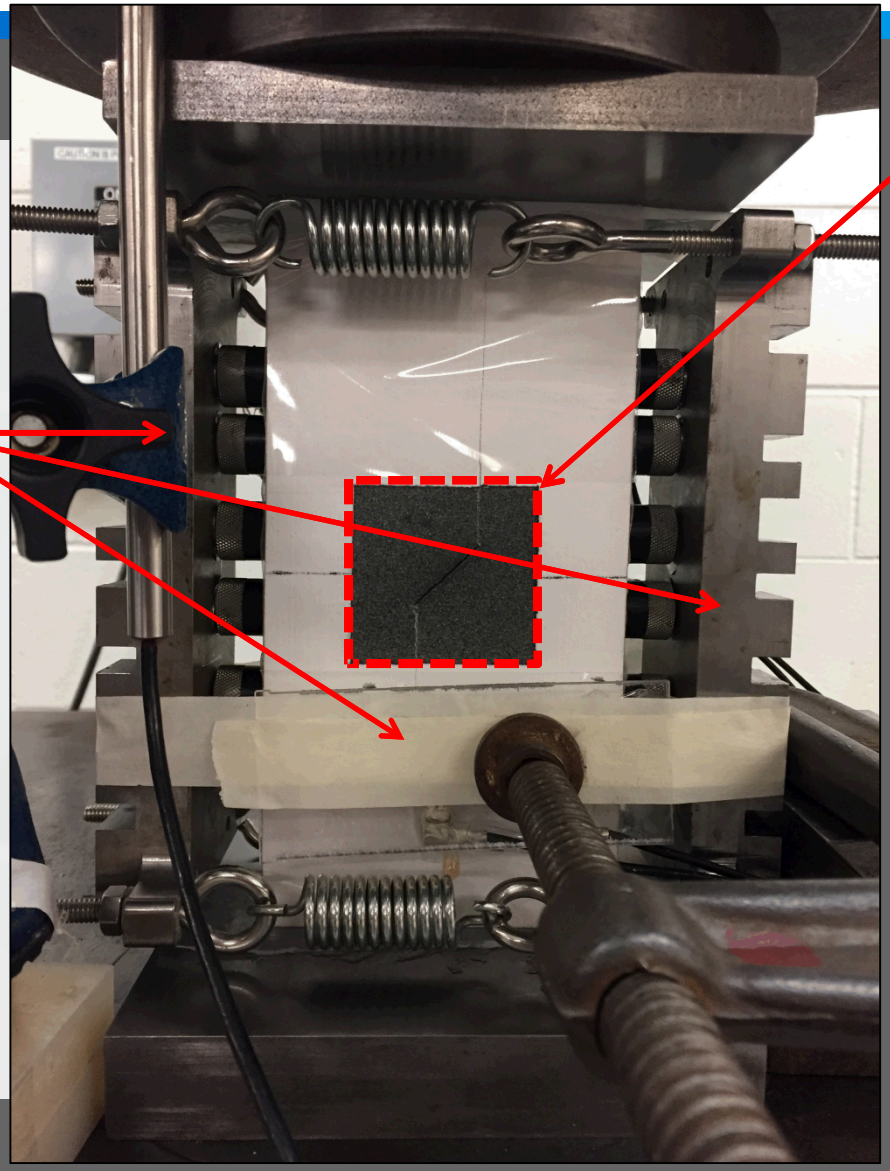
  – Negative printing (e.g., mold) with other materials (ceramics, gypsum)

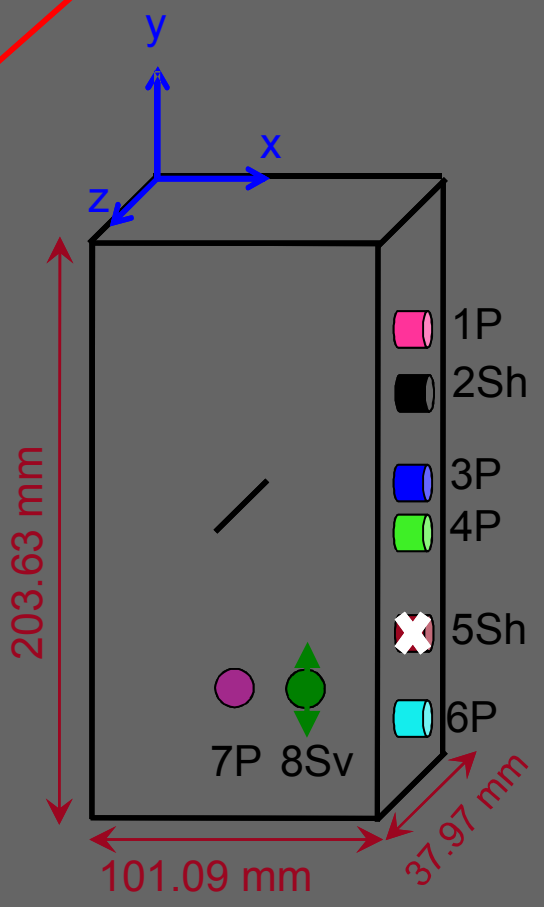
Back-ups

Uni-axial Compression Loading

DIC - region

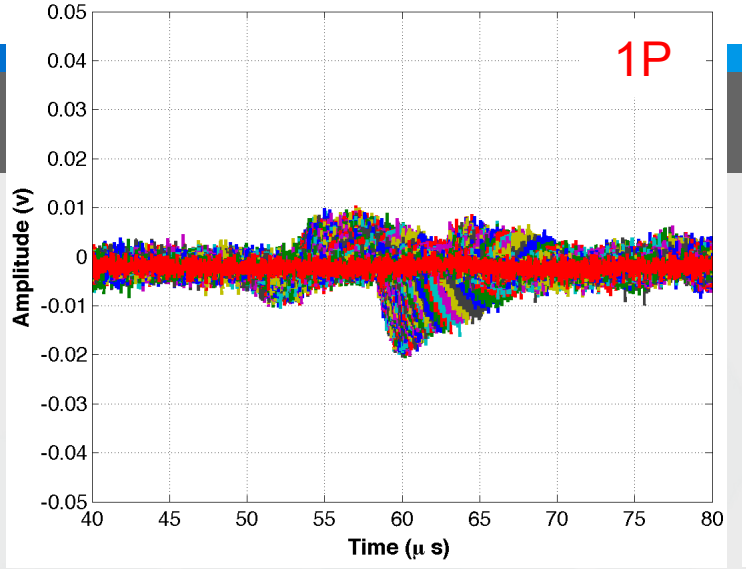
Transducers:
Linear Array

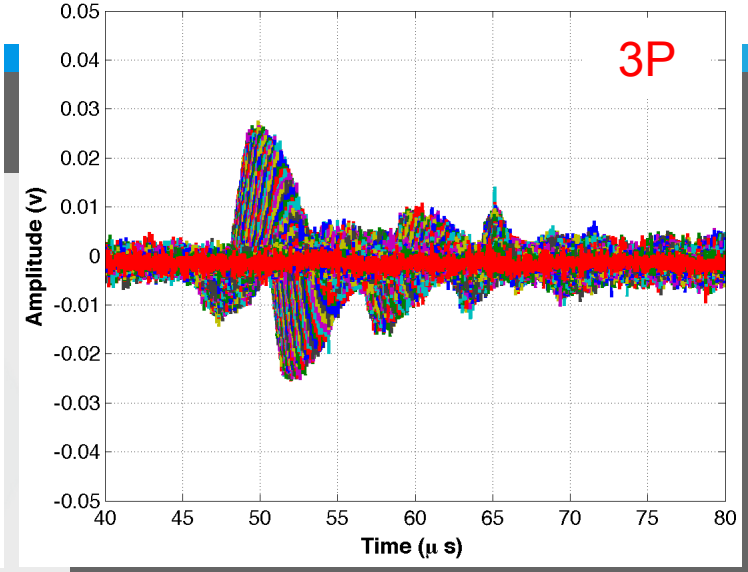


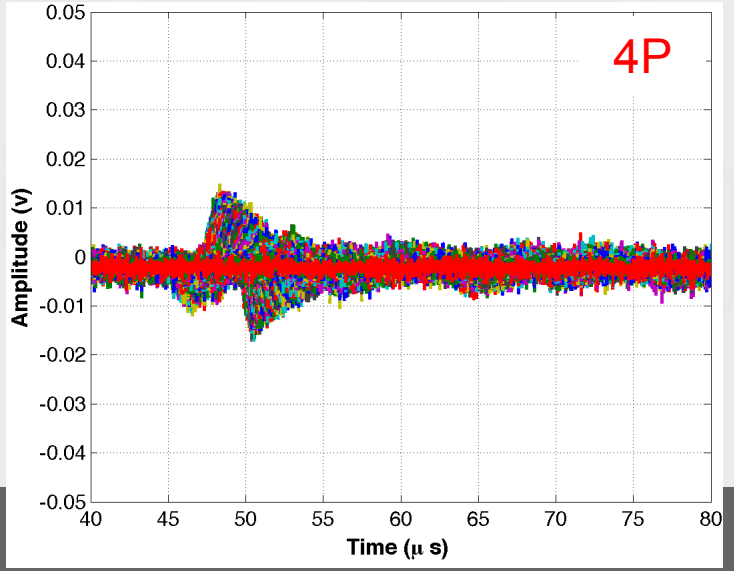


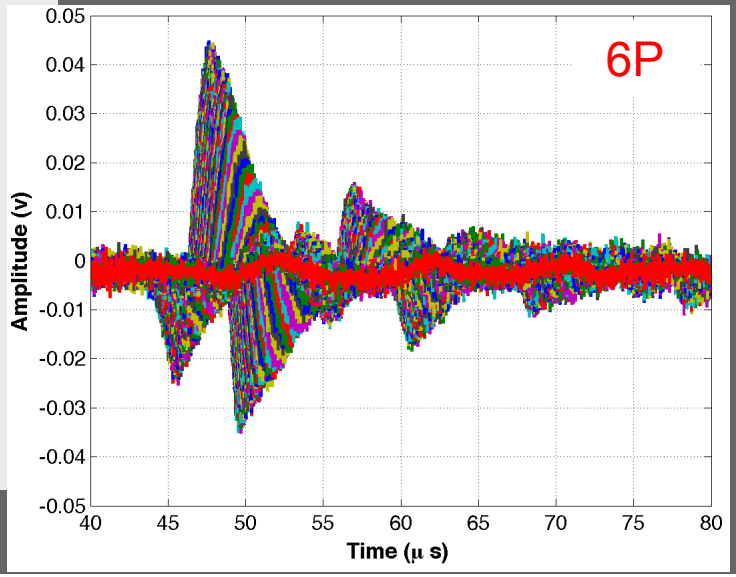
Only showing source transducers

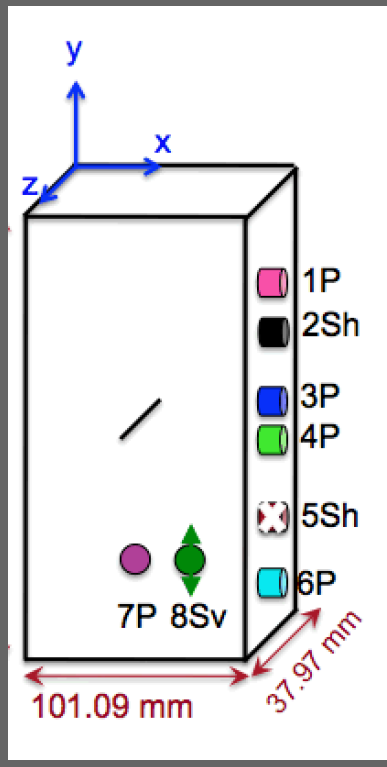
Transmitted P-Waves during Uniaxial



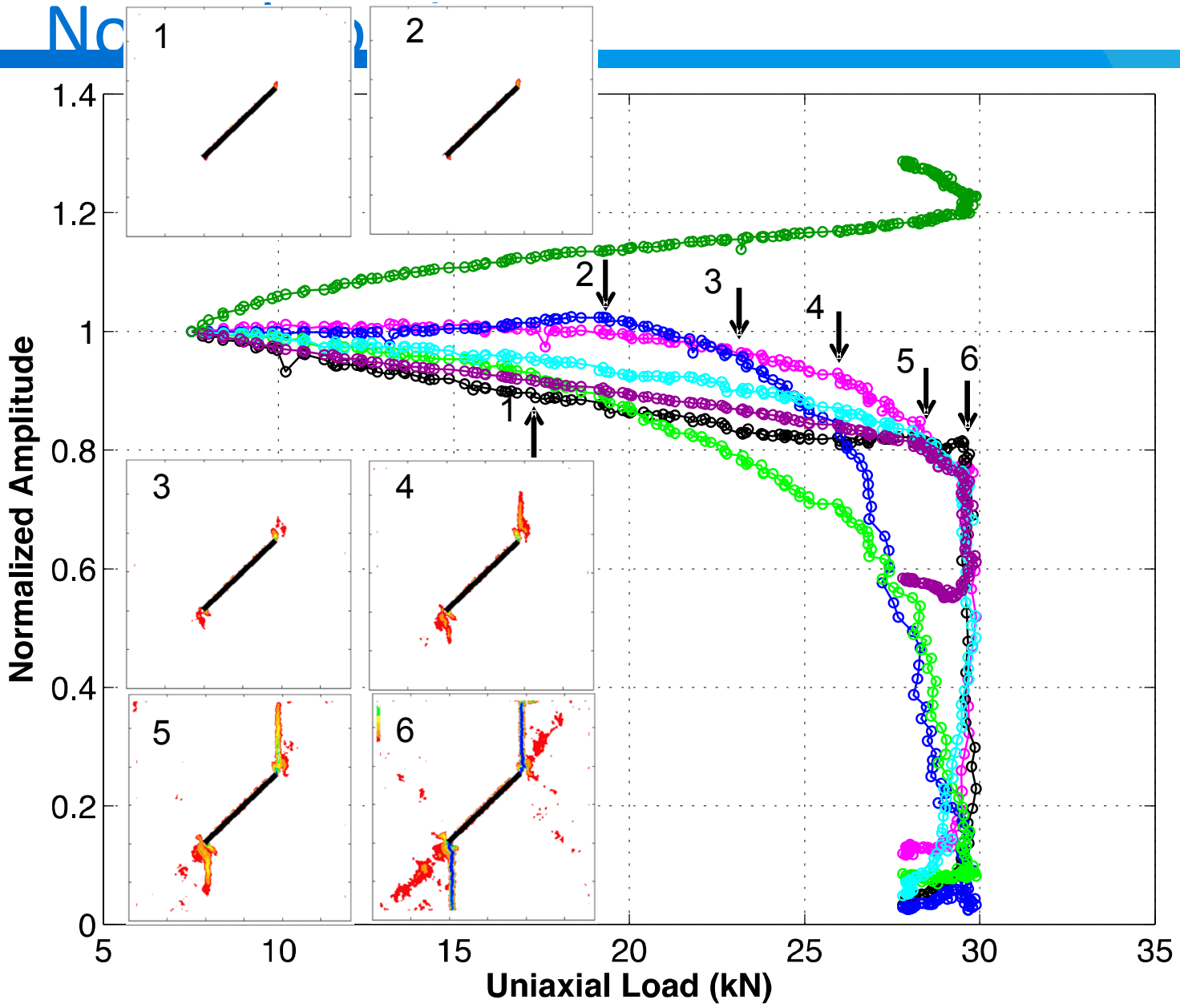


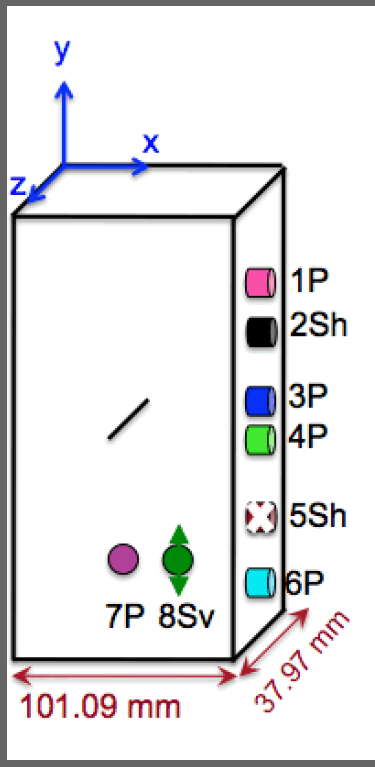






Normalized Transmitted Amplitude vs. No



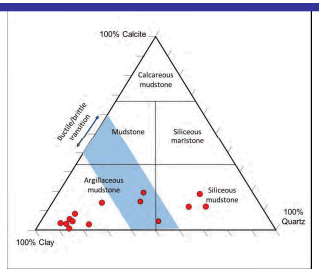


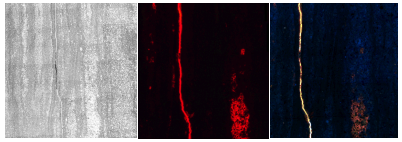
Multiscale characterization of physical, chemical, and mechanical heterogeneity of geomaterials

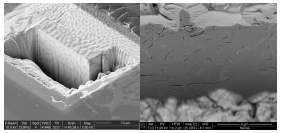
Macroscopic and microscopic lithofacies (optical petrography)

Optical and Confocal Microscopy

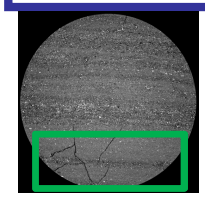
Focused-Ion Beam & Broad-Ion Beam for milling

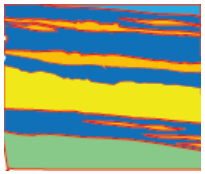


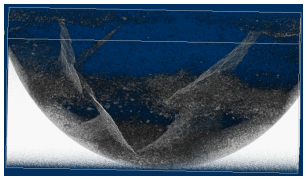


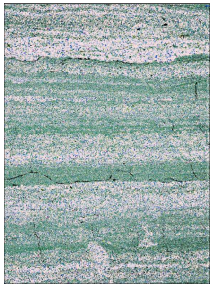


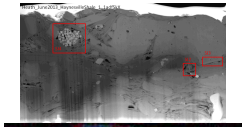
3D multiscale microCT
X-ray probe and MAPS Mineralogy

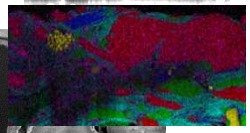


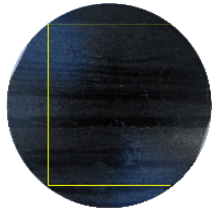












SEM, AC-STEM, EDS

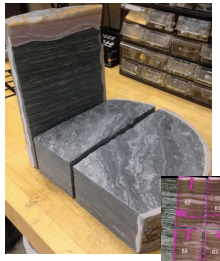
Electron Microscopy

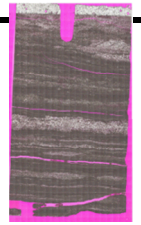
1 m

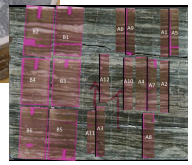
1 0^{-3}m

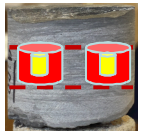
1 0^{-6}m

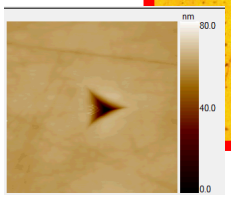
1 0^{-9}m

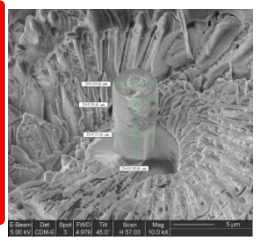


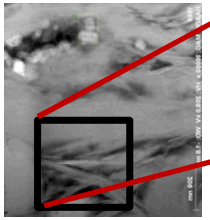


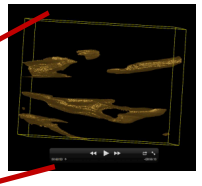




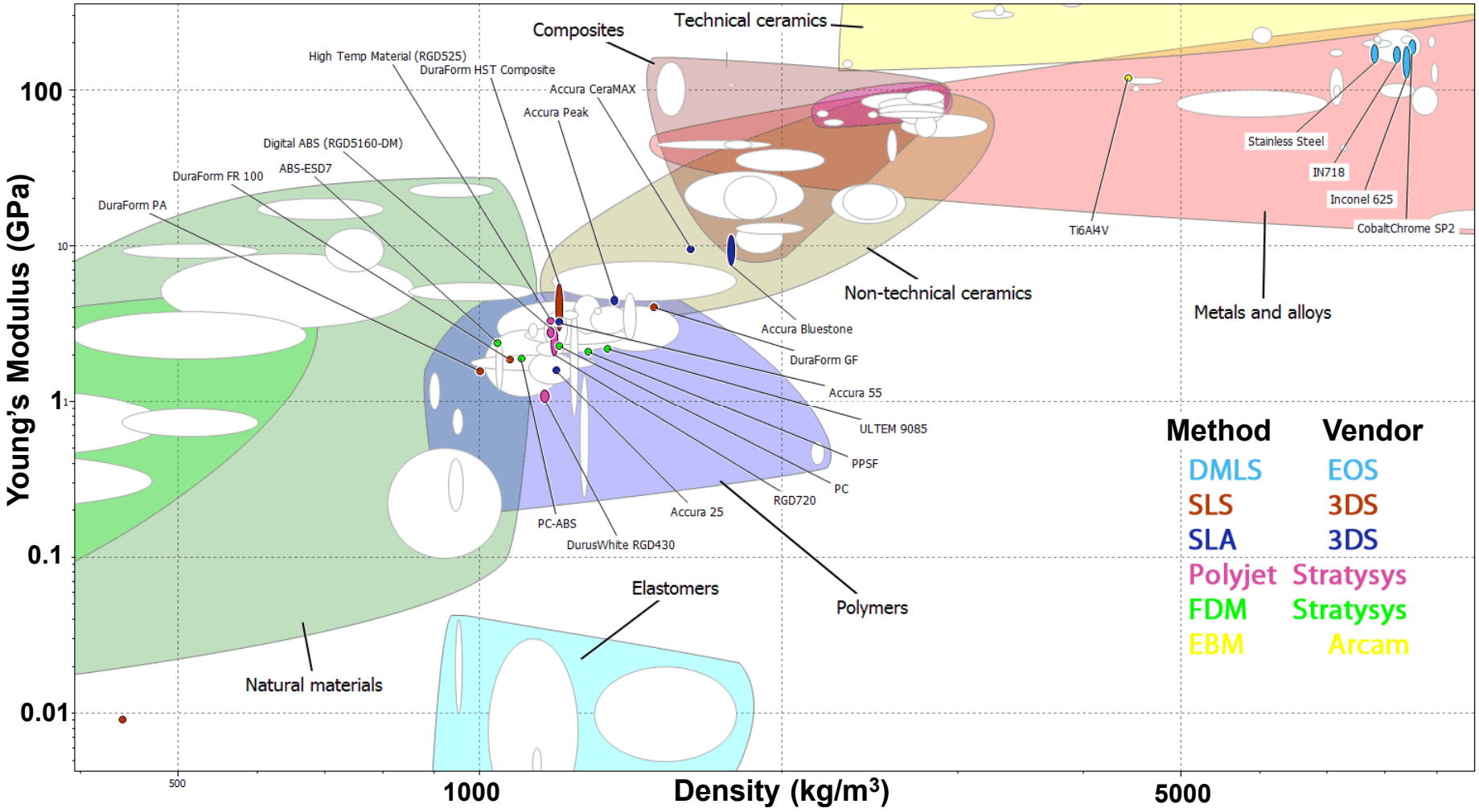








Material properties for 3D printing



Randal Schubert, HRL Laboratories @ 2013

Process Limits with synthetic geomaterials

- ❑ “Completion” is casting (not machining), so reproducibility and finish is not consistent
- ❑ Less flexible with pore structures/complex geometries and printing practices (support structures, powder removal, overhangs)
- ❑ Printing resolution limits
- ❑ Additional post processing

Particularly with pore structures

- ~100μm and ~500μm features with plastic materials and powder/granular, respectively
- Pore to part ratio limits and layering features

1) Binder: type (viscosity, adhesiveness) and amount, droplet size and speed
2) Powder: physical (particle size) & chemical properties
3) Printing layer thickness, direction
4) Post processing: Chemical (Adhesive infiltration) and Physical (heating)