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3D Printing and Digital Rock Physics for Geoscience Applications

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Exceptional service in the national interest

GSA 2016 Annual Meeting

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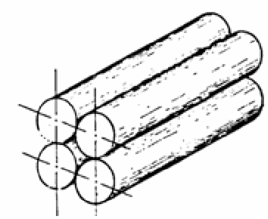
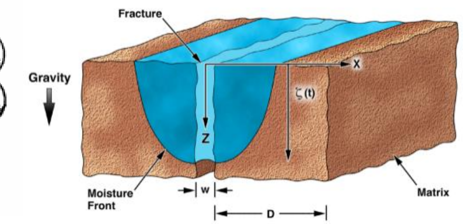
Outline

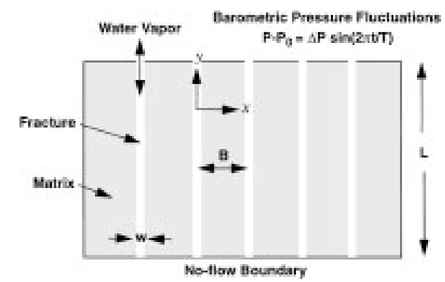
- Our motivation for 3D printing & Digital Rock Physics (DRP)
  - KEY → mesoscale to macroscale
- Digital rock physics overview and issues
  - DRP helps deal with heterogeneity, multiscale
- Digital rock physics schema can be advanced via 3D printing
- A workflow coupling 3D printing and DRP for Geosciences
- Science challenges that can be addressed
- Additive manufacturing (3D printing) overview
- 3D printing for geosciences

Shortcomings of current understanding of poromechanics

- Models of poromechanics and multiphase flow in fractured rock are based on simplistic porous texture, e.g. bundled capillary tubes, 2D slot fractures or penny-shaped cracks.
- Current understanding of poromechanics "smears" the effects of pore-scale structure
- Applicability of spatially averaged "cubic law" and Biot effective stress concepts in fractured media, and coupled effects on flow paths is poorly understood.
- 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.



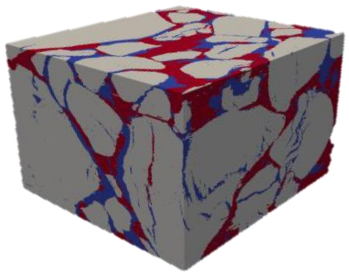




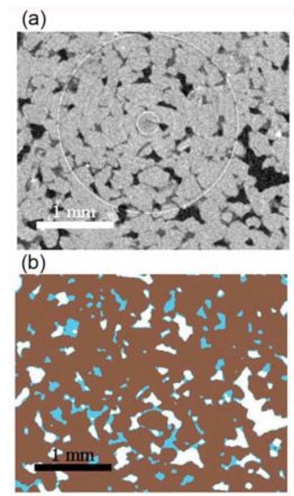
Martinez, 1999

Venerable conceptualizations of porous media

Real porous microstructure



Li-ion electrode



Iglauer et al 2011

Sandstone

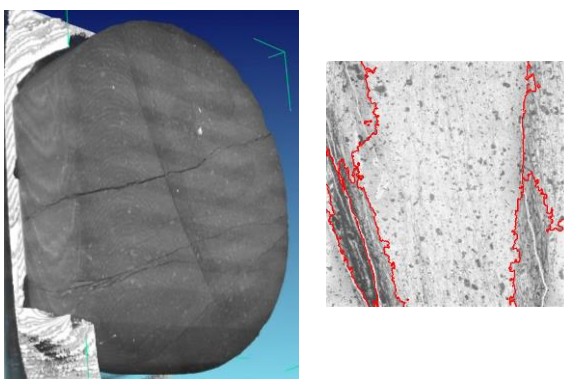
3D printing application for geosciences

- Develop methodology to connect pore-scale structure to macro-scale behavior to advance constitutive models for poro-hydro-mechanics of fractured rock
- Develop methodology for additive manufacturing of synthetic media that mimics natural media and enables creation of custom/functional porous material a potentially disruptive technology for geosciences
- Method to test material response independent of pore structure variability

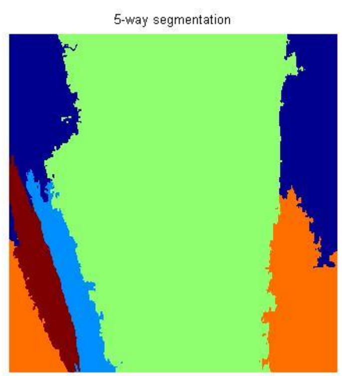
Workflow for Digital Rock Physics

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

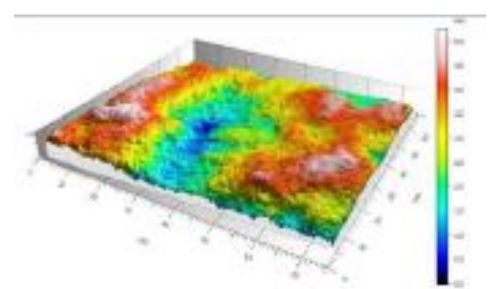
- DRP can help us characterize and understand the role of heterogeneity and multiscale aspects of porous geologic media
- Multiscale imaging can support upscaling



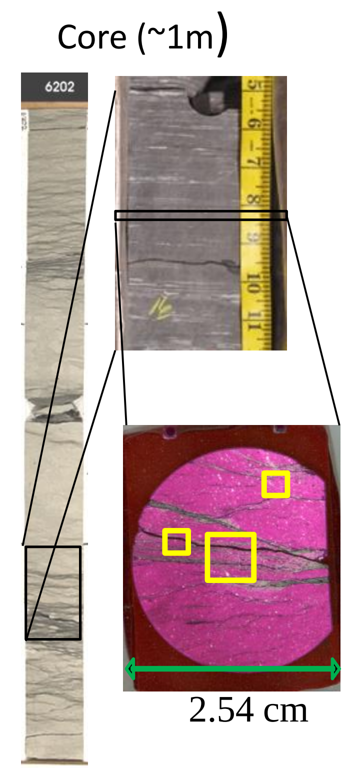
Multiscale Imaging



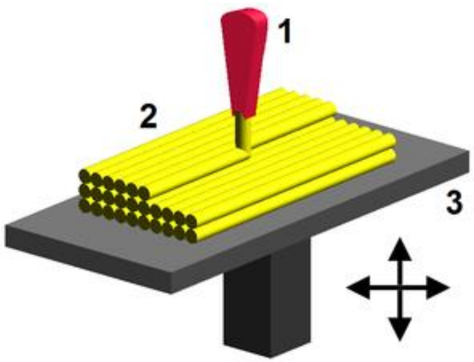
Multiscale Features



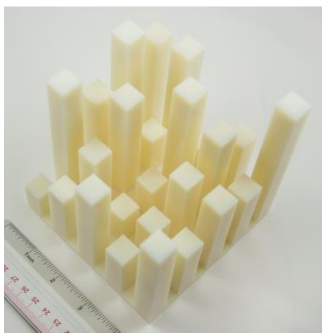
Topological Analysis

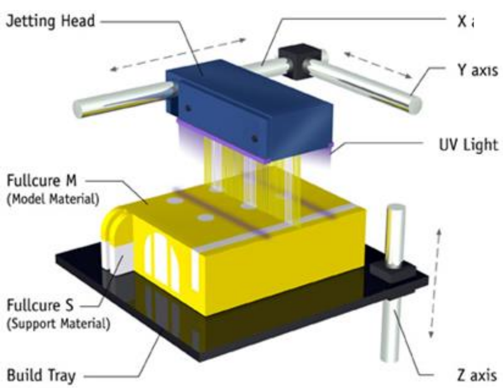


Representative 3D Printing Process Categories

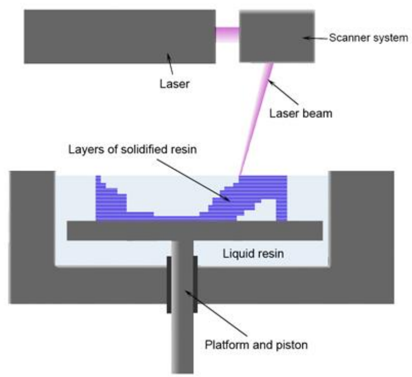


"Fused deposition modelling", Wikipedia

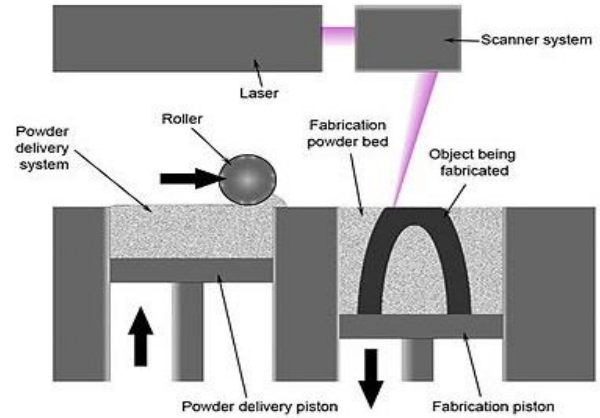




Objet material jetting, www.me.vt.edu



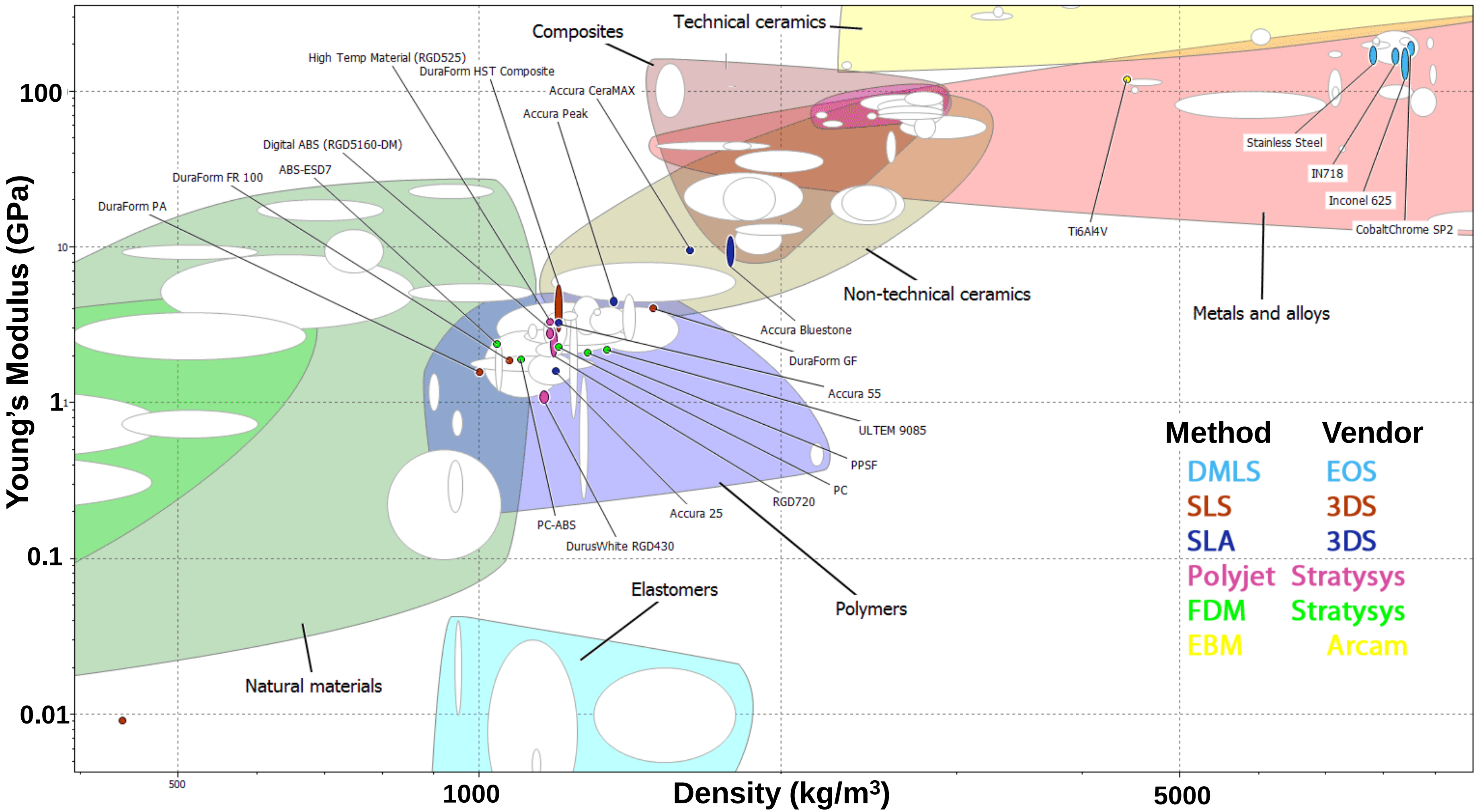
"Stereolithography", Wikipedia



"Selective laser sintering", Wikipedia

- 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

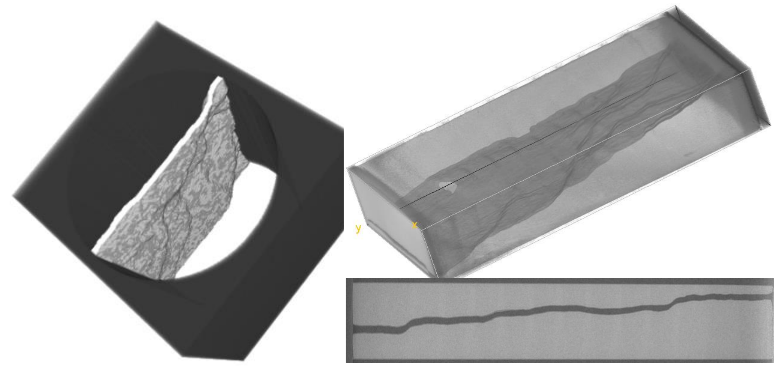
Material properties for 3D printing



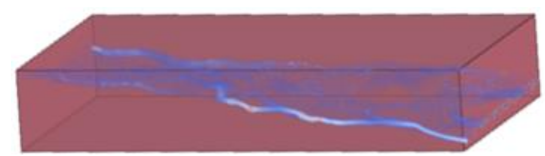
Randal Schubert, HRL Laboratories @ 2013

Single Fracture Printing and Analysis

- Two sets of micro-CT image stacks at different resolutions for a single fracture system
- Fractures printed with clear plastic materials and gypsum
- Printed fracture network was scanned using microCT at 12 microns resolution
- Feature-based image interpolation technique (e.g., SuperResolution) will be tested with two image sets
- Single fracture system will be tested for coupled hydro-mechanical relations



(Left) microCT Image of fracture (@38 and 59 μm)
(right) microCT image of printed fracture (@12 μm)



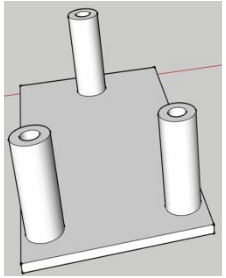
Lattice Boltzmann simulation flow field

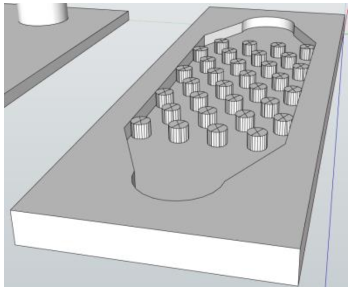
3d printed single fracture network (left), fracture aperture (middle), fracture with gypsum (right)

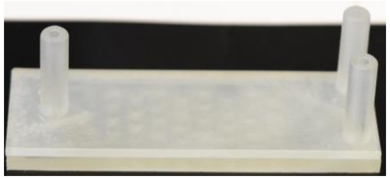
Yoon, Martinez, Ingraham, Dewers (In prep), 3D printing applications for a single fracture system

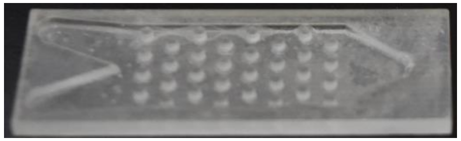
Micro pattern designs

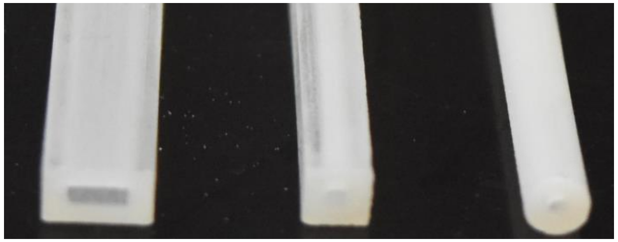
- Design of various pore structure and capillarity patterns
- Enclosing system with Inlet and outlet (either printed or commercially available parts)
- Different parts (e.g., top and bottom parts) are printed separately and assembled and each unit is printed together
- Some natural materials will be filled with patterns for reactive transport experiments
- Wettability and surface roughness of printed products will be evaluated thoroughly







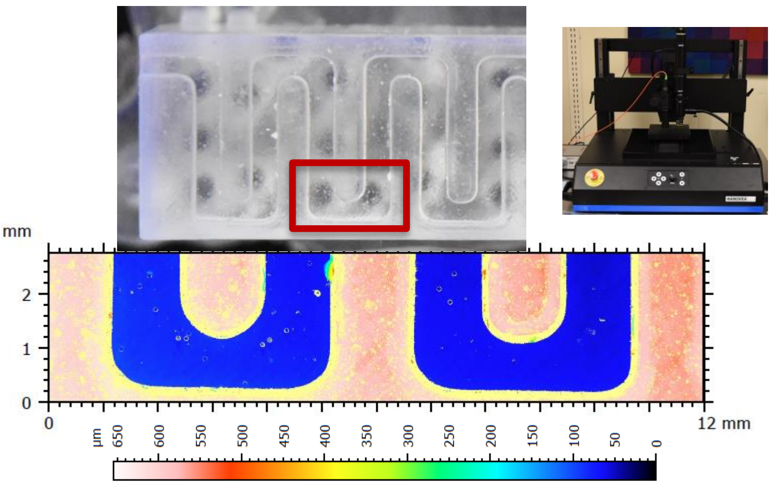




Formlabs Form 1+ & 2

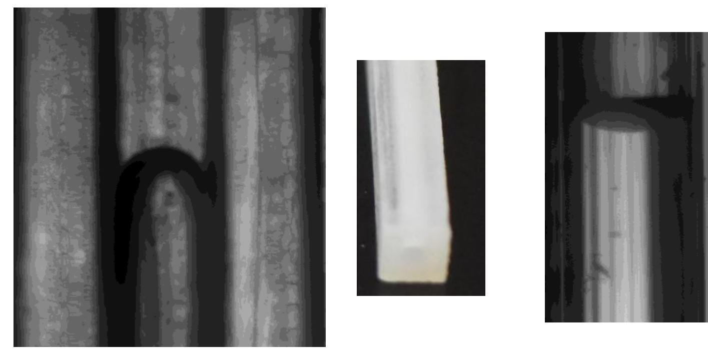
Characterization of Printed Materials

- Surface roughness measured with a new profilometer
- Contact angle measurement
- Wettability will be controlled by various surface treatment methods

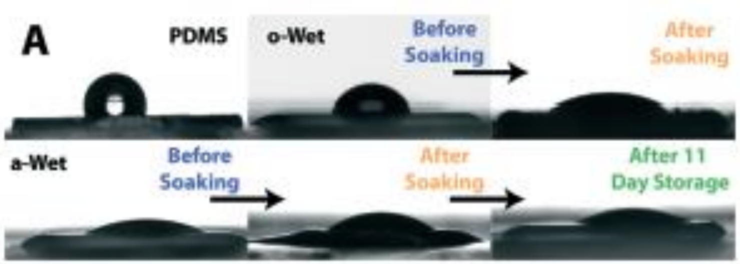


Surface roughness measurement
(~±5µm on flat surface, ~±50µm on rough surface)

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



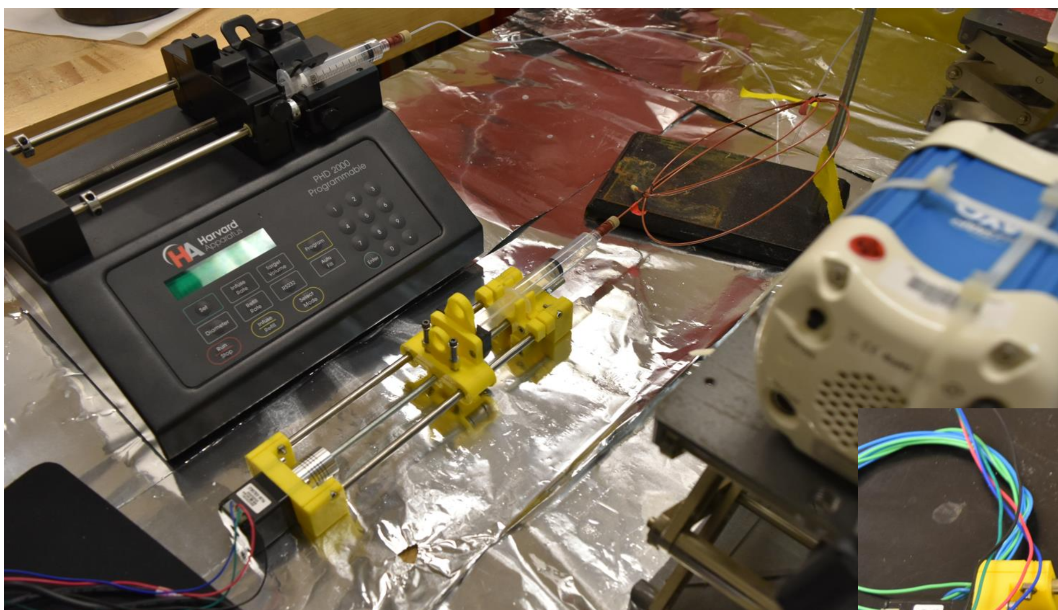
Contact angle measurement
Left: non-wetting on printed channel (middle), and wetting contact angle on glass capillary

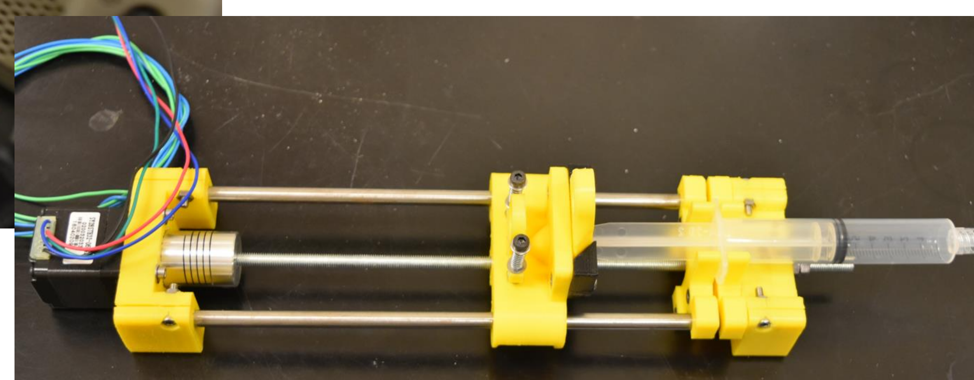


Water contact angle measurement of surfactant functionalized PDMS surfaces (Fatona et al., 2015, LOAC)

3D Printed Syringe Pumps

- Modified an open source design of 3D printed syringe pump system (Wijnen et al., 2014, PLOS ONE)
- Pumping rate can be adjusted with motors
- Overall cost of building materials, electronics, and connectors are ~ $100
- Pump and sensor system software can be integrated into a single package so that an entire experiment can be planned and executed from a single interface

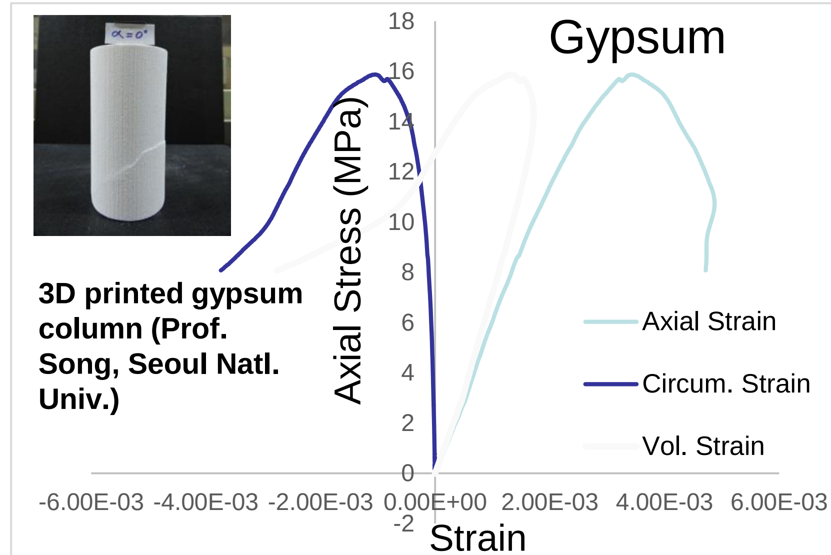




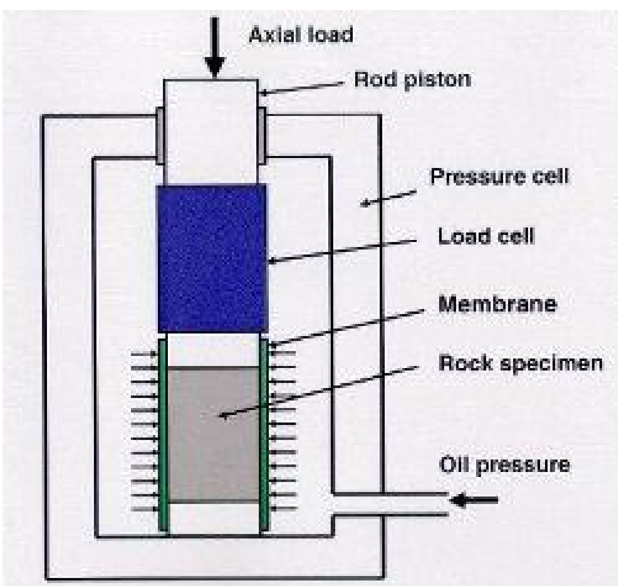
3D printing with Gypsum powders

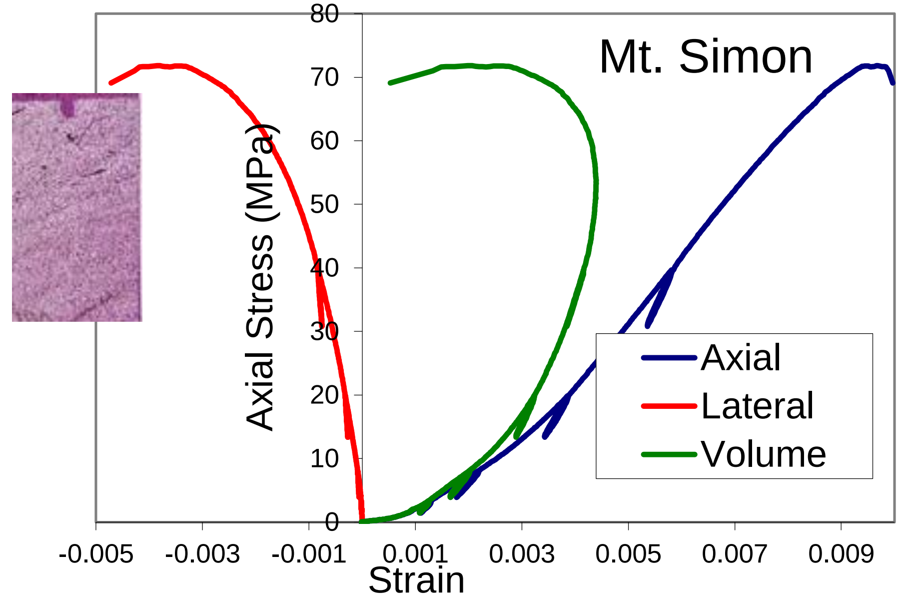
3D printed cores (Gypsum+Binder) behave like geomaterials

- 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”



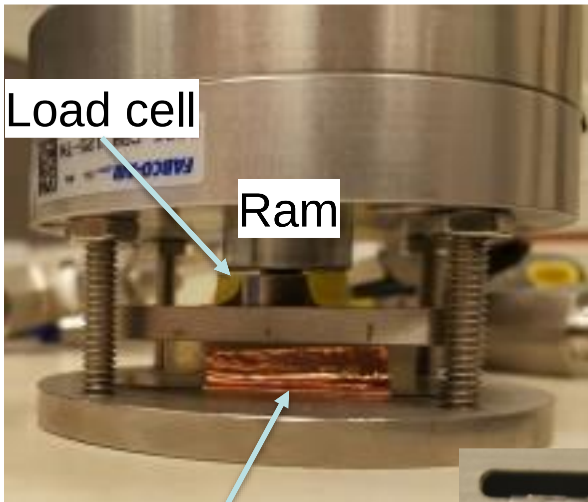
3D printed gypsum column (Prof. Song, Seoul Natl. Univ.)



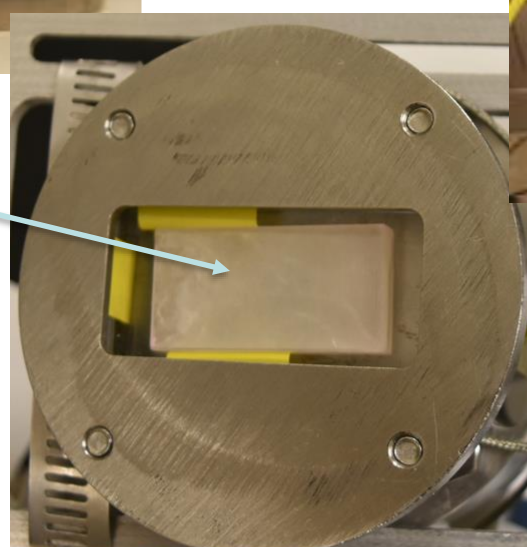


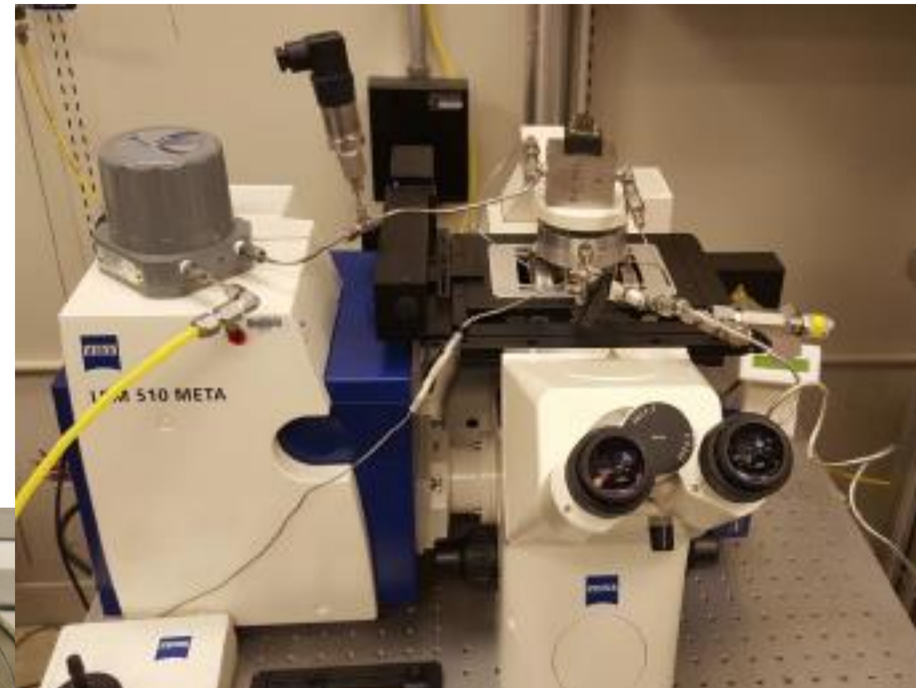
Microscopic measurement of 3D printed fracture constitutive behavior

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

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 poromechanics testing
  - Contact angle and wettability experiments (in progress)
  - Mini load frame with laser imaging is tested (in progress)
  - 3D printed syringe pump systems will be tested with 3D printed structures to demonstrate the applicability of integrated system