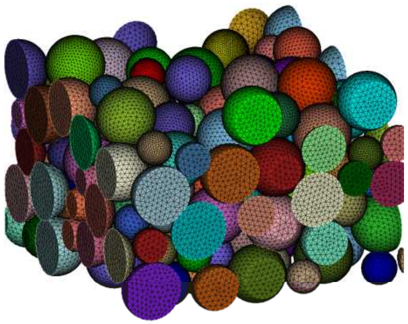
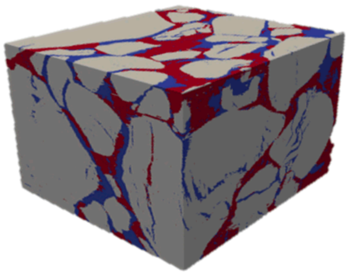
SAND2014-20384C





3D Printing and Digital Rock Physics for the Geosciences

Mario Martinez, Hongkyu Yoon, and Thomas Dewers
Sandia National Laboratories
Albuquerque, New Mexico

December 15, 2014

Sandia National Laboratories

Exceptional service in the national interest

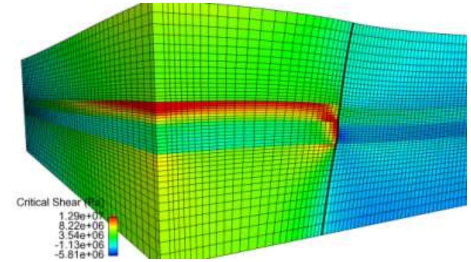
U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

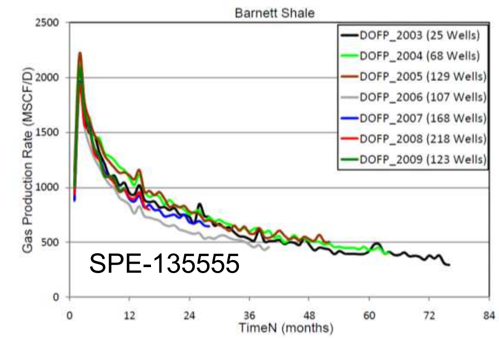
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Research to advance our understanding of geomaterials

- Develop advanced validated constitutive models for geomechanics and multiphas flow that directly impact our ability to predict:
  - aquifer response to injected fluids
  - hydrocarbon production decline,
  - efficiency of subsurface carbon storage,
  - Induced seismicity

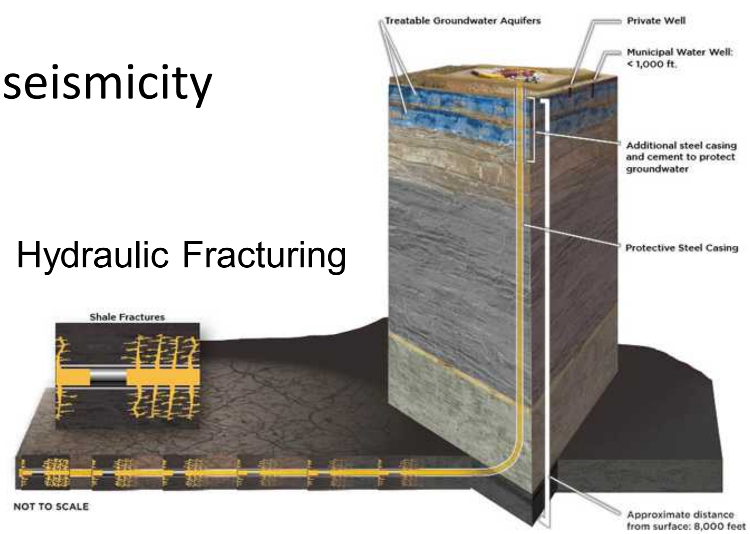


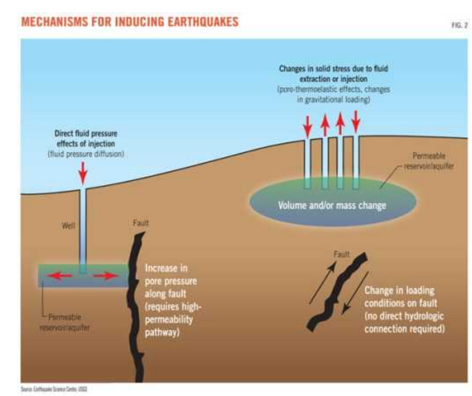
Injection-pressure-induced deformation and shear failure



Production decline

Hydraulic Fracturing

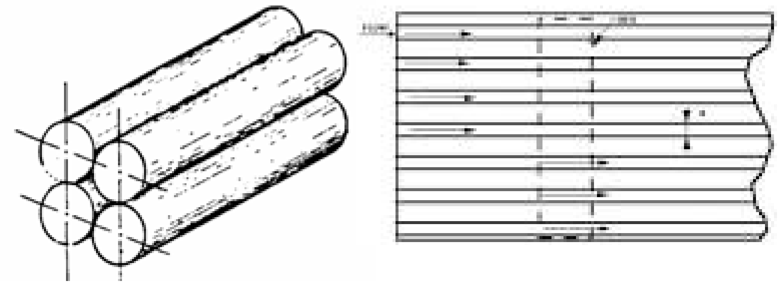




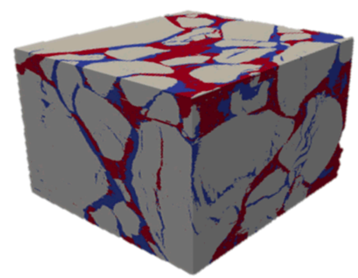
Induced seismicity

Digital rock physics for understanding poromechanics

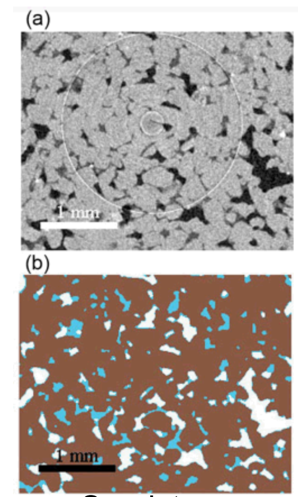
- Models of poromechanics, multiphase flow, and wave propagation are based on simplistic porous texture, e.g. penny-shaped cracks, spherical pores, bundled capillary tubes, and volume-averaging.
- Current understanding of poromechanics “smears” the effects of pore-scale structure (occluded porosity, organic/inorganic pockets)
- Applicability of Biot effective stress concepts in anisotropic media, partial saturation and the effects of plastic yielding can be addressed via digital rock physics.
- 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.



Venerable conceptualizations of porous media



Porous electrode



Sandstone

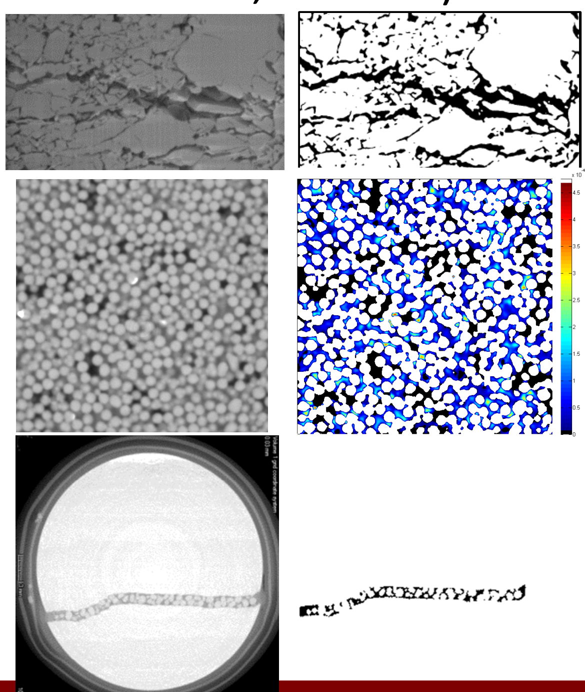
Iglauer et al 2011

Image analysis and digital rock physics has advanced our understanding of porous media

Segmentation Process	3D Digital Rock Construction	Quantitative Analysis

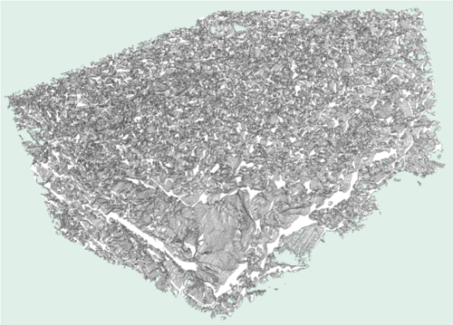
Segmentation Process

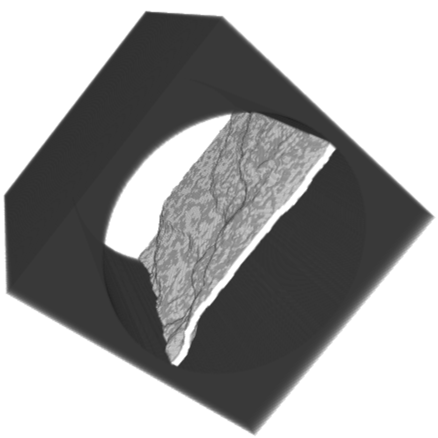
- Alignment
- Enhance contrasting
- Multiple Filtering
- Thresholding
- Post processing (e.g, dilation, erosion)



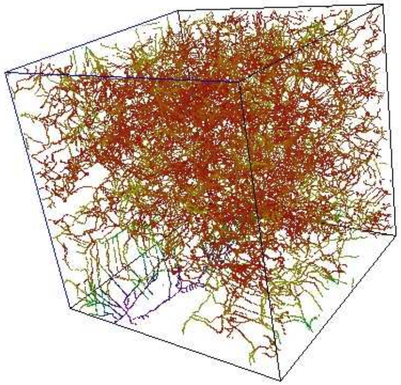
3D Digital Rock Construction

- Binary or ternary pore and fluid distribution construction



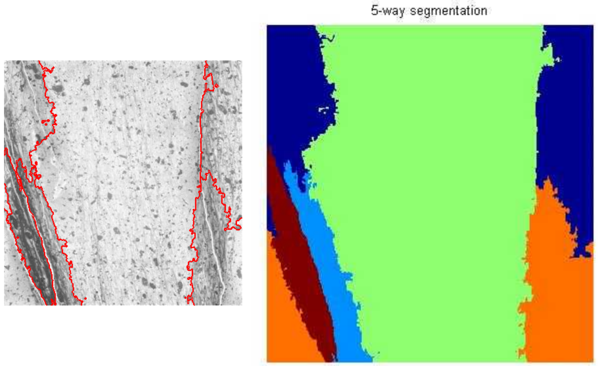


Quantitative Analysis



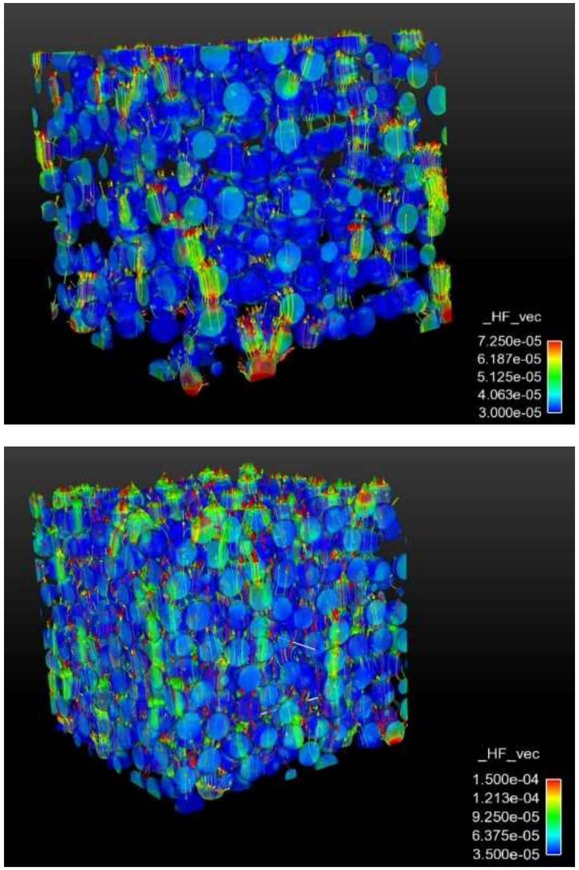
Medial Axis Analysis

Topological Analysis



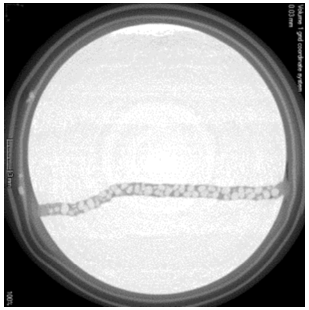
Modeling at the Mesoscale

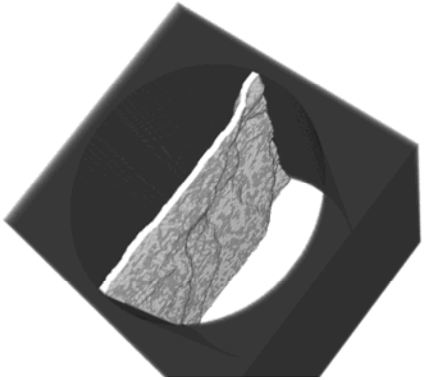
Sierra Mechanics/CDFEM

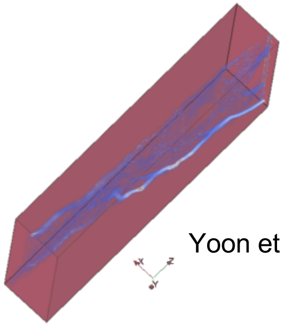


Effective Thermal Conductivity of Particle Dispersions
Jeremy Lechman, SNL

Lattice Boltzmann



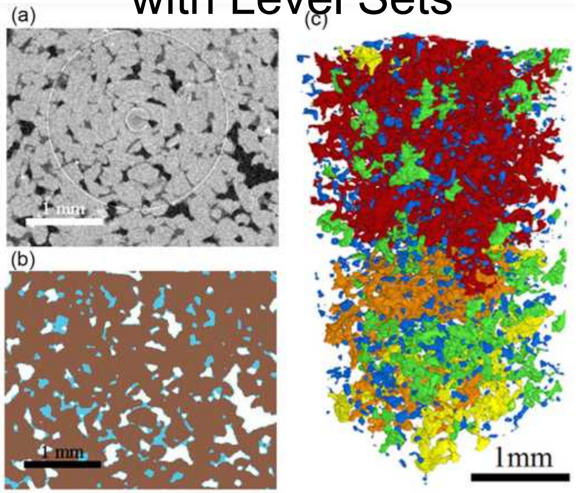




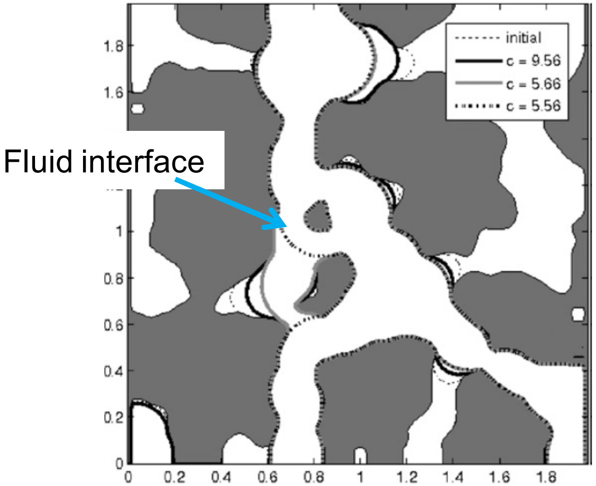
Flow of “frac” fluid in proppant-containing fracture

Yoon et al. SNL

Multiphase Flow with Level Sets



Iglauer et al 2011



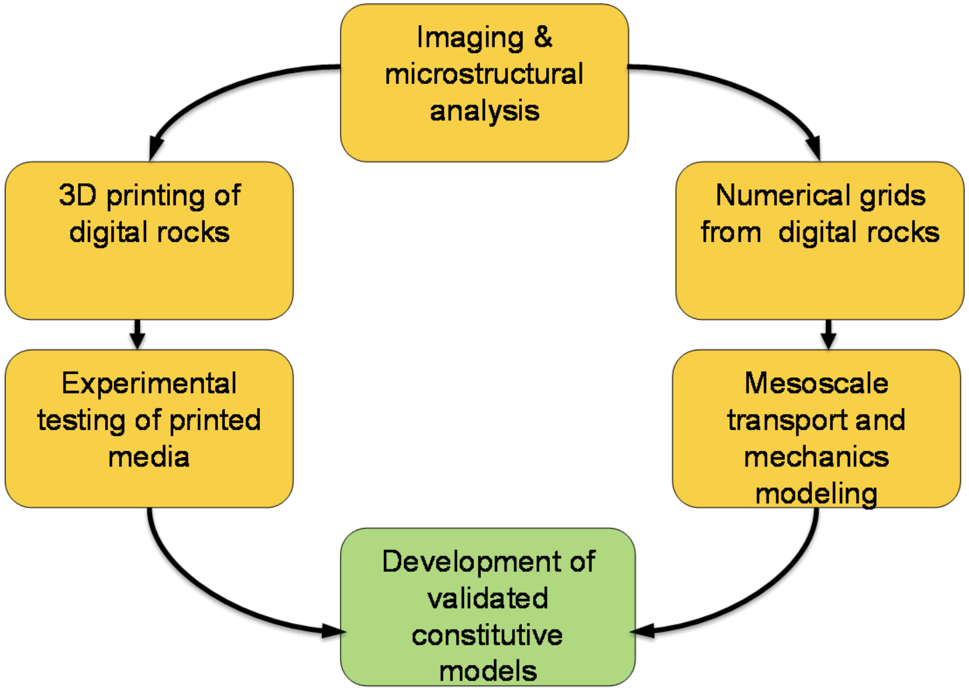
Prodanovic & Bryant 2006

Digital rock schema could be improved with 3D printing

Reproducible synthetic media that mimic natural media, potentially enabling a limitless set of experiments benefiting all manner of scientific research

3D printing enables us to:

- surmount problems with sample-to-sample heterogeneity
- to test material response independent from pore-structure variability
- develop functional porous structures
- print porous specimen with integrated test frame
- addresses issues of scale-up

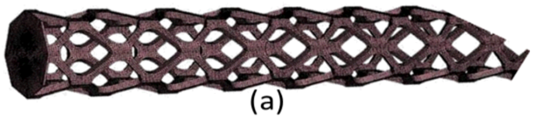


Impact:

- Science-based approach to develop advanced constitutive laws
- Testing and modeling on same pore topologies and materials
- Scale dependence & model validation

3D printing as the "next big thing"

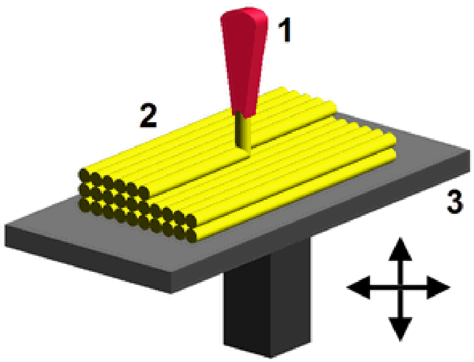
- Additive Manufacturing (ASTM F2792), aka, 3D printing is projected to revolutionize manufacturing – GE Aircraft report "… we are at the dawn of the next Industrial Revolution …"
- State of the Union Address – 3D print-driven manufacturing hub
- National Labs join America Makes (Ref: 3Dprint.com)
- Europe utilizing 3D printing in their nuclear industry
- GE's newest aircraft engine is designed with parts made from 3D printing
- Biomedical – porous lattice metallic implants and prosthetic limbs
- Makerbot (available through Home Depot)
  - Toys, dishes, automotive, electronics, prototype models
- Key benefits of AM
  - Easily and economically build complex geometries with internal features impossible or impractical with traditional manufacturing techniques
  - Parts on demand
  - Adaptive Topological Optimization (shapes optimized for function)



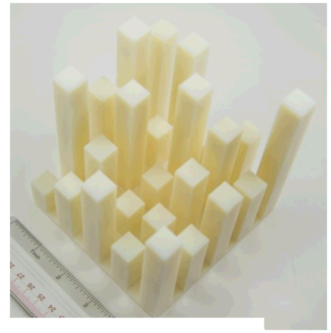
Weight-optimized torsion bar

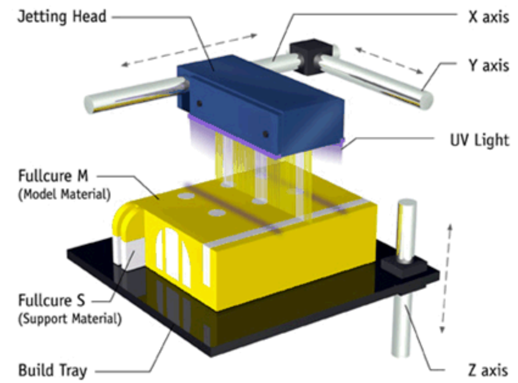
Representative 3D Printing Process Categories

Sandia National Laboratories

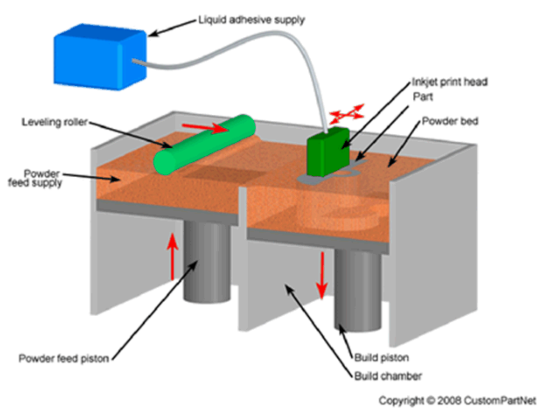


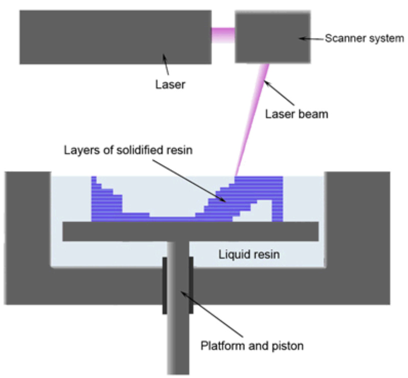
“**Fused deposition modelling**”, **Wikipedia**





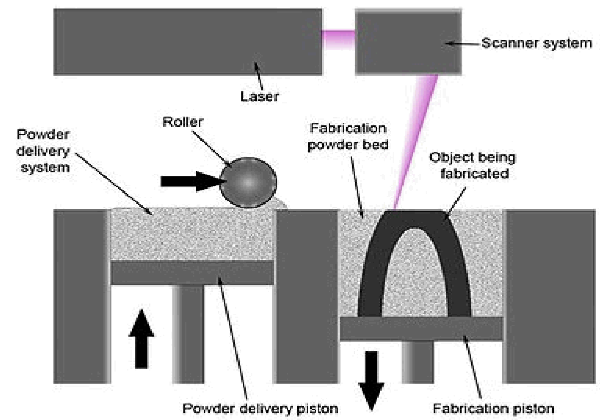
Objet material jetting, **www.me.vt.edu**





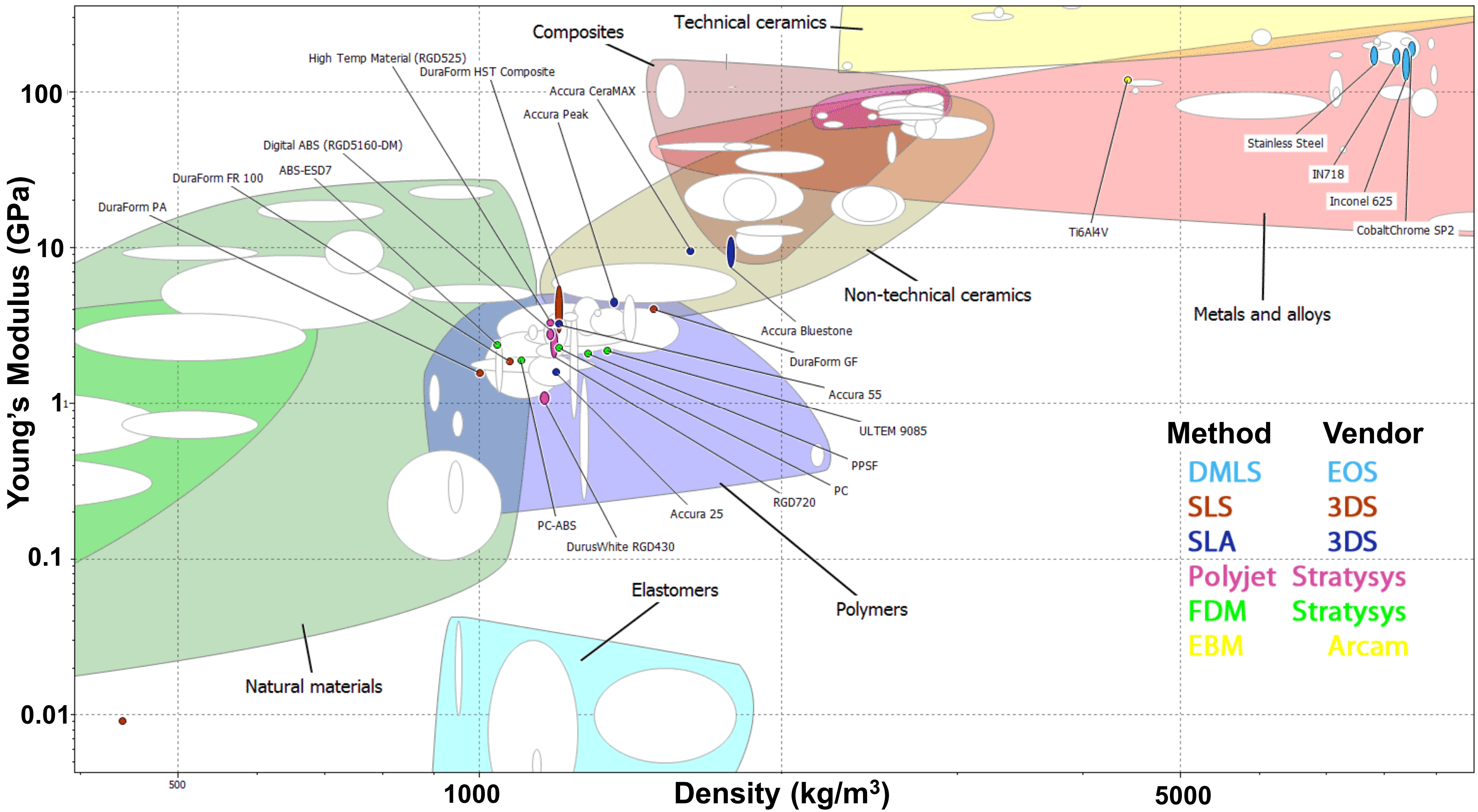
“**Stereolithography**”, **Wikipedia**

Binder jetting, **www.utwente.nl**



“**Selective laser sintering**”, **Wikipedia**

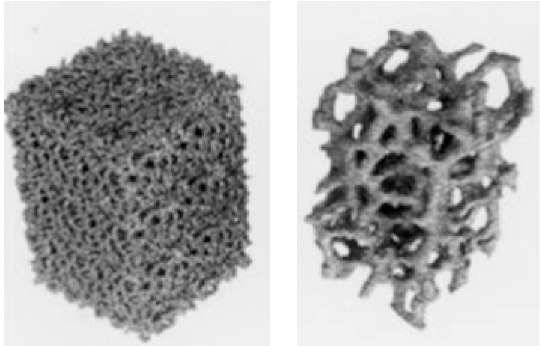
Material properties for 3D printing



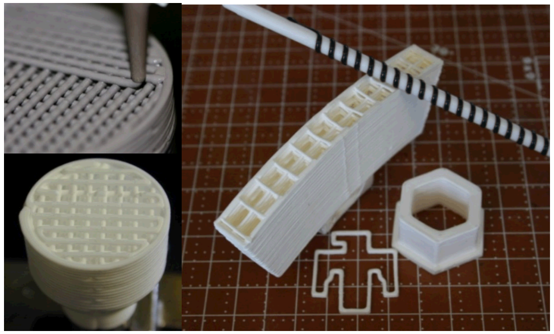
Randal Schubert, HRL Laboratories @ 2013

3D Printing of digital rocks

- Issues
  - Materials & characteristics (brittle vs ductile)
  - Feature size
  - Finish
- Attainable porous structure features:
  - 100 micron (preferably less) pore sizes
  - ~2 cm^3 specimen for testing
  - Wettability manipulation
  - Real pore structures on specimens greater than 1 REV



Metal Foam (UTEP)

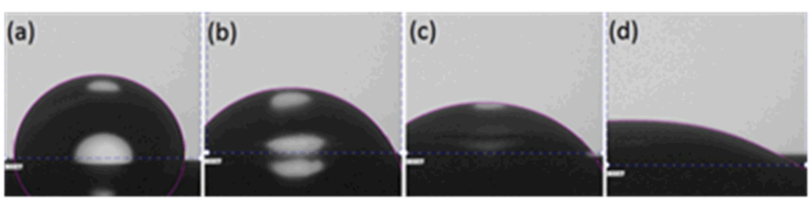


direct write extrusion casting

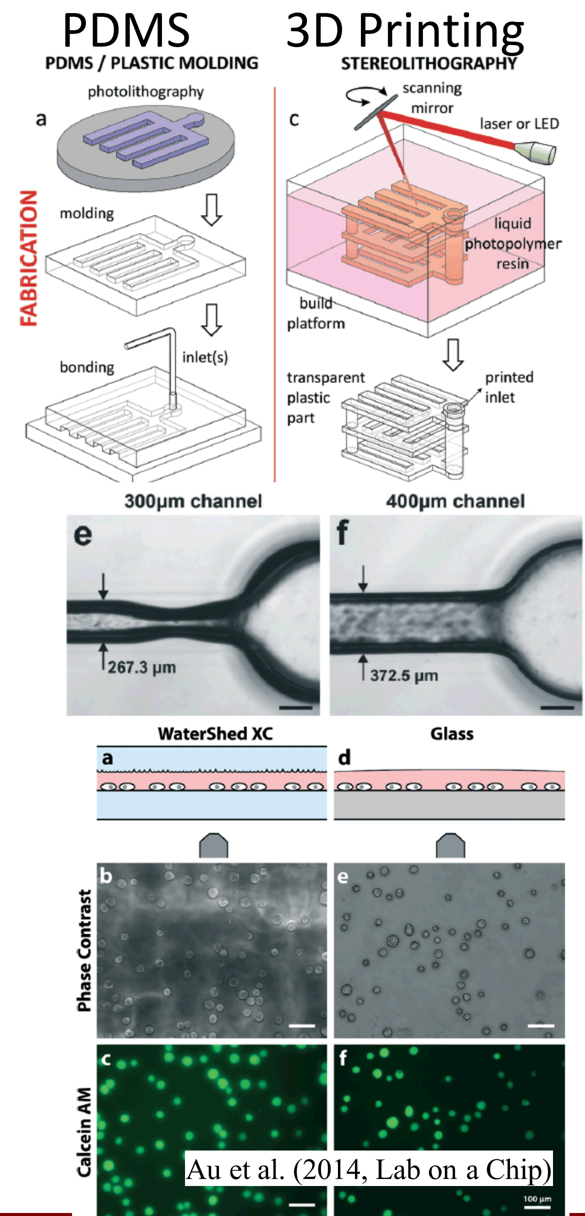
Technology	Materials	Min. feature size (mm)
fused deposition modelling (FDM)	thermoplastics (ABS, PLA, nylon, PC…)	~0.5 mm
material jetting	photocurable plastics	~0.4 mm
laser sintering	metals (SS, Inconel, Al…) ceramics (alumina, Ceramet, WC)	~0.2 mm ~0.5 mm
binder jet printing	gypsum / acrylate	unknown
stereolithography (SLA)	photocurable resins / epoxies	<0.1 mm claimed
direct write	inks, slurries, paste, resins, etc., any material w/1-1x10^6 cPs viscosity	material dependent

Sandia National Laboratories

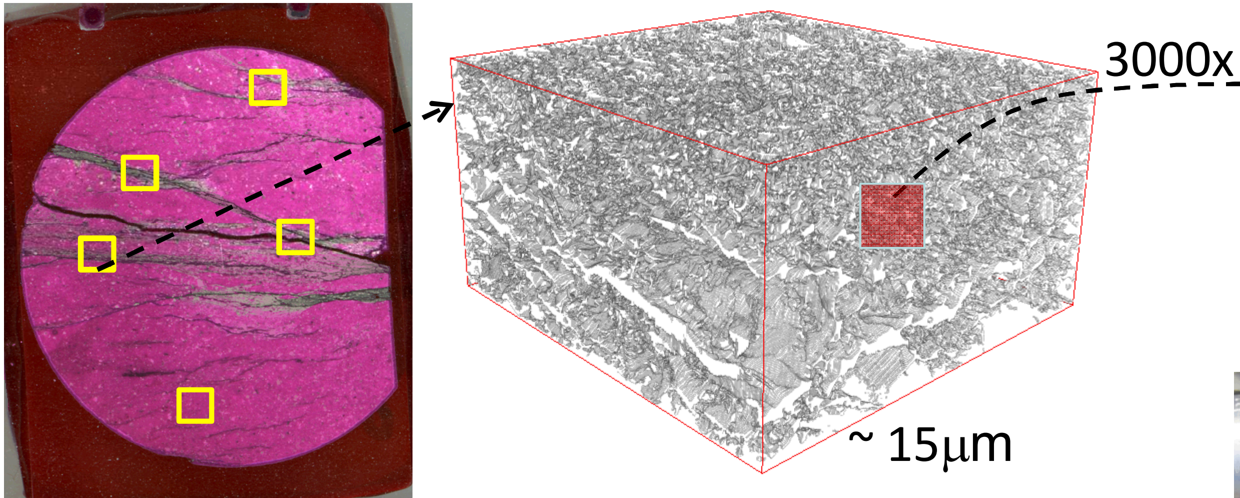
- Stereolithography(SL):
  - Rapid prototyping technique to print in transparent 3D polymer structures from a liquid photopolymer resin with a focused laser or LED
  - Printing resolution at 20-100’s μm corresponding to a minimum channel width of ~200 μm
  - Simplified design processing for complex device
  - Desktop SL 3D printers are available!!
  - Printing on pre-processed surfaces (e.g., biochemically treated or nanopatterned surfaces)
  - Feasibility of imaging
  - Surface wettability can be adjusted after printing

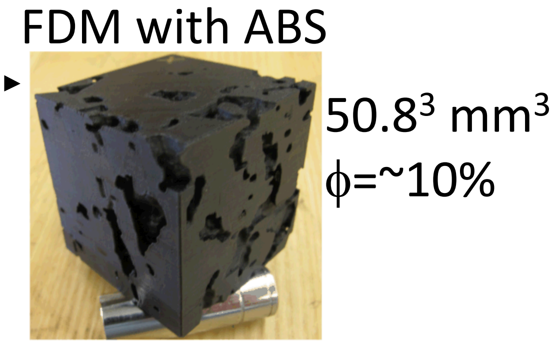


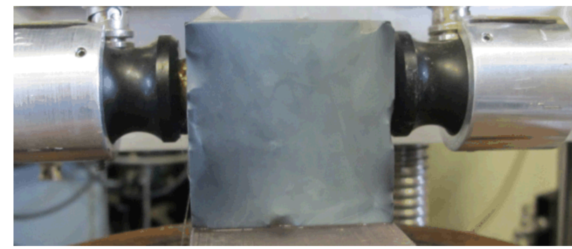
Static Water Contact Angles of self assembled nanoparticles on printed surface with variation of an additive contractions resulting; (a) 93°, (d) 31°.



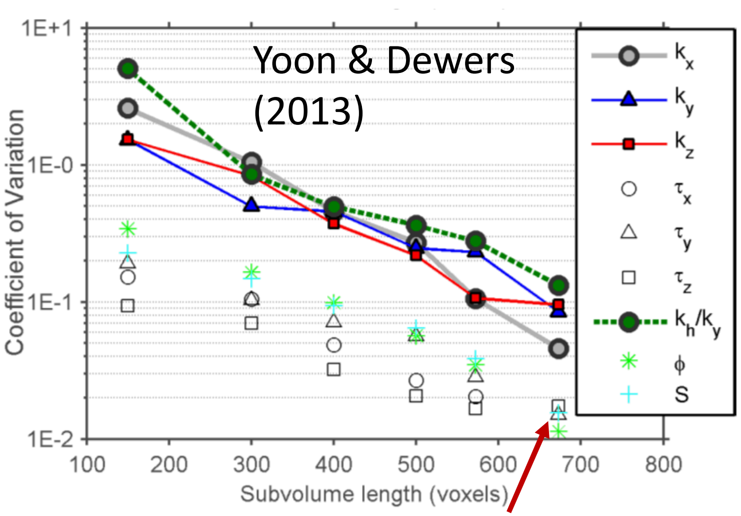
Digital Rock Physics with 3D printing at SNL

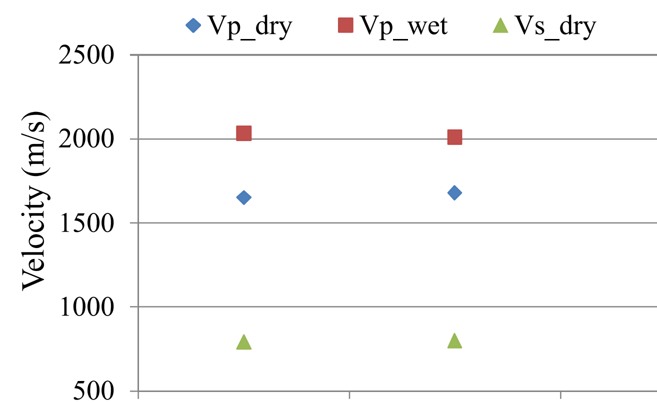






AE testing





FIB-SEM sample volume has a size of statistical elementary volume at ~ 10 μm

Conclusions

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

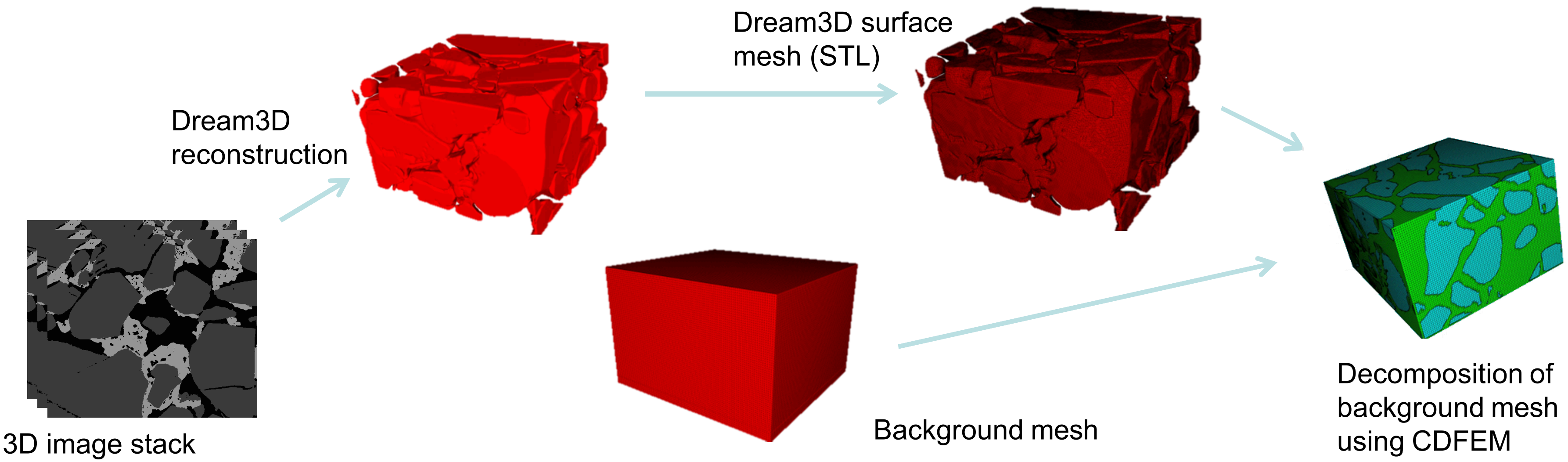
Backup slides

Workflow for Digital Rock Physics

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

Digital rock physics workflow for mesoscale simulation

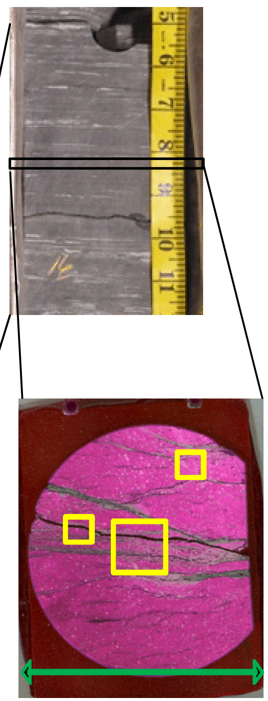
- We utilize both FEM and Lattice-Boltzmann methods, the latter can utilize voxel data directly. The former requires some form of mesh generation
- Despite the availability of commercial software for building grids based on voxel descriptions, the ability to design well-conditioned grids for modeling remains somewhat of an art.



Multi-Scale Imaging (potential for upscaling?)

Characterization of pore structures, surface properties, patterns using various techniques such as optical microscopy, microCT, FIB-SEM, TEM, EDS

Core (~1m)

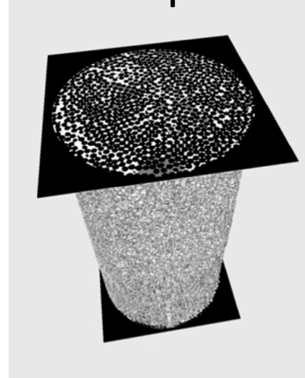


2.54 cm

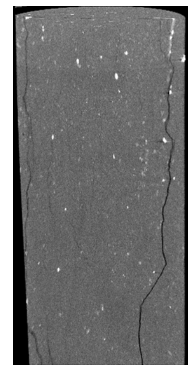
Thin Section

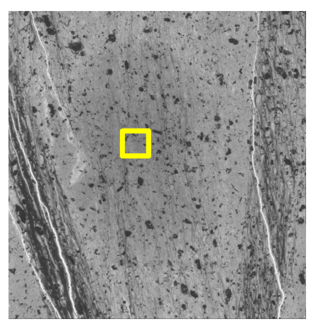
X-ray computed Tomography (CT)

Beads packing

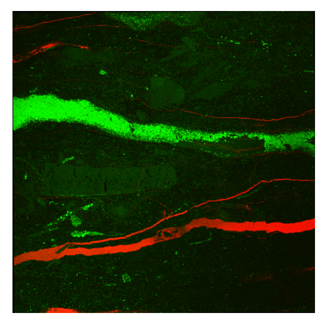


Fracturing





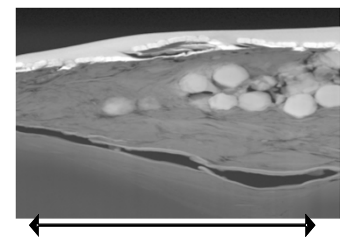
Optical Microscopy



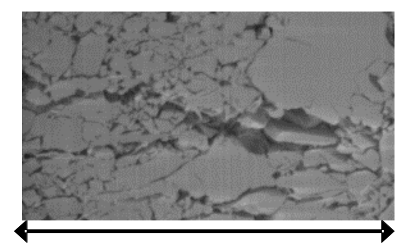
Fluorescent Microscopy

Laser Scanning Confocal Microscopy

TEM/EDS for mineral compositions



5 µm (~1 nm res.)



15 µm (~15 nm res.)

Focused Ion Beam/SEM

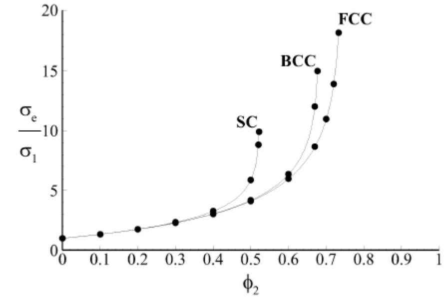
comments:

- Concern about surrogate geomechanical properties of printed media
  - 3D printing of ceramics and/or calcium carbonate (limestone) is possible, and we do not anticipate studying fracture or strain localization, but anticipate heterogeneity and occluded porosity can be studied in REV specimens
- Control of surface properties and whether treatments might weaken printed media
  - Surface properties are important for multiphase flow configurations; we would use treatments (vapor deposition) to minimize interactions with printed material
- How will upscaling be tackled?
  - Tests and models performed at various scales will be combined for application of response function approach, utilizing Dakota optimization technology on multiple model realizations
- How is large strain going to be modeled with Lattice Boltzmann?
  - Mesoscale and macroscale flow models will utilize LB and Sierra; Mesoscale and macroscale geomechanical models will be performed with Sierra Mechanics or ABAQUS
- Suggested starting with idealized porous structures
  - We've discussed this as a potential risk mitigation strategy

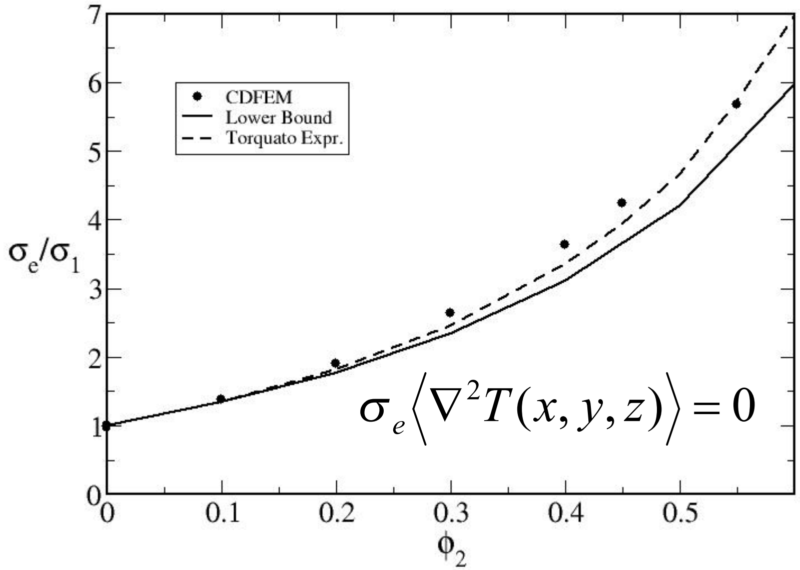
Sierra Mesoscale Example:
Effective Thermal Conductivity of Particle Dispersions

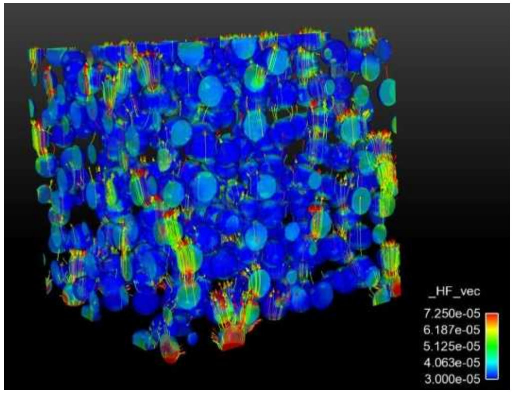
Sandia National Laboratories

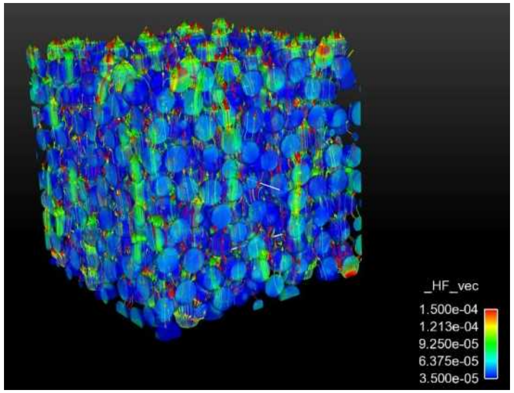
- Verification of CDFEM for Average thermal conductivity in static random dispersions
  - Particle configurations taken from Brownian Dynamics Simulations of Repulsive Colloids
  - Suspending fluid insulating, particles conductive (ratio of conductivities ~ 1000)



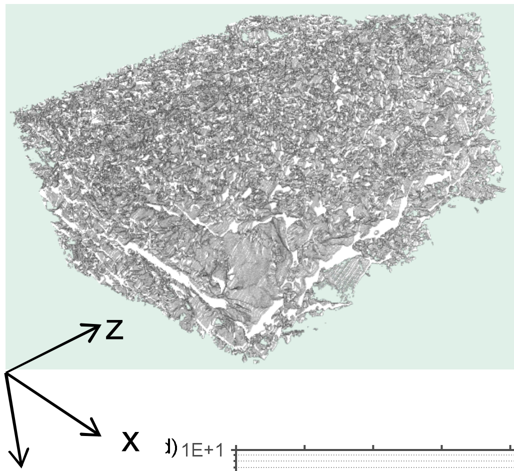
$$\left\langle \nabla \cdot \left(\sigma(x,y,z) \nabla T(x,y,z) \right) \right\rangle = 0$$

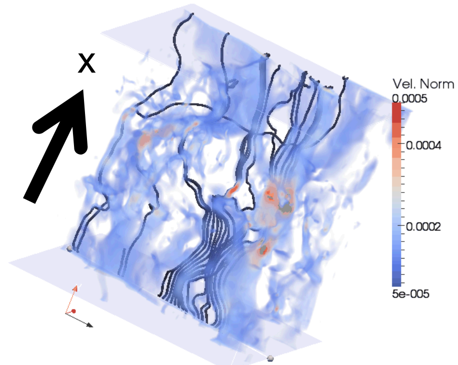


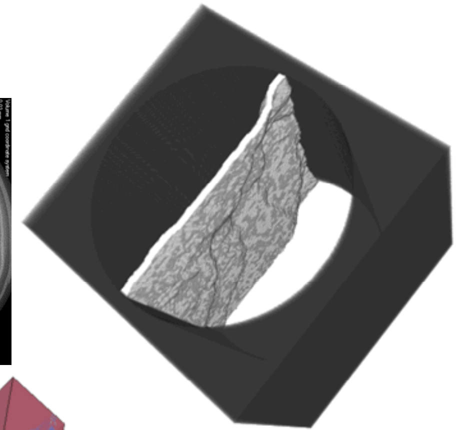


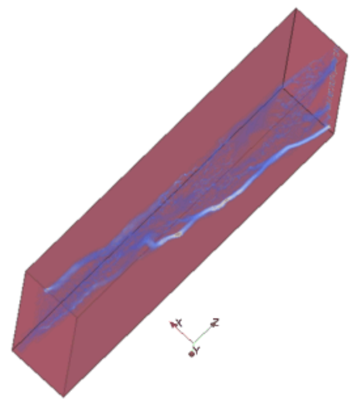


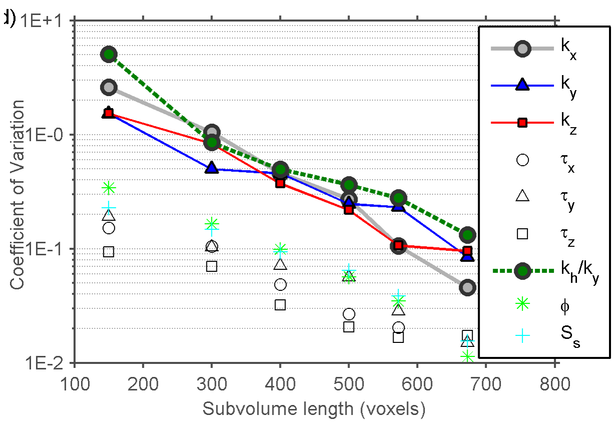
Pore Scale Lattice Boltzmann Simulations











Fracking fluid flow in the presence of proppants

- Estimation of anisotropic permeability and tortuosity at multiple scales
- Single phase flow simulations to determine a representative element volume
- Develop constitutive models for parametric models for continuum scale models - Sierra Mechanics