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3D printing application for flow and mechanical deformation in a single fracture network

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Exceptional service in the national interest

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National Nuclear Security Administration

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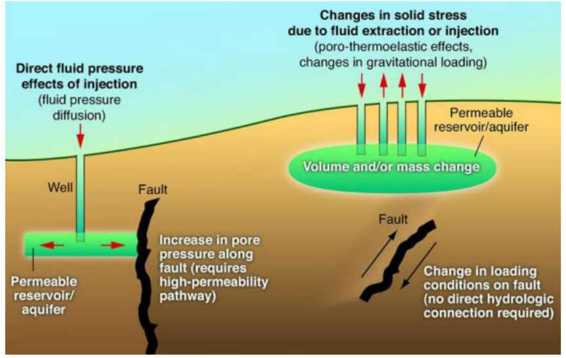
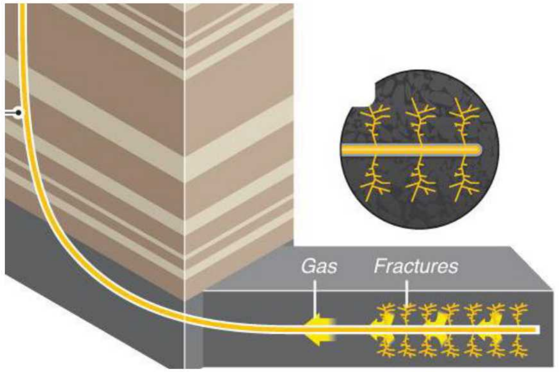
Motivations

- Develop a methodology to improve our understanding of flow and transport processes in fractured and porous rock that directly impact our ability to predict:
  - Aquifer response to injected fluids
  - Hydrocarbon production decline
  - Efficiency of subsurface carbon storage
  - Induced seismicity



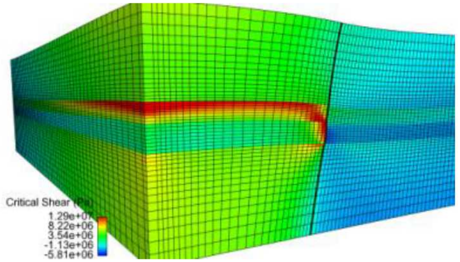
Induced seismicity

USGS: http://earthquake.usgs.gov/ Research/induced/modeling.php



Hydraulic Fracturing

Source: Reuters (National Geographic, Chesapeake Energy, EIA, USGS)

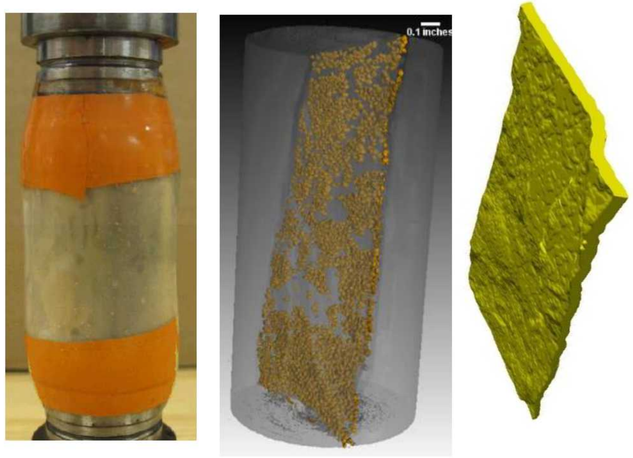


Injection-pressure-induced deformation and shear failure (Martinez et al., IJGGC 2015)

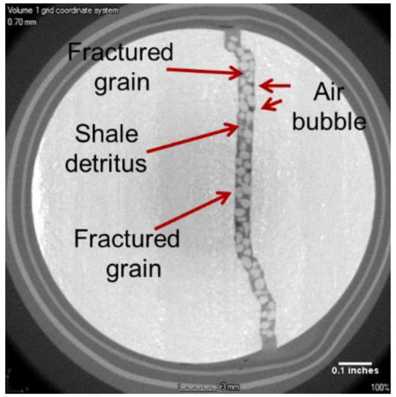
- Experimental Design
- Experimental Results
- Numerical Simulations

Single Fracture Network

- Single fracture network created in a lab
- Originally designed for testing proppants' behavior under stress conditions
- Pure sands (#20-30; 0.6-0.85mm) were placed and permeability changes were measured
- A series of microCT scanning was obtained at different conditions



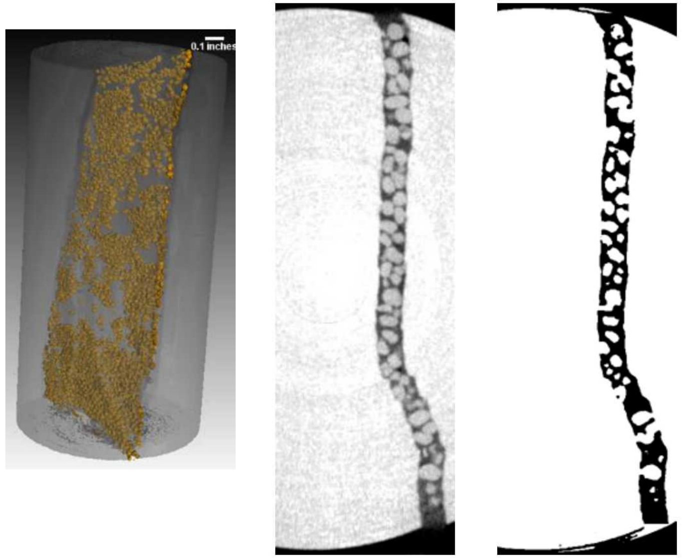
Testing core, rendered image of core, and single fracture network



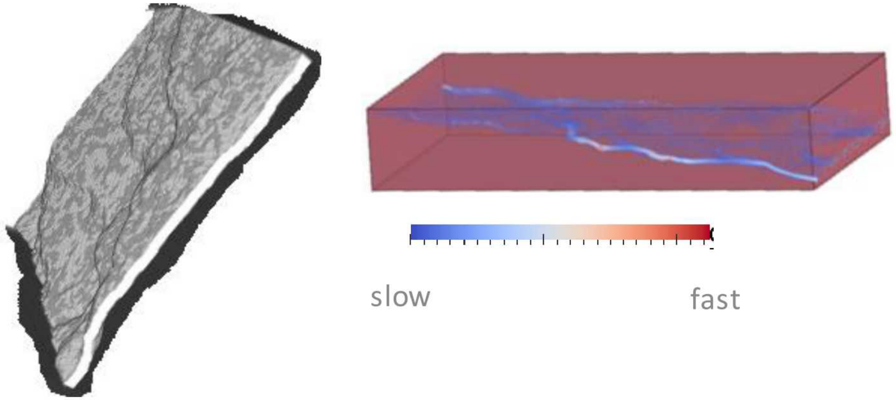
Micro-CT image with proppants in a fracture (Ingraham et al., ARMA, 2015)

Design for Single Fracture Network

- MicroCT image of a single fracture system (200 to 1000 microns aperture)
- 3D segmented result was analyzed by lattice Boltzmann simulations
- Average permeability was calculated as ~80-90 Darcy in the presence of proppants
- For 3D printing work, fracture network without proppants was considered



Testing core, one microCT image and segmented one



3D view of fracture network with proppants (left) and velocity profiles from lattice Boltzmann simulation (right)

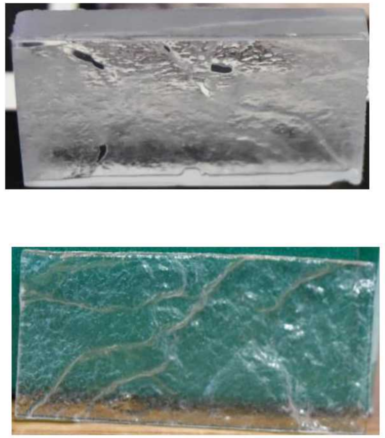
STL image of the fracture without proppants

Yoon et al. (In prep)

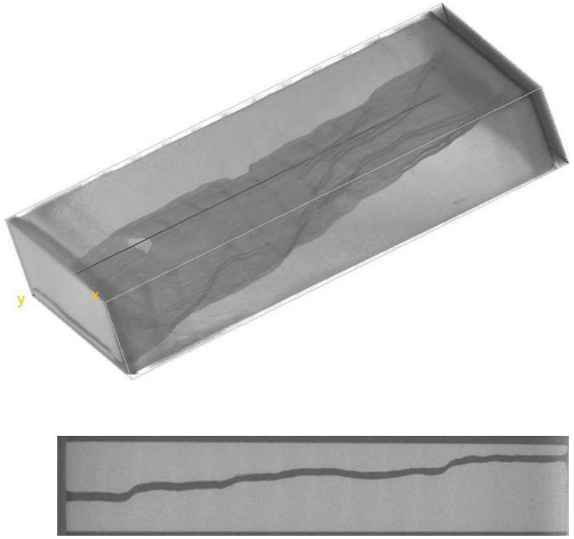
3D printing

- Initially single piece of fracture network was printed with clear resins
- Various 3D printers with stereolithography (SLA) [FormLabs, 3D Systems, Stratasys]
- Printed fracture network was scanned using microCT (12 microns resolution)

STL image for 3D printing



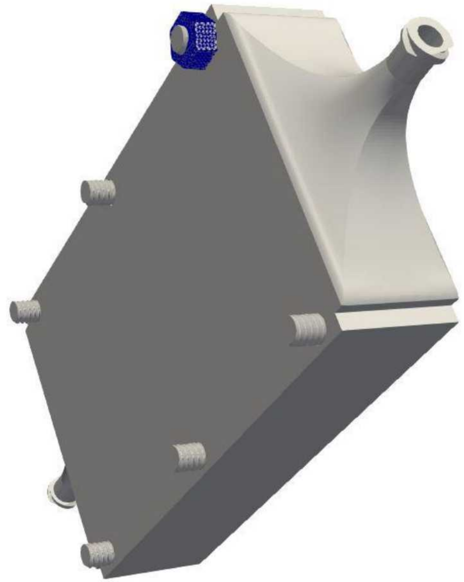
Printed examples



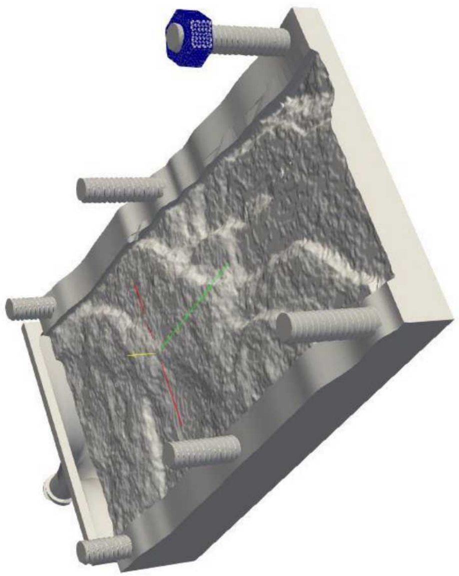
microCT image of printed fracture (@12 μm)

Advances in Printing Design 1

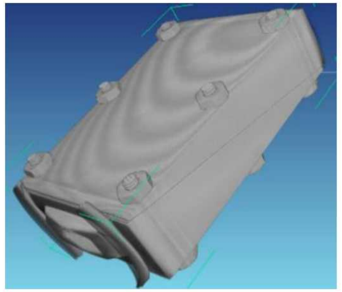
- Multiple printing designs of single fracture system
- Flexible printing options with luer lock ports for inlet and outlet
- Comparison of microCT images of printed fracture with original microCT images



STL image for 3D printing



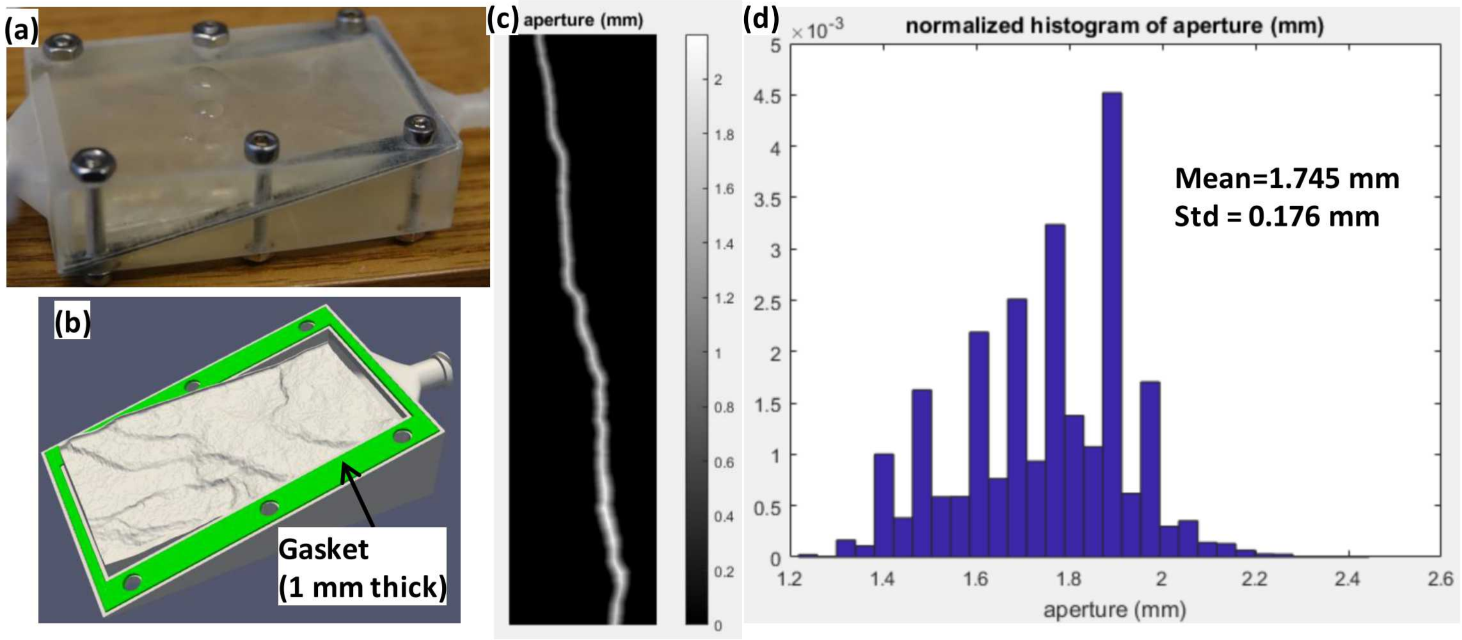
Half piece of fracture



Assembled printed fracture with the luer lock

Advances in Printing Design 2

- Improvement in details of connection, fitting, and assembly
- Sealing gasket was also printed (at least water tight)



(a) Assembled fracture network. Note that the steel screw was replaced with nylon for microCT imaging.

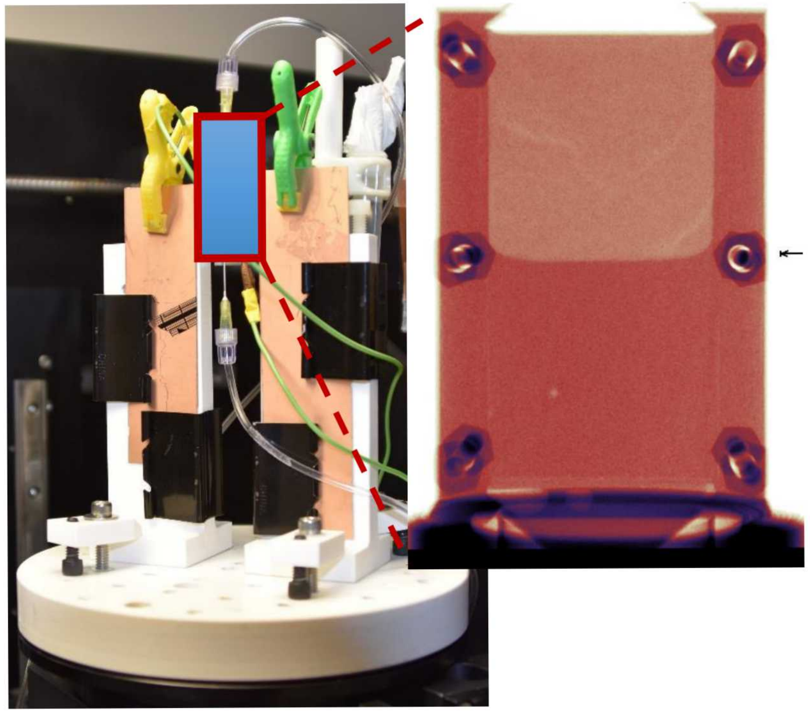
(b) STL format of the bottom part of the fracture with a gasket of 1mm thickness.

(c) Aperture distribution calculated from the segmented microCT image.

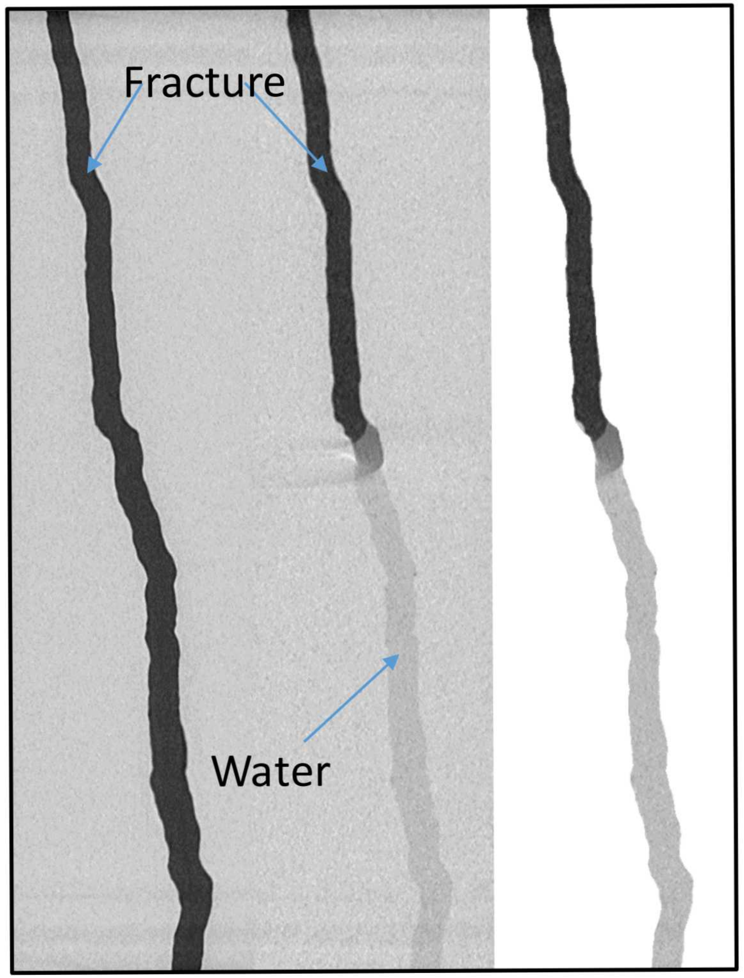
(d) Normalized histogram of aperture distribution over a stack of microCT images (540 images).

- Experimental Design
- Experimental Results
- Numerical Simulations

Water Flow in the Printed Fracture

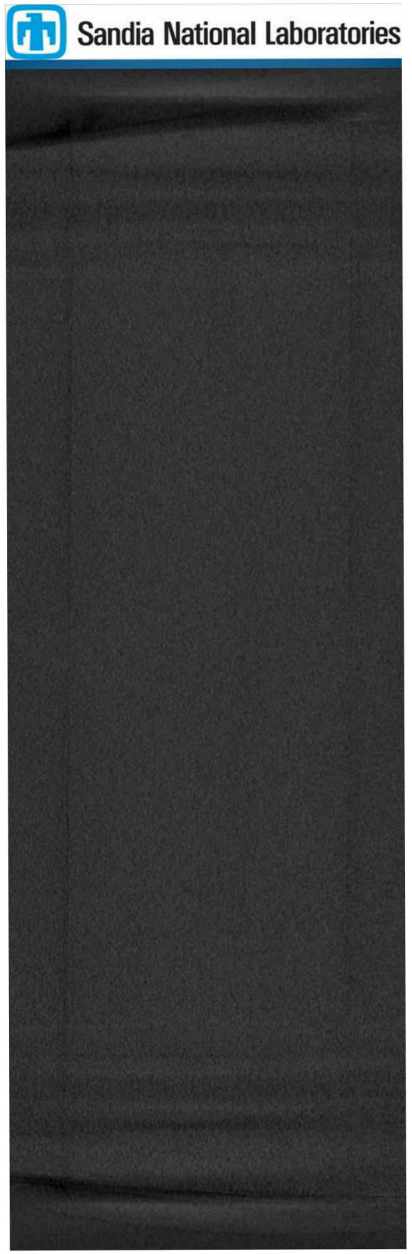


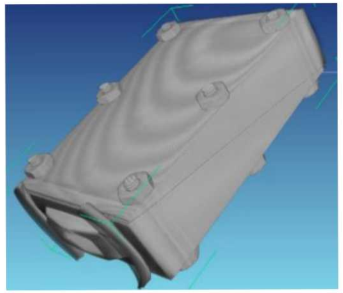
MicroCT stage (printed) and
water flow image



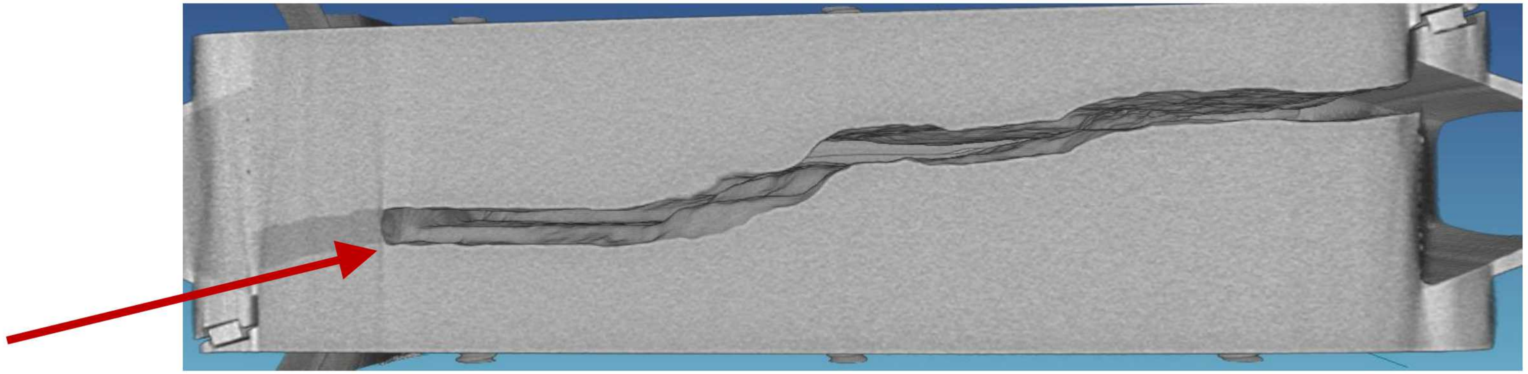
No water, with water, and
masked with no water image

MicroCT image

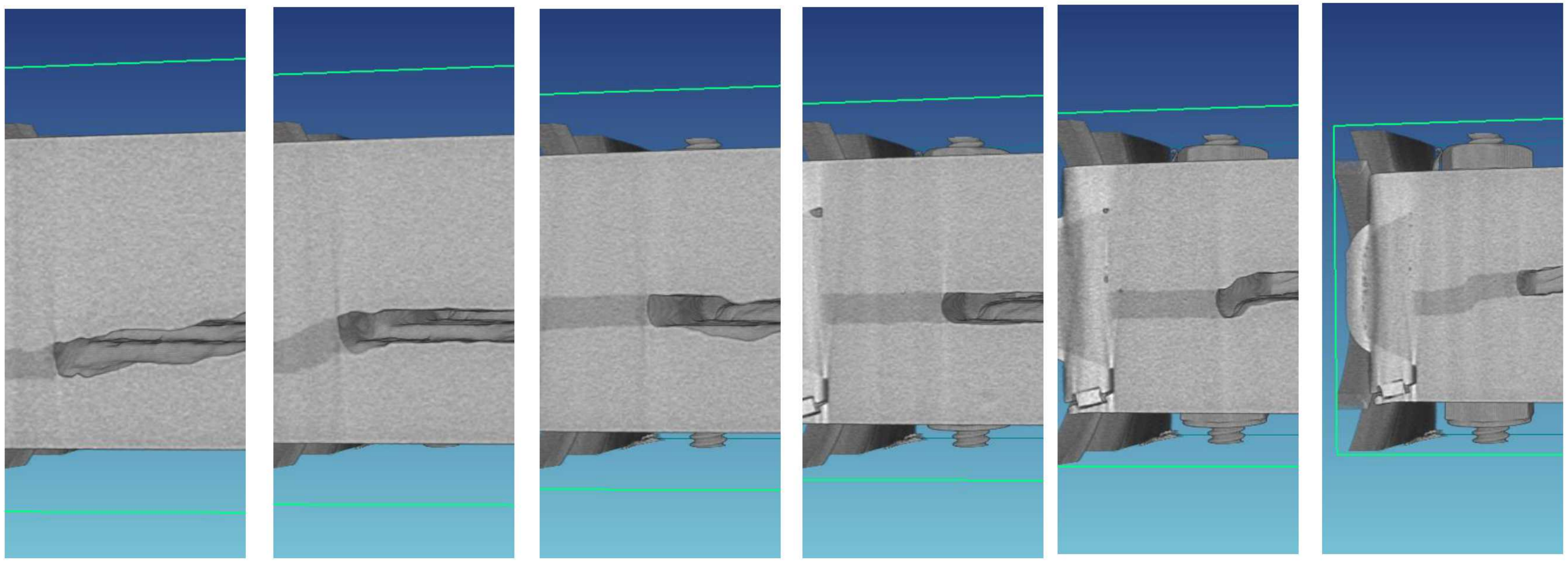




Water Flow in the Printed Fracture

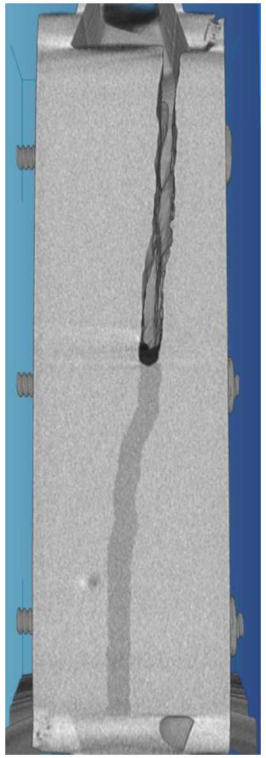


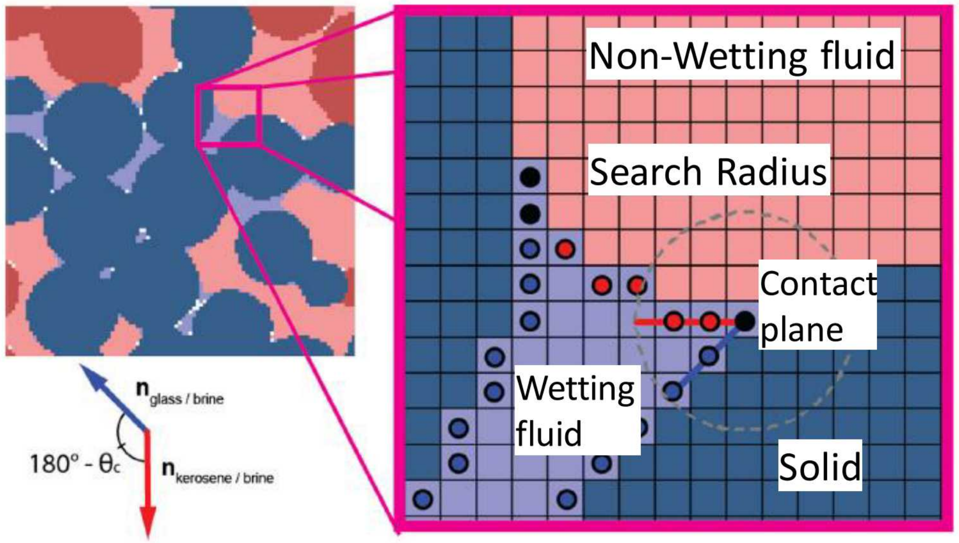
Water-air interface



Automated 3D Contact Angle Computation

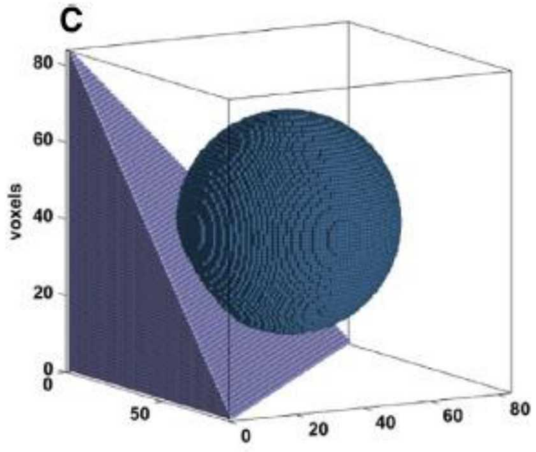
- Contact angle is not a single value in 3D
- Manual calculation is very tedious and cherry-picking
- Automated 3D contact angle algorithm (Klise et al., 2016) is applied

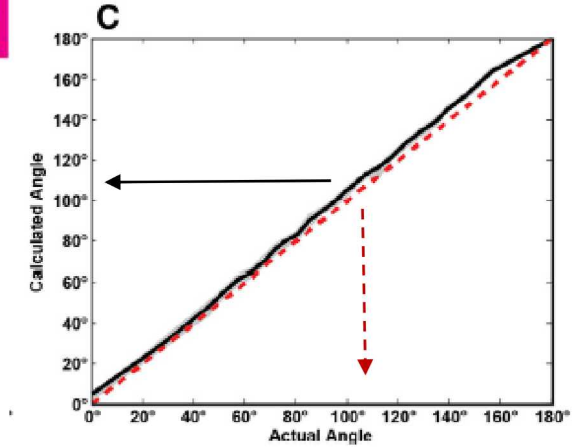




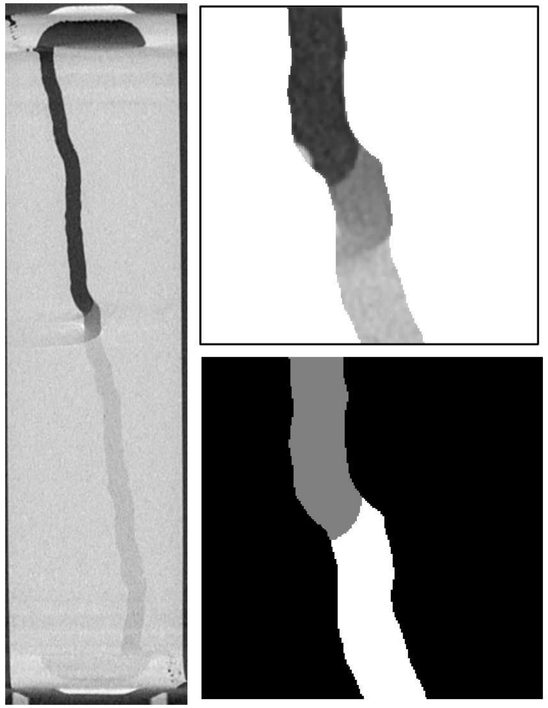
2D view of interface identification, contact points and contact angle calculation

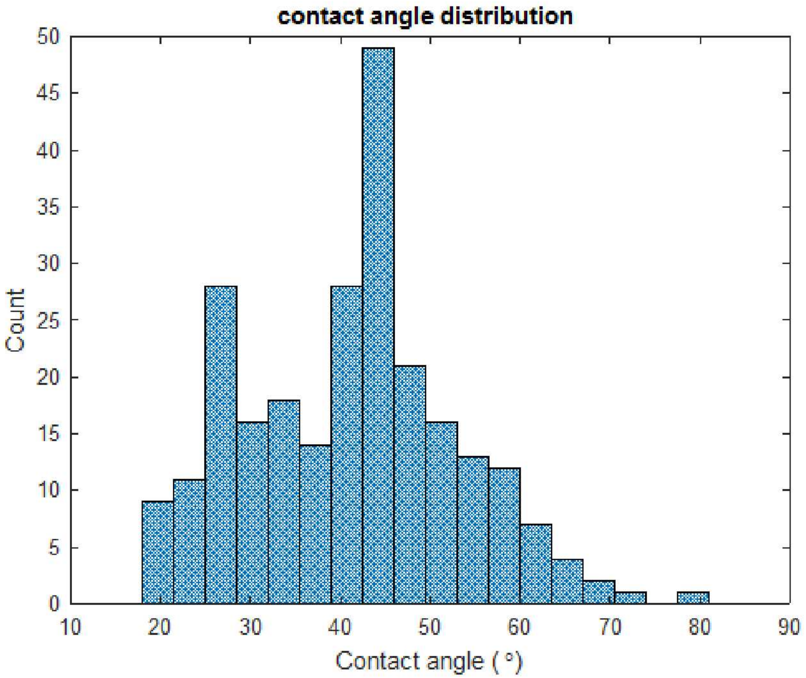
Klise et al. (2016, AWR)





3D Contact Angle Distribution





mean=41.5° (std=11.95°)
min=19.0° and max=80.5°

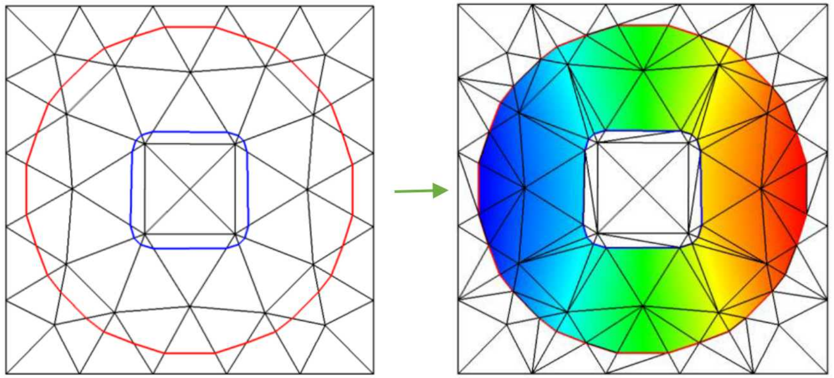
Note: ~ 250 contact angels were captured

- Experimental Design
- Experimental Results
- Numerical Simulations

Conformal Decomposition Finite Element Method (CDFEM)

- Sierra/Aria: Sandia National Labs Galerkin FEM platform for solving nonlinear, implicit, and transient coupled-physics problems, with a focus on transport equations

- Conformal Decomposition Finite Element Method (CDFEM)
  - Level set field(s) define materials or phases
  - Decompose non-conformal elements into conformal ones
  - Obtain solutions on conformal elements in traditional manner
  - Utilized transiently to support topological evolution

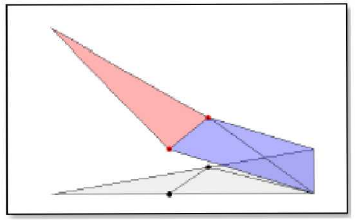


- Properties
  - Supports wide variety of interfacial conditions (identical to boundary fitted mesh)
  - Avoids manual generation of boundary fitted mesh
  - Supports general topological evolution (subject to mesh resolution)

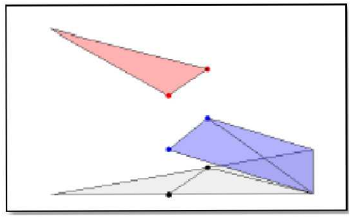
- Similar to finite element adaptivity
  - Uses standard finite element assembly including data structures, interpolation, quadrature
  - Extensive verification efforts have proven appropriate mass/energy conservation

CDFEM for Multiphase Flow

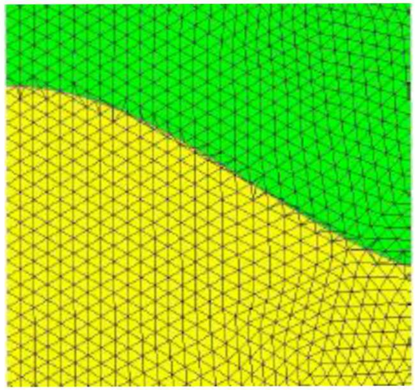
- CDFEM used to provide dynamic discretization for multiphase flow with interfaces that do not conform to static finite element meshes
- Level set that advects with the flow is used to define the interface locations
- Adds degrees of freedom (velocity and pressure) by adding nodes to mesh which lie on the exact interface location
- Can apply boundary conditions directly at interface
  - Surface tension
  - Wetting line models



Weakly discontinuous velocity



Strongly discontinuous velocity



Conformal mapping with two phases separated with an interface

Computational Model

- Galerkin triangular/tetrahedral finite elements to discretize Navier-Stokes equation using Sandia Sierra multi-physics suite
- Level Set Equation
  - Advection equation

$$\frac{\partial \phi}{\partial t} + u \cdot \nabla \phi = 0$$

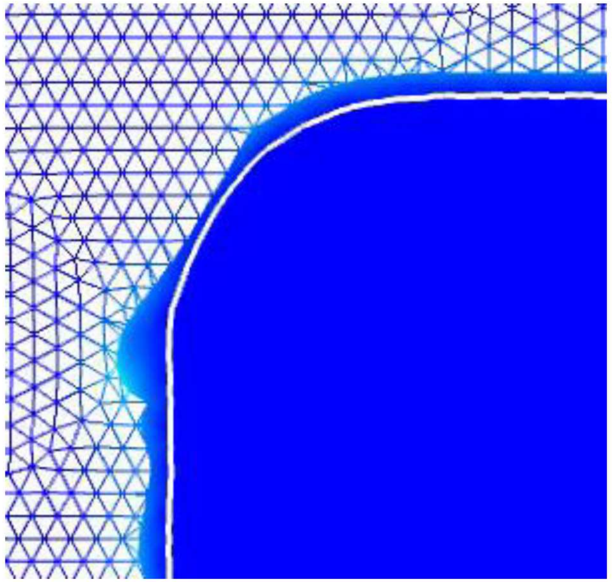
  - Galerkin, Backward Euler

$$\int_{\Omega} \frac{\phi - \phi^n}{\Delta t} N_i \, d\Omega + \int_{\Omega} u \cdot \nabla \phi \, N_i \, d\Omega = 0$$

  - Streamline-upwind/Petrov-Galerkin stabilization

$$N_i \Rightarrow N_i + \tau_\phi u \cdot \nabla N_i, \; \tau_\phi = \left[\left(\frac{2}{\Delta t} \right)^2 + u_i g_{ij} u_j \right]^{-\frac{1}{2}}$$

  - Periodic renormalization
    - Compute nearest distance to interface



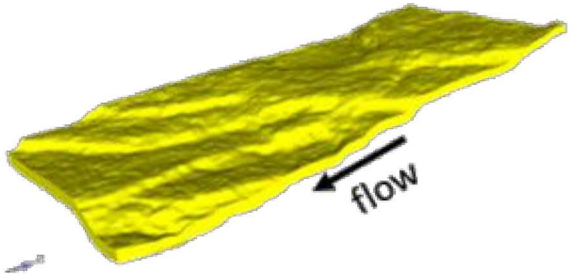
- Interface boundary conditions

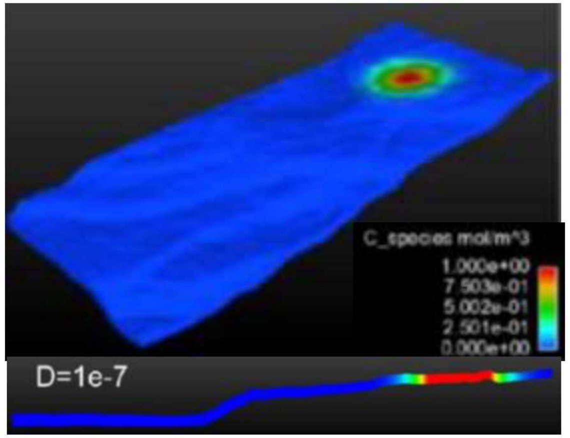
$$[\mathbf{u}]_\Delta = 0, \qquad \mathbf{x} \in \Gamma \qquad \textit{(impermeability)}$$

$$[-p\mathbf{I} + \mu(\mathbf{x}) \left(\nabla \mathbf{u} + \nabla \mathbf{u}^{\mathrm{T}} \right)]_\Delta \cdot \hat{\mathbf{n}} = -\gamma \kappa \hat{\mathbf{n}}, \qquad \mathbf{x} \in \Gamma \qquad \textit{(surface tension)}$$

Flow and Dispersion in Fracture

- Cut this block grid of the fracture surfaces (stereolithography)
- CDFEM for local grid refinement on the level sets of fracture surfaces
- Separate unstructured grid blocks for the fracture and the surrounding solid ("rock"), separated by interfaces with the same level of fidelity that was in the original STL file

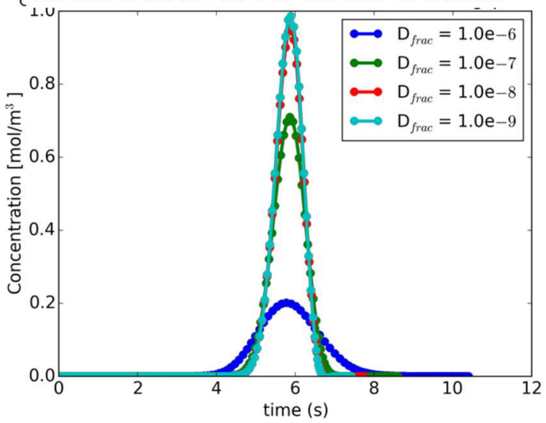




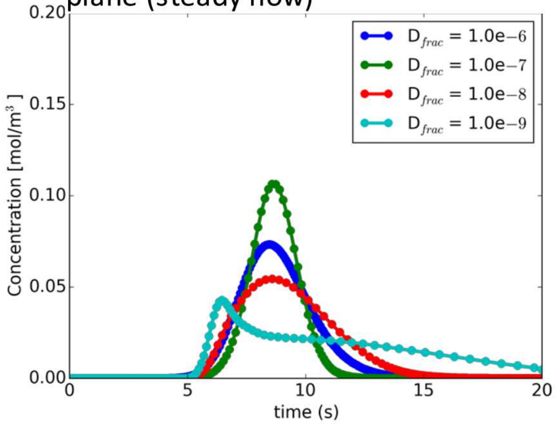
Permeability (fluid dynamics)

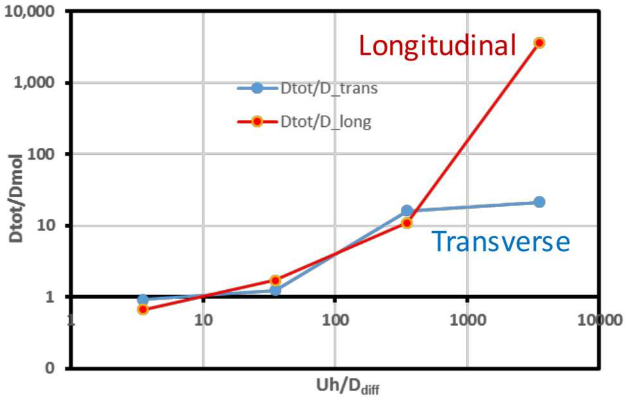
b_{geom} = 0.64 mm
k_{hyd} = 4.1x10^{-8} m^2
b_{hyd} = 0.7 mm

Concentration at the center of outlet



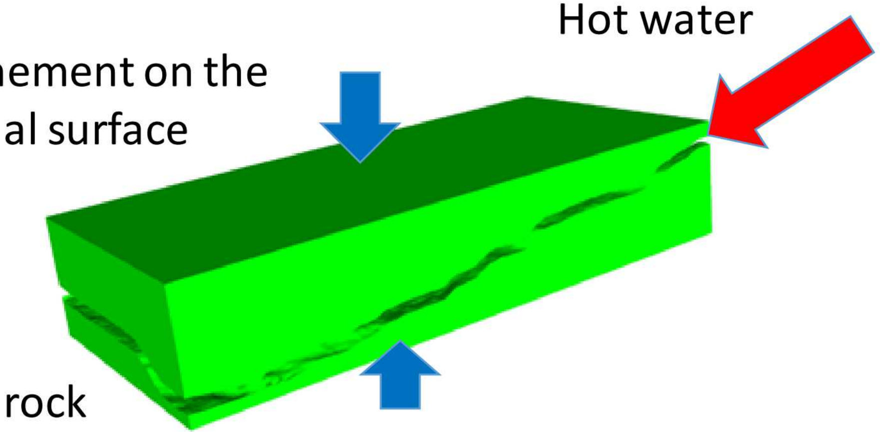
Mean concentration over the outlet plane (steady flow)

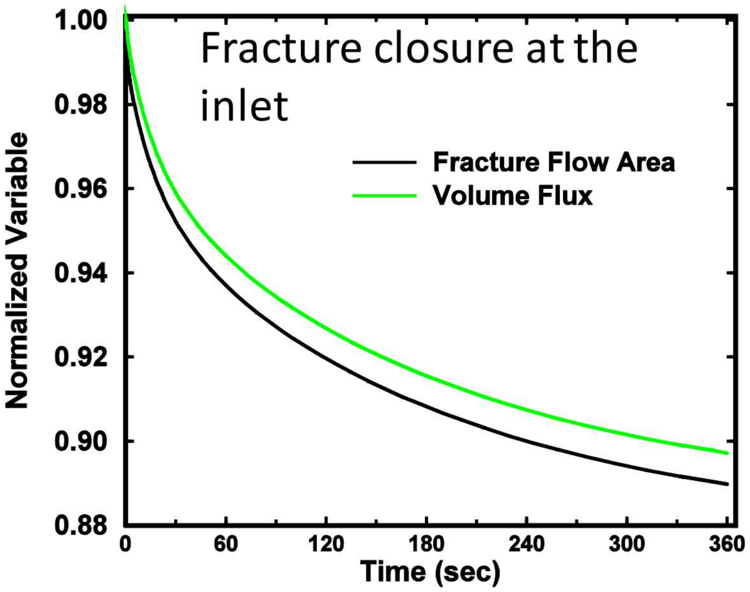


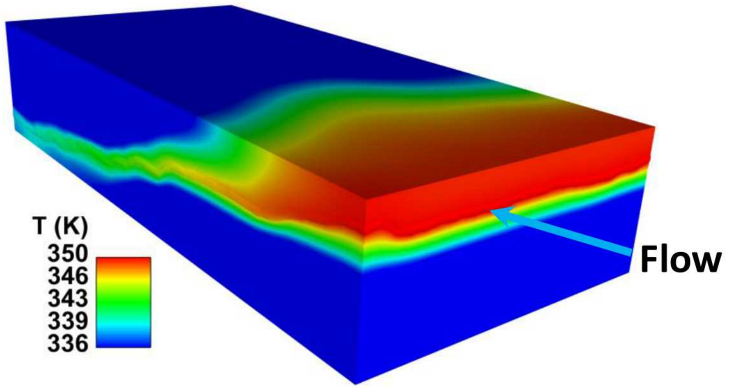


Peclet Number

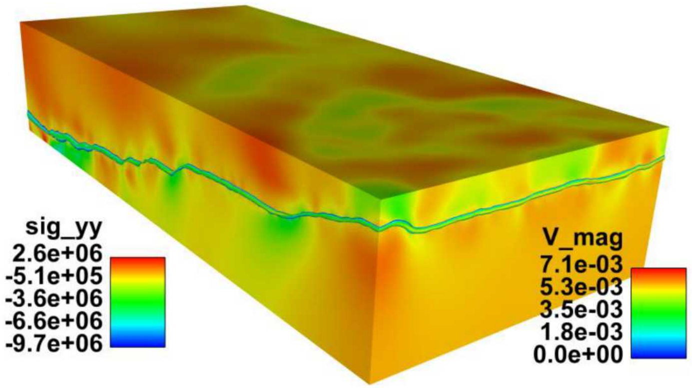
Closure by Thermal Expansion in Fracture







Thermal transport in fracture and heat diffusion into rock

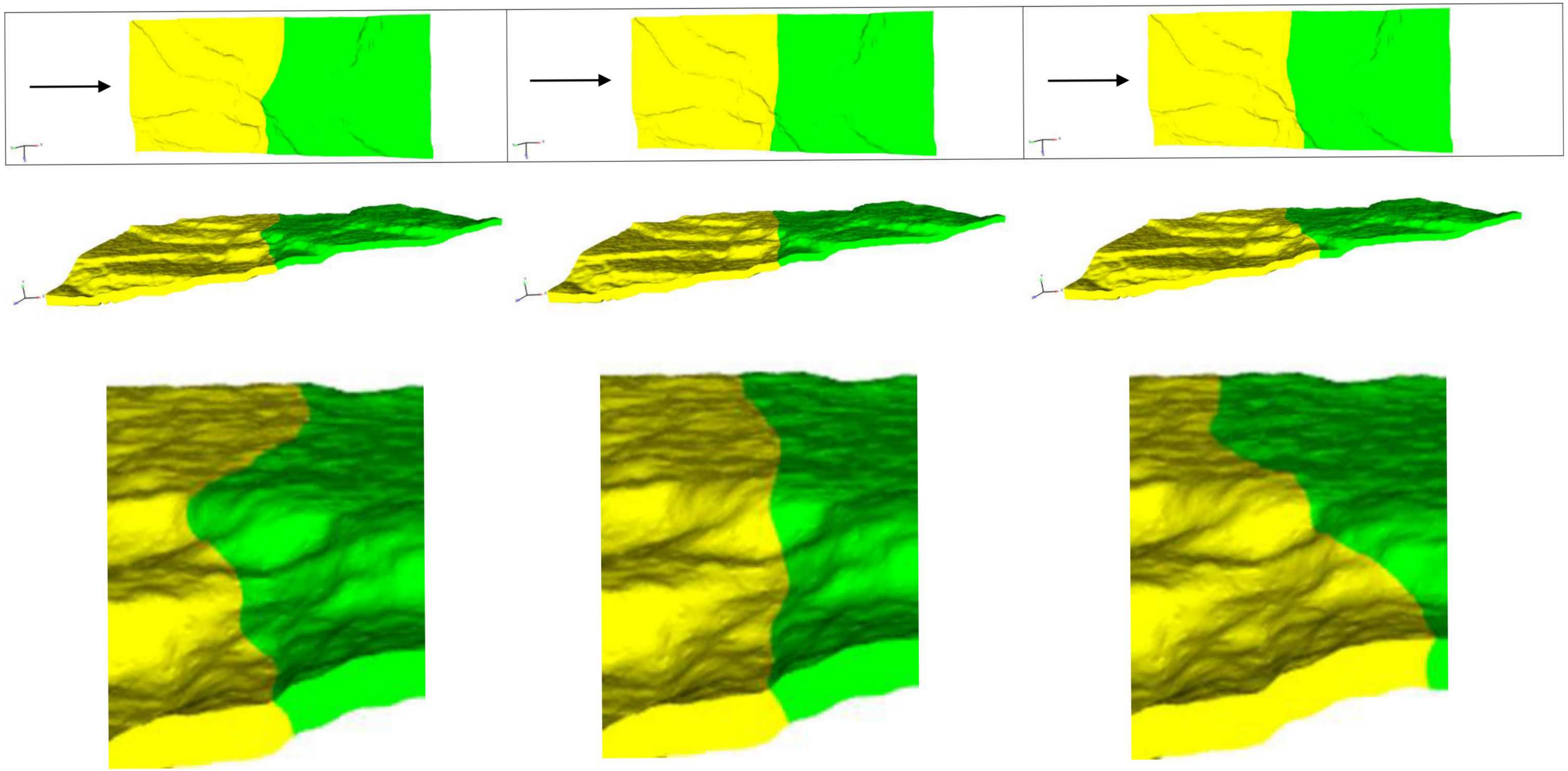


Thermal expansion stress under confinement

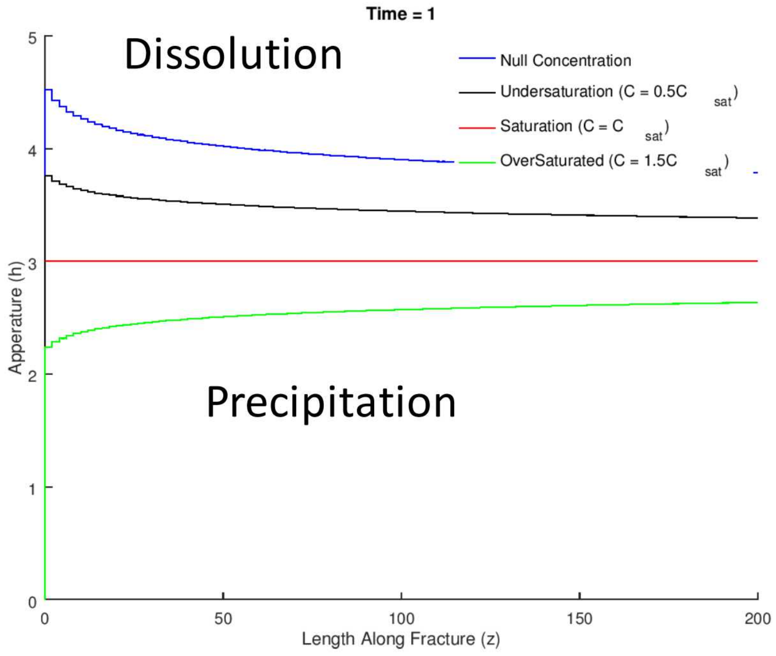
Multiphase Flow Simulations

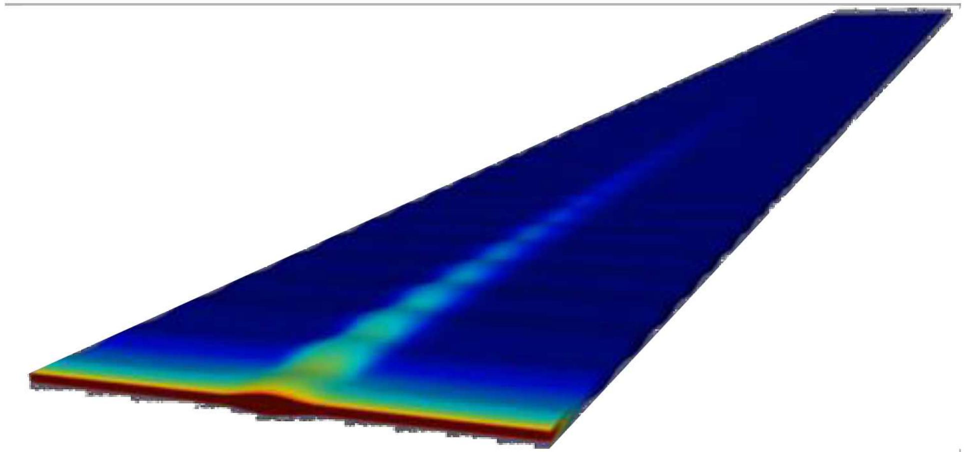
Contact angle variations (flow from left to right)

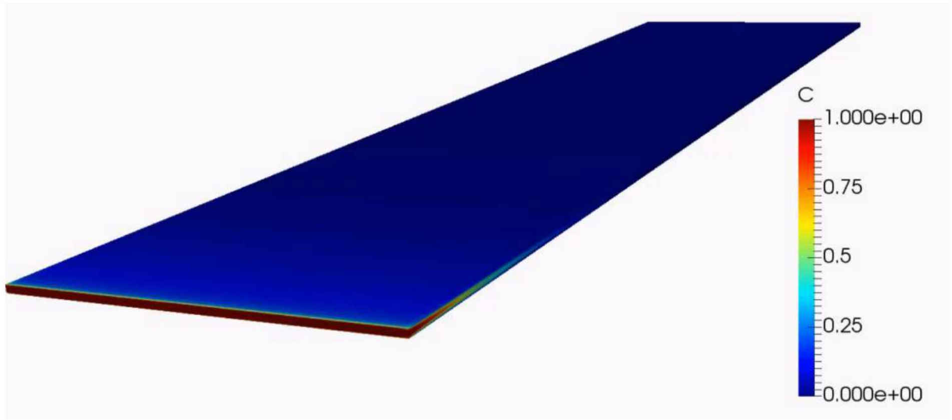
CA = 120 degree | CA = 100 degree | CA = 55 degree

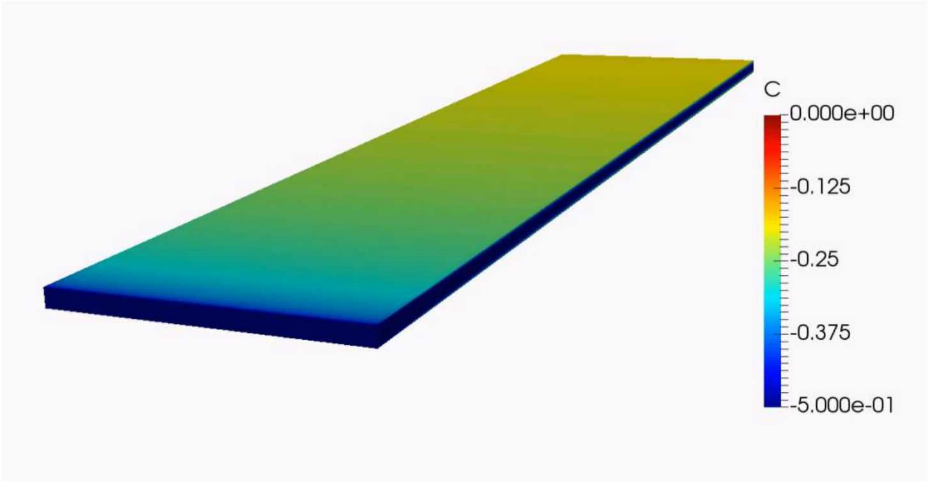


Reactive Transport Simulations









Using an OpenFOAM modified from Starchenko et al. (2016, JGR)

Summary

- 3D printing of porous and fractured structures augmented with digital rock physics has high potential to advance our understanding of poromechanics
- CDFEM for multiphase flows
  - Sharp interface method
  - CDFEM design encapsulates interface motion/discretization and finite element assembly/physics
- Developed a methodology for additive manufacturing of synthetic media that mimics natural media and enables creation of custom/functional porous material