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Numerical and Experimental Validation of Flow Testing in 3D Printed Single Fracture Network

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Sandia National Laboratories

Exceptional service in the national interest

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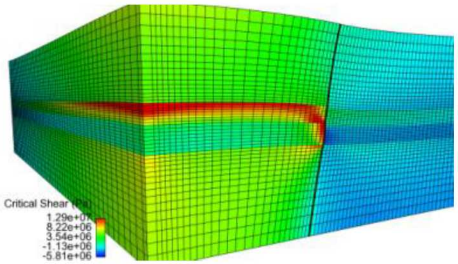
National Nuclear Security Administration

Motivations

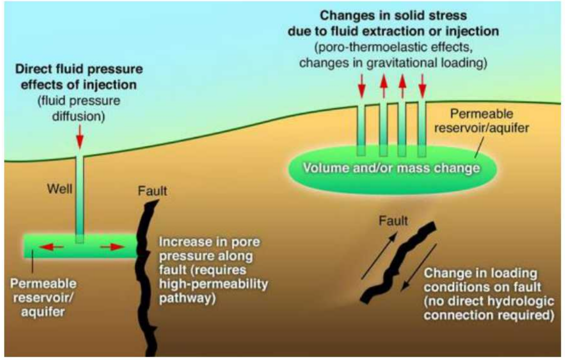
- Develop a methodology to improve our understanding of flow and transport processes in fractured and porous rock that directly impact our ability to predict:
  - Aquifer response to injected fluids
  - Hydrocarbon production decline
  - Efficiency of subsurface carbon storage
  - Induced seismicity

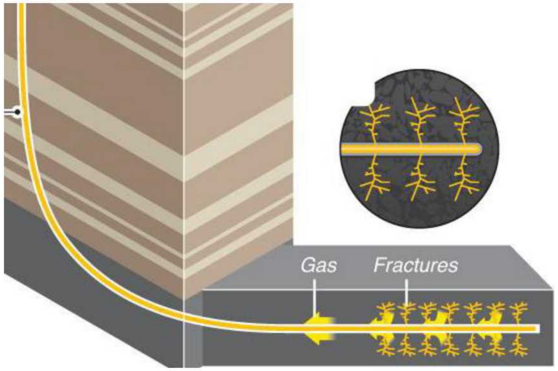


Injection-pressure-induced deformation and shear failure (Martinez et al., IJGGC 2015)

Induced seismicity

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



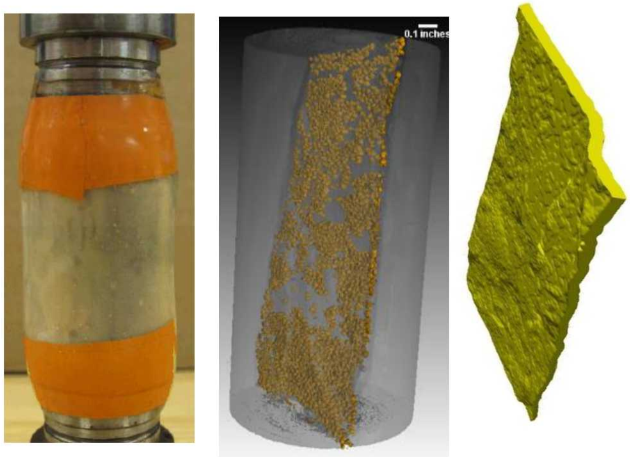


Hydraulic Fracturing

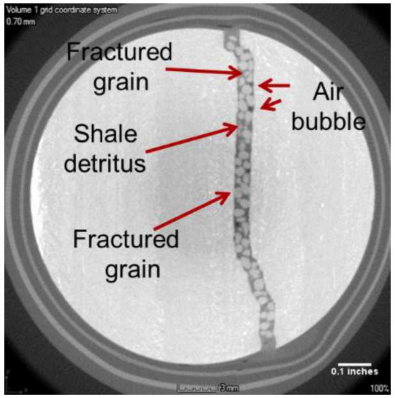
Source: Reuters (National Geographic, Chesapeake Energy, EIA, USGS)

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



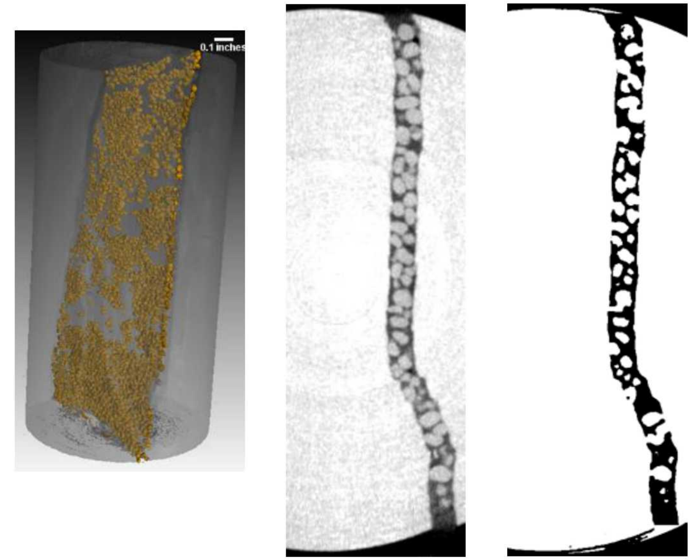
Testing core, rendered image of core, and a vies of fracture network (Ingraham et al., ARMA, 2015)



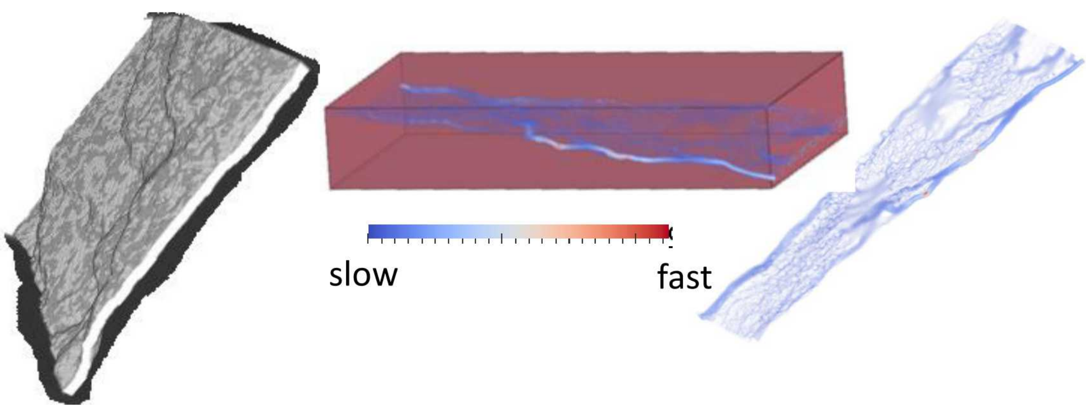
Micro-CT image with proppants in a fracture (Ingraham et al., ARMA, 2015)

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)

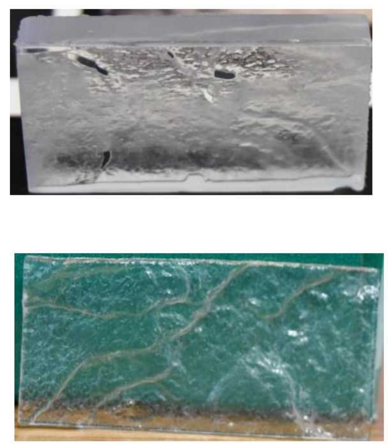
STL image of the fracture without proppants

Yoon et al. (In prep)

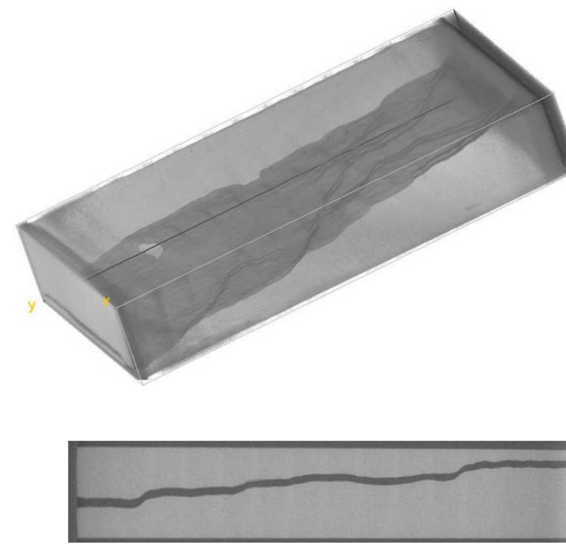
3D printing

- 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



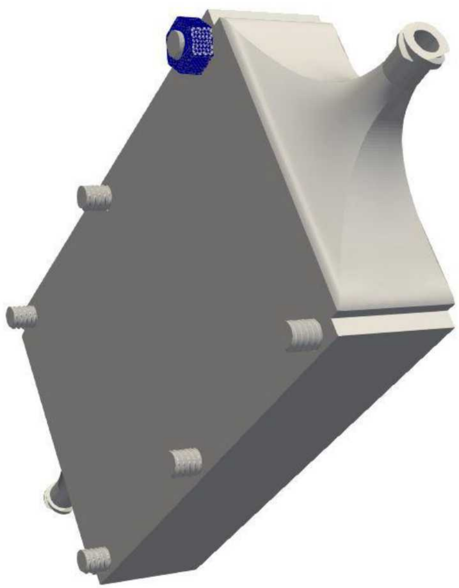
Printed examples



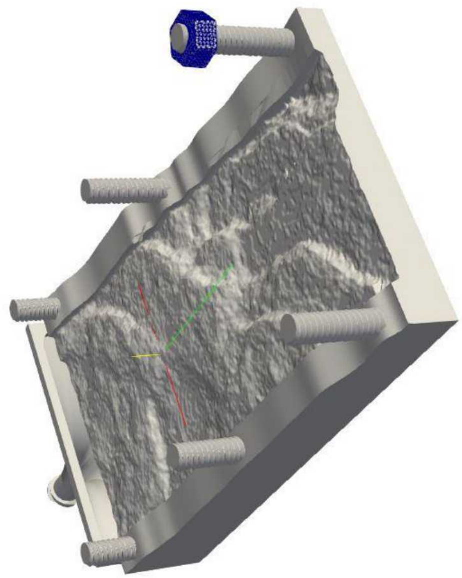
microCT image of printed fracture (@12 μm)

Advances in Printing Design 1

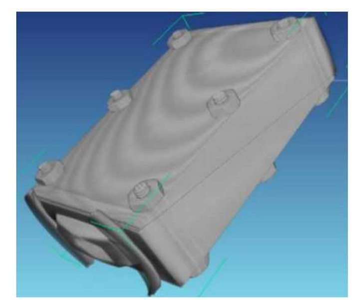
- Multiple printing designs of single fracture system
- Flexible printing options with luer lock ports for inlet and outlet
- Comparison of microCT images of printed fracture with original microCT images
- Single fracture system for coupled hydro-mechanical relations



STL image for 3D printing



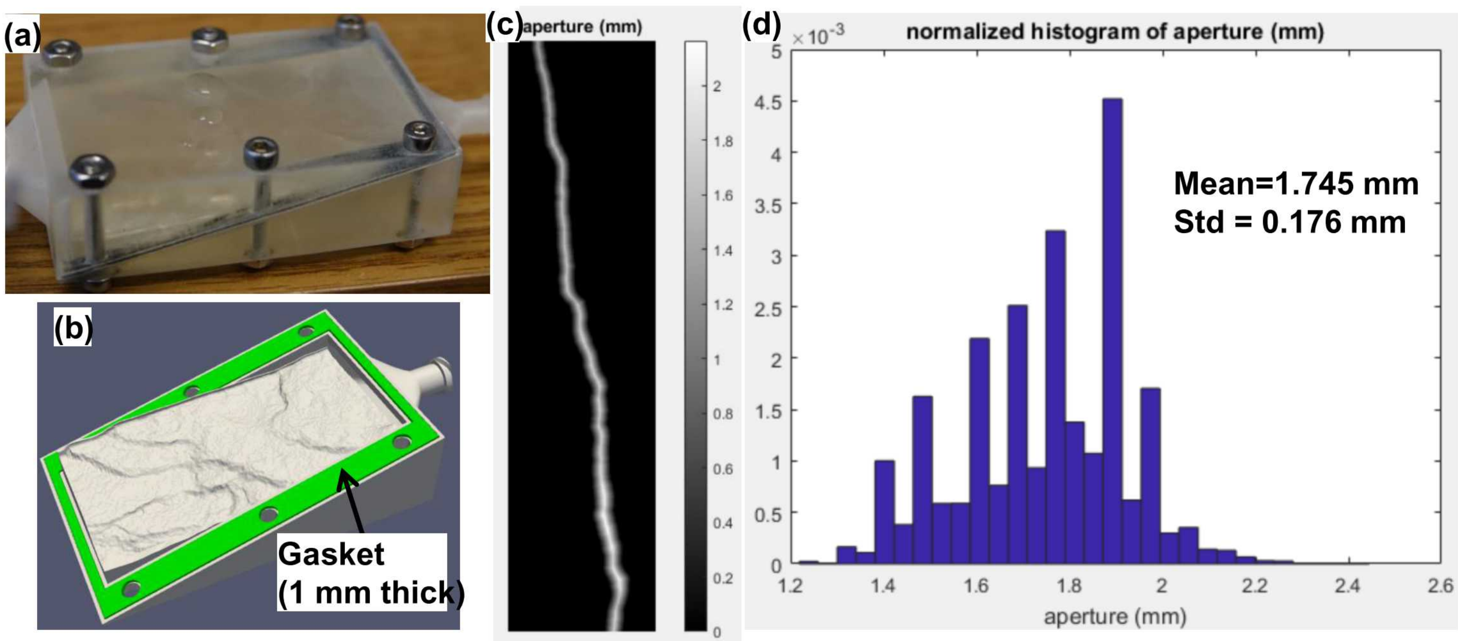
Half piece of fracture



Assembled printed fracture with the luer lock

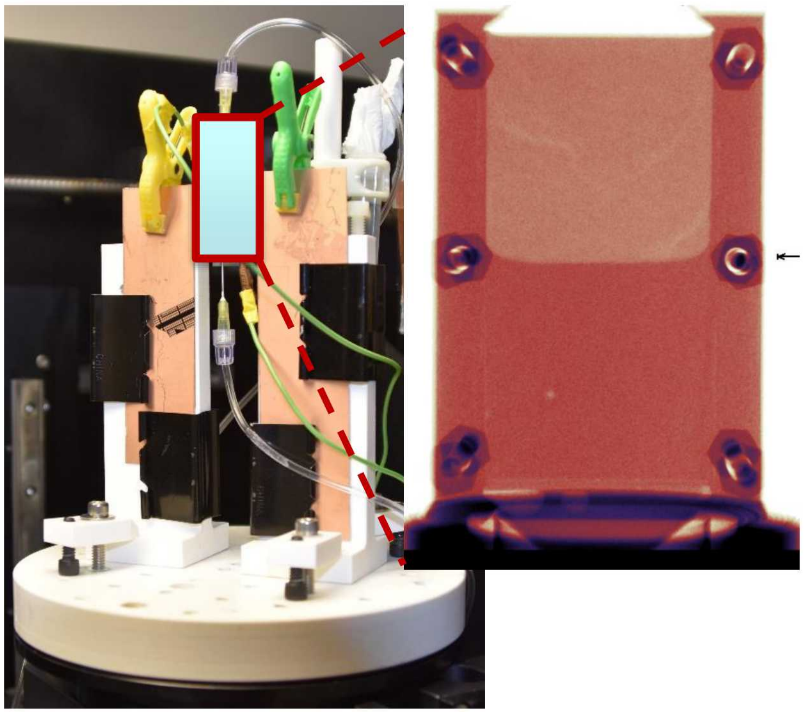
Advances in Printing Design 2

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

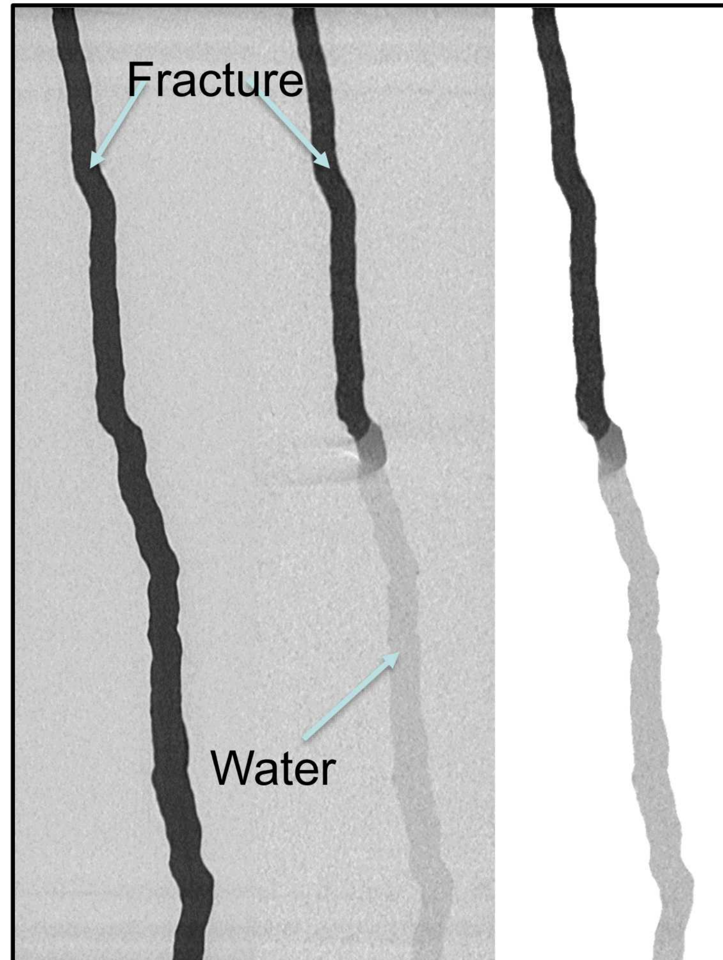


(a) Assembled fracture network. Note that the steel screw was replaced with nylon for microCT imaging. (b) STL format of the bottom part of the fracture with a gasket of 1mm thickness. (c) Aperture distribution calculated from the segmented microCT image. (d) Normalized histogram of aperture distribution over a stack of microCT images (540 images).

Water Flow in the Printed Fracture

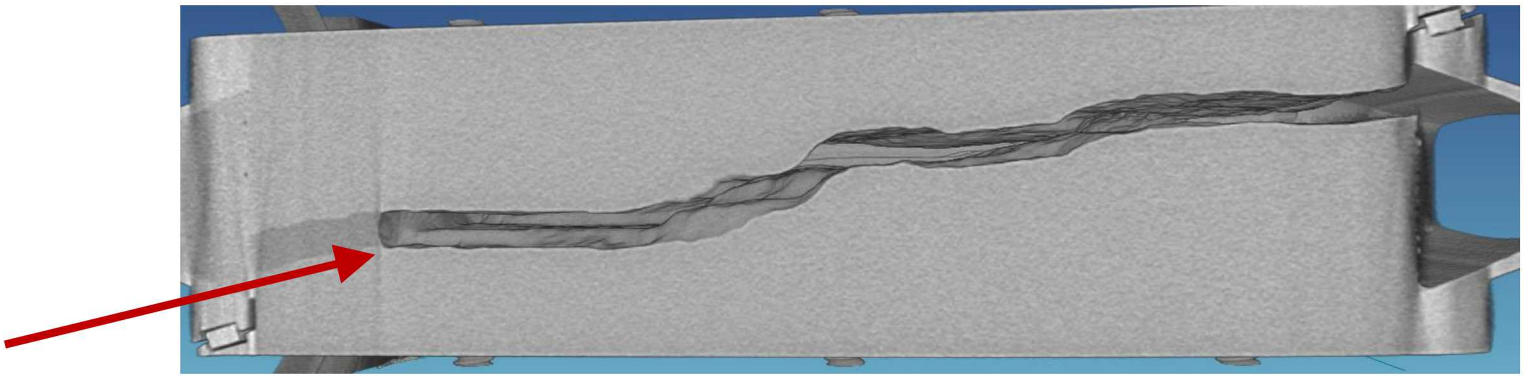


MicroCT stage (printed) and
water flow image

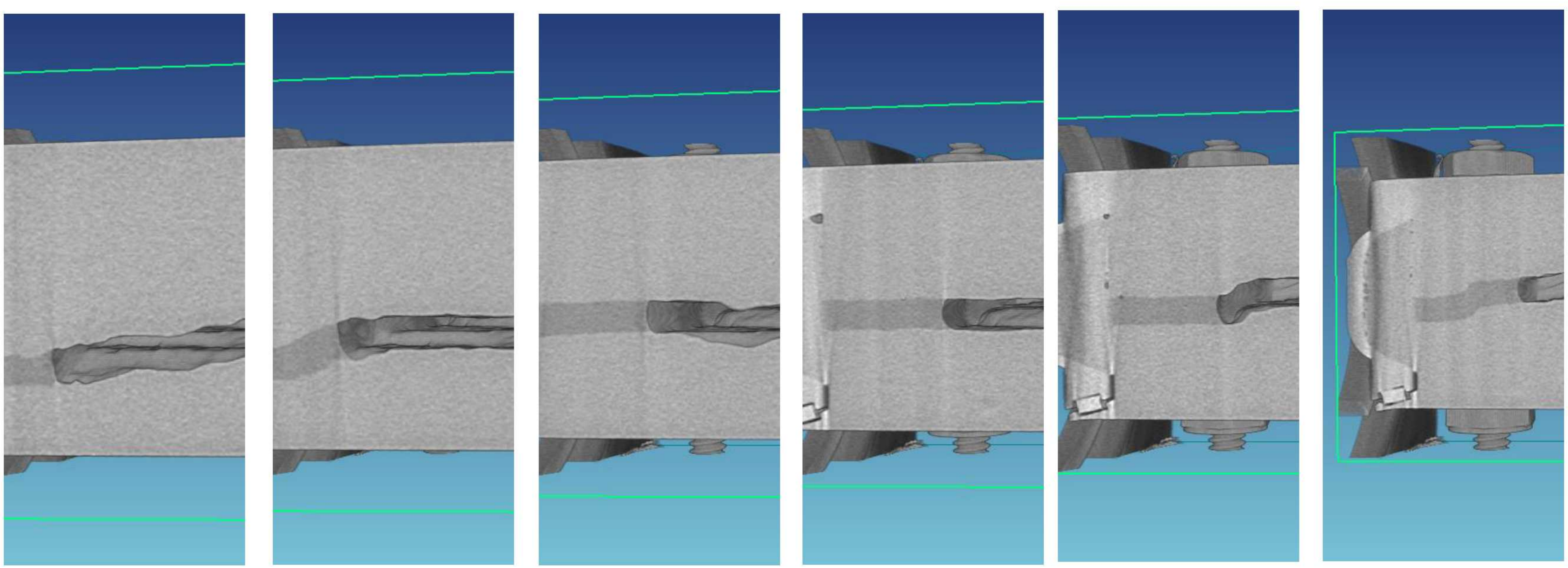


No water, with water, and
masked with no water image

Water Flow in the Printed Fracture

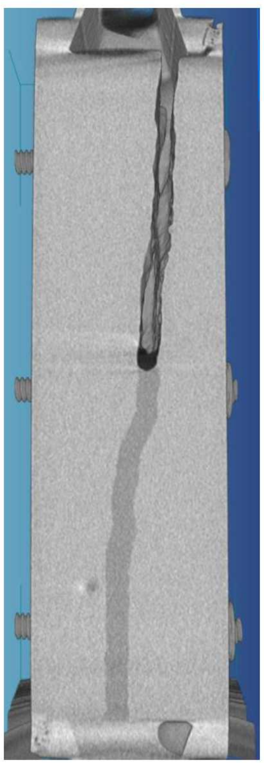


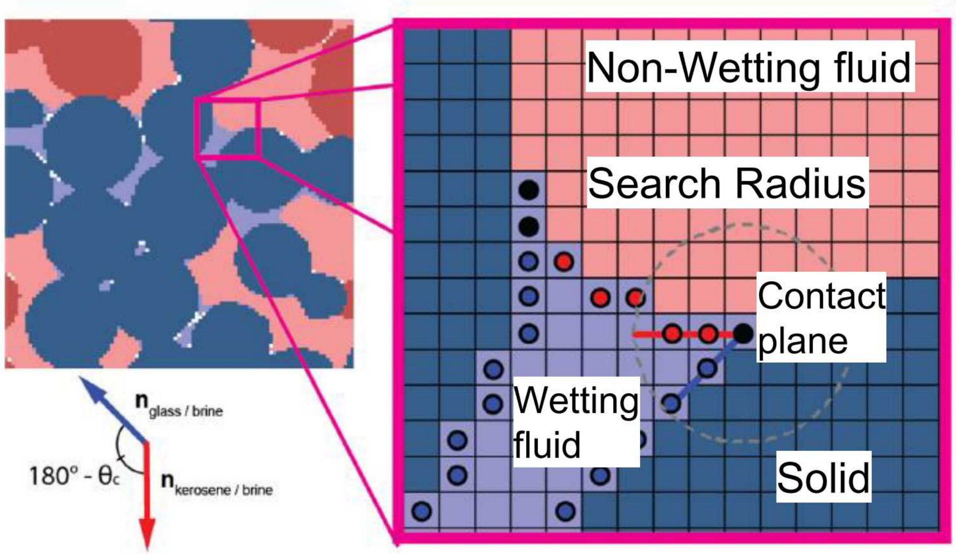
Water-air interface

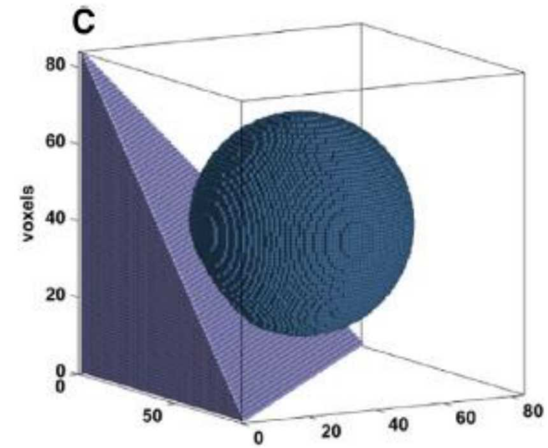


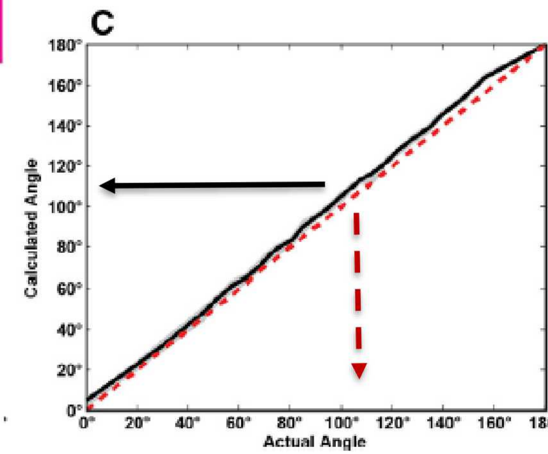
Automated 3D Contact Angle Computation

- 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





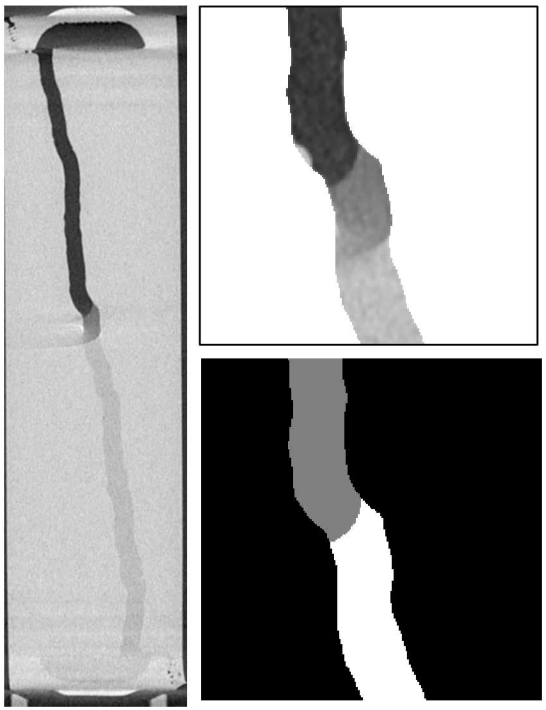


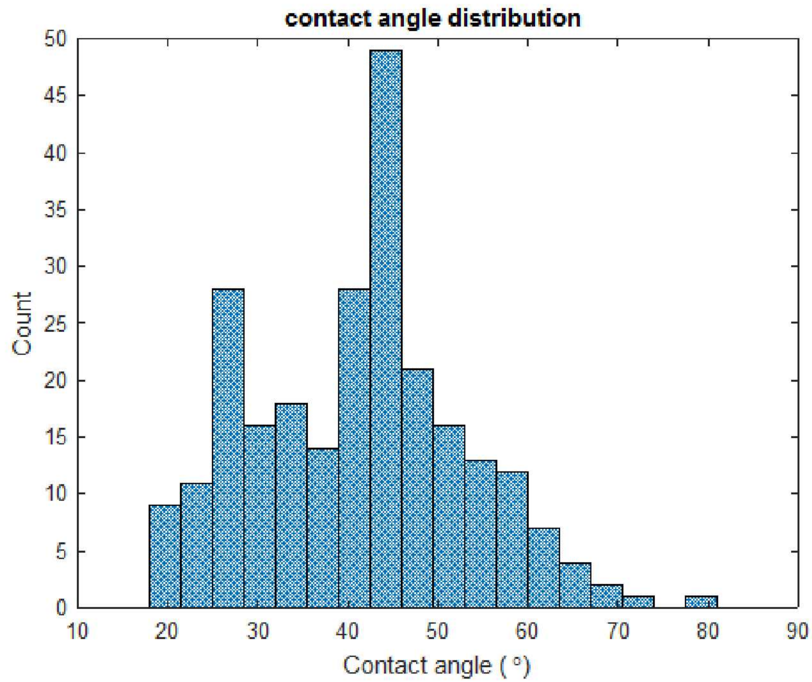


2D view of interface identification, contact points and contact angle calculation

Klise et al. (2016, AWR)

3D Contact Angle Distribution

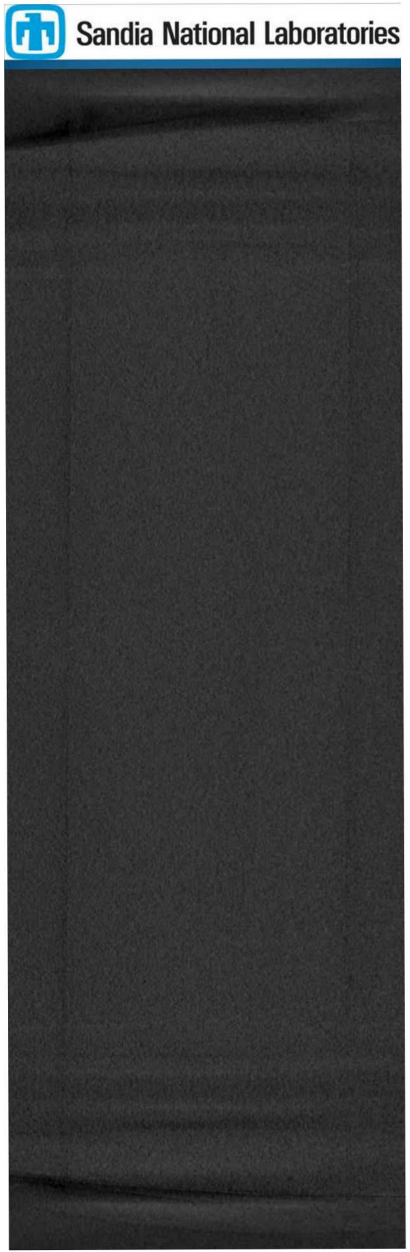


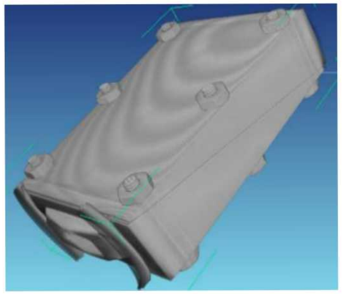


mean=41.5° (std=11.95°)
min=19.0° and max=80.5°

Note: ~ 250 contact angels were captured

MicroCT image

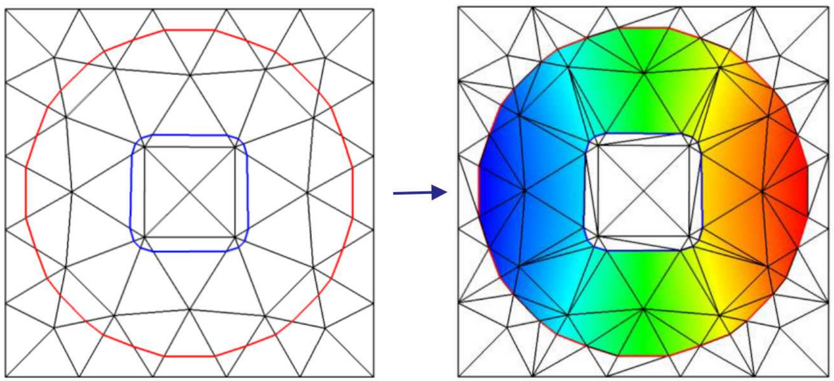




Finite Element Methods for Moving Interfaces

- 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

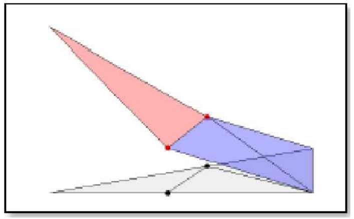


- Properties
  - Supports wide variety of interfacial conditions (identical to boundary fitted mesh)
  - Avoids manual generation of boundary fitted mesh
  - Supports general topological evolution (subject to mesh resolution)

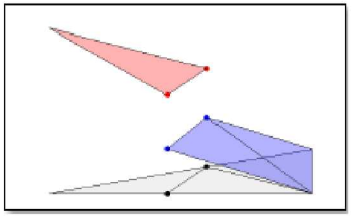
- Similar to finite element adaptivity
  - Uses standard finite element assembly including data structures, interpolation, quadrature
  - Extensive verification efforts have proven appropriate mass/energy conservation

CDFEM for Multiphase Flow

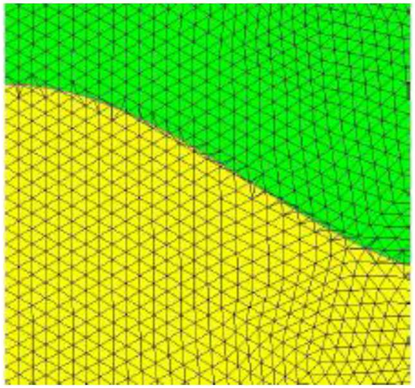
- CDFEM used to provide dynamic discretization for multiphase flow with interfaces that do not conform to static finite element meshes
- Level set that advects with the flow is used to define the interface locations
- Adds degrees of freedom (velocity and pressure) by adding nodes to mesh which lie on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



Weakly discontinuous velocity



Strongly discontinuous velocity



Computational Model

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

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

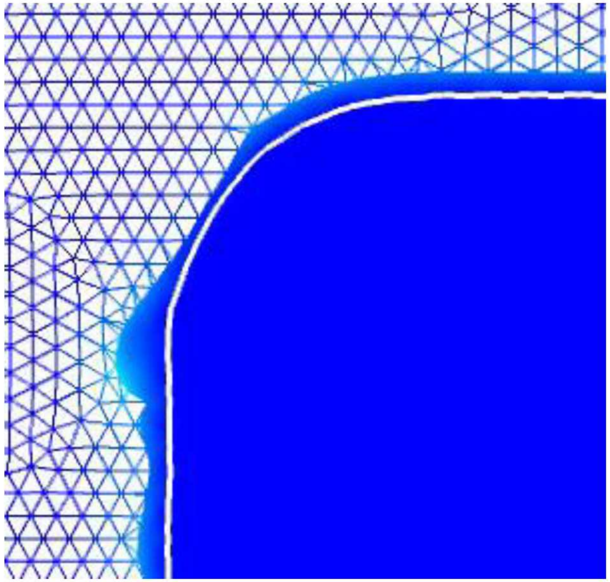
  - Galerkin, Backward Euler

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

  - 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

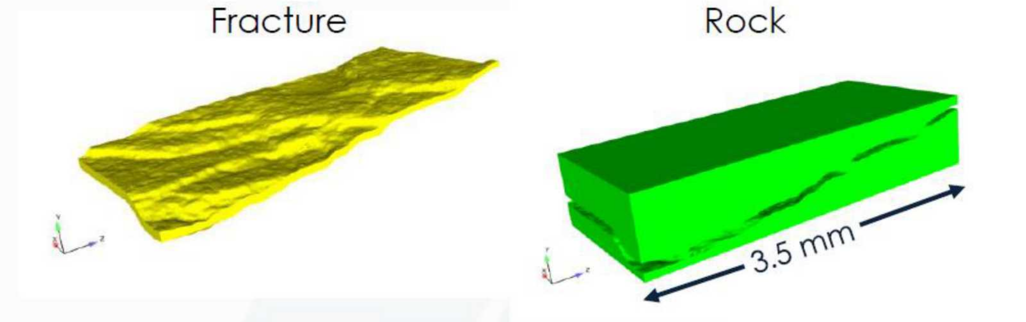


- Interface boundary conditions

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

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

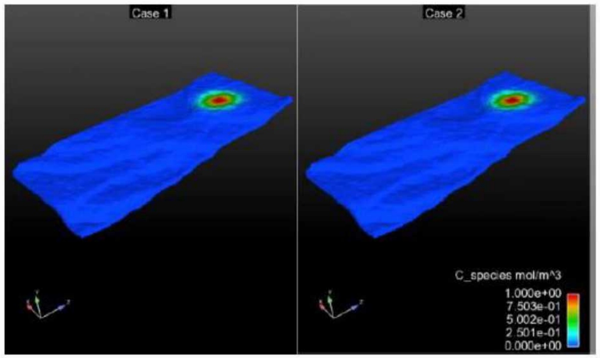
Flow and Dispersion in Fracture

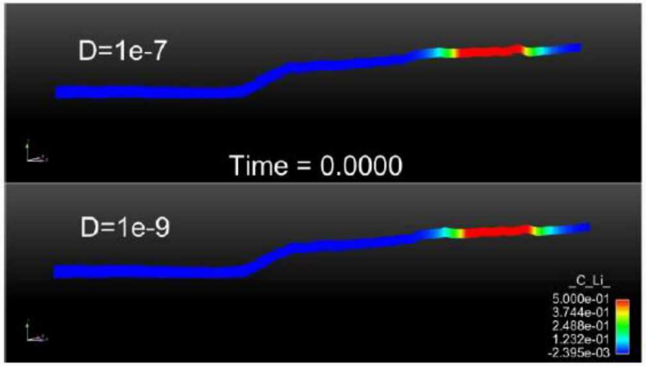


Permeability (fluid dynamics):

$b_{geom} = 0.64$ mm
$k_{hyd} = 4.1 \times 10^{-8}\ m^2$
$b_{hyd} = 0.7$ mm

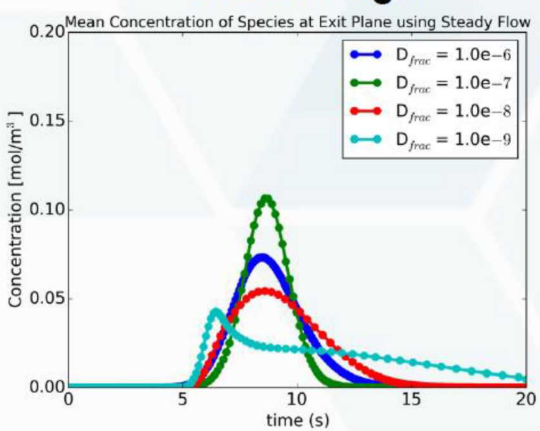
Flow and transport simulation



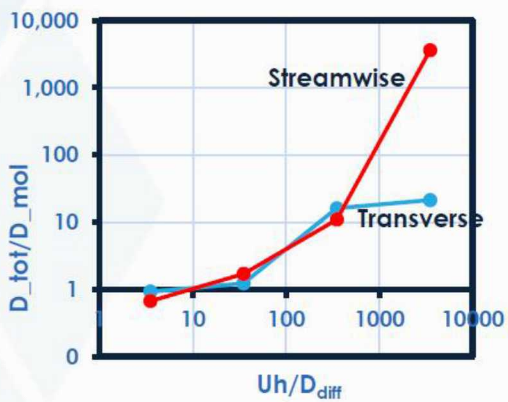


Fluid dynamics and transport in fracture at varying Peclet number

Breakthrough



Dispersion (2nd moment)

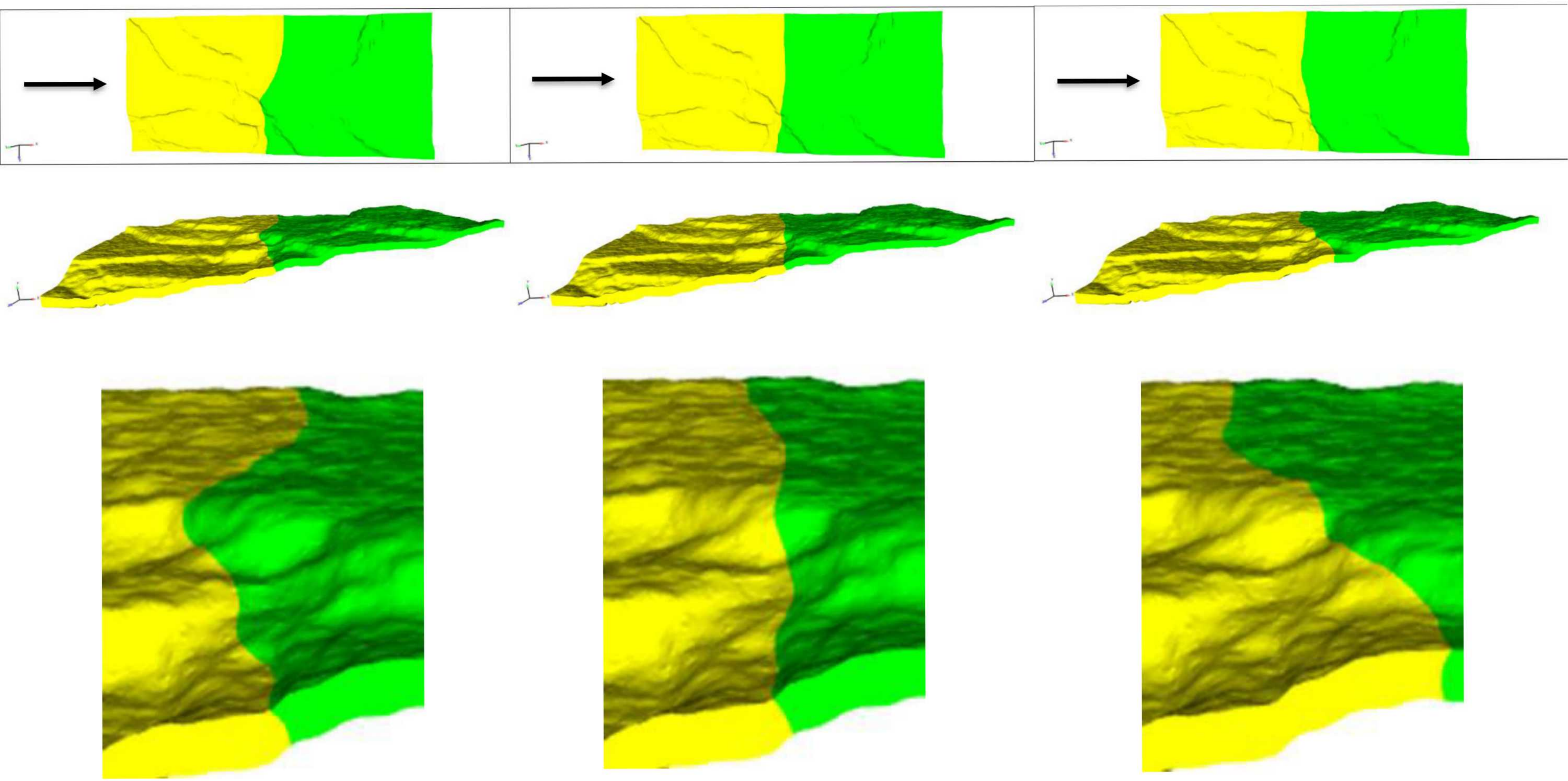


Long tails at large Pe

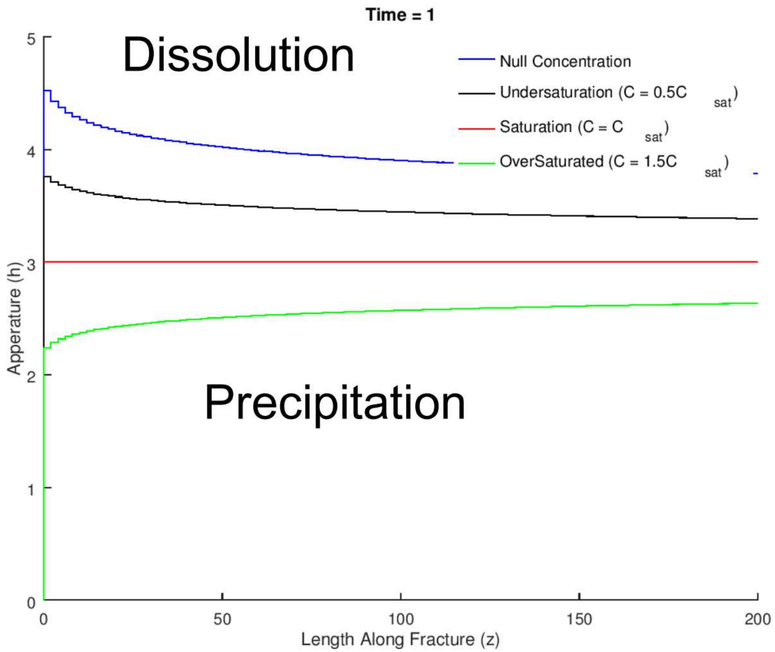
Multiphase Flow Simulations

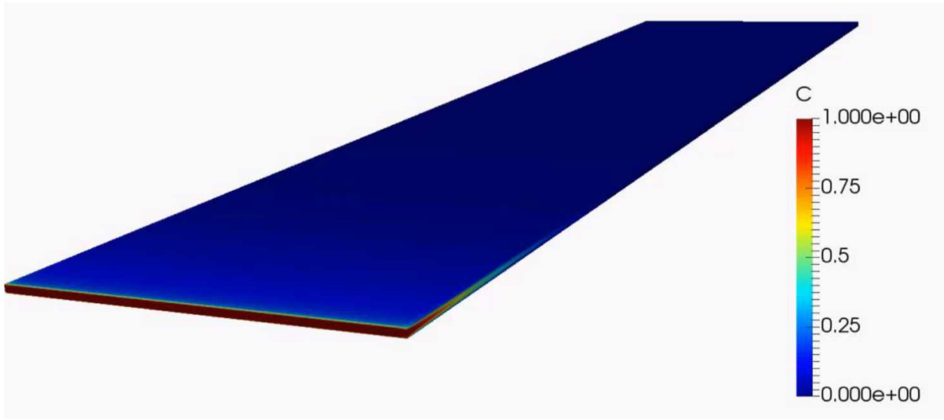
Contact angle variations (flow from left to right)

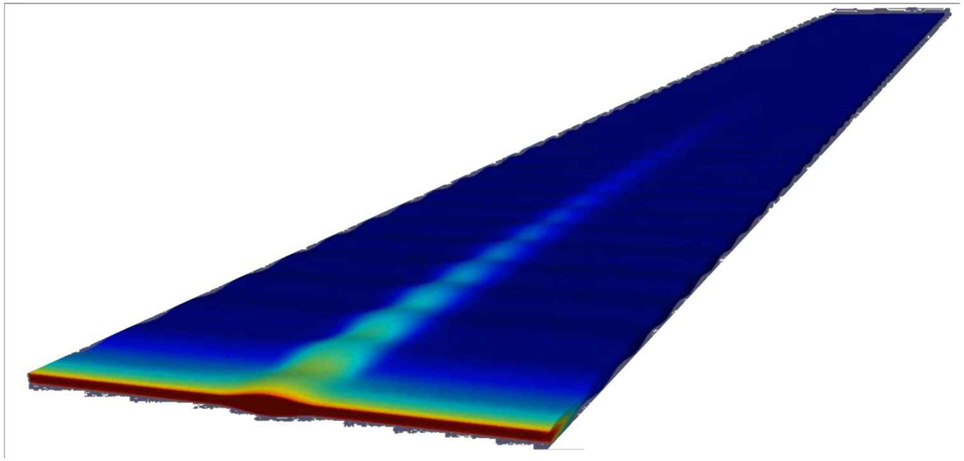
CA = 120 degree | CA = 100 degree | CA = 55 degree

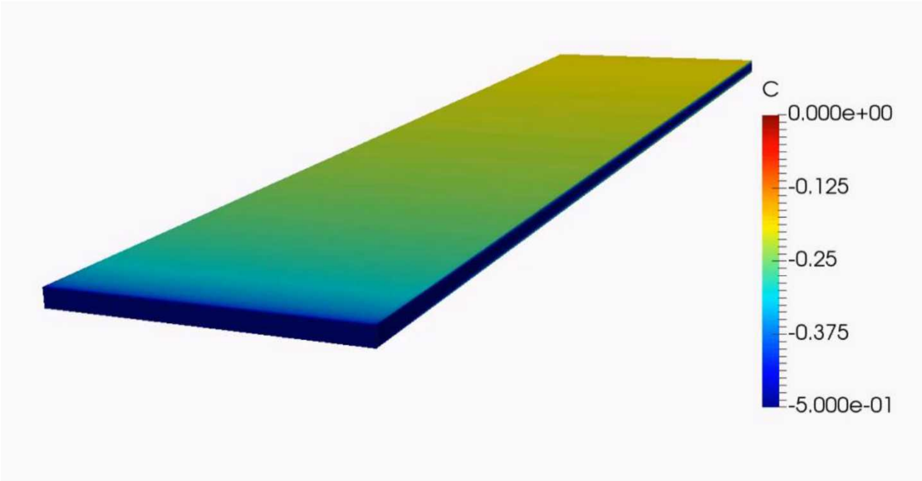


Reactive Transport Simulations







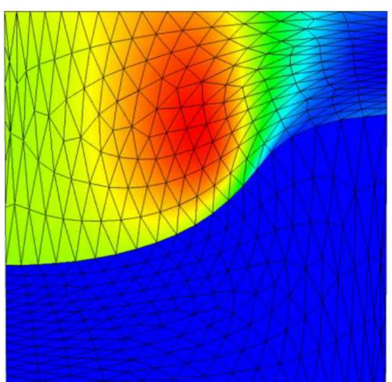
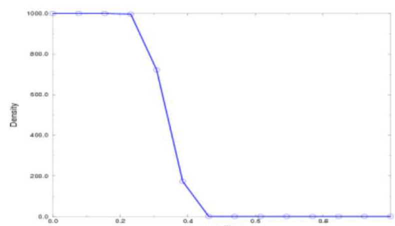
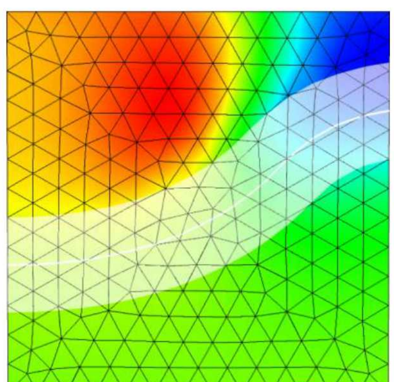
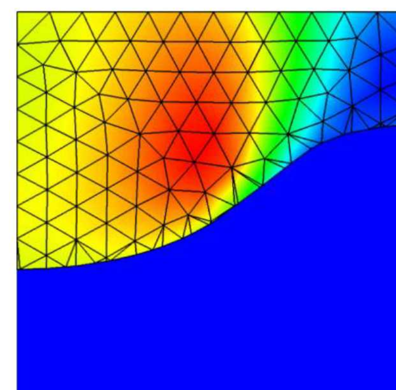


Using an OpenFOAM modified from Starchenko et al. (2016, JGR)

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

Finite Element Methods for Moving Interfaces

		Enriched Finite Element Methods	
ALE	Diffuse LS	XFEM	CDFEM
• Separate, static blocks for gas and liquid phases • Static discretization 	• Single block with smooth transition between gas and liquid phases • Static discretization  	• Single block with sharply enriched elements (weak or strong) spanning gas and liquid phases • Interfacial elements are dynamically enriched to describe phases	• Separate, dynamic blocks for gas and liquid phases • Interfacial elements are dynamically decomposed into elements that conform to phases 

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ermal Applications Tested at Sandia