Predicting Transmissivity of a Fracture Under Shearing

Amir Mofakham[1], M. Stadelman[2,3], G. Ahmadi[1,2,3], K. Shanley[2,3,4], D. Crandall[2]

Aug. 2017

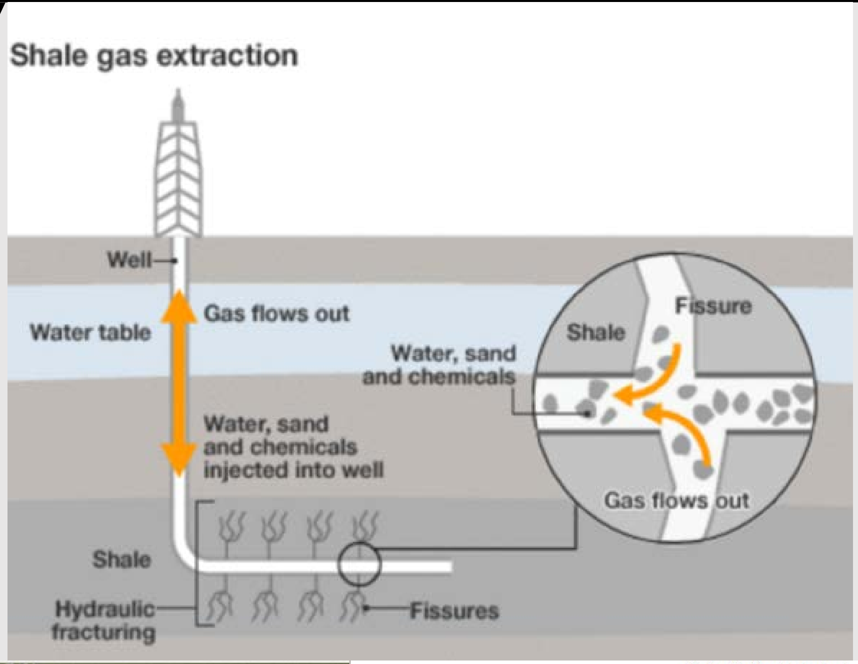
[1] Department of Mechanical and Aeronautical Engineering, Clarkson University, Potsdam, NY
[2] National Energy Technology Laboratory, U.S. Department of Energy, Morgantown, WV
[3] Oak Ridge Institute for Science Education, Oak Ridge, TN
[4] Division of Engineering Programs, State University of New York at New Paltz, New Paltz, NY

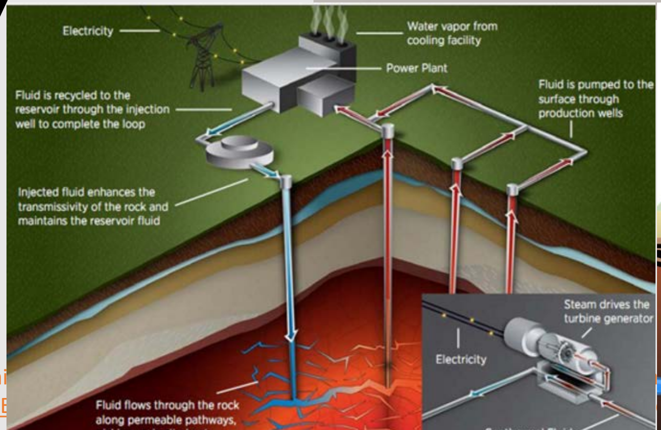
Outline

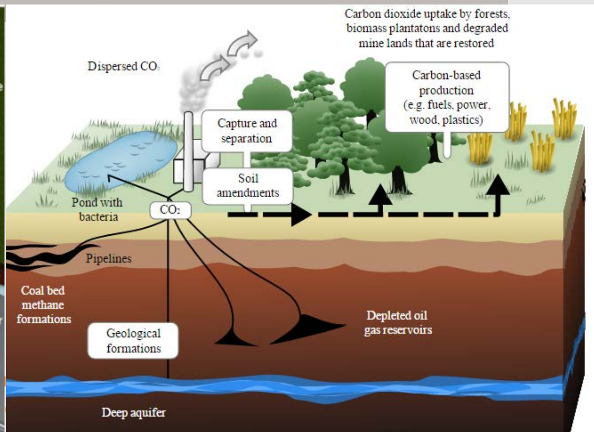
- Introduction
  - Fractures
  - Shearing
- Experimental Tests Rock Fractures at NETL in Morgantown
  - Preparing the sample
  - Mechanical shearing
  - Computed tomography (CT) scan
  - Permeability measurement
- Numerical Models
  - Full Navier-Stokes simulations
  - Modified Local Cubic Law (MLCL) method
  - Improved Cubic Law
- Results and Conclusions

Introduction

- Fractures are conduits in subsurface rocks
  - Unconventional oil and gas resources
  - Carbon sequestration reservoir
  - Enhanced geothermal system



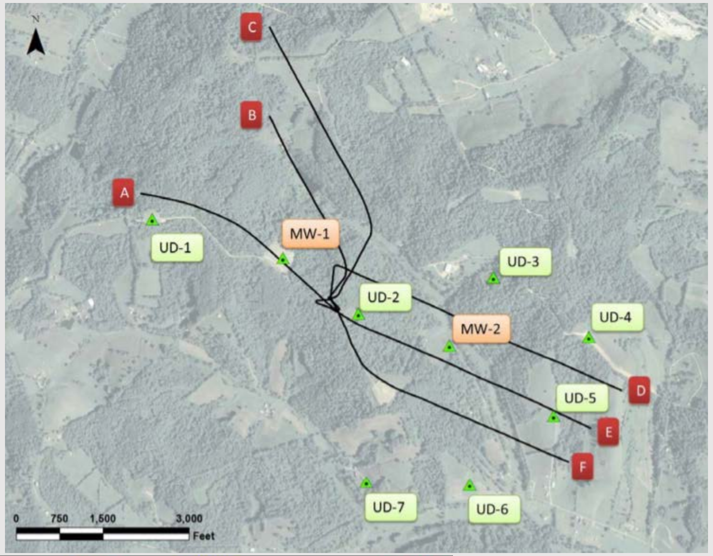


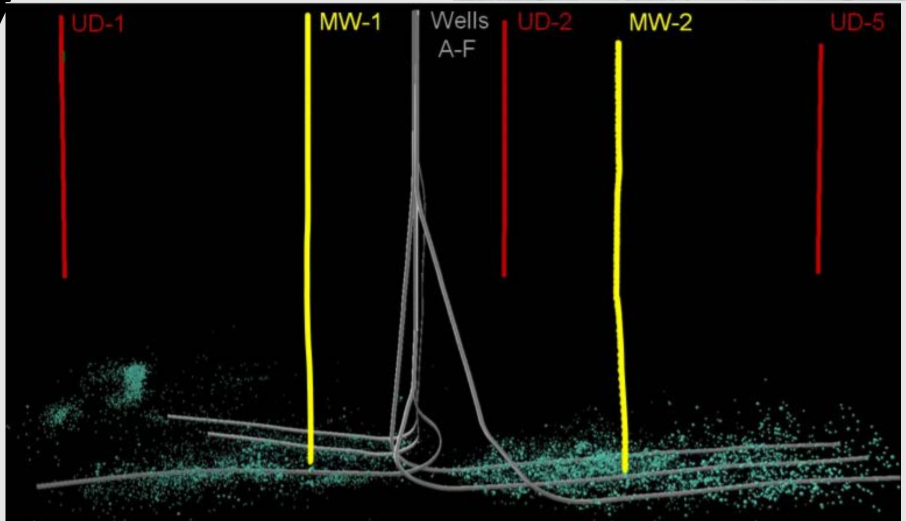


Hammack, R., Harbert, W., Sharma, S., Stewart, B., Capo, R., Wall, A.: An evaluation of fracture growth and gas/fluid mi
Laboratory: NETL-TRS-3-2014. https://www.netl.doe.gov/File%20Library/Research/onsite%20research/publications/NE

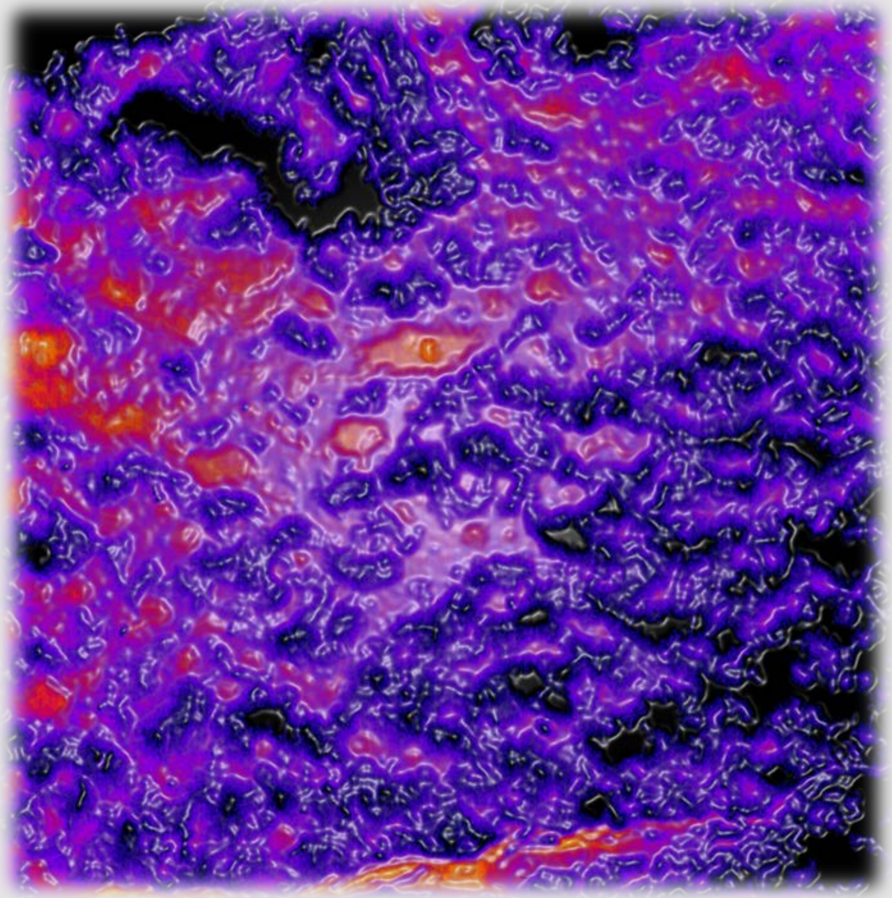
Introduction

- Shearing is associated with micro-seismic events
  - Human Activities
    - Hydraulic fracturing
  - Change properties
    - Geometrical
    - Hydraulic



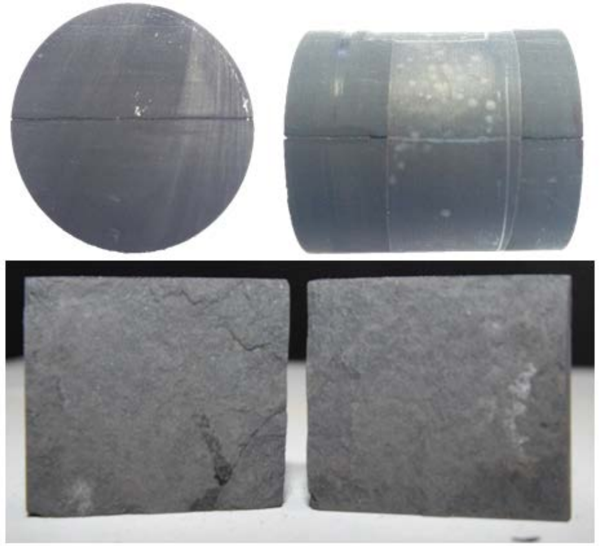


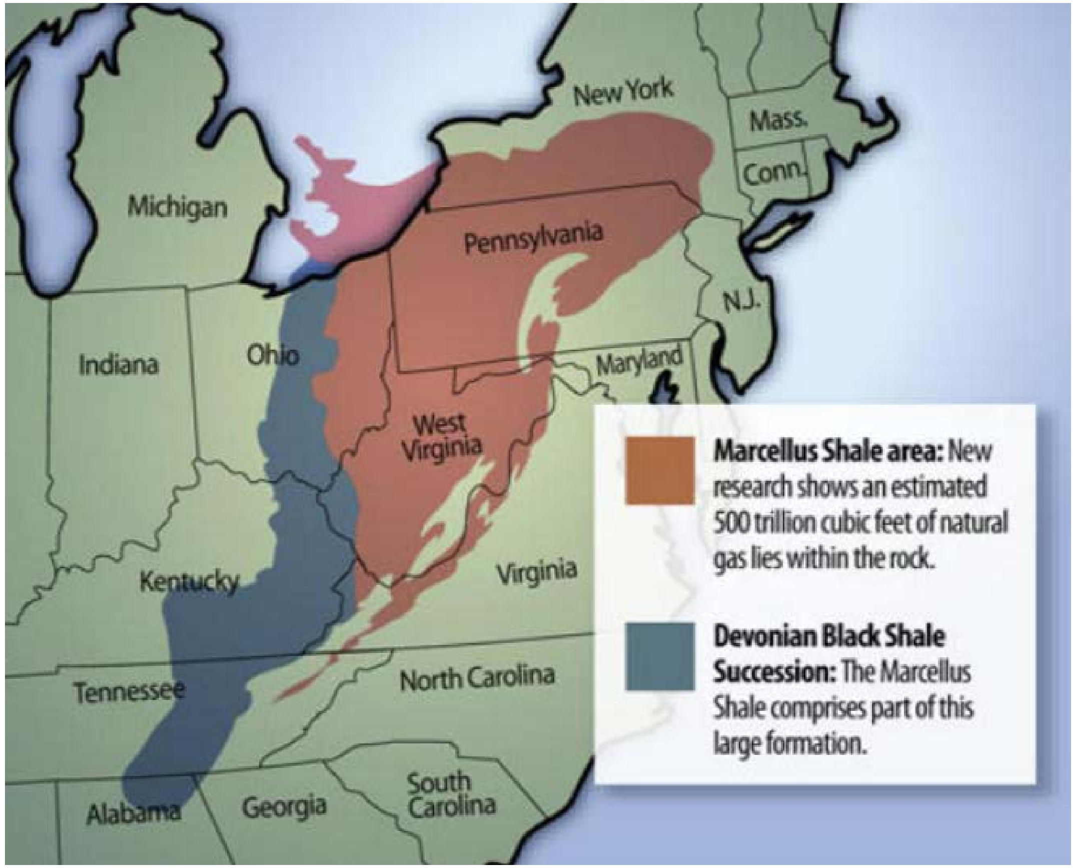
Experimental Section



Sample

- Sample
  - Marcellus shale
    - Giant shale resource of natural gas
  - 3.8 (cm) diameter, 3.8 (cm) length
  - No natural fractures
    - Mechanically fractured

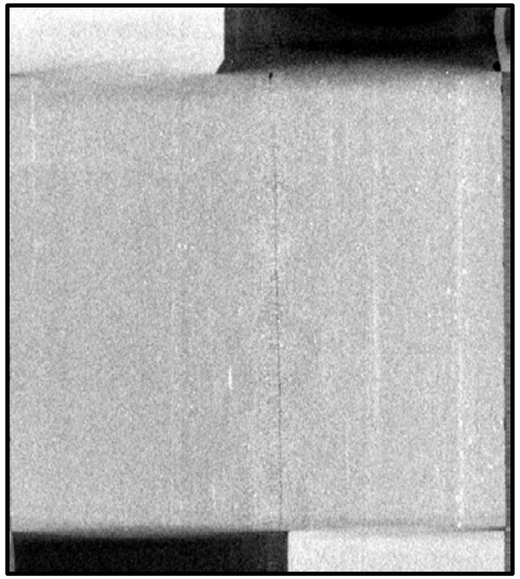


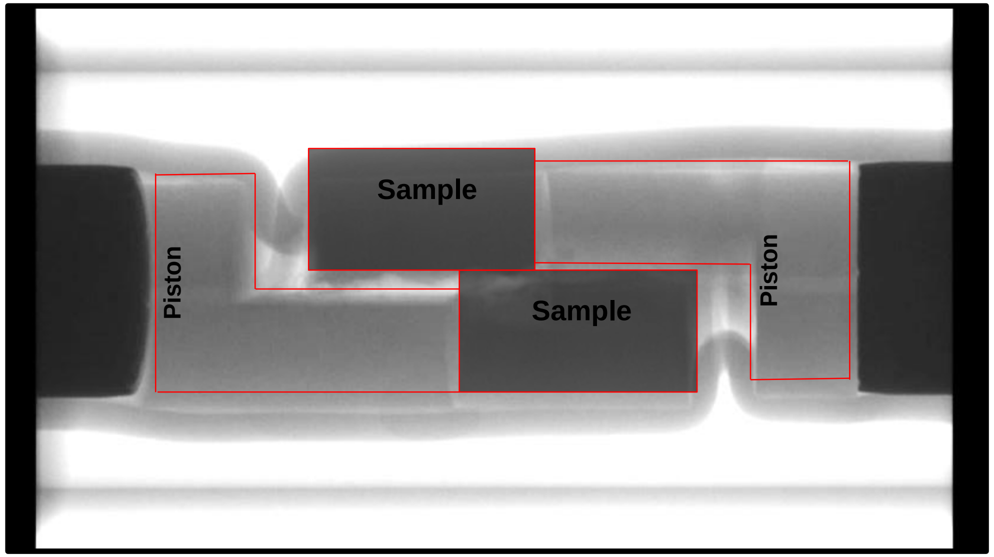


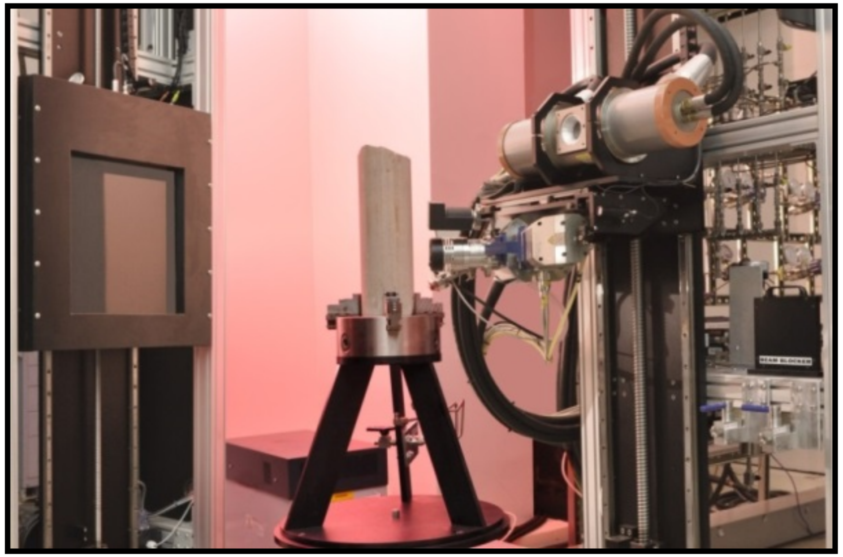
Shearing Apparatus

- Modified pistons within a Hassler core holder to shear fractured rocks in discrete steps
  - Total displacement of 4 cycles: 3.2 (mm)

- Industrial computed tomography (CT) scanning with 26.8(μm) resolution
  - Obtain the geometry of the fracture

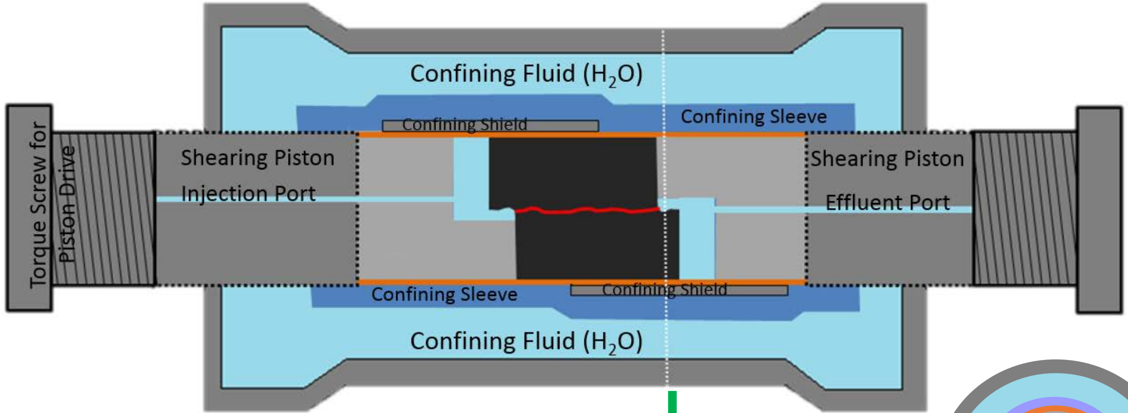




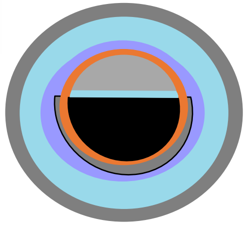


Permeability Measurements

- Water fluid was injected with different flow rates (0-10 mL/min)
- Pressure drops were measured (0-2 MPa)

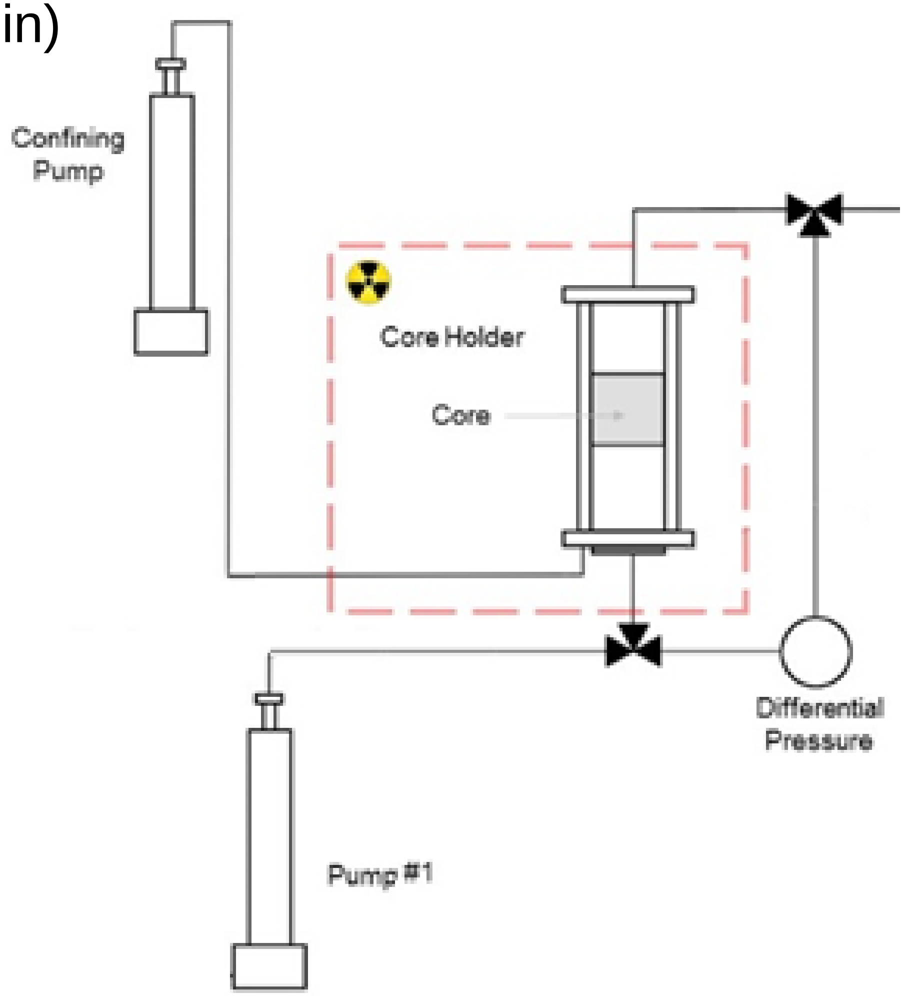


Schematic of current shearing apparatus with core

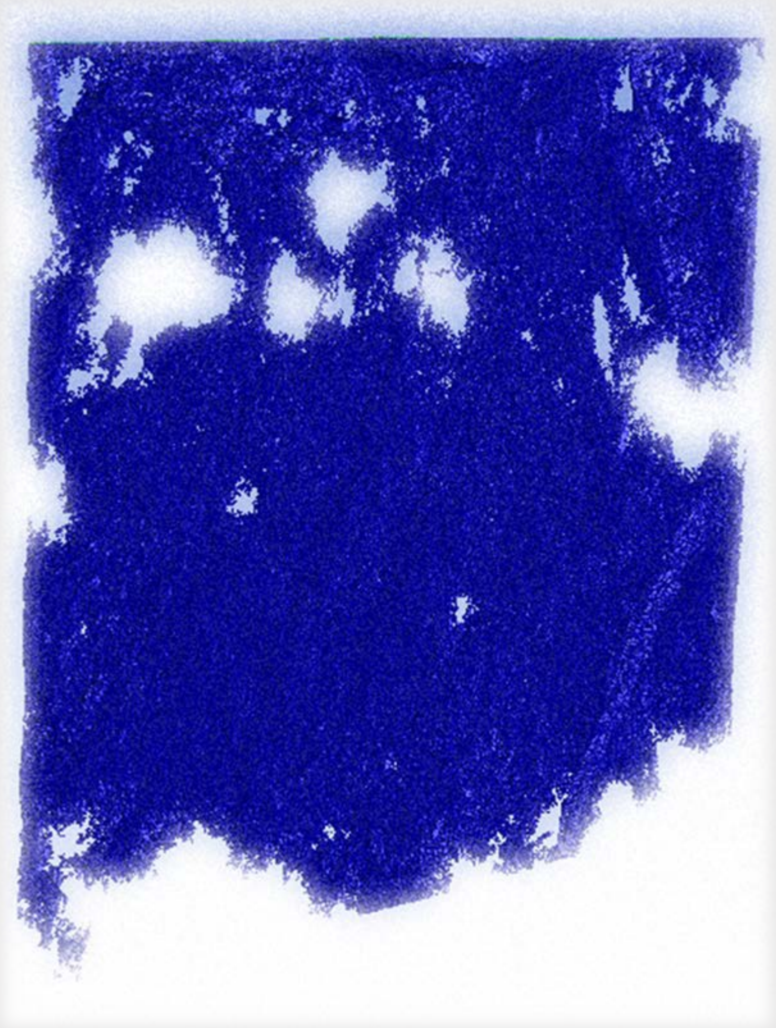


Cross-sectional view

(mm)

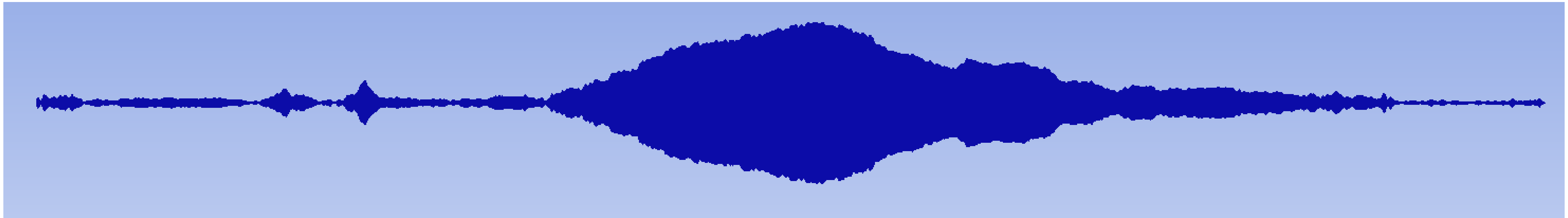


Numerical Section



Generating Geometry

- Geometry
  - Full Map
    - Original resolution
  - Average Map
    - Reduced resolution
    - The small scale features of the rough fracture
    - Need less computational time
    - Effect of scan resolution



Numerical Models

- ANSYS-Fluent Software
  - Solve Conservation of Mass and Momentum Equations

$$\nabla \cdot \mathbf{u} = 0$$

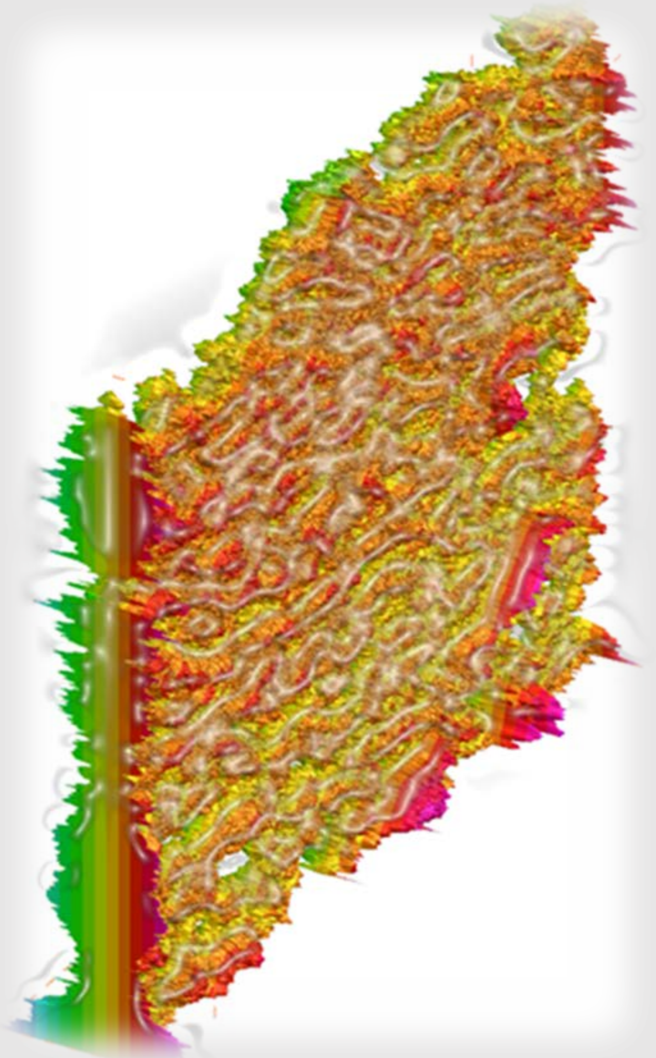
$$\rho\mathbf{u} \cdot \nabla\mathbf{u} = -\nabla\mathrm{P} + \mu\nabla^2\mathbf{u} + \rho\mathbf{g}$$

- Modified Local Cubic Law (MLCL) Model
  - Collection of interconnected small parallel plates
  - Laminar creeping flow
  - Gradual variation
  - Reynolds Equation: $0 = -\nabla P + \mu\nabla^2 \mathrm{u}$
  - $0 = -\mathrm{T}_{\mathrm{x}_{i,j}}\left(\mathrm{P}_{i+1,j} - \mathrm{P}_{i,j}\right) + \mathrm{T}_{\mathrm{x}_{i-1,j}}\left(\mathrm{P}_{i,j} - \mathrm{P}_{i-1,j}\right) - \mathrm{T}_{\mathrm{z}_{i,j}}\left(\mathrm{P}_{i,j+1} - \mathrm{P}_{i,j}\right) + \mathrm{T}_{\mathrm{z}_{i,j-1}}\left(\mathrm{P}_{i,j} - \mathrm{P}_{i,j-1}\right)$
  - $\mathrm{T_x} = \beta_x \frac{\mathrm{h}^3\Delta \mathrm{z}}{12\Delta \mathrm{x}}$, $\mathrm{T_z} = \beta_z \frac{\mathrm{h}^3\Delta x}{12\Delta z}$

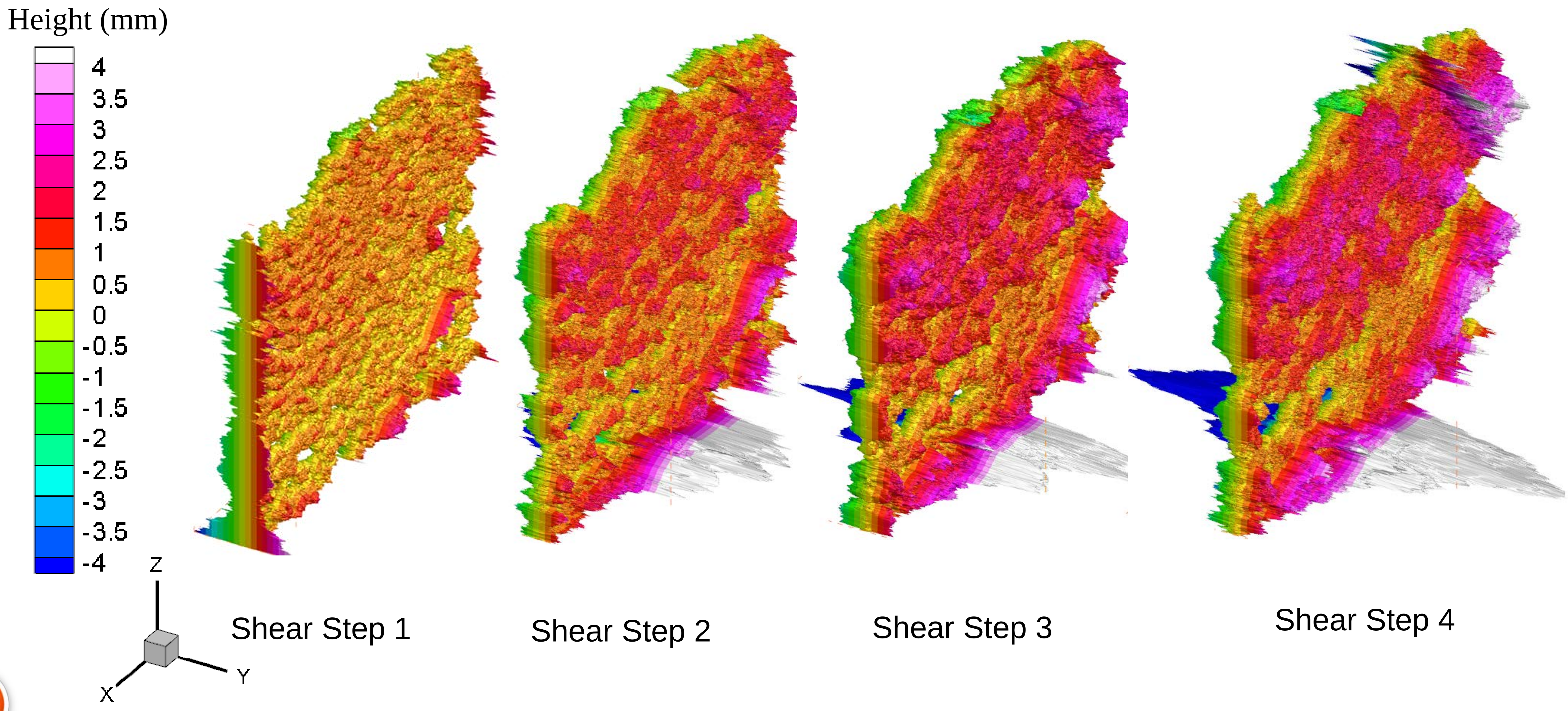
Numerical Models

- Cubic Law
  - $\Delta p = \frac{12\ \mu L}{W {h_m}^3} Q$
- Improved Cubic Law
  - Roughness $h_{eq} = h_m \left(1 + 9\left(\frac{\sigma_{apert}}{h_m}\right)^2\right)^{-\frac{1}{6}}$
  - Inertia and undulation $h_{eq} = h_m \left(1 - \frac{\sigma_{apert}}{h_m}\frac{\sqrt{\sigma_{slope}}}{10}\sqrt{Re}\right)^{\frac{1}{3}}$
  - Equivalent aperture height
    - $h_{eq} = h_m \left(1 + 9\left(\frac{\sigma_{apert}}{h_m}\right)^2\right)^{-\frac{1}{6}} \left(1 - \frac{\sigma_{apert}}{h_m}\frac{\sqrt{\sigma_{slope}}}{10}\sqrt{Re}\right)^{\frac{1}{3}}$
    - $\Delta p = \frac{12\ \mu L}{W {h_{eq}}^3} Q$

Results

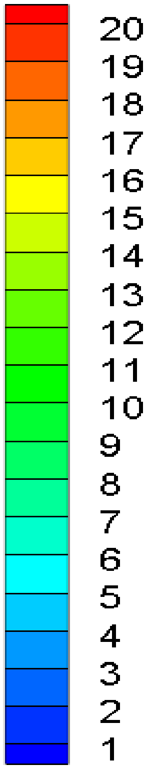


Aperture Maps

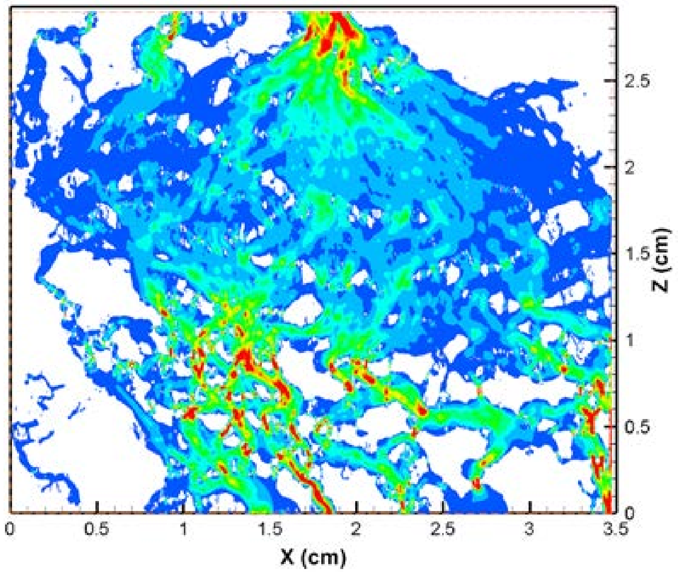


Velocity Contours

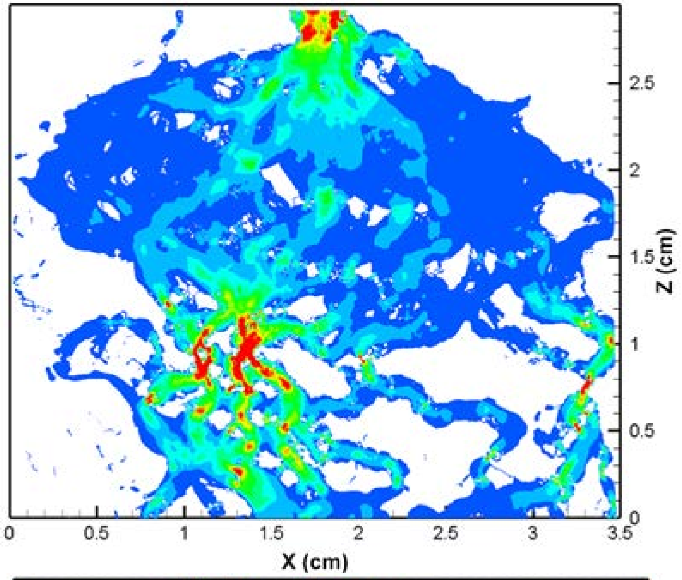
Velocity Magnitude (cm/s)



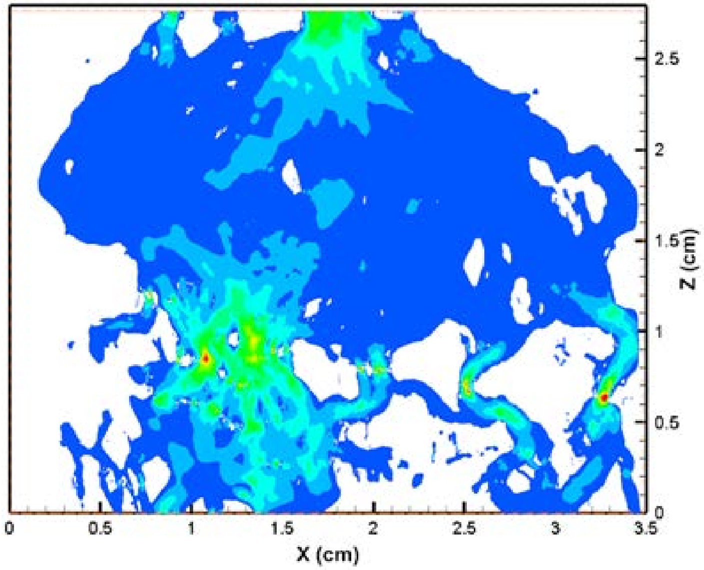
Shear Step 1



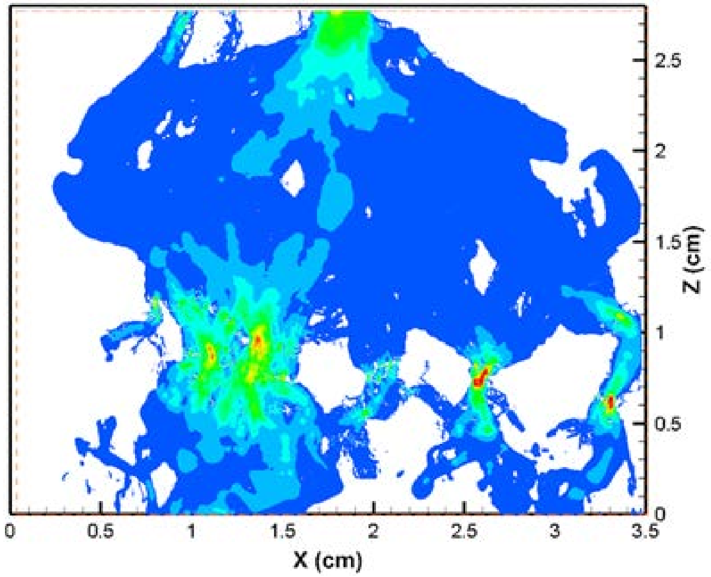
Shear Step 2



Shear Step 3

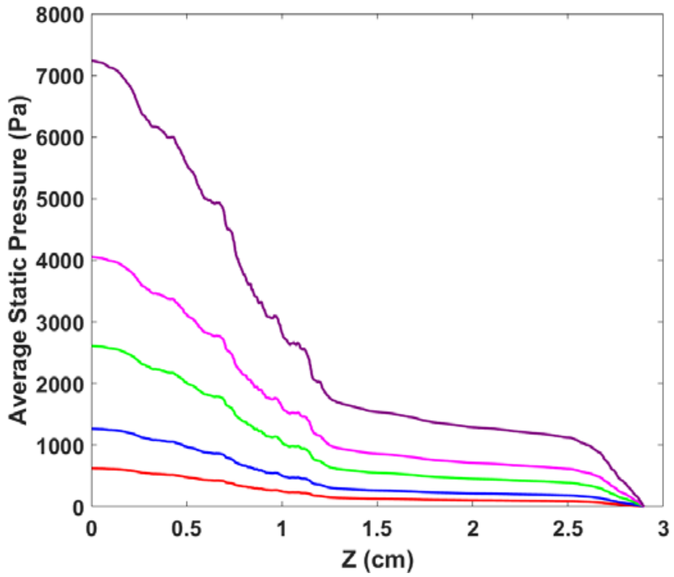


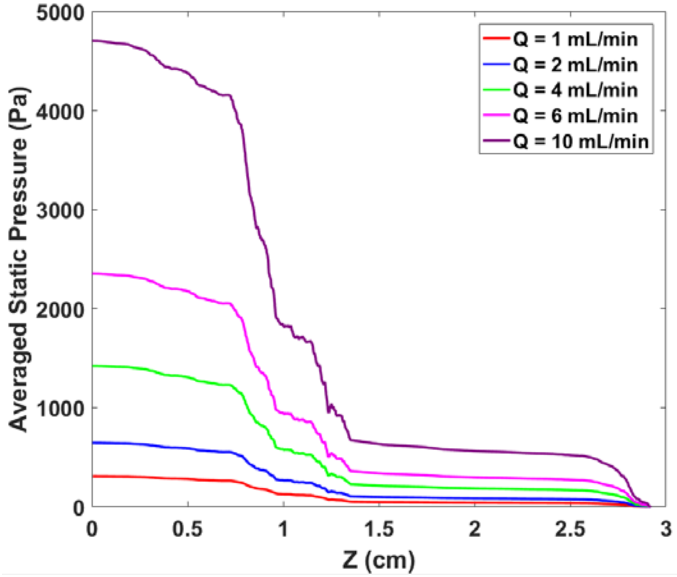
Shear Step 4



Pressure Drops

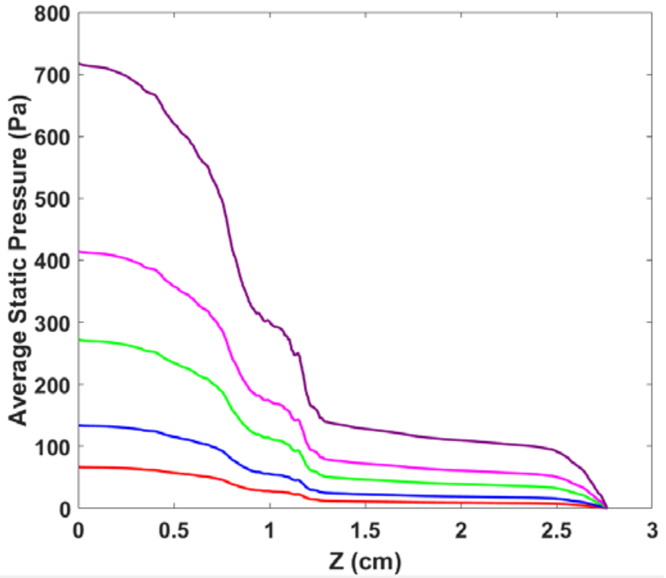
Shear Step 1

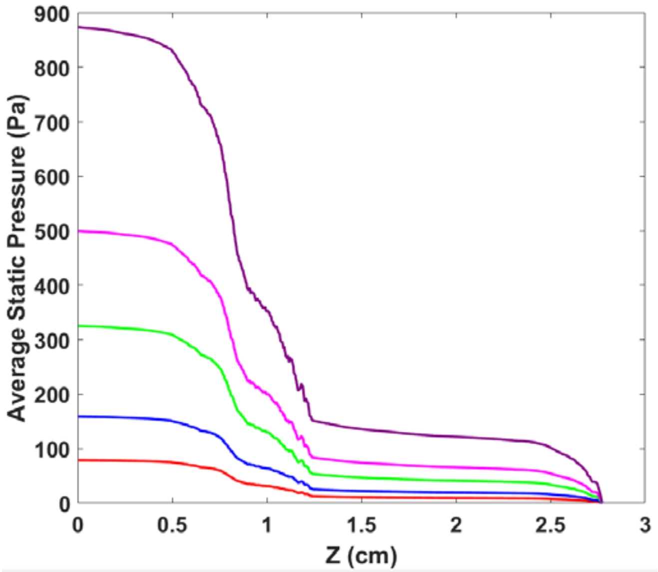




Shear Step 2

Shear Step 3

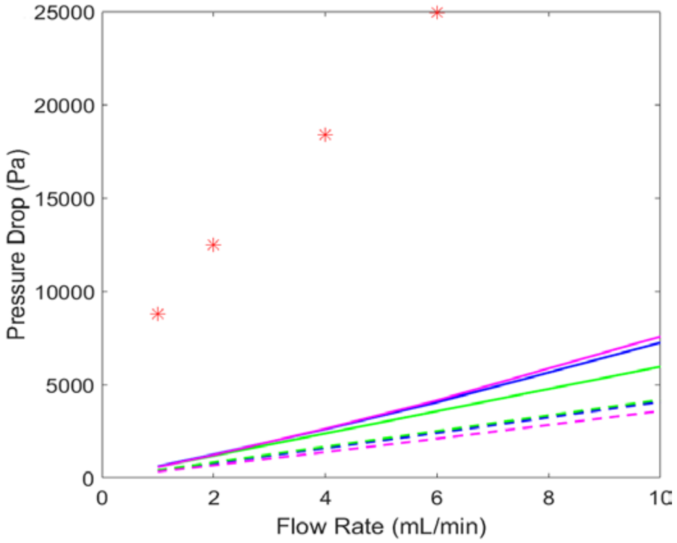




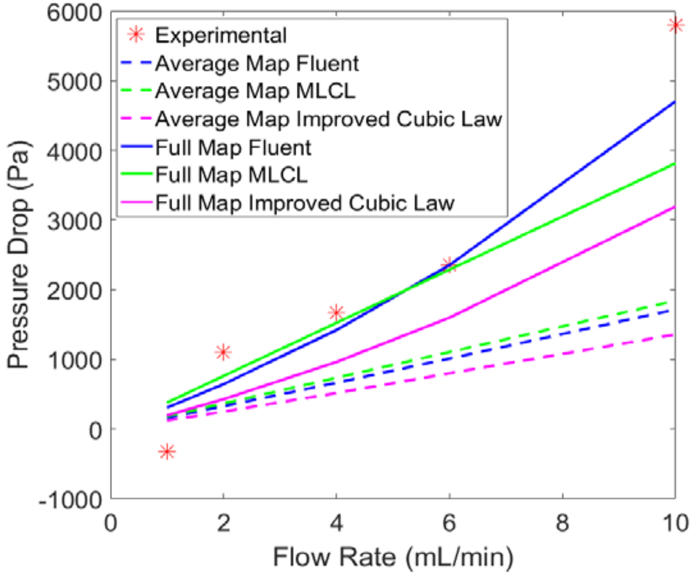
Shear Step 4

Comparison

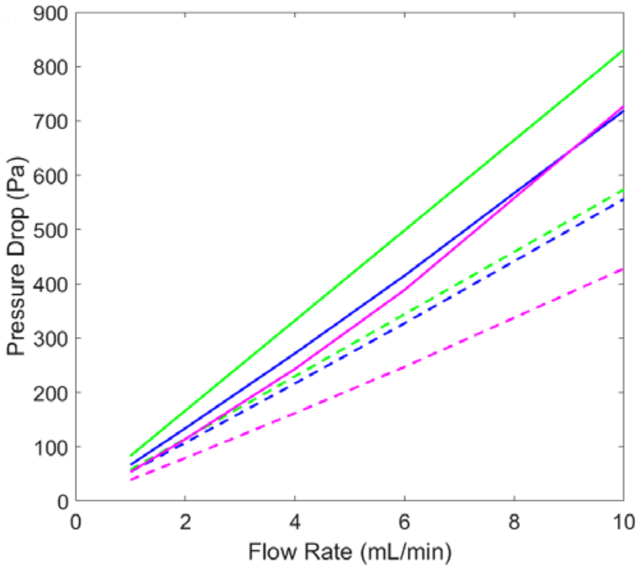
Shear Step 1



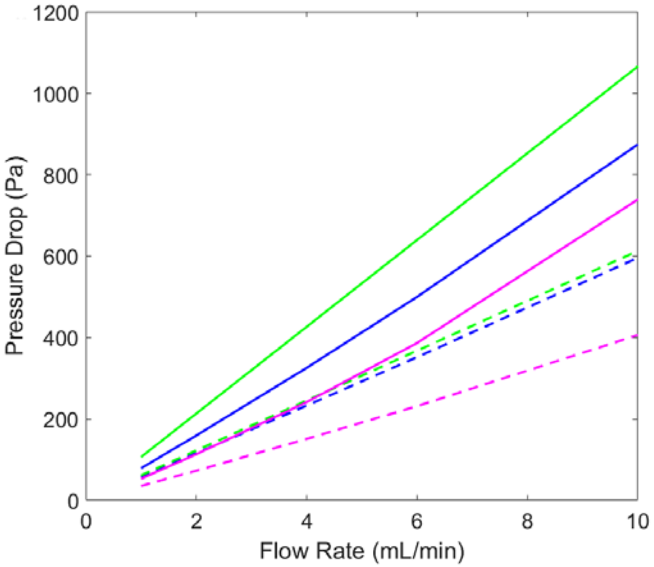
Shear Step 2



Shear Step 3



Shear Step 4

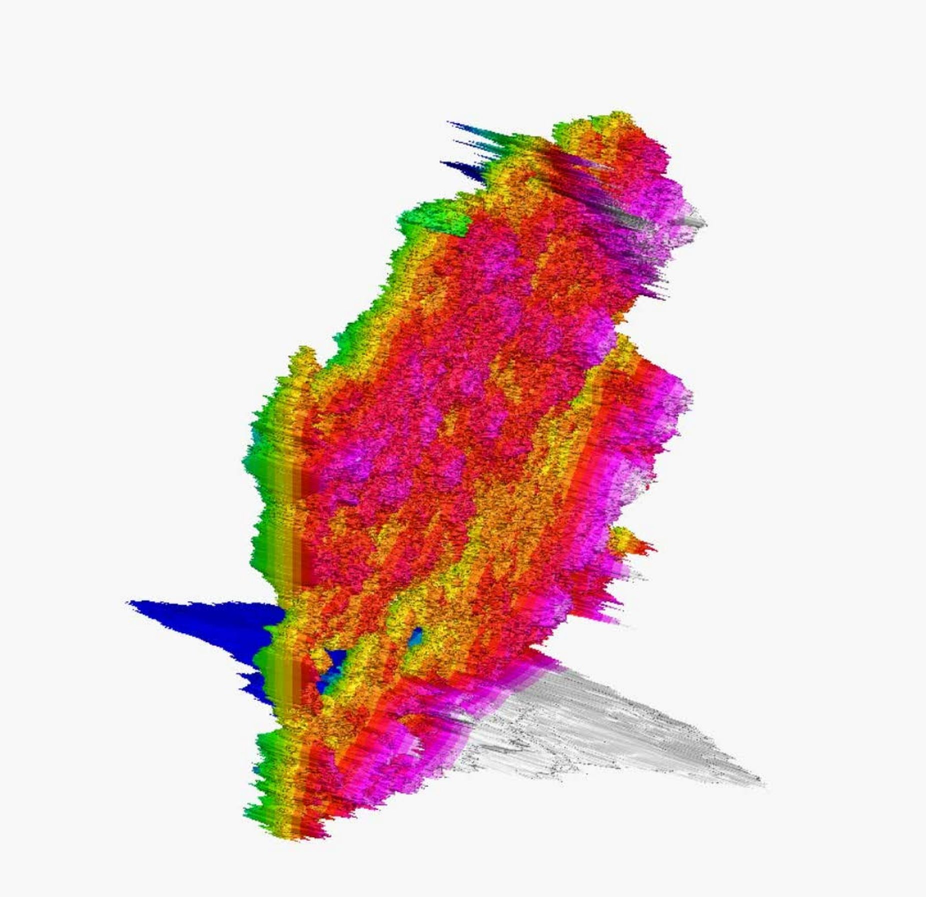


Summary

- A sheared Marcellus shale fracture was studied experimentally.
  - Sheared at different steps.
  - Permeability was measured at different flow rates.
  - The fracture was CT scanned at a high-resolution of 26.8 µm.
  - Geometry of the fractures was captures at each step.
- Low-resolution representations of the CT scans were created at 268 µm (average map).
- The fracture flows were studied numerically for both the average and full maps.
  - ANSYS-Fluent Software.
  - The MLCL method.
  - The Improved Cubic Law.

Conclusions

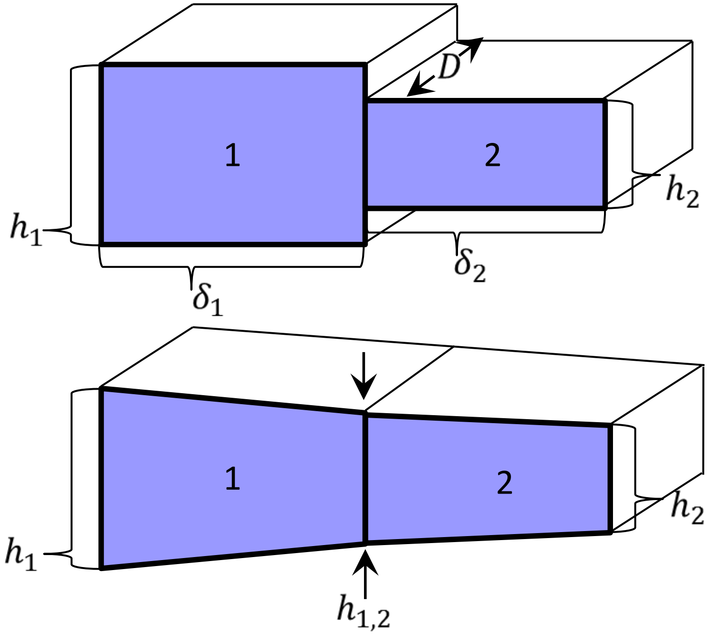
- Shearing increased the average aperture.
- Pressure drops decreased.
- Flow velocities decreased.
- Smaller pressure drops for the average compared to those of the full map.
- Significant effects of small scale surface roughness.
- Importance effects of the resolution of the CT scan.
- Agreement between the numerical predictions.




thank you!

Local Cubic Law Simulations

Grid Block Transition:



Local Cubic Law:

$$Q = \frac{(h_{1,2}^3 \cdot D)}{(12 \cdot \mu)} \cdot \frac{\Delta P_{1,2}}{\delta_{1,2}}$$

Stokes Tapered Plate Correction:

$$\delta_{1,2} = \frac{\delta_1 + \delta_2}{2} \qquad \tan(\theta_{1,2}) = \frac{|h_1 - h_2|}{\delta_{1,2}}$$

$$h_{1,2}^3 = \left[\frac{2 \cdot h_1^2 \cdot h_2^2}{h_1 + h_2}\right] \cdot \left[\frac{3(\tan(\theta_{1,2}) - \theta_{1,2})}{\tan^3(\theta_{1,2})}\right]$$

This method strongly tends towards the smaller aperture

Brush, Thomson. April 3, 2003. Fluid Flow in synthetic rough-walled fractures: Navier-Stokes, Stokes and local cubic law simulations.

Image Processing

- CT scanning relies on capturing a large number of 2D x-ray
- Bulk matrix of rock was generated
- Fracture geometry was isolated via imageJ