Relating fracture aperture to hydraulic and elastodynamic properties of dynamically-stressed under true-triaxial stress conditions

Clay Wood[1], P. Manogharan[2], J. Rivière[2], D. Elsworth[3,1], P. Shokouhi[2], C. Marone[4,1]

[1]Dept. of Geosciences, Pennsylvania State University
[2]Dept. of Engineering Science and Mechanics, Pennsylvania State University
[3]Dept. of Energy and Mineral Engineering, EMS Energy Institute, and G3 Center, PSU
[4]Dipartimento di Scienze della Terra, La Sapienza Università di Roma

Motivation

Dynamic Stressing (seismicity, subsurface stimulation, etc.) is correlated with the following field observations:

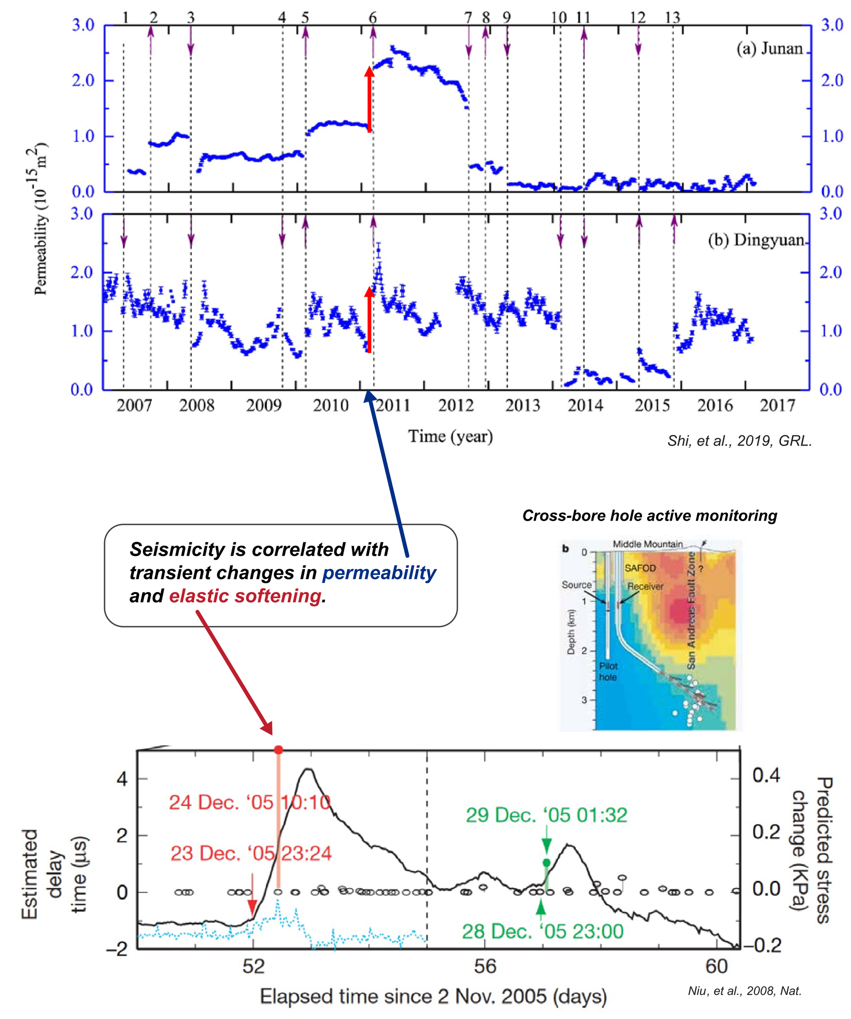
- transient decrease in wave velocity of fractured rock (elastic softening)
- temporary change in permeability

Key Questions:

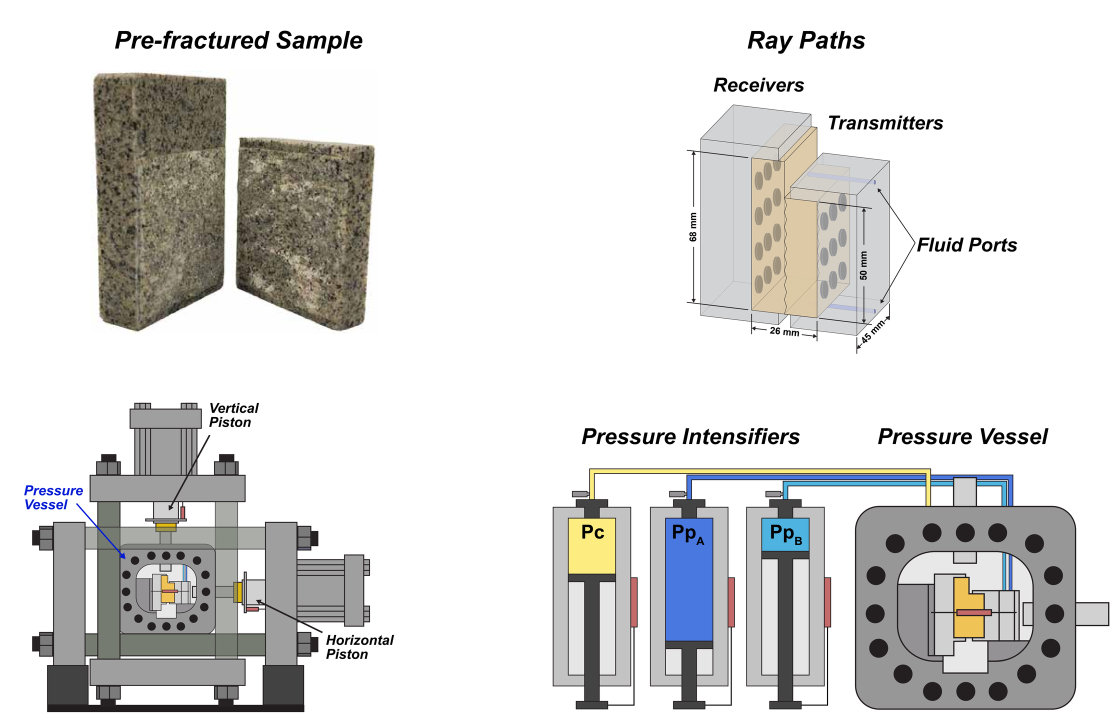
- What are the fundamental mechanisms that relate hydraulic (flow, permeability) and elastic properties of rocks?
- How does the geometry of faults and fracture rocks (i.e. interface aperture) effect the hydraulic and elastic properties?

Focus of this work:

- Relate ***fracture aperture*** to hydro-mechanical properties of dynamically-stressed tensile fractured rock using experimental apparatus.

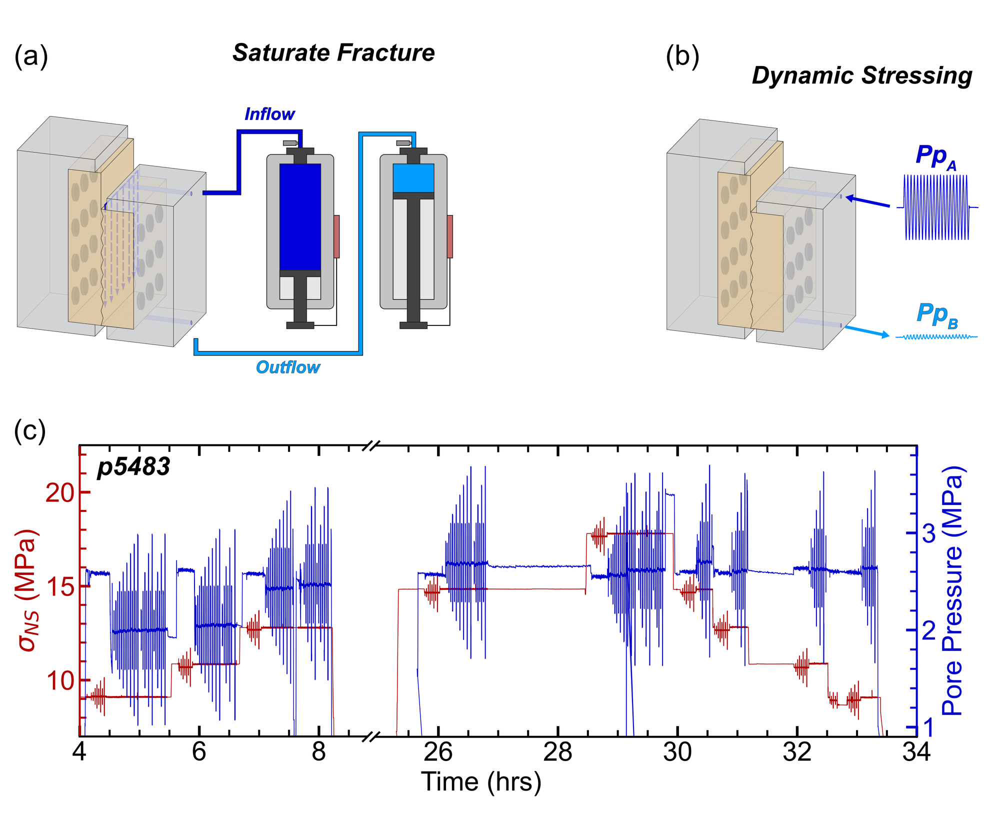


Experimental Configuration



(a) L-shape block of Westerly granite tensile fractured before experiment using a Brazillian Test load frame.
(b) Schematic of sample between two loading platens which contain embedded piezoelectric transducers (PZTs) and fluid ports that confine flow along fracture plane.
(c) Experiments were conducted in the Penn State Rock and Sediment Mechanics laboratory using the Biaxial Deformation Apparatus (Biax). The Biax has servo-controlled vertical and horizontal pistons and a 10 kHz 24-bit analog to digital data recorder.
(d) A pressure vessel is inserted into the Biax to create true triaxial loading. Pressure intensifiers control the confining pressure and fracture (PpA and PpB) fluid pressures.

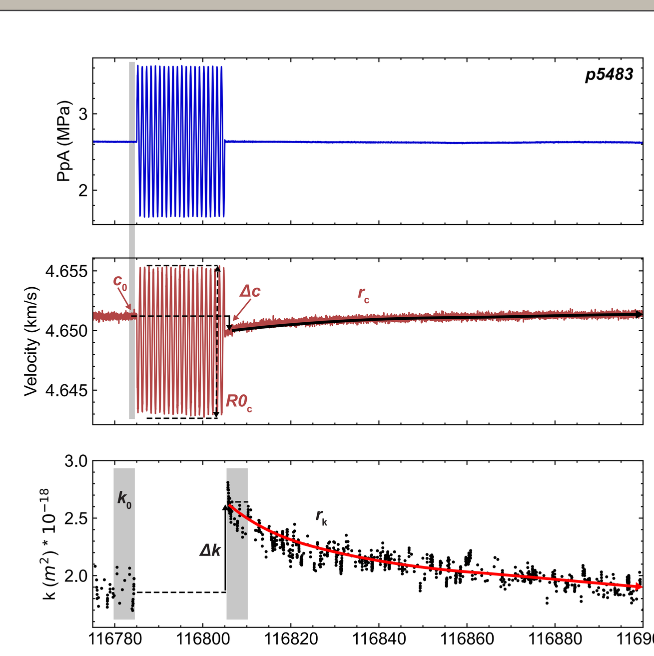
Modulating fracture properties with dynamic stressing



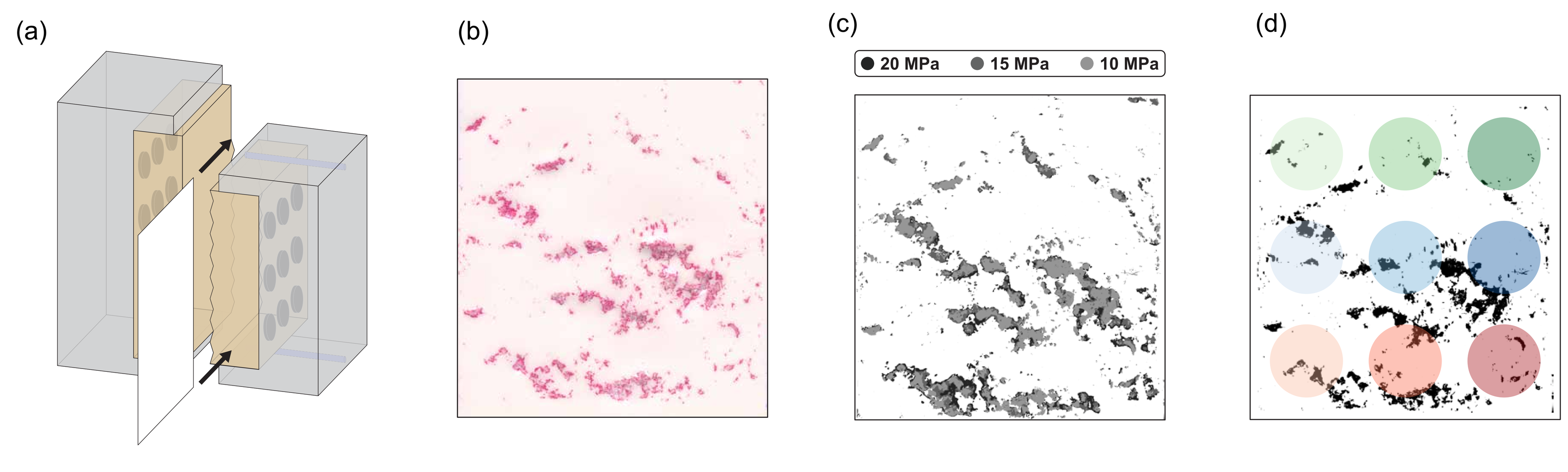
(a) Sample is sealed in a latex membrane and fracture is saturated with water. Then, a 1.5 MPa fluid pressure gradient is applied throughout the experiment.
(b) Dynamic stressing of inlet fluid pressure (PpA) at 1 Hz and amplitudes ranging from 0.2 to 1.0 MPa.
(c) Overview of entire experiment, showing the repeated dynamic stressing protocol and the increasing and decreasing applied normal stress (closing and opening of the fracture aperture).

Elastodynamic and hydraulic responses to dynamic stressing

- Pore pressure oscillation (blue) at 1 MPa amplitude and 1 Hz.
- Dynamically-induced changes in p-wave velocity (red) and permeability (black) are shown below.
- Permeability measurements are shown only for steady state flow when the inlet/outlet flow rates differ by < 5%
- Nonlinearity elastic parameters $\Delta c/c_0$ and $R0_c$ characterize the relative change and the instantaneous change, respectively
- Hydraulic properties of fracture are quantified with relative change in permeability ($\Delta k/k_0$)

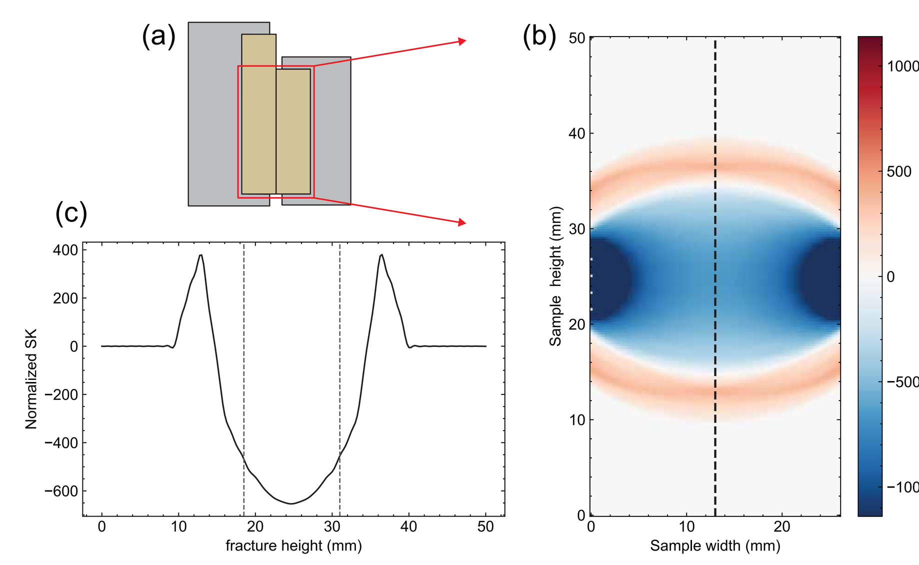


Fracture Characterization

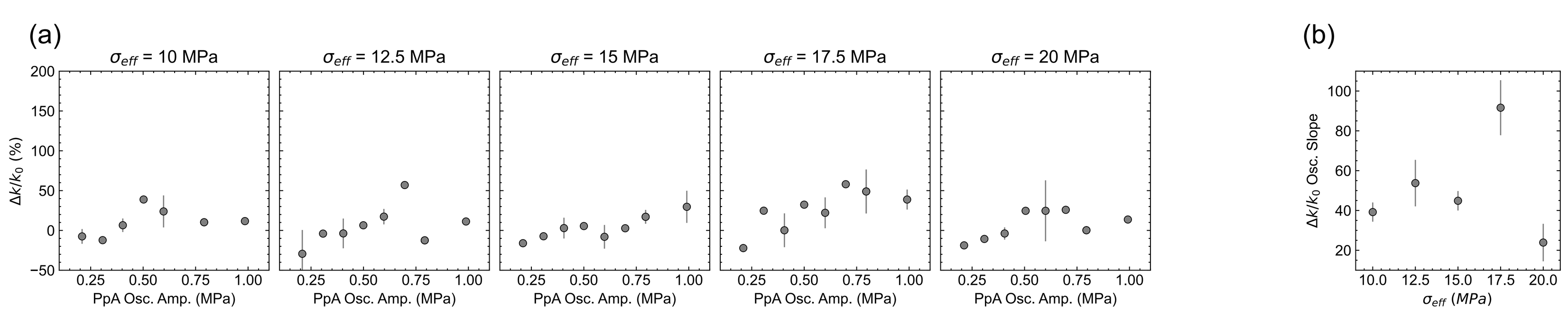


(a) Pressure sensitive film inserted between two halves of fracture.
(b) Example of pressure sensitive film loaded to 10 MPa. Darker magenta shows where fracture is in contact.
(c) Overlay of pressure films to illustrate how contact are evolves with applied stress.
(d) Colored circles demarcate parts of fracture probed by active-source PZTs.

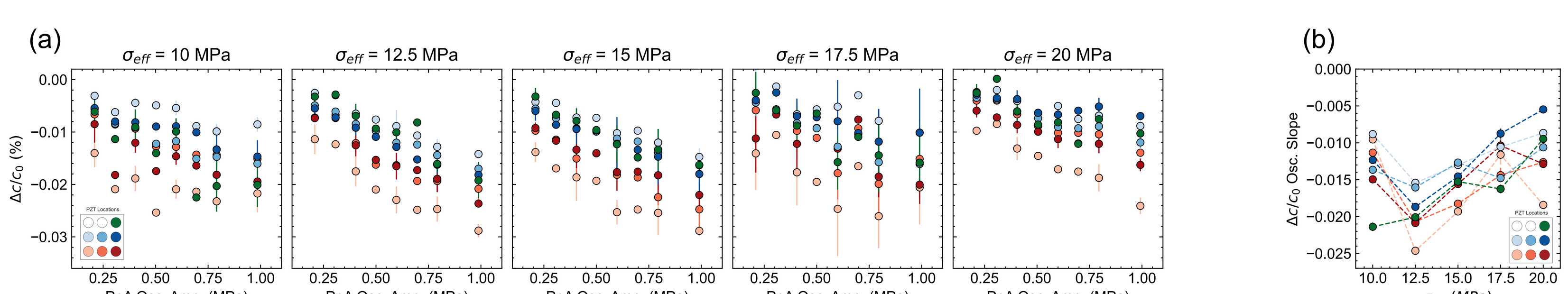
(a) Diagram of L-shape configuration with region of interest outlined in red.
(b) Plot of sensitivity kernel model – intensity represents response of transmitted wave to perturbation – showing the Fresnel zone in blue.
(c) Profile of sensitivity kernel along the fracture plane. Dashed gray vertical lines indicate the half-power bandwidth of the Fresnel zone, where the transmitted waves are most sensitive to perturbations along the travel path (left to right).



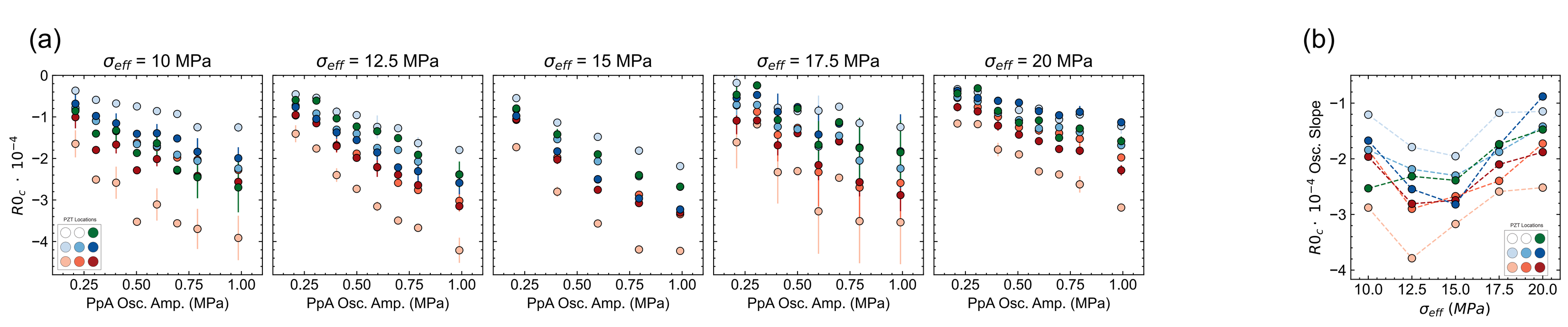
Effect of fracture aperture (applied stress)



(a) Relative change in permeability with increasing PpA oscillation amplitude with increasing applied stress.
(b) Slopes of $\Delta k/k_0$ vs. oscillation amplitude show a general decrease with fracture close.

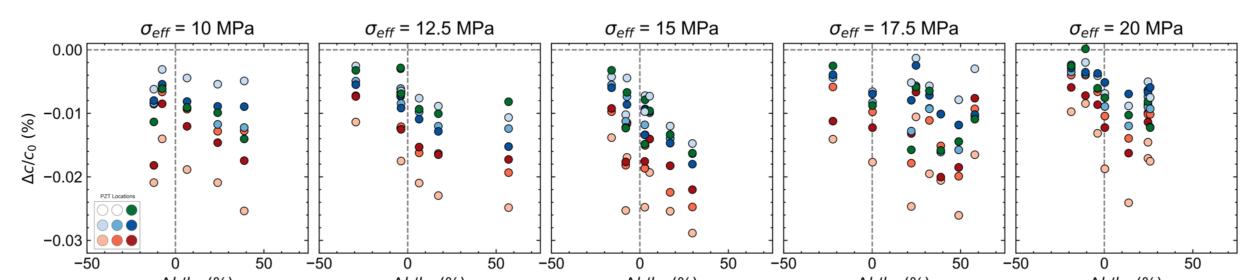


(a) Relative velocity change as a function of PpA oscillation amplitude with increasing applied stress. Colors correspond to PZT transmitter-receiver area across fracture plane.
(b) Magnitude of $\Delta c/c_0$ – this measure of nonlinearity – decreases with progressive fracture closure.



(a) Elastic softening parameter, $R0_c$, as a funciton of PpA oscillation amplitude with increasing applied stress. Colors correspond to PZT transmitter-receiver area across fracture plane.
(b) Magnitude of elastic softening decreases with progressive fracture closure.

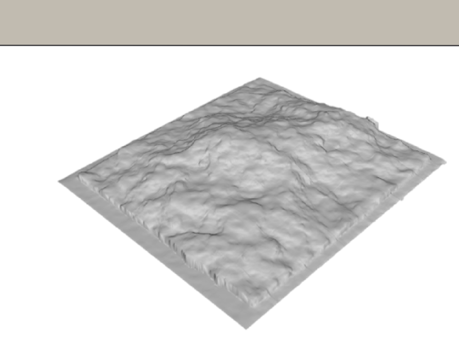
Relating nonlinear elasticity and permeability



Relative change in velocity as a function of relative permeability change. As fracture aperture closes, increased applied stress, both the magnitude of nonlinearity and permeability enchancement decrease.

Future directions

- ***Numerical simulation*** of fluid flow and p-wave transmission using high-resolution profilometry, constrained by experimental data.
- Determining the effect of ***roughness*** on elastodynamic and hydraulic properties of fractured rock



PennState College of Earth and Mineral Sciences
PennSUL Penn State Ultrasonics Lab
U.S. Department of Energy Office of Science

This work is supported by DOE-SC0017585 to PS.
CM acknowledges support from the European Research Council Advance Grant 835012 (TECTONIC) and US Department of Energy grants DE-SC0020512 and DE-EE0008763