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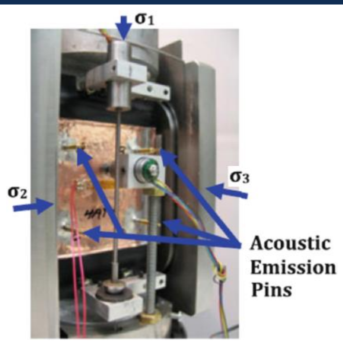

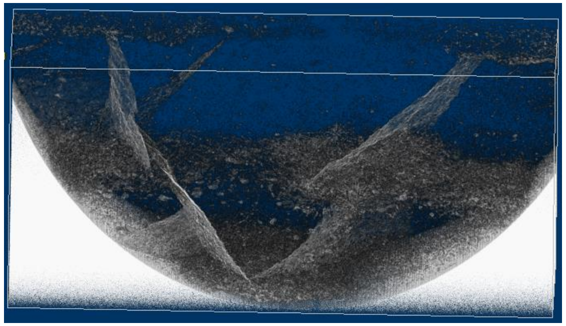

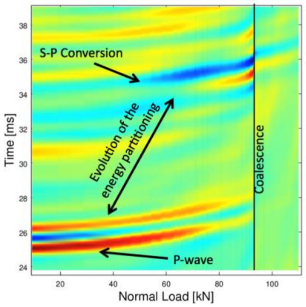

Integrated Geomechanics and Geophysics in Induced Seismicity: Trigger Physics

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Laura Pyrak-Nolte & Antonio Bobet (Purdue Univ.)

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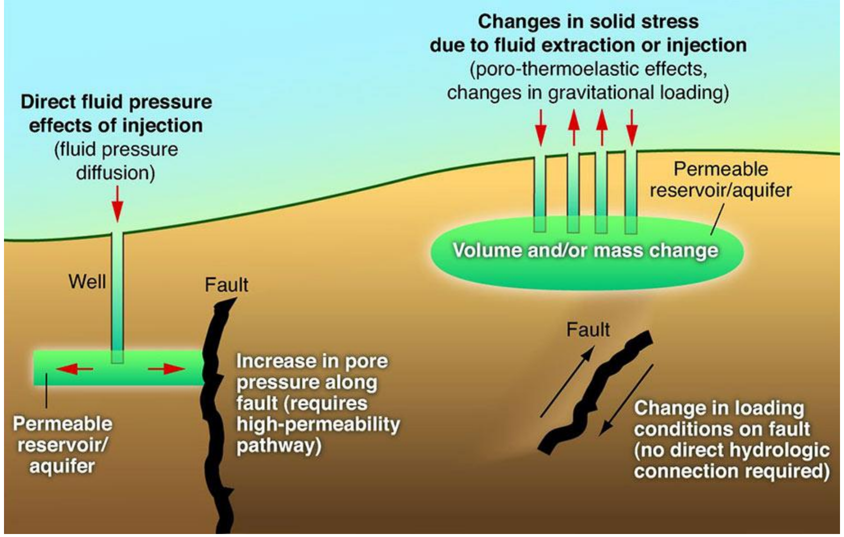
U.S. DEPARTMENT OF ENERGY | NNSA National Nuclear Security Administration | LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT | PURDUE UNIVERSITY

Project Purpose

- Fluid injection or withdrawal causes changes in pore pressure, resulting in stress variations, hydraulic fracturing, fault (re-)activation, and/or fluid saturation changes
- Methodology to reduce risks of induced seismicity and improve modern energy activities in the subsurface:
  - Disposal of water associated with energy extraction (e.g., oil and gas)
  - Geothermal energy production
  - Subsurface carbon storage

Induced (human-caused) seismicity

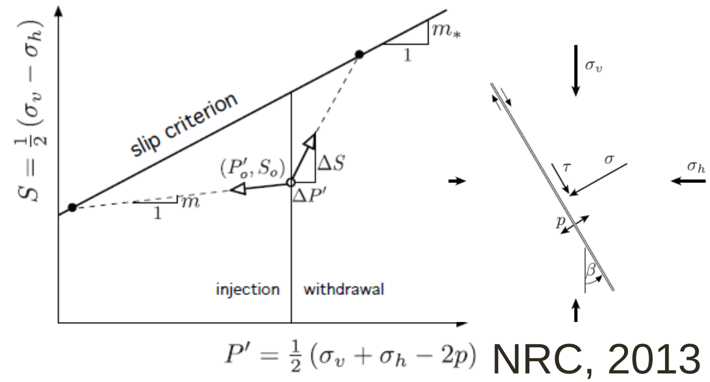


USGS: http://earthquake.usgs.gov/Research/induced/modeling.php

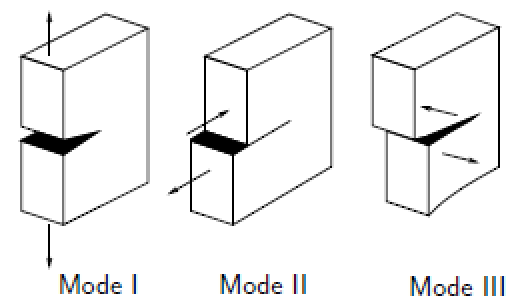
- New groundwork for remote characterization of rock failure by identifying the precursors to the induced seismicity in fractured systems

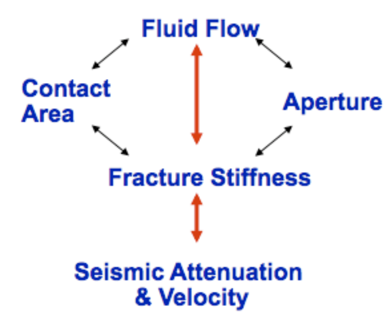
Shortcomings of current understanding of induced seismicity in mechanical discontinuities

- Continuum models employing simple Mohr-Coulomb theory are limited in their ability to account for mechanical discontinuities such as a fracture and/or fault system and induced seismicity.
- Crack initiation, propagation and coalescence of pre-existing discontinuities loaded in mixed mode I-II-III has remained virtually unexplored.
- Precursor(s) to the induced seismicity from existing fracture systems - linking mechanical discontinuities, fracture mechanics, pore pressures and stress to the geophysical signatures – is key, yet remains elusive as a result of the heterogeneity and resulting scale dependence.

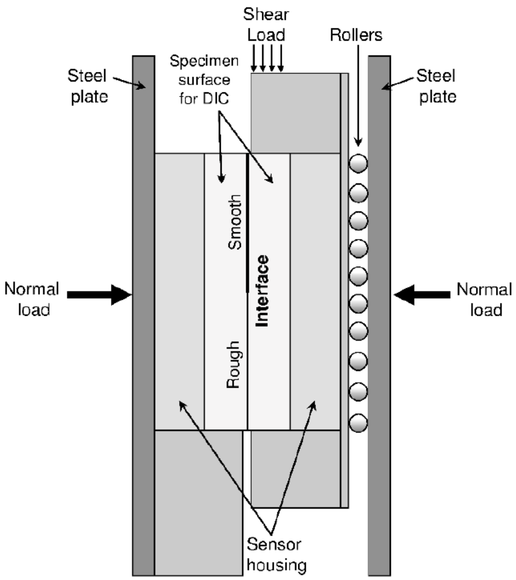


NRC, 2013



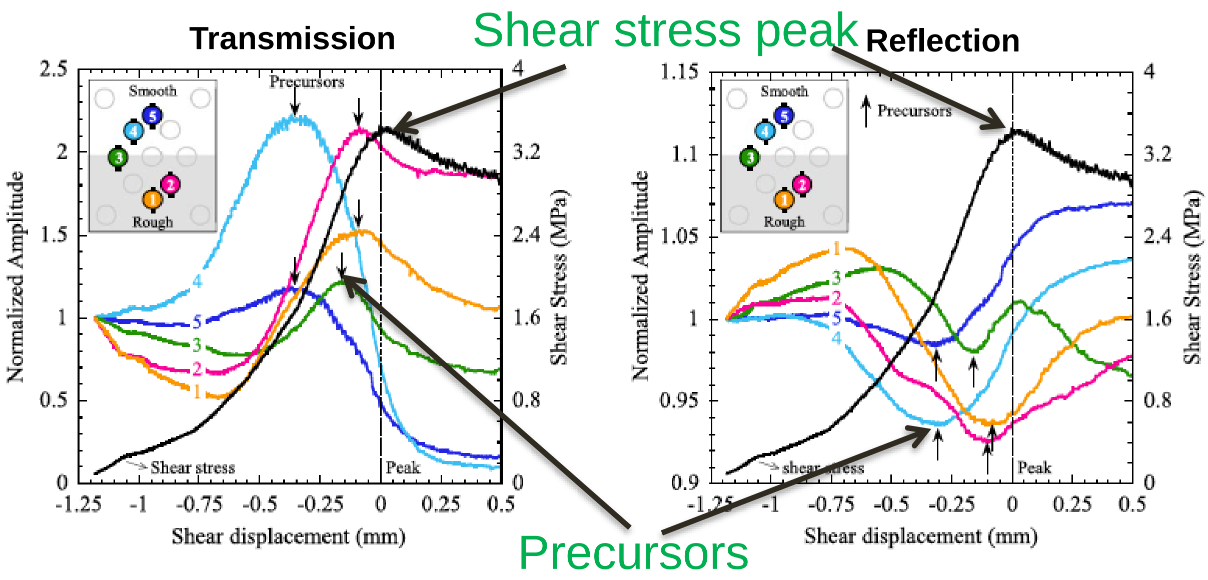


Precursors to Slip along a Mechanical Discontinuity



Bi-axial testing

(Hedayat et al, 2014)



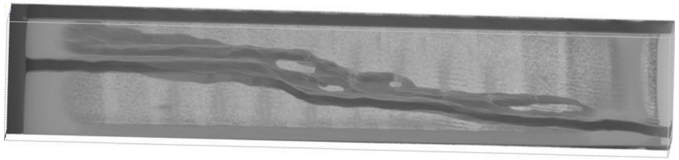
► Increase in transmitted shear wave amplitude prior to achieving the peak shear stress

► Post pre-peak seismic response depends on the frictional characteristics of the interface

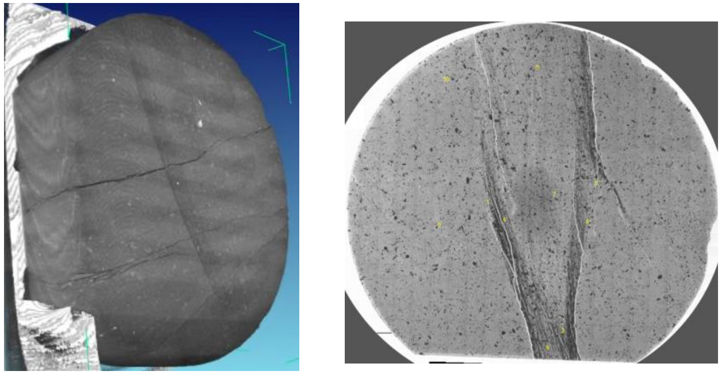
Need to determine how these results apply in a more realistic setting with spatial and temporal variations in pre-existing discontinuities, stress and pressure fields, fluid migration and rock types

Micro-Computed Tomography and Acoustic Microscopy

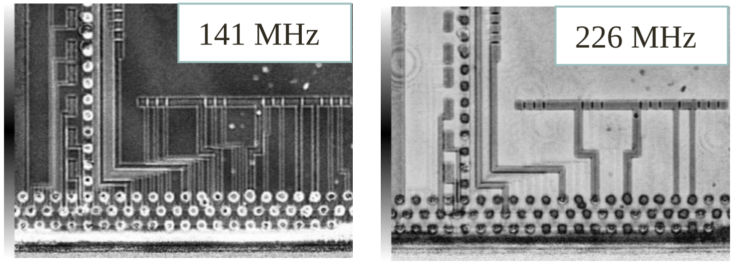
- X-ray micro-computed tomography (microCT) and acoustic microscopy (AM) at Sandia's X-Ray CSAM Lab
  - Characterize initial and induced fractures before, during, and after testing
  - Verify the seismically interpreted fracture evolution
- Reconstructed digital rock based on microCT & AM:
  - Create numerical mesh for forward modeling of fracture initiation and propagation & coupled flow and mechanical simulations
- In-situ 3D & 4D imaging of testing
  - Digital volume correlation (DVC)



3D CT image of printed fracture



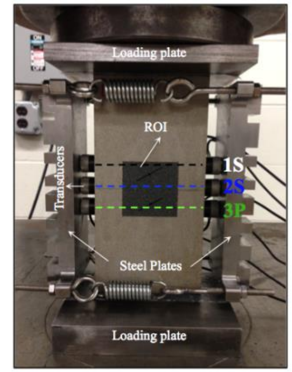
CT image of carbonate rock & thin section



Acoustic Microscopy images: Various features resonate differently

Fracturing Testing and Seismic Signal Acquisition

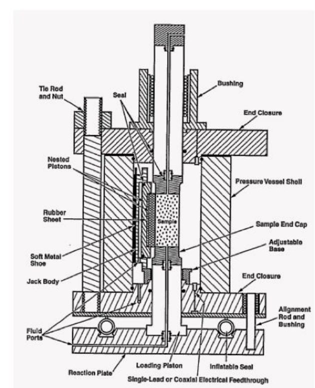
- Experimental specimens with multiple pre-existing flaws:
  - Natural rocks (Indiana limestone, granite, or other relevant rock types)
  - 3D printed samples from Sandia
  - Flaw geometry will be designed to yield both compression and two directions of stresses along the planes of the flaws
  - Dry/fluid saturated, pressure-temperature conditions

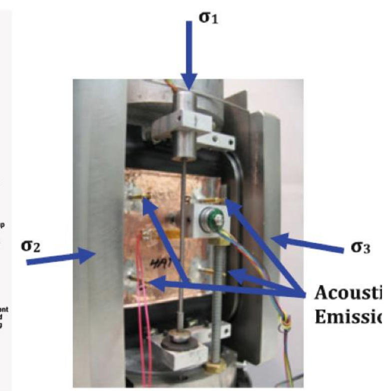


Uni-axial

Bi-axial testing

- Experimental deformations under uniaxial, biaxial, cyclic (compression-compression), and triaxial loadings will be quantified using :
  - Digital Imaging Correlation (DIC - resolution ~ 2.5 x 10-6 m) and DVC (3D with micro-CT) to monitor crack tips for initiation and propagation phenomena of new cracks and coalescence
  - Stationary seismic arrays will record the full waveform using both transmitted and reflected waves during loading

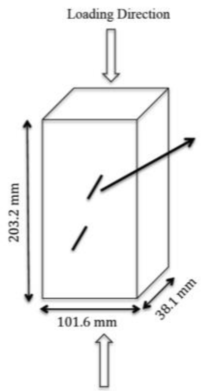


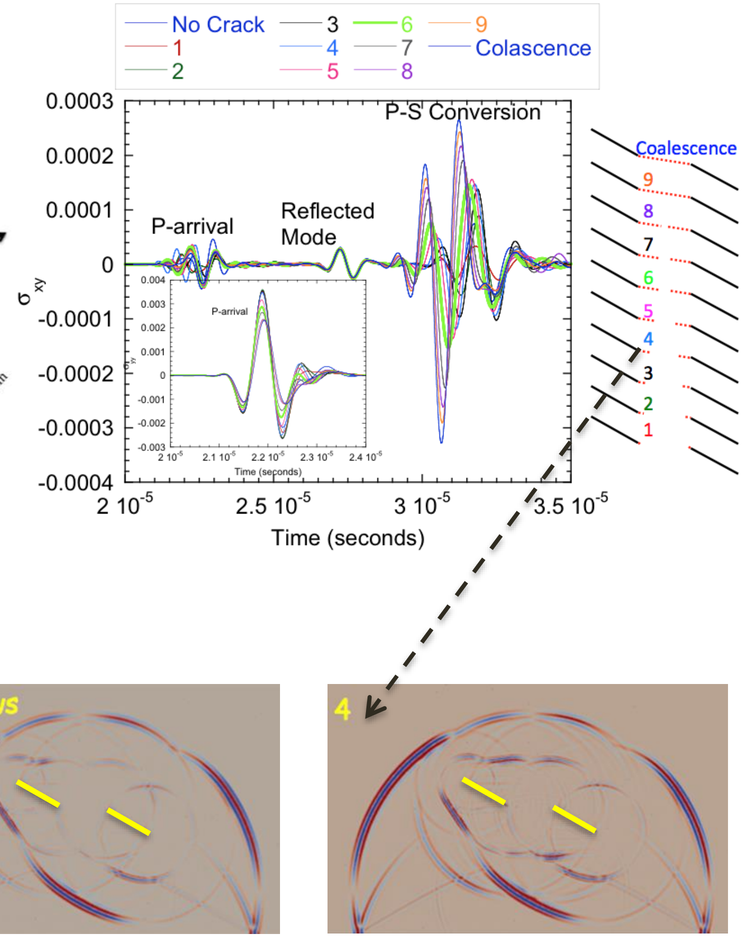


Triaxial testing cell (Wawersik et al., 1997)

Seismic Signal Acquisition and Analysis

- Full waveform measurements with AE and seismic wave transmission/reflection:
  - Delineate the stages of crack initiation and propagation
  - Use bi-& tri-axial loading conditions and crack orientations to achieve mixed-mode I-II-III loading with and without pore pressure
- Experimental data will be analyzed in conjunction with computer simulations:
  - Identify all possible components of the signals (body wave, converted modes, guided modes, etc.)
  - Interpret the hydraulic properties of fractures
  - Develop the relationship between the interpreted stiffness of the fractures and fluid flow (w/ micro-CT images)





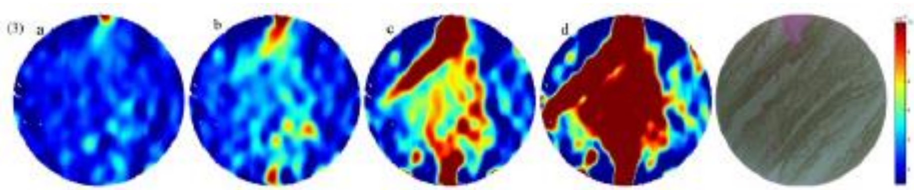
Simulated shear stress wavefront propagating from bottom to top

Forward and Inverse Modeling of Fracturing and Wave Propagation

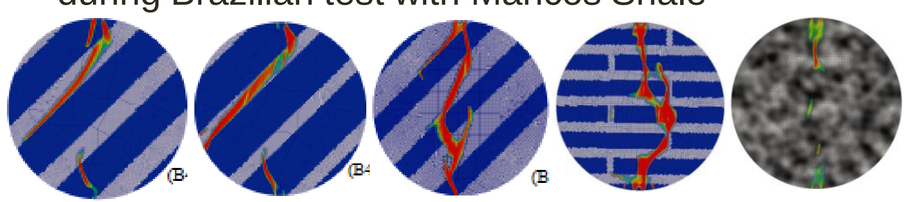
Differential Equations Analysis Library.II

DEAL.II Open Source Finite Element Library

- Fracture mechanics with mode I-II-III:
  - Brittle Fracture (elastic)
  - Plastic fracture
  - Pore pressure
- Coupled acoustic-elastic equations
- THMC coupling



Tensile strain based on DIC imaging during Brazilian test with Mancos Shale



Phase field modeling of crack initiation and propagation under different conditions

- Full waveform inversion (FWI) :
  - Multiple sources
  - Higher order
  - Global optimization
  - Local mesh refinement
- Various physics:
  - In- & compressible Euler, compressible Navier-Stokes
  - Acoustic wave, Darcy, and Helmhotz

Determine the sensitivity of the scattered wavefield to spatial variations caused by stress, existing and propagating fracture topology, material properties, stress gradients and fluids

Shale Poromechanics: Heterogeneity, Flow, Failure, and Creep

Multiscale characterization of physical, chemical, and mechanical heterogeneity of shale