Integrating Lab and Numerical Experiments to Investigate Fractured Rock

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In collaboration with Herbert Einstein, Brian Evans, Germán Prieto, and their groups

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Massachusetts Institute of Technology

Earth Resources Laboratory

Fracture Processes and Problems

- Example Processes:
    - Slip – seismic or silent?
        - E. g., > 99.9% of HF deformation is “silent!
    - Fracture transmissivity before and after slip

- Example problems
    - Interaction of hydrofractures and pre-existing natural fractures?
        - Establishment of transmissive fracture networks
    - Induced seismicity
        - Hazard? Diagnostic of where fractures slip?
    - Carbon sequestration

Why now is a good time to advance fracture studies

- New experimental capabilities:
  - Large volume apparatus
  - High data rate acoustic emission monitoring
  - Clever experimental design

- New numerical capabilities
  - Parallel software
  - Parallel computers

- Well established collaborations
  - Brian Evans Group – "high" P & T, large volume
  - Herbert Einstein Group – high-resolution visualization
  - Germán Prieto Group – Seismology in a pressure vessel
  - Brad Hager Group – Dynamic earthquake source model computations

Our approach

- Conduct low pressure HF tests in which the fracturing process can be observed both visually and with AE
  - Vary external stresses, flow rates/pressures, material

- Conduct high pressure HF tests in which the fracturing process can be observed with AE
  - Vary external stresses, flow rates/pressures, material

- Analyze high bandwidth recordings of AE using modern seismological techniques
  - Estimate magnitude, moment tensor, stress drop, seismic efficiency, . . .

- Numerical models of dynamic rupture and wave propagation in laboratory geometries
  - Vary external stresses, flow rates/pressures, material
  - Calculate magnitude, moment tensor, stress drop, seismic efficiency, . . .

- Joint interpretation of results

Scaling is Crucial – Examine governing equations

1- Conservation of fluid mass.

$$Q_0 t = 2\pi \int_0^{R_f} w r' \, dr' + \pi \int_0^{t} \frac{K'_l R_f^2(t')}{\sqrt{t - t'}} \, dt'$$

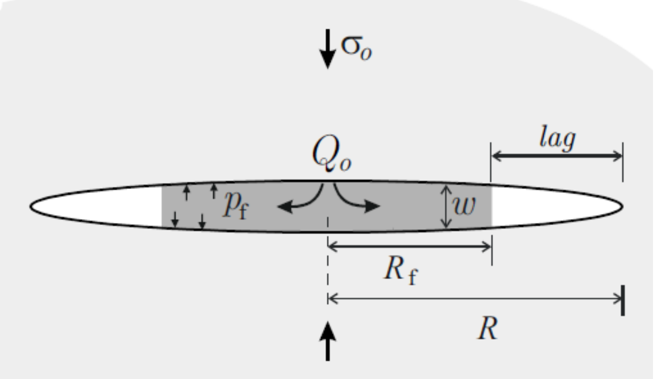
2- Elastic deformation

$$K' = \frac{8}{\pi} \sqrt{\frac{2}{R}} \int_0^{R} \frac{p \, r'}{\sqrt{R^2 - r'^2}} \, dr'$$

3- Fracture criterion

$$K' = 4 \sqrt{\frac{2}{\pi}} K_{Ic}$$

R	fracture length		
σ_o	min. (lith.) prin. stress	E'	*Plane strain modulus*
R_f	fluid-filled frac. length	H	*sample length*
w	frac. width	K_{IC}	frac. toughness
Q_o	fl. injection rate	K'	stress Intensity
p	fl. net pressure	K'_l	Fluid leak-off constant
μ	fl. viscosity		



Detournay, 2016

Dimensionless Time Constants

σ_o	min. (lith.) prin. stress	E'	*Plane strain modulus*
Q_o	fl. injection rate	K'	modified mode I fracture toughness
H	desired fracture length	K'_l	Fluid leak-off constant

$$\phi_1 = \left(\frac{\bar{\mu} \quad Q_0 \quad E'^3}{H \quad K'^4} \right)$$

viscosity

$$\phi_2 = \frac{K'}{\sigma_0 \quad H^{1/2}}$$

Fluid lag

$$\phi_3 = \left(\frac{K' \quad Q_0}{K'^{\,2}_l H^{3/2} E'} \right)$$

Leak-off

	$\phi_3>1$		$\phi_3<1$ (leakoff)	
	$\phi_1<1$	$\phi_1>1$	$\phi_1<1$	$\phi_1>1$
$\phi_2<1$	Toughness	Viscosity	Toughness	Viscosity
$\phi_2>1$	Toughness	Viscosity and Fluid lag	Toughness	Viscosity and Fluid lag

After Bunger et al., 2005; Detournay, 2016

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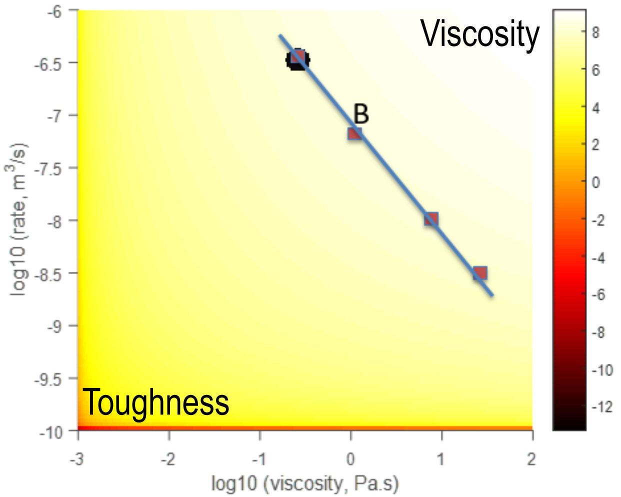
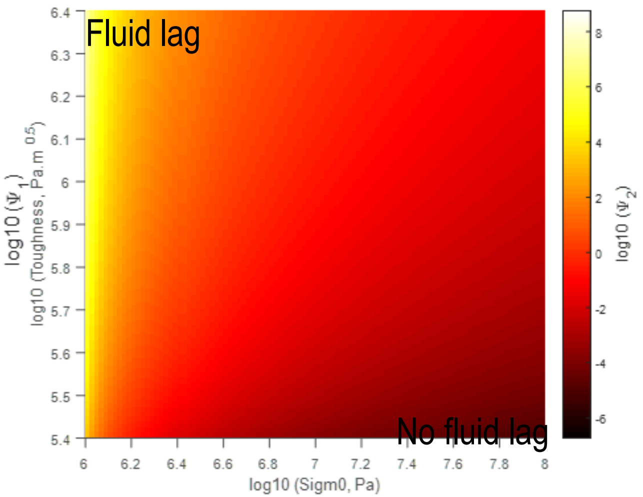
Experiment Design - Scaling





Fluid name: Silicone oil	A	B	C	D
Fluid Viscosity (P·s)	0.1	1	5	12.5
Injection rate (m^3/sec)	3.6×10^{-06}	4×10^{-8}	7×10^{-9}	3×10^{-9}

Experiments by Saied Mighani indicate AE number & magnitude correlate with fracture regime. Can lab experiments and moment tensor analyses provide a better way to identify fracture regimes in the field?

Measuring mechanical properties at reservoir conditions

Research Staff: Yves Bernabé, Brian Evans, Uli Mok

Large volume, multi-physics platform

Conventional triaxial mechanical

Samples 10 cm x 20 cm

σ^{mean}_{eff} 140 MPa (20 kpsi);
Pore P_f 120 MPa (18.5 kpsi);
Axial load 400 MPa (1.1 Mpf)

Temp. 120°C (250°F)

Internal load and displacement

Simultaneous property meas.

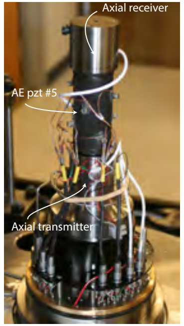
Permeability, p- & s-wave velocity, mechanical

Acoustic:16 sensor array. 250 MS/s cont. streaming

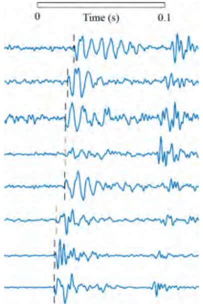
AE location, moment tensor anal.

Independent pore fluid pressure and chemistry

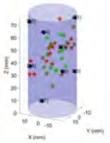
Conventional triaxial test

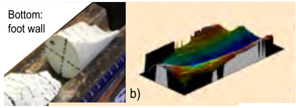


AE acq.& anal.



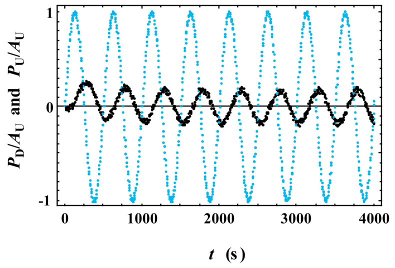
Loc. mom. ten.
& microstructure





Prospects and opportunities

- Microstrain mapping in “ductile” rocks at reservoir conditions (Also see work by Einsteins’ group, CEES)
- Harmonic flow measurements during deformation
  - Investigating hydromechanical coupling
  - Multi-physics measurements in new equipment
- Porosity and permeability changes during flow of single- and two-phase fluids
  - Acoustic velocity monitoring
  - Fluid chemistry measurements
- Joint properties
  - Rate of change of transport and mechanical properties
- State variable description of properties
  - Incorporation into larger scale calculations and models
  - Comparison with field-scale geophysical observations

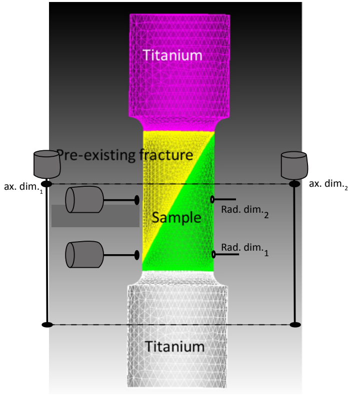


Unified approach: Joint reactivation and AE

(Brian Evans, German Prieto, Chen Gu, Farrokh Sheibani)

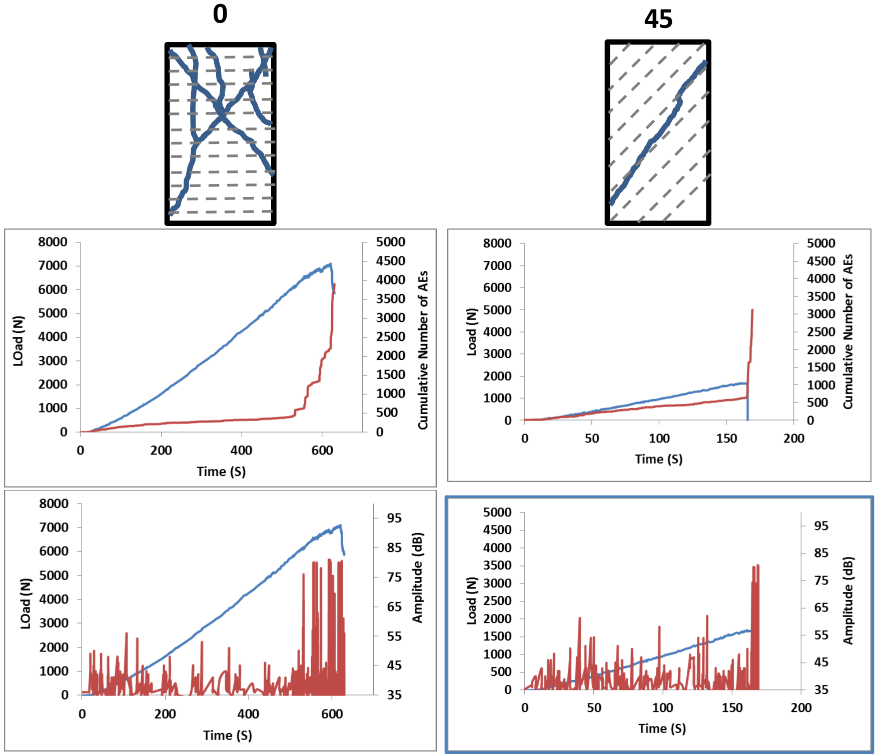
- **How do properties of reactivated joints change with slip and loading?**
  - Deformation under varying normal loads?
    - Elastic and inelastic
    - Crystalline rocks vs. shales
  - Relation of μ_{friction} and friction const. (d_c) to
    - roughness, total displacement, normal load, loading rate, T, and pore-fluids?
  - Constraints of AE on fault mechanisms?
    - Energy budget microseismics vs. slip?
    - AE locations and source mechanisms? (moment tensor analysis)
  - **Effects on hydraulic conductivity**
    - Roughness, slip distance, ...
    - Morphology of fluid flow through a rough surface? (4D seismic monitoring)

- **Mechanical**
  - Force and load point
  - Axial & radial LVDT (μm accuracy)
- **AE sensors: velocity & event measurements**
  - Number, location, spatial dimension, freq. distribution, magnitude distribution, moment tensor, spectral content

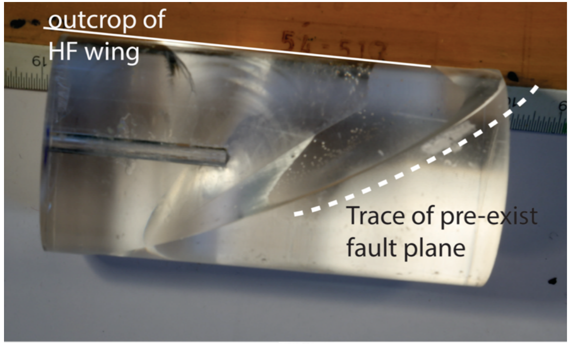


Joint properties: Stiffness, transmissivity, and reactivation

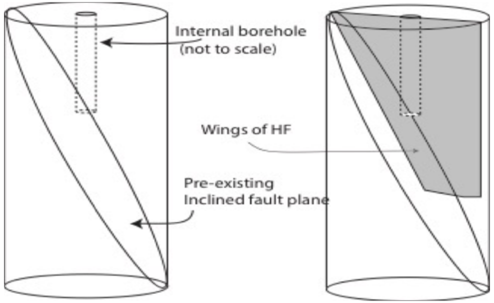
- Joint roughness
  - Rock type
  - Relation of loading direction to bedding
  - Mean lithostatic stress vs. differential stress, pore fluid pressure
    - HF versus compressive failure
- Correlate rupture processes with AE
  - Mag., moment tensor, and number
  - Mag. distribution (b value)
- Correlate fracture mechanism with transmissivity and joint stiffness
- Test methods of relating acoustic wave transmission to joint transmissivity
  - (Pyrak-Nolte and others)

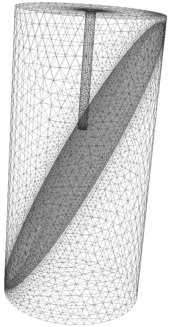


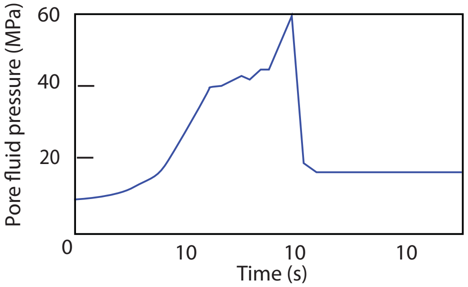
Interaction of HF with pre-existing fracture



Why is the hydraulic fracture perpendicular to the pre-existing fracture?



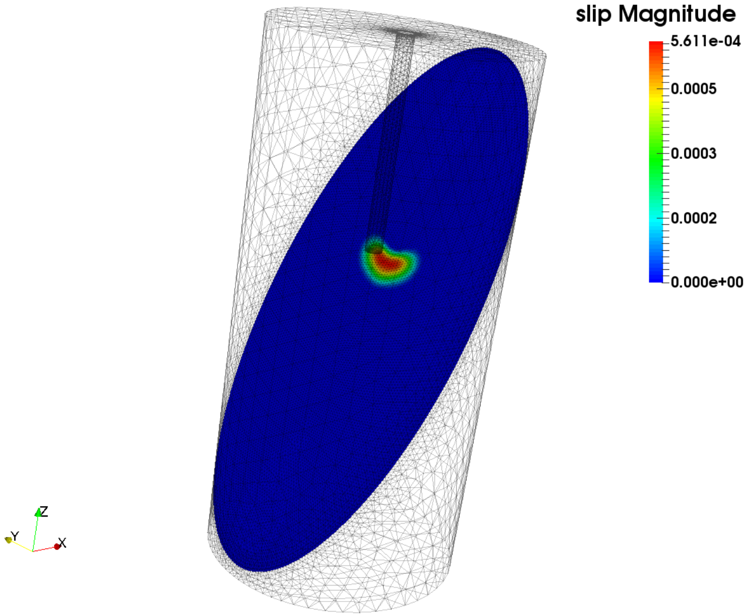


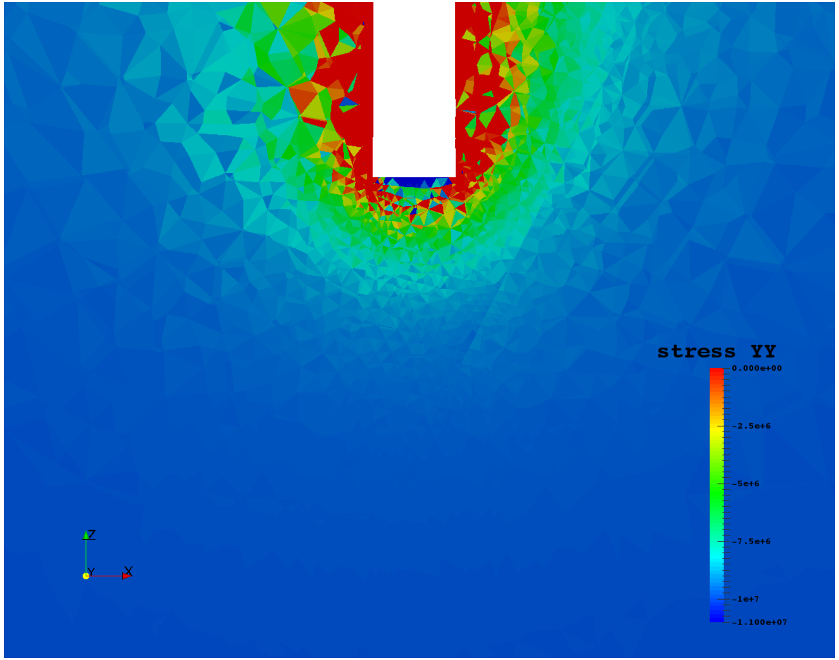


- Value of stress at wellbore breakout: Uniaxial stress = 15.7 MPa, Confining Stress = 10 Mpa and Wellbore pressure = 60 MPa.
- For Plexiglas, E = 3.3 GPa, and Poisson’s ratio = 0.37.
- Static friction coefficient is around 0.3 for the polished saw-cut surface in Plexiglas (pre-pressurization experiment).

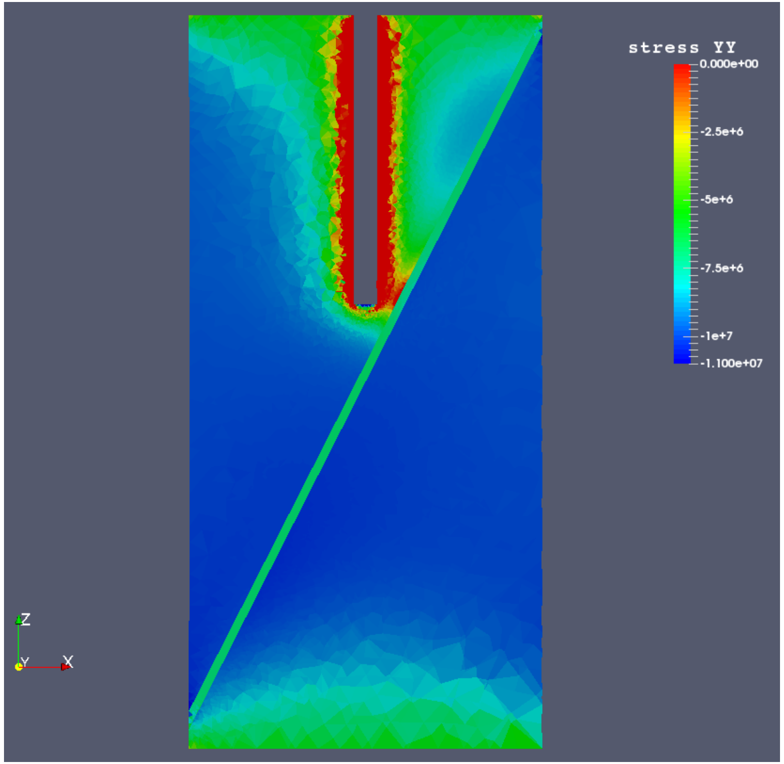
Interaction of HF with pre-existing fracture

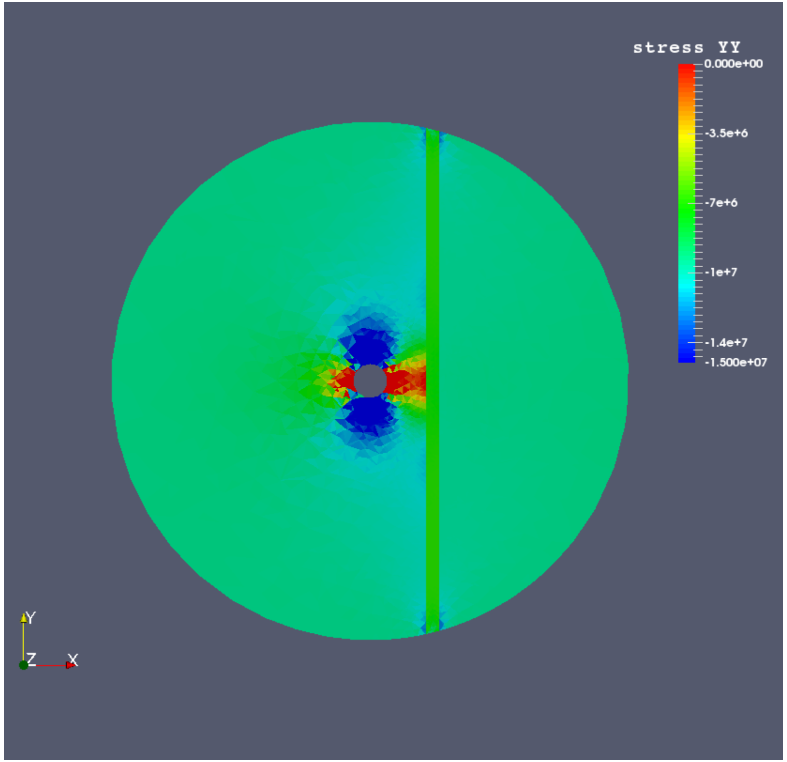
For $\mu = 0.25$, slip on the fracture from pressurizing borehole makes σ_{yy} more tensile above fracture, more compressive below, breaking axial symmetry



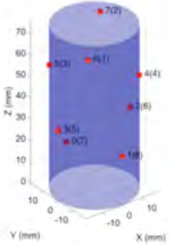


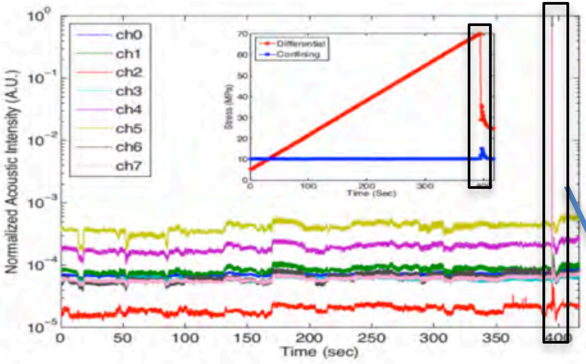
Alternative – High compliance fracture



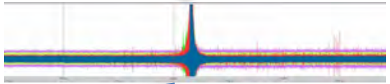


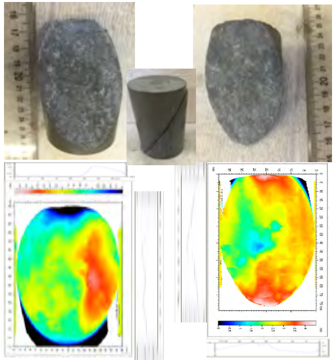
Triaxial tests on rocks

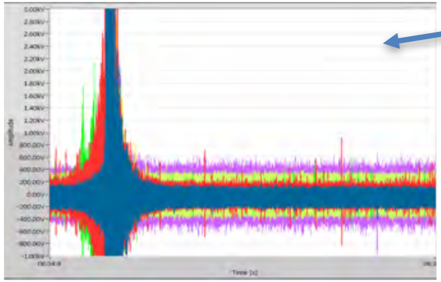


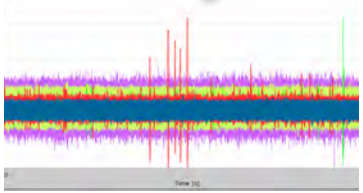


Detection
Location
Moment Tensor
Inversion









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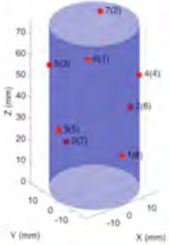

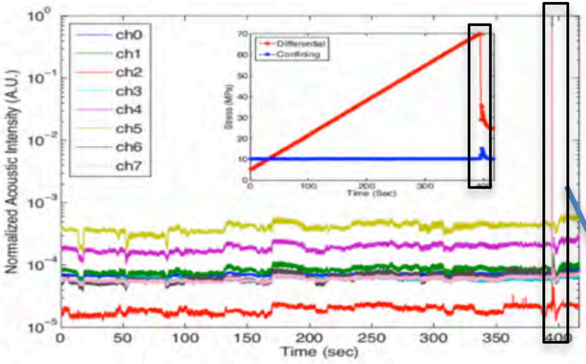

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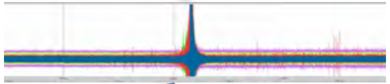

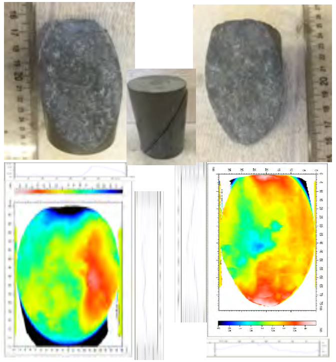

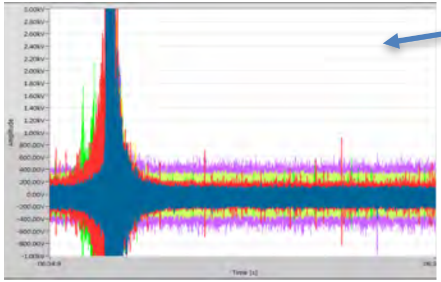

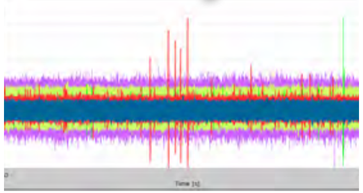

Effects of loading of platens on stress & dynamic rupture