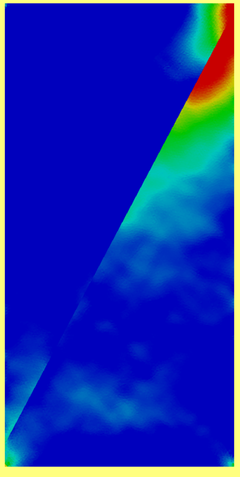
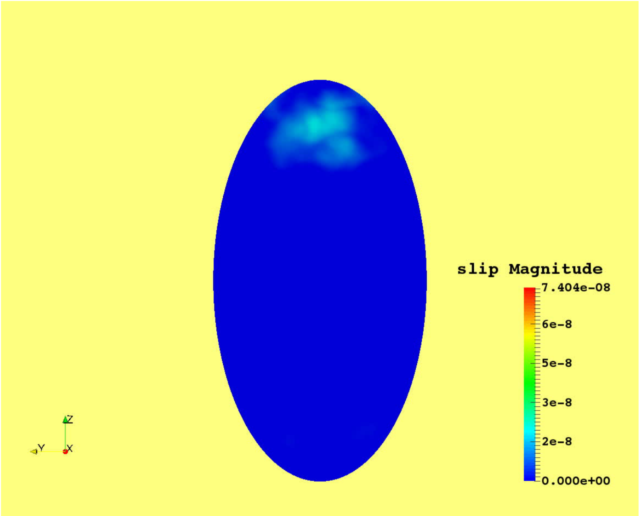
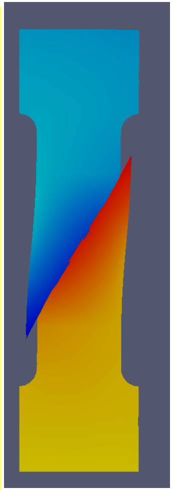
Rupture Evolution and Slip Distribution on Fracture Plane



σ_{zz} on plane
perp to fracture

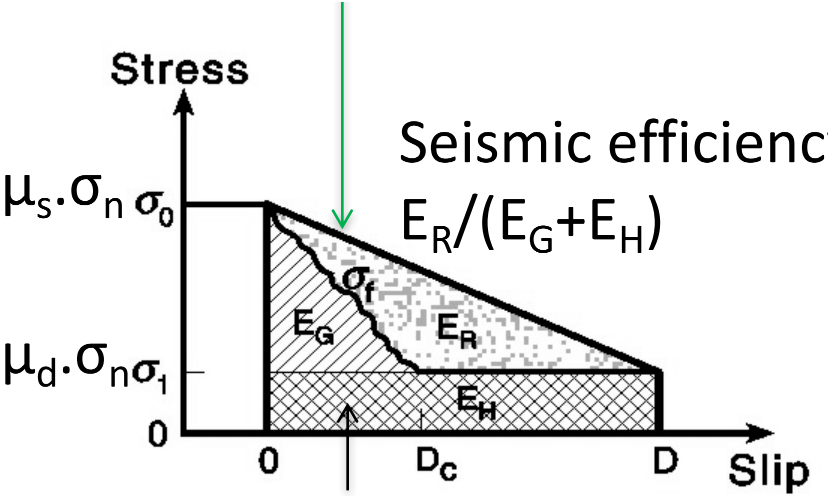




Displ. on plane
perp tp fracture

Seismic slip requires slip-weakening friction model

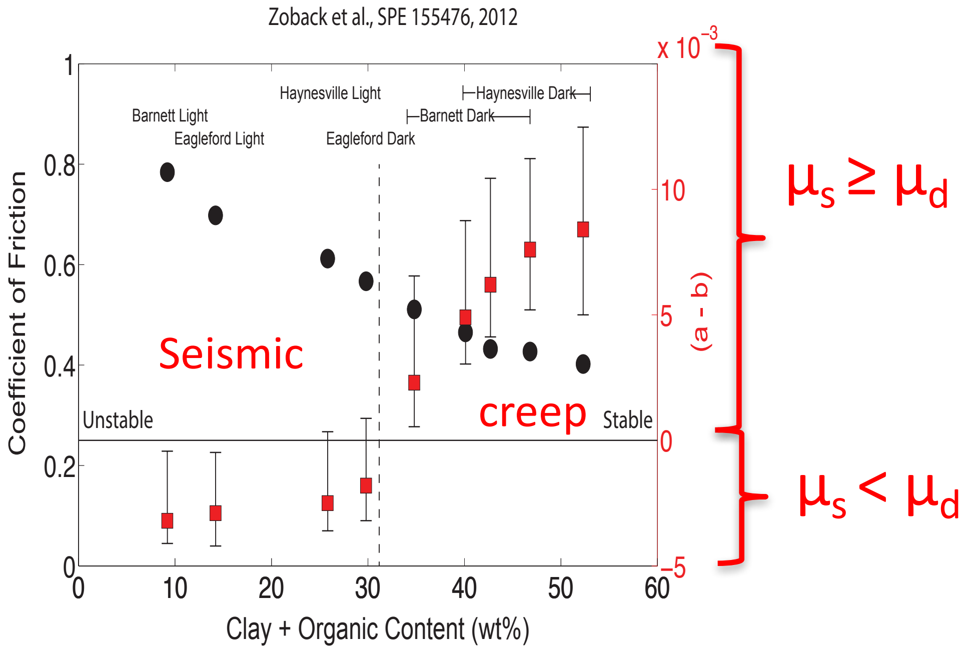
Slope depends on Elastic Modulus, Fault Friction, and Fracture size



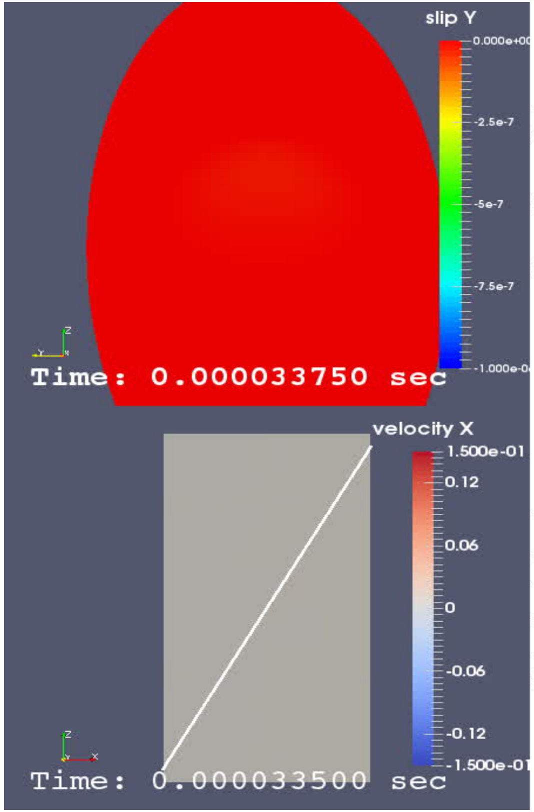
Seismic efficiency= $E_R/(E_G+E_H)$

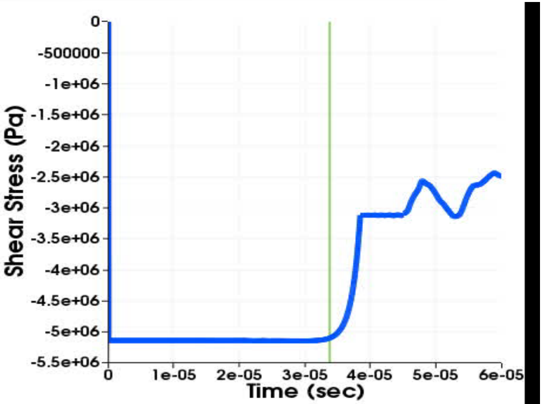
Frictional heating

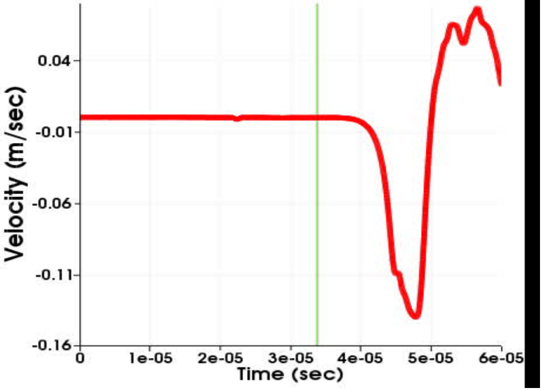
Slip weakens over distance D_c

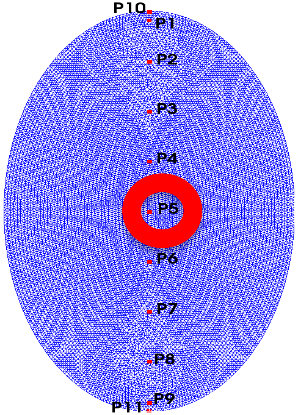


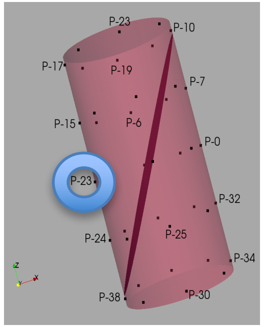
Unstable Sliding, Stress Drop, Slip Rate and Elastic Waves





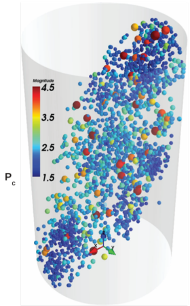


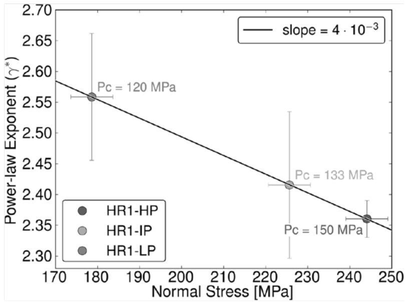




Joint reactivation in shales

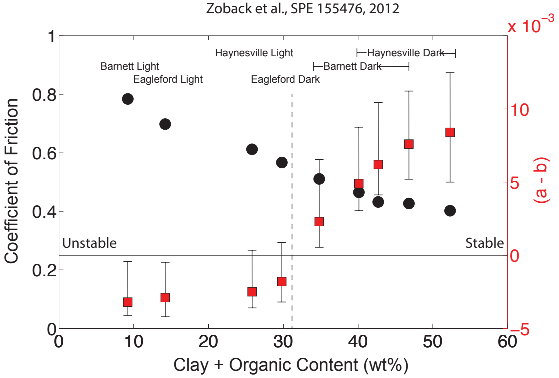
- Crystalline rocks at large d_{slip}
  - Roughness of secondary importance
  - Slip-weakening & rate-state friction
    - *Mature tectonic* faults
- Cryst. rocks w/ small d_{slip}
  - Width of AE locations



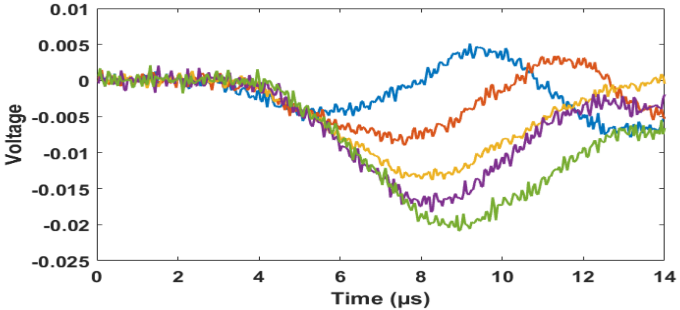


  - k fault slip rate, G modulus, β power, H Hurst exponent (H↑ roughness ↑)
  - Width AE dist. ↑ as Roughness & σ_n ↑
- Shale friction
  - Velocity weakening if clay+org >30%
  - Effects of roughness, normal load, effective pressure?

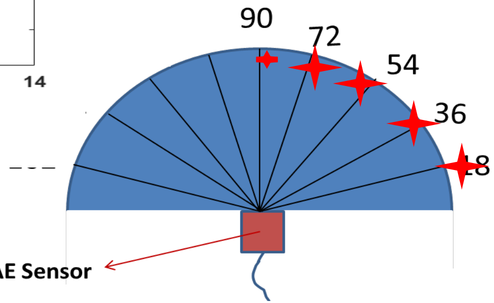
Zoback et al., SPE 155476, 2012

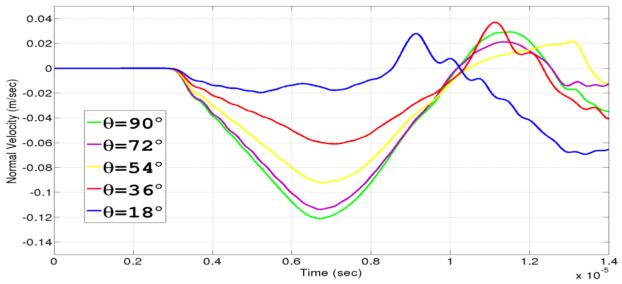


Dynamic Model Verification, Ball Drop Test- P-wave & S-wave Radiation Patterns



Measured Voltage

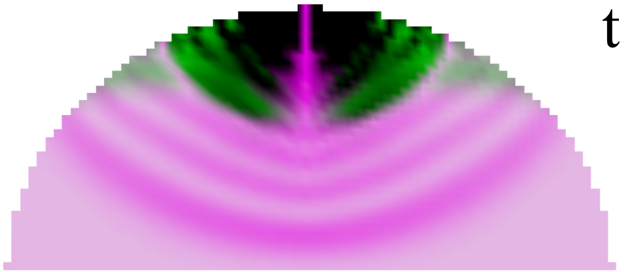




Calculated Velocity

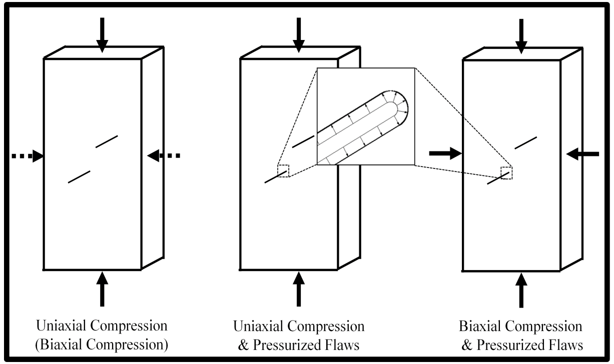
t = 3.0 μsec

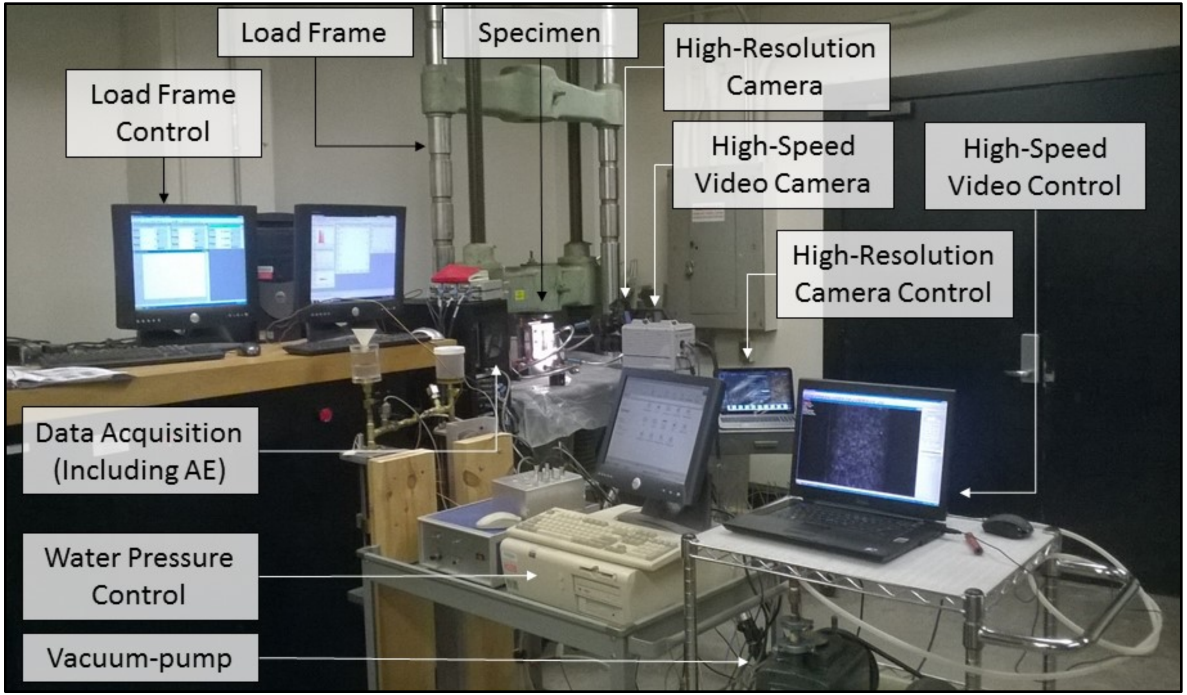
90°



18°

Low pressure HF experiments – Einstein Lab





Prismatic specimens, pre-existing flaws

Flaws can be internally pressurized

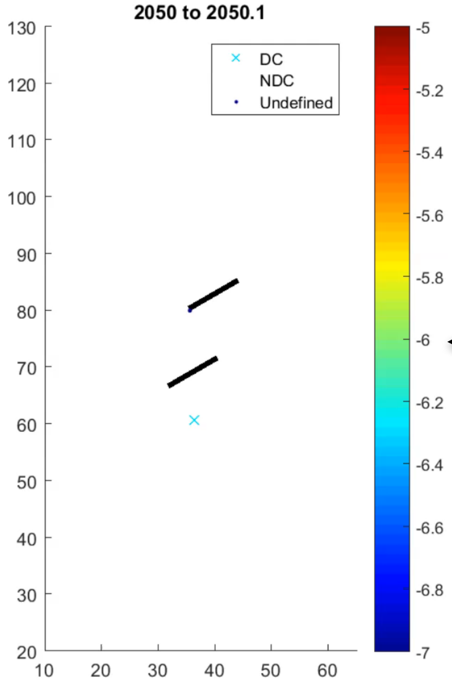
Uniaxial or biaxial external stresses

Visual (high speed and high resolution)

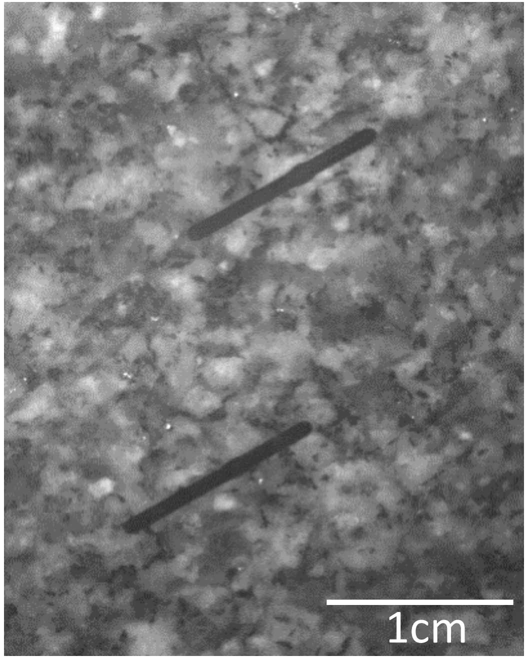
AE observations

Multiple observations of fracture initiation & propagation

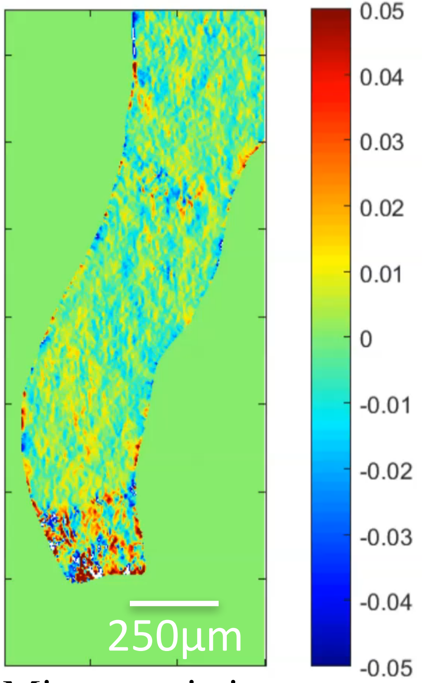
Bing Li: Relate visual observations to acoustic emissions (laboratory analogue to microseismicity), given that fractures are not directly accessible in the field.



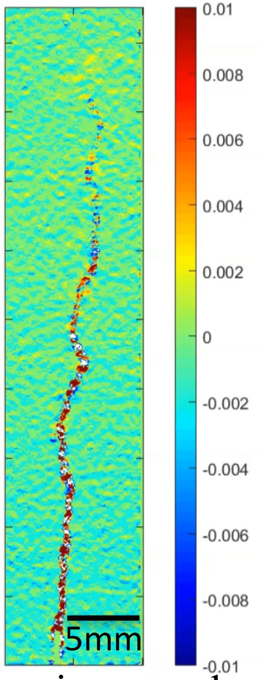
Acoustic Emissions



High speed video



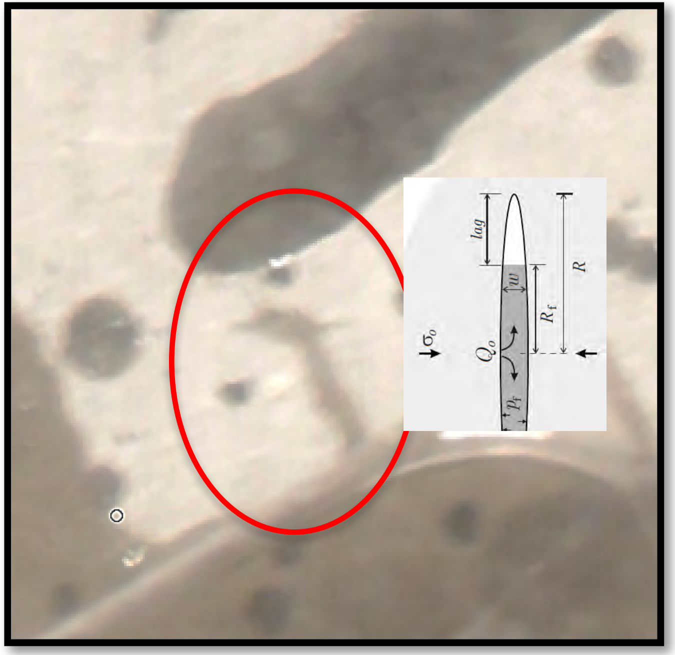
Microscopic images



Specimen-scale

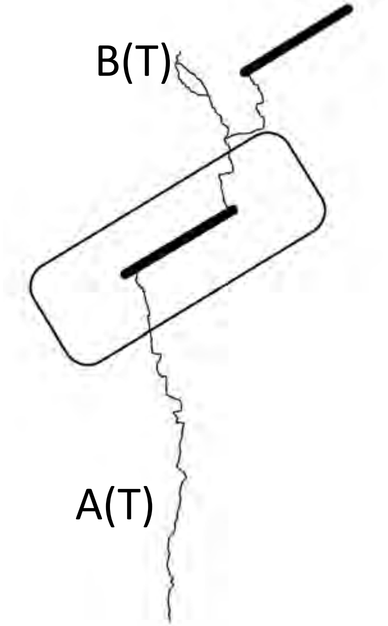
HF experiment showing crack tip ahead of fluid front

(Courtesy Omar Al Dajani)



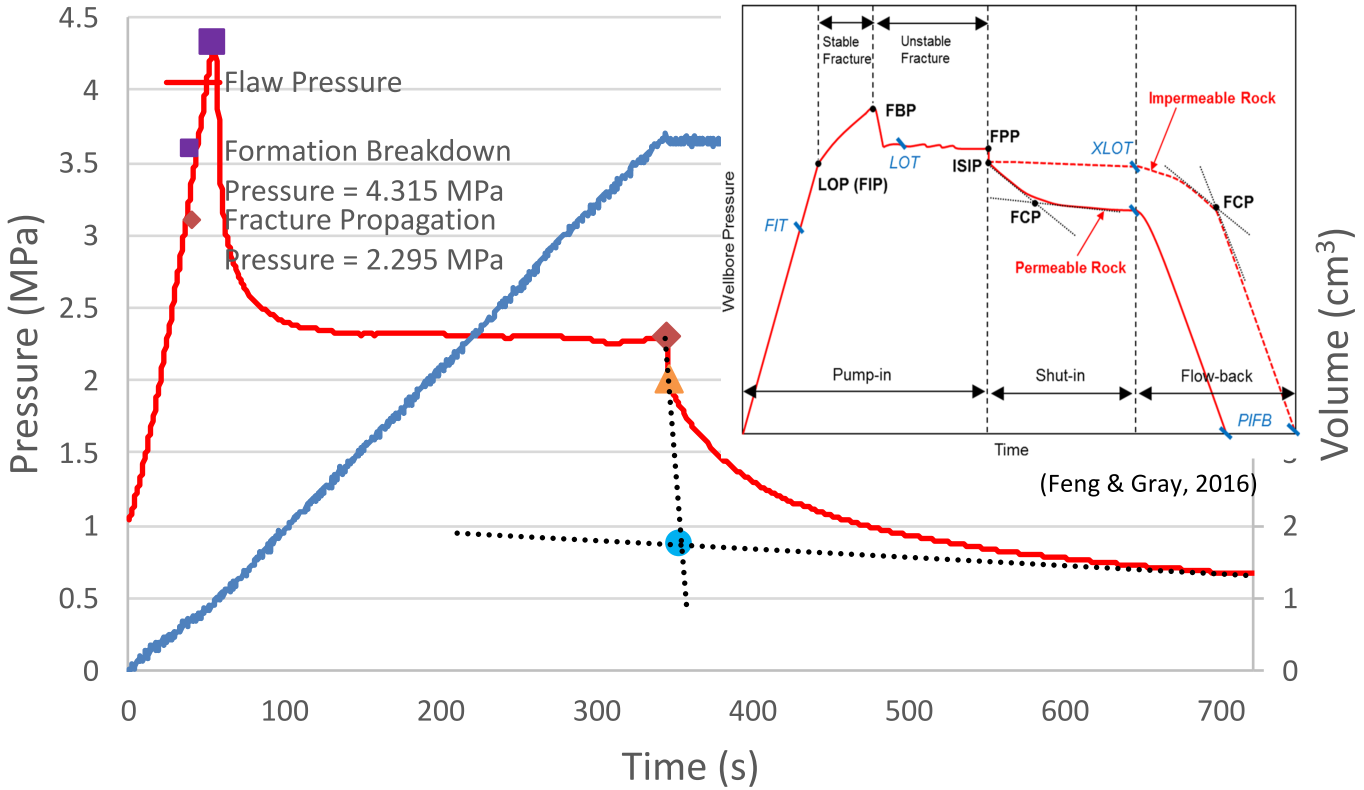
$P_{breakdown} = 3.53$ MPa

$V_{injected} = 2.461$ cm^3



Equipment and results - low pressure HF experiments

HF experiment showing "classic" pressure time behavior



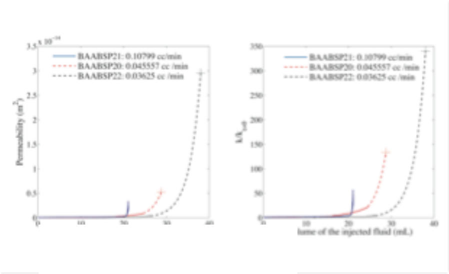
Summary

- Understanding processes associated with fractures is a rich problem.

- Combining Lab and Numerical investigations is a productive approach
  - Provide insights
  - Raise questions and paradoxes
    - Why are numerical earthquakes larger than AE events?

- ERL has special capabilities
  - High volume triaxial apparatus
  - Visualization of deformation via multiple approaches
  - Computation of quasi-static loading triggering dynamic failure, wave propagation
    - “realistic” fault failure parameterizations

Permeability changes during flow of unsaturated fluids



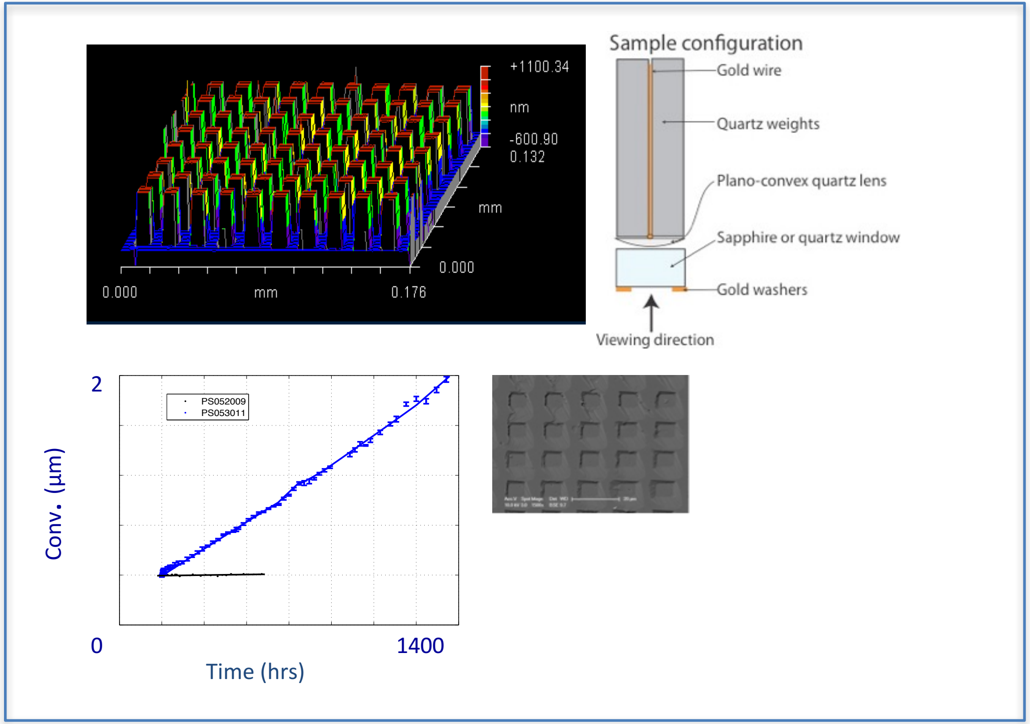
Before dissolution

After breakthrough

- Core-flood in micritic, reef limestone
  - Flow rates >0.03 and <0.1 mL/min.
  - Pore fluid =H_2O sat. with CO2, i.e., chemically reactive fluid
  - Rapid increases in k at ”breakthrough”
- SEM and microtomography images
  - Wormhole develops in 3-18 hours with dramatically increasing permeability
- Numerical modeling
  - Pore-scale heterogeneity important
  - “Kinetic switch” along selected path
  - Spatial correlations greatly facilitate wormhole formation

Relations among mechanical behavior, fluid transmissivity and acoustic properties of joints (cont.)

- **Creep deformation: Effects of fluids**
  - Pressure solution deformation
    T≤ 600°C $P_f \leq 200$ MPa
    micron scale pillars
  - Cementation, fracturing and pressure solution
    - partitioning between mechanisms enigmatic



Work in progress, see also:

Fitzenz, D. D., Y. Bernabé, S. H. Hickman, and B. Evans (2008), Incorporating intergranular pressure solution into models of fault zone deformation, *EOS Trans. AGU*, *89*(53), Fall Meet. Suppl., Abstract T53C-1965.

Bernabé, Y., B. Evans, and D. D. Fitzenz (2009), Stress transfer during pressure solution compression of rigidly coupled axisymmetric asperities pressed against a flat semi-infinite solid, *Pure and Applied Geophysics*, *166*(5-7), 899-925, doi:10.1007/s00024-009-0477-2.

Bernabé, Y., and B. Evans (2014), Pressure solution creep of random packs of spheres, *Journal of Geophysical Research: Solid Earth*, *119*(5), 4202-4218, doi:10.1002/2014jb011036