Probing rock mechanical properties of fault zones: A field-based structural geology approach

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Summary

Problem:

In situ mechanical properties (elastic moduli, fracture toughness, permeability, etc.) of fault zone rocks can vary markedly from properties measured in the laboratory due to scale, healing, and alteration during exhumation.

Question:

How can a field-based ***Structural Geology*** approach be used to differentiate between laboratory and *in situ* properties?

Approach:

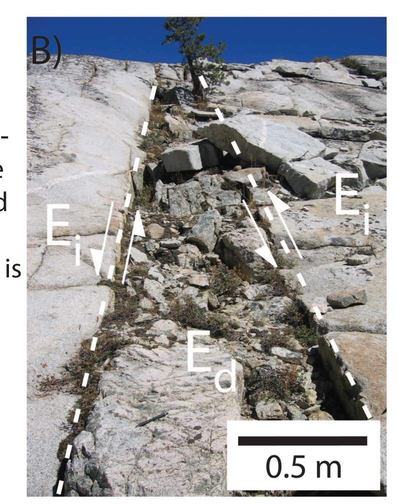
An ***inegrated* field**, **laboratory** & **theoretical** approach (from Pollard & Fletcher, 2005):

(1) Identify natural experiment → **(2) Map structures** → **(3) Idealize problem** (Infer kinematics, boundary conditions, rheology) → **(4) Set up and solve mechanical problem** → **(5)** Use solution to **estimate physical property** & **compare to field measurements**

Experiment 1: Elastic Moduli

Background:

Stiffness of damaged rocks, represented here as damaged Young's Modulus E_d is clearly less than intact rocks E_i



(Griffith, Sanz, and Pollard, *Pageoph*, 2009)

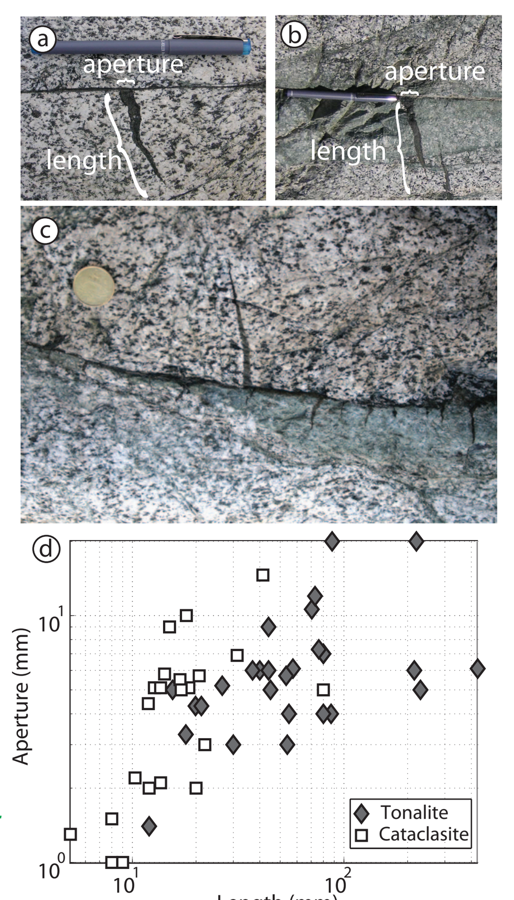
On crustal scale faults damage can result in stiffness reductions of ~40% over large fault-normal distances (> 1 km) throughout the seismic cycle (1 ky or more) (Cochran et al., *Geology*, 2008). Stiffness constrains the amount of elastic strain energy that can be stored in the rocks during tectonic loading and released during an earthquake, and near fault changes in stiffness can result in significant stress rotation (Faulkner et al., 2006)

Questions:

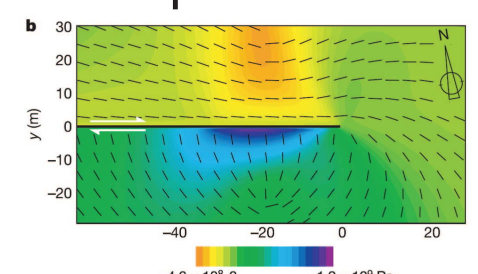
(1) How large is stiffness reduction close to seismic fault
(2) How much softening takes place at seismogeinic depths?
(3) How to eliminate healing from stiffness measurements?

Solution: *Study Pseudotachylyte Injection Veins*

Field Observations:

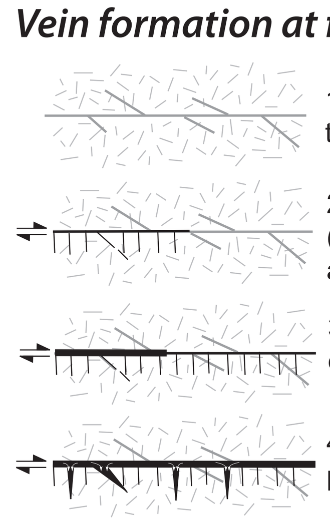


Conceptual Model:



Di Toro, Nielsen, and Pennaccioni, *Nature* (2005) showed that vein orientations and distribution can be explaned by the near-tip stress field of a mode II shear rupture (earthquake) propagating near the shear wave speed (C_S) for tonalite

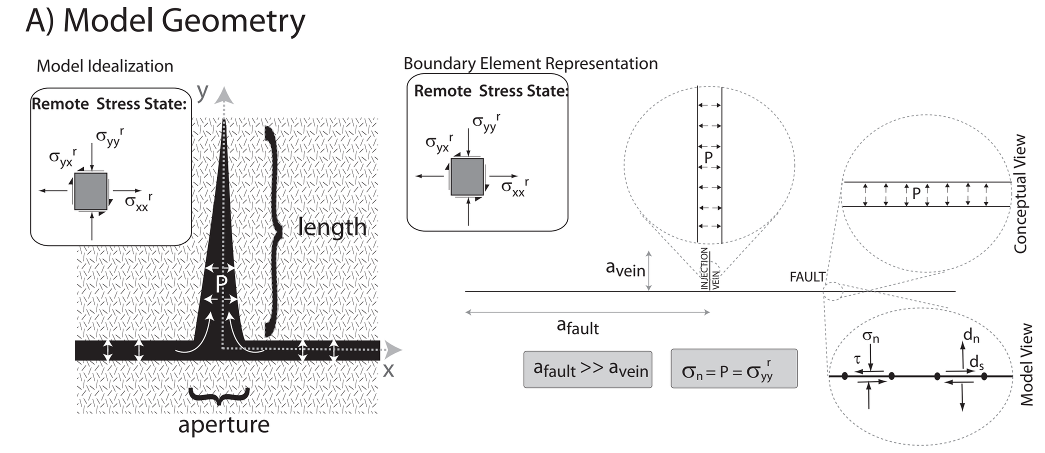
Vein formation at field site:



1) Pre-existing fractures
2) Asymmetric damage (tensile cracks) formed at passing shear rupture
3) Friction melting generated in sliding zone
4) Pressurized melt exploits tensile cracks

Mechanical Model:

A) Model Geometry

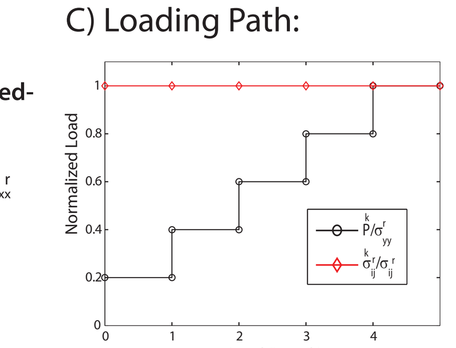


B) Loading Cases:

(i) Transiently Perturbed-Uniaxial
$\sigma_{xx}^r = 0$ MPa
$\sigma_{yx}^r = 0$ MPa
$\sigma_{yy}^r = 111$ MPa

(ii) Transiently Perturbed-Bi-Axial
$\sigma_{xx}^r = 50$ MPa
$\sigma_{yx}^r = -20$ MPa
$\sigma_{yy}^r = 111$ MPa

C) Loading Path:



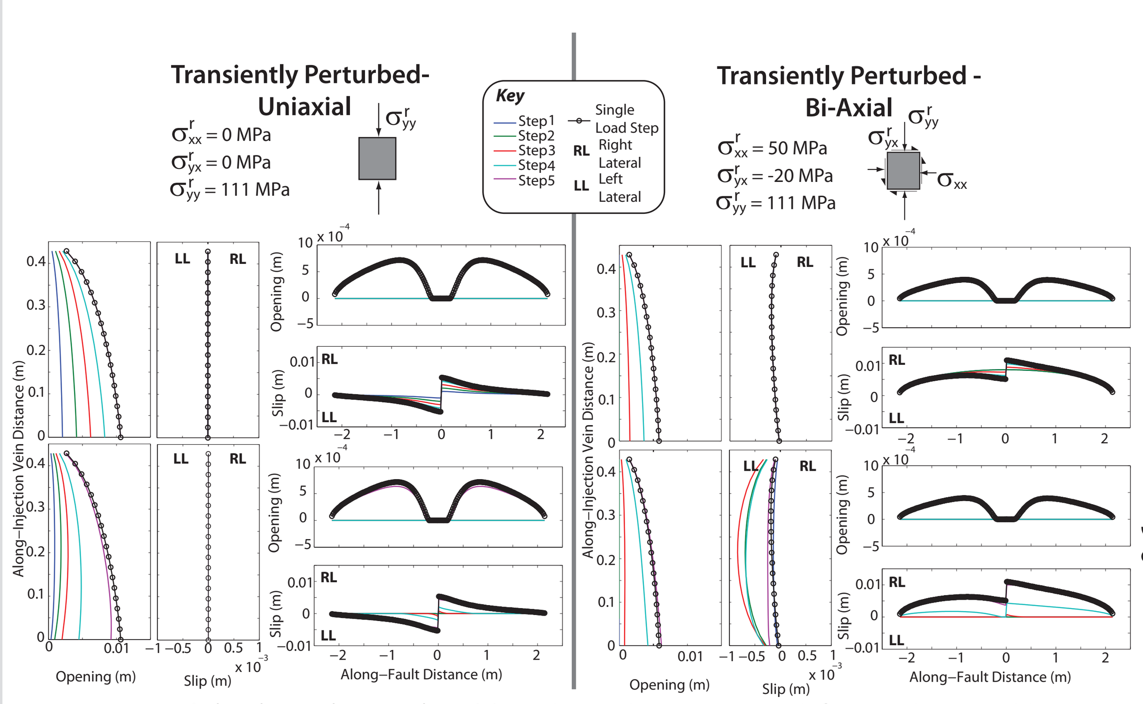
For each model iteration:

Given
(1) a_{vein}, vein length
(2) Traction BCs

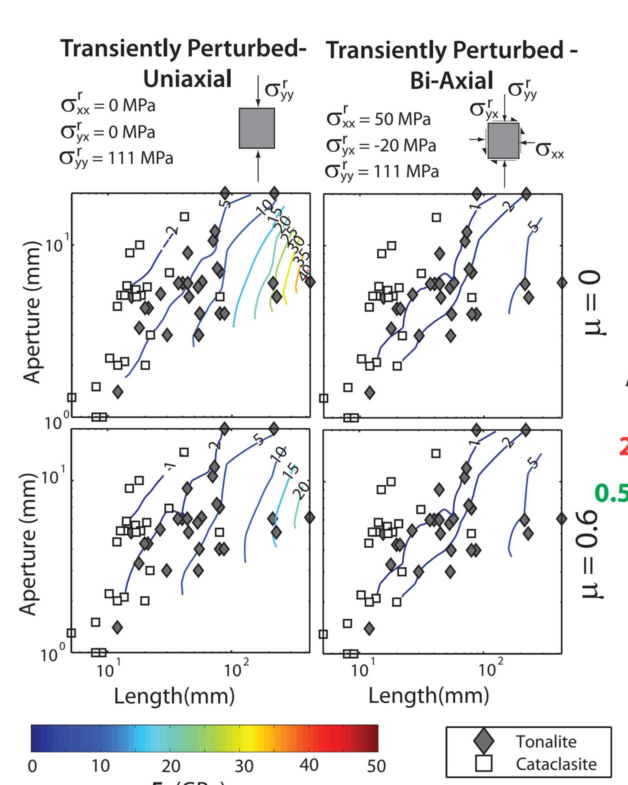
→ **Indep.Variables**
(1) E, Young's Modulus
(2) μ, friction coeff
(3) σ_{xy}^r, varied in 2 Cases (above)

→ **Dep.Variable**
w, vein width (max opening)

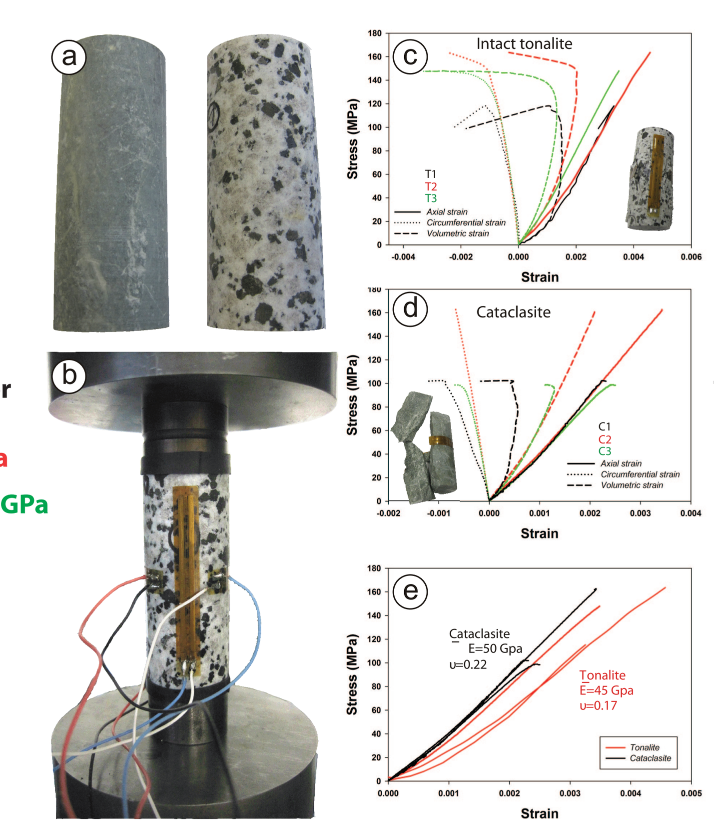
Results:



Injection vein opening is enhanced by: *(1) Mechanical interaction with frictional contact/slip*
(2) Zero (or tensile) fault-normal stress



Average Values for All Simulations:
2GPa<$E_{tonalite}$<9GPa
0.5GPa<$E_{cataclasite}$<3.5GPa



Average Values for Lab Measurements:
$E_{tonalite}$=45GPa
$E_{cataclasite}$=50GPa

Experiment 2: Fracture Toughness

Background/Obs./Model

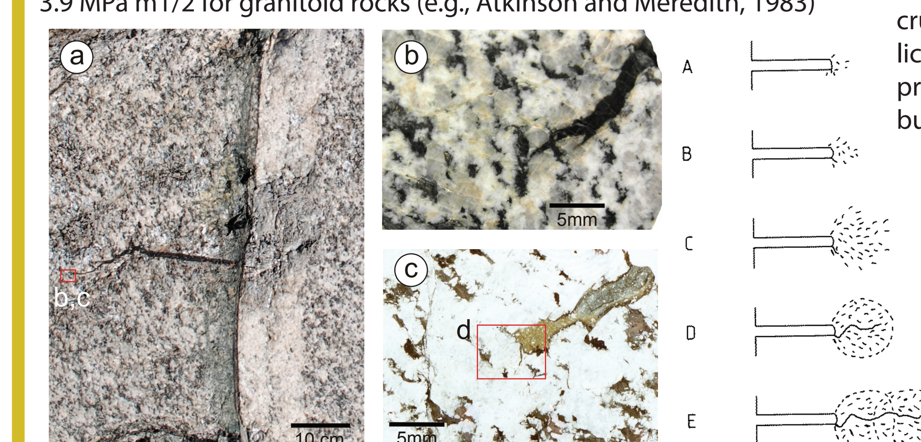
A condition for the onset of crack propagation is when the stress intensity factor equals the fracture toughness:

$$K_I = K_{Ic} \quad (1)$$

The model I stress intensity factor for a crack of half-length *a* embedded in an infinite linear elastic medium is given by

$$K_I = \Delta\sigma_I \sqrt{a} = \left(\sigma_{xx}^r - \sigma_{xx}^c\right)\sqrt{a} \quad (2)$$

where $\Delta\sigma$ is the driving stress given by the difference between the remote normal stress acting on the crack (σ_{xx}^r)and the pressure (σ_{xx}^c) acting directly on the crack faces, and the stress intensity has units of MPa.m$^{1/2}$. Laboratory measurements of typically range between 0.6 and 3.9 MPa m1/2 for granitoid rocks (e.g., Atkinson and Meredith, 1983)

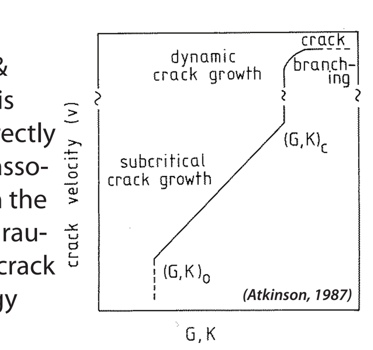


Irwin (1958) showed that the energy release rate associated with mode I crack extension can be directly related to the mode I stress intensity factor as:

$$G_I = \frac{\pi(1-\upsilon)}{2\mu} K_I^2 \quad (3)$$

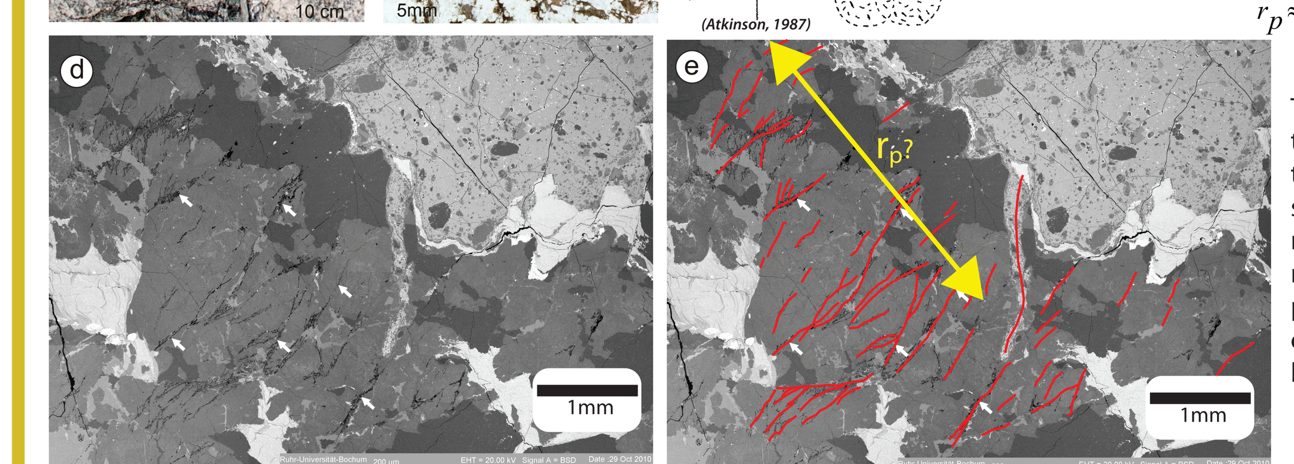
Where the energy release rate G is the energy expended per unit length of crack extension and i twice the surface energy, γ: $G = 2\gamma = G_{Ic}$

Understanding K_{Ic}, G_{Ic}, K_I, & G_I,under *in-situ* conditions is critical becuase they are directly related to the stress levels associated with tensile failure in the crust, the mechanics of hydraulic fracture, the velocity of crack propagation, and the energy budget of fracturing.



Irwin (1958) used the asymptotic near tip stress field around a crack of half-length *a*, and assumed that the size of the process zone of a propagating crack is determined by the distance from the crack tip at which the maximum normal stress exceeds the yield stress, of the material, yielding an expression for the radius of the process zone, r_p:

$$r_p \approx \frac{K_I^2}{\sigma_{ys}} \approx \frac{a}{2}\left(\frac{\sigma_{xx}^r - \sigma_{xx}^c}{\sigma_{ys}}\right) \quad (4)$$

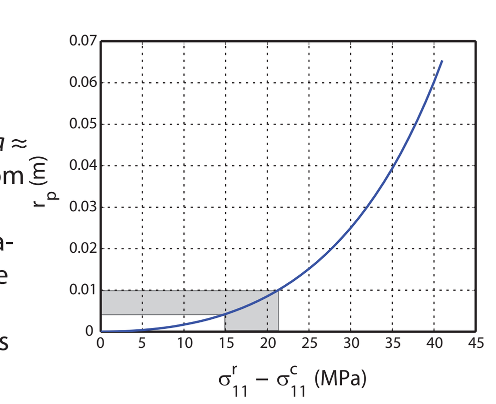


Taking the yield stress to be the difference between the uniaxial tensile strength, σ_t, of the material and the normal stress acting perpendicular to the crack, this expression becomes:

$$r_p \approx \frac{a}{2}\left(\frac{\sigma_{xx}^r - \sigma_{xx}^c}{\sigma_t - \sigma_{xx}^r}\right) \quad (5)$$

Results:

Using the ***rough*** data from the injection vein above, $r_p \approx 5$ mm and $a \approx 28$ cm. Furthermore, from Experiment 1 we have $\sigma_{xx}^c = P = 111$ MPa, a reasonable guess for tensile strength is $\sigma_t = 10$MPa, and the only unknown is σ_{xx}^r.



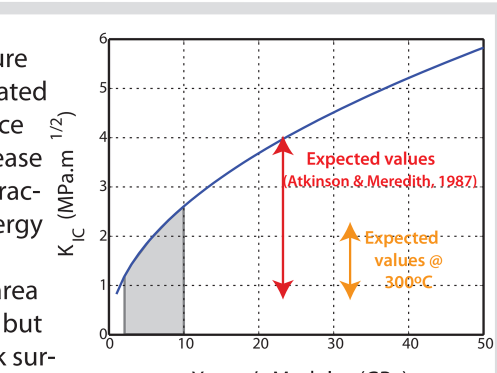
Therefore using (5), one can plot a range of driving stresses or (for the case of a pressurized crack) fluid overpressures. Note that to get a value of close to the value observed in the field, the overpressure needs to be very small (see the gray shaded area, above)

Finally, the mode I fracture toughness can be estimated by noting the equivalence between the energy release rate in (3) and that as a fracture propagates, the energy release rate is not just a function of the surface area of the main crack plane, but also all of the microcrack surfaces being created in the process zone, i.e.:

$$G_{Ic} = 2\gamma * \#microcracks \quad (6)$$

Rearranging (3)yields:

$$K_{Ic} = \sqrt{\frac{2\mu G_{Ic}}{\pi(1-\upsilon)}} \quad (7)$$



Using a Poisson's ratio ν=0.25 and using a rough estimate of the surface energy of a fracture (γ=50 J/m2), one can relate the fracture toughness to the effective *E* for the same injection vein using (7).

Conclusions/Implications

(1) Pseudotachylyte injection veins show systematic length to thickness ratios which vary differently according to rock type

(2) This systematic relationship reflects the *in situ* coseismic stiffness of the fault rocks

(3) *In situ* coseismic Young's Modulus of fault rocks is 0.5-2 orders of magnitude less than laboratory measurements, likely due to damage

(4) *In situ* fracture toughness of fault rocks appears to be consistent with lab values (but this is rough)

(5) An integrated field-based Structural Geology approach to studying rock mechanical properties is an effective tool for scaling laboratory rock mechanical investigations to seismogenic depths

Approach Efficacy

Challenges & Limitations

-Non-constant boundary conditions
-P-T-t dependent rheologies
-Processes involving large strains

May yield non-unique solutions

Other Applications

Properties/Parameters:
-Permeability *(e.g. Mitchell et al., EPSL, in press)*
-Fault Friction *(e.g., Niemeijer et al., JSG, 2012)*
-Healing Rate
-Rupture Velocity *(Di Toro et al., Nature, 2005; Griffith et al., Geology, 2009)*
-Fluid Pressure *(e.g., Rowe et al., EPSL, in press)*
-Heat Flow *(e.g., Polissar et al., EPSL, 2011)*
-Stress

Processses:
-Dynamic vs. Static Properties & Processes
-Hydraulic Fracture

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