The effect of dilatancy and compaction on the stability of fluid infiltrated fault gouge

Jon Samuelson
Chris Marone
Derek Elsworth

Outline

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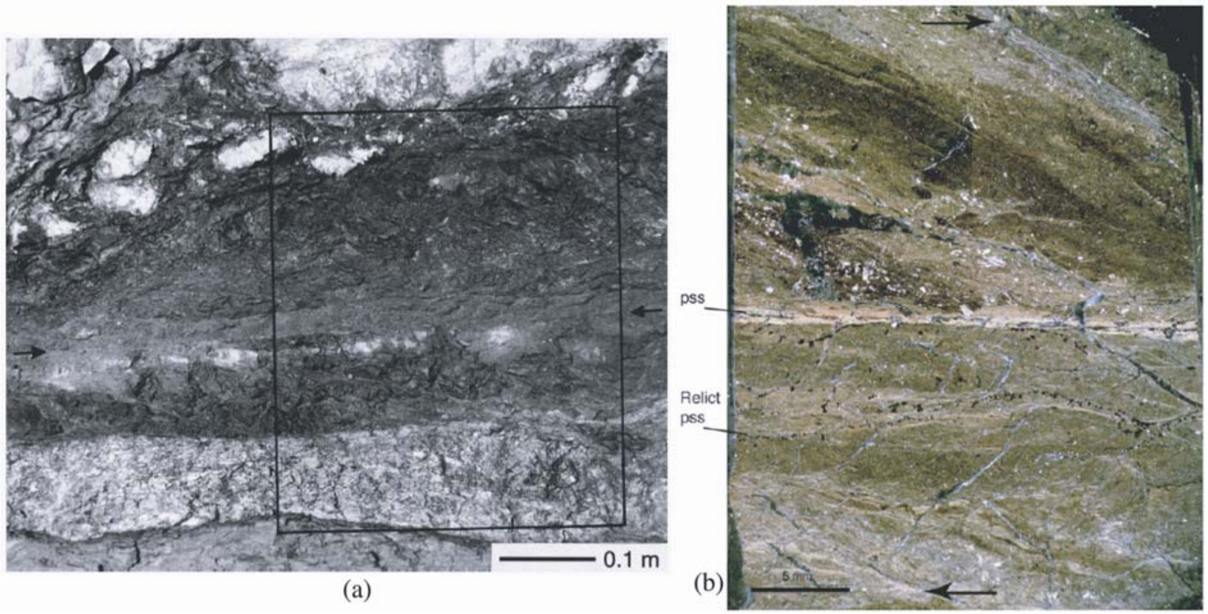
Fault zones and fault gouge

(USGS Photo)

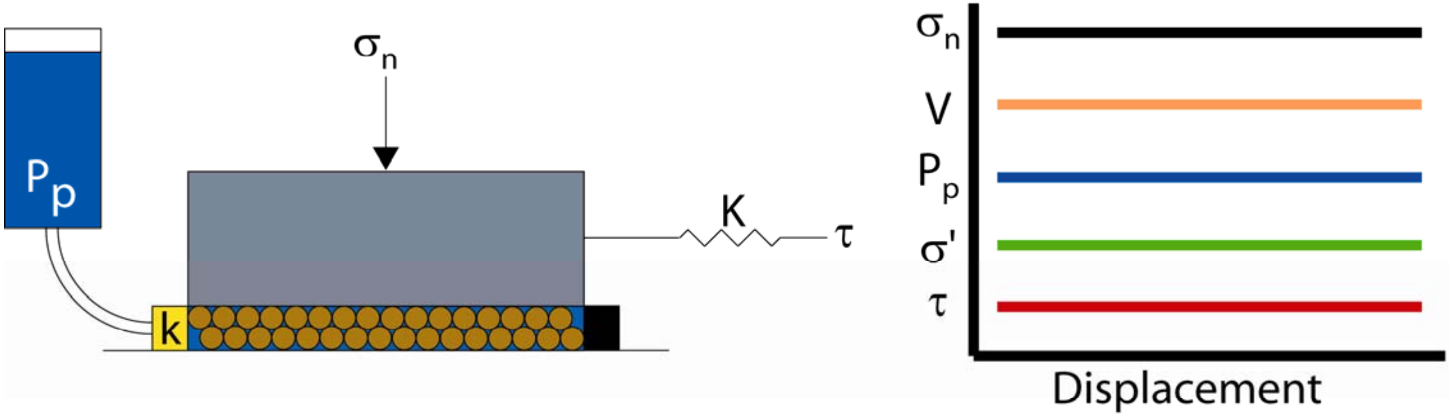
Fault core: Accomodates most of the strain between the plates. Typically 10's of μm to a few mm in thickness.

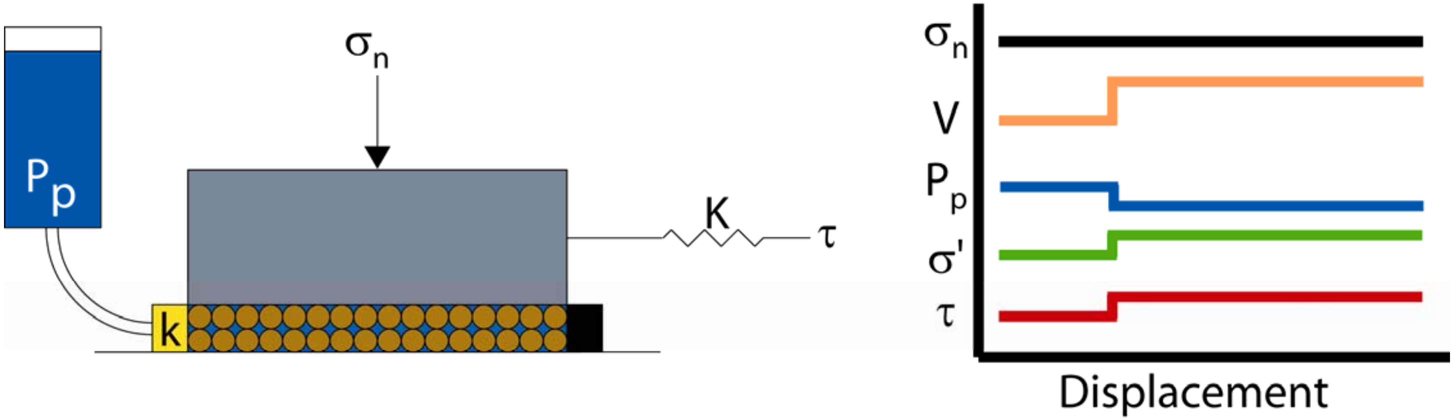


(Rice, 2006)

Simple Spring-Slider Model of Dilating Granular Layer Showing Dilatancy Hardening

Coulomb-Mohr Failure: $$\tau = c + \mu(\sigma_n - P_p)$$

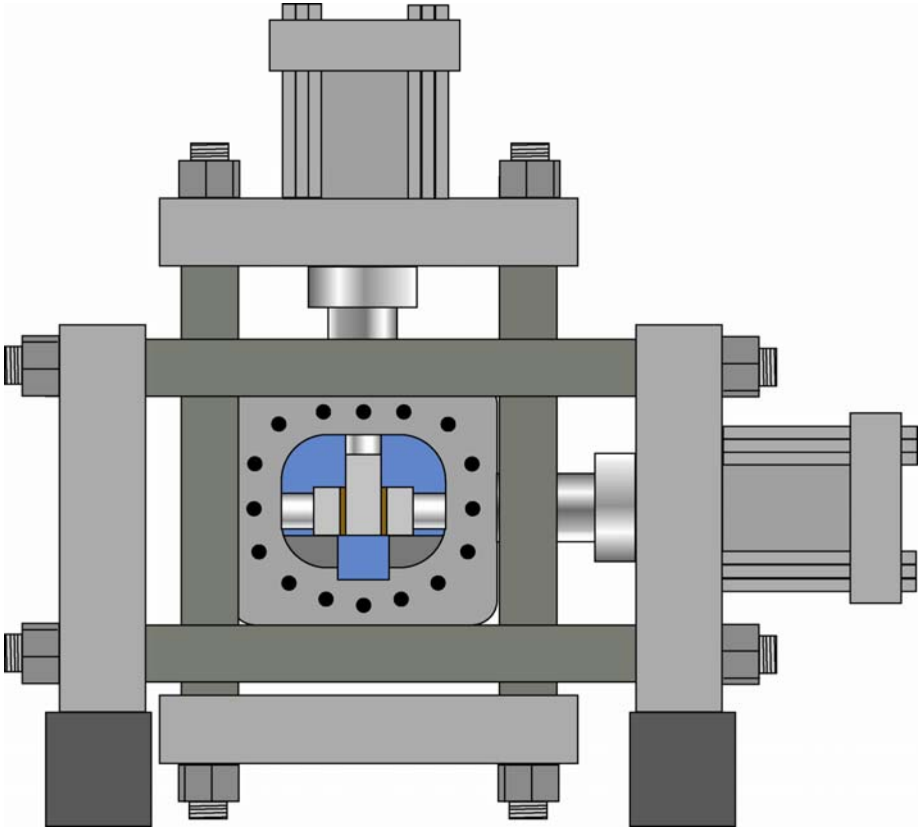




Experimental Design

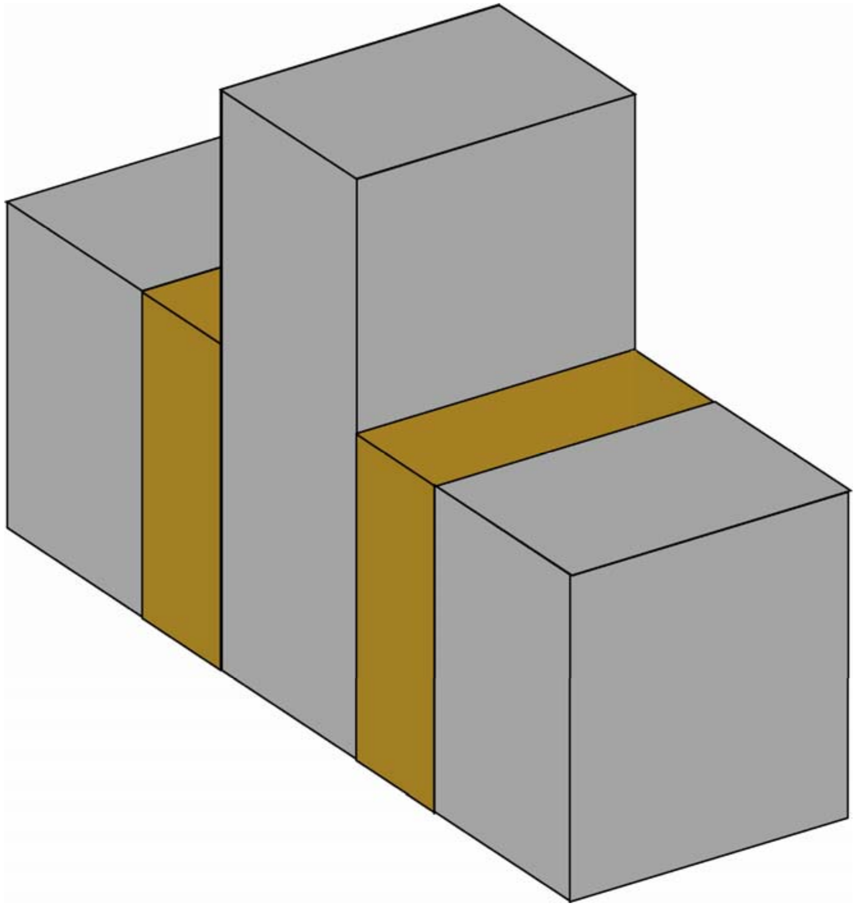
- Experiments are conducted in a biaxial deformation apparatus using a triaxial pressure vessel

- Double direct shear geometry



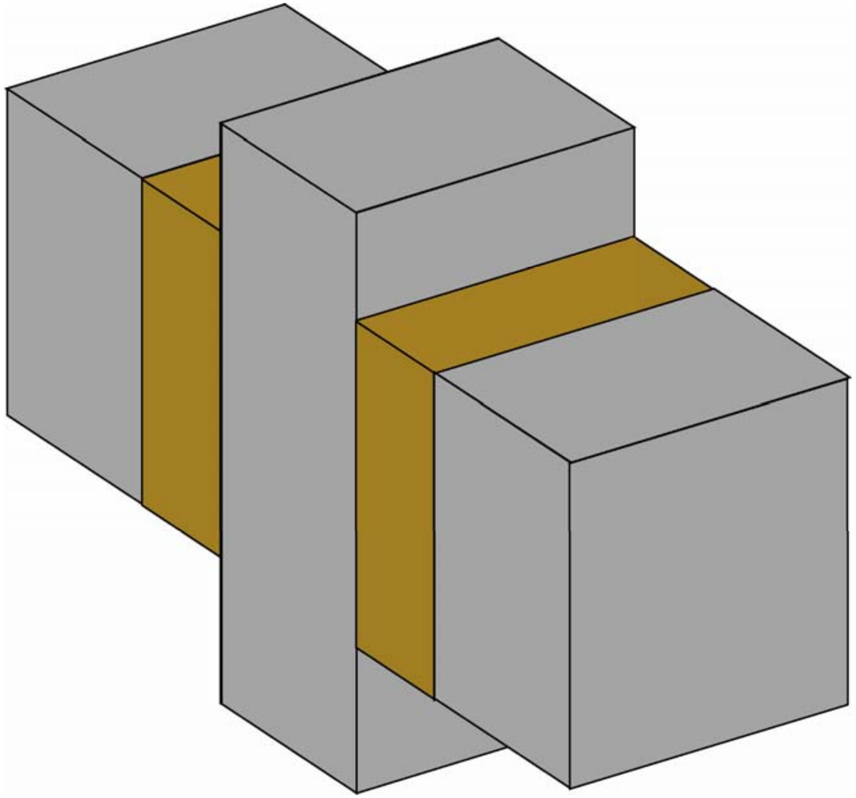
Experimental Design

- Sample blocks have a 5 x 5 cm nominal contact area
- Layers are constructed using a specially designed leveling jig at an initial thickness of ~4 mm
- Contact area is grooved to ensure that frictional sliding occurs within the layer rather than at the edges

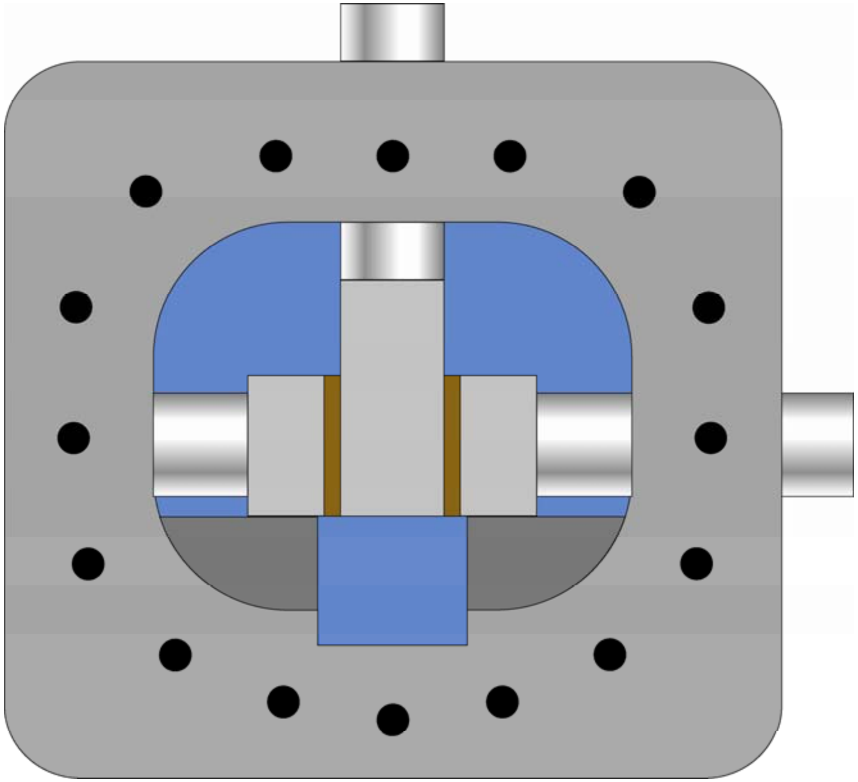


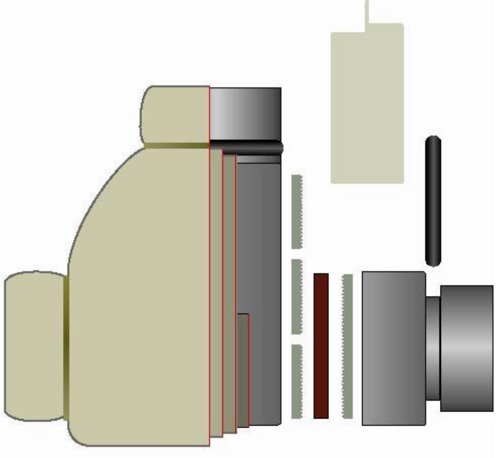
Experimental Design

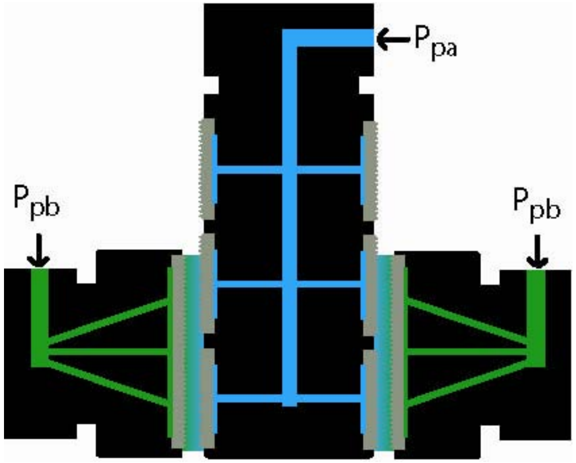
- Normal stress (σ) is applied by squeezing the blocks together
- Shear stress (τ) is generated by pushing the center block down through the granular layers at a constant velocity



Experimental Design

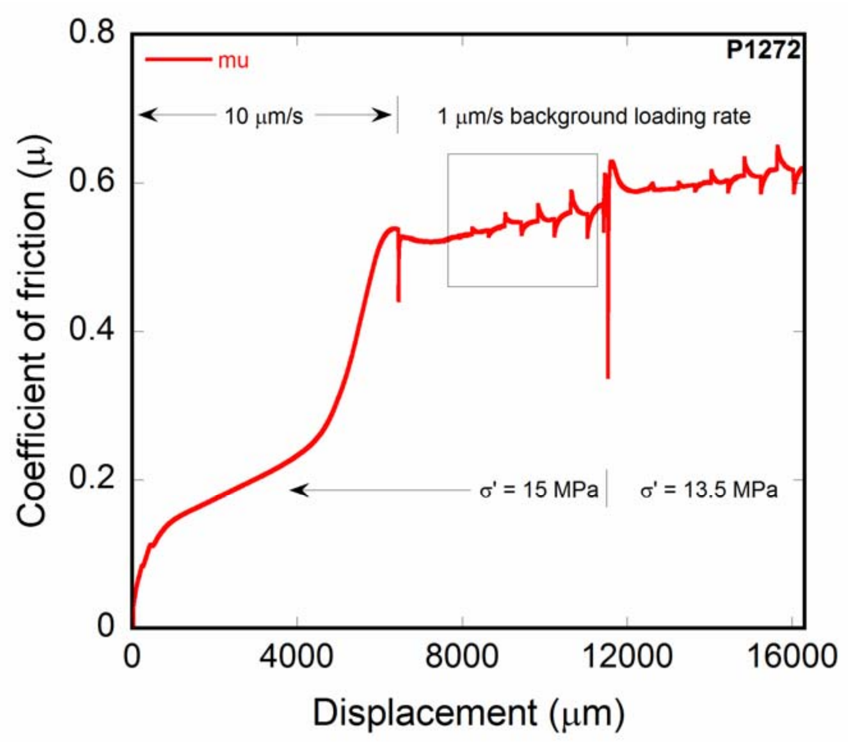




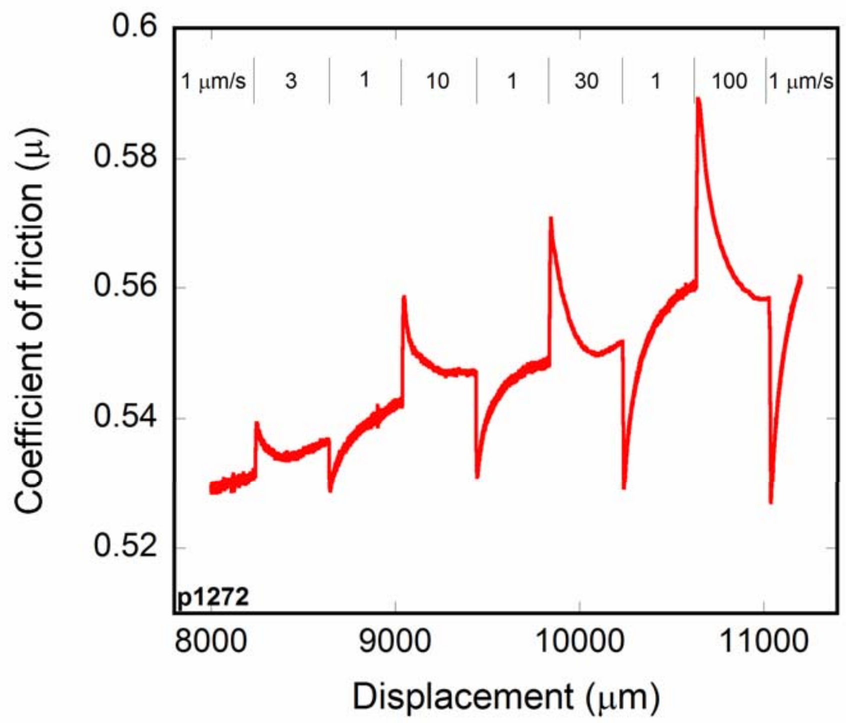


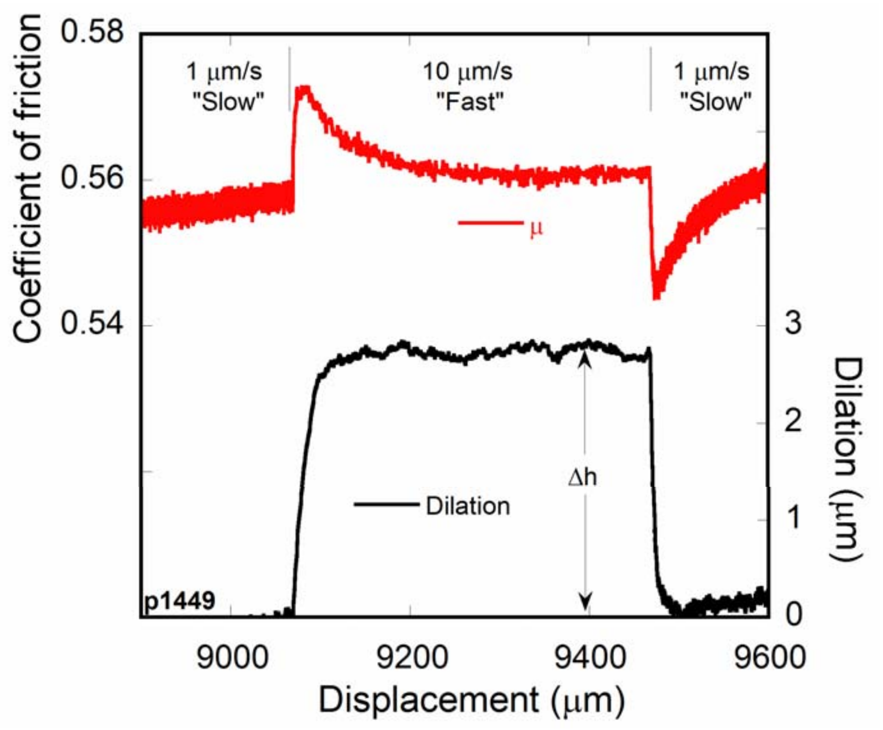
Experimental Results

- Initial run in at 10μm/s followed by a reduction to 1μm/s
- Effective normal stresses of 30, 20, 15, 10, 5, 2, and 0.8 MPa were used
- Velocity steps were conducted once the layer had reached it's approximate steady state frictional strength



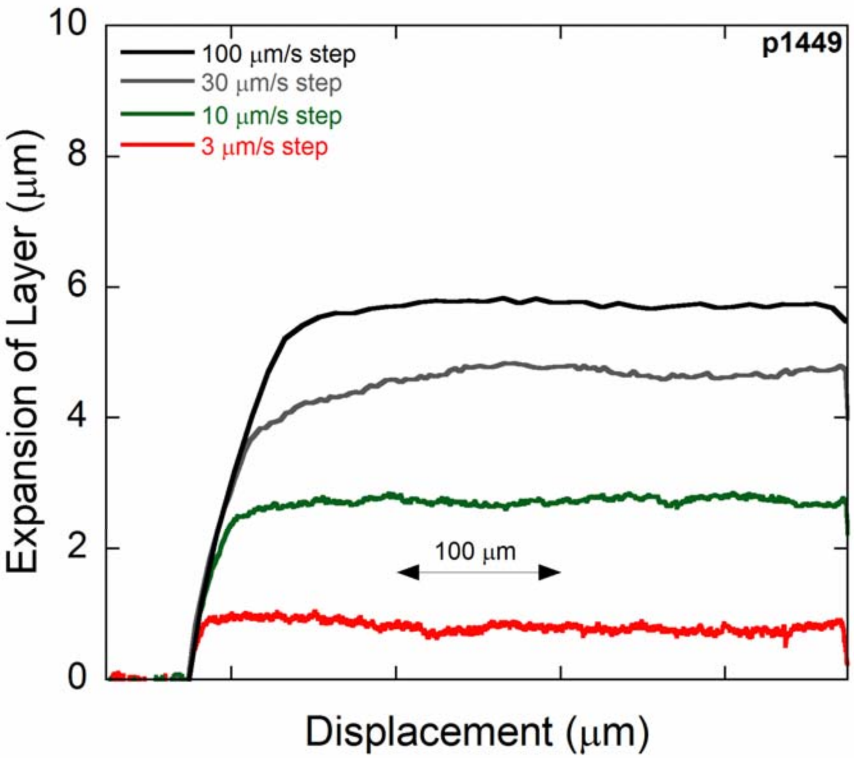
Experimental Results

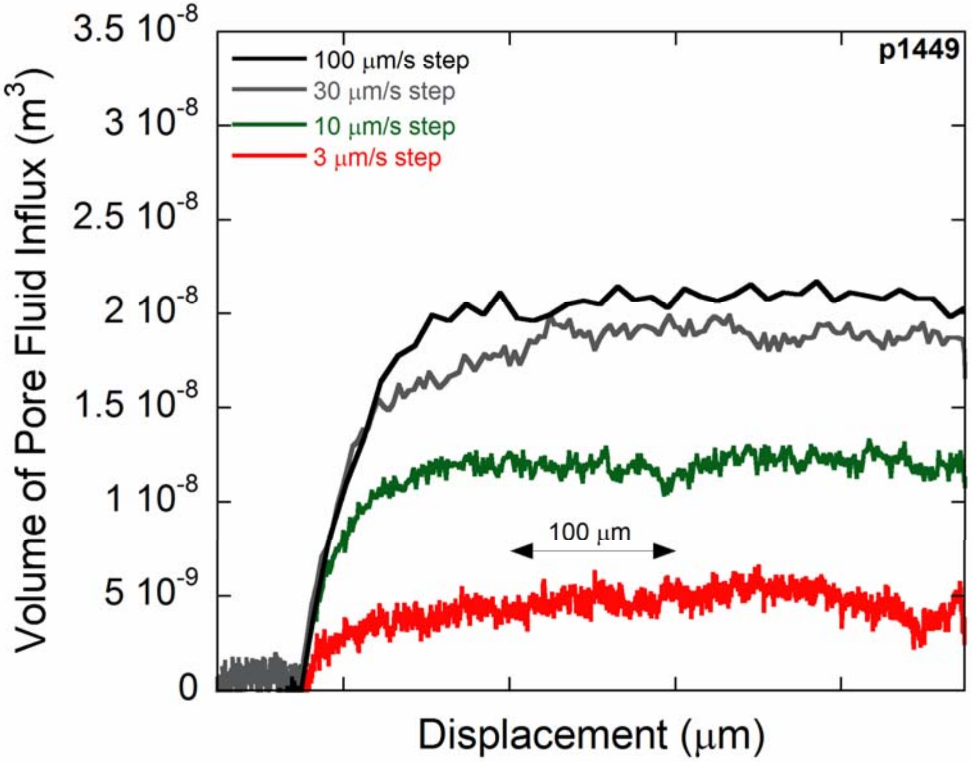




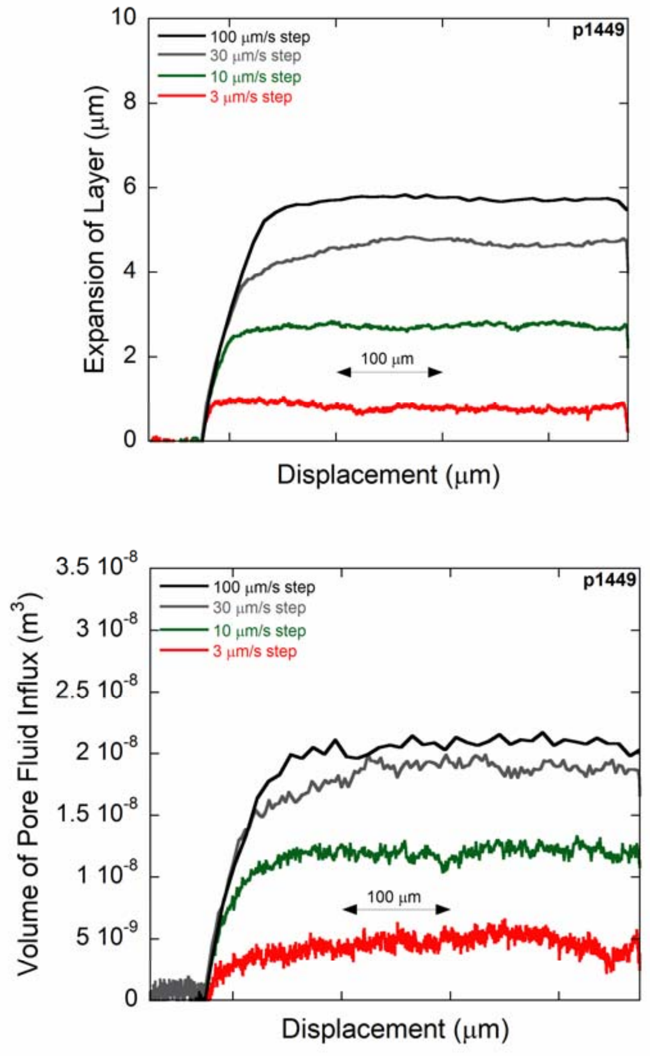
Experimental Results

- Magnitude of dilation increases as the size of the velocity step
- Excellent correlation between dilation as measured by physical expansion of the gouge layer and as measured by the volume of fluid influx

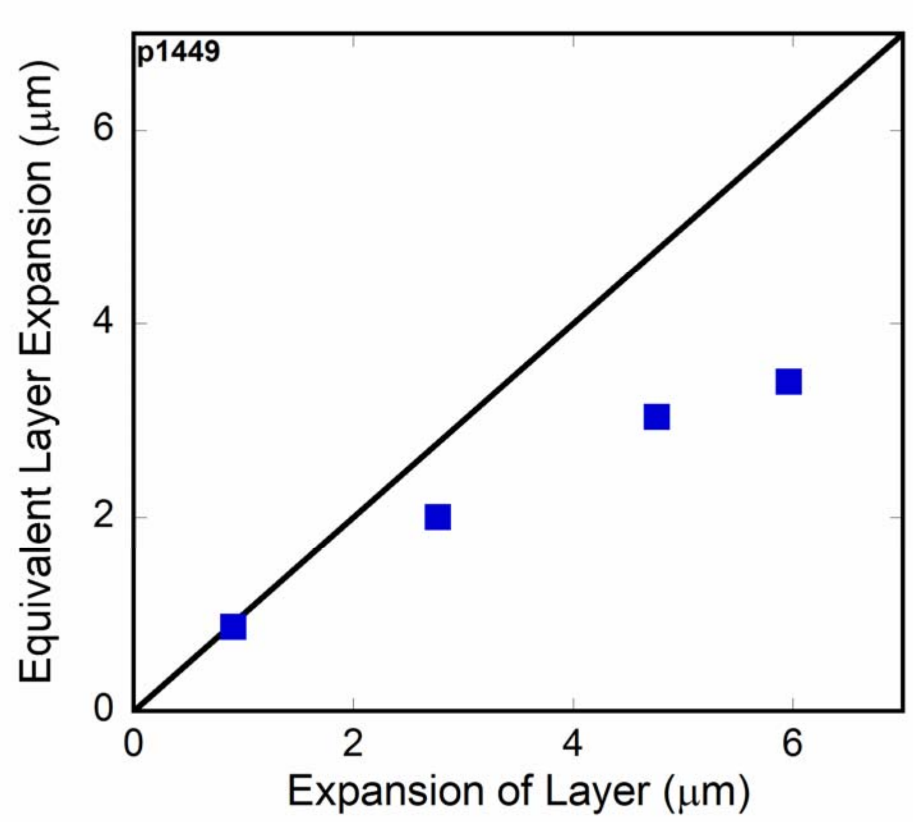




Experimental Results

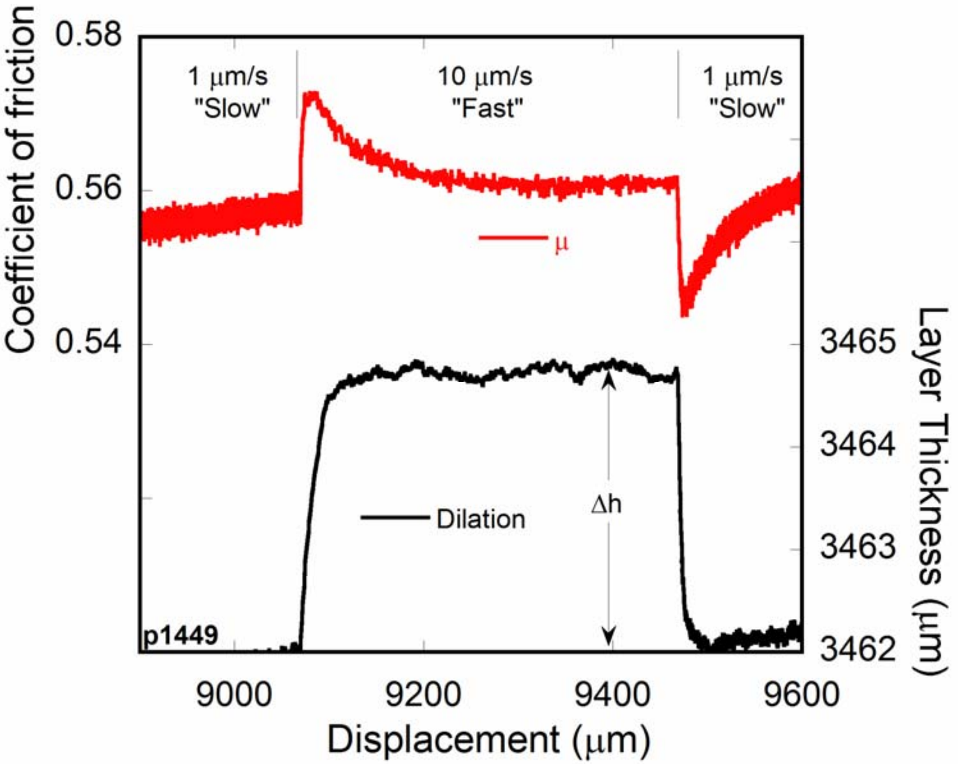


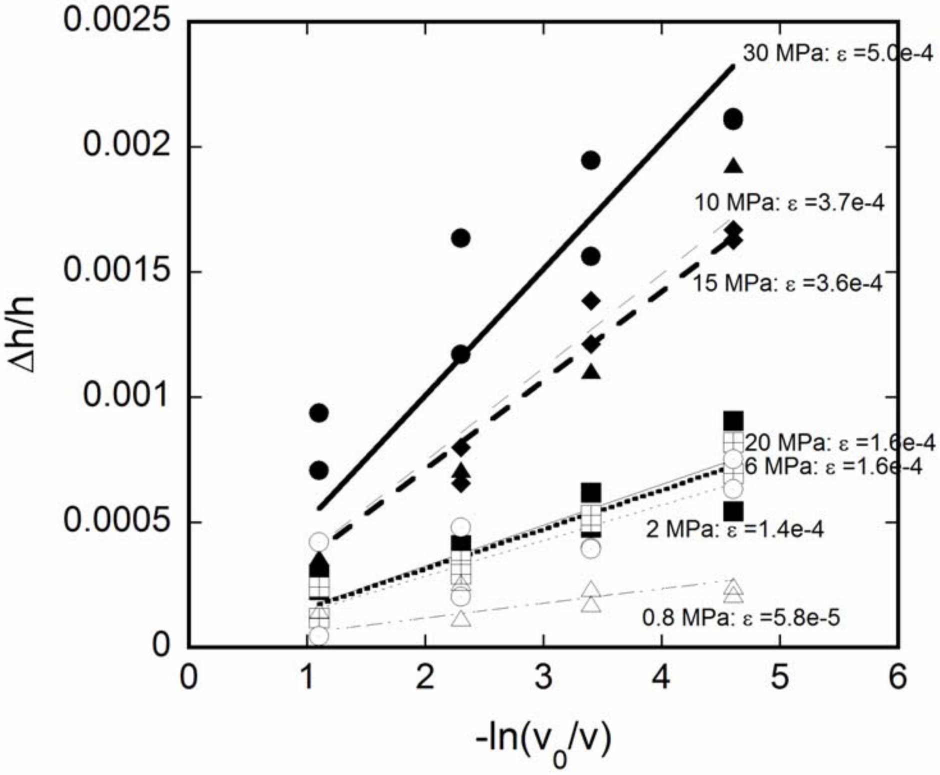
Error between physical dilation of layer and equivalent dilation equates to a few mm^3



Experimental Results

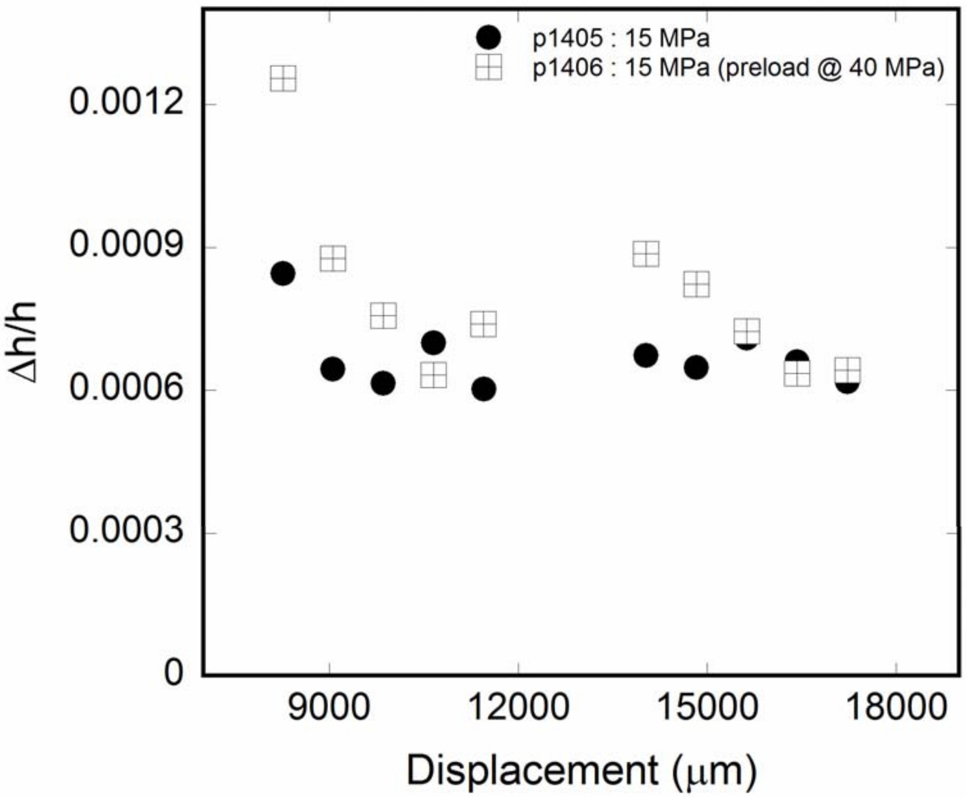
$$\Delta\phi_{ss} \cong \frac{\Delta h}{h} = -\varepsilon \ln\left(\frac{v_0}{v}\right)$$ Segall and Rice (1995)



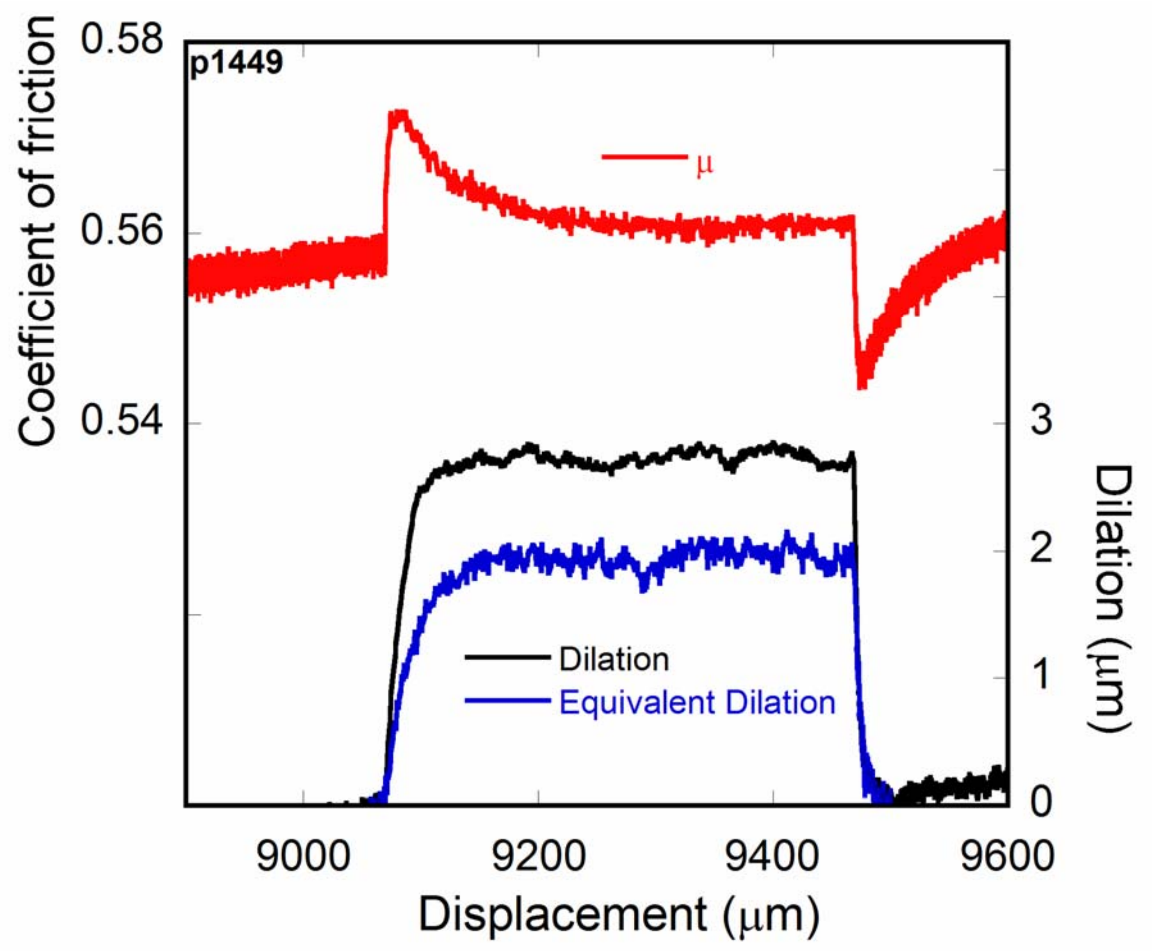


Hypothesis Test: Does initial porosity control the magnitude of dilation?

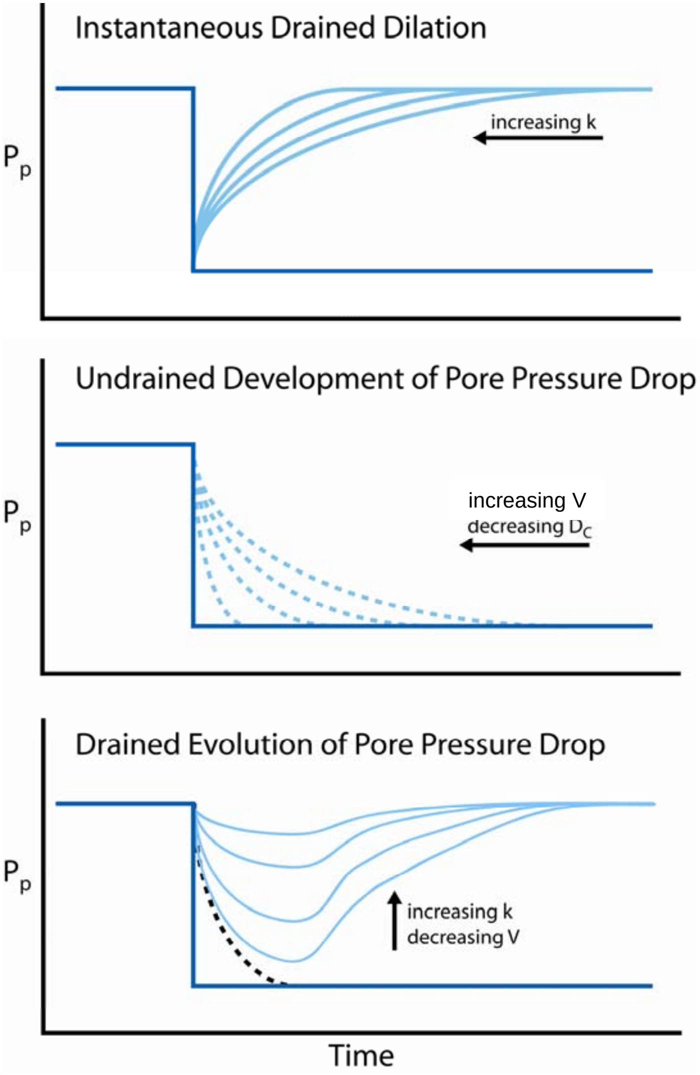
- Repeated velocity steps from 1 to 10 μm/s
- p1405 run at constant normal stress of 15 MPa
- p1406 loaded to 40 MPa prior to shearing when load was reduced to 15 MPa



Experimental Results



Conceptual Model



Model Description

$$\frac{\partial P_D}{\partial t_D} - \frac{\partial^2 P_D}{\partial x^2} - f_D = 0$$

$$f_D = \frac{1}{\ln(\frac{v_0}{v})} V_D \left(\frac{-(\frac{v}{v_0} - 1)e^{-V_D t_D}}{1 + (\frac{v}{v_0} - 1)e^{-V_D t_D}} \right)$$

$$P_D = \frac{\phi_0}{(\phi_\infty - \phi_0)} \frac{(p - p_0)}{K} = \frac{\phi_0}{\varepsilon \ln(\frac{v_0}{v})} \frac{(p - p_0)}{K}$$

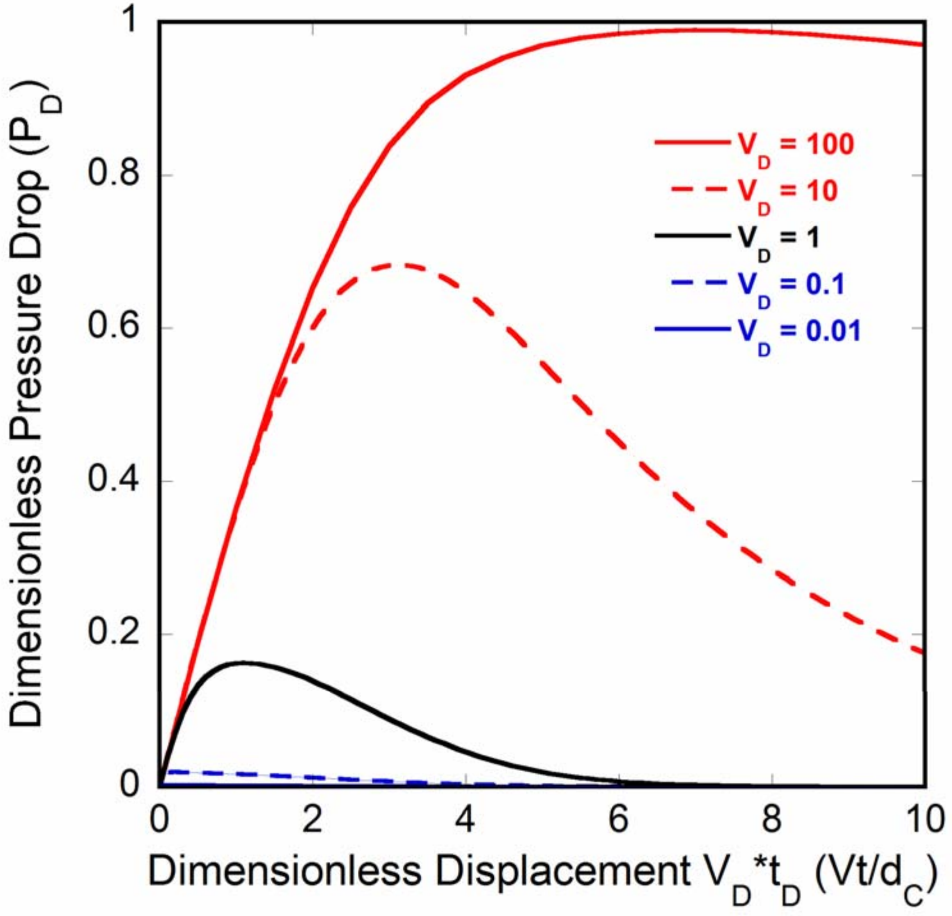
$$t_D = \frac{ct}{a^2}$$

$$V_D = \frac{va^2}{cd_c}$$

$$x_D = \frac{x}{a}$$

$$c = \frac{k}{\mu} K$$

Model Results



$$\Delta\phi = -\varepsilon \ln\left(\frac{v_0}{v}\right) \qquad V_D = \frac{va^2}{cd_c}$$

$$\Delta p_{\max} = -K\frac{\Delta\phi}{\phi_0} \qquad c = \frac{k}{\mu}K$$

Δp_{max} and V_d for real fault?

$0.000058 \le \varepsilon \le 0.00050 \qquad 1e-4 \le \Delta\phi \le 2.5e-3$

$K = 2.2\,GPa \qquad \phi_0 = 0.15 \qquad k = 1\times10^{-21}m^2$

$\mu = 0.89e-3\,Pa\cdot s \qquad a = 200\,\mu m \qquad d_C = 25\,\mu m$

$v = 10\frac{\mu m}{s}$

$$V_D \cong 6.5$$

$$1.5\,MPa \le \Delta p \le 36.7\,MPa$$

Conclusions

- Under these experimental conditions the dilatancy coefficient increases with normal stress rather than decreases.

- Normally loaded (consolidated) samples show little change in the magnitude of dilation with increasing strain, whereas over-consolidated samples show initially increased dilation that gradually becomes indistinguishable from the normally loaded sample.

- Our data suggest that low permeability, high slip velocity fault zones undergoing shear induced dilation may exhibit transient reductions in pore pressure and therefore increases in effective stress. This quasi-drained behavior will have a dilatancy hardening effect on the gouge layer inhibiting seismic rupture.

- Dilational decompression of the gouge layer is potentially very large perhaps completely depressurizing low permeability layers in some cases, but is likely not a major factor in our experiments where we document drainage that is nearly synchronous with dilation.

Future Work

- Work to ensure that the permeability of the flow distribution frits is not the limiting factor in fluid flow in our experimental system

- Determine dependency of ε on layer thickness, and large strain by setting them as experimental control variables

- Use low permeability, large thickness (high V_D) material to measure the magnitude of dilatant strengthening

- Use real rather than simulated fault gouge to constrain potential real world estimates of fault permeability changes and pore pressure fluctuations