Dilatancy hardening, rupture stabilization and instability in hydraulically isolated faults

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EGU2020-6217
in Session TS5.3:
The Mechanics of Earthquake Faulting: a multiscale approach
EGU May 2020

Introduction

We present laboratory observations of the hydro-mechanical interactions of hydraulically isolated faults. Shear-induced dilation or compaction of the fault zone can produce important variations in P_p. Feedback of fault strength occurs through variations in effective normal stress:

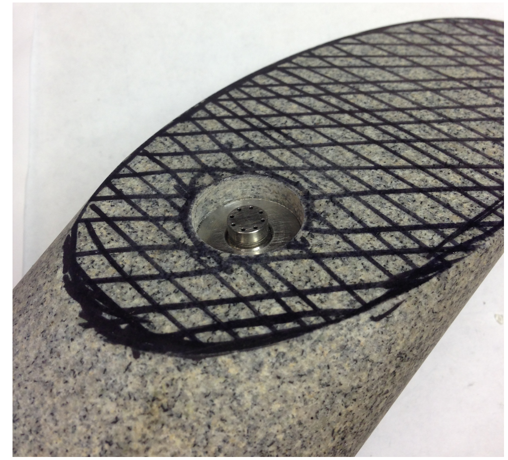
$$\mu_{eff} = \tau/(\sigma_n - P_p)$$

Proposed effects include *Dilatancy Hardening*, *Thermal Pressurization*, *P_p Compartmentalization/Overpressure*, and *Slow Slip*

Yet, few direct measurements of P_p transients exist.

New Approach: Direct Measurement of Fault Pore Pressure

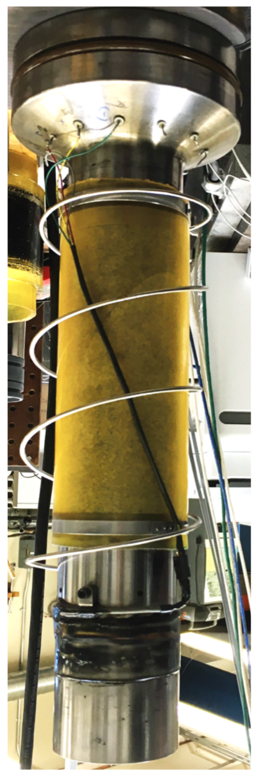
Miniaturized Pore Pressure Transducer
Provides direct measurement of Fault Zone Pore Pressure

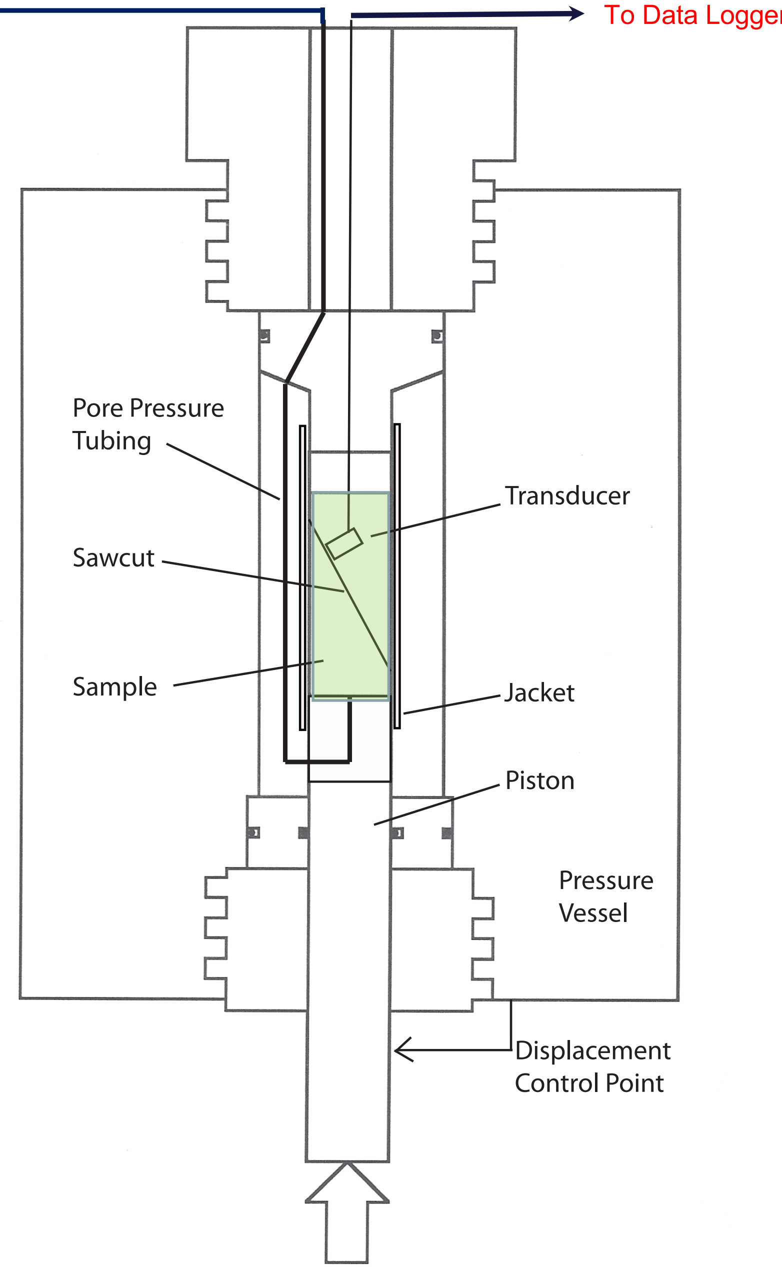


Proctor et al., *GRL*, submitted

Schematic view of sample in pressure vessel

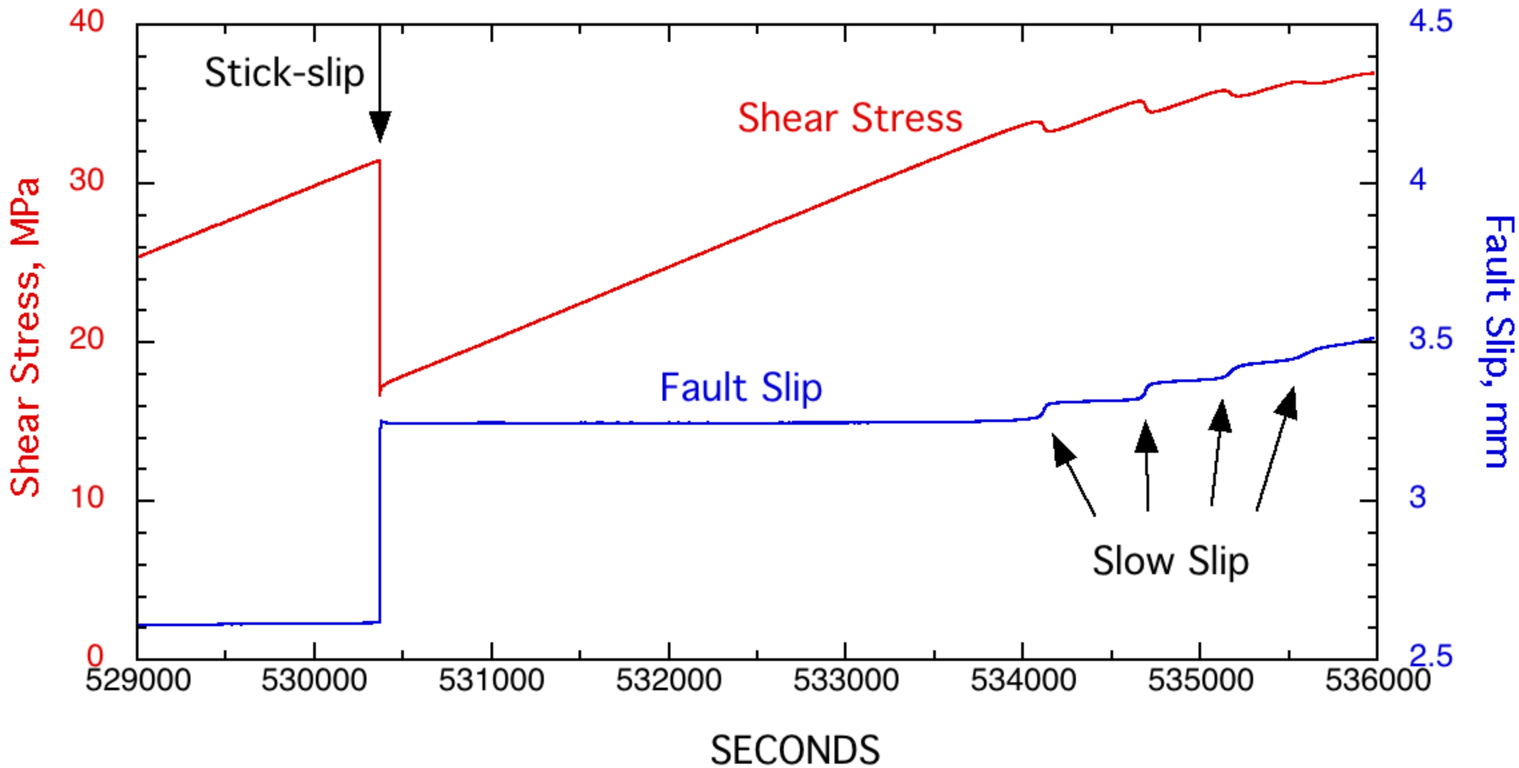
External Pore Pressure Pump
(Controls pressure on bottom face of granite sample)





Stick-Slip followed by Slow Slip Events

Bare Surface Granite, Isolated Fault
Pconf = 40 MPa
Loading Rate = 0.2 μm/s



Proctor et al., *GRL*, submitted

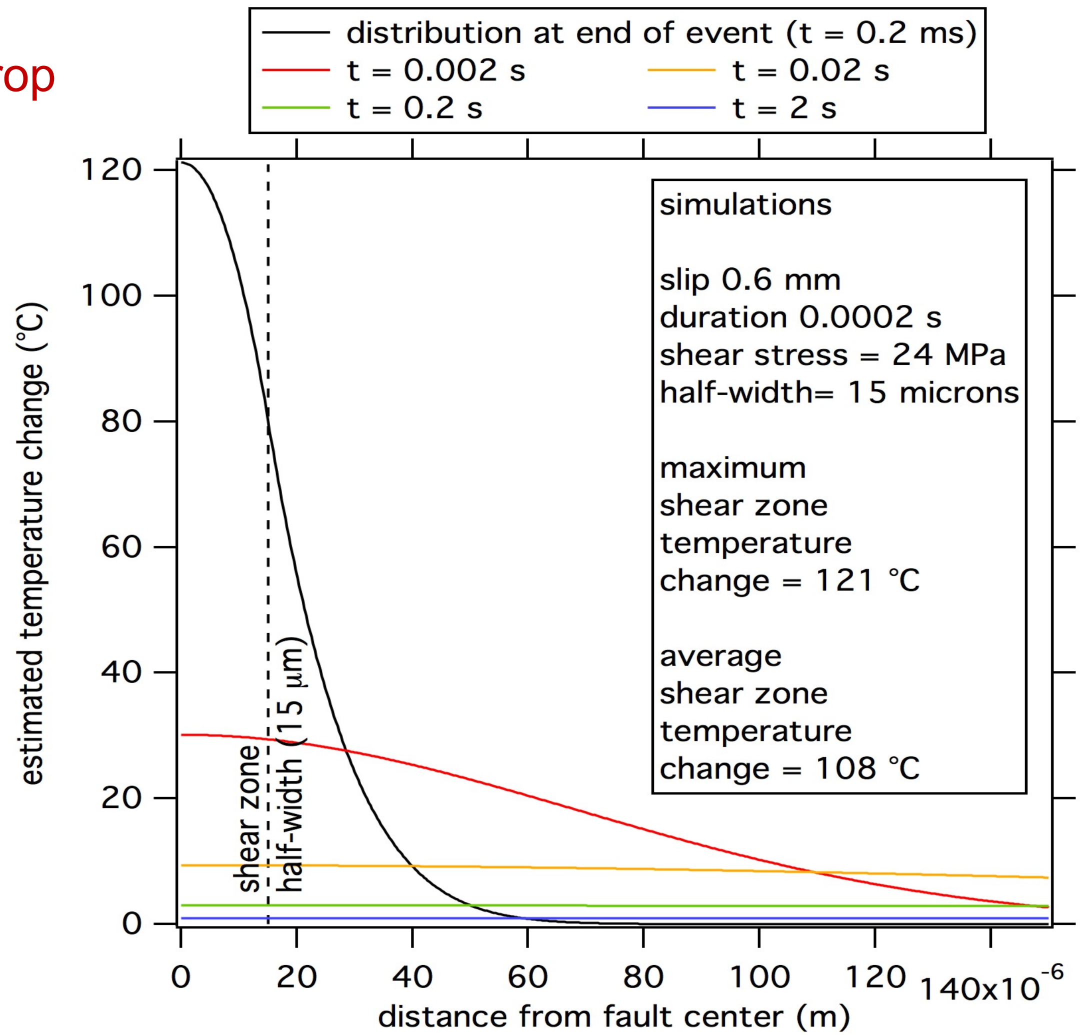
1D Heat Calculation for Stick-slip Event

Thermal Pressurization may contribute to stress drop

Constant heat production during slip event

Thermal diffusion away from Fault zone

Average temperature in fault zone at end of slip event may exceed 100°C



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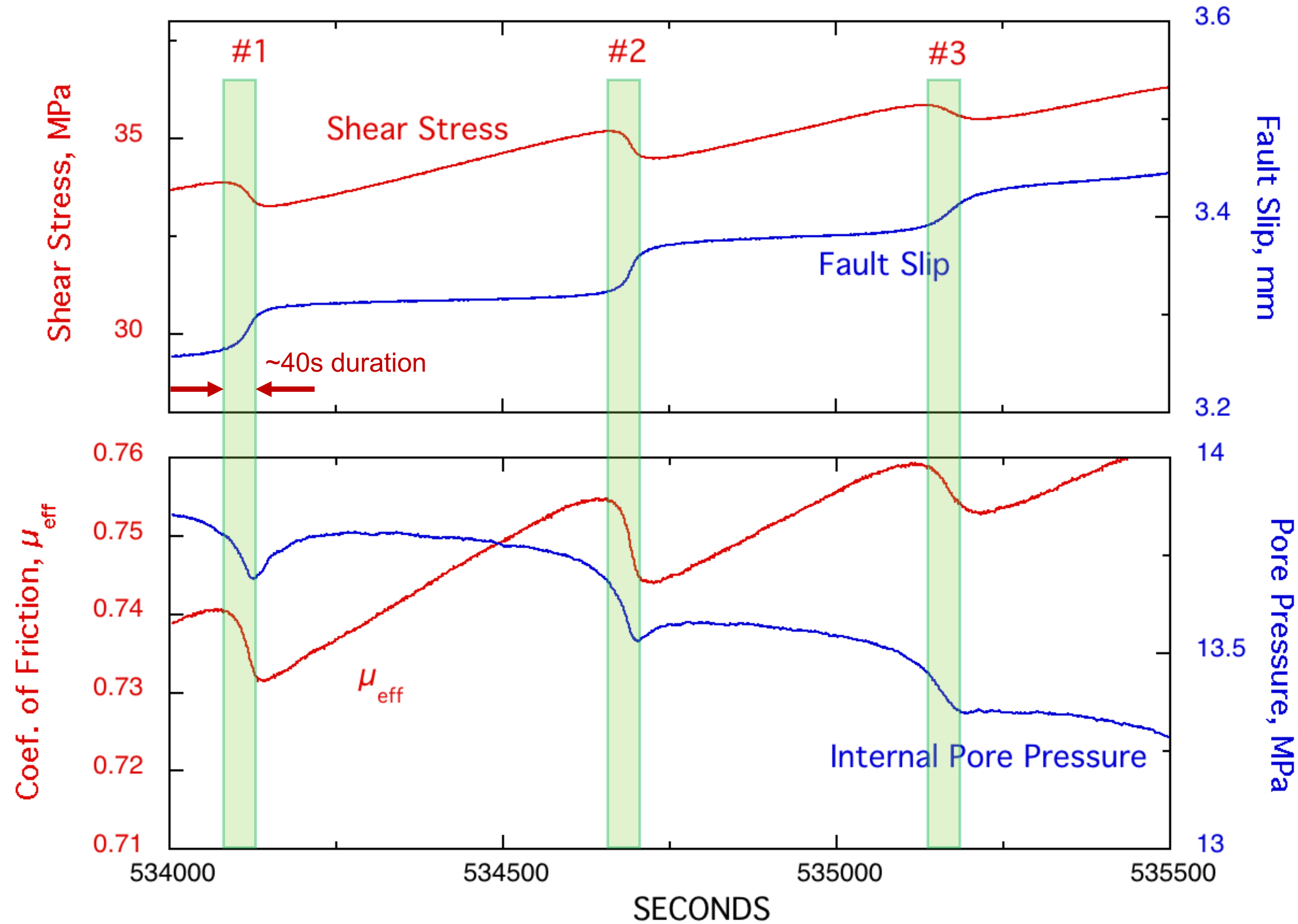
Sequence of Slow Slip Events

Drop in Pore pressure stabilizes slip

Bare Surface Granite, Isolated Fault
Pconf = 40 MPa
Loading Rate = 0.2 μm/s



Proctor et al., *GRL*, submitted

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 100, NO. B11, PAGES 22,155–22,171, NOVEMBER 10, 1995

Dilatancy, compaction, and slip instability of a fluid-infiltrated fault

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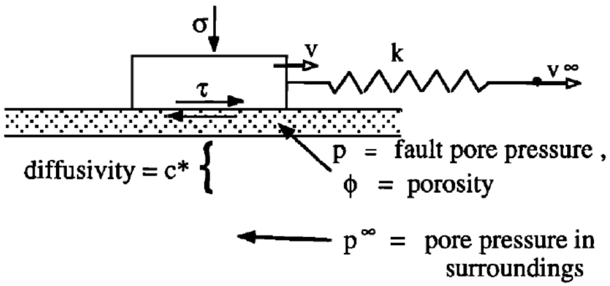


Figure 2. Simple spring slider model.

Assumed: pore fluid obeyed diffusion eq
With porosity change as a source term

$$c\nabla^2 p - \frac{\partial p}{\partial t} = \frac{\dot{\phi}_{\mathrm{plastic}}}{\beta} \quad (12a)$$

$$\beta = \phi(\beta_f + \beta_\phi) \quad (12b)$$

$$c = \frac{\kappa}{\nu\beta} \quad (12c)$$

Constitutive Equations for Porosity

Following the critical state concept in soil mechanics, we postulate the existence of a steady state porosity, although here we regard that value as a function of velocity. The experimental data discussed above suggests that at constant slip speed porosity evolves toward steady state over a distance d_c. Thus, by analogy with (3), we consider the simple evolution equation for porosity

$$\dot{\phi} = -\frac{v}{d_c}(\phi - \phi_{ss}), \quad (14)$$

where here, and in what follows, it is implicit that we are referring to inelastic changes in pore volume, i.e., ϕ corresponds to ϕ_{plastic}.

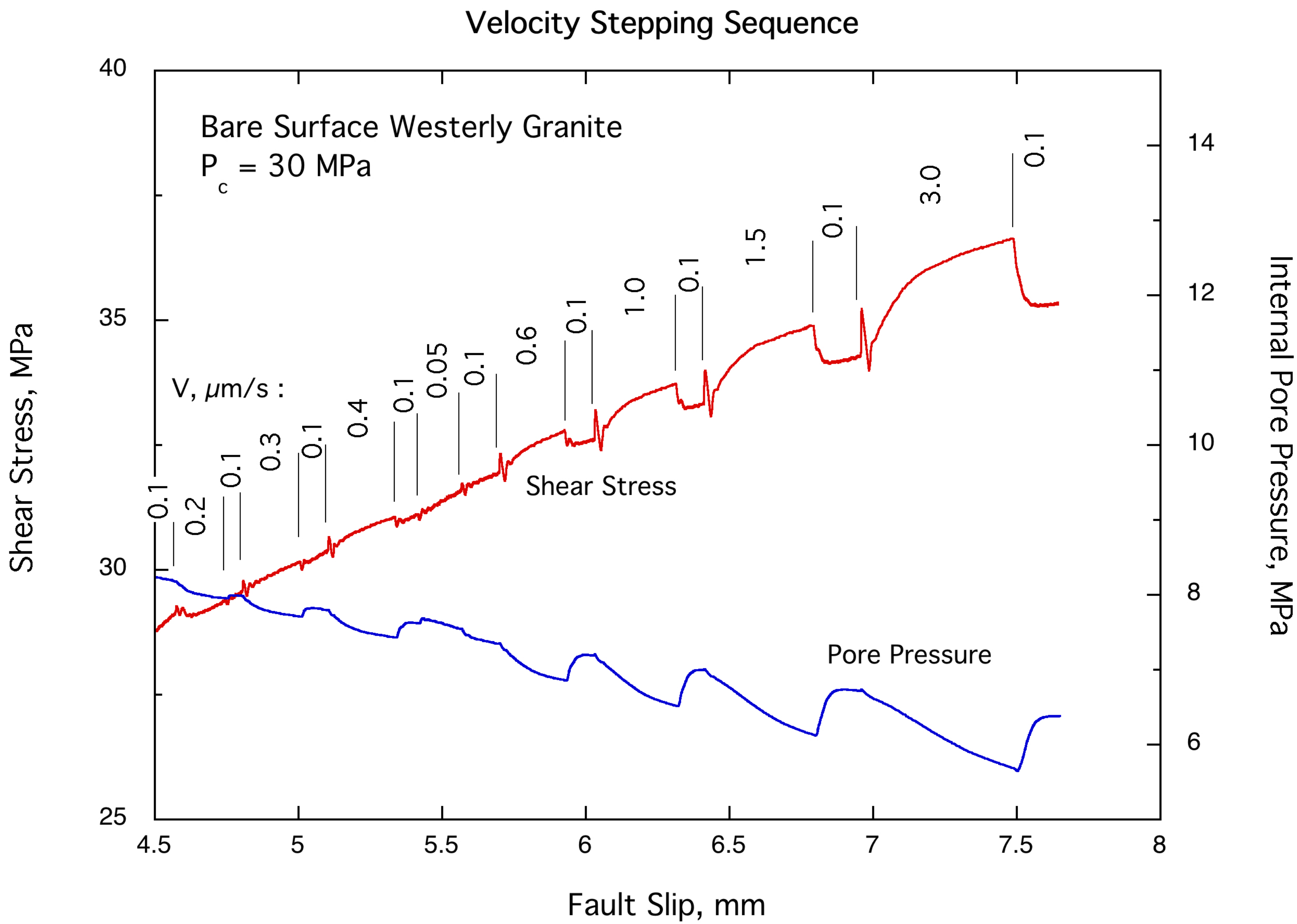
As a starting point, we take the steady state porosity to depend only on velocity. Rapid rates of deformation correspond to greater steady state porosities, while slow rates of deformation correspond to low values of porosity. We postulate the following relation:

$$\phi_{ss} = \phi_0 + \varepsilon \ln\left(\frac{v}{v_0}\right) \quad (15)$$

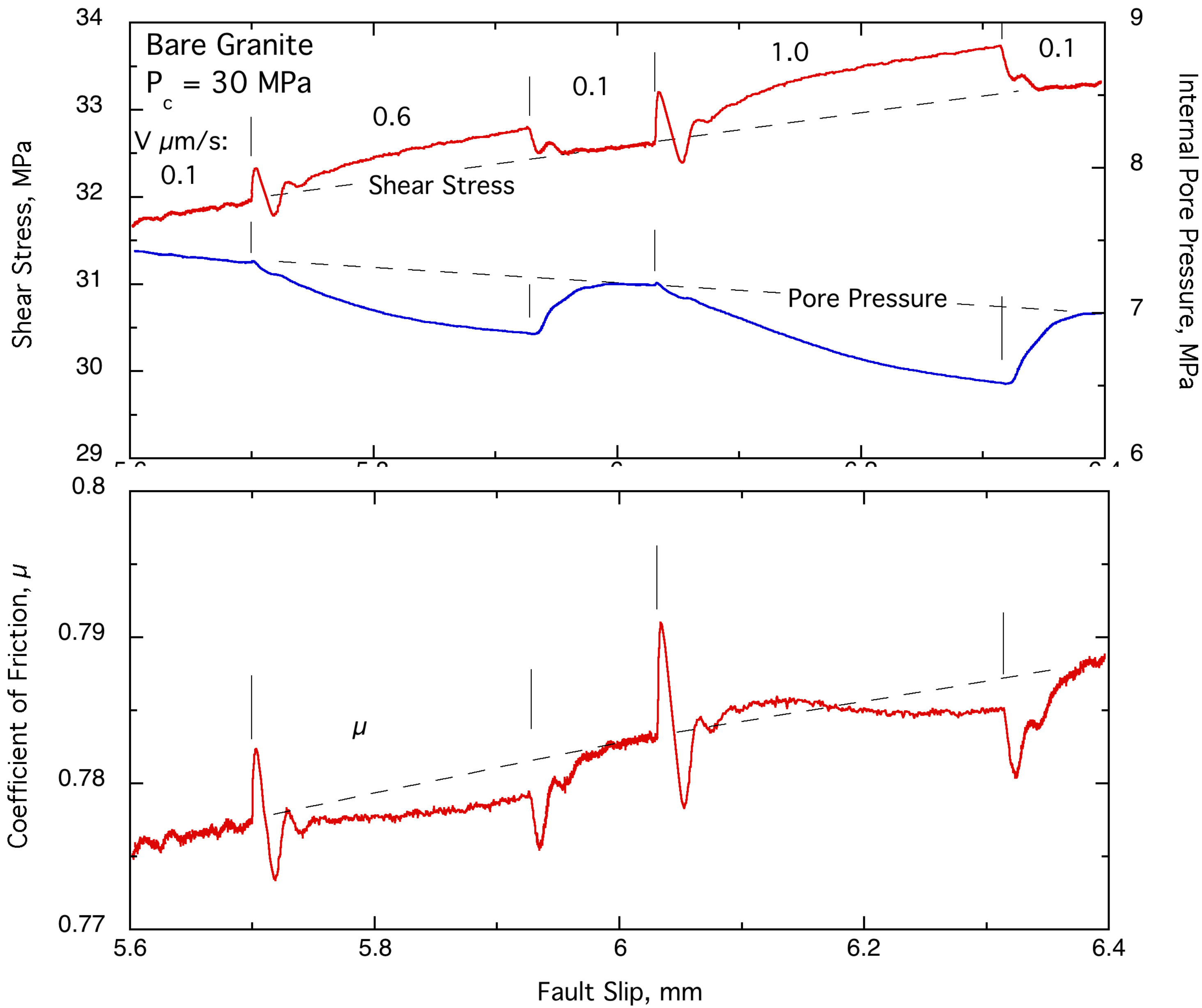
where ε is a "dilatancy coefficient." Note that the substitution of (15) and (14) into (13) shows that ε and β influence the stress and slip history only through the ratio ε/β.

Also assumed porosity change
only depended on velocity

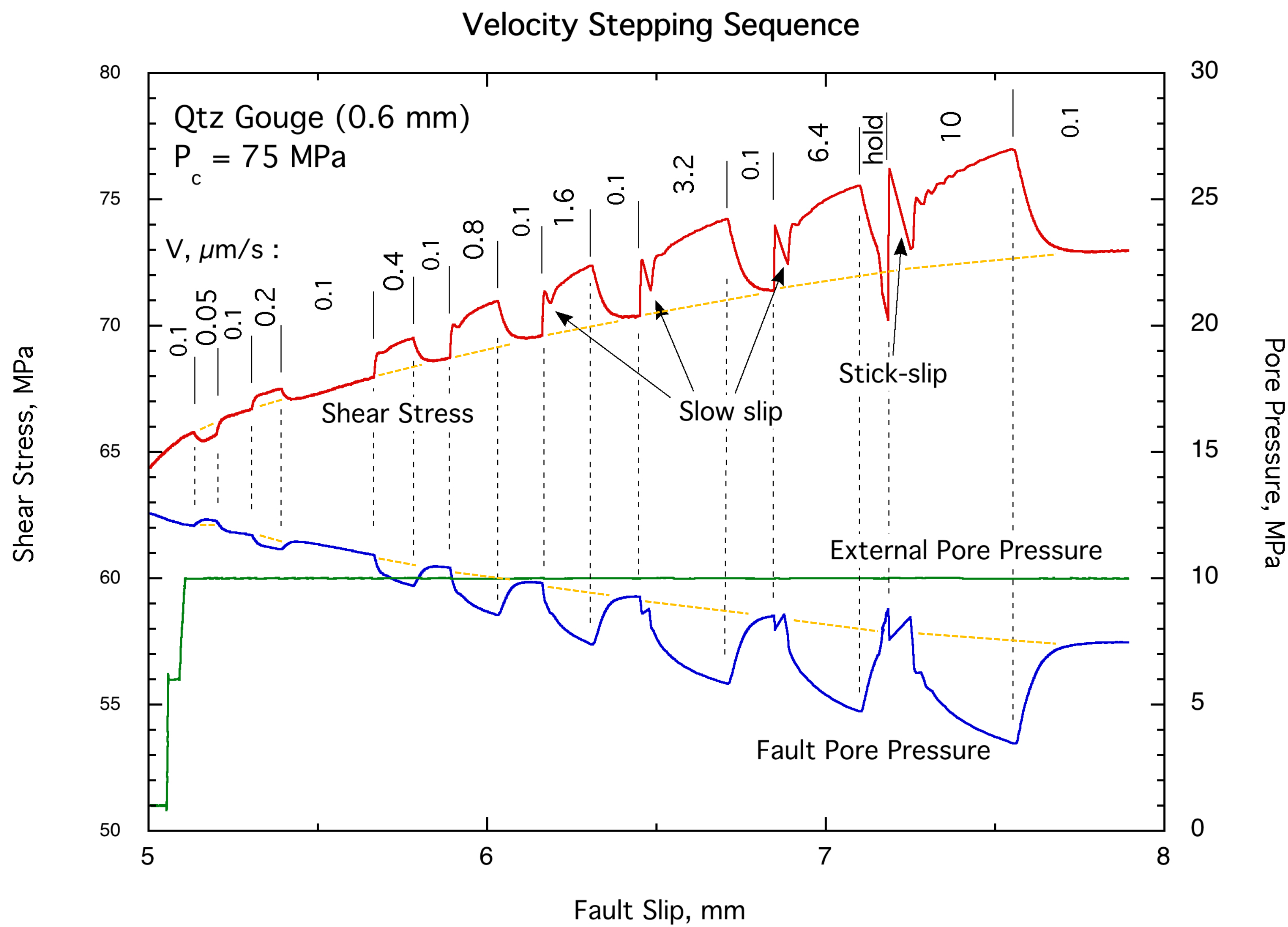
from Segall and Rice (1995)



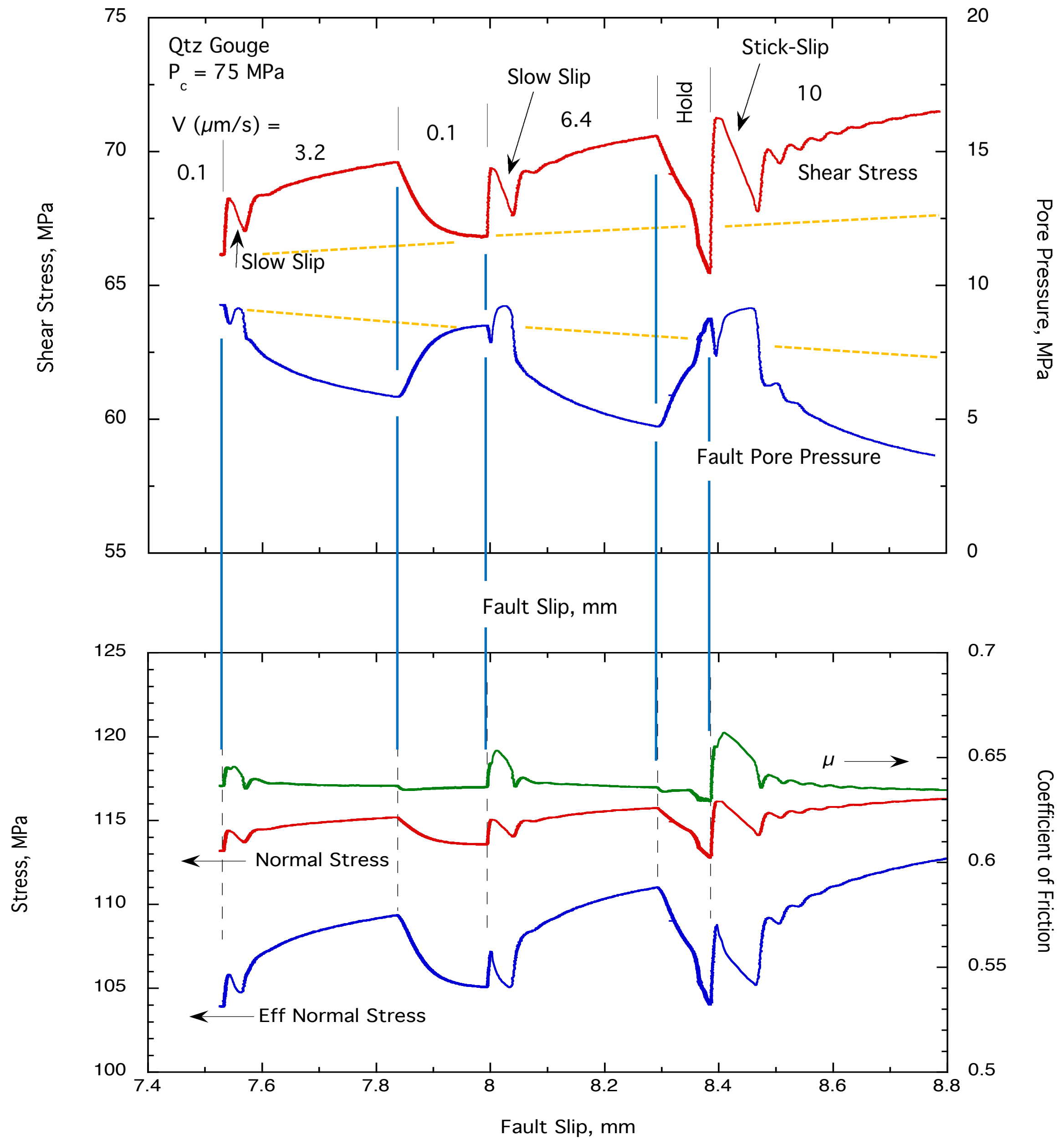
Velocity Stepping Sequence
Bare Surface Westerly Granite
P_c = 30 MPa
V, μm/s :
0.1
0.2
0.1
0.3
0.1
0.4
0.1
0.05
0.1
0.6
0.1
1.0
0.1
1.5
0.1
3.0
0.1
Shear Stress
Pore Pressure
Shear Stress, MPa
Internal Pore Pressure, MPa
Fault Slip, mm
40
35
30
25
14
12
10
8
6
4.5
5
5.5
6
6.5
7
7.5
8



Bare Granite
P_c = 30 MPa
V μm/s:
0.1
0.6
0.1
1.0
0.1
Shear Stress
Pore Pressure
Shear Stress, MPa
Internal Pore Pressure, MPa
34
33
32
31
30
29
9
8
7
6
μ
Coefficient of Friction, μ
0.8
0.79
0.78
0.77
5.6
5.8
6
6.2
6.4
Fault Slip, mm



Velocity Stepping Sequence
Qtz Gouge (0.6 mm)
P c = 75 MPa
V, µm/s :
0.1
0.05
0.1
0.2
0.1
0.4
0.1
0.8
0.1
1.6
0.1
3.2
0.1
6.4
hold
10
0.1
Shear Stress
Slow slip
Stick-slip
External Pore Pressure
Fault Pore Pressure
Shear Stress, MPa
Pore Pressure, MPa
Fault Slip, mm
80
75
70
65
60
55
50
30
25
20
15
10
5
0
5
6
7
8



Qtz Gouge
P_c = 75 MPa
V (μm/s) =
0.1
3.2
0.1
6.4
10
Slow Slip
Slow Slip
Hold
Stick-Slip
Shear Stress
Fault Pore Pressure
Shear Stress, MPa
Pore Pressure, MPa
Fault Slip, mm
75
70
65
60
55
20
15
10
5
0
Normal Stress
Eff Normal Stress
μ
Stress, MPa
Coefficient of Friction
125
120
115
110
105
100
0.7
0.65
0.6
0.55
0.5
7.4
7.6
7.8
8
8.2
8.4
8.6
8.8
Fault Slip, mm

Conclusions

- Pore pressure transients from 0.1 to >10 MPa are observed in hydraulically *Isolated* or *Partially Isolated* faults
- Both Increasing P_p (compaction) and Decreasing P_p (dilation) occur as precursors and coseismically
- Dilation 1) delays stick-slip and 2) may lead to slow slip
- Compaction 1) de-stabilizes the fault and 2) may cause an accelerated preparation phase
- Dilation/Compaction are both *Displacement* and *Velocity* sensitive
- 0.6 mm gouge layer produces P_p transients that are an order of magnitude larger than transients on bare surface granite
- In many cases, P_p transients dominate fault stability when compared to Rate and State Friction effects