Dilatancy hardening, rupture stabilization and instability in hydraulically isolated faults

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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:

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

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

Proctor et al., GRL, submitted
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
Dilatancy, compaction, and slip instability of a fluid-infiltrated fault

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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 \( d_s \). Thus, by analogy with (3), we consider the simple evolution equation for porosity

\[
\dot{\phi} = -\frac{v}{d_c}(\phi - \phi_{ss}),
\]

where here, and in what follows, it is implicit that we are referring to inelastic changes in pore volume, i.e., \( \phi \) corresponds to \( \phi_{\text{plastic}} \).

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:

\[
\phi_{ss} = \phi_0 + \epsilon \ln\left(\frac{v}{v_0}\right)
\]

where \( \epsilon \) is a “dilatancy coefficient.” Note that the substitution of (15) and (14) into (13) shows that \( \epsilon \) and \( \beta \) influence the stress and slip history only through the ratio \( \epsilon/\beta \).

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

Also assumed porosity change only depended on velocity

from Segall and Rice (1995)
Bare Surface Westerly Granite
$P_c = 30$ MPa

Shear Stress, MPa

Pore Pressure, MPa

Fault Slip, mm

$V, \mu m/s:$

- 0.1
- 0.2
- 0.3
- 0.4
- 0.1
- 0.05
- 0.1
- 0.6
- 0.1
- 1.0
- 0.1
- 1.5
- 0.1
- 3.0
- 0.1

Internal Pore Pressure, MPa
Bare Granite

\( P_c = 30 \text{ MPa} \)

\( V = 0.6 \text{ \mu m/s} \)

0.1

Shear Stress

0.6

Pore Pressure

0.1

Internal Pore Pressure, MPa

Coefficient of Friction, \( \mu \)

Fault Slip, mm
Qtz Gouge (0.6 mm)
$P_c = 75$ MPa

Shear Stress, MPa

Fault Slip, mm

Velocity Stepping Sequence

$V, \mu m/s$:

- 0.1
- 0.05
- 0.1
- 0.2
- 0.4
- 0.1
- 0.8
- 0.1
- 1.6
- 0.1
- 3.2
- 0.1
- 6.4
- Hold
- 10
- 0.1

Stick-slip

External Pore Pressure

Fault Pore Pressure
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.