Fluid injection and the mechanics of frictional stability of shale-bearing faults

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Injection induced earthquakes

Large scale fluid injection can generate overpressure and induce seismicity by reactivating existing ancient faults.

Important to characterize:

- Type of slip behavior
  - Aseismic creep
  - Slow-slip
  - Fast-slip

What is the fault response to fluid pressure stimulation?

Modified after Davies et al., 2013
Fault Reactivation vs. Frictional Slip Stability

The increase in fluid pressure along a fault will decrease the effective normal stress that clamps the fault in place favoring fault reactivation.

\[ \tau = \mu (\sigma_n - P_f) \]

*Hubbert and Rubey, 1959 Bull. Geol. Soc. Am*
Fault Reactivation vs. Frictional Slip Stability

Upon reactivation slip behavior is described via the **Rate- and State- Frictional Properties:**

1. **potentially seismic** (Velocity Weakening)
2. **aseismic** (Velocity Strengthening)

Criterion for fault stability defined by the critical stiffness \( k_c \)

\[
k_c = \frac{\left( \sigma_n - P_f \right) (b-a)}{D_c}
\]

- \( k < k_c \) \( \Rightarrow \) Unstable sliding
- \( k \sim k_c \) \( \Rightarrow \) Conditionally stable sliding
- \( k > k_c \) \( \Rightarrow \) Stable sliding

*Gu et al., 1984 JGR; Leeman et al., 2016 Nat.Comm.*
Outstanding questions:

• What is the coupling between hydrological and mechanical properties of a simulated fault during fluid pressurization?

• How fault rheology and frictional stability are influenced by fluid pressurization?
Experimental set-up

Biaxial Apparatus
in a Double Direct Shear configuration
within a Pressure Vessel

Details in Scuderi et al., 2017 EPSL
Experimental set-up

Biaxial Apparatus
in a Double Direct Shear configuration
within a Pressure Vessel

Shale simulated fault gouge: Illite (60%), Quartz (27%), Kaolinite (9%)

Details in Scuderi et al., 2017 EPSL
Fault strength is low $\mu=0.28$

Fault permeability $k\sim 10^{-19} \text{ [m}^2\text{]}$
Creep Experiments

Shear Stress ($\tau$), MPa
Time, minutes
Up-Stream fluid pressure, MPa
Constant Pf
Injection 1MPa/h
Injection 0.2MPa/12min
$\lambda = 0.4$
$\lambda$ increases
(1) (2) (3) Creep test
Steady State Shear Strength ($\tau_{ss}$)
90% $\tau_{ss}$
80% $\tau_{ss}$
Failure

Details in Scuderi et al., 2017 EPSL; Scuderi and Collettini, 2018 JGR
Creep Experiments

\[ \tau = \mu (\sigma_n - P_f) \]

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Failure

Fault
Reactivation

\[ \Delta P_f \]

Effective normal stress ($\sigma'_n$)
Creep Experiments - slip behavior upon fluid pressurization

Increase fluid pressure causes fault acceleration followed by steady state slip at higher slip rate

Fault acceleration remains slow with peak slip velocity of ~ 100µm/s

Scuderi and Collettini, 2018 JGR
Creep Experiments - Fluid diffusion

- Up-stream
- Down-stream
- Fluid Injection
- Fluid Equilibration

Graph showing:
- Slip (δ) [μm]
- Fluid pressure [MPa]
- Time [minutes]

Key markers:
- 28 min
- 32 min
- 33 min
Creep Experiments - Fault zone structure

Fluid injection

B-Shear Bulk
Y-Shear
Principal slip zone

Fluid injection
Conceptual model for fault zone deformation

\[
t = \mu (\sigma_n - P_f)
\]

Overpressurized principal slip surfaces
Fault gouge accelerates

Fluid diffusion
Fault gouge decelerates

Fluid pressure equilibration
fault gouge slip at new velocity

Scuderi and Collettini, 2018 JGR
Conceptual model for fault zone deformation

Failure Criterion
Fault Reactivation
Shear Stress ($\tau$)
Effective normal stress ($\sigma'_n$)

$$\tau = \mu (\sigma'_n - P_f)$$

Time of acceleration
~20 minutes

Accumulated slip
~10 mm

Slip velocity remains
< 100 $\mu$m/s

Overpressurized principal slip surfaces
Fault gouge accelerates

Fluid diffusion
Fault gouge decelerates

Fluid pressure equilibration
fault gouge slip at new velocity
Do fault gouge always fail by slow slip upon fluid pressurization?

Details in:
Scuderi and Collettini, 2016 SciRep
Scuderi et al., 2017 EPSL;
Scuderi and Collettini, 2018 JGR
Summary

• Fluid pressurization can promote slow but accelerated fault slip in a fault gouge that is characterized by velocity strengthening behavior (i.e. aseismic creep) acting as an efficient weakening mechanism.

• The observed fault slip behavior is the result of the complex interaction between hydrological, frictional and structural properties of the fault gouge.

• Accelerated aseismic creep can transfer stress to adjacent fault patches that are prone to earthquake nucleation providing a mechanism to trigger seismicity.