On the nature of induced seismicity: Control from initial state of stress

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Fluid induced seismicity

Field evidence

Modified from Ellsworth, 2013; Rubinstein and Mahani, SRL 2015, ...
Fluid induced seismicity

Field evidence

Modified from Ellsworth, 2013; Rubinstein and Mahani, SRL 2015, ...
Shear stress, GPa

Normal stress, GPa

Unstable

\[ \text{Friction} = \frac{\tau}{\sigma_n} = 0.6 \]

[Byerlee, PAGEOPH, 1978]
Unstable earthquakes

Nature

Shear stress, GPa

Normal stress, GPa

Friction = $\frac{\tau}{\sigma_n} = 0.6$

$[\text{Byerlee, PAGEOPH, 1978}]$
Shear stress, GPa vs. Normal stress, GPa

Unstable earthquakes

Friction = $\tau / \sigma_n = 0.6$

Nature

Byerlee, PAGEOPH, 1978
Basic concept

Fluid-induced fault reactivation

![Graph showing the relationship between normal stress and shear stress](image)

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[Byerlee, PAGEOPH, 1978]
Fluid-induced fault reactivation

Basic concept

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Fluid-induced fault reactivation

Basic concept

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Normal stress, GPa

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Fluid-induced fault reactivation

Shear stress, GPa

Normal stress, GPa

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[Byerlee, PAGEOPH, 1978]
Mohr-Coulomb approach is “0D”:
- Injection is **local**, reactivation is **global**.
- Stress distribution is key: **non-local** effects (e.g., Viesca & Rice, 2012; Garagash & Germanovich, 2012).

Friction of interface is **not a constant material** (Ben-David et al., 2011)
- Stress distribution along the fault?
- Unknown of the fluid pressure leading to fault reactivation.

Stress/pore pressure distribution depends on:
- injection rate
- permeability/hydraulic diffusivity (and its P dependence!).

If fault reactivates:
- rupture velocity?
- Rupture length?

**Potential damage**
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Potential damage
• triaxial experiments on saw-cut Westerly Granite and low permeability Andesite.

• Very smooth (ground) surface.

• Stress relaxation conditions: lock

• Piston at given stress, then inject.

• $P_c = 30; 60 & 95 \text{ MPa}, Q = 90\% \text{ of static friction}$

• Injection rate: 1, 10, 100, 1000 MPa/min.
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• Piston at given stress, then inject.

• $P_c = 30; 60 & 95$ MPa, $Q = 90\%$ of static friction

• Injection rate: 1, 10, 100, 1000 MPa/min.
The larger the injection rate, the larger the fluid pressure (effective friction) leading to instability.
Fluid-induced reactivation

Influence of injection rate and stress

Large injection rate, or low fault permeability: high pore pressure excess for reactivation

[Passelègue et al, GRL, 2018]
Fluid-induced reactivation

Fluid pressure distribution along the fault
Fluid-induced reactivation

Fluid pressure distribution along the fault

Measurement borehole

Strain gages ($\varepsilon$)

transmitted wave

injection borehole

ultrasonic transducer

Shear stress, Fluid Pressure [MPa]

Injection site

Opposite borehole

Time [s]

Slip [mm]
2D diffusion model: (See poster M. Almakari)

- Input: fluid pressure in injection site
- Inversion of the fluid pressure in the borehole

Output: Evolution of the hydraulic diffusivity, Pf distribution

Hydraulic diffusivity enhanced by slip events, and effective stress drop!
Fluid-induced reactivation

Influence of fluid pressure heterogeneities

Shear stress [MPa]

Effective normal stress [MPa]
Fluid-induced reactivation

Influence of fluid pressure heterogeneities

\( \overline{P_f} \) (from profile inverted)
\( \tau_0 \) (from strain gages array)
Fault reactivates close to expectations. **What about the nature of seismicity?**
Nature of seismicity

Influence of pressure heterogeneities
Nature of seismicity

Influence of pressure heterogeneities
Fast ruptures observed for high initial stress and/or strong fluid pressure heterogeneity?
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Nature of seismicity

Influence of pressure heterogeneities

Dynamic events: Large/long nucleation
Slow slip events: Small nucleation

\( C_R > V_r > 180 \text{ m/s} \)

\( V_r \approx 0.13 \text{ m/s} \)

Fast ruptures observed for high initial stress and/or strong fluid pressure heterogeneity?
Nature of seismicity

Work in progress:

Nucleation is complicated

Control from initial state of stress ($\tau_0$ and $P_f$)

Propagation is not? (LEFM)

Freund 1990; Svetlisky et al., 2018
Nature of seismicity

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$$V_r = C_R \left( 1 - \frac{(\bar{\sigma}_n - \bar{P}_f)}{\tau_0^2} \frac{\delta_c (f_s - f_d)E^*}{\pi l / 2(1 - \vartheta^2)} \right)$$
Work in progress:

**Nature of seismicity**

**Control from initial state of stress** \((\tau_0 \text{ and } P_f)\)

**Nucleation is complicated...**

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Expects our experimental results!

\[ \tau_0 \quad P_f \quad V_r \]
Work in progress:

Nucleation is complicated...  \[ \frac{V_s}{\Delta \tau} E \propto V_r = C_R \left( 1 - \frac{(\sigma_n - P_f)}{\tau_0^2} \delta_c \left( f_s - f_d \right) E^* \right) \frac{\pi l/2(1 - \theta^2)}{\tau_0} \]

Explains our experimental results!

Control from initial state of stress ($\tau_0$ and $P_f$)

Nature of seismicity

Propagation is not? (LEFM)

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$\tau_0$  $P_f$  $V_r$  $L_c$
Nature of seismicity

Control from initial state of stress ($\tau_0$ and $P_f$)

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Explains our experimental results!

Problem: Value of stress in nature?
• Injection-induced slip: **non-local** problem.
• High injection rates or low permeability fault! **local** overpressures.
• Pore fluid diffusion **far behind** slip and/or rupture front.
• Local fluid overpressure drives stress transfer and entire fault reactivation!

• Rupture speed **depends** of the stress acting along the fault!
• What about rupture length? Also predictable from LEFM!
• Nucleation processes are complicated in experiments: Finite fault size problem!
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Thanks for your attention