Rock and fluid thermodynamics control the dynamics of induced earthquakes

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UNDERSTAND THE MICROPHYSICAL INTERACTIONS BETWEEN PORE FLUID AND RESERVOIR FAULTS DURING INDUCED EARTHQUAKES
Methods - Experiments

Stick-Slip experiments under Triaxial stress conditions
\[ \sigma_1 > \sigma_2 = \sigma_3 \]

- **Samples:**
  30 ° Saw cut westerly granite cylinders
  \((\varphi=40 \text{ mm } ; H=88 \text{ mm})\)

- **Instrumentation:**
  - External measurements:
    \[ \sigma_1 ; \sigma_3 ; p_f ; \varepsilon_1 \]
  - Internal sensors:
    Near fault strain gauges

Best analogue for earthquakes
Methods - Stick-slip experiments

Elastic loading until shear strength is reached

$\varepsilon_1 = 10^{-5} \text{ s}^{-1}$; sampling frequency = 100 Hz
Results- 100 Hz measurements

\[ P_{\text{eff}} = P_c - P_f = 70 \text{ MPa} \]

Pf held constant during experiment

Three pore pressure configurations (DRY, Low Pf, High Pf)
Results - 100 Hz measurements

P_{ceff} = P_c - P_f = 70 \text{ MPa}

P_f \text{ held constant during experiment}

Three pore pressure configurations (DRY, Low Pf, High Pf)

\[ \varepsilon_1 = 10^{-5} \text{ s}^{-1}; \text{ sampling frequency } = 100 \text{ Hz} \]
Results - 100 Hz measurements

\[ P_{\text{ceff}} = P_c - P_f = 70 \text{ MPa} \]

Pf held constant during experiment

Three pore pressure configurations (DRY, Low Pf, High Pf)

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Results - 100 Hz measurements

Water Pressure ==
Lower coulomb strength.

Pceff = Pc - Pf = 70 MPa
Pf held constant during experiment

Three pore pressure configurations (DRY, Low Pf, High Pf)
Results - Static stress drop Vs. Slip

Pceff = Pc - Pf = 70 MPa
Pf held constant during experiment

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**Results – Dynamic stress drop**

\[ \varepsilon_1 = 10^{-5} \text{s}^{-1}; \text{sampling frequency} = 100 \text{ Hz} \]

- **A**
  - High Pf
  - Low Pf
  - Dry (\(\sigma_3 = 70 \text{ MPa and } pf = 0 \text{ MPa}\))
  - Low fluid pressure (\(\sigma_3 = 71 \text{ MPa and } pf = 1 \text{ MPa}\))
  - High fluid pressure (\(\sigma_3 = 95 \text{ MPa and } pf = 25 \text{ MPa}\))

- **B**
  - Dynamic recording of near fault stress
  - \(P_{\text{ceff}} = P_c - P_f = 70 \text{ MPa}\)
  - Pf held constant during experiment

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Results – Dynamic stress drop

1 curve = 1 dynamic event
Largest dynamic stress drops at **Low Pf**
Results – Dynamic Friction

A. ε = 10^{-3} \text{s}^{-1}; \text{sampling frequency} = 100 \text{ Hz}

Dry (σ3 = 70 MPa and pf = 0 MPa), low fluid pressure (σ3 = 71 MPa and pf = 1 MPa), high fluid pressure (σ3 = 95 MPa and pf = 25 MPa)

B. \text{Time (s)}

C. \text{Time (μs)}

D. \text{Sampling frequency} = 10 \text{ MHz}

E. \text{Shear stress drop (MPa)}

F. \text{Dynamic friction}

Large Magnitude

Small Magnitude

DRY

LOW Pf

HIGH Pf

Peak static shear stress (MPa)

Dynamic friction

Static friction

CONTEXT METHODS RESULTS MODEL IMPLICATIONS
Asperity temperature model - Description

Flash Temperature = maximum transient temperature responsible for weakening

\[ \Delta T = f(\tau_a, v) - g(T, \rho_w(P,T), C_{pw}(P,T)) \]

Heat source rate  Temperature buffering

Bowden and Tabor, 1969
Archard, 1959
Violay et al, 2013

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Asperity temperature model - Description

Thermophysical properties of fluid depend on Pressure & Temperature

\[ \Delta T = f(\tau_a, v) - g(T, \rho_w(P,T), C_{pw}(P,T)) \]

Heat source rate
Temperature buffering

Dependence on P & T!

Bowden and Tabor, 1969
Archard, 1959
Violay et al, 2013

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Asperity temperature model - Results

Thermodynamic phase transitions control Temperature rise

$\Delta T = \frac{1}{\rho_Q c_{PQ} \sqrt{k \pi}} \left( \tau_a v \sqrt{t_c} - \frac{V_w \rho_w}{t_c \pi a^2} (T C_{Pw} + L_w) \sqrt{t_c} \right)$

Heat source rate
Temperature buffering

Thermal Weakening: helps earthquake propagation
Water's supercritical transition: buffers fault's heat
Water Vaporization: allows temperature rise

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Thermal pressurization model

- Difference DRY and LOW Pf ??

- Stress drop at HIGH PF ??

THERMAL PRESSURIZATION.

Thermal pressurization accounts for reduction in dynamic friction

\[
\Delta p = \frac{\Lambda}{1 + \sqrt{\frac{\alpha_h \gamma d}{\alpha_{th}}} \Delta T}
\]

Rice, 2006

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CONCLUSIONS.

Thermodynamics control dynamic weakening processes during earthquake rupture.
Careful! – $\sigma_N$ Evolves with depth!

High Depth $\Rightarrow$ Higher stress $\Rightarrow$ FLASH HEATING

Thermophysical properties of water and rock should be taken into account in physics based models.
QUESTIONS ?
Asperity temperature model – Parameter description

\[ \Delta T = \frac{1}{\rho_{Qz} C'_{pqz} \sqrt{k\pi}} \left( \tau_{a} v \sqrt{t_{c}} - \frac{V_{w} \rho_{w}}{t_{c} \pi a^2} (TC_{pw} + L_{w}) \sqrt{t_{c}} \right) \]

\( \Delta T \) in °C is the temperature rise at the contacting asperities.

\( v \) in \( m.s^{-1} \) is the slip rate relative to the contacting asperities.

\( t_{c} \) in s is the average contacting time between asperities which is defined as \( t_{c} = \frac{a}{v} \) by Rice, 2006.

\( \tau_{a} \) in MPa is the shear stress acting on a single asperity at the onset of instability.

\( a \) in m is the average size of asperities defined as \( a = \sqrt{\frac{F}{M \pi P_m}} \). Where:

- \( F \) in N is the normal force applied to the surface.
- \( M \) is the number of asperities in contact as defined by Dietrich and Kilgore, 1994 and calculated for our surface.
- \( P_m \) in Pa the critical yield stress or penetration hardness of Quartz.

\( \rho_{Qz} \) in \( kg.m^{-3} \), \( C'_{pqz} \) in \( J.kg^{-1}.K^{-1} \) and \( k \) in \( m^2.s^{-1} \) are respectively the density, specific heat and thermal conductivity of Quartz.

\( \rho_{w} (P, T) \) in \( kg.m^{-3} \) and \( C_{pw} (P, T) \) in \( J.kg^{-1}.K^{-1} \) are respectively the density and specific heat of water.

\( V_{w} \) in \( m^3 \) is water volume interacting with asperities during shear heating defined in the same manner as Violay et al, 2013 over a thickness of 100 μm.