Earthquake Ruptures with Thermal Weakening and the Operation of Faults at Low Overall Stress Levels

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Maximum compressive stress at 68±7° from local SAF strike (from borehole breakouts, hydraulic fracturing, earthquake focal mechanisms)

[Townend and Zoback, 2004]
1. Maximum compressive stress at 68±7° from local SAF strike
2. Stresses in crust cannot exceed static friction (assuming $f_s \approx 0.8$)

⇒ Maximum $\tau/(\sigma - p)$ on SAF is $\sim 0.3$

[Noda, Dunham, and Rice, submitted 2008]
Stresses in SAFOD Pilot Hole:
\( \tau / (\sigma - p) \approx 0.2 - 0.3 \) at 2.2 km depth

[Hickman and Zoback, 2004]
Fault Mechanics and Dynamic Weakening Mechanisms

**Stress constraints:** low stresses acting on major faults

**Geologic constraints:** lack of pseudotachylytes (melted rock) near slip surface

**Heat flow constraints:** lack of heat flow signature around faults

Dynamic weakening reduces fault shear strength, $\tau$, but *only during rapid sliding* ($V \approx \text{m/s}$); caused by changes in:

$$\tau = f(\sigma - p)$$

$f = \text{coefficient of friction (reduced by flash heating of asperity contacts)}$

$p = \text{pore pressure (raised by thermal pressurization)}$

$\sigma = \text{normal stress}$
Features of a Dynamic Weakening Model

“static” friction $f_s \approx 0.8$

$\frac{\tau}{(\sigma - p)} = 0.2302$ (shear / effective normal stress)

$2w = 100 \mu m$ (shear zone width)

$x = 8 m$

reasonable static stress drop

low stress during slip

[Noda, Dunham, and Rice, submitted 2008]
Weakening Mechanisms

1. Flash Heating of Microscopic Asperity Contacts

*Strongly velocity-weakening friction*

\[ \frac{df}{dt} = \frac{a}{V} \frac{dV}{dt} - \frac{V}{L} \left[ f - f_{ss}(V) \right] \]

- Conservation of energy and fluid with
  - distributed shear zone (~100 µm wide)
  - diffusion of heat and fluid (“adiabatic, undrained” when transport neglected)
  - thermal and hydraulic properties from drilling projects and exhumed faults

2. Thermal Pressurization of Pore Fluid

- undrained pressurization
  \[ \left( \frac{\partial p}{\partial T} \right)_u \sim \text{MPa/K} \]
Faults Host Ruptures at Low Background Stress Levels

(flash heating is essential, thermal pressurization plays minor role)


\[ \tau^b = \tau^\text{pulse} \]

\[ \tau^b = \tau^\text{dyna} \]

\[ 2w = 100 \mu m \]

[Damaged] (thermal pressurization less effective)

[Uncertainty in hydraulic properties]

[Intact] (thermal pressurization more effective)

[Noda, Dunham, and Rice, submitted 2008]
Self-Similar Scaling

Scaling (of slip pulses, not cracks) consistent with natural earthquakes: 
\( \sim 0.14 \) mm slip / m rupture length = 0.14 m/km

\[ \tau^b = 0.2302 \sigma_o \] (pulse)  \[ \tau^b = 0.2381 \sigma_o \] (crack)

\[ r = 0.8, \ 2w = 100 \ \mu m \]

snapshots every 350 \( \mu s \)

[Noda, Dunham, and Rice, submitted 2008]
Succession of Weakening Mechanisms at Rupture Front

State evolves very quickly, subsequent weakening from thermal pressurization

Summary: Strong rate-weakening permits slip pulses on faults at $\frac{\tau}{(\sigma-p)} \sim 0.3$ (rupture mode fairly insensitive to thermal pressurization)

Open question: How to use these laws in large-scale simulations? Increase $L$? Increase both $L$ and hydraulic properties (holding dimensionless ratios fixed)?

[Noda, Dunham, and Rice, submitted 2008]
Thermal Pressurization of Pore Fluids by Distributed Shear Heating

Conservation of fluid mass (neglecting changes in $p$ from fault-zone strains)

$$\frac{\partial p}{\partial t} = \alpha_{hv} \frac{\partial^2 p}{\partial y^2} + \Lambda \frac{\partial T}{\partial t}$$

$p$ = pore pressure
$\alpha_{hv}$ = hydraulic diffusivity
$\Lambda$ = undrained pressurization

Conservation of energy

$$\frac{\partial T}{\partial t} = \alpha_{th} \frac{\partial^2 T}{\partial y^2} + \frac{\tau \dot{\gamma}}{\rho c}$$

$T$ = temperature
$\alpha_{th}$ = thermal diffusivity
$\rho c$ = volumetric heat capacity

Conservation of fluid mass

$$\int \dot{\gamma}(y) dy = V$$

$\dot{\gamma}$ = strain rate
$V$ = slip velocity

heat while holding fluid mass $m$ fixed (undrained response)

- thermal expansion coefficient of water ($\sim 10^{-3}$ K$^{-1}$) $>>$ solid matrix
- water and matrix equally compressible ($\sim$ GPa$^{-1}$)

$$\Lambda = \left( \frac{\partial p}{\partial T} \right)_m \sim \text{MPa/K}$$

[Rice, 2006; building on Sibson, 1973 and many others; thermal and hydraulic properties of fault-zone materials constrained by measurements from exhumed faults and drilling projects]