Models Bridging Subduction and Earthquake Dynamics
Show Fault Strength as a Strain-average Quantity

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Aim

- What strength / friction values are appropriate across various scales?

  - Geodynamic modelers interested in simulating subduction and plate tectonics: $\mu_{\text{eff,static}} < \sim 0.05$
  
  - Earthquake modelers interested in frictional sliding typically use Byerlee's friction ($\mu \sim 0.6-0.85$): $\mu_{\text{eff,static}} > \sim 0.5$

$$\mu_{\text{eff}} = 1 - \frac{P_f}{P} = 1 - \lambda$$

- Are these results as far apart as they seem? I show that
  - Recent cross-scale and earthquake models converge perspectives
  - Analytical considerations constrained by observations and laboratory experiments suggest $\mu_{\text{eff, char}}$ is about 0.02 - 0.3
Long-standing debate: How weak or strong? Why?

- Absent local heat flow anomaly
  [e.g., Lachenbruch and Sass, 1992]

- Stress field rotation & z-indep. stress drop
  [e.g., Hardebeck, 2015]

- Differential stress estimates
  [e.g., Seno, 2009]

- Sustain subduction in models
  [e.g., Zhong et al., 1998; Duarte et al., 2015]

- …

\[\sigma \sim O(1) \text{ MPa} \quad \sigma \sim O(2) \text{ MPa}\]

- Strong
  \[\mu_{\text{eff}} \sim 0.5\]

- Weak
  \[\mu_{\text{eff}} \sim 0.05\]

…

Laboratory experiments
(e.g., Byerlee, 1978)

In-situ stress measurements
(e.g., Brody et al., 1997)

Dip orientation of earthquakes on (re-activated) faults
(e.g., Sibson and Xie, 1998)

Sustain mountains

…

Data: Behr & Platt, EPSL, 2011

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I. Revisit arguments

- Absent local heat flow anomaly  
  [e.g., Lachenbruch and Sass, 1992]

- Stress field rotation & z-indep. stress drop  
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- Differential stress estimates  
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- **Sustain subduction in models**  
  [e.g., Zhong et al., 1998; Duarte et al., 2015]

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- **Sustain mountains**

- ...

Data: Behr & Platt, EPSL, 2011
II. Estimate what mechanisms are most important

- Absent local heat flow anomaly  
  [e.g., Lachenbruch and Sass, 1992]

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- Sustain mountains

- …

- What weakening mechanism is most important?
  - High pore fluid pressures
  - Low static friction
  - Large dynamic earthquake weakening

- …
Rocks are almost always strong, but not at coseismic slip rates where most strain occurs.

- High-speed lab experiments reveal enhanced dynamic weakening [e.g., Di Toro et al., Nature, 2011]
  - Low slip rates $\mu_{\text{eff}} \sim 0.7$
  - High coseismic slip rates $\mu_{\text{eff}} \sim 0.15$

\[ \gamma = 1 - \frac{\mu_d}{\mu_s} \]

\[
\begin{align*}
\text{Static friction} & \quad \downarrow \\
\text{Dynamic friction} & \quad \downarrow
\end{align*}
\]

99.9% of space and time

Large part strain
Models simulating both long- and short-term dynamics

- Included dynamic weakening in geodynamic models [Seismo-Thermo-Mechanical; STM; van Dinther et al., 2013a,b]

Conservation of mass, momentum and heat
Visco-elasto-plastic rheology

>> Spontaneous state and geometry
e.g., stress, temperature, viscosity, fluid distribution

Small time steps
+ rate-dep. friction
+ inertia

>> Spontaneous rupture nucleation, propagation and arrest
For subduction, mountain building, and reasonable earthquake characteristics need $-0.005 < \mu_{\text{eff, static}} < -0.125$

- Need fluid weakening to allow for subduction along shallow megathrust
- But not too much! Still need interseismic locking to build stresses to generate events
- Need dynamic weakening to generate events
Very weak @ very limited space or time does not mean weak throughout lithosphere!

- Temporarily weak (~10 MPa min.) and continuously overpressurized megathrust does not mean weak throughout lithosphere!
- Could still build mountains

\[ \sigma'_{\text{II}} \approx 40 \text{ MPa}, \text{ but elsewhere still almost GPa} \]

\[ \mu_{\text{eff, static}} = 0.05 \]
Long-term fault strength as a strain-average quantity

» Rocks are “always” strong, but weak during dynamic slip, where most strain occurs → How do we account for that in long-term models?

- Consider friction as a strain-average quantity:
  - Time-integrated mechanical energy dissipation

For equations I refer to van Dinther, in prep.

>> Derive constraints from observations and laboratory experiments
Rocks are “always” strong, but weak during dynamic slip, where most strain occurs → How do we account for that in long-term models?

Consider friction as a strain-average quantity, since

- Time-integrated mechanical energy dissipation

\[ H = \int \sigma_{ij(d)} \dot{\varepsilon}_{ij(d)} dt + \int \sigma_{ij(s)} \dot{\varepsilon}_{ij(s)} dt \]

- Mechanical consistency of energy and strain for unresolved dynamics requires

\[ \sigma_{II(c)} = \frac{\varepsilon_{II(d)}}{\varepsilon_{II(d)} + \varepsilon_{II(s)}} \sigma_{II(d)} + \frac{\varepsilon_{II(s)}}{\varepsilon_{II(d)} + \varepsilon_{II(s)}} \sigma_{II(s)} \]

- With stress limited by strength (parameters) and

**seismic coupling** \( \chi = \frac{M_0 \Sigma}{M_{0e}} \)

**pore fluid pressure ratio** \( \lambda = \frac{P_f}{P} \)

**dynamic weakening** \( \gamma = 1 - \frac{\mu_d}{\mu_s} \)

- Long-term average, effective friction is strain-averaged as

\[ \mu_{eff(c)} = \chi(1 - \lambda)(1 - \gamma)\mu(s) + (1 - \chi)(1 - \lambda)\mu(s) \]

>> Derive constraints from observations and laboratory experiments
Long-term, effective friction for pore fluid pressure vs. dynamic weakening

$$\lambda = \frac{P_f}{P}$$

Feasible long-term friction values from data:
~ 0.02 - ~0.3

- Best guess:
  - $\mu_s = 0.7$ [e.g., DiToro et al., Nature, 2011]
  - $\chi = 0.3$ [e.g, McCaffrey, BSSA, 1997]
What do we need for long-term weak faults ($\mu_{\text{eff,c}} < 0.05$)?

- What is needed for subduction to occur in geodynamic models? (i.e., $\mu_{\text{eff,c}} < 0.05$; e.g., Zhong et al., 1998; Buijter et al., 2001; Sobolev & Babeyko, 2005; Duarte et al., 2015)

  » Dynamic weakening can bring pore fluid pressures in more acceptable range, but still requires largely over-pressurized megathrust

Best guess:

- $\mu_s = 0.7$ [e.g., DiToro et al., Nature, 2011]
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What do we need for long-term weak faults ($\mu_{\text{eff},c} < 0.05$)?

- Dynamic weakening can bring pore fluid pressures in more acceptable range, but still requires largely over-pressurized megathrust.

- Best guess from data:
  - $\mu_s = 0.7$ [e.g., DiToro et al., Nat., 2011]
  - $\chi = 0.3$ [e.g., McCaffrey, BSSA, 1997]

- Maximum seismic coupling:
  - $\mu_s = 0.7$ [e.g., DiToro et al., Nat., 2011]
  - $\chi = 1.0$ [only S. Chile currently]

- Weak fault material:
  - $\mu_s = 0.2$ [talc]
  - $\chi = 0.3$ [e.g., McCaffrey, BSSA, 1997]

- Most extreme case - not realistic:
  - $\mu_s = 0.2$ [talc]
  - $\chi = 1.0$ [only S. Chile currently]
What do we need for long-term weak faults ($\mu_{\text{eff,c}} < 0.05$)?

- Dynamic weakening can bring pore fluid pressures in more acceptable range, but still **requires largely over-pressurized megathrust**

(highly over-pressurized faults unless full seismic coupling)

- (or a different weakening mechanism is missing)

- (or long-term models incorrect)
Alternatively avoid fluid over-pressurized megathrusts through higher $\mu_{\text{eff},c}$

» IF subduction with realistic characteristics can occur in long-term geodynamic models for

$\mu_s = 0.2 \text{ [talc] }$
$\chi = 0.3 \text{ [e.g., McCaffrey, BSSA, 1997] }$

$\mu_{\text{eff},c} \sim 0.1$ for statically very weak megathrust (too weak)

$\mu_{\text{eff},c} \sim 0.2-0.3$ for weak, but potentially reasonable megathrust

» I have not seen this
Relative effectiveness of weakening mechanisms

» Most effective way to remove highly over-pressurized faults remains reducing static friction (not earthquake slip)

<table>
<thead>
<tr>
<th>Double</th>
<th>Reduces $\mu_{\text{eff (char)}}$ at reference values by</th>
<th>Reduces $\mu_{\text{eff (char)}}$ at full seismic coupling by</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. pore fluid pressure</td>
<td>67%</td>
<td></td>
</tr>
<tr>
<td>2. static friction</td>
<td>50%</td>
<td></td>
</tr>
<tr>
<td>3. seismic coupling</td>
<td>47%</td>
<td></td>
</tr>
<tr>
<td>4. friction drop</td>
<td>20%</td>
<td>50%</td>
</tr>
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</table>
Apparently weak faults also work better for dynamic earthquake ruptures (DR)

- Lab-observed large strength drops allowed in slip/rate-weakening DR models through distinctly increased pore fluid pressures

- 2016 M7.8 KAIKOURA earthquake only jumps for large fluid pressures ($\lambda \sim 0.66$)

$$\Delta\tau \sim (\mu_s - \mu_d)(1 - \lambda)$$

Ulrich et al., Nat. Comm., 2019
Strongly rate-dep. friction, $\gamma \sim 0.8$

» Strain occurs around $\mu_{eff} \leq 0.1$
Recent modeling results show that long- and short-term results are not so far apart as they seem.

Feasible long-term friction values from models: $\mu_{\text{eff,c}} \sim 0.02 - 0.20$

- Best guess: $\mu_s = 0.7$ [e.g., DiToro et al., Nature, 2011]
- $\chi = 0.3$ [e.g., McCaffrey, BSSA, 1997]
Conclusions

- Models at, and across, all time scales support (somewhat) weak megathrusts
  - $\mu_{\text{eff},c} \sim 0.02 \text{ to } 0.2$

- Long-term strength is a strain-average quantity
  - Described by pore fluid pressure ratio, static friction, seismic coupling, and dynamic friction

- Analytical considerations constrained by data and laboratory experiments support (somewhat) weak megathrusts
  - $\mu_{\text{eff},c} \sim 0.02 \text{ to } 0.3$

- Megathrusts are mainly weak due to distinctly to highly over-pressurized pore fluids

  - Geodynamic models not resolving earthquake dynamics are within their right within bold range (and can justify choice)