Dramatic Reductions in Fault Friction at Earthquake Slip Rates

Many thanks for providing data and slides go to:
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Nick Beeler, Vikas Prakash, Toshi Shimamoto,
Jim Rice, Nadia Lapusta
Main Point

- Friction of rock at slip velocities < 1 mm/s is relatively high, 0.6-0.8 (Byerlee’s law)
- Most *in situ* stress measurements in the upper crust suggest tectonic stresses are relatively high, bounded by Byerlee’s law
- As I will show, many potential high slip speed weakening mechanisms exist, all possibly giving low coseismic friction
- If dynamic friction at seismic slip rates (~1 m/s) is low, then either:
  1. Earthquake stress drops could be large, potentially creating extreme ground motion, or
  2. Tectonic stress is actually lower than the *in situ* measurements suggest
Outline

• Proposed mechanisms for reduction in friction at high slip rates
• Where available, recent laboratory results on them
• Implications for earthquake stress drops and for tectonic stresses
Difficult to Reproduce Earthquake Conditions in Lab

Simultaneously need to have:

- High slip rates (1-3 m/s)
- Large displacements (up to 20 m)
- High effective normal stresses (50-200 MPa)
- Elevated pore-fluid pressures (0.4-1 times $\sigma_v$)

Consequently present experimental data compromise on one or more of these
Dynamic fault weakening mechanisms

1. Normal interface vibrations
2. Dynamic normal stress reduction from elastic mismatch
3. Acoustic fluidization
4. Elastohydrodynamic lubrication
5. Thermal pressurization of pore fluids
6. Local “Flash” weakening/melting at asperity contacts
7. Interfacial lubrication by frictional melt
8. Lubrication by thixotropic silica gel layer
Normal Interface Vibrations

Proposed by Brune et al., 1993
Involves either opening of surface or dynamic reductions in normal stress during sliding
Thus shear resistance is much reduced
Is theoretically predicted only in cases where differences in elastic properties exist across the interface (bimaterials, i.e. next mechanism)
Has been seen in experiments using identical foam rubber blocks
Intuitively might be expected during sliding of surfaces with small-scale roughness – asperities bouncing off one another
Not well understood; could be important for earthquakes
Dynamic Normal Stress Reduction
From Elastic Mismatch


Involves dynamic reductions in normal stress near rupture tip during sliding on a bimaterial interface.

Can result in propagation of a wrinkle-like pulse.

Is theoretically predicted if differences in elastic properties exist across the interface.

Magnitude depends on amount of elastic mismatch & on difference between static and dynamic friction.

Observed elastic mismatches across San Andreas fault from 5 to 30% are sufficient.

Could be important for earthquakes.
Acoustic Fluidization

Proposed by Melosh, 1979, 1996

Involves acoustic waves bouncing around inside a shearing granular aggregate with sufficient intensity to partially hold the particles apart.

Thus shear resistance is much reduced.

Is an interesting idea, but whether it can actually occur is unclear.

Experiments to investigate it have been proposed, but I know of no results.

Not well understood; importance for earthquakes is questionable.
Elastohydrodynamic Lubrication

Proposed by Brodsky and Kanamori, 2001

Involves increases in pressure of a fluid separating two irregular sliding surfaces due to the viscous fluid being actively squeezed by closing gaps

Pressure would increase in closing gaps and decrease in opening gaps

In order to get a net increase in pressure, elastic distortion of the solids occurs in the pressurized gaps, making the geometry asymmetrical

Shear resistance is reduced due to the increase in fluid pressure (effective normal stress lowered)

Hydrodynamic lubrication is well-known in journal bearings, but the geometry is more favorable

No relevant experiments

Water insufficiently viscous. Not clear whether it can be important for more viscous fluids like melt or silica gel.
Elastohydrodynamic lubrication

Fluid trapped in fault exerts a normal pressure tending to separate surfaces, reducing effective normal stress and thus weakening fault

\[ P_L \approx \frac{6 \eta V L \Delta H}{H^3} \]
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Thermal Pressurization of Pore Fluid


Involves thermal expansion of pore fluid in a fault separating relatively impermeable rocks for sufficiently rapid and localized slip that elevated temperatures result.

Could be overcome by dilatancy of the fault zone if this occurs and persists with slip.

Experimental evidence lacking, but relevant lab experiments still remain to be conducted.

Well understood theoretically; Applicability for faults still unclear; Could be important for earthquakes.
Thermal Pressurization of Pore Fluid

[Energy conservation]

\[ \frac{\tau V}{h} = \rho^o c_{sp,ht} \frac{dT}{dt} + 2 \frac{q_h}{h} \]

Assume adiabatic conditions \((q_h = 0)\).

Neglect dilatancy \((d\eta^{pl}/dt = 0)\).

[Fluid mass conservation]

\[ \frac{dp}{dt} - \Lambda \frac{dT}{dt} + \frac{1}{\beta} \frac{d\eta^{pl}}{dt} = -2 \frac{q_f}{\rho_f \beta h} ; \quad q_f = -\frac{\rho_f k}{\eta_f} \frac{\partial p}{\partial y} \]

[Lachenbruch: We can neglect \(q_h\) if \(h > 3.5 (c_{th} \delta / V_{avg})^{1/2}\)]

or \(h > 3.5 \text{ mm} (\delta / \text{m})^{1/2}\) using \(V_{avg} \approx 1 \text{ m/s}\)

Overall Rotary Shear Apparatus

Sample Assembly with Internal Rotary and Axial Displacement Transducers
Quartzite was water saturated and had permeability of $10^{-19}$ m$^2$


Theory of Mase and Smith, 1983
But with no water, behavior is the same!

We will return to the explanation for the weakening later: silica gel

More experiments needed on rocks that don't show gel weakening
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“Flash” Weakening/Melting at Asperity Contacts


Involves local transient heating of short-lived contacts by frictional sliding at very high asperity contact stresses.

Shear resistance is reduced either due to thermal softening or to melting.

Theoretically is only effective above a velocity that depends on local strength and dimensions of asperities.

Originally observed experimentally by flashes of light seen in transparent materials.

Weakening has been observed in rocks that fits predictions of this mechanism (Goldsby and Tullis, 2003; Prakash, 2003). Direct proof still needed.

Could be important for earthquakes.
Calculations of Weakening Due to Flash Melting

- Flash heating is local heating at tips of contacting asperities
  - Bowden and Tabor saw small flashes of light when they looked at a sliding surface through a transparent plate

- Jim Rice developed simple model for strength as a function of velocity for asperities of one size

- Extension using a distribution of asperity sizes and assuming non-zero strength of melted contacts (Nick Beeler)
Flash Heating Analysis of *Rice* (1999)

\[ D = \text{contact size} \]
\[ V = \text{slip rate} \]

Contact lifetime
\[ \theta = \frac{D}{V} \]

\( T_w \) is weakening \( T \)
\( T_f \) is ave. fault \( T \)

\( T < T_w : \tau \text{ constant} = \tau_c \)
\( T \geq T_w : \tau \text{ negligible} \)

\( \tau \) at asperity contact

Simple model assumed
Theory \((\textit{Rice}, 1999)\)

\[ \theta_w = \text{time to weaken} \]

Equate heat input \(\tau_c V \theta_w\)

to thermal energy storage \(\rho c (T_w-T_f)\)

over an effective distance \(\sqrt{\pi c_{th} \theta_w}\)

\[ \theta_w = (\pi c_{th}/V^2) \left[ \rho c (T_w-T_f)/\tau_c \right]^2 \]

Will weaken if [time to weaken] is < [lifetime of asperity], or

\[ \theta_w < \theta \quad \text{when} \quad V > V_w = (\pi c_{th}/D) \left[ \rho c (T_w-T_f)/\tau_c \right]^2 \]

Representative values: \(c_{th} = 1 \text{ (mm)}^2/\text{s}, \rho c = 4 \text{ MJ/m}^3\text{K}, \)

\(D = 5 \mu\text{m}, T_w-T_f = 1000 \text{ K} \) and \(\tau_c = 7 \text{ GPa} \)

Gives \(V_w = 0.1 \text{ m/s}\) for onset of severe thermal weakening

Also, \(0 < V < V_w\) : Friction \(= \mu_0 \approx 0.6\), and

\(V > V_w\) : Friction \(= \mu_0 (V_w/V) \approx 0.6 (V_w/V)\)
Unconfined Rotary Shear Friction Experiment

Flash Weakening

\[ \sigma_n = 5 \text{ MPa} \]

High speed
\[ V \leq 0.38 \text{ m/s} \]

Small Displacement:
\[ \delta = 4 \text{ cm} \]

David Goldsby
Quartz Velocity and Friction in one 90 deg. Rotation

David Goldsby
At lower speeds this rapid weakening is not seen.

It is reversible with no time delay – Namely healing is instantaneous.

\[ f = f_0 \frac{V_w}{V} \quad f_w = 0 \]  
\[ f = f_w + (f_0 - f_w) \frac{V_w}{V} \quad f_w > 0 \]

(Rice, 1999)  
(Beeler and Tullis, 2003)

**David Goldsby**
Quartz:

Similar Behavior is Seen for Several Rock Types:
Friction coefficient is 0.2 at seismic slip rates

Granite:

Gabbro:

David Goldsby
Plate Impact Pressure-Shear Friction Experiment

Flyer plate

3.25 inch single stage gas-gun

Tilt adjustment

Target plate

Holographic diffraction grating

Combined normal and transverse displacement interferometry

Fiber glass projectile

Target holder

Vikas Prakash
Torsional Kolsky bar apparatus

Vikas Prakash
Conditions Assessable Using Non-conventional Experimental Techniques to Measure Sliding Resistance at Seismic Slip Rates

<table>
<thead>
<tr>
<th></th>
<th>Pressure Shear Friction Experiment</th>
<th>Kolsky-bar Friction Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal pressure</td>
<td>100 MPa to 2 GPa</td>
<td>1-100 MPa</td>
</tr>
<tr>
<td>Slip speed</td>
<td>1-50 m/s</td>
<td>1-10 m/s</td>
</tr>
<tr>
<td>Slip distance</td>
<td>&lt; 0.5 mm</td>
<td>10 mm</td>
</tr>
</tbody>
</table>

The Kolsky-bar friction experiment can access more interesting ranges of normal pressures and slip distances than the pressure shear friction experiment, but also at high slip speeds.

Vikas Prakash
Results from Plate Impact Pressure-Shear Pilot Experiments

Results on a dense Arkansas novaculite: Could be compatible with flash melting and enlargement of viscous melt layer

Vikas Prakash
Topography of Surfaces

Before sliding

After Sliding – crests smoothed off

Vikas Prakash
Torsional Kolsky Bar Results (Exp001)

Exp001 (Normal Pressure 32.2 MPa)
Tribo-Pair: Quartz on Quartz

Interfacial Slip Velocity

Coefficient of Kinetic Friction

Interfacial Slip Distance (mm)

Coefficient of Kinetic Friction

Interfacial Slip Velocity (m/s)

Vikas Prakash
What Might Be Done to Verify The Weakening Is Due to Flash Weakening/Melting?

Theory says: \[ V_w = \left( \frac{\pi c_{th}}{D} \right) \left[ \rho c \left( T_w - T_f \right) / \tau_c \right]^2 \]

Thus as \( T_f \) increases \( V_w \) will decrease, so changing ambient Temperature \( T_f \) will make predictable changes in \( V_w \)

Also as \( D \) increases \( V_w \) increases, so changing surface roughness should change \( D \) and so \( V_w \)

Attempts to observe small amounts of melt at asperities also should be made, but it is difficult
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Interfacial Lubrication by Frictional Melt

Proposed by Jeffreys, 1942; McKenzie and Brune, 1972

Involves enough frictional heating to create a layer of melt separating the adjoining blocks

Shear resistance would seem to be reduced, but viscous coupling can be a factor

Theory is complex due to negative feedback between weakening and heating

Has been seen in experiments at low normal stresses, but strength is a complex function of slip (Tsutsumi and Shimamoto, 1997; Hirose and Shimamoto, 2005)

Occurs during some earthquakes, generating pseudotachylytes, but not clear how frequently
High-velocity Rotary Shear in Kyoto

Friction in the presence of melt at low normal stress

Granite, Dieterich (1978)

Gabbro, Tsutsumi and Shimamoto (1997)

Visible melting

No visible melting

Tsutsumi & Shimamoto, 1997
Weakening-strengthening-weakening behavior

\[ \sigma_n = 1.25 \text{ MPa, } \mu_{ss} = 0.6, \quad D_c = 15 \text{ m and slip up to } 80 \text{ m} \]

[redrawn from Hirose and Shimamoto, 2003]
Weakening-strengthening-weakening behavior

\( \sigma_n = 1.25 \text{ MPa}, \)  
\( \mu_{ss} = 0.6, \)  
\( D_c = 15 \text{ m} \)  
and slip up to 80 m

First weakening = flash melting

\( \mu_{peak} \)  
\( \nu = 0.85 \text{ m/s} \)  
\( \sigma_n = 1.25 \text{ MPa} \)

[redrawn from Hirose and Shimamoto, 2003]

Hirose & Shimamoto, 2003
Weakening-strengthening-weakening behavior

\[ \sigma_n = 1.25 \text{ MPa, } \mu_{ss} = 0.6, \quad D_c = 15 \text{ m} \]

and slip up to 80 m

First weakening = flash melting

\[ \text{gabbro} \quad \nu = 0.85 \text{ m/s} \]
\[ \sigma_n = 1.25 \text{ MPa} \]

Hirose & Shimamoto, 2003
Weakening—strengthening—weakening behavior

\( \sigma_n = 1.25 \text{ MPa} \),
\( \mu_{ss} = 0.6 \),
\( D_c = 15 \text{ m} \)
and slip up to 80 m

First weakening = flash melting

Second weakening = melt layer

\( \nu = 0.85 \text{ m/s} \)
\( \sigma_n = 1.25 \text{ MPa} \)

Hirose & Shimamoto, 2003
Rock fabric is very similar

- tonalite
- pseudotachylyte
- cataclasite

EXPERIMENT

Di Toro

NATURE

50 mm
Injection Veins of Pseudotachylyte

Loss to veins similar to loss in experiments? Yes, but here $P_{melt}$ can be high.

- pseudotachylyte
- cataclasite
- tonalite
What Are Implications of Doing Unconfined Experiments Where Melt is Lost?

Melt loss occurs in both, either to exterior or to melt veins.
However, melt pressure may be quite different.
If resistance is due to viscosity, then the viscosity and so the shear resistance will not be very pressure dependence.
However, the apparent friction will be much lower if the normal stress is much higher.
Experiments are needed at elevated normal stress where the fluid is either retained or at least the melt pressure stays high.
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Lubrication by Thixotropic Silica Gel Layer


Involves generation of a layer of silica gel by interaction of water with SiO₂.

Shear strength of gel is lowered by fast slip and large slip – thixotropic – strength depends on competition between time dependent strengthening and strain dependent weakening.

Was discovered in experiments on quartz, but occurs in rocks with over 50 percent SiO₂.

Could be important for earthquakes. Field evidence for its operation may be hard to find.
Unconfined Rotary Shear Friction Experiment

- **High speed**
  - $V \leq 0.20 \text{ m/s}$

- Large Cumulative Displacement:
  - $\delta = 4.5 \text{ m}$

- Normal Stress:
  - $\sigma_n = 5 \text{ MPa}$

- By David Goldsby
Friction Drops at High Speed, Slowly Recovers at Low Speed

Di Toro, Goldsby, & Tullis, 2004
Slip Dependence for Gel Weakening

\[ \sigma_n = 5 \text{ MPa} \]

Friction coefficient vs. Displacement, mm

Di Toro, Goldsby, Tullis, 2004
Friction for Quartz Rocks Extrapolates to Zero at Seismic Slip Rates

Extrapolation from low-speed friction

Observed high speed behavior

‘Quasi-static’ friction experiments

Large stress drop

Seismic Slip Speeds

Di Toro, Goldsby, & Tullis, 2004
Controlled Humidity Test in 1-atm Apparatus

Dry $N_2$ gas

Steel

Novaculite

Steel

$F_N$

90°

$V = 3 \text{ mm/s}$
Controlled Humidity Tests

Water is needed for the weakening
Reflected Light Image of Mirror Surface

novaculite

Dark spots = porosity-caused pits in surface

\[ \delta = 62 \text{ m}, \ V = 3 \text{ mm/s}, \ \sigma_n = 5 \text{ MPa} \]
SEM Image

FLOW FEATURES

5 µm
Friction Coefficients for Granite, Feldspar and Quartz Extrapolate to <0.4 at Seismic Slip Rates

Roig Silva et al., 2004
\( \mu_{\text{SS}} \) decreases with SiO\(_2\) content above 50 wt.\%
Thixotropic Behavior of Silica Gels

Characterized by particles with bonds between them that can be disrupted by strain – many paints and clays are thixotropic.

Often called shear thinning, since the viscosity gets lower as strain increases.

After strain, bonds become stronger with time.

This means that the strength results from competition between strain-induced weakening and time-induced strengthening.

Thus expect:
- Weaker at higher velocity
- Time-dependent healing with low or zero velocity

This is what we observe!
Friction From These Weakening Mechanisms

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Values:
- 0.0-0.6
- ~0.2
- <0.5-0.6
- <0.2
Implications of Low Dynamic Strength for Earthquake Stress Drops and/or for Tectonic Stress Magnitudes

A dilemma exists if dynamic stresses are low:

If tectonic stresses are close to static frictional strength, then one would expect larger stress drops and accelerations than are typically observed.

A model with low tectonic stresses can overcome static friction and be compatible with low stress drops, but then one would expect to find low measured in situ stress values, rather than those that typically seem bounded by static frictional strength.
Slip Velocity and Shear Stress at the Tip of a Propagating Rupture

From Beeler and Tullis (1996)

An example for rate and state friction parameters that give a self-healing rupture; Propagation time = 25.00 s
One Possibility for Initial Stress Compared to Static and Dynamic Friction

High Stress Model:
- Large stress drop
- Static friction overcome mostly by initial stress.

LARGE ACCELERATION
Alternate Possibilities for Initial Stress Compared to Static and Dynamic Friction

High Stress Model:
- Large stress drop
- Static friction overcome mostly by initial stress.

Brittle, Low Stress Model:
- Small stress drop
- Static friction overcome by large dynamic stress concentration.

LARGE ACCELERATION

SMALL ACCELERATION
Dynamic Rupture Models with Extreme High Speed Weakening
Uses Thermal Pressurization and Flash Weakening

High normal stress + weak patch in the middle
(Corresponds to ~8 km depth)

Steady-state velocity strengthening

Steady-state velocity strengthening

ss velocity weakening

Nadia Lapusta
Example with Low Initial Shear Stress

Rupture overcomes static friction via stress concentration

Most slip occurs at very low stress (dyn. weakening)

Static stress drop is much smaller than what one would expect because shear stress before the earthquake is much smaller than static strength.

Nadia Lapusta
Fault models with strong dynamic weakening based on Thermal Pressurization and Flash Weakening satisfy several observational constraints.

Operates with low stress, low heat production!

*V_w = 0.1 \text{ m/s}, L = 40 \text{ mm}, \text{ weak patch } 160/8 = 20 \text{ MPa}*

**Average static strength of the fault**

**Average shear stress on the fault**

Shear stress based on heat generation

Nadia Lapusta
Conclusions

1. Many high-slip-velocity weakening mechanisms potentially exist
2. Much remains to be understood about them
3. From what we know, the shear resistance from many of them is quite low
4. If shear resistance during earthquakes is low then either:
   A. The stress drops during earthquakes could be large, apparently larger than is typically observed, or
   B. The initial tectonic stress is low, so the stress drops are acceptably low. The static friction is overcome by dynamic stresses at the tip of the propagating rupture