• Frictional healing, Fault healing; Rate-state friction

• Healing: Affect of loading rate, shear stress, chemical environment, granular packing -- Stressed vs. unstressed frictional aging

• Application of RSF laws to the full seismic cycle of stick-slip, frictional restrengthening, and interseismic reloading
Application of RSF laws to the full seismic cycle of stick-slip, frictional restrengthening, and interseismic reloading
Stressed Aging

Aging rate depends on the rate of shearing

(Marone, 1998, Nature)
Frictional Healing, $\Delta \mu$

Hold Time (s)

(Marone, 1998)

$V_{s/r}$ (µm/s)

- 1
- 3
- 10
- 30
- 100

$\left( t_h V_{s/r} \right)$
The rate of frictional healing depends on the rate of shearing (Marone, 1998, Nature)

Rate State Friction Laws predict this behavior
Fault Healing and the Seismic Cycle: Repeating Earthquakes

How do faults regain strength between earthquakes?

Vidale et al., 1994; Peng, Vidale, Marone & Rubin, GRL 2005
$M \sim 1.5$;

- $z \sim 6$ km
- $M_0 \sim 5.5 \times 10^{11}$ Nm
- $d = 0.025$ s
- $r \sim 40$ m
- $\Delta\sigma \sim 4.5$ MPa
• Fault slip rate varies during the seismic cycle (coseismic, afterslip, interseismic)

• Average shear stress level varies throughout the seismic cycle

• The rate of frictional healing depends on the rate of shearing

Cumulative relative moment

Morgan Hill, M6.2

Anomalously low moment event

M 4.2 at 1.2 Km


Year

0 5 10 15 20

Cumulative relative moment

Shear Stress

Stick-slip failure; variable loading rate

Time
\[ M_o = G \pi r^2 \bar{u} \]

\[ \Delta \sigma = \frac{7 \pi}{16} G \frac{\bar{u}}{r} \]

\[ M_o = \frac{16}{7} r^3 \Delta \sigma \]
Fault slip rate varies during the seismic cycle (coseismic, afterslip, interseismic).

Average shear stress level varies throughout the seismic cycle.

The rate of frictional healing depends on the rate of shearing.

Rate State Friction Laws predict this behavior.
Friction Law
\[ \mu = \mu_0 + a \ln \left( \frac{V}{V_0} \right) + b \ln \left( \frac{V_0 \theta}{D_c} \right) \]

State Evolution
\[ \frac{d\theta}{dt} = 1 - \frac{V \theta}{D_c} \]
\[ \frac{d\theta}{dt} = -\frac{V \theta}{D_c} \ln \left( \frac{V \theta}{D_c} \right) \]

Elastic Coupling
\[ \frac{d\mu}{dt} = k \left( V_{lp} - V \right) \]
Assuming:

- Lab values for friction parameters $a$ and $b$
- Lab & Field-based estimate of $D_c$
- $D_c$ proportional to shear zone width
- Stiffness $k \sim G/r$
Healing rate of Calaveras repeaters agrees with room-T friction experiments, and shows predicted break in slope due to initial, rapid postseismic slip.

Earthquakes:
$\Delta \tau \sim 2$ MPa per decade in time

Lab Friction Experiment
$\Delta \mu \sim 0.01$ per decade in time
$\sigma \sim 100$ MPa
$\Delta \tau = \sigma \Delta \mu$
$\Delta \tau \sim 1$ MPa per decade in time

Peng, Vidale, Marone & Rubin, GRL 2005
Rate of fault healing varies with depth and is negative in some cases.

Peng, Vidale, Marone & Rubin, GRL 2005
Rate of fault healing: varies with depth is negative in some cases
• Frictional healing: Time dependent, chemically-assisted mechanism, slip rate matters, shear stress level matters

• Fault healing: old faults are strong, earthquake stress drop increases with log recurrence time for major tectonic faults.

• Repeating earthquakes: small events, complex behavior
Modeling the effect of normal force vibration 1.

Rate and State Friction Theory
\[
\mu(\theta, v, \sigma) = \mu_0 + a \ln\left(\frac{v}{v_o}\right) + b \ln\left(\frac{v_o \theta}{D_c}\right)
\]

\[\frac{d\theta}{dt} = 1 - \frac{v \theta}{D_c}\]  \quad \text{Deiterich Law}

\[\theta = \theta_o \left(\frac{\sigma_{\text{initial}}}{\sigma_{\text{final}}}\right)^{\frac{\alpha}{b}}\]  \quad \text{Normal Stress}

\[\frac{d\mu}{dt} = k' (v_{lp} - v)\]  \quad \text{Elastic Coupling}

\[T_c = 2\pi \frac{D_c}{V} \sqrt{\frac{a}{b-a}}\]  \quad \text{Critical Vibration Period}

\[K_c = \sigma \left(\frac{b-a}{D_c}\right) + \frac{mv_0^2 (b-a)}{D_0^2}\]  \quad \text{Critical Stiffness}
Tremor is modulated by Love wave shear stress, Denali
Delayed triggering is expected for rate-state friction

Friction change (e.g. weakening) requires finite slip & time
Lab: Normal Stress Vibrations

Critical period observed

Normal Force Vibrations

\[ A = 1 \text{ MPa}, \quad T = 0.1, \quad 20 \text{ s} \]

Sliding Velocity = 10\,\mu\text{m}/\text{sec}
Critical period is 1 to 2 sec.
Also, Phase lag. Friction response lags stressing. Could explain delayed triggering.

No frictional response to high frequency oscillations.
These are all good reasons to bother with Rate and State Friction
Fault Structure

Marone, 1998
Fracture and Consolidation (Rate Strengthening Processes)

Adhesive Friction at Contact Junctions (Potentially Rate Weakening)
The critical slip distance for shear zones of finite width

Fault zone of finite width; multiple, sub-parallel slip surfaces

Surfaces obey rate and state friction

Marone, C., Cocco, M., Richardson, E., and E. Tinti, 2009
The critical slip distance for shear zones of finite width

Fault zone of finite width; multiple, sub-parallel slip surfaces

Surfaces obey rate and state friction

Marone, C., Cocco, M., Richardson, E., and E. Tinti, 2009
Rate/State Friction

• Variations in behavior as a function of shear localization

Critical slip distance scales with:
• particle size
• shear zone width

Fine particles are factor of 100 smaller than coarse

Marone & Kilgore, 1993
Critical slip distance for shear zones of finite width

Multiple asperity contacts
- Subparallel
- Distributed across the shear zone
Fault zone of finite width; multiple, sub-parallel slip surfaces

Surfaces obey rate and state friction
Fault zone of finite width; multiple, sub-parallel slip surfaces

Surfaces obey rate and state friction

Rate and State Friction:

• Positive direct effect means that any surface that slips more than another surface will be the stronger of the two
Fault zone of finite width; multiple, sub-parallel slip surfaces

Surfaces obey rate and state friction

Rate and State Friction:
- Positive direct effect means that any surface that slips more than another surface will be the stronger of the two
- Additional increments of slip will occur elsewhere in the shear zone
Governing Equations

Radiation damping

\[
\mu_i(\theta_i, v_i) = \mu_o + a \ln \left( \frac{v_i}{v_o} \right) + b \ln \left( \frac{v_o \theta_i}{L} \right)
\]

\[
\frac{d\theta_i}{dt} = 1 - \frac{v_i \theta_i}{L}
\]  (Dieterich Law)

\[
\frac{d\theta_i}{dt} = -\frac{v_i \theta_i}{L} \ln \left( \frac{v_i \theta_i}{L} \right)
\]  (Ruina Law)

\[
\frac{1}{k_i} = \frac{1}{K_{ext}} + \sum_{j=1}^{i} \frac{1}{K_{int_j}}
\]

Elastic Coupling

\[
\mu_i = \frac{\tau_o}{\sigma_n} - \frac{G}{2\beta \sigma_n} (v_i - v_{pl}) + k \left( v_{pl} T - v_i T \right)
\]

Radiation damping
Governing Equations

\[ \frac{d\theta_i}{dt} = 1 - \frac{v_i \theta_i}{L} \]  
(Dieterich Law)

\[ \frac{d\theta_i}{dt} = -\frac{v_i \theta_i}{L} \ln\left(\frac{v_i \theta_i}{L}\right) \]  
(Ruina Law)

\[ \frac{dv_i}{dt} = \frac{k (v_{\text{pl}} - v_i) - b \frac{d\theta_i}{\theta_i}}{\frac{a}{v_i} + \frac{G}{2\beta \sigma_n}} \]

\[ \frac{1}{k_i} = \frac{1}{K_{\text{ext}}} + \sum_{j=1}^{i} \frac{1}{K_{\text{int}_j}} \]

Elastic Coupling

- Weakest surface slips
- Stresses are continuous
- Strength varies according to rate/state friction

Parameters: \(a=0.012\), \(b=0.016\), \(L=10\mu m\)  
\(h=6\) mm, \(G= 30\) GPa, \(\sigma_n= 100\) MPa,  
\(K_{\text{ext}}= G/h\); \(K_{\text{int}}/K_{\text{ext}} =10\);  
\(v_{\text{ref}}=1e-6\) m/s, \(v_{\text{pl}} = 1\) cm/s

Fault zone width varies from 0 to 60 cm.