Mechanics of Earthquakes and Faulting

Lecture 13 , 16 Mar. 2021

www.geosc.psu.edu/Courses/Geosc508

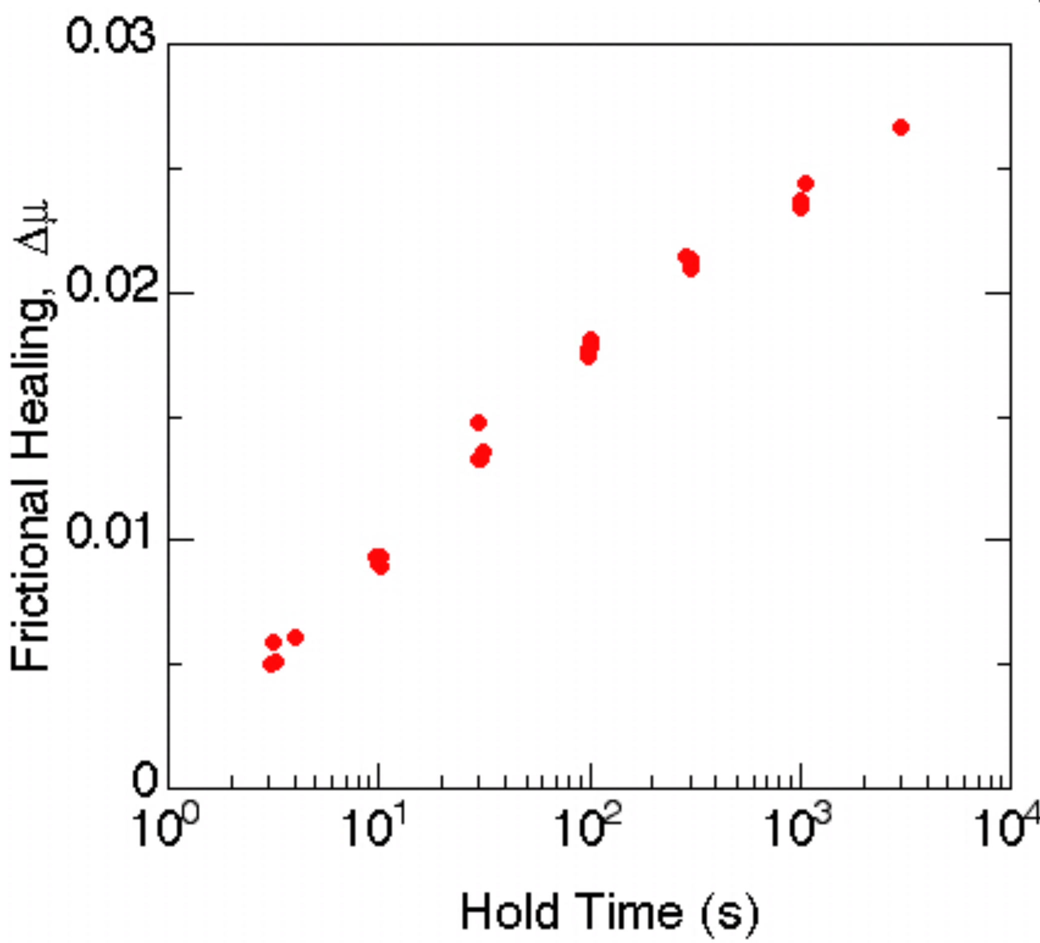
- Frictional healing. Aging and rate state friction. Application to tectonic faults and measurements of fault healing
- Normal stress oscillations and the critical vibration period for friction
- Healing: Affect of loading rate, shear stress, chemical environment, granular packing   --Stressed vs. unstressed frictional aging
- Next time: role of healing for connecting friction to fracture mechanics
- Slow earthquakes and the opportunity to further investigate the application of rate state friction laws to instability.
- Recent lab work showing repetitive stick-slip instability for the complete spectrum of slip behaviors – A new opportunity to investigate the mechanics of slow slip
- Mechanisms: Why are they slow?
- Quasi-dynamic frictional instability (positive feedback, self-driven instability)

Rate (v) and State (θ) Friction Constitutive Laws

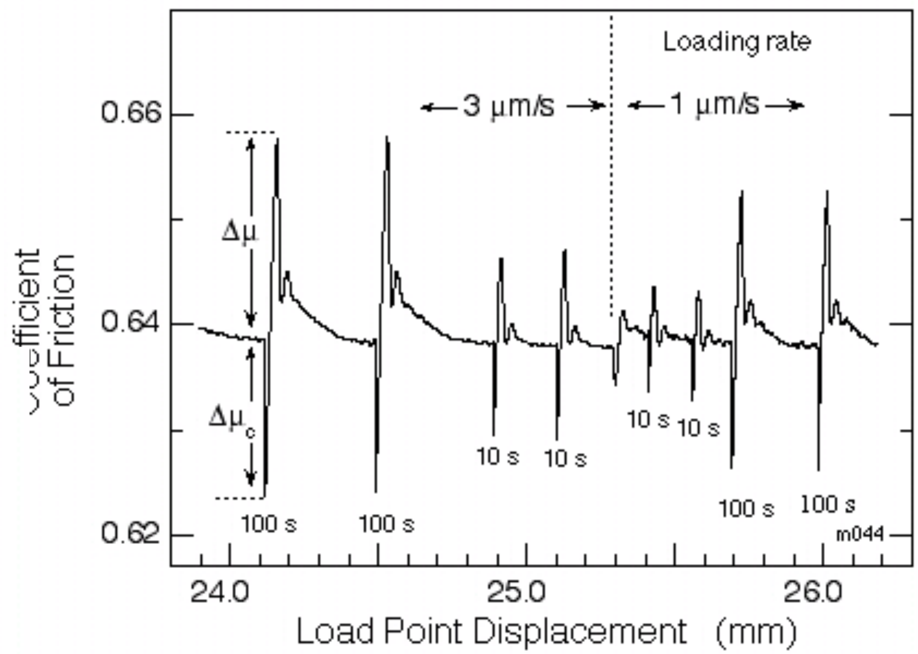
1) $$\mu(\theta, V) = \mu_o + a\, ln\left(\frac{V}{V_o}\right) + b\, ln\left(\frac{V_o\theta}{D_c}\right)$$

2) $$\frac{d\theta}{dt} = 1 - \frac{V\theta}{D_c}$$

3) $$\frac{d\mu}{dt} = k(V_{lp} - V)$$ Elastic Coupling



Modeling experimental data

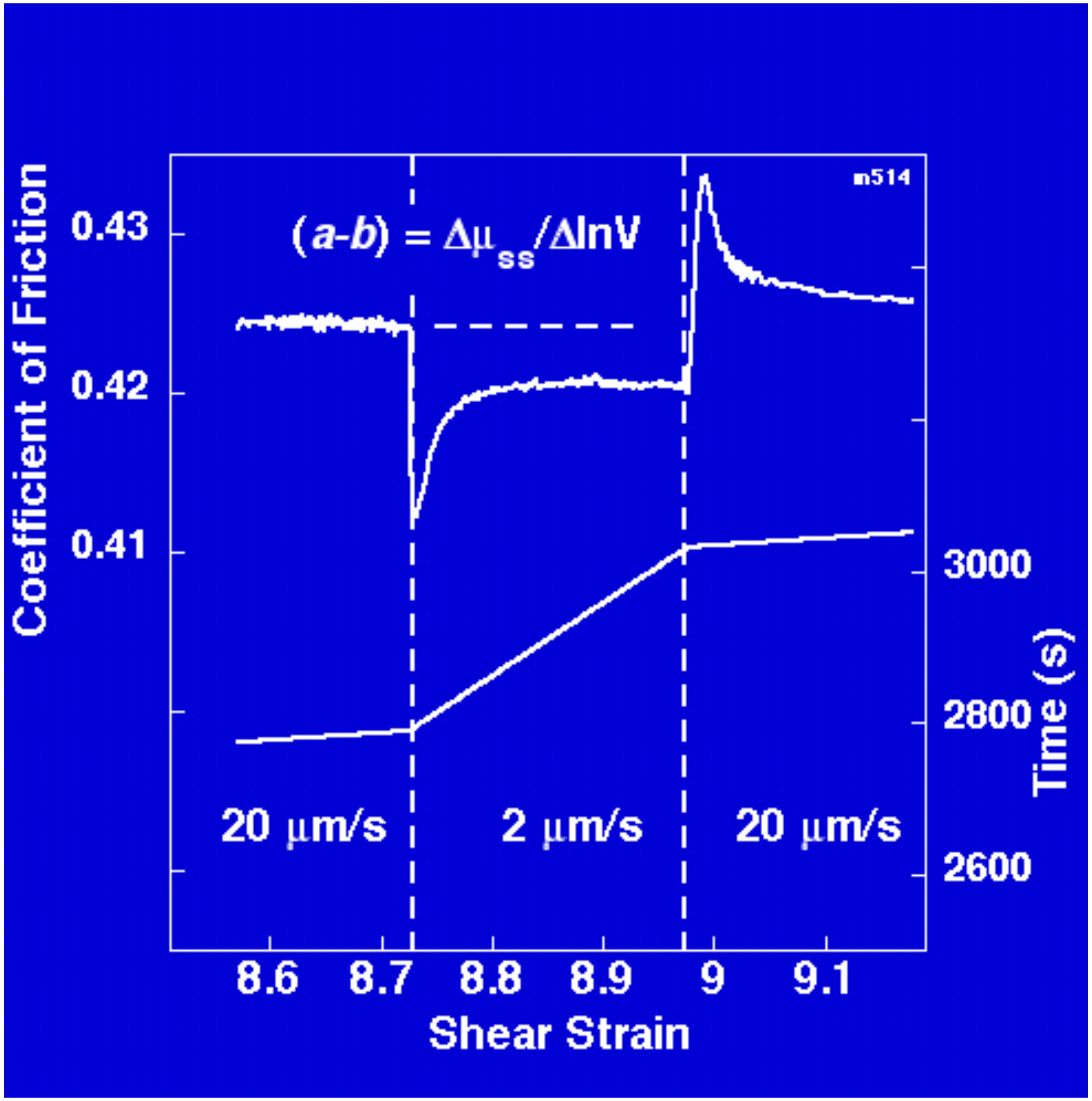


$$\frac{d\mu}{dt} = k(V_{lp} - V)$$

Measuring the velocity dependence of friction

Frictional Instability

Requires (a-b) < 0



Constitutive Modelling

Rate and State Friction Law

Elastic Interaction, Testing Apparatus

$$\mu(\theta,v) = \mu_0 + a\ln\left(\frac{v}{v_o}\right) + b\ln\left(\frac{v_o\theta}{D_c}\right)$$

$$\frac{d\theta}{dt} = 1 - \frac{v\,\theta}{D_c}$$

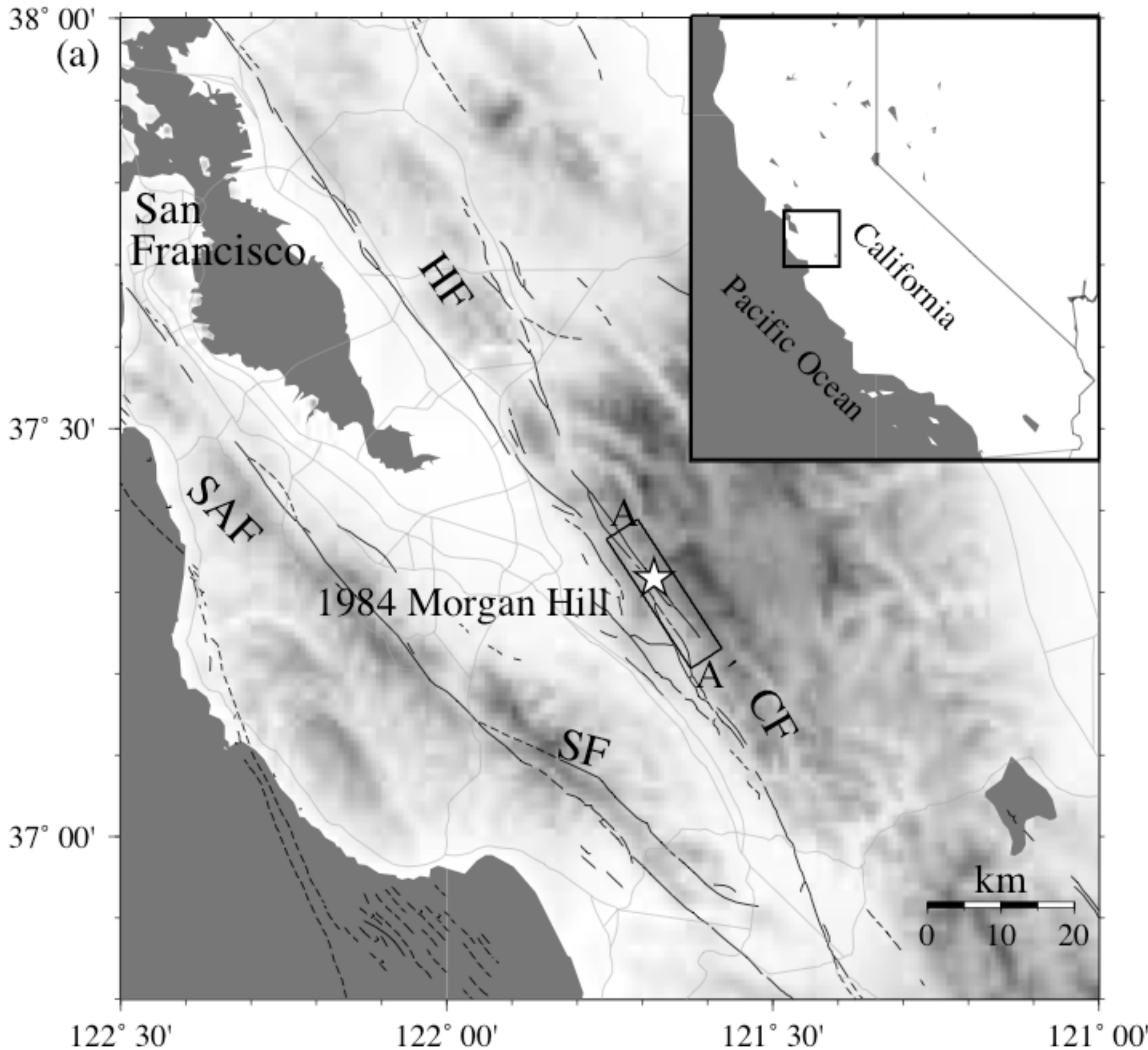
$$\theta_{ss} = \frac{D_c}{v}$$

$$\Delta\mu_{ss} = (a-b)\ln\left(\frac{v}{v_o}\right)$$

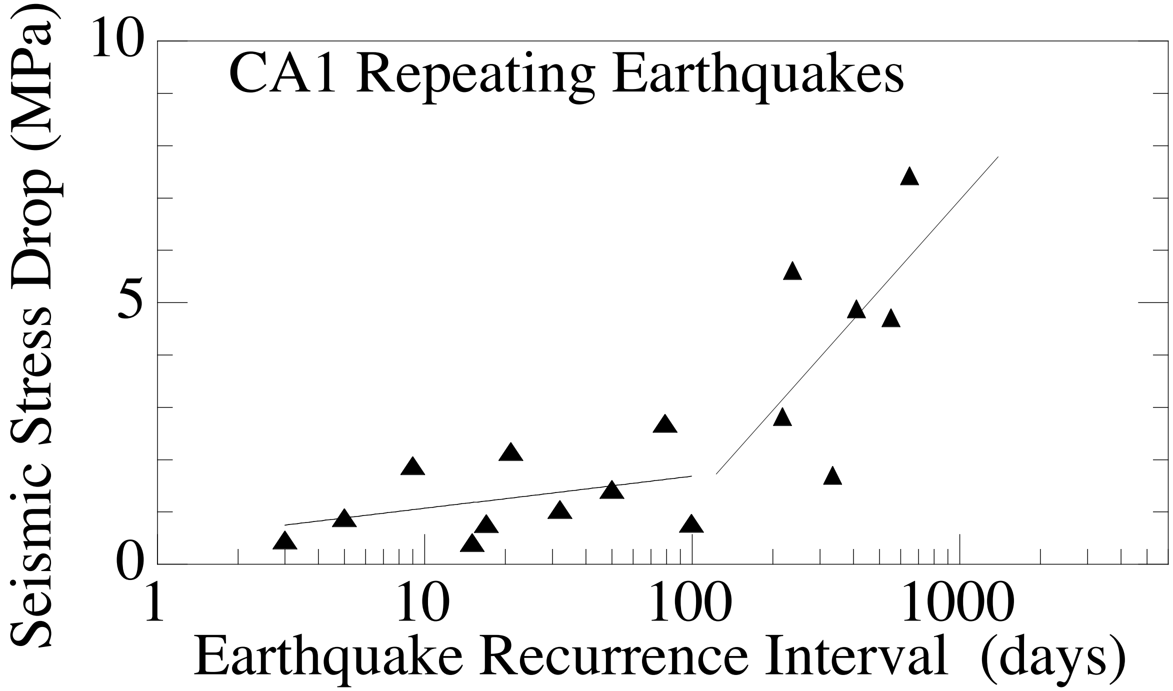
$$\frac{d\mu}{dt} = k'\left(v_{lp} - v\right)$$

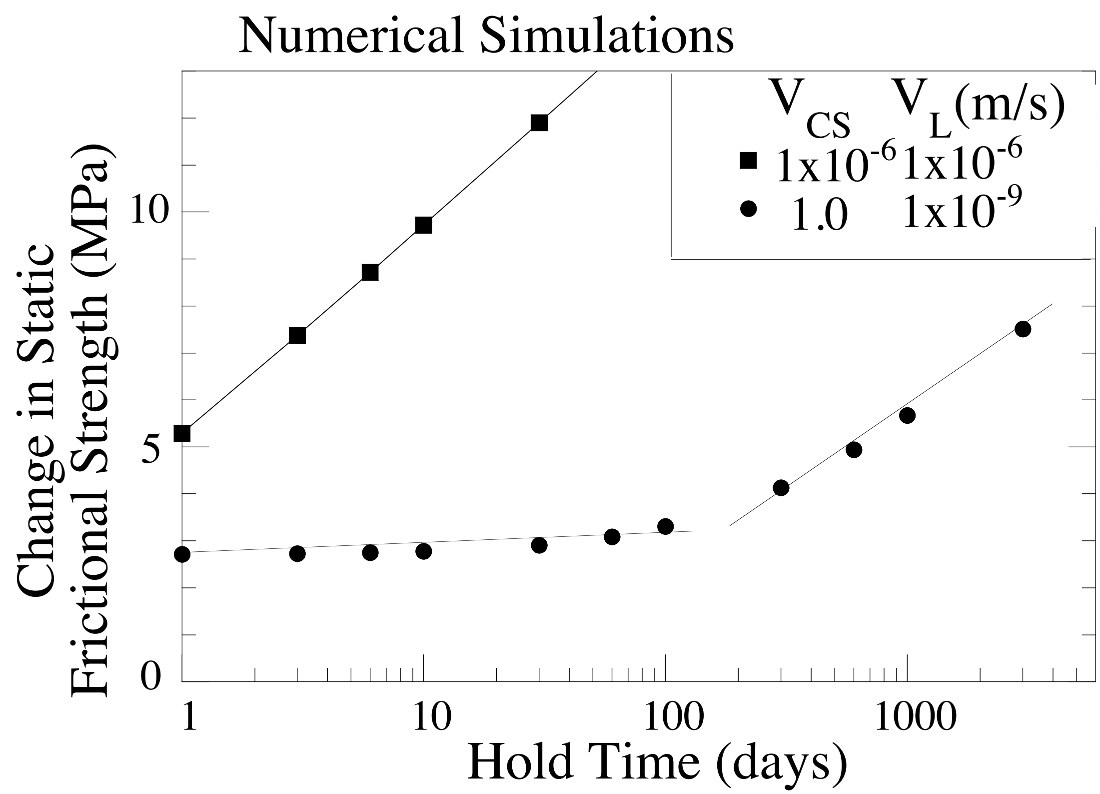
Fault Healing and the Seismic Cycle: Repeating Earthquakes

How do faults regain strength between earthquakes?



Vidale et al., 1994; Peng, Vidale, Marone & Rubin, GRL 2005

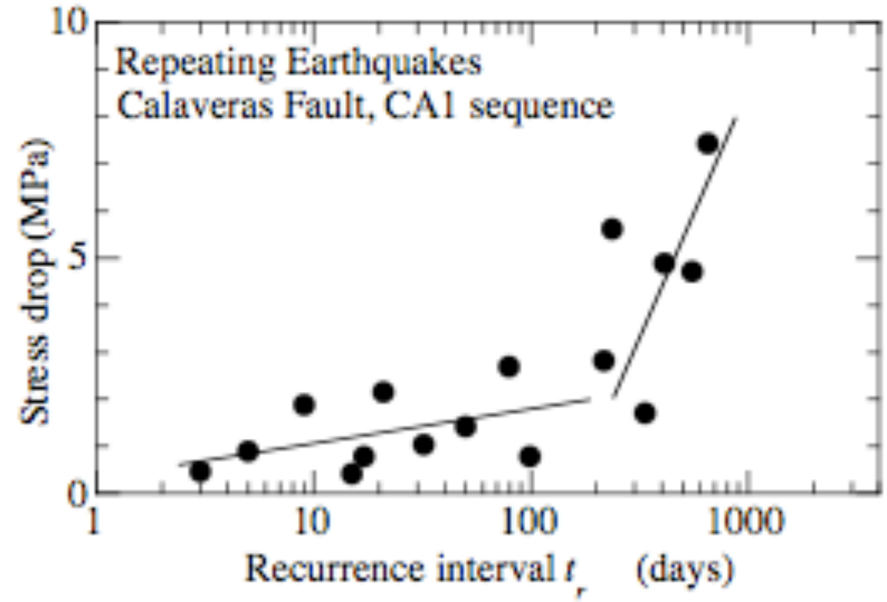




Assuming:

- Lab values for friction parameters *a* and *b*
- Lab & Field-based estimate of Dc
    - Dc proportional to shear zone width
- Stiffness k ~ 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:

$\Delta\tau$ ~ 2 MPa per decade in time

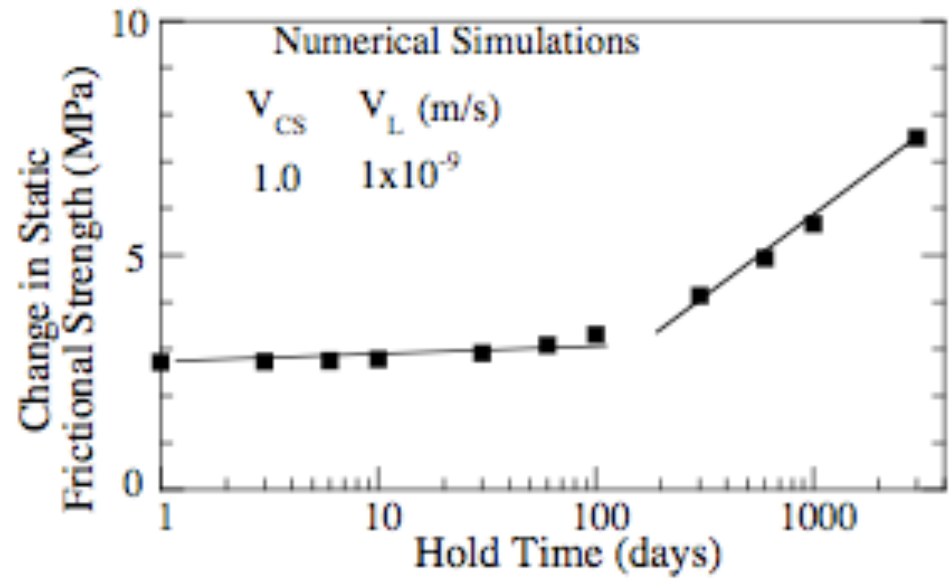
Lab Friction Experiment

$\Delta\mu$ ~ 0.01 per decade in time

σ ~ 100 MPa

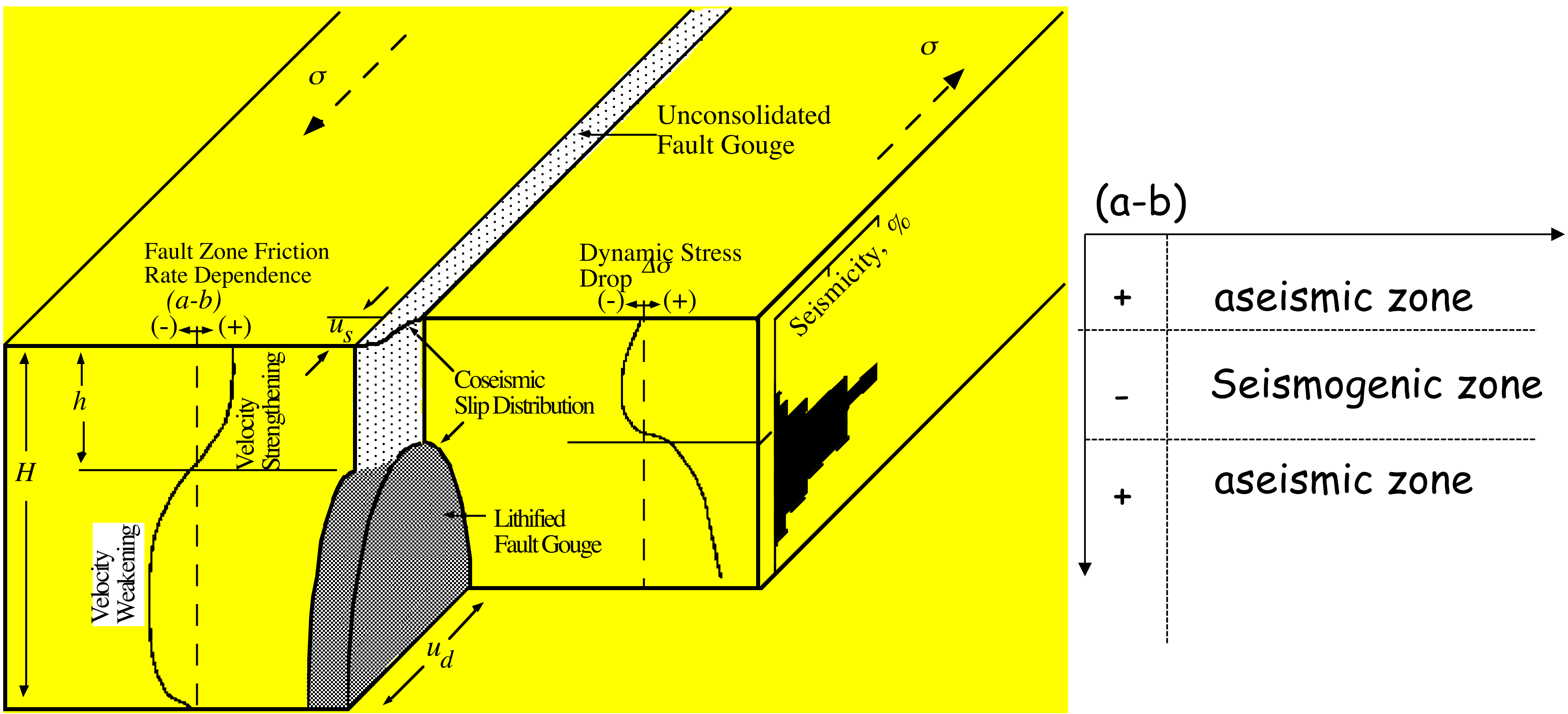
$\Delta\tau = \sigma \Delta\mu$

$\Delta\tau$ ~ 1 MPa per decade in time



Marone, Nature, 1998

- 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

$$\mu(\theta,v,\sigma) = \mu_0 + a\ln\left(\frac{v}{v_o}\right) + b\ln\left(\frac{v_o\theta}{D_c}\right)$$

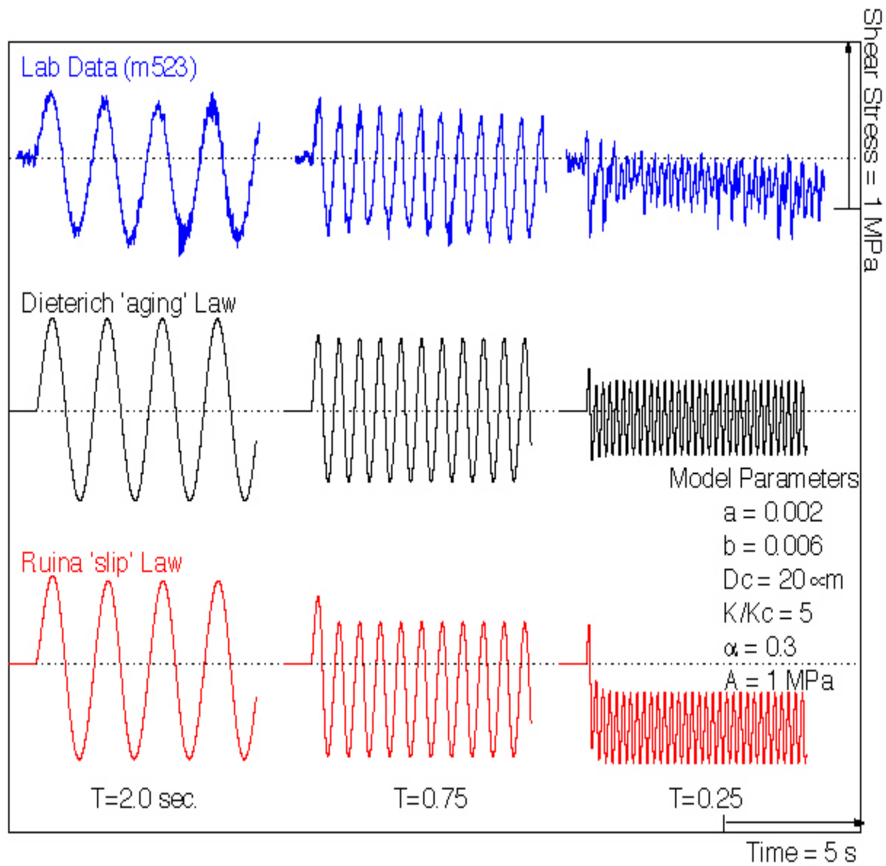
$$\frac{d\theta}{dt} = 1 - \frac{v\theta}{D_c}$$ *Deiterich Law*

$$\theta = \theta_o \left(\frac{\sigma_{initial}}{\sigma_{final}}\right)^{\frac{\alpha}{b}}$$ *Normal Stress*

$$\frac{d\mu}{dt} = k' \left(v_{lp} - v\right)$$ *Elastic Coupling*

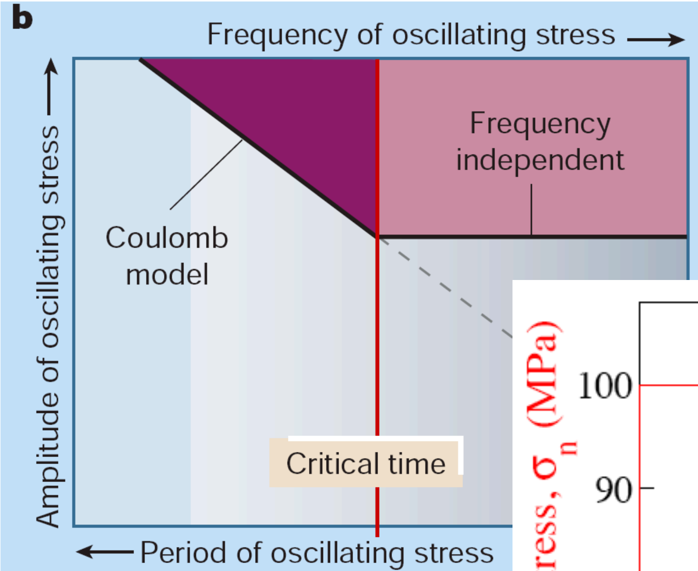
$$T_c = 2\pi\frac{D_c}{V}\sqrt{\frac{a}{b-a}}$$ *Critical Vibration Period*

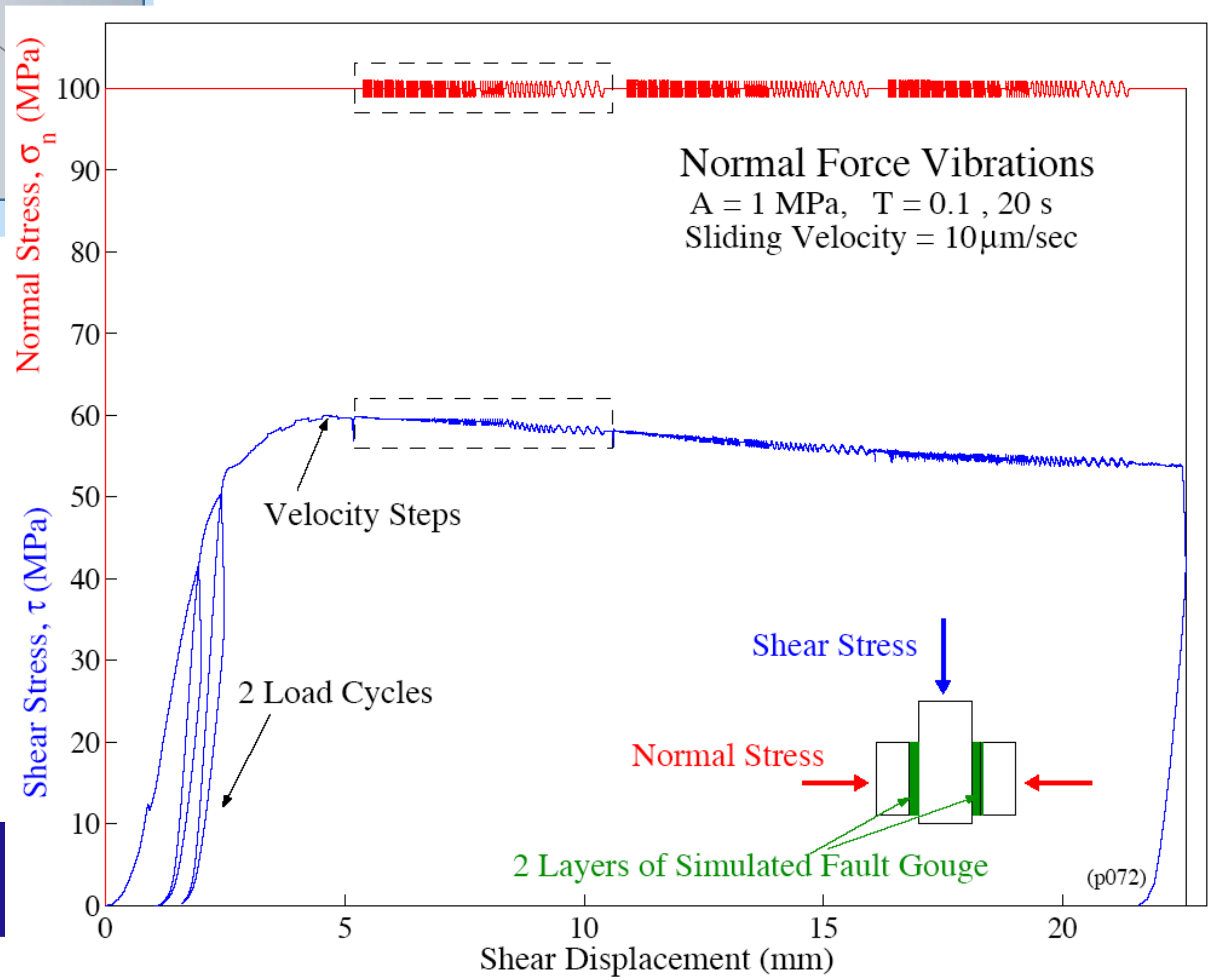
$$K_c = \sigma\frac{(b-a)}{D_c} + \frac{m v_0^2 (b-a)}{D_0^2}$$ *Critical Stiffness*



Tc ~ time needed to slip a distance Dc

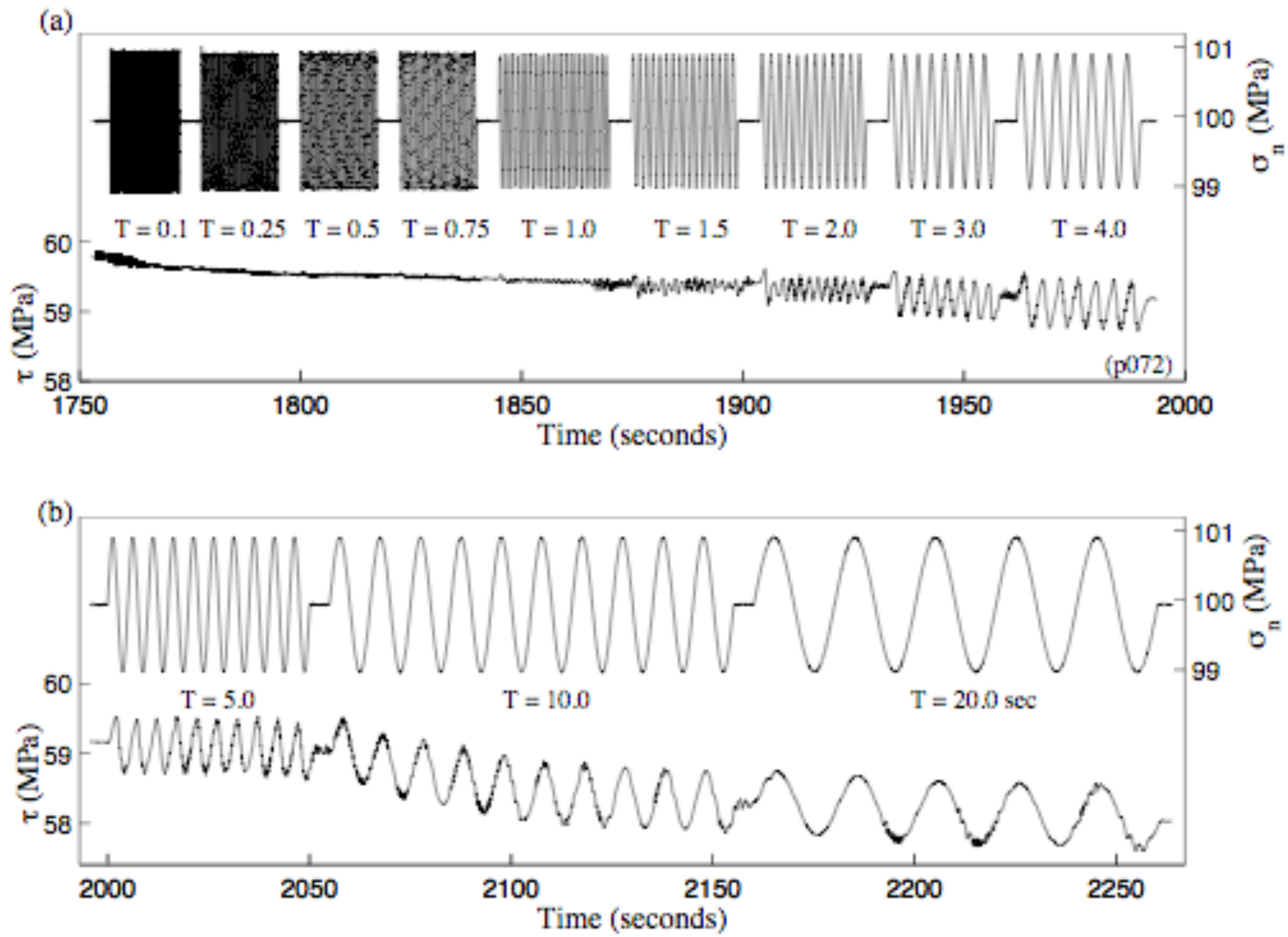
Lab: Normal Stress Vibrations
Critical period observed





Boettcher & Marone, JGR, 2004

Boettcher & Marone, JGR, 2004

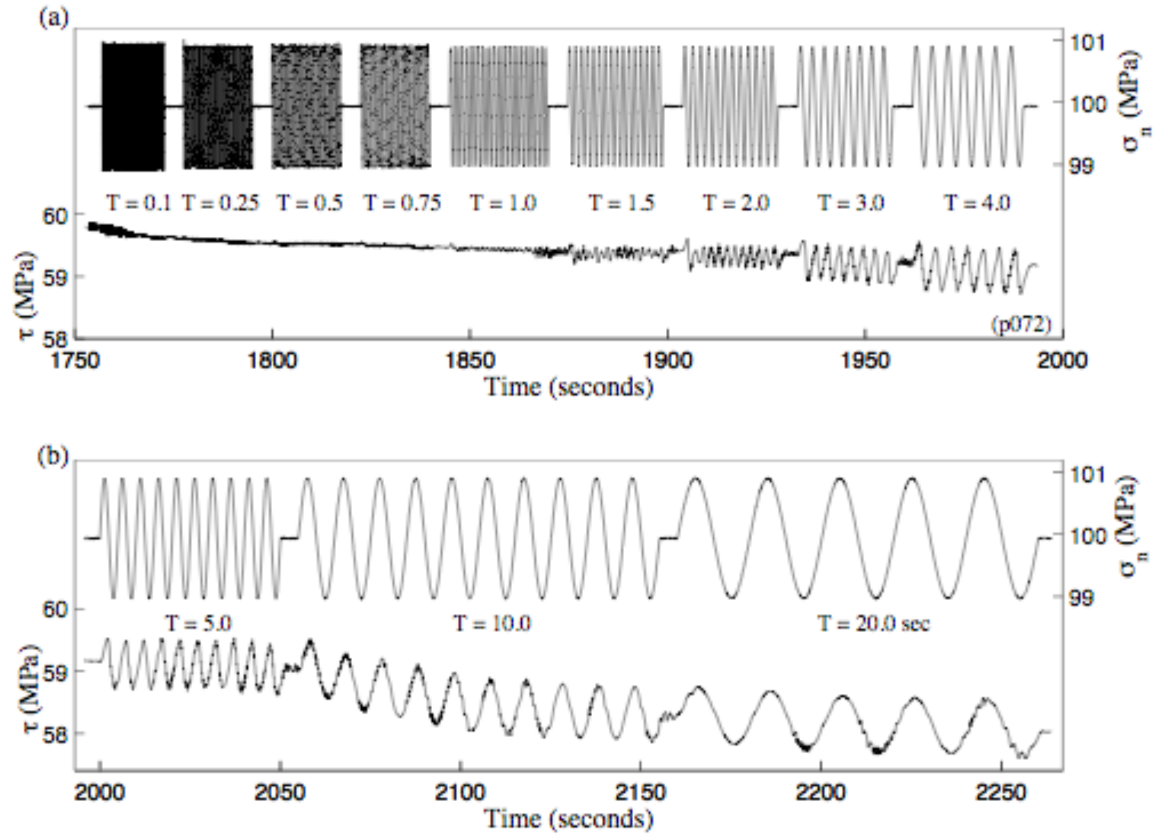


Critical period is 1 to 2 sec.

Boettcher & Marone, JGR, 2004

Critical Vibration Period

$$T_c = 2\pi \frac{D_c}{V}\sqrt{\frac{a}{b-a}}$$



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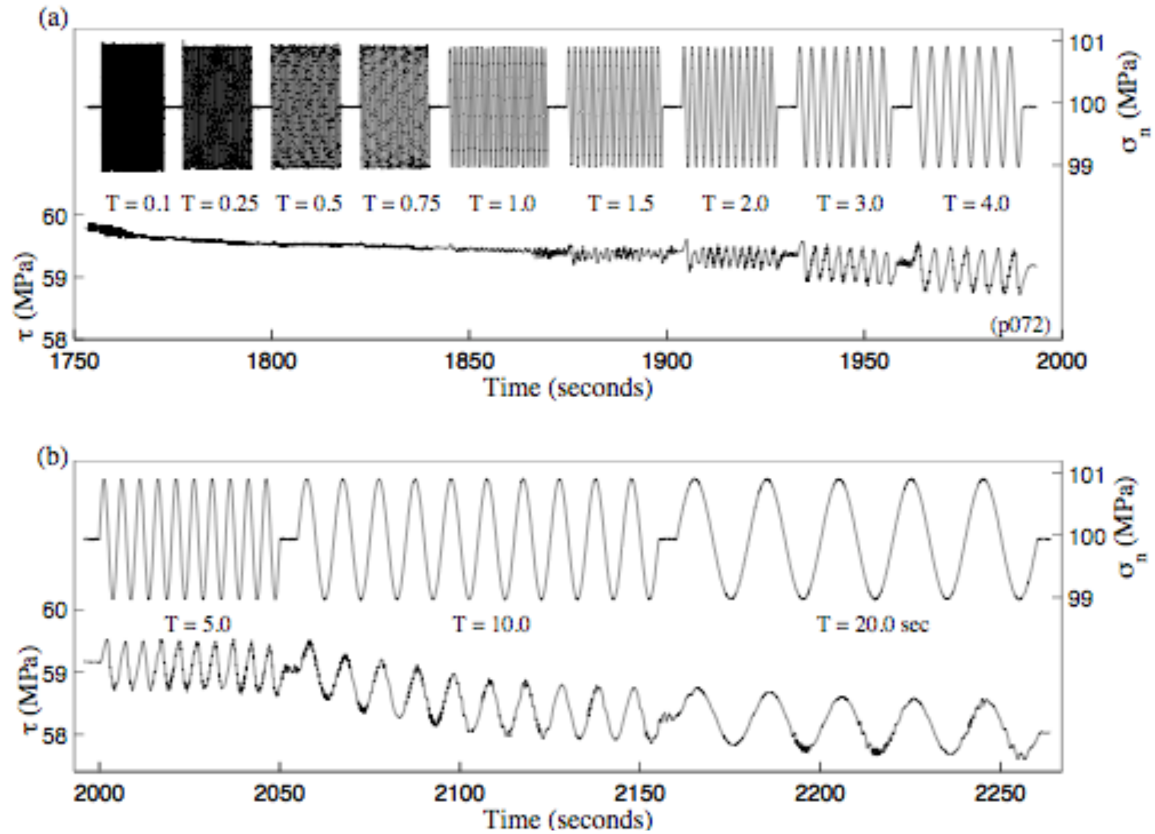
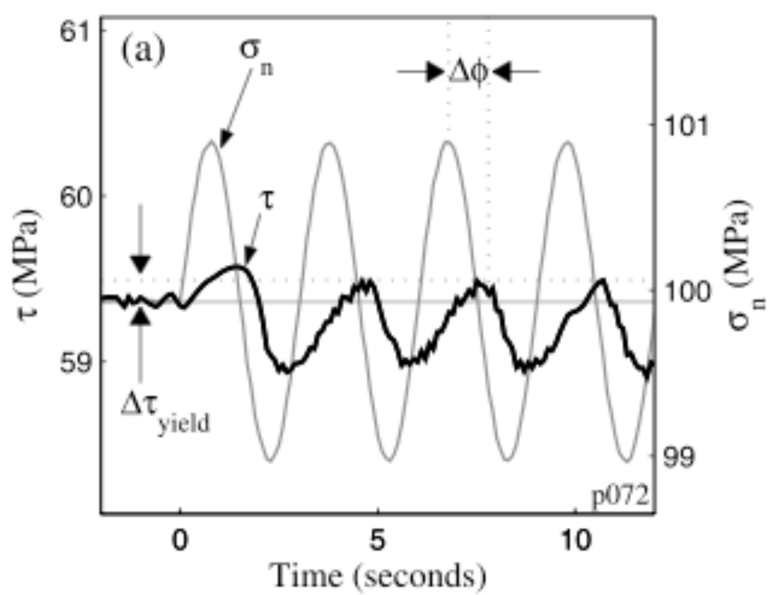
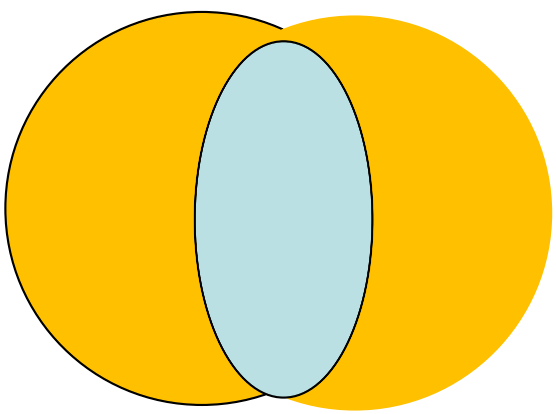


Critical Vibration Period

$$T_c = 2\pi \frac{D_c}{V}\sqrt{\frac{a}{b-a}}$$





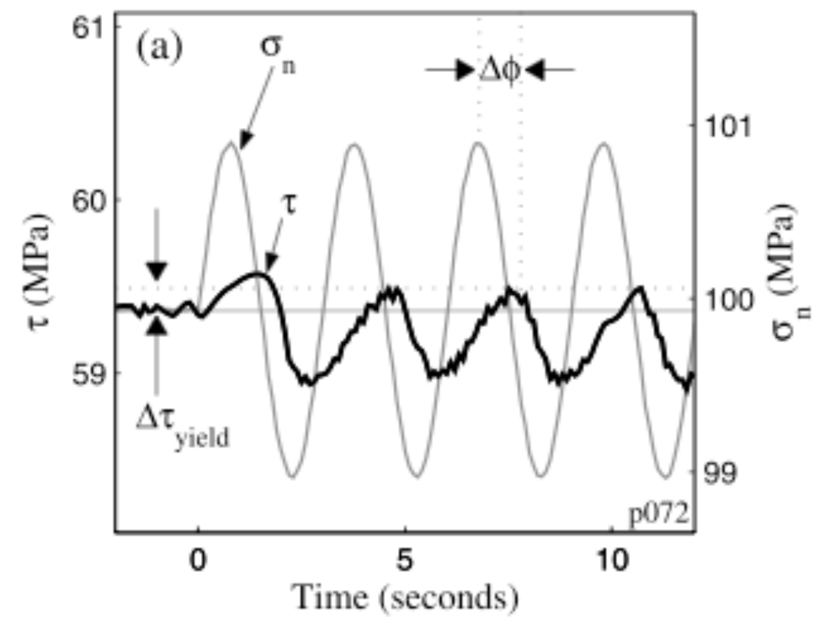
Time needed to slip a distance D_c = D_c/V

Boettcher & Marone, JGR, 2004

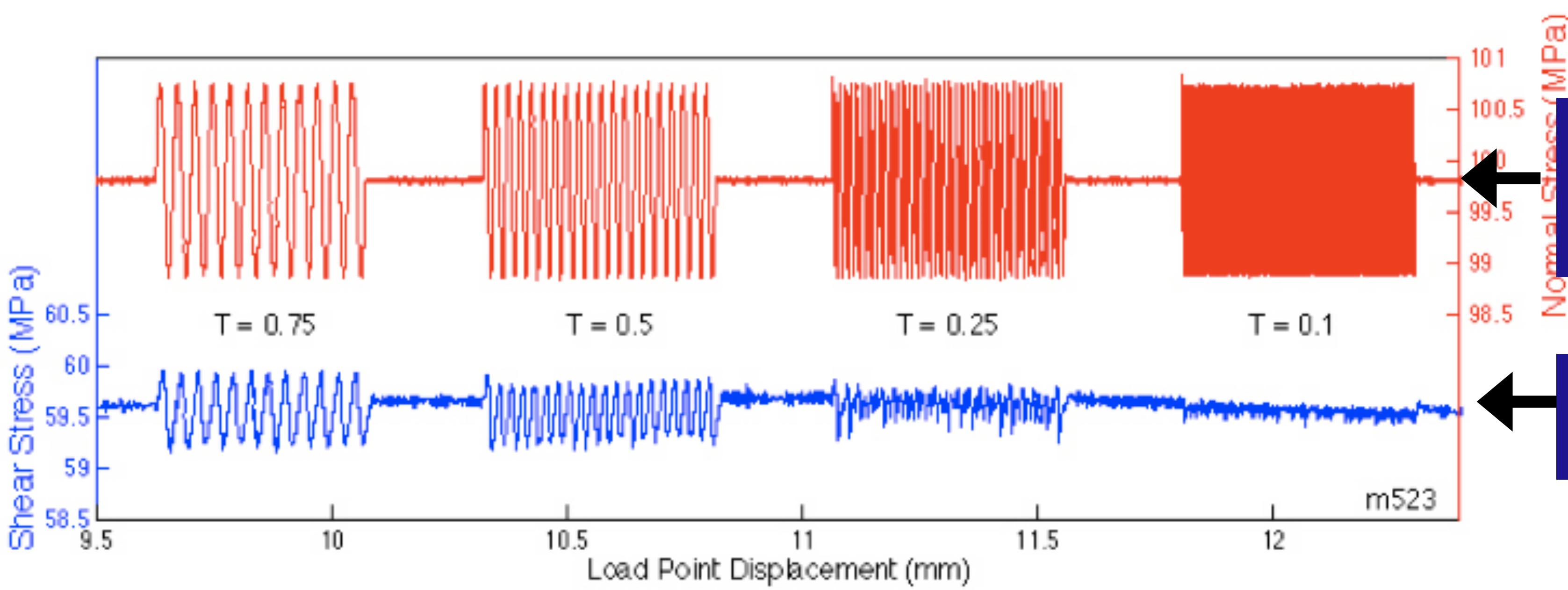
Also, Phase lag.

Friction response lags stressing.

Could explain delayed triggering



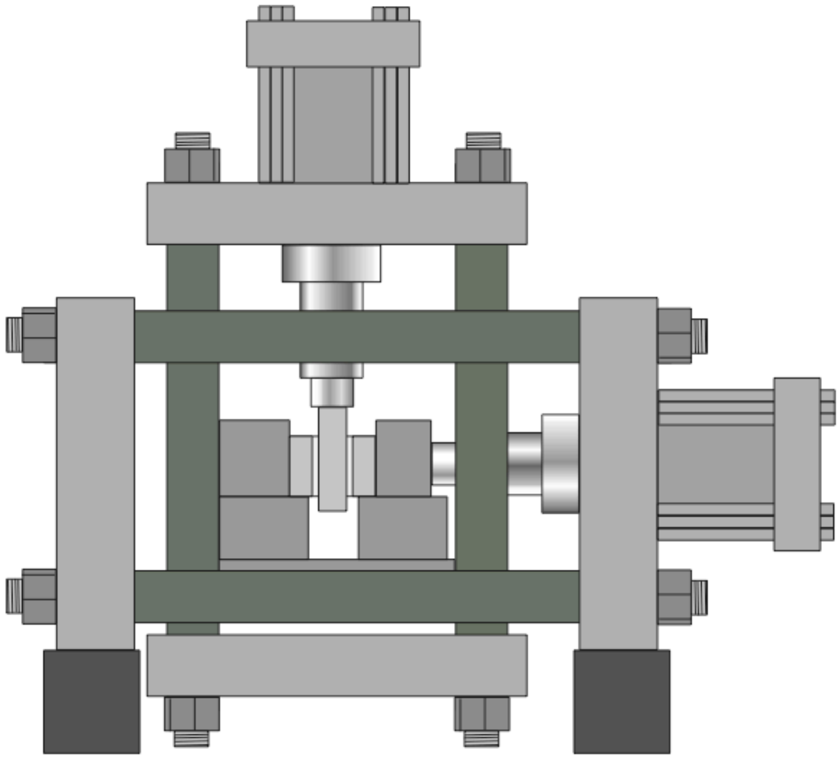
No frictional response to high frequency oscillations



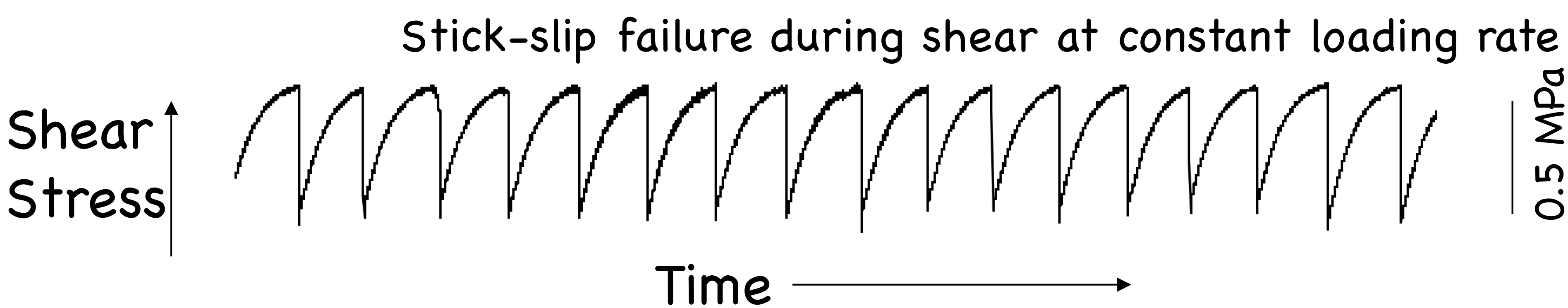
Normal Stress Oscillation

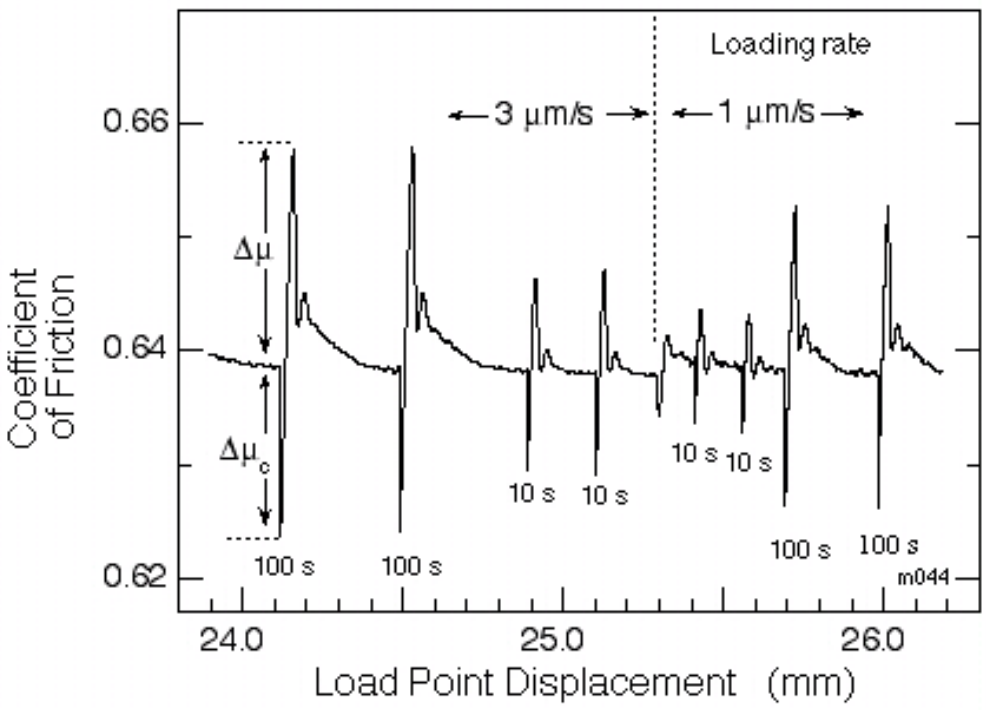
Frictional strength

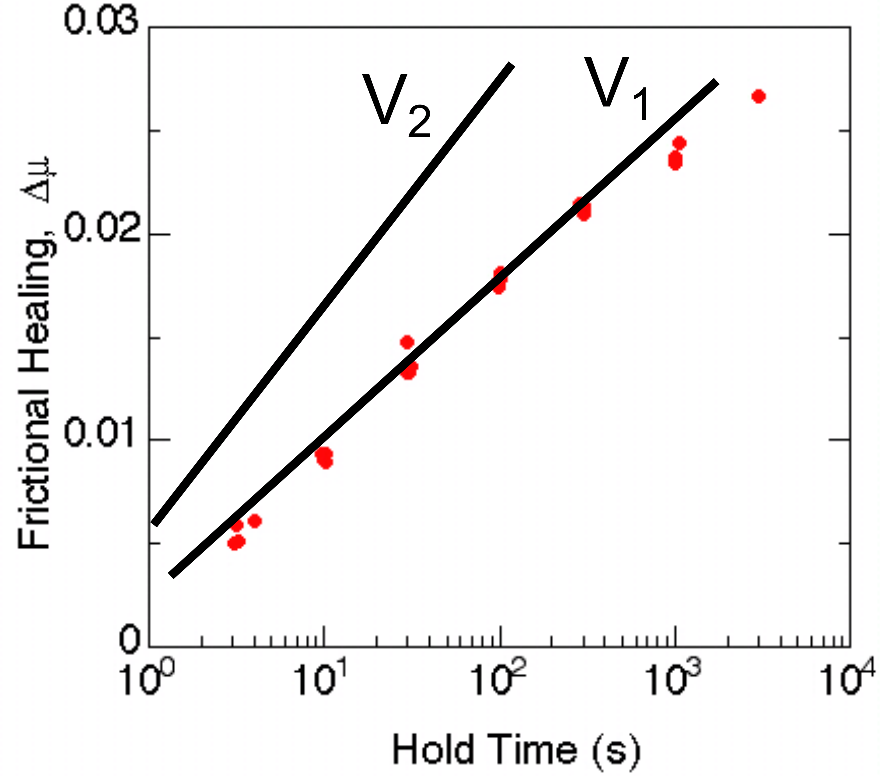
How do fault/frictional surfaces heal (regain strength) after failure?



Earthquakes & Fault Mechanics: seismic cycle, fault reactivation.
(friction and stick slip: doors, windows, machines, ships in dry dock, dancers…)

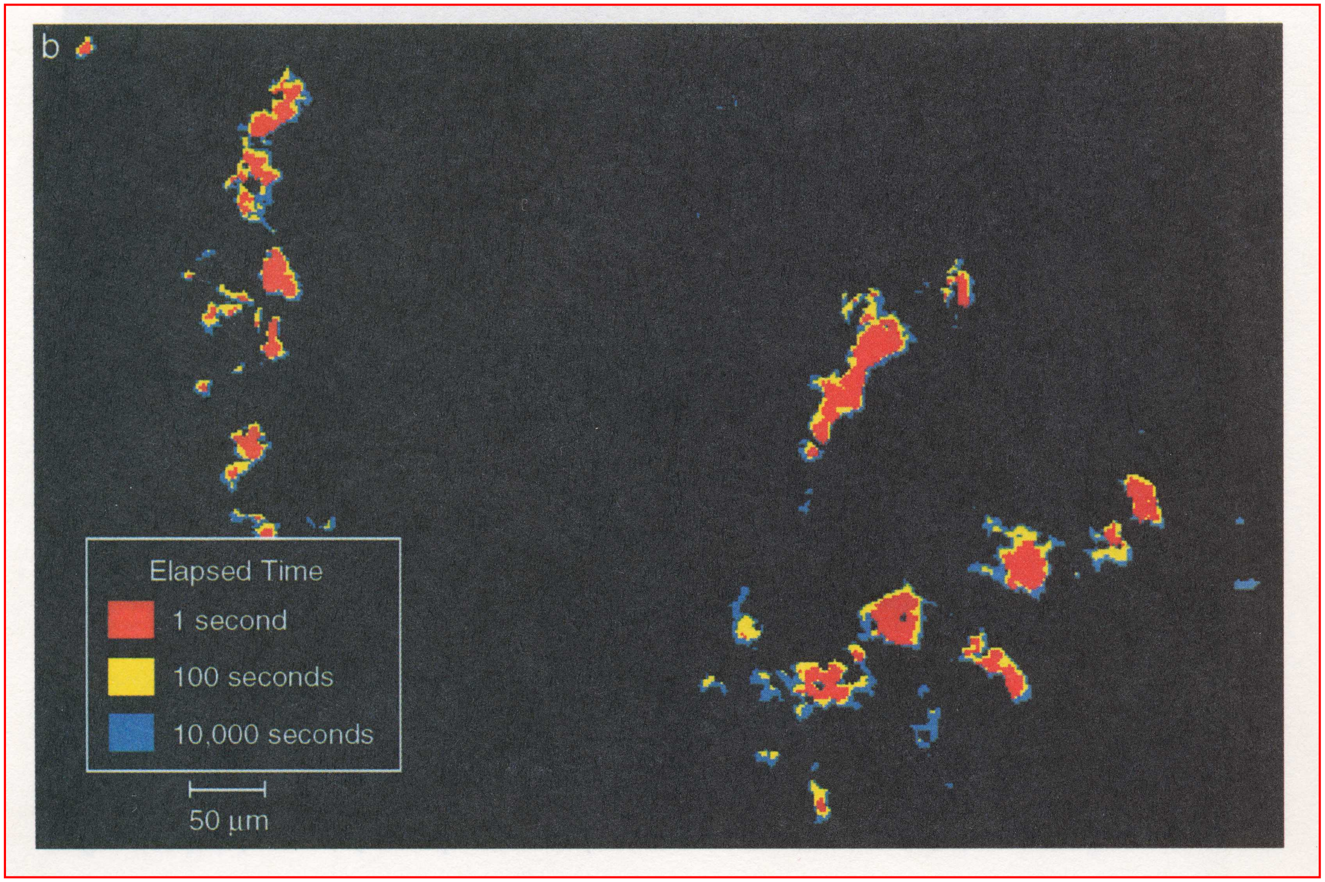






Frictional aging.

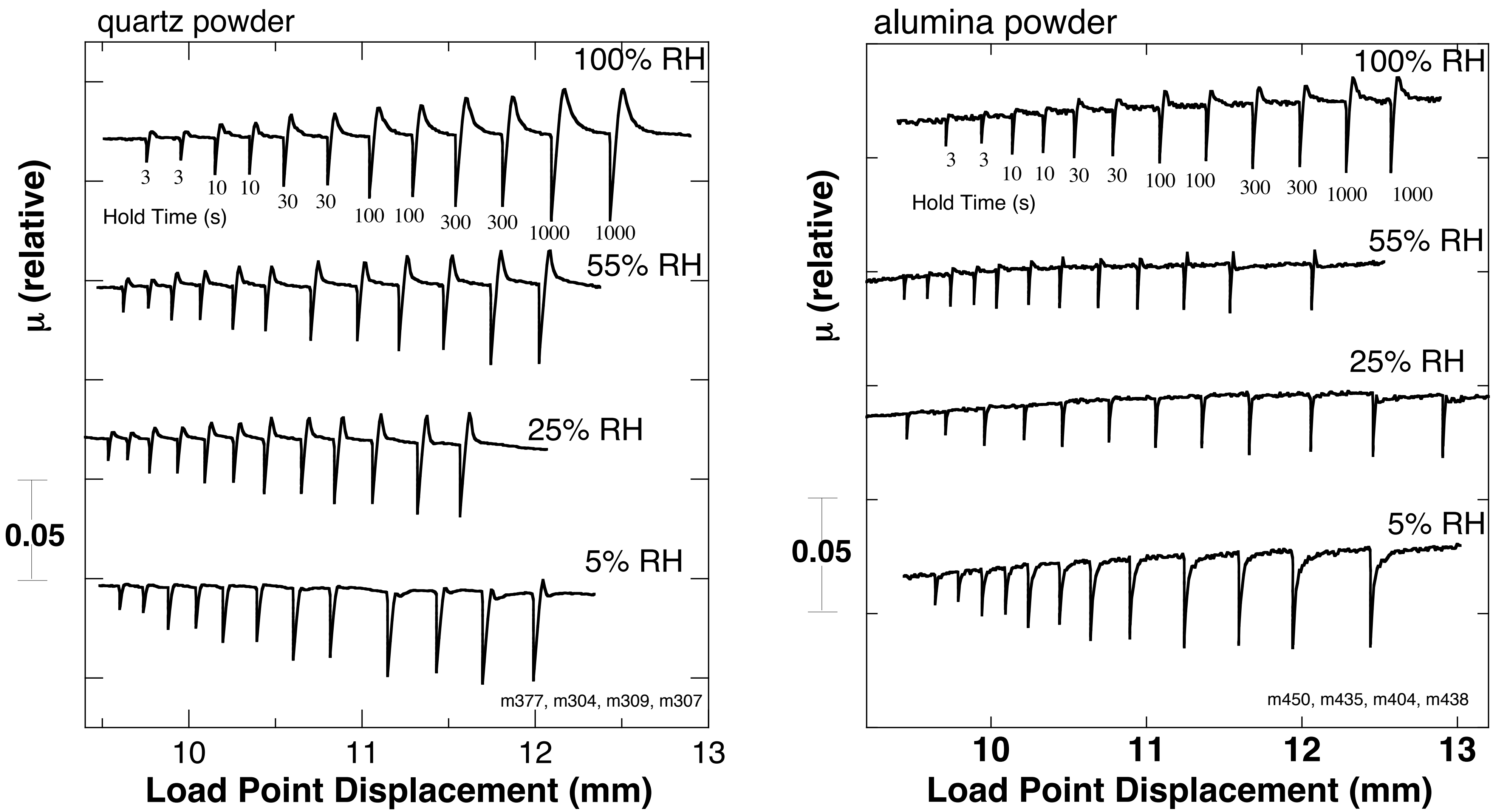
Time dependent friction from time dependent contact area



Dieterich and Kilgore [1994]

Time dependent growth of contact (acyrlic plastic)- true static contact

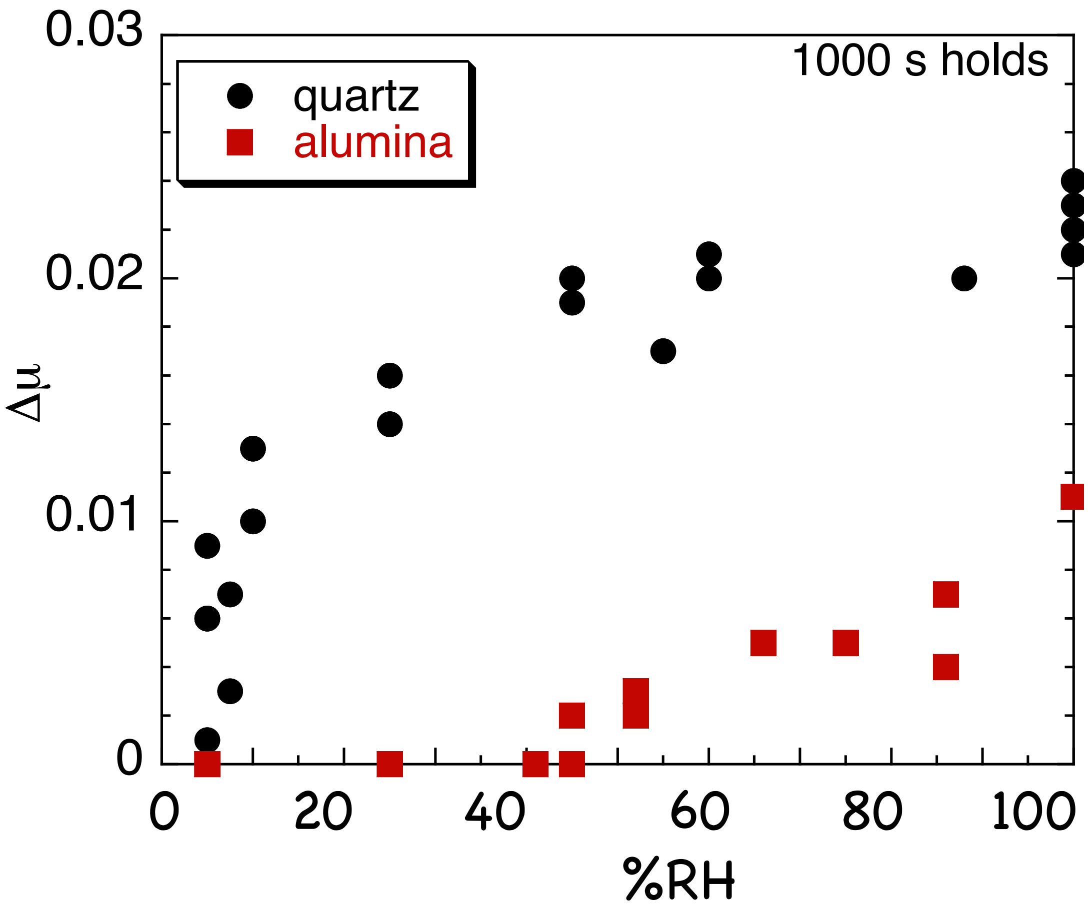
Chemically-Assisted Frictional Aging; Creep at Adhesive Contact Junctions



In-situ Particle Comminution; Production of Fresh Surface Area

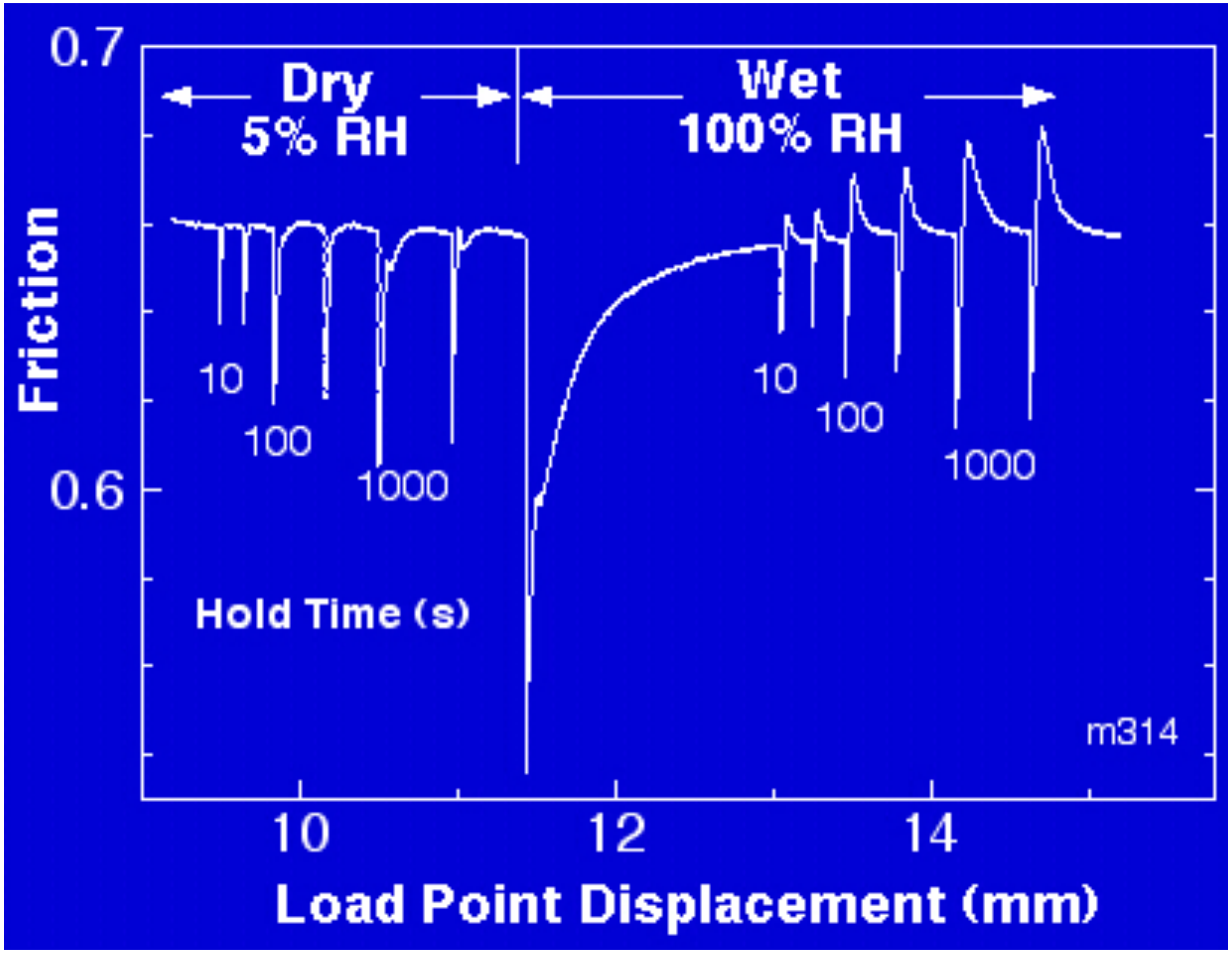
Frye and Marone, JGR 2002

Granular quartz



Hydrolytic Weakening causes enhanced rate of strengthening

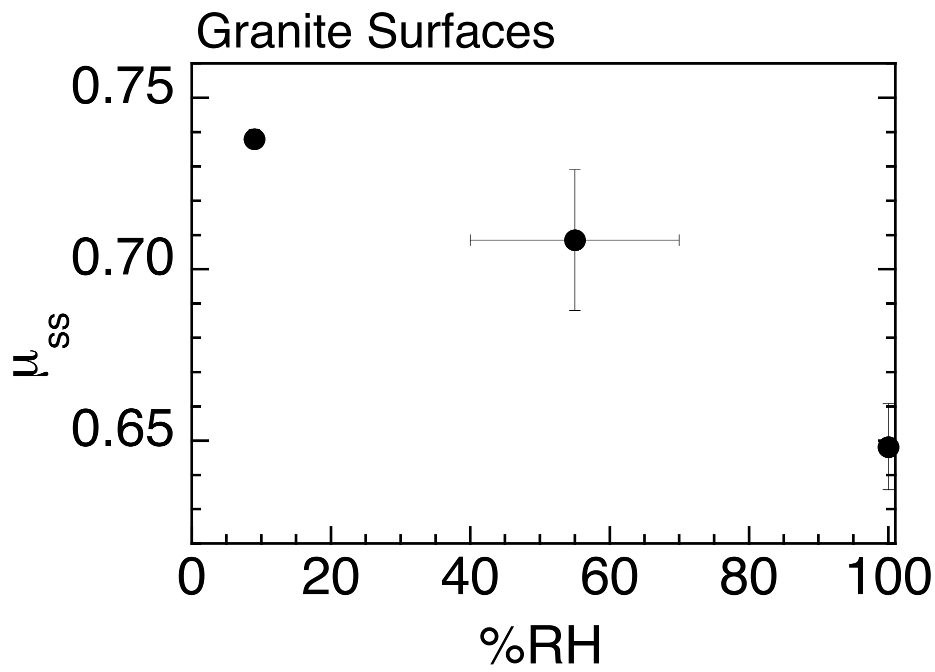
Chemically-Assisted Frictional Aging; Creep at Adhesive Contact Junctions



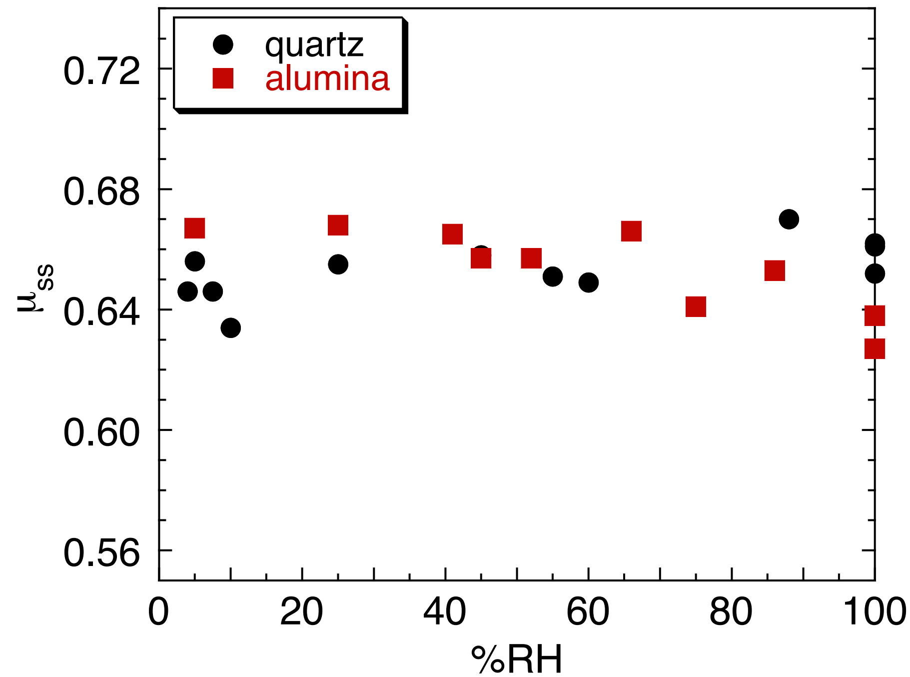
Frye and Marone, JGR 2002

Hydrolytic Weakening causes enhanced rate of strengthening, but base level frictional strength is unchanged

Granite Surfaces



Granular Materials



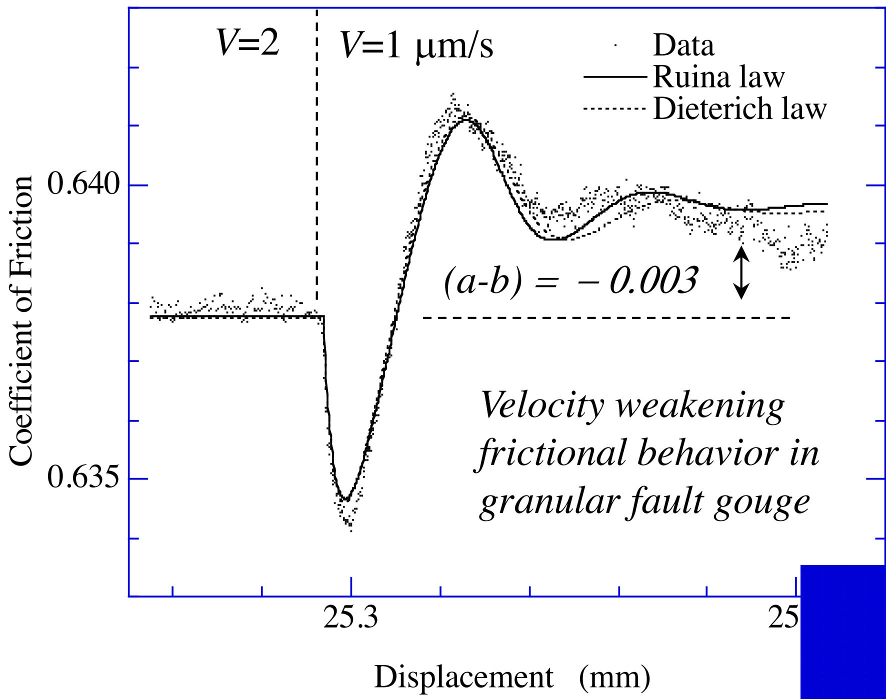
Solid Surfaces: Base level of frictional strength decreases with increasing water content (cf. Dieterich & Conrad, 1984)

Granular Materials: Frictional strength is independent of water content

Interpretation: Contact junctions subject to time dependent strengthening or growth, which inhibits sliding, but particle rolling is not affected by these factors.

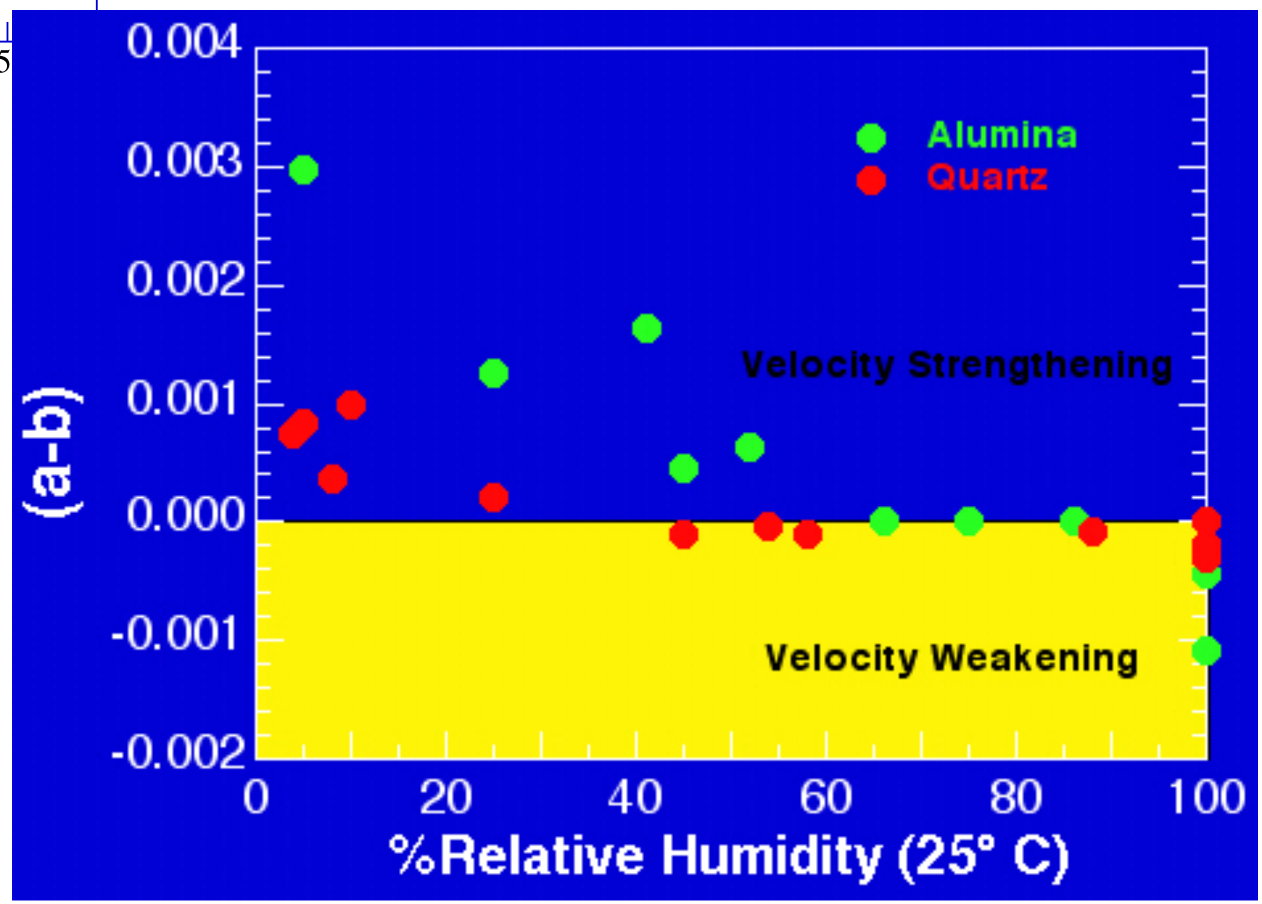
Frye and Marone, JGR 2002

Empirical laws, based on laboratory friction data



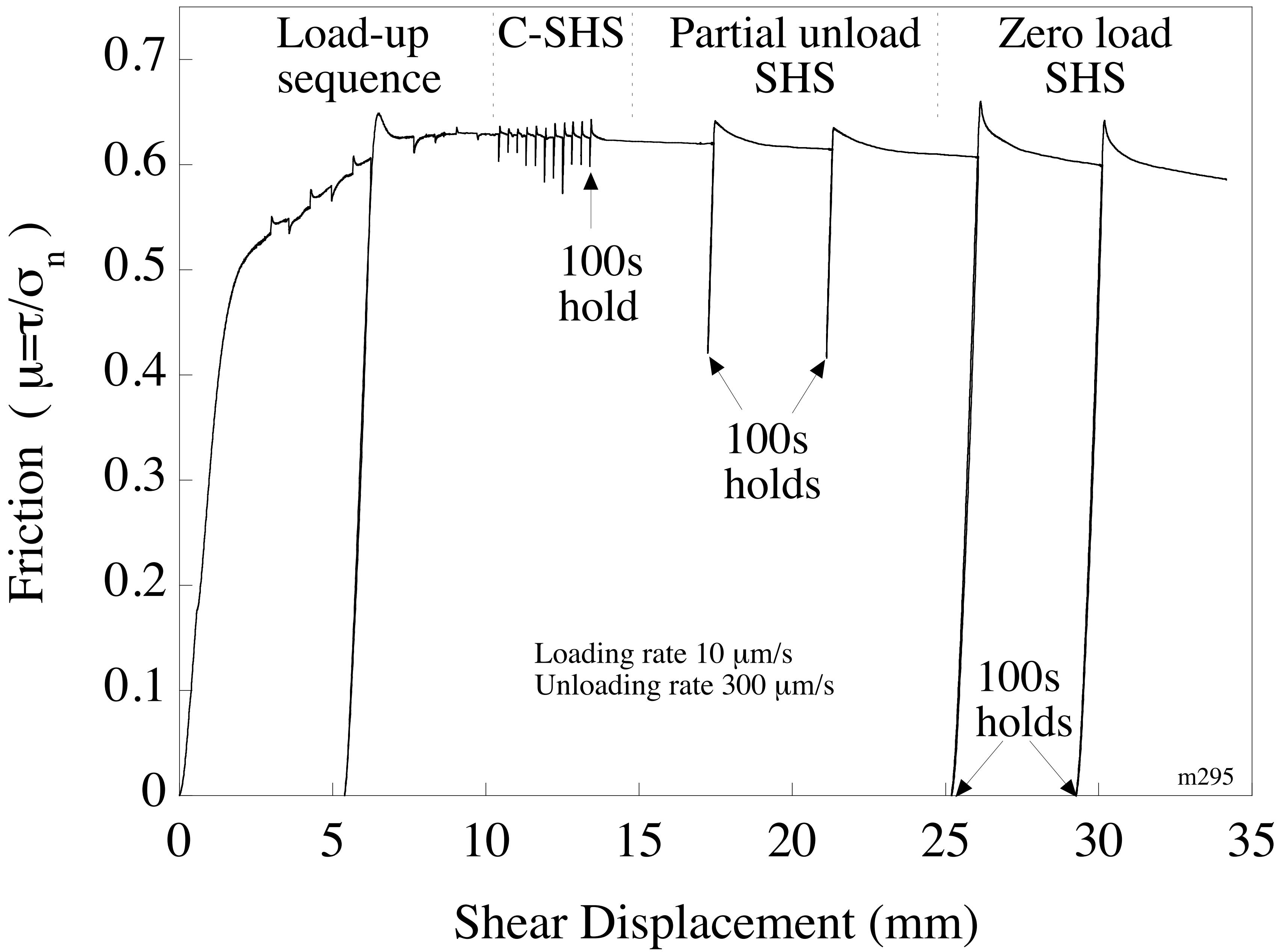
Velocity dependence of steady state friction varies changes from positive to negative. (cf. Tullis and co-workers)

Chemically-assisted creep at adhesive contact junctions



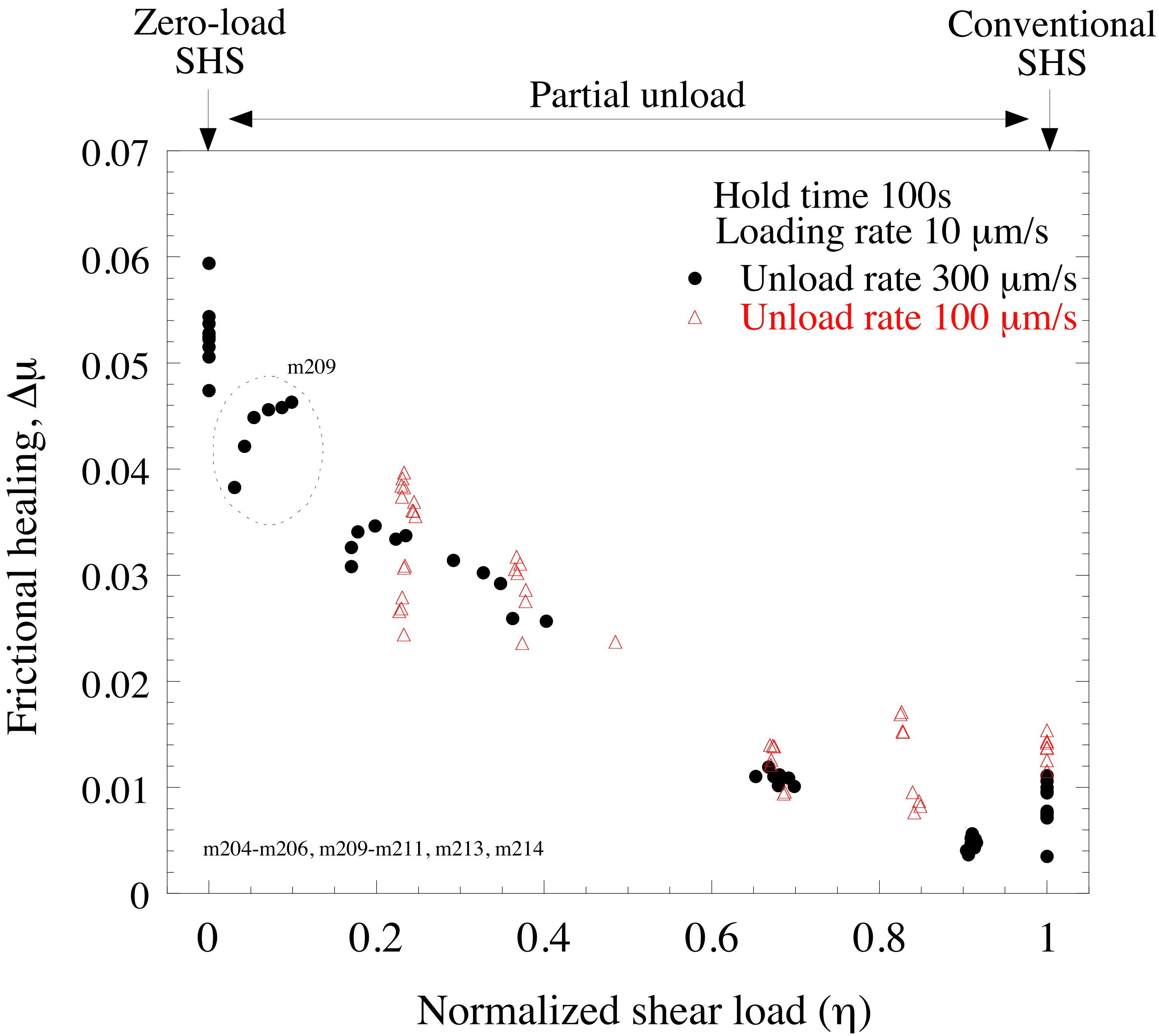
Frye and Marone, JGR 2002

Stresses v. Unstressed Aging



Karner & Marone (GRL 1998, JGR 2001)

100 s holds, Healing rate varies systematically with shear stress



Karner & Marone (GRL 1998 JGR 2001)