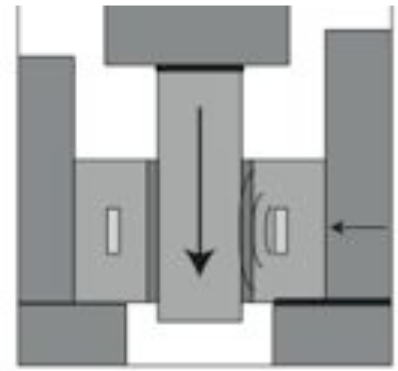
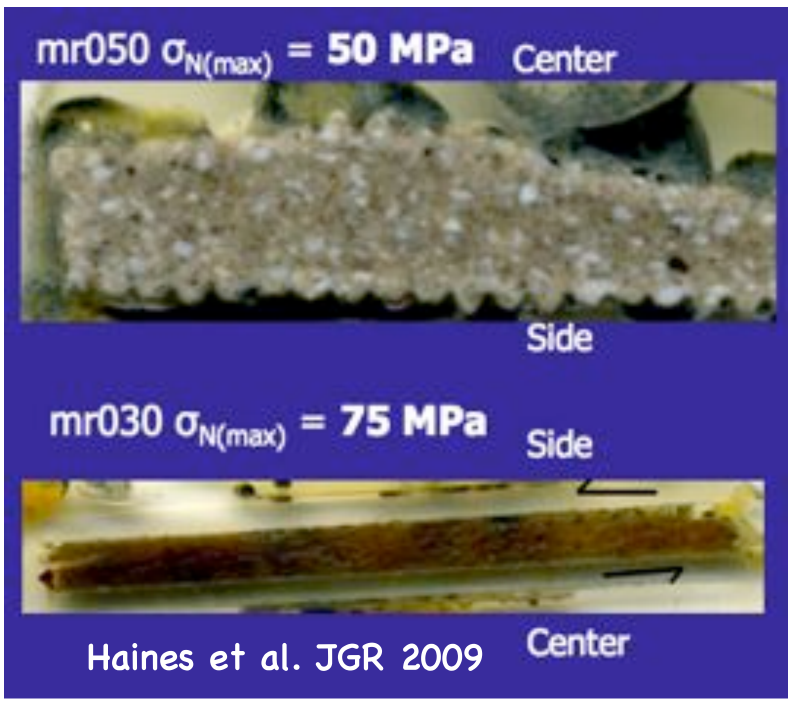
The Strength and Rheology of Brittle Fault Zones

C. Marone, Penn State

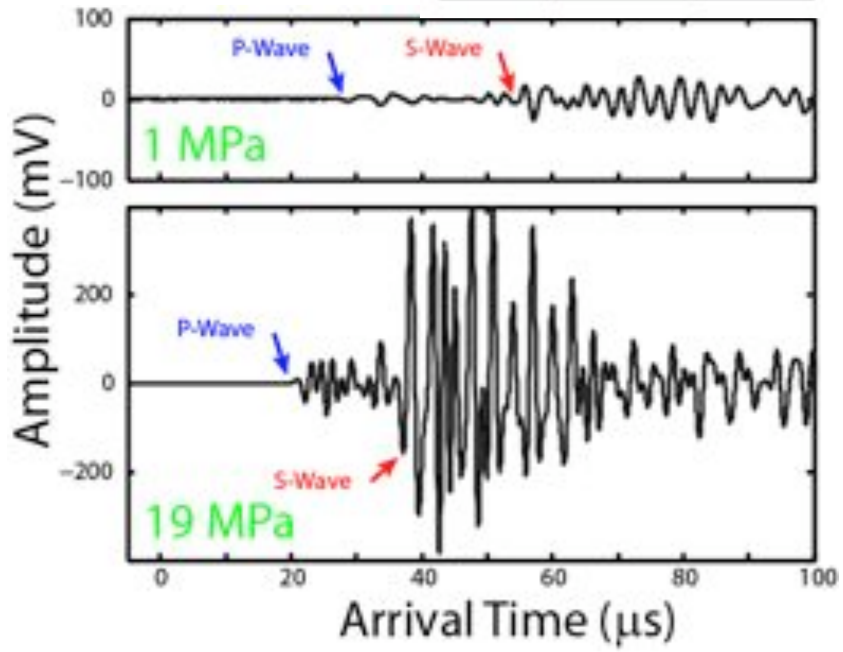
With: Demian Saffer, Derek Elsworth, Andre Niemeijer, Cristiano Collettini, Massimo Cocco, Paul Johnson, Sam Haines, Igor Faoro, Andy Rathbun, Jon Samuelson, Matt Ikari, Matt Knuth and Bryan Kaproth

NMCDEF, June 2009





Haines et al. JGR 2009



Knuth, Tobin, Saffer & Marone 2009

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Field Studies of Exhumed and Active Faults

The Strength and Rheology of Brittle Fault Zones

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Field Studies of Exhumed and Active Faults

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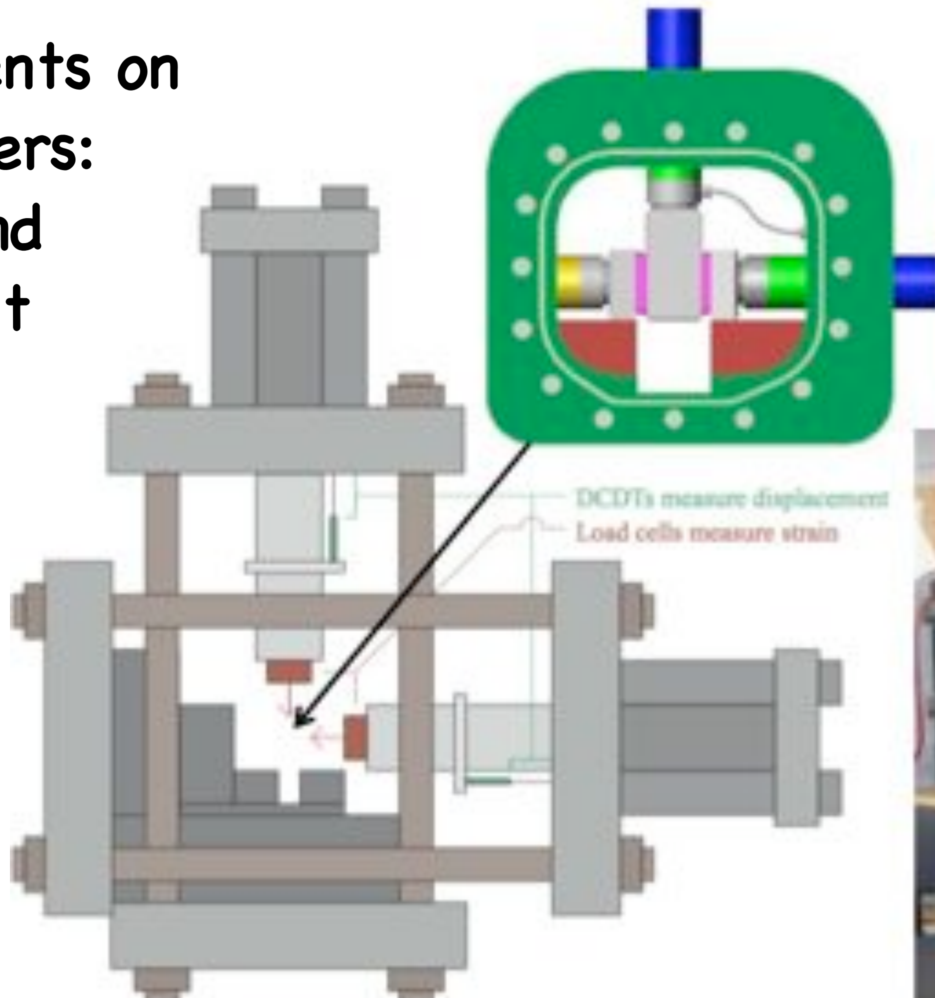
Lab experiments on sheared layers: synthetic and natural fault gouge



Double direct biaxial loading apparatus at Penn State

The Strength and Rheology of Brittle Fault Zones

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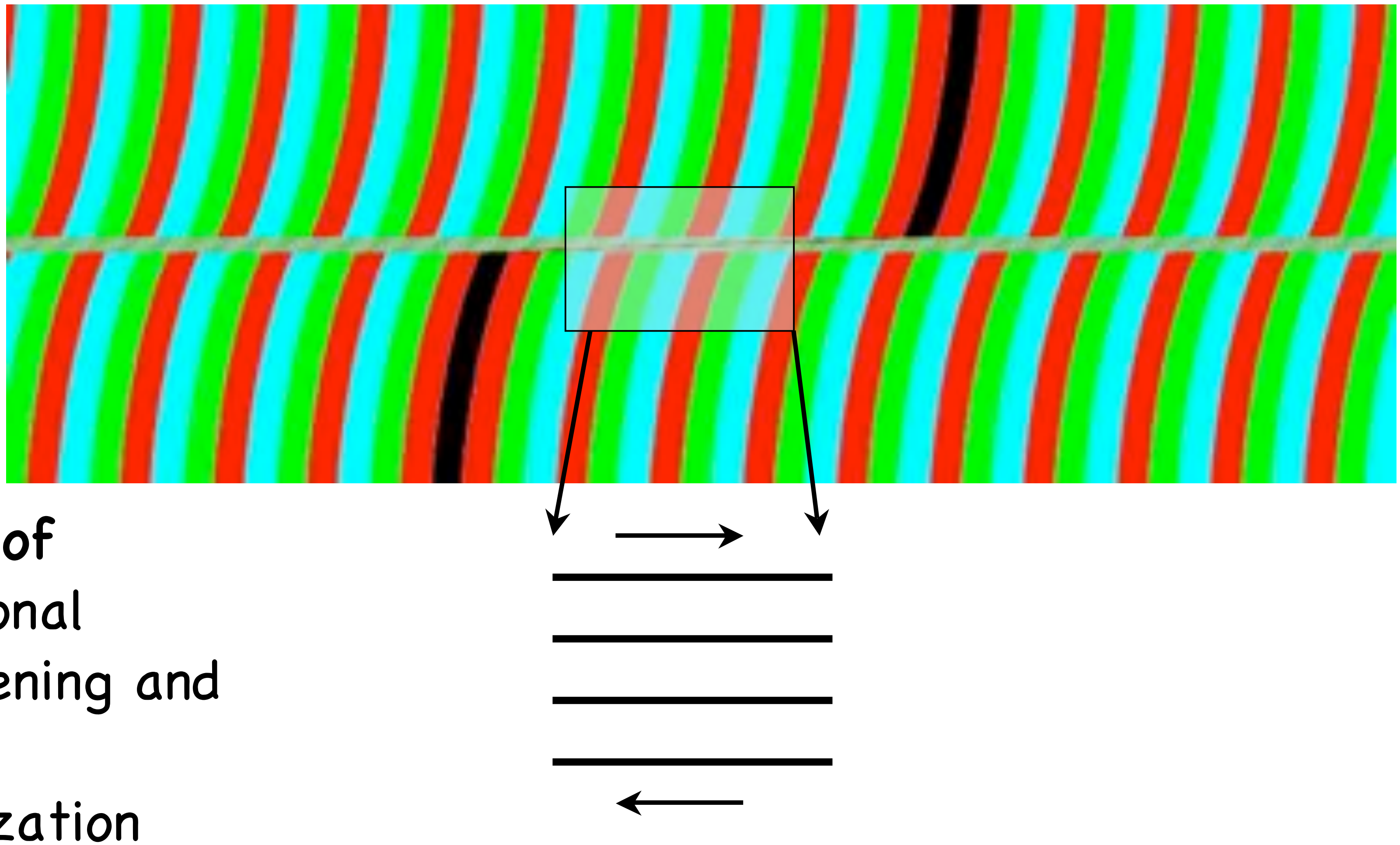

Model of
frictional
weakening and
shear
localization

The Strength and Rheology of Brittle Fault Zones

C. Marone, Penn State Center for Geomechanics, Geofluids & Geohazards

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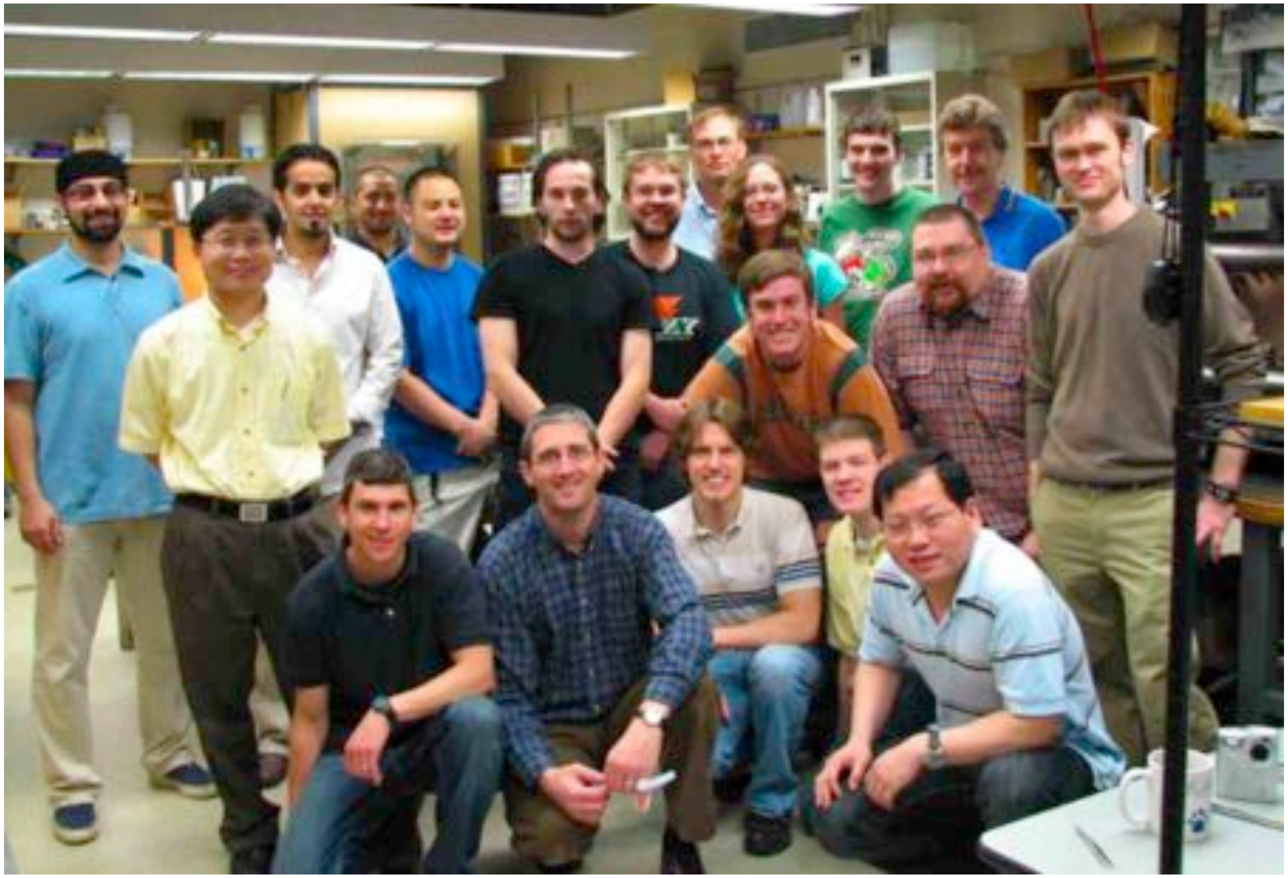
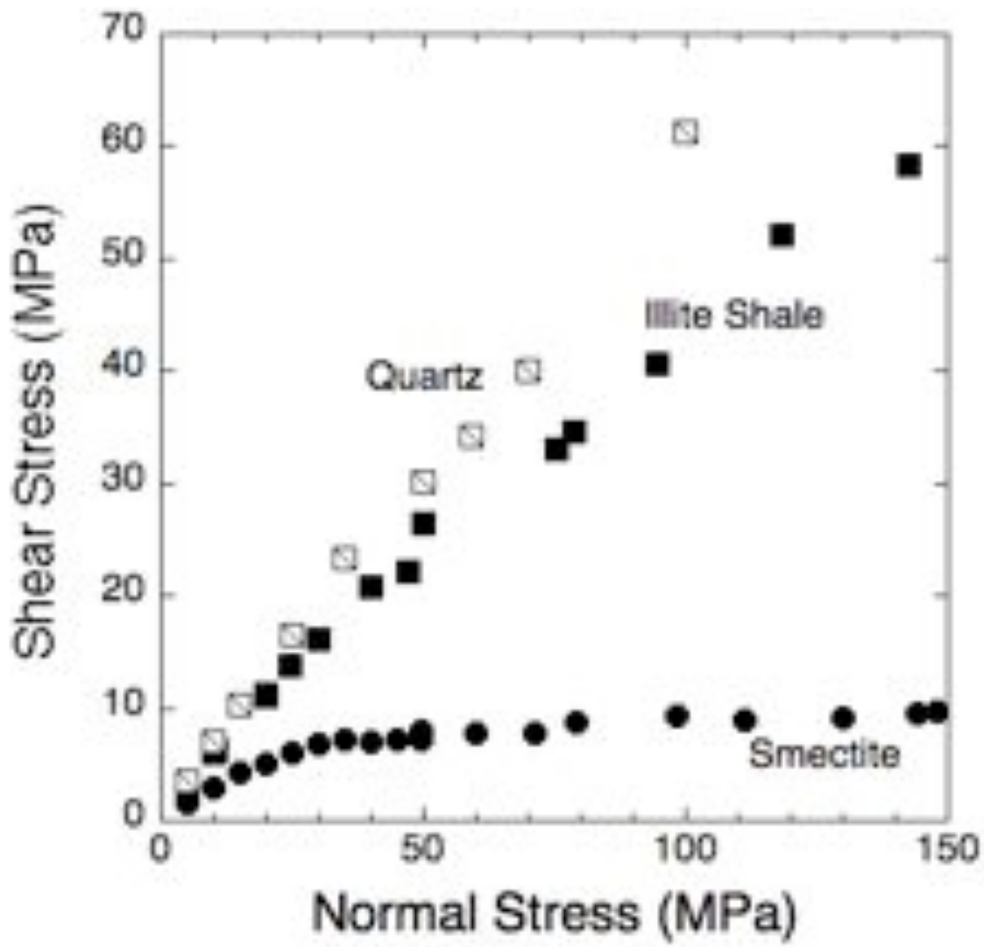


The *Strength* and *Rheology* of *Brittle* Fault Zones



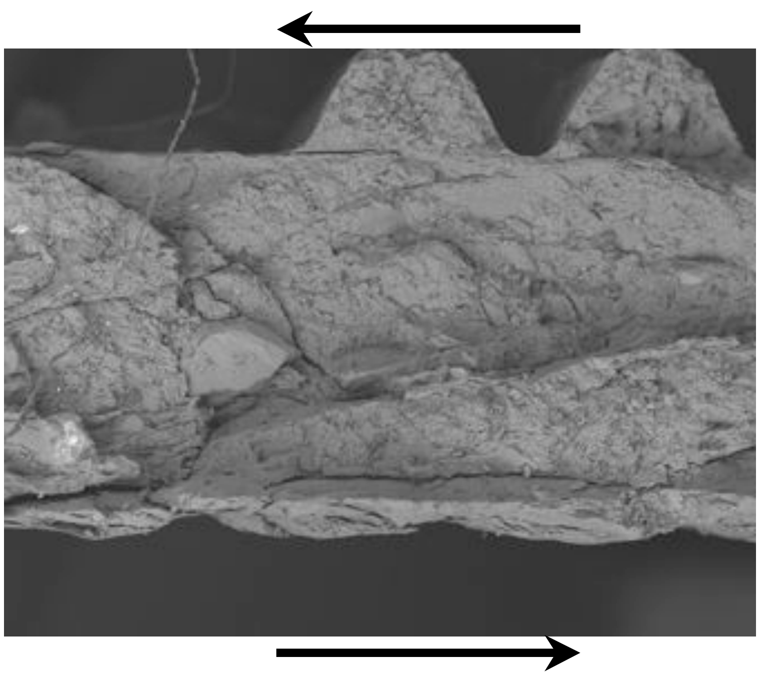
Marone & Saffer, 2007

The Strength and Rheology of Brittle Fault Zones

1. Why bother with rate/state friction?
   Rate dependence, healing, triggering, complex behavior

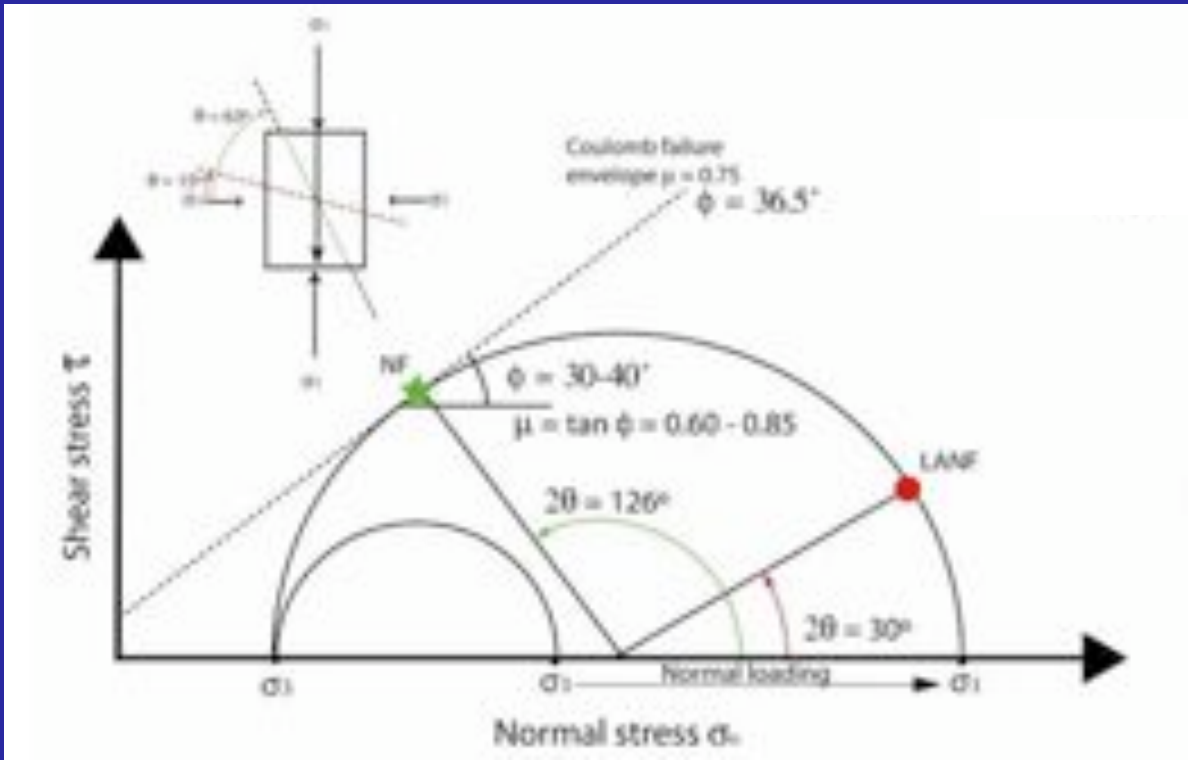
2. Fault strength and weak materials
   Fabric & surface coatings; mixtures of strong & weak materials

3. Fault zones of finite width
   Modeling, implications of rate/state properties



Frictional healing, Restrengthening
Time dependence of "static" friction
Aging of frictional contacts

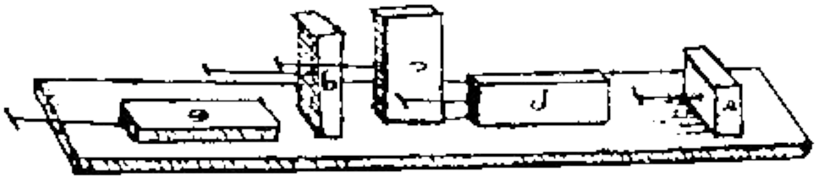
C. A. Coulomb (1736-1806)

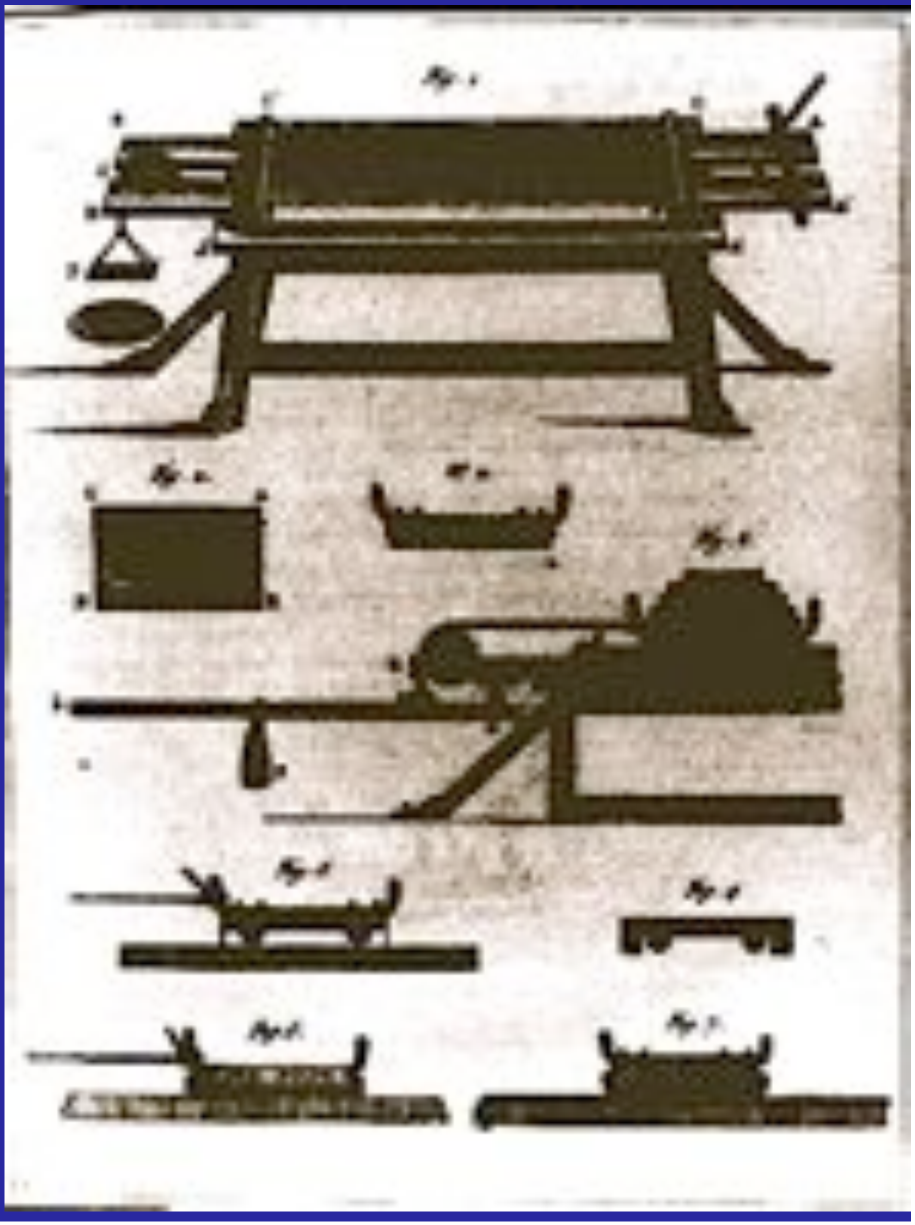


Coulomb-Mohr Brittle Failure

Frictional healing, Restrengthening
Time dependence of “static” friction
Aging of frictional contacts

C. A. Coulomb (1736-1806)





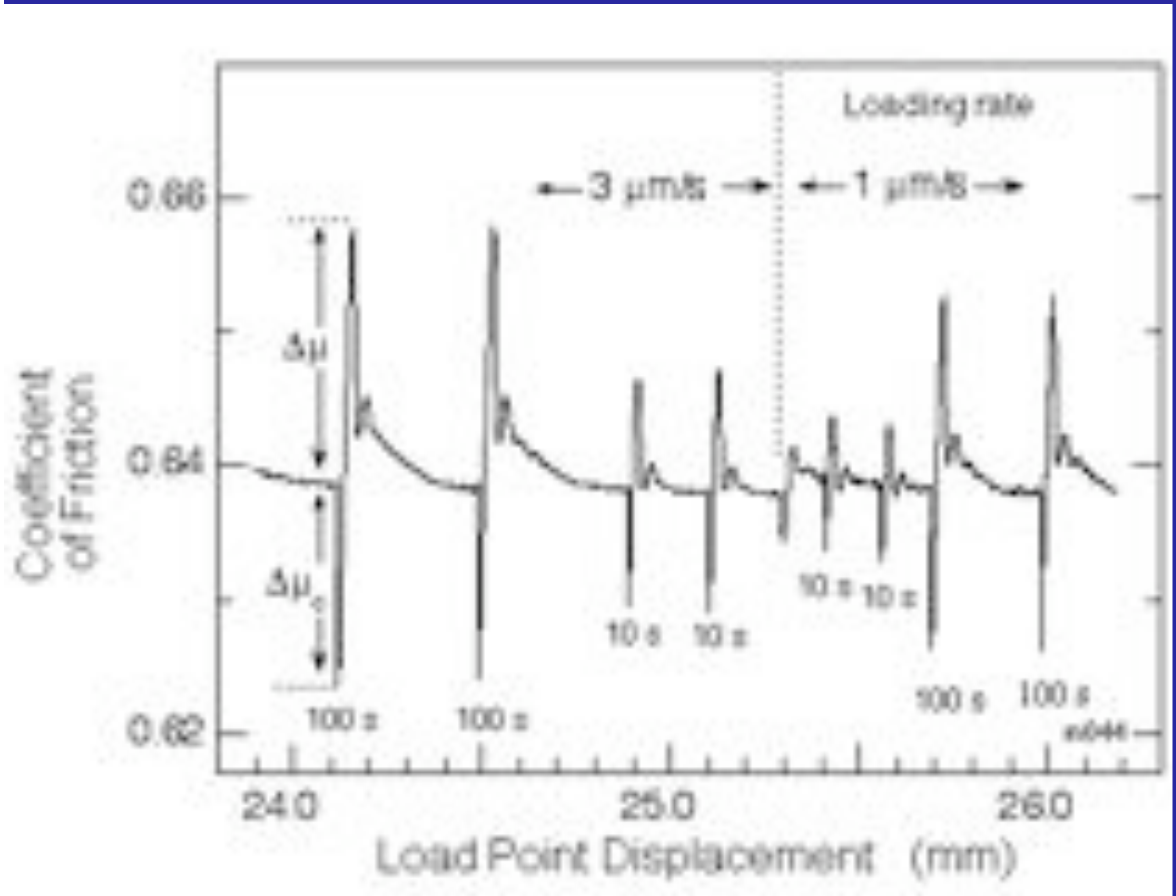
Time dependence of “static” friction

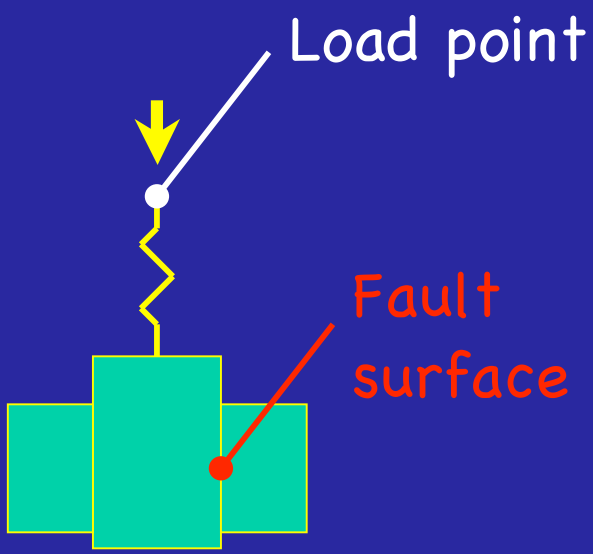
Table 9.1

	T (time of repose, min)	$A + mT^{\mu}$ (static friction force, lbf)
I^{re} observation	0	$A = 502$
II^{e}	2	790
III^{e}	4	866
IV^{e}	9	925
V^{e}	26	1,036
VI^{e}	60	1,186
VII^{e}	960	1,535

static friction of two pieces of well-worn oak lubricated with tallow.

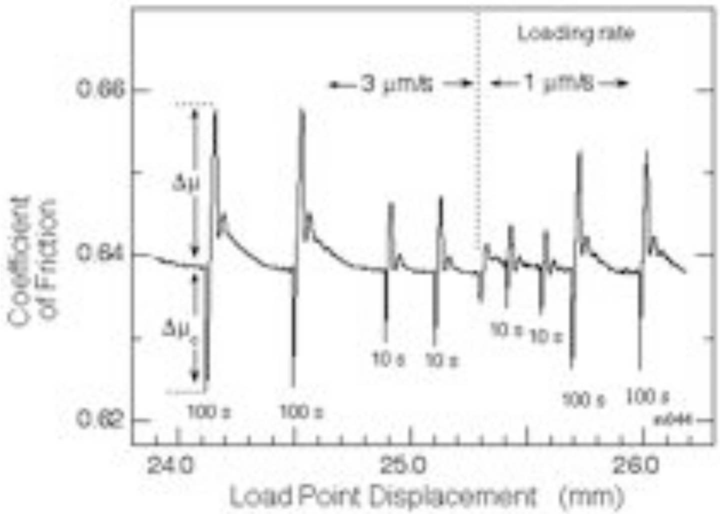
Frictional Healing
Stressed aging

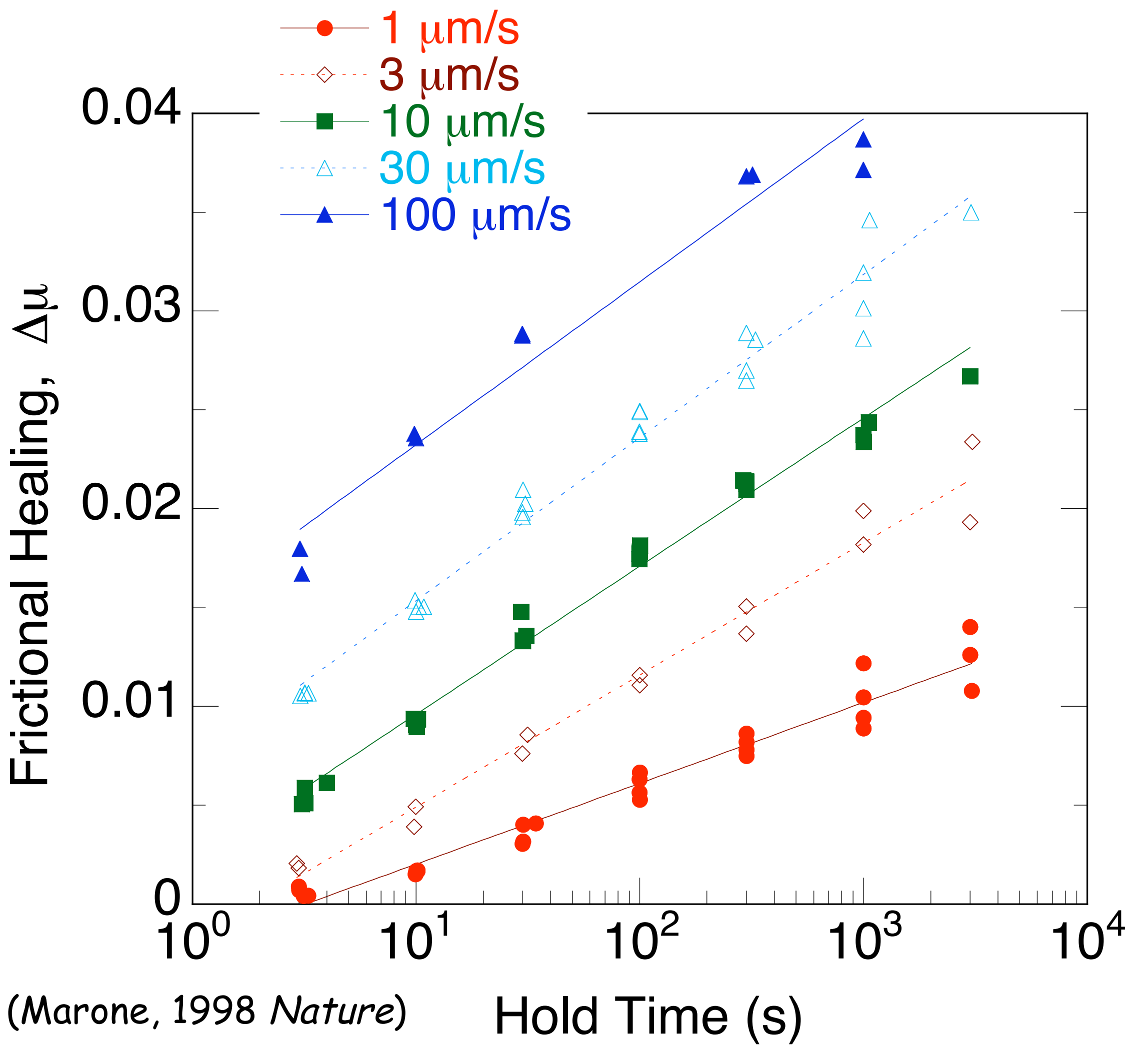




Steady state friction & the rate of healing vary with sliding velocity

Angular quartz particles (100-150 μm), 3 mm thick, 25 MPa normal stress. Marone, 1998





(Marone, 1998 *Nature*)

Stressed Aging

Frictional aging depends on the rate of shearing

Duality:

Dependence of friction on time of (*static*) contact.

Dependence of (*dynamic*) friction on sliding rate.

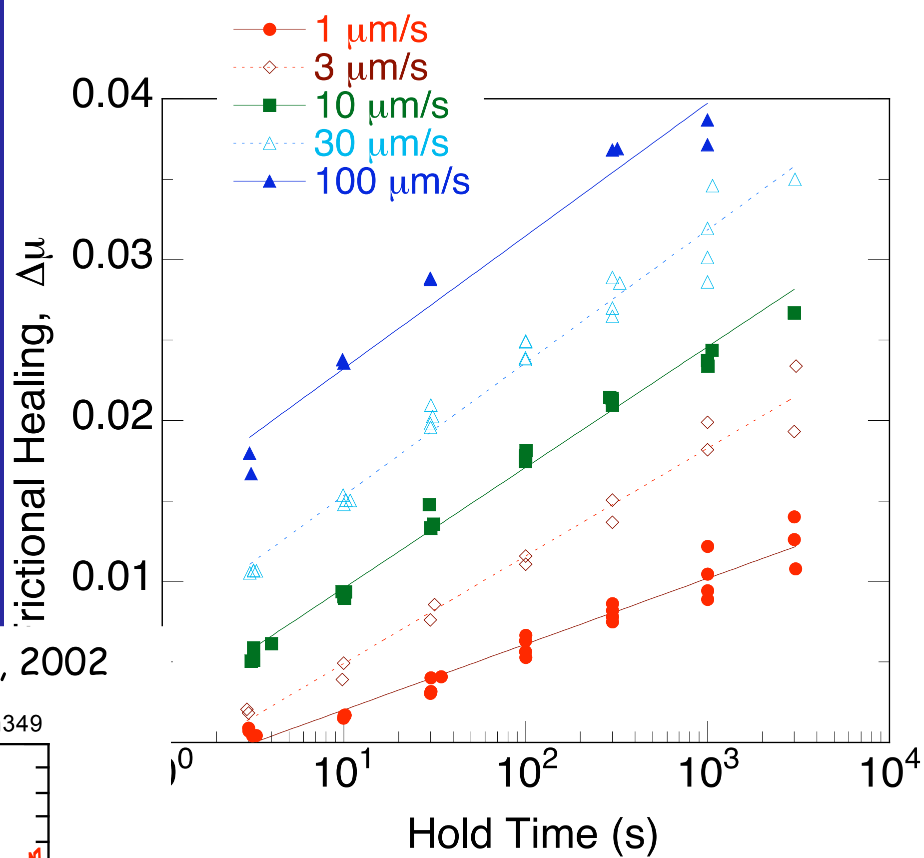
Static and *dynamic* friction are special cases of a more general behavior referred to as Rate and State Friction

Rate of frictional healing:

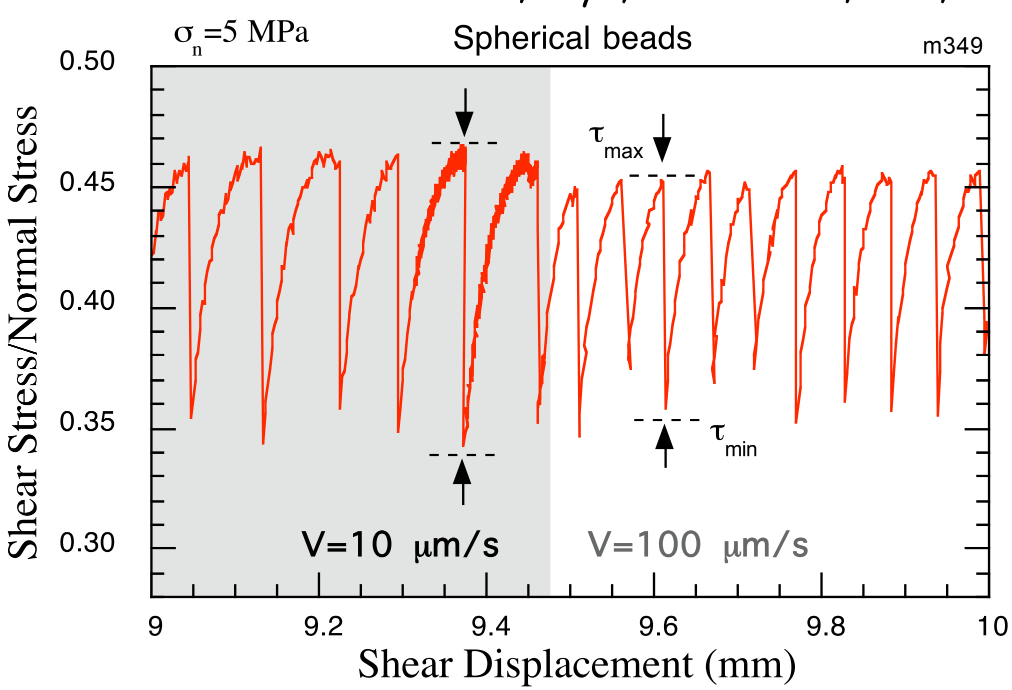
$\Delta\mu$ ~ 0.005 to 0.01 per decade in time

$\Delta\mu$ ~ 0.01 per decade in slip (time*V)

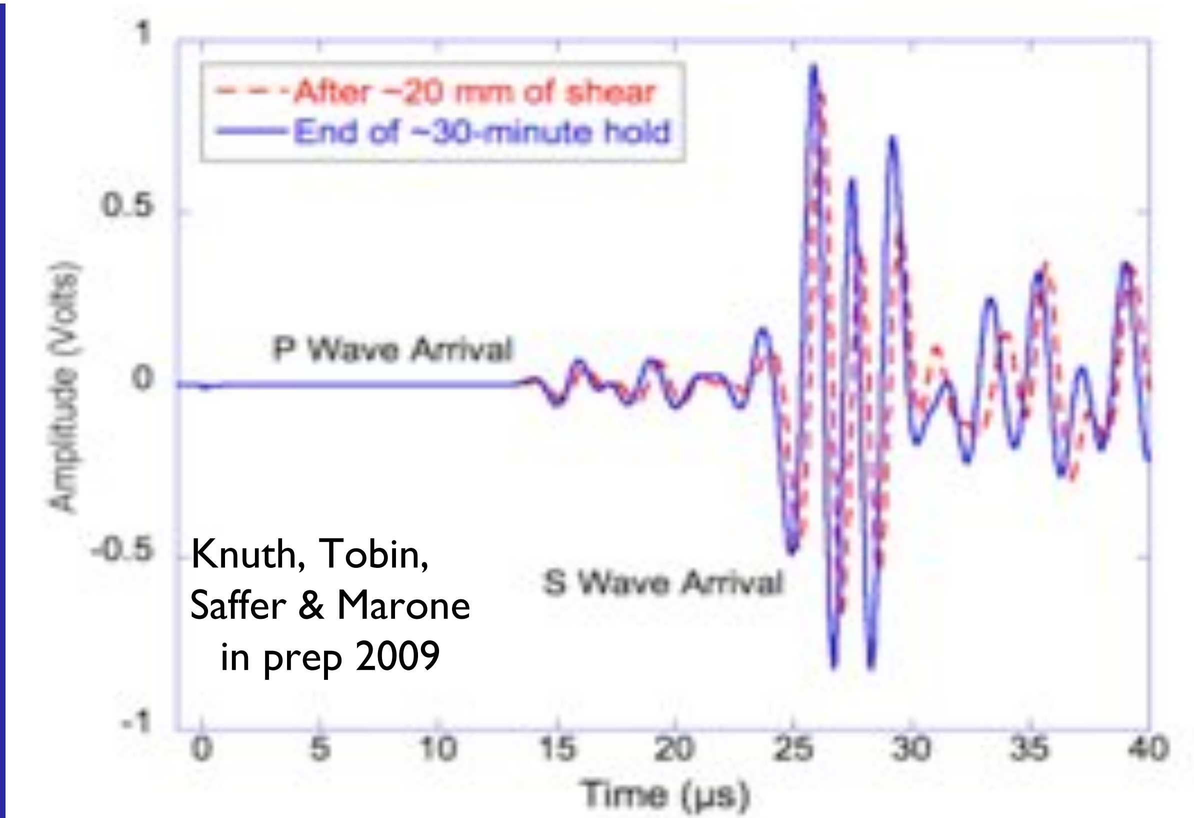
Rate and State Friction explains why this applies to aging, stick slip, and steady sliding



Mair, Frye, and Marone, JGR, 2002



(Marone, 1998 *Nature*)



What is the mechanism of frictional healing?

Friction Law

$\mu = \mu_o + a \ln(V/V_o) + b \ln(V_o\theta/D_c)$

State Evolution

$d\theta/dt = 1 - V\theta/D_c$

$d\theta/dt = -V\theta/D_c \ln(V\theta/D_c)$

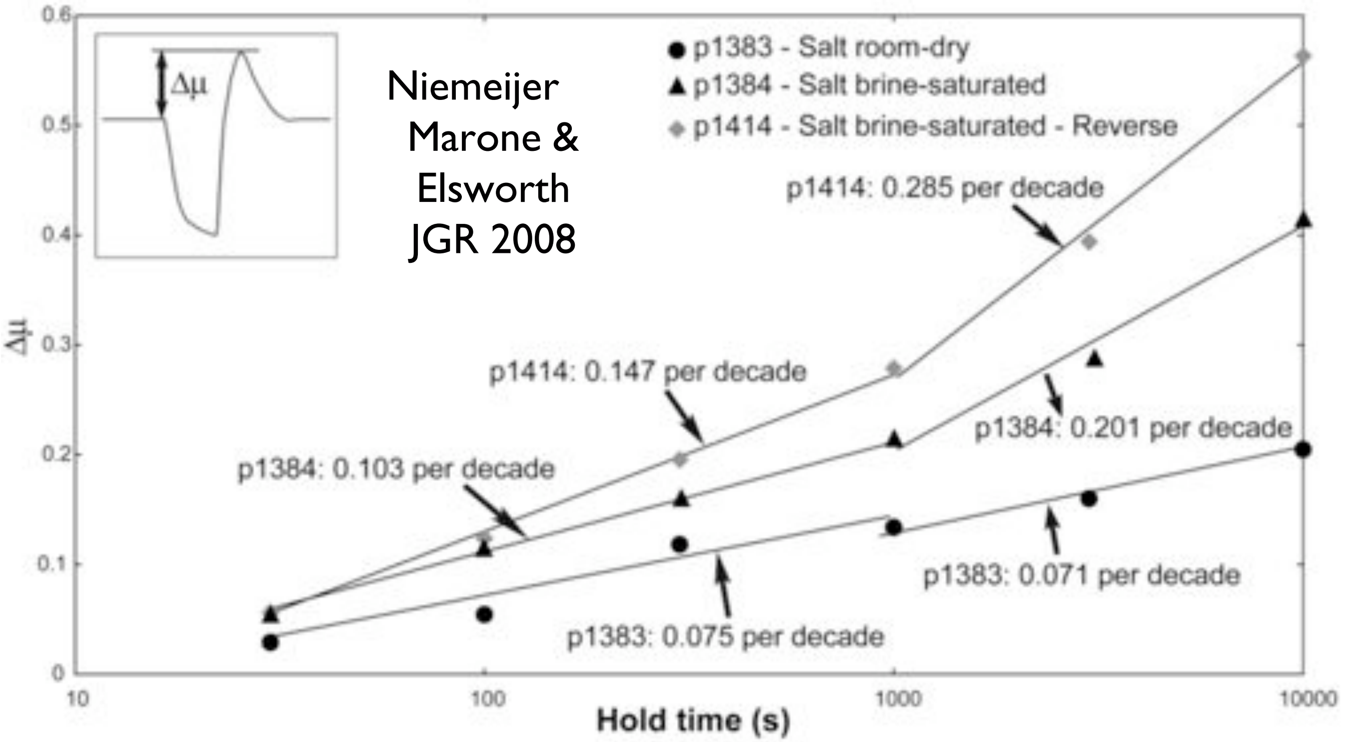
Elastic Coupling

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

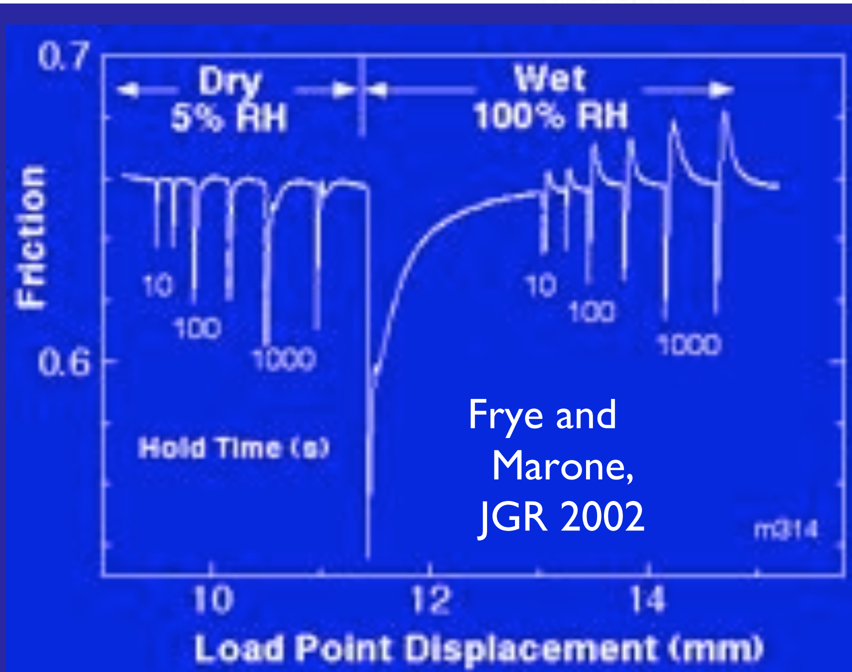
Thermally-activated process

$$v = v_o \exp\left(\frac{\mu - \mu_o - b\varphi}{a}\right)$$

$$\dot{\varepsilon} = \dot{\varepsilon}_o \exp\left[-\frac{(Q - \tau_c\Omega)}{kT}\right]$$

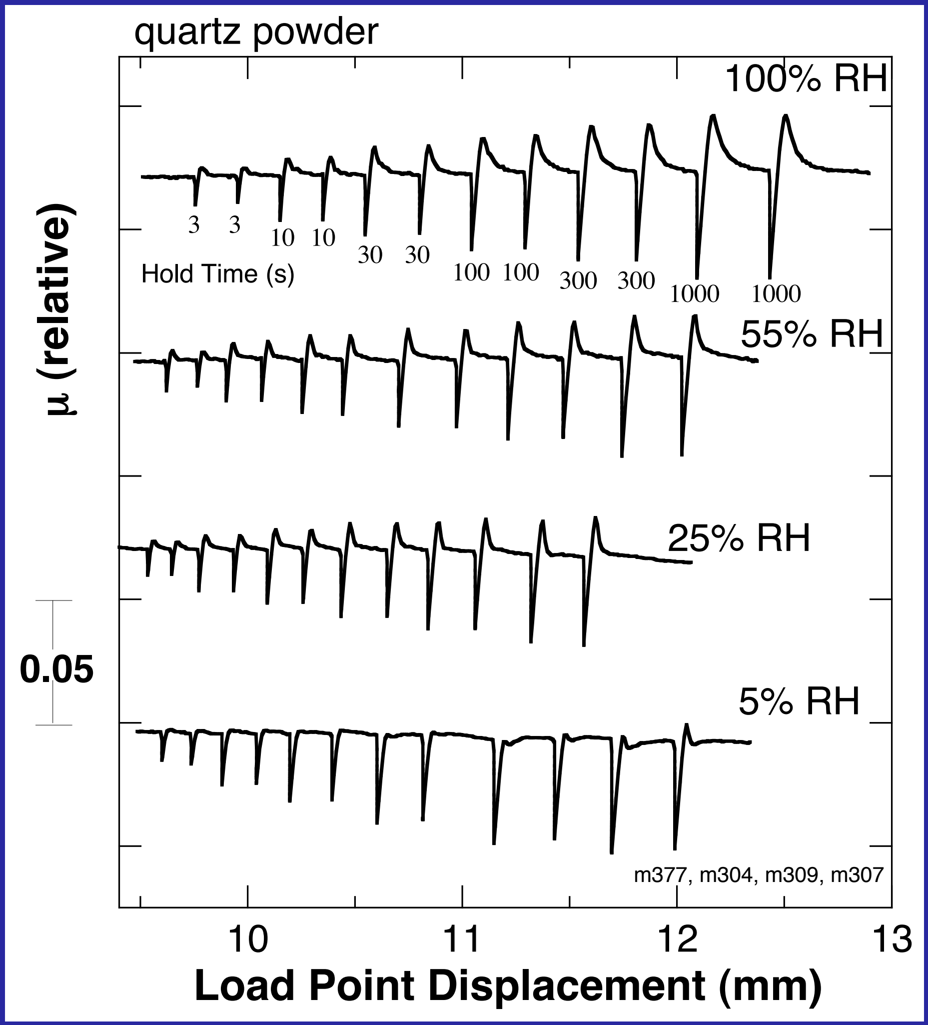


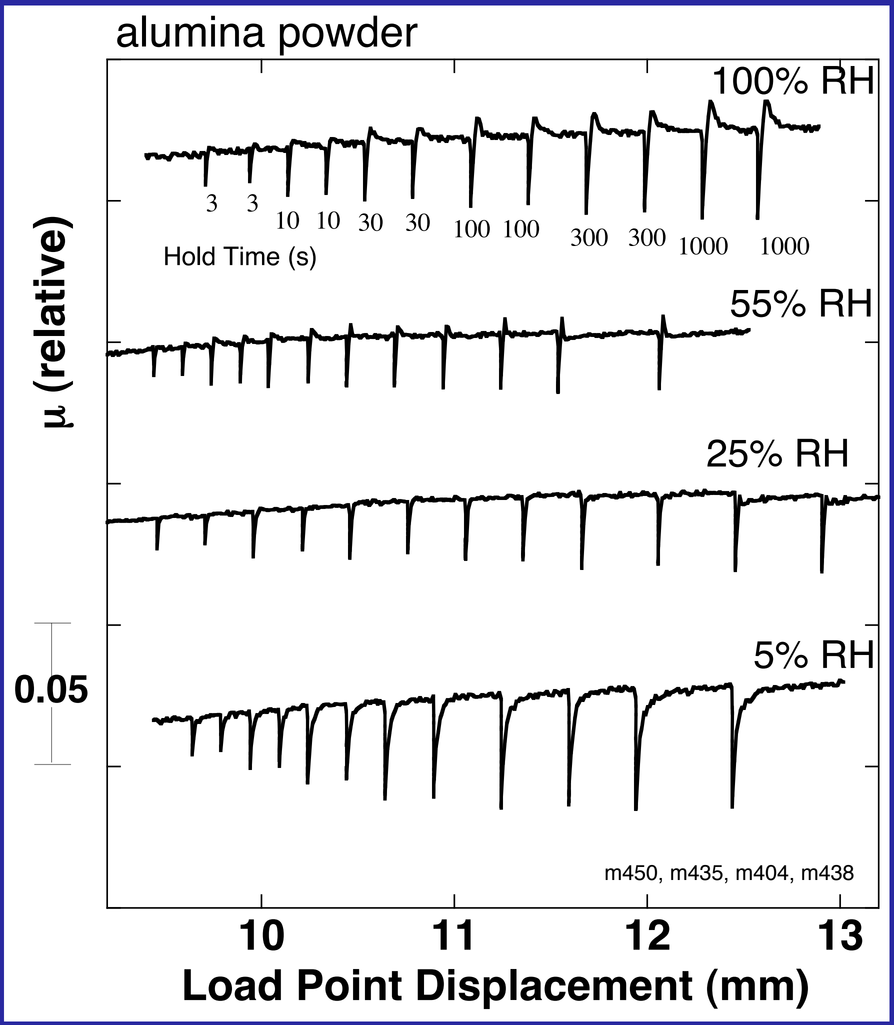
Chemically-Assisted Frictional Aging; Creep at Adhesive Contact Junctions



Hydrolytic weakening causes enhanced strengthening, but kinetic friction is unchanged

Chemically-Assisted Frictional Aging; Creep at Adhesive Contact Junctions

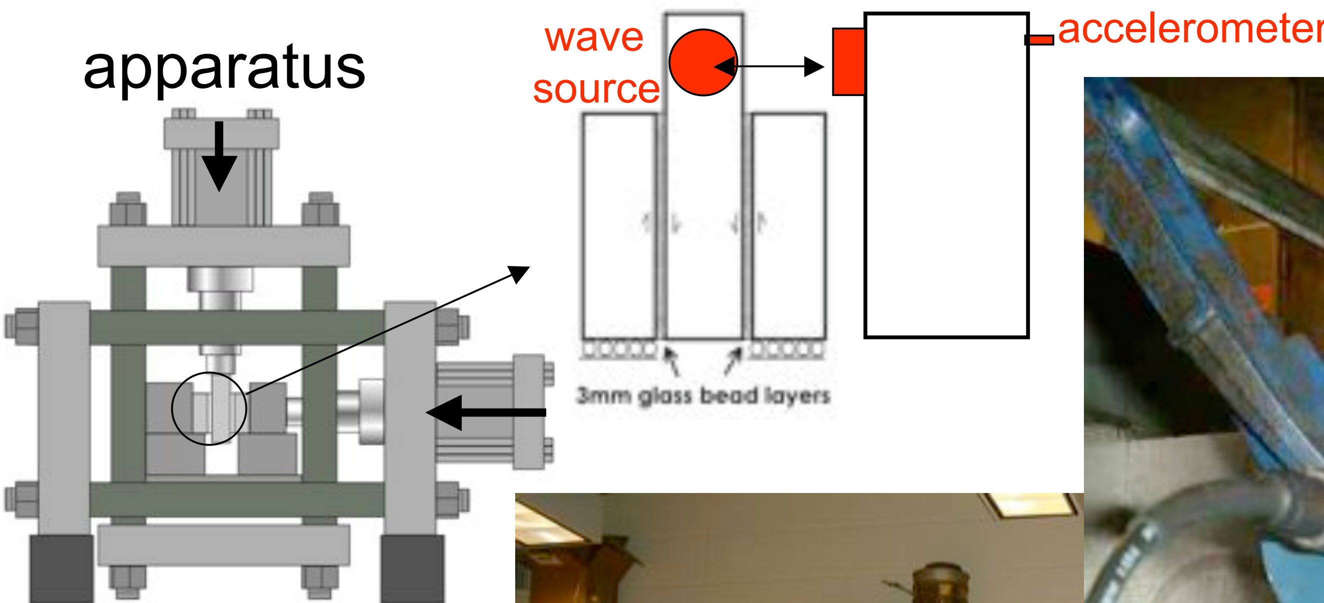


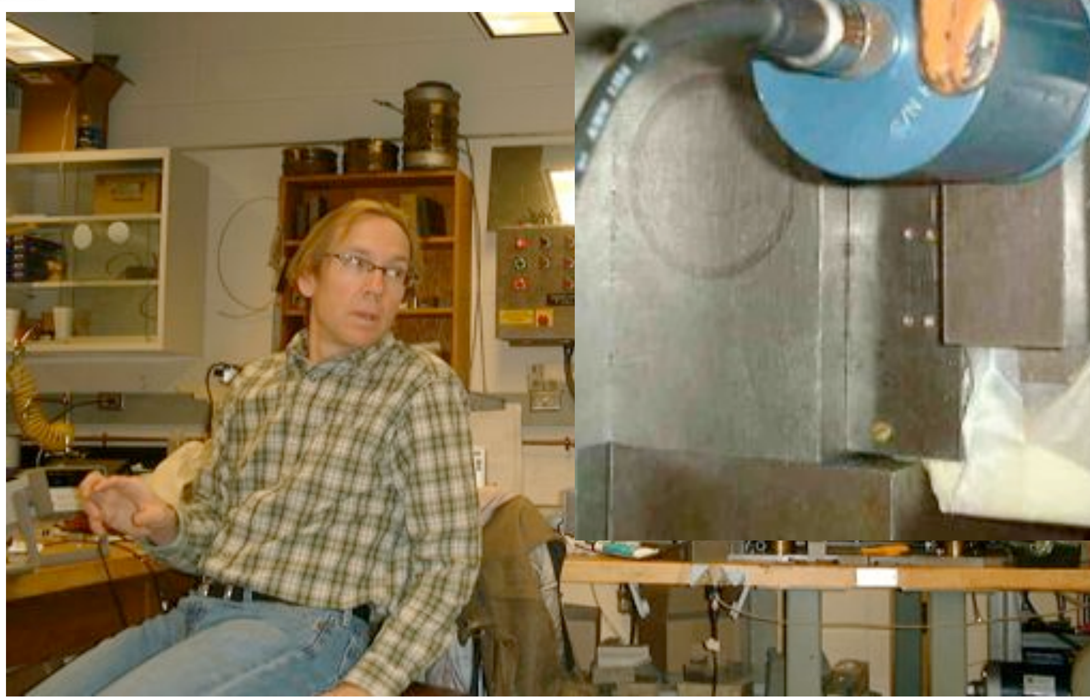


Frye and Marone, JGR 2002

Effects of acoustic waves on stick–slip friction

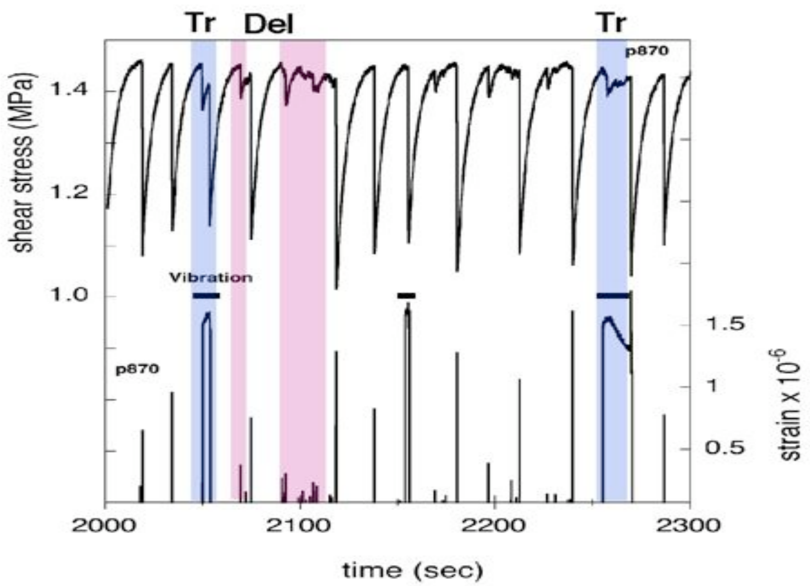
Johnson, Savage, Knuth, Gomberg & Marone, Nature, 2008.

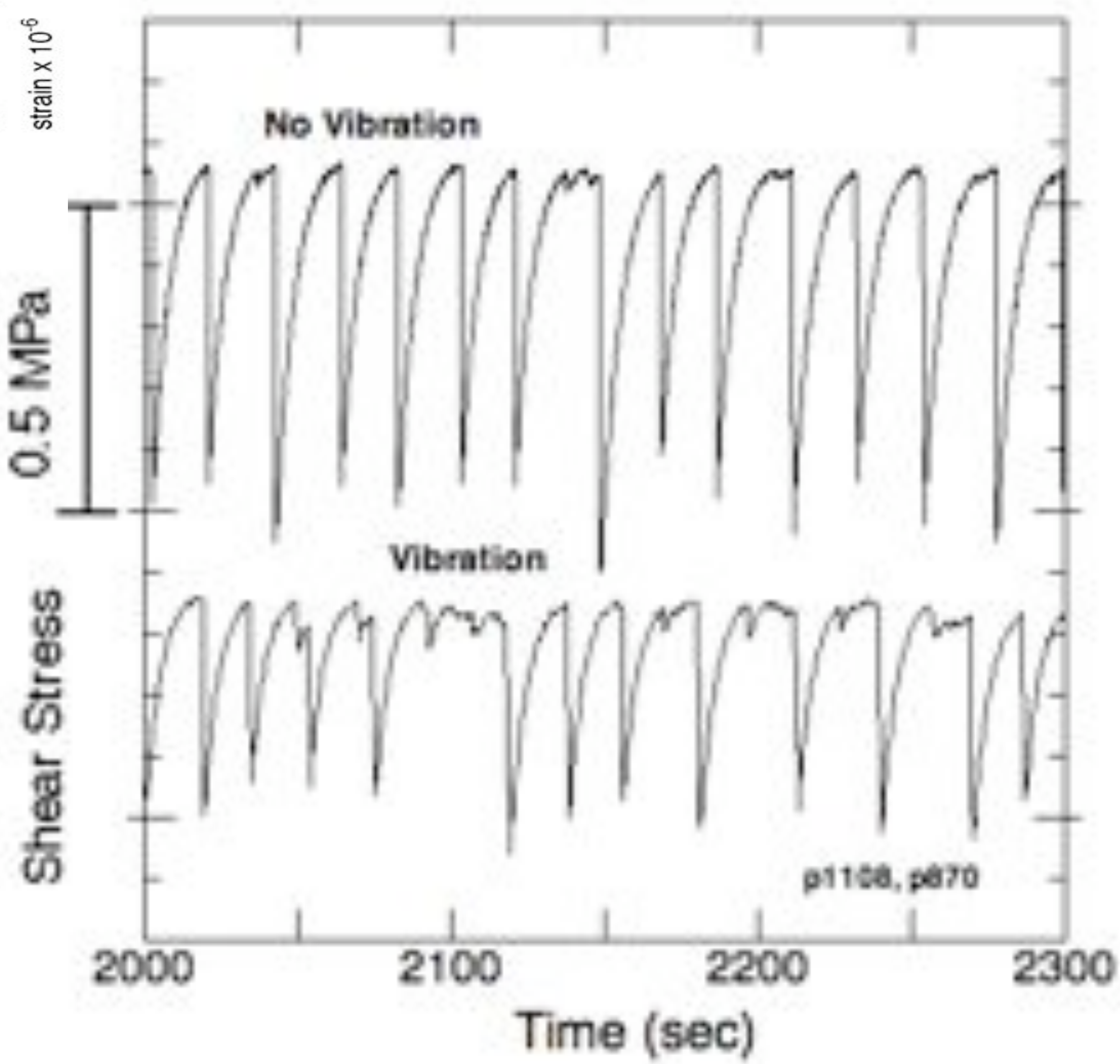




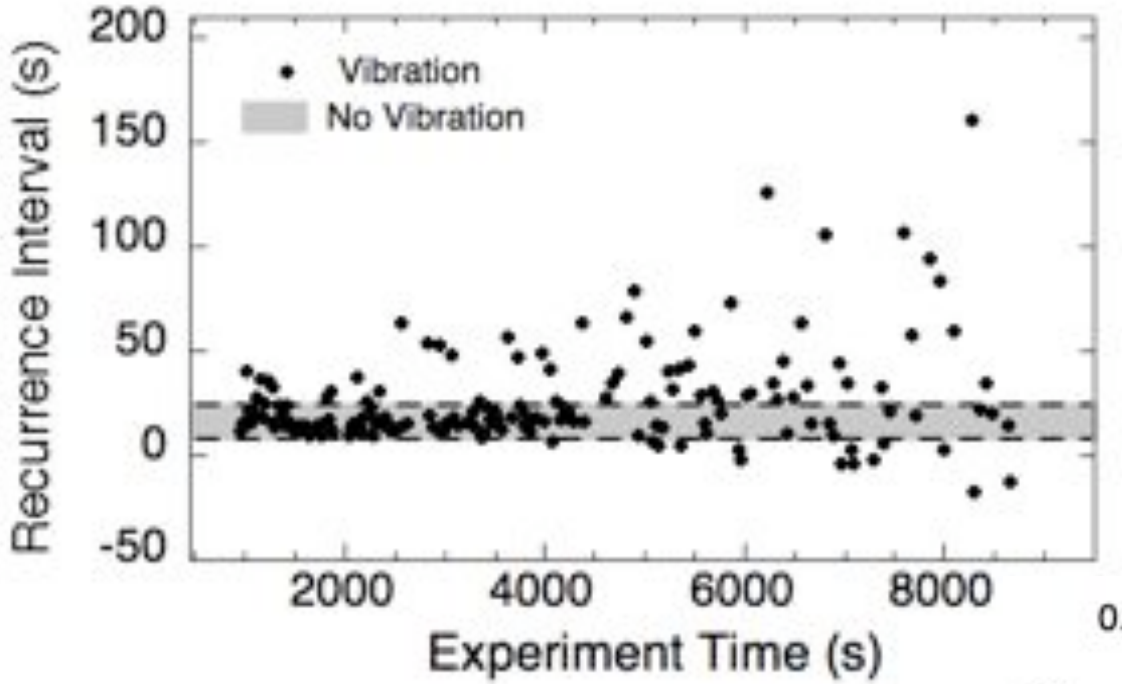
- 5 MPa normal stress
- background shearing rate of 5 μm/sec

Effects of acoustic waves on stick–slip

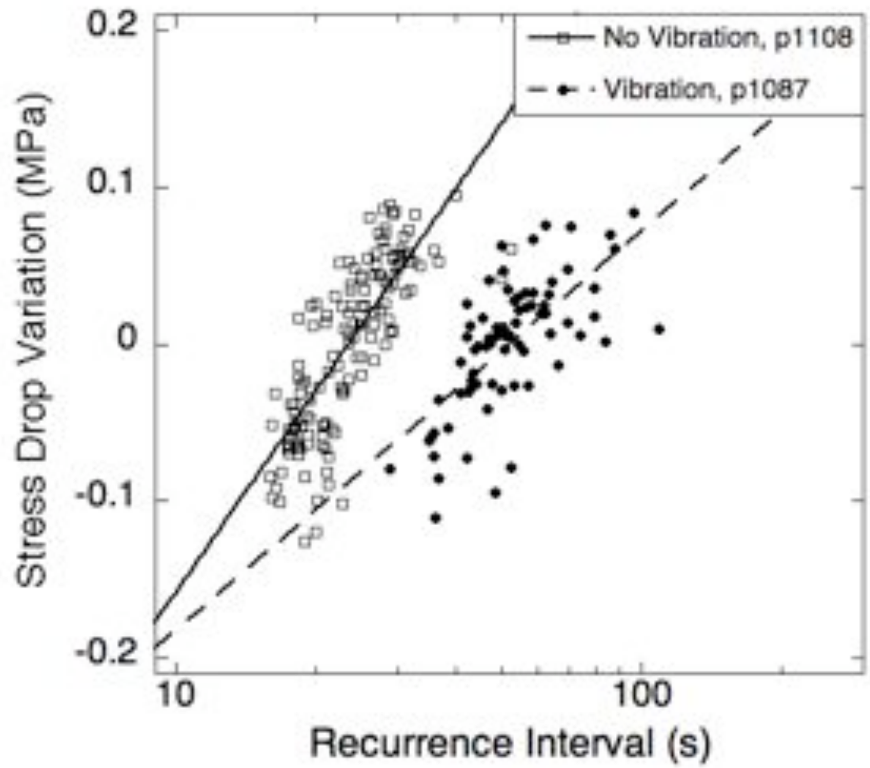




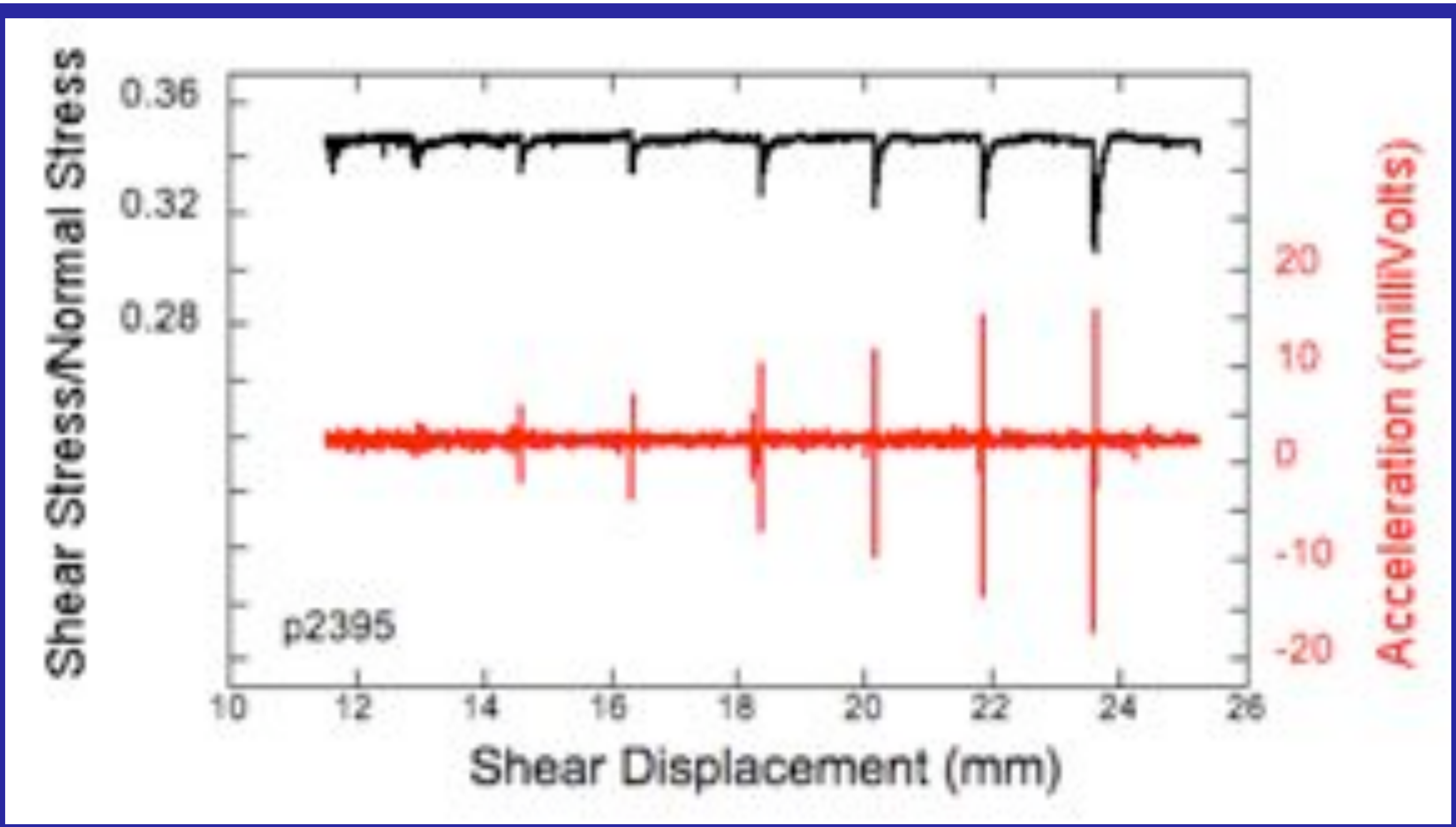
Johnson et al.,
Nature, 2008



Johnson et al., Nature, 2008



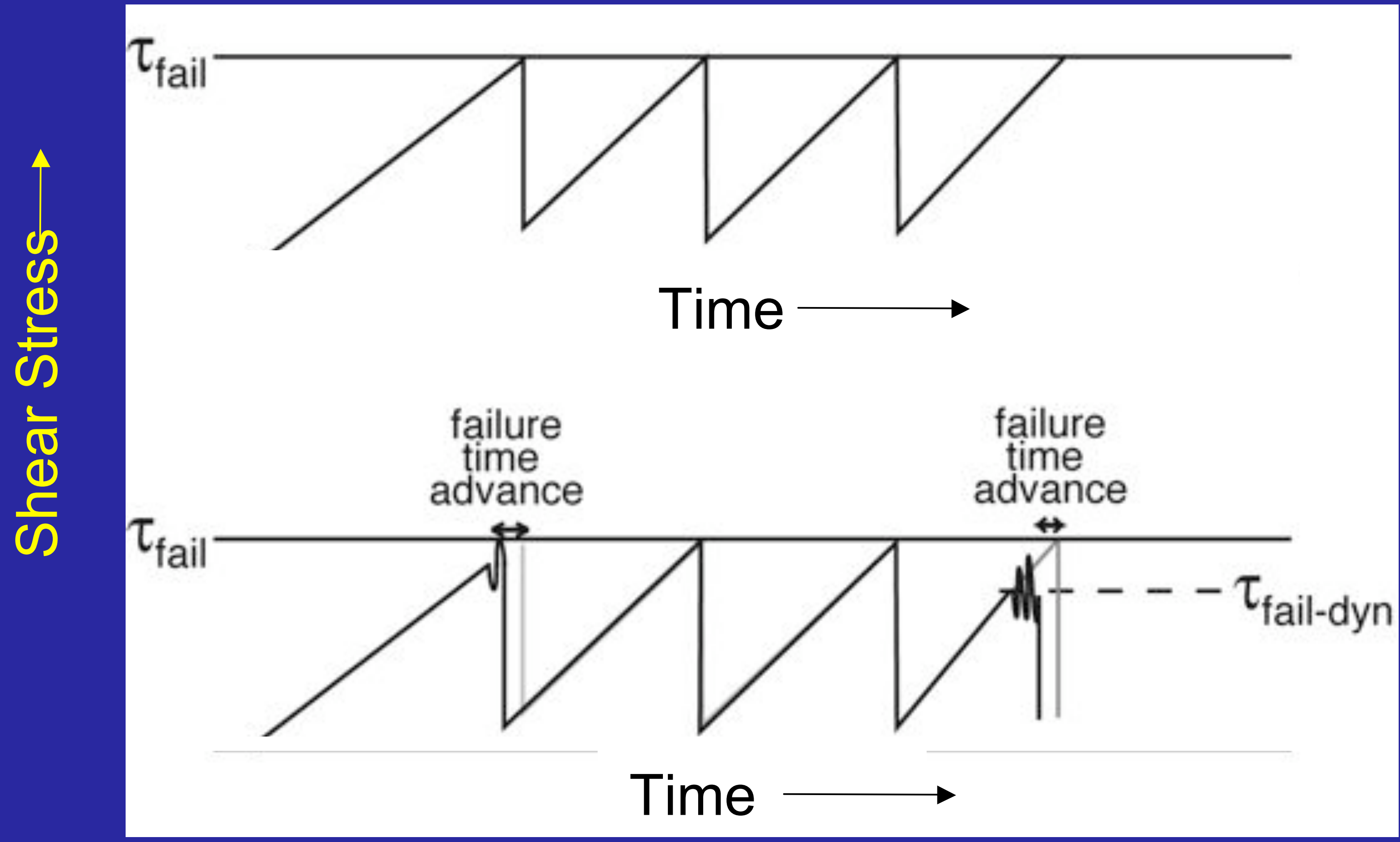
Acoustic Vibration disrupts regular stick slip, leads to smaller stress drop



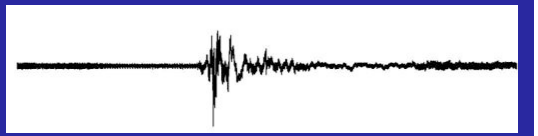
Johnson and Marone, ms. In prep, 2009

Stress drop in slow, quasi-stick-slip events scales with acoustic vibration amplitude

Earthquake Triggering by Shaking



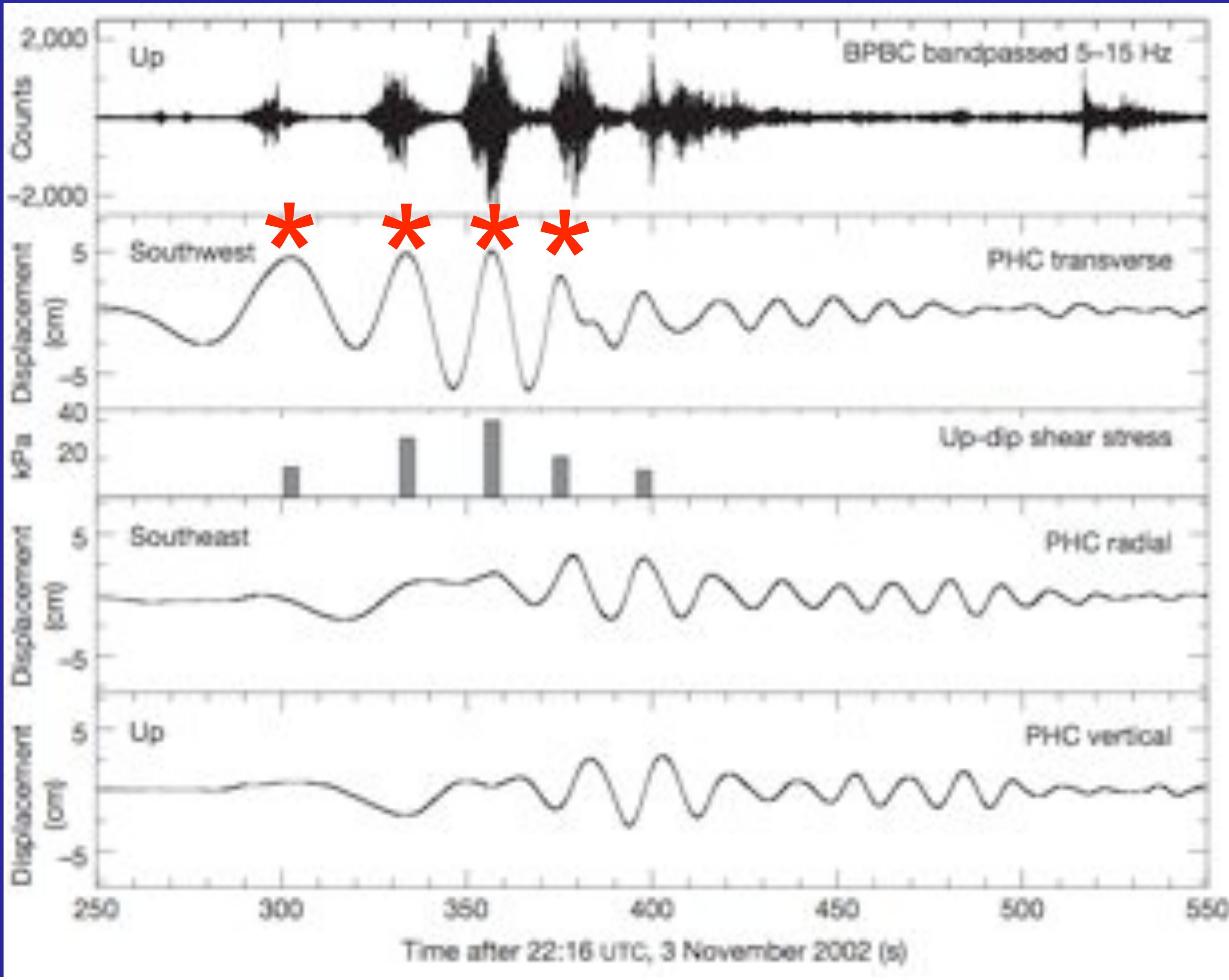
- Fault weakening by dynamic stresses
- Clock advance
- Initial stress matters



Seismic Strain

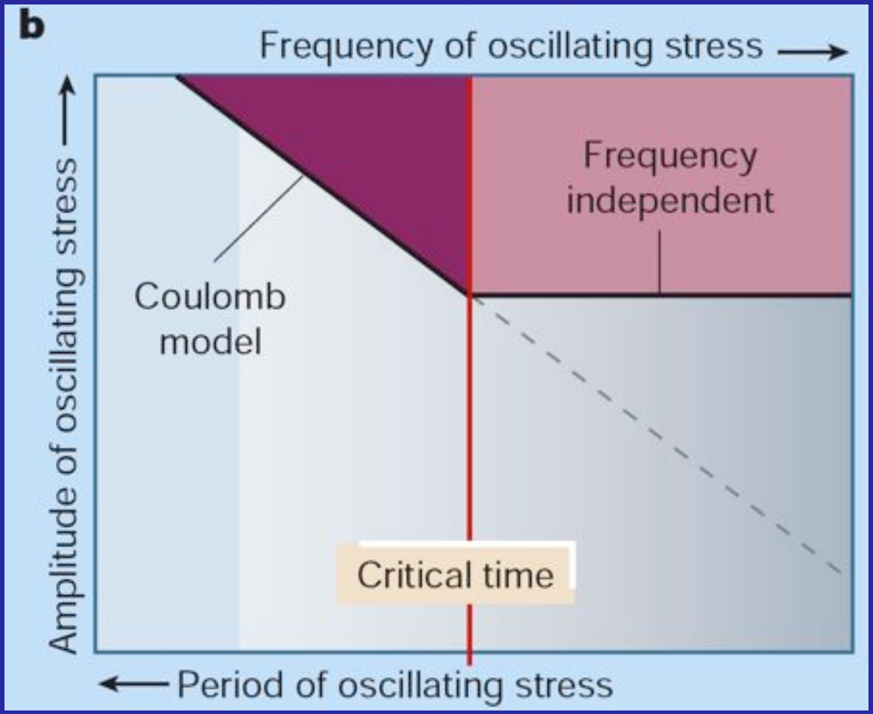
Tremor is modulated by Love wave shear stress, Denali

Rubinstein et al., 2007

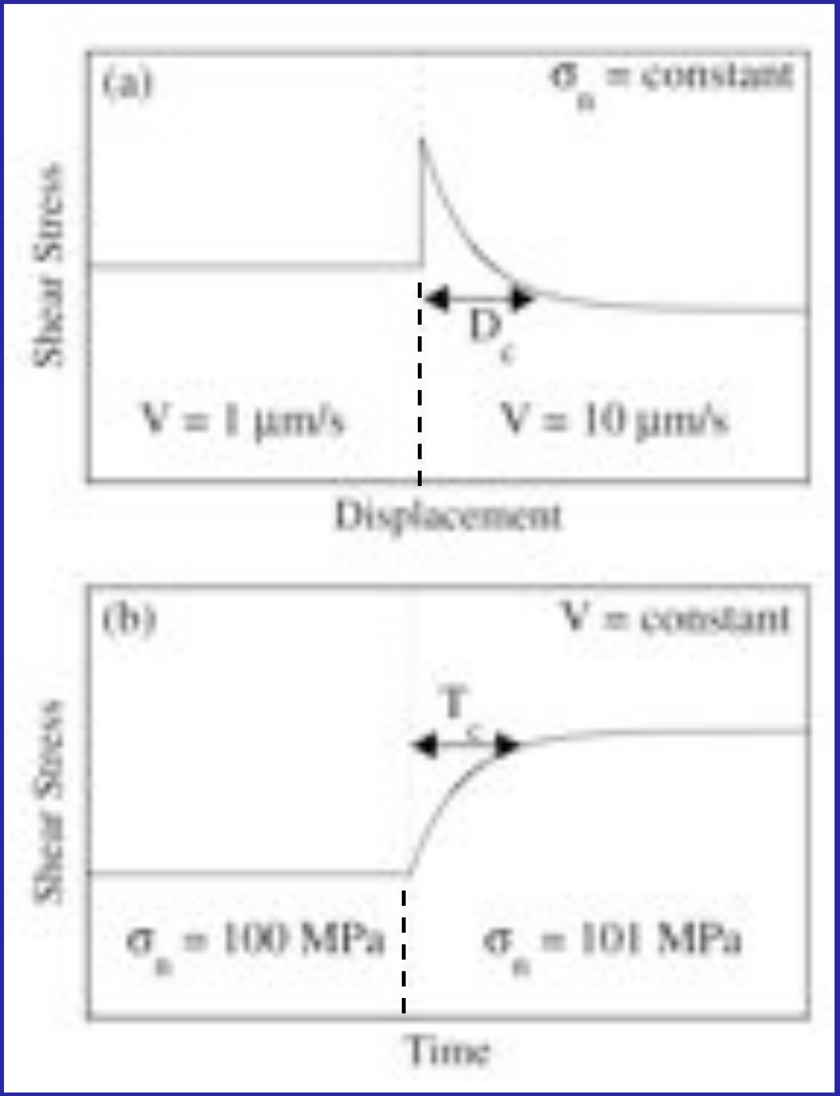


Delayed triggering is expected for rate-state friction

Friction change (e.g. weakening) requires finite slip & time

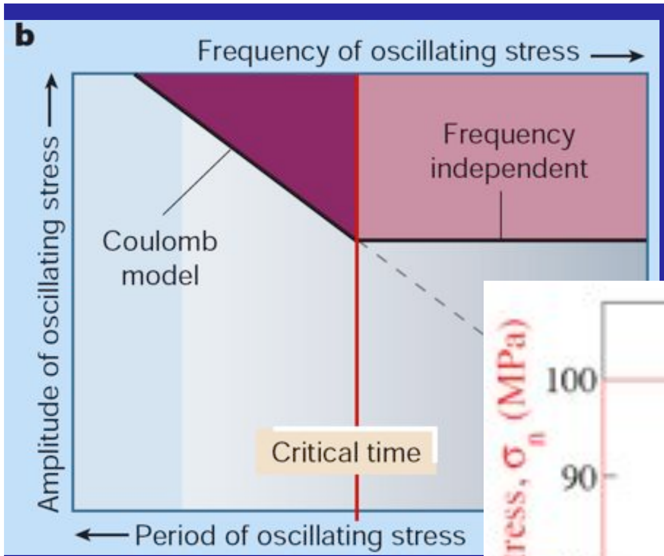


Scholz 2003



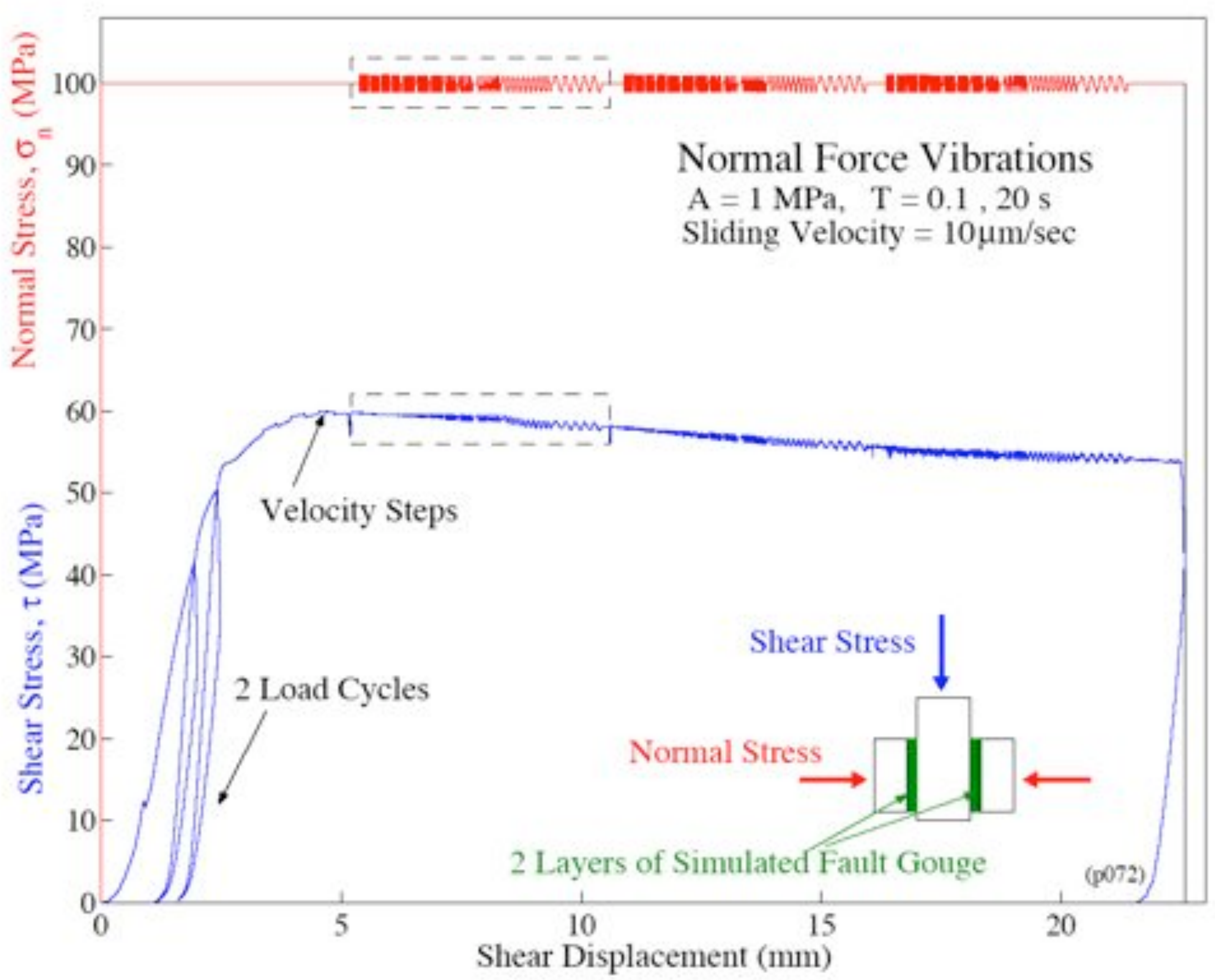
Boettcher & Marone, JGR, 2004

Lab: Normal Stress Vibrations
Critical period observed



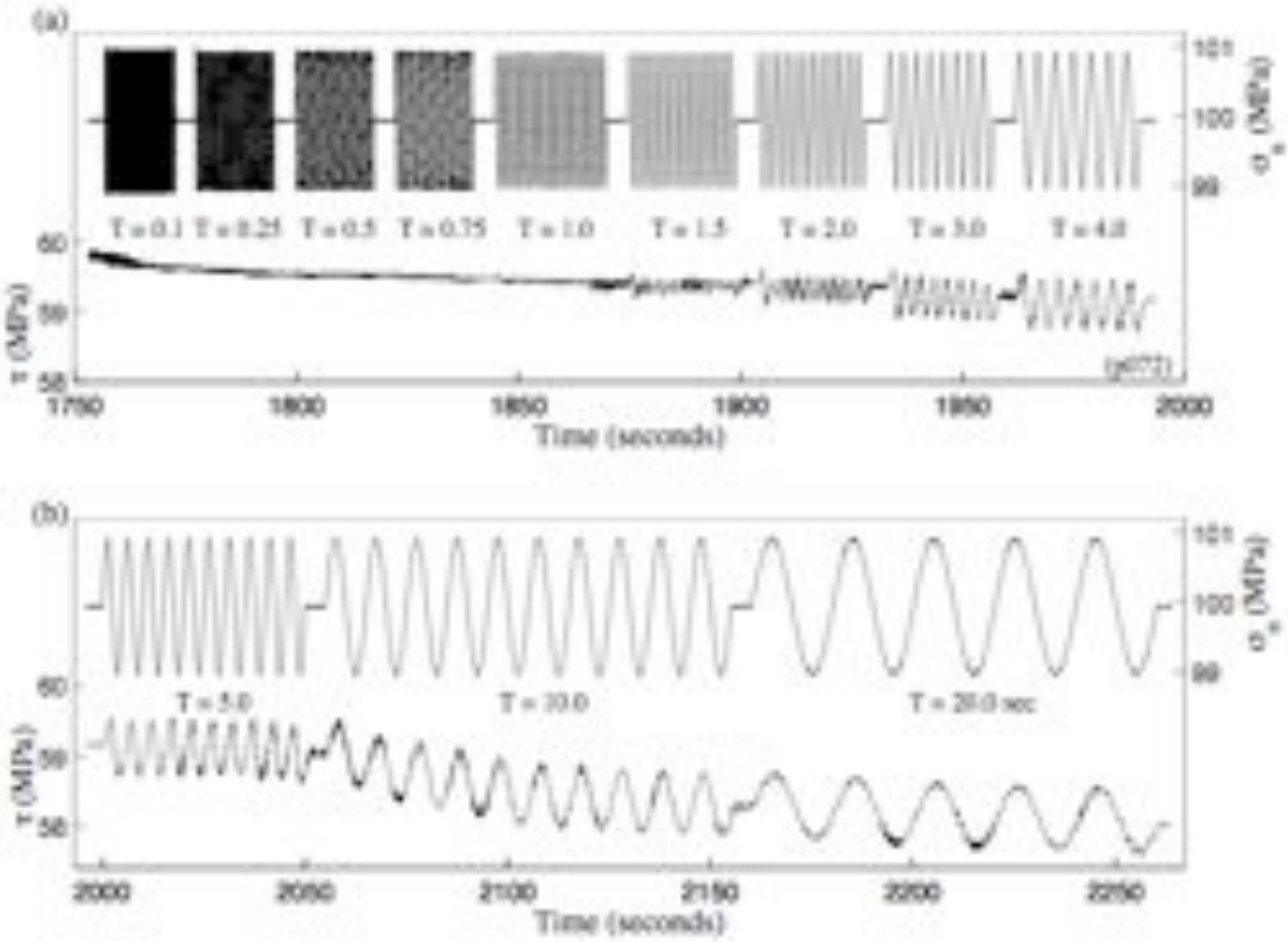
Scholz 2003

Boettcher & Marone, JGR, 2004



Effects of Normal Stress Vibrations on Creeping Faults

Boettcher & Marone, JGR, 2004

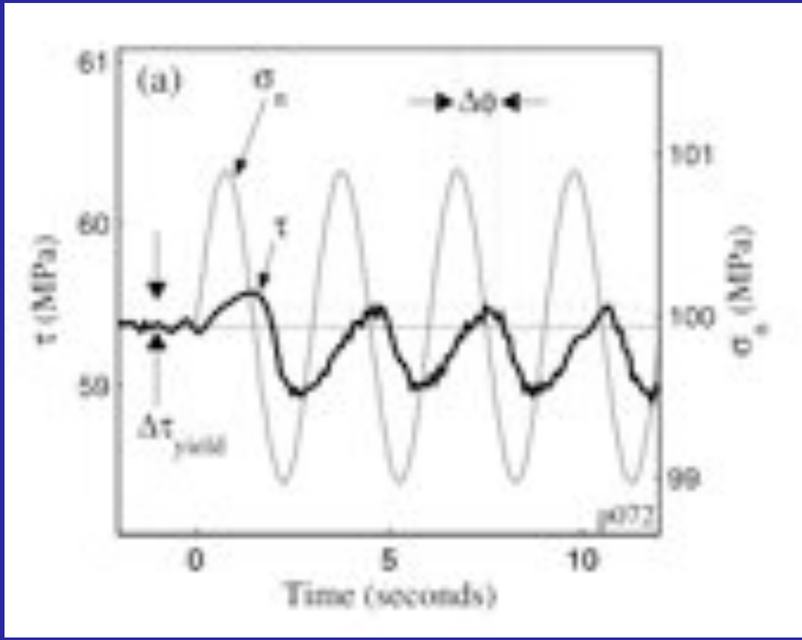


Critical period is 1 to 2 sec.

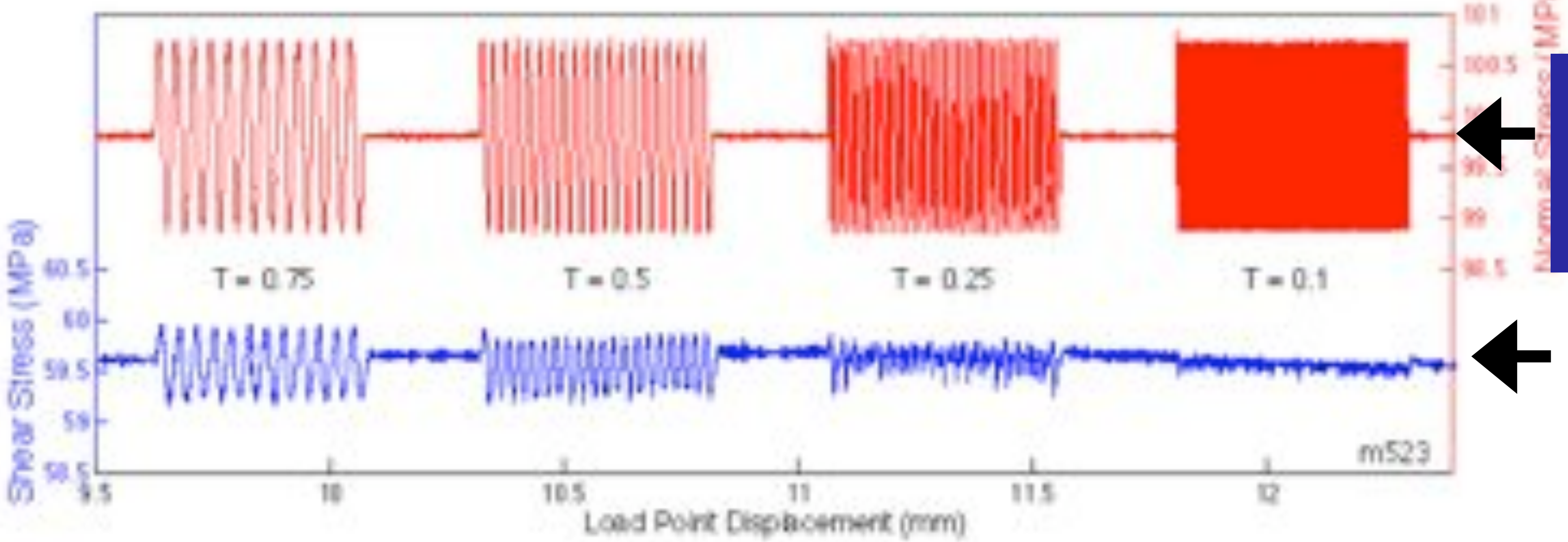
Also, Phase lag.
Friction response lags stressing.
Could explain delayed triggering

Boettcher & Marone, JGR, 2004

Phase lag



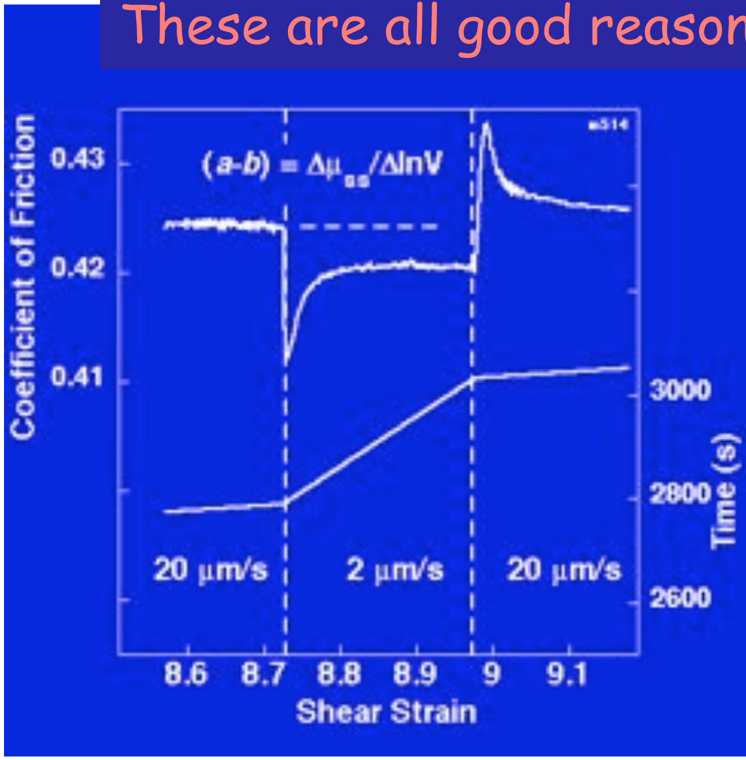
No frictional response to high freqency oscillations

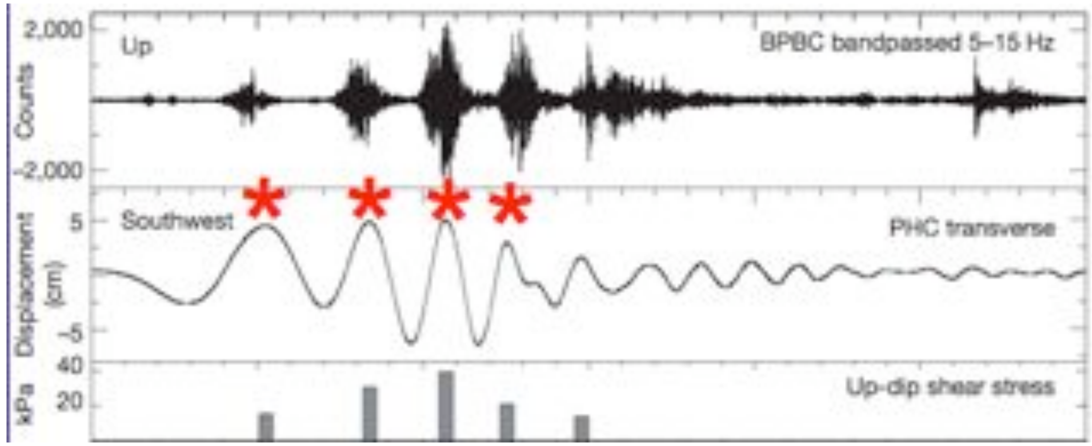


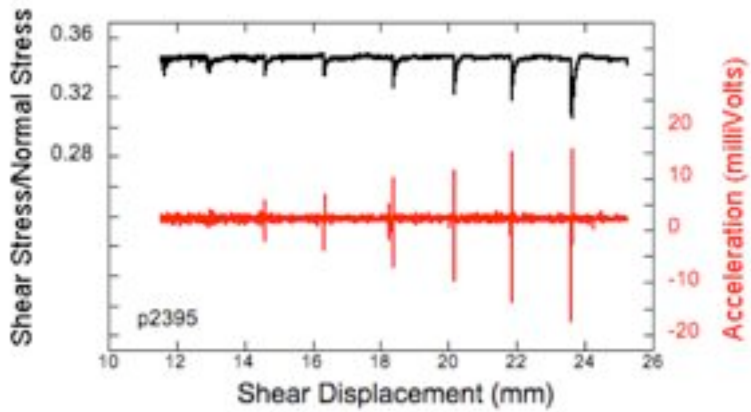
Normal Stress Oscillation

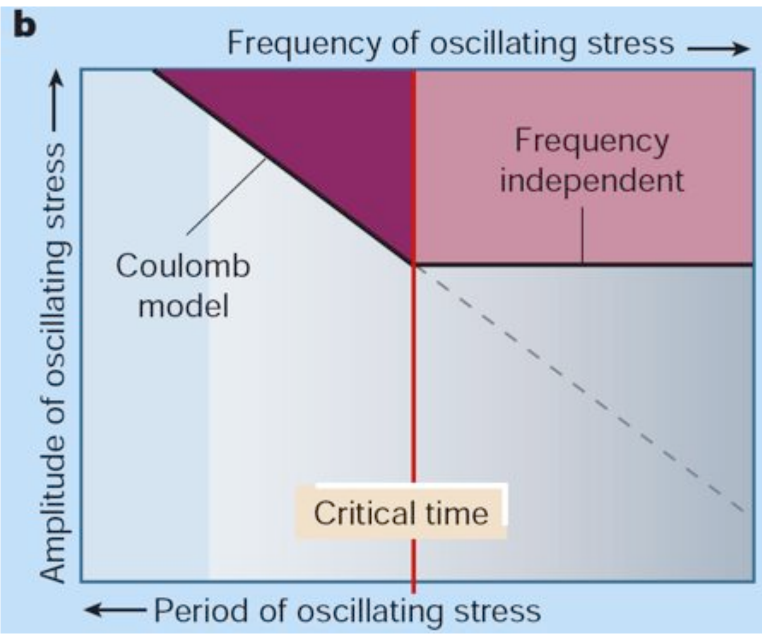
Frictional strength

These are all good reasons to bother with Rate and State Friction









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

$$\frac{d\theta}{dt} = 1 - \frac{v\theta}{D_c}$$ Dieterich State Evolution

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

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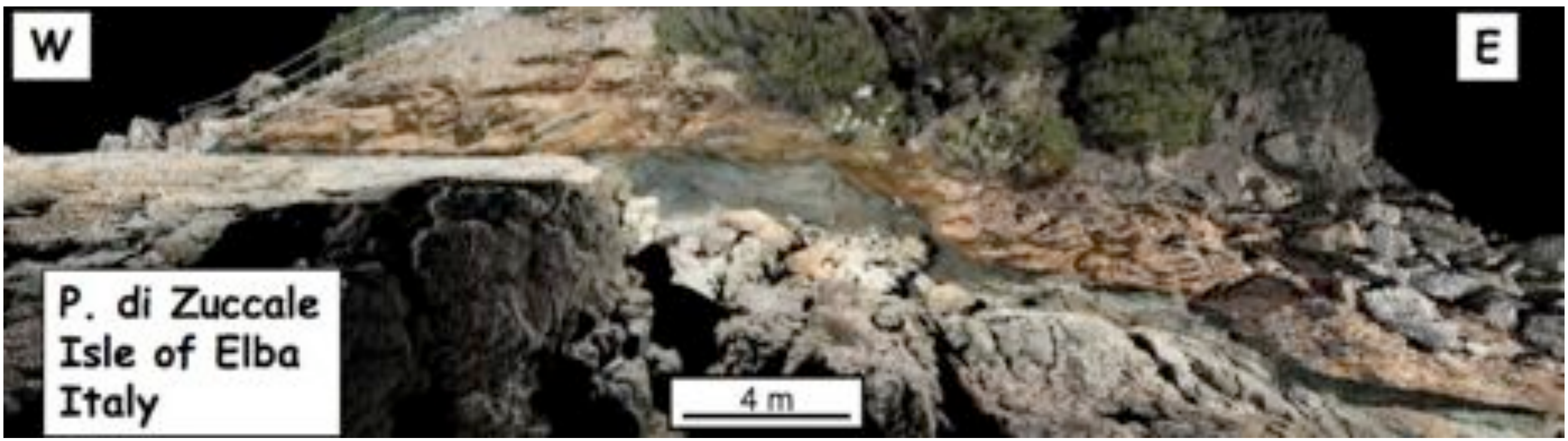
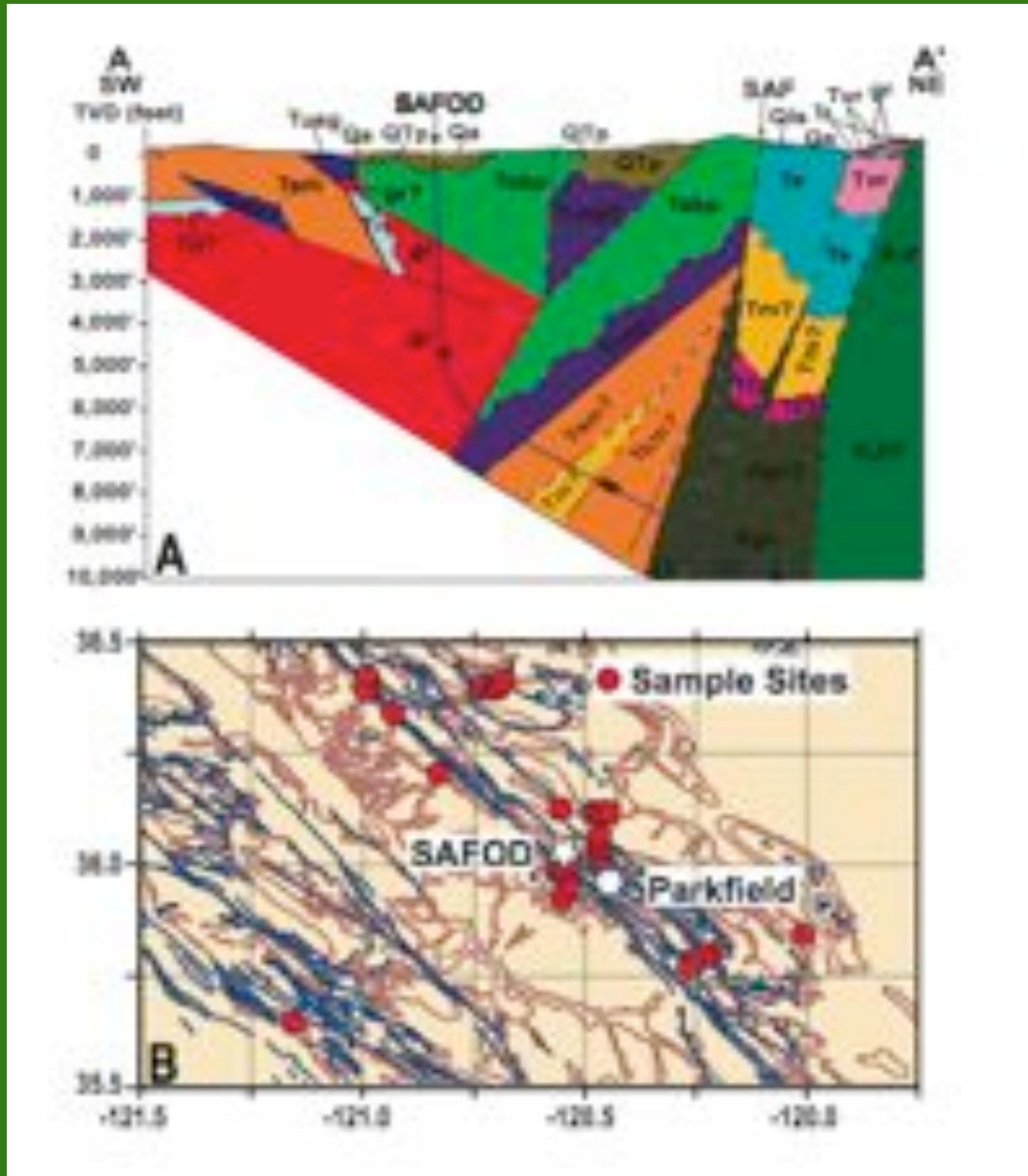


C. Collettini

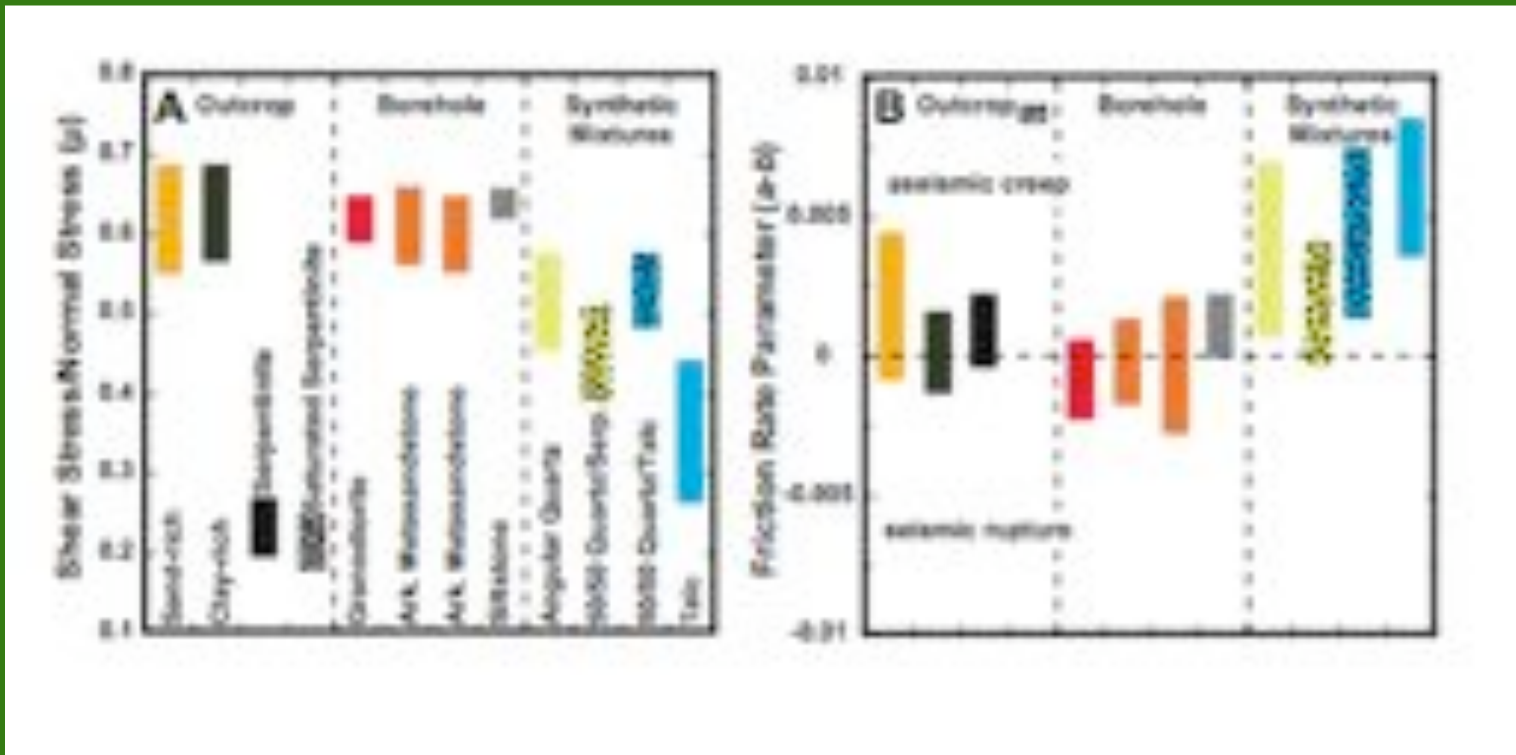
SAFOD and surrounding rock

Phase I & II drilling, surface samples



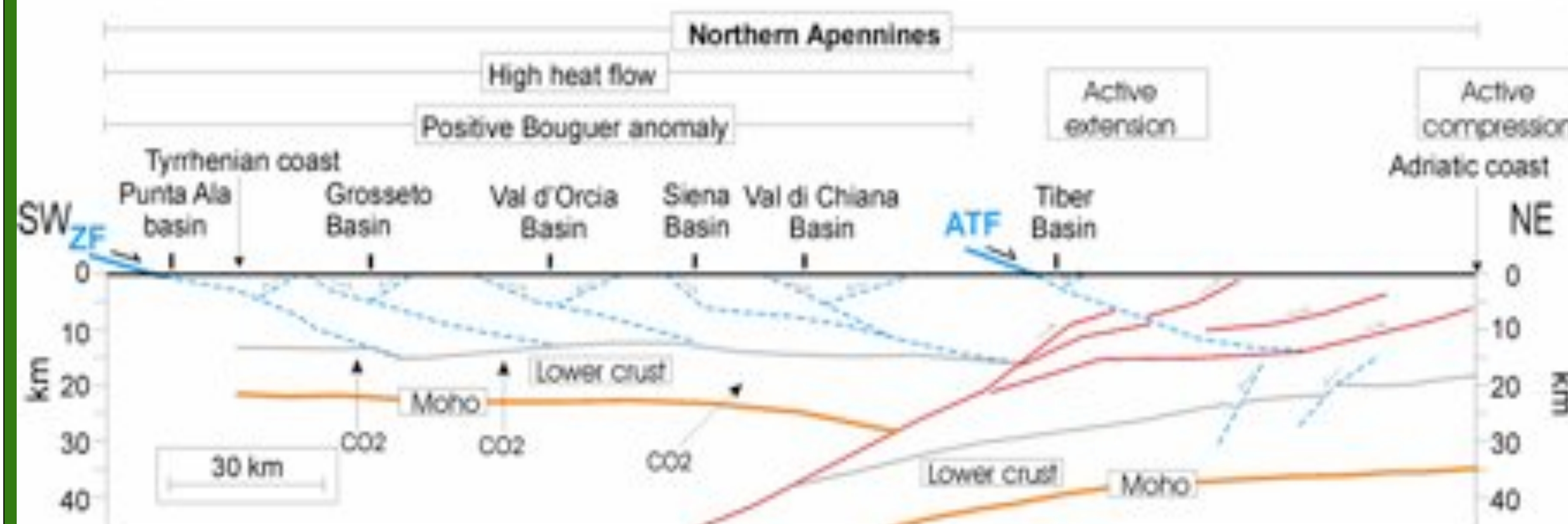
Carpenter, Marone, and Saffer, GRL, 2009

SAFOD and surrounding rock



Carpenter, Marone, and Saffer, GRL, 2009

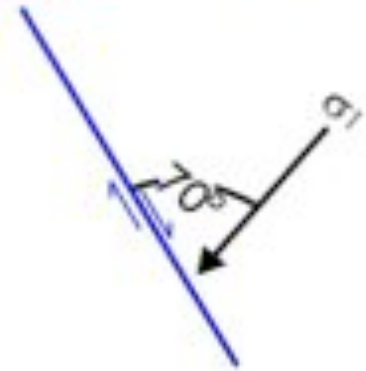
Zuccale Fault is part of a system of low angle normal faults in central Italy



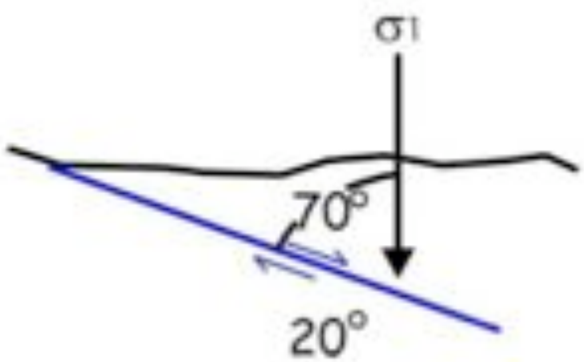
C. Collettini

Weak fault: a fault that moves under low-resolved differential stress (σ_1-σ_3) i.e. a fault at high angle from σ_1 direction.

Map view: weak San Andreas fault



Section view: Low Angle Normal Faults



Collecting Samples from the Zuccale Fault, Isle of Elba

Tino Marone & Claudio Collettini

~~Cutting~~ Sculpting Samples for friction tests, in-situ shear geometry

	L2	L3
calcite	43%	39%
tremolite	36%	26%
talc	6%	15%
smectite	15%	20%
phyllosilicates	21%	35%

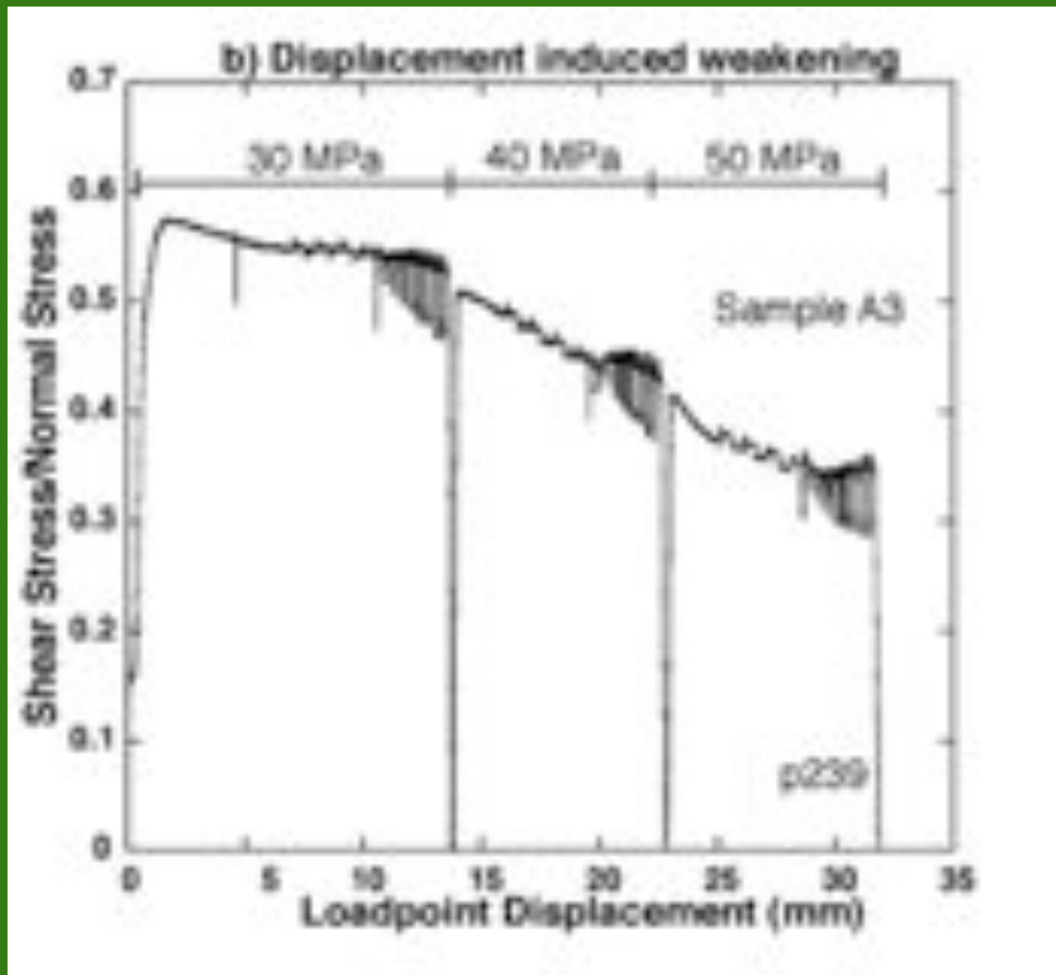
Differential thermal analysis coupled with mass spectrometer;

XRPD on bulk starting sample;

XRPD on the fine fraction (< 2 μm).

Fault zone fabric and fault weakness, *Submitted to Nature*

C. Collettini, A. Niemeijer, C. Viti and C. Marone



Numelin, T., Marone, C. and E. Kirby, Frictional properties of natural fault gouge from a low-angle normal fault, Panamint Valley, CA, *Tectonics*, 2007

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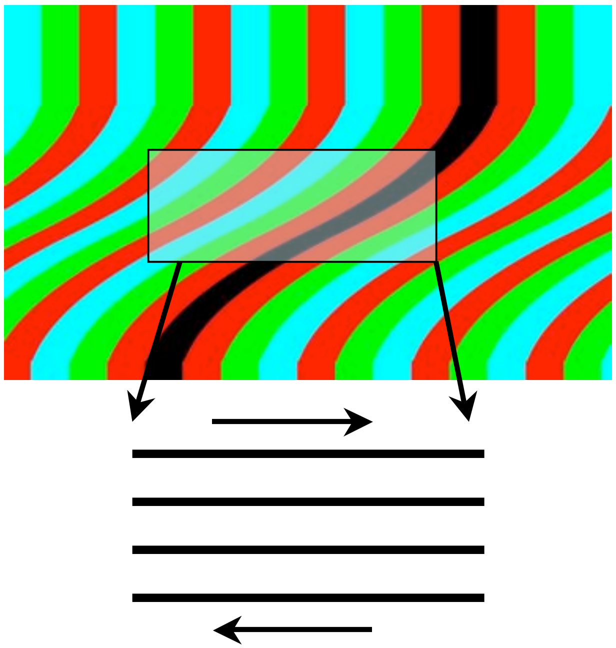
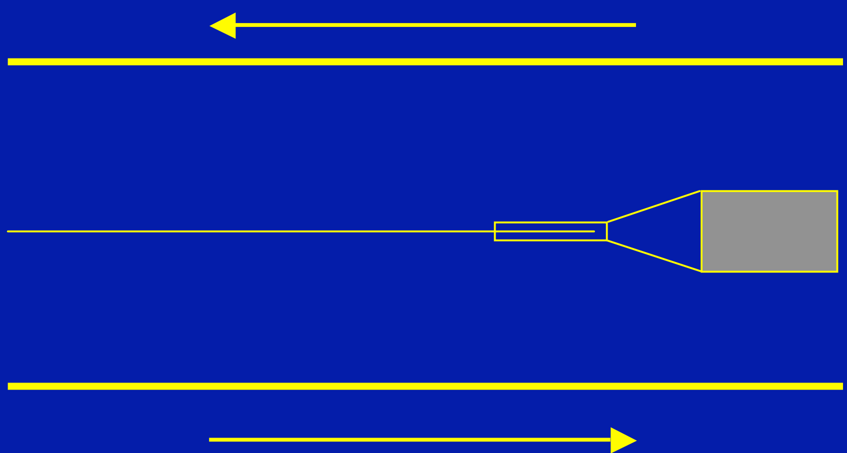


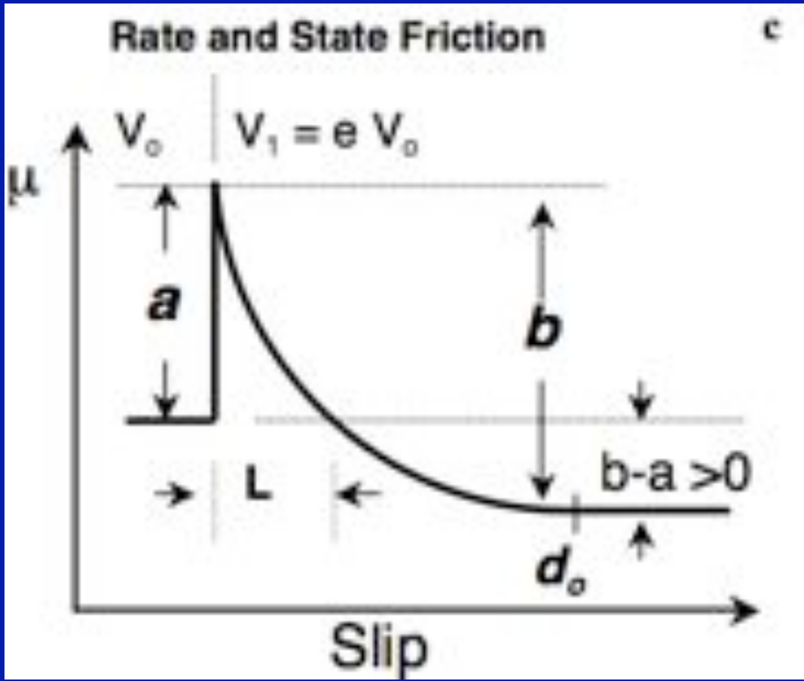
3. Fault zones of finite width
   Modeling, implications of rate/state properties

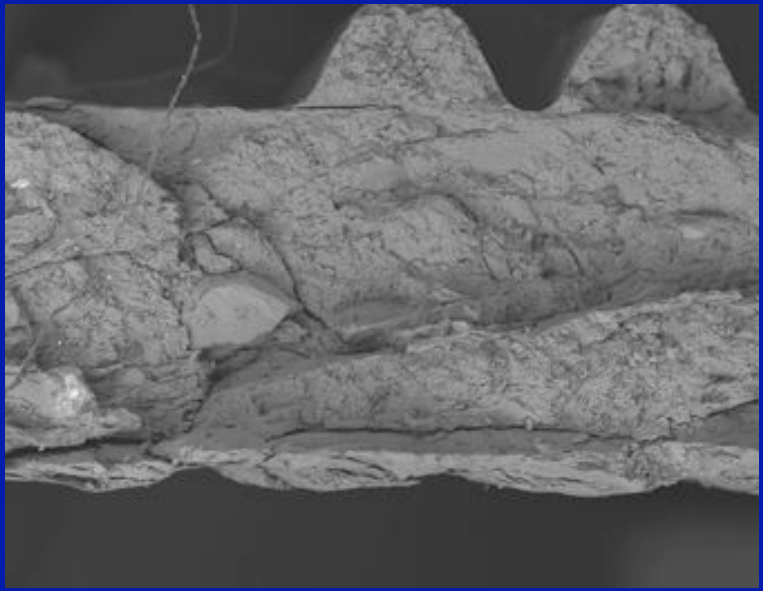
Model of frictional weakening and shear localization

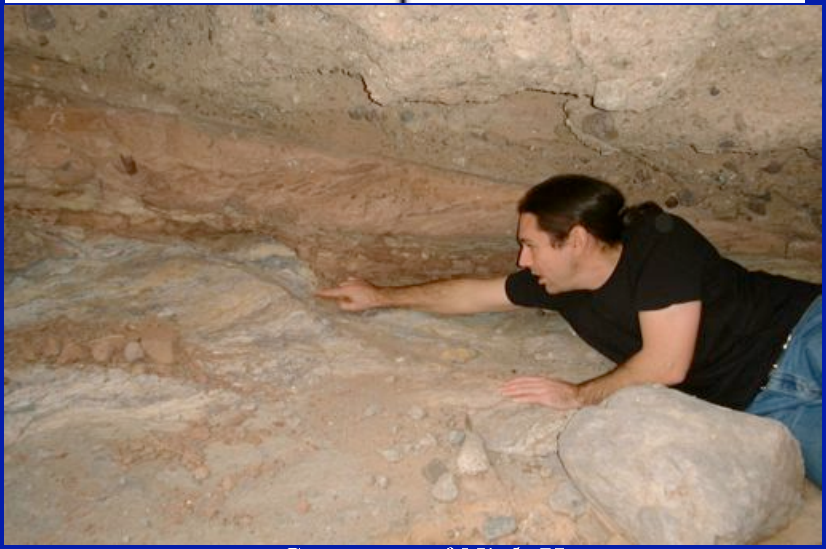
- **Fault zone of finite width;** multiple, sub-parallel slip surfaces
- **Surfaces obey rate and state friction**
- **Effective critical slip distance**
- **Effective fracture energy (seismological breakdown work)**

Marone, Cocco, Richardson, & Tinti, The critical slip distance for seismic and aseismic fault zones of finite width, International Geophysics Series, 2009.







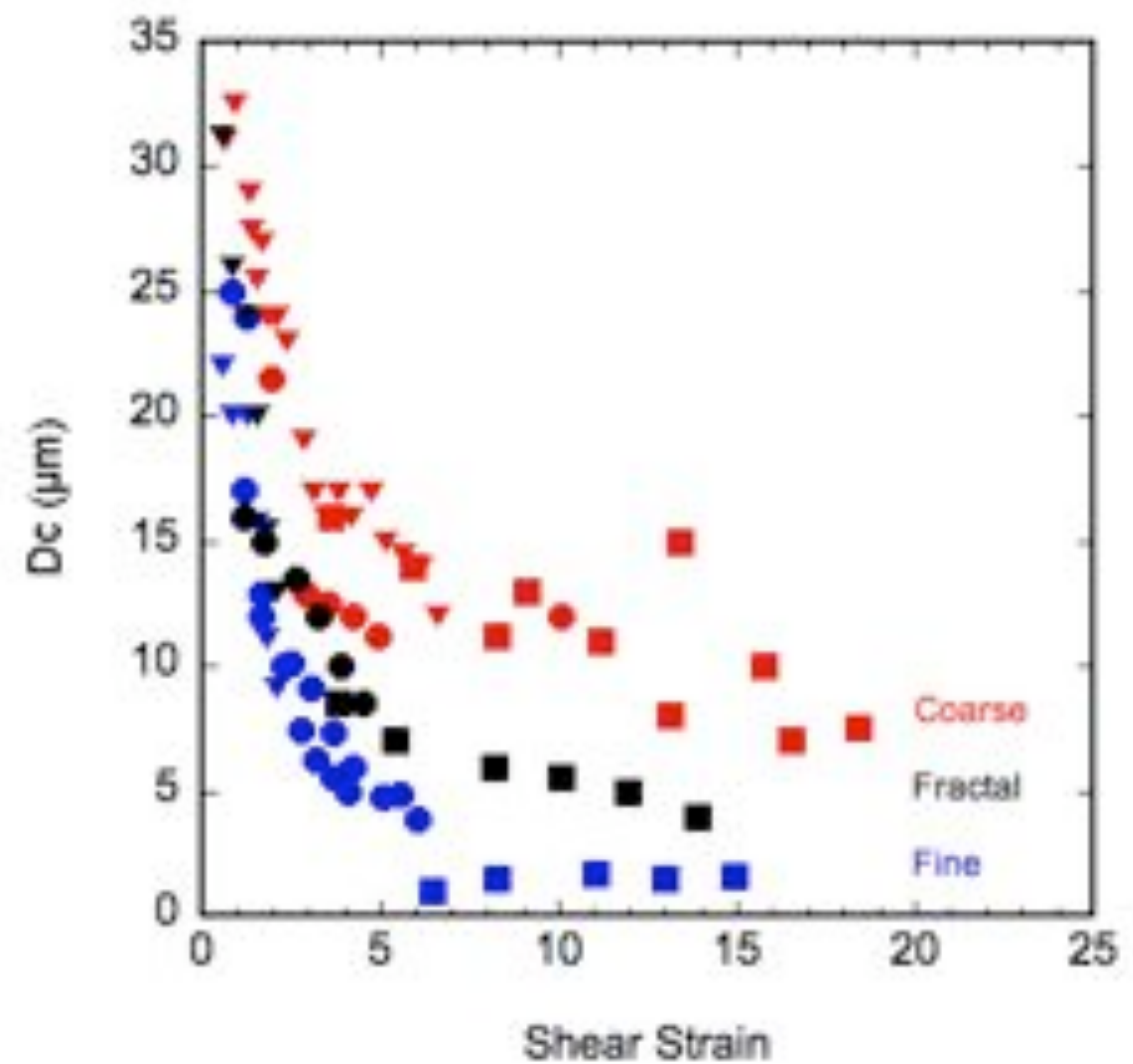


Courtesy of Nick Hayman

Rate/State Friction

- Variations in behavior as a function of shear localization

Granular Quartz



Critical slip distance scales with:

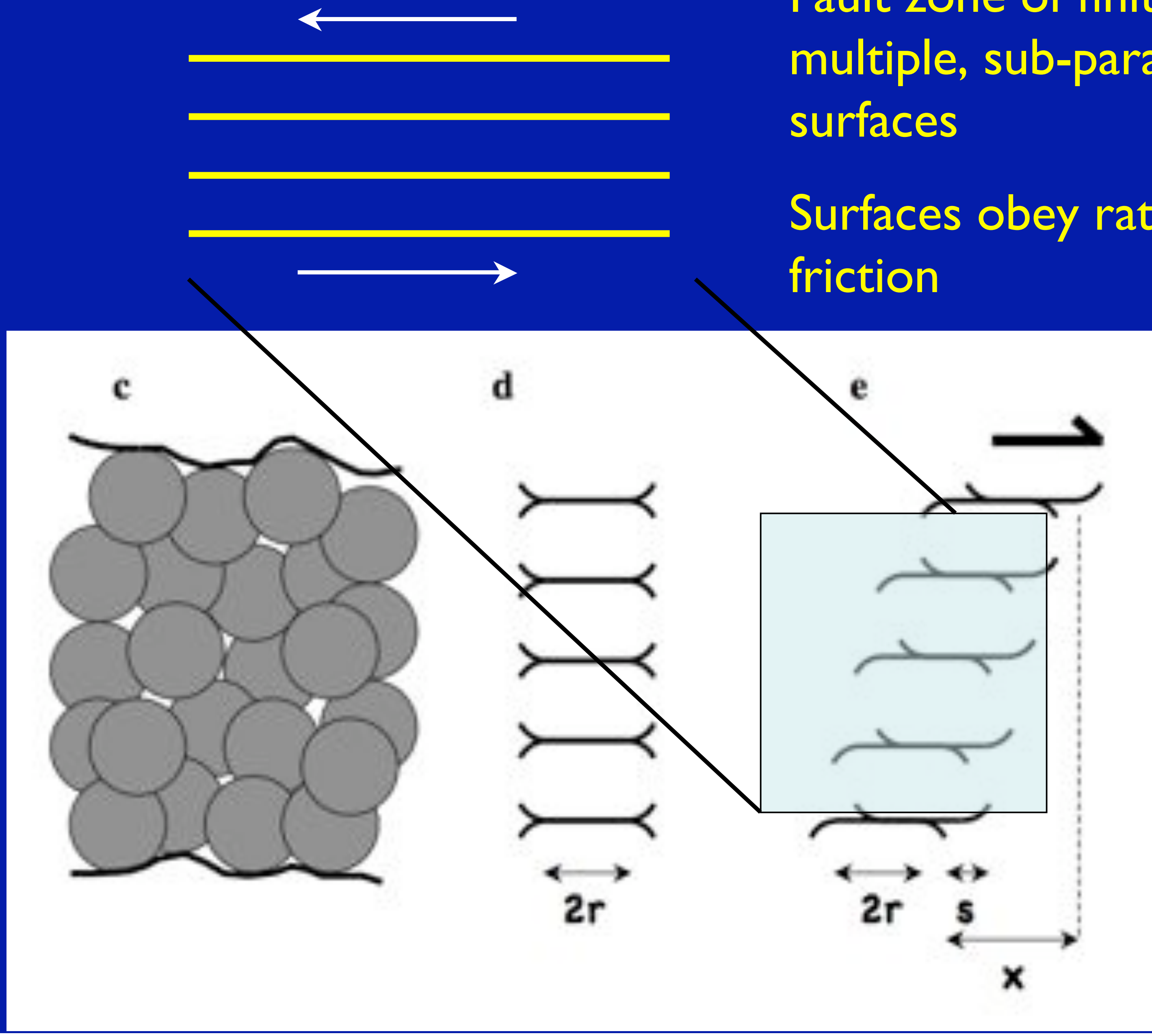
- particle size
- shear zone width

Marone & Kilgore, 1993

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

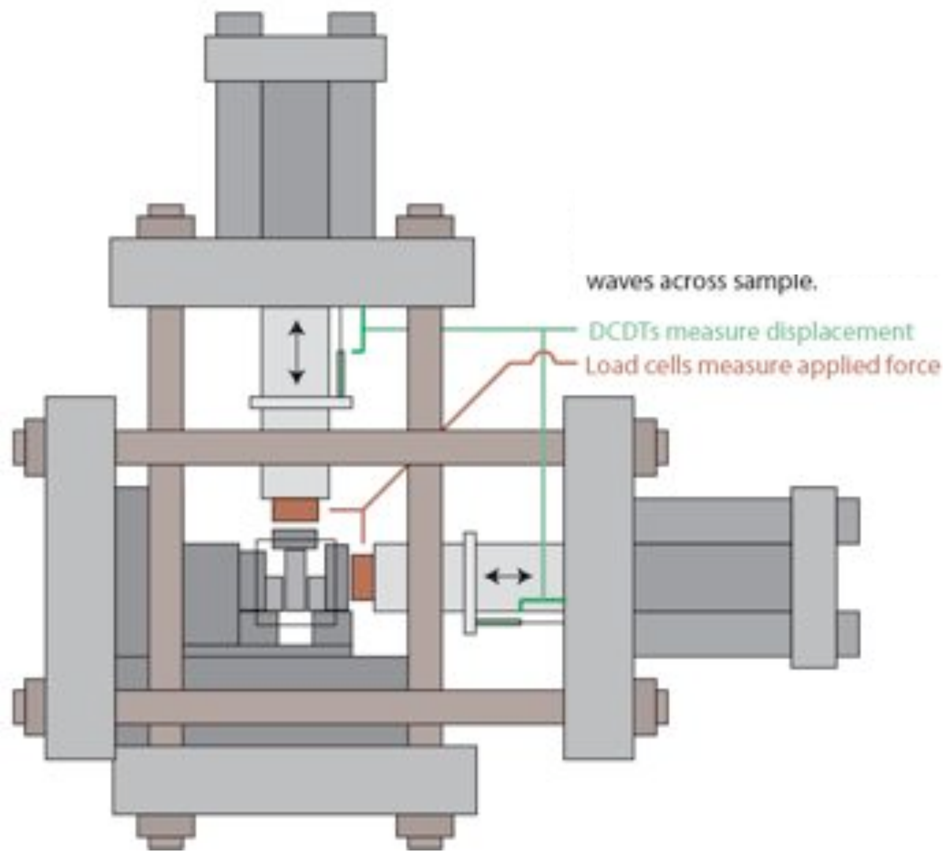


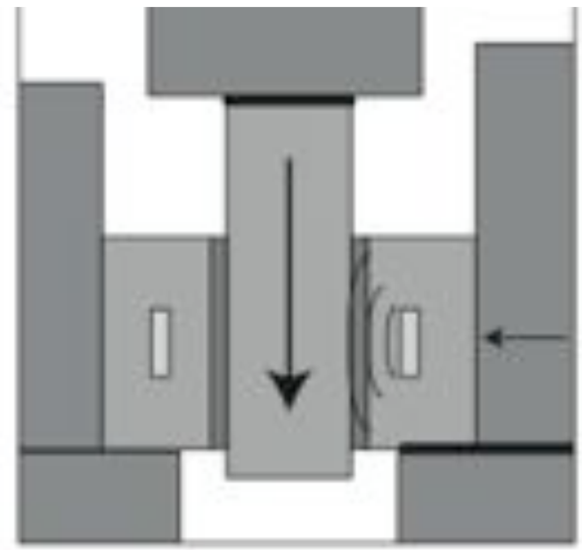
Ultrasonic Velocity of a Sheared Fault:

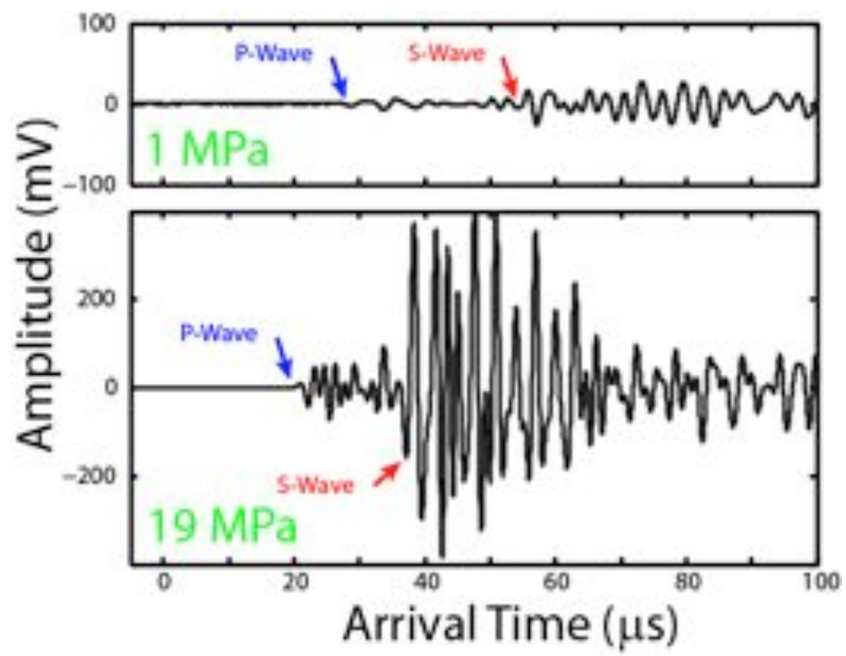
Initial Measurements from Sites IODP/Nankai C0001 and C0002.

Velocity reflects the evolution of dynamic elastic moduli during both compaction and shear deformation.

Double-direct shear configuration



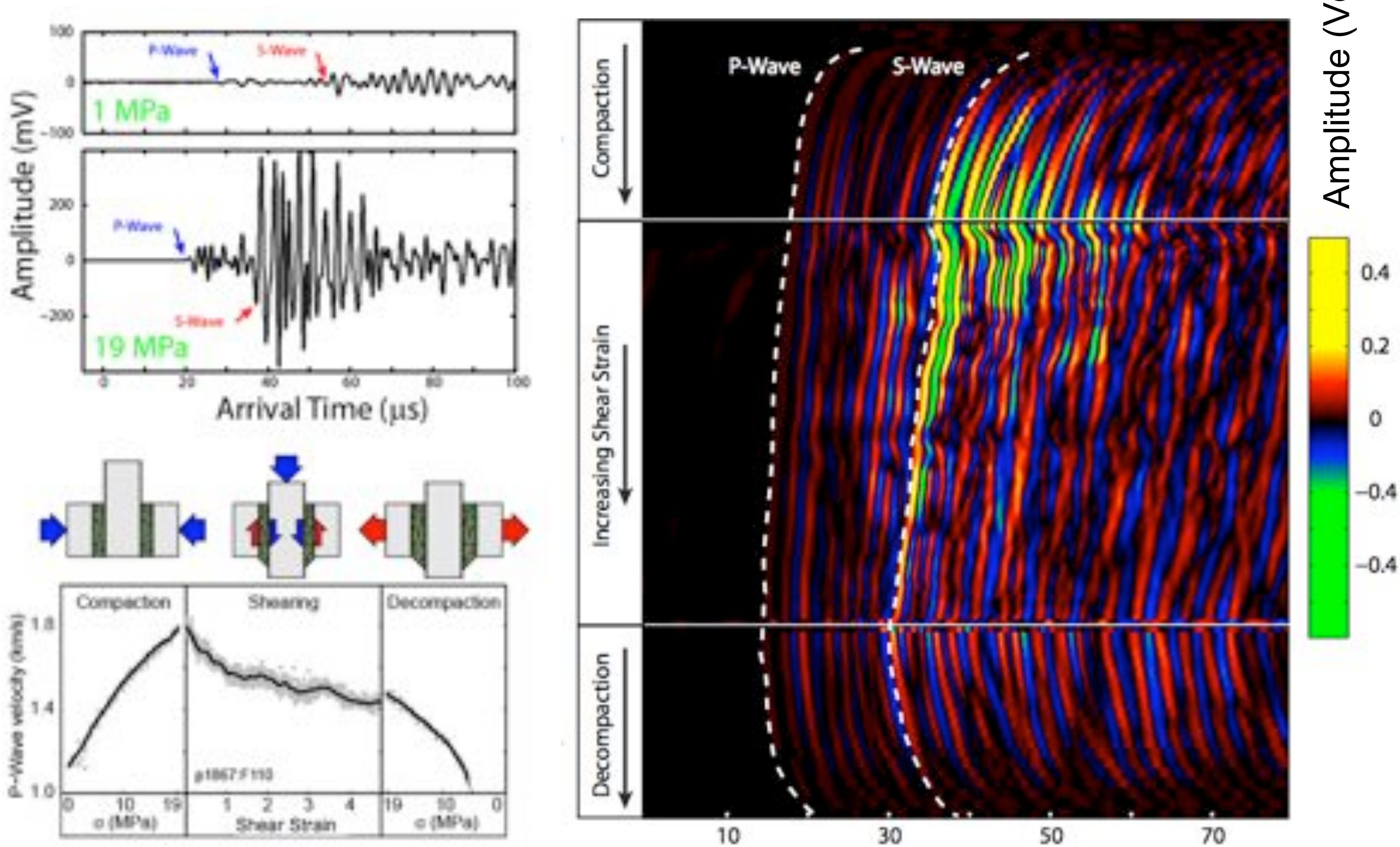




Knuth, Tobin, Saffer & Marone 2009

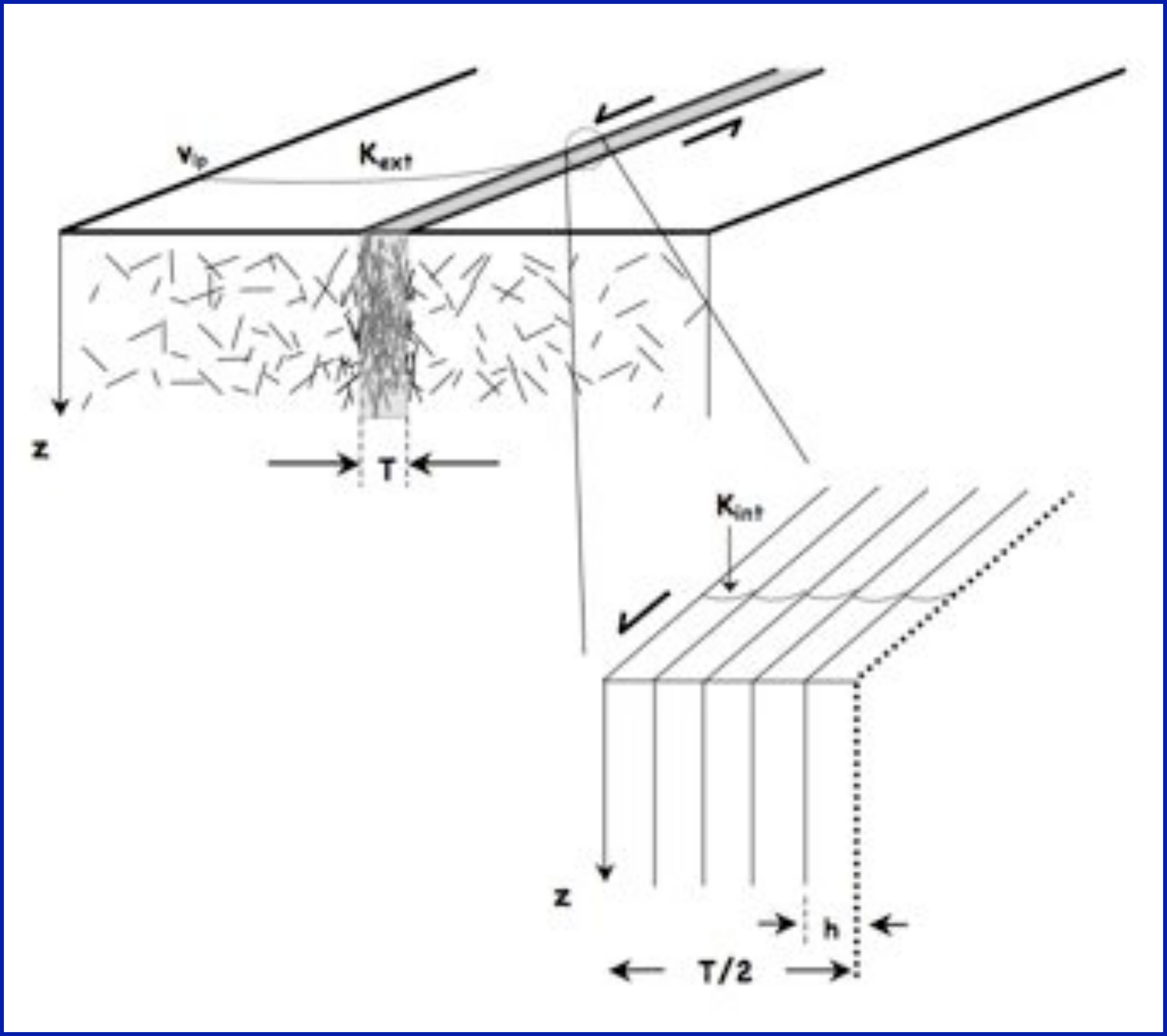
Ultrasonic Velocity of a Sheared Fault:

Initial Measurements from Sites IODP/Nankai C0001 and C0002.



Knuth, Tobin, Saffer & Marone 2009

Frictional response of a shear zone of finite width

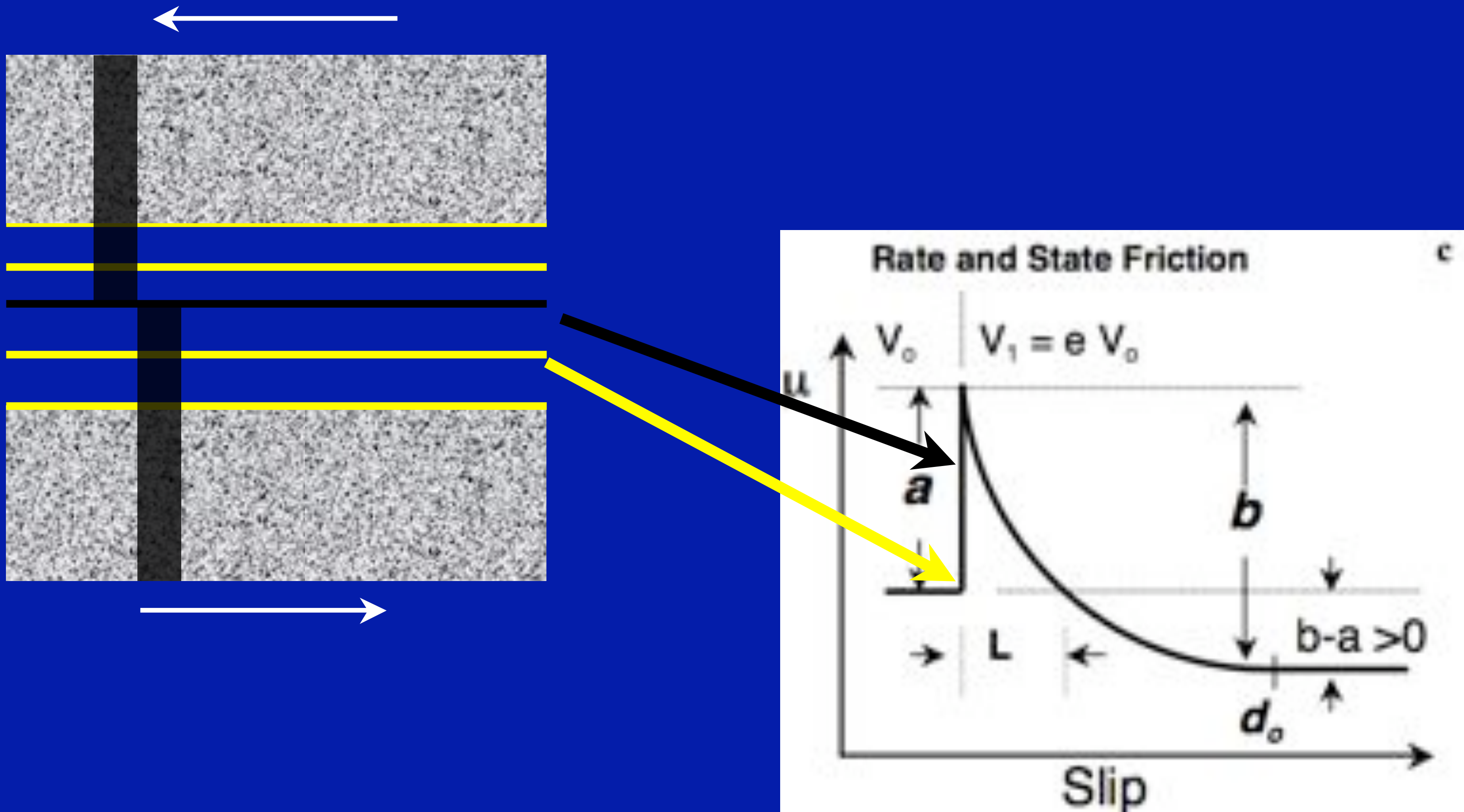


Fault zone of finite width;
multiple, sub-parallel slip surfaces

Surfaces obey rate and state friction

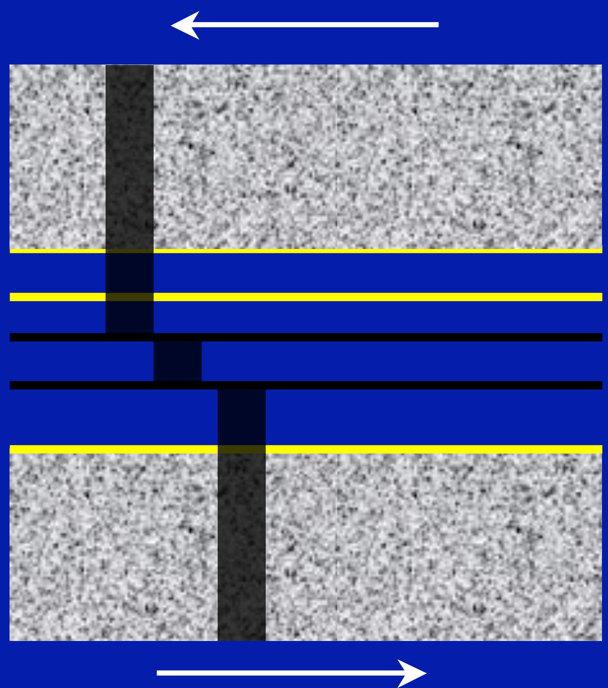
Rate and State Friction:

- Positive direct effect means that any surface that slips more than another surface will be the stronger of the two



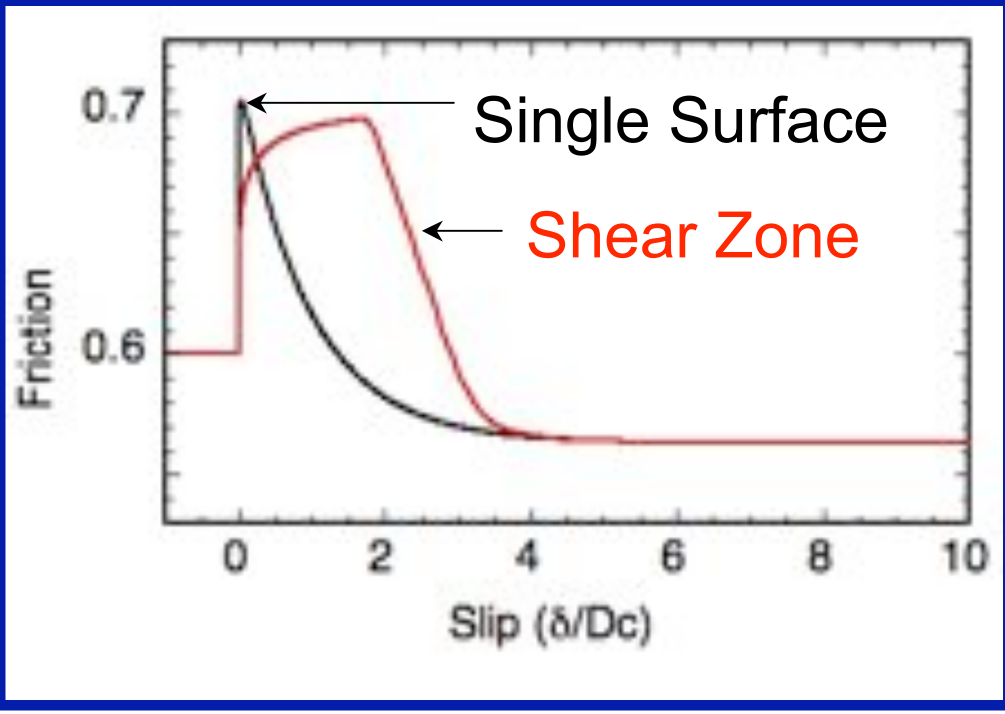
Fault zone of finite width;
multiple, sub-parallel slip surfaces

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

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

$$\frac{d\theta_i}{dt} = 1 - \frac{v_i\theta_i}{L}$$

(Dieterich Law)

$$\frac{d\theta_i}{dt} = -\frac{v_i\theta_i}{L} ln\left(\frac{v_i\theta_i}{L}\right)$$

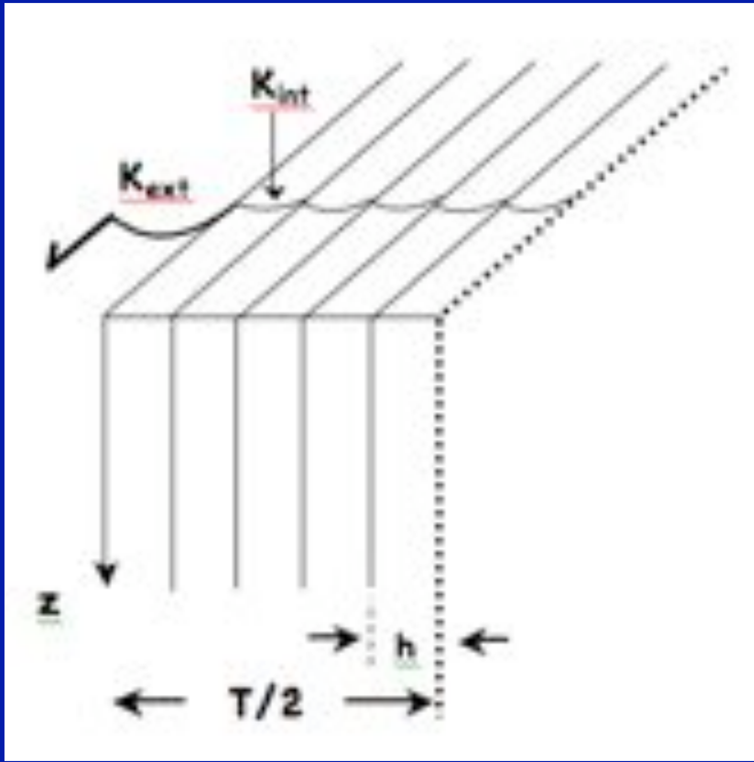
(Ruina Law)

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

Elastic Coupling

$$\mu_i = \frac{\tau_o}{\sigma_n} - \frac{G}{2\beta\sigma_n}(v_i - v_{pl}) + k\ (v_{pl}\, t - v_i\, t)$$

Radiation damping



Governing Equations

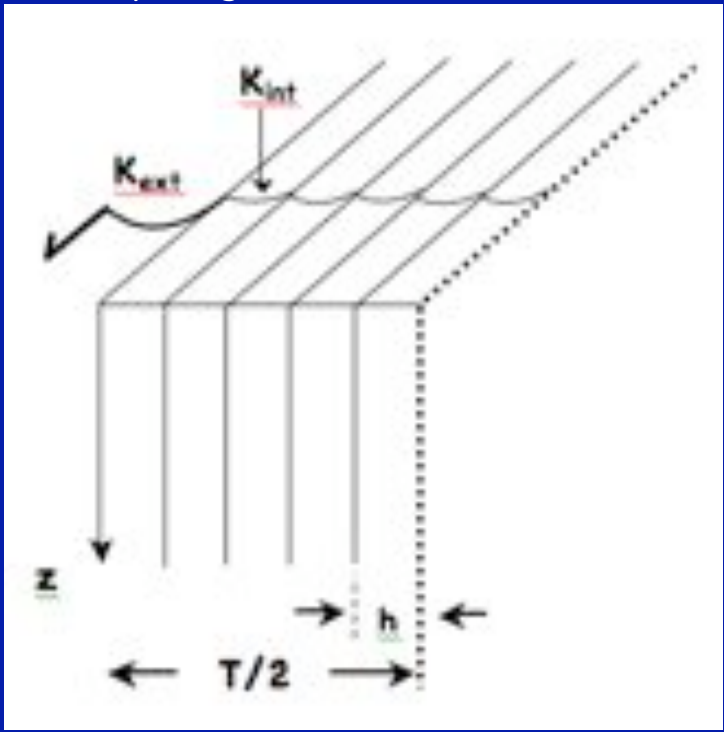
$$\frac{d\theta_i}{dt} = 1 - \frac{v_i\theta_i}{L}$$ (Dieterich Law)

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

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

$$\frac{1}{k_i} = \frac{1}{K_{ext}} + \sum_{j=1}^{i} \frac{1}{K_{\mathrm{int}_j}}$$

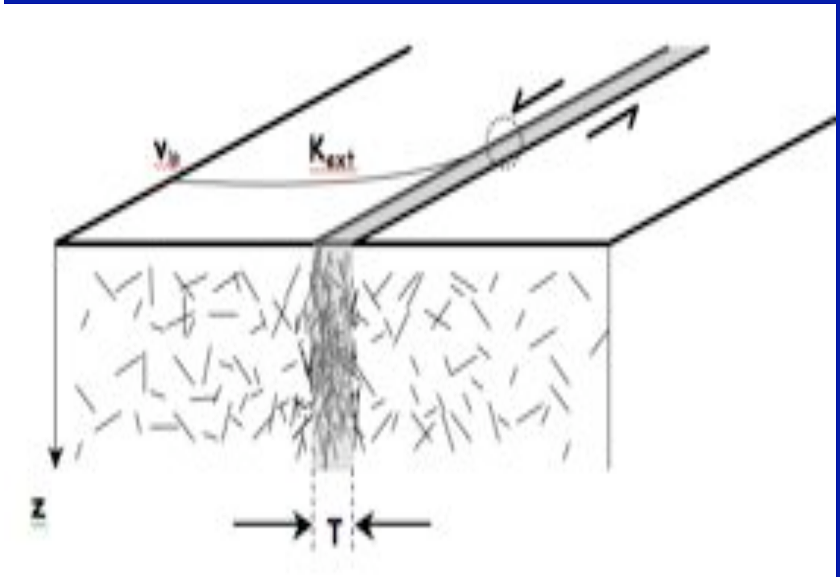
Elastic Coupling

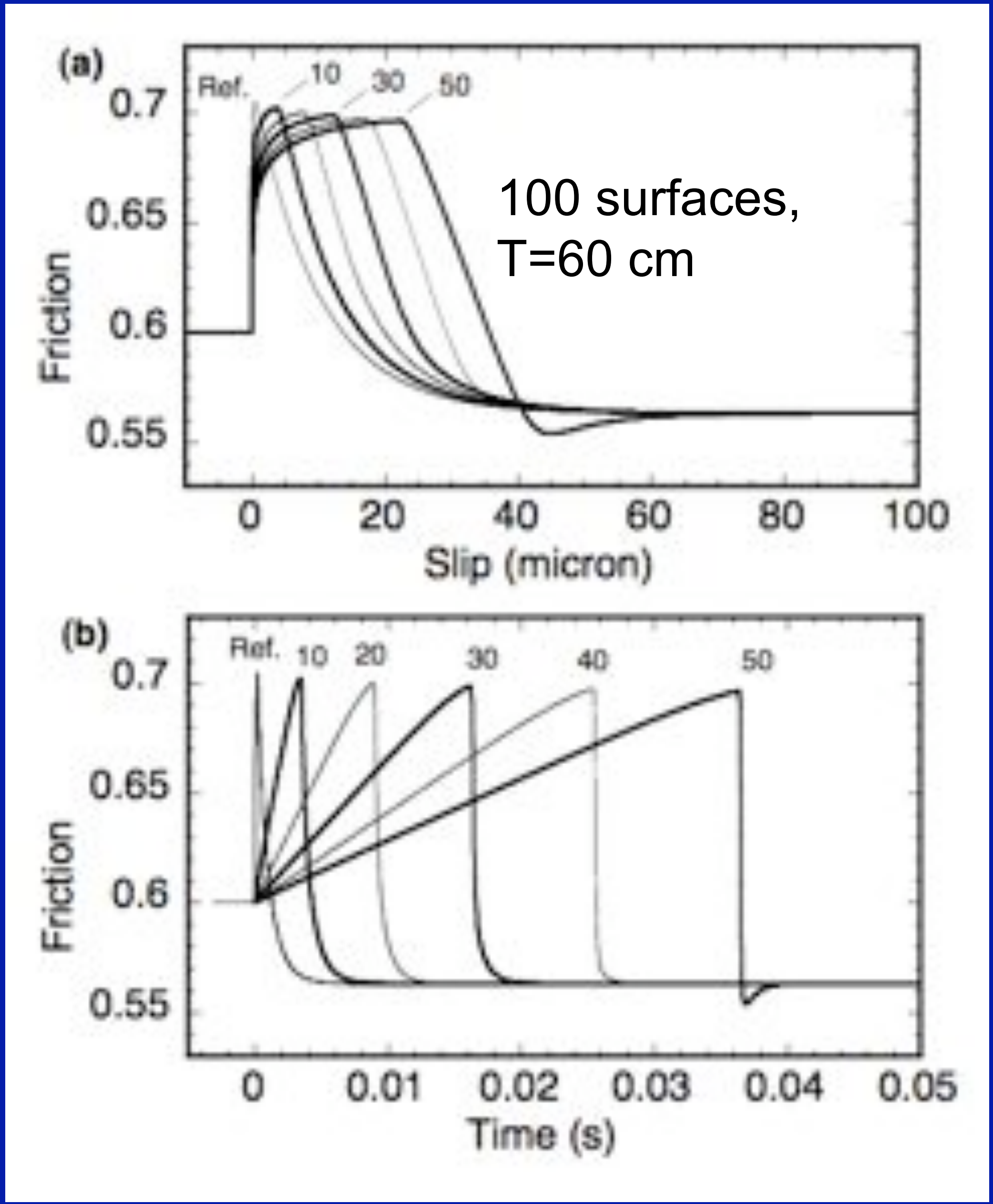


- Weakest surface slips
- Stresses are continuous
- Strength varies according to rate/state friction

- Parameters: a=0.012, b=0.016, L=10μm
  h=6 mm, G= 30 GPa, σ_n= 100 MPa,
  K_{ext}= G/h; K_{int}/K_{ext} =10;
  v_{ref}=1e-6 m/s, v_{pl} = 1 cm/s
  Fault zone width varies from 0 to 60 cm.

Frictional response of a shear zone of finite width





- **Parameters:**
  a=0.012, b=0.016, L=10μm
  h=6 mm, G= 30 GPa,
  σ_n= 100 MPa, *K_{ext}= G/h;*
  K_{int}/K_{ext} =10;
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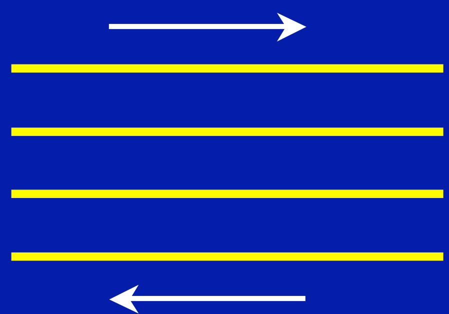
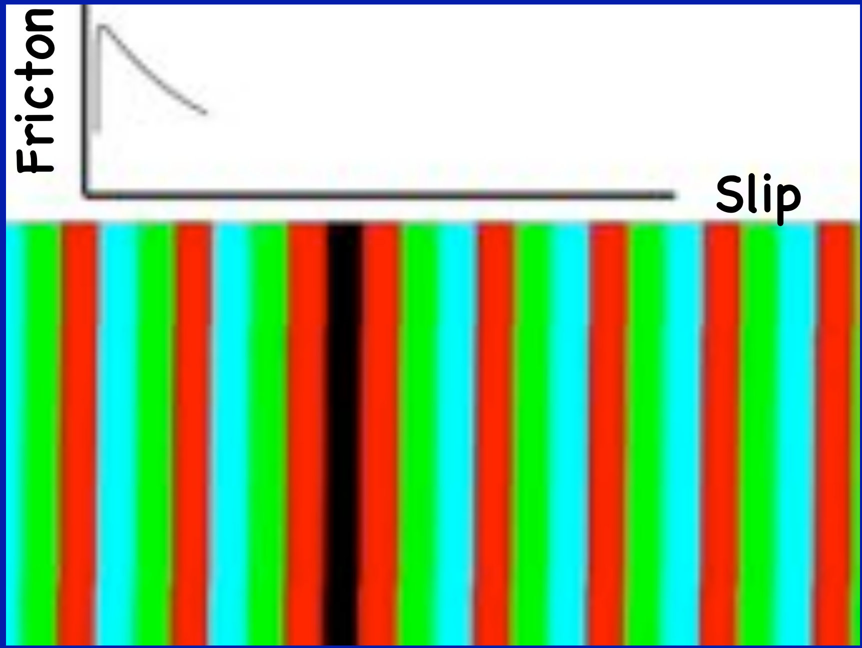
Frictional response of a shear zone of finite width





- **Parameters:**
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  h=6 mm, G= 30 GPa,
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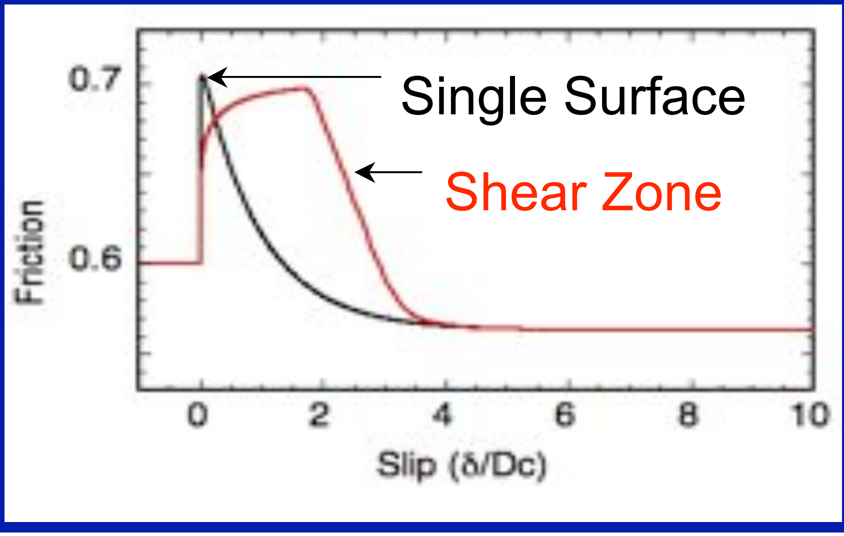
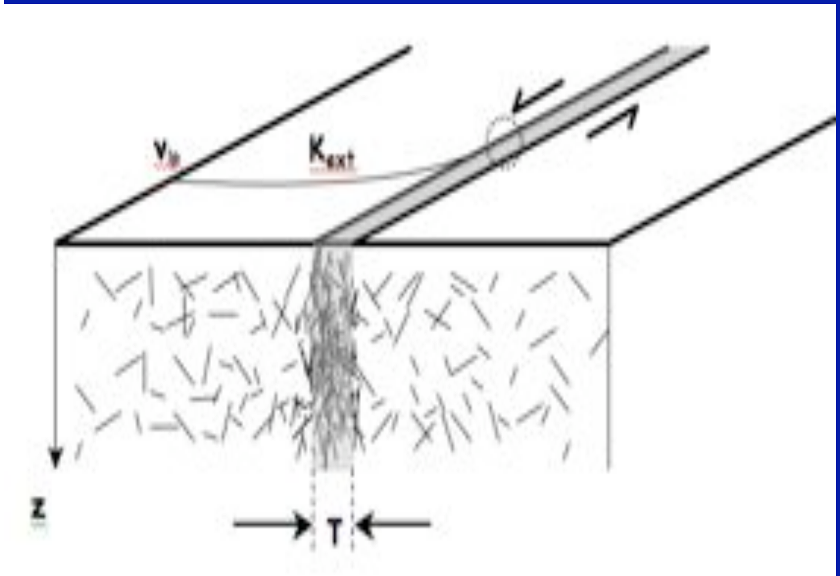
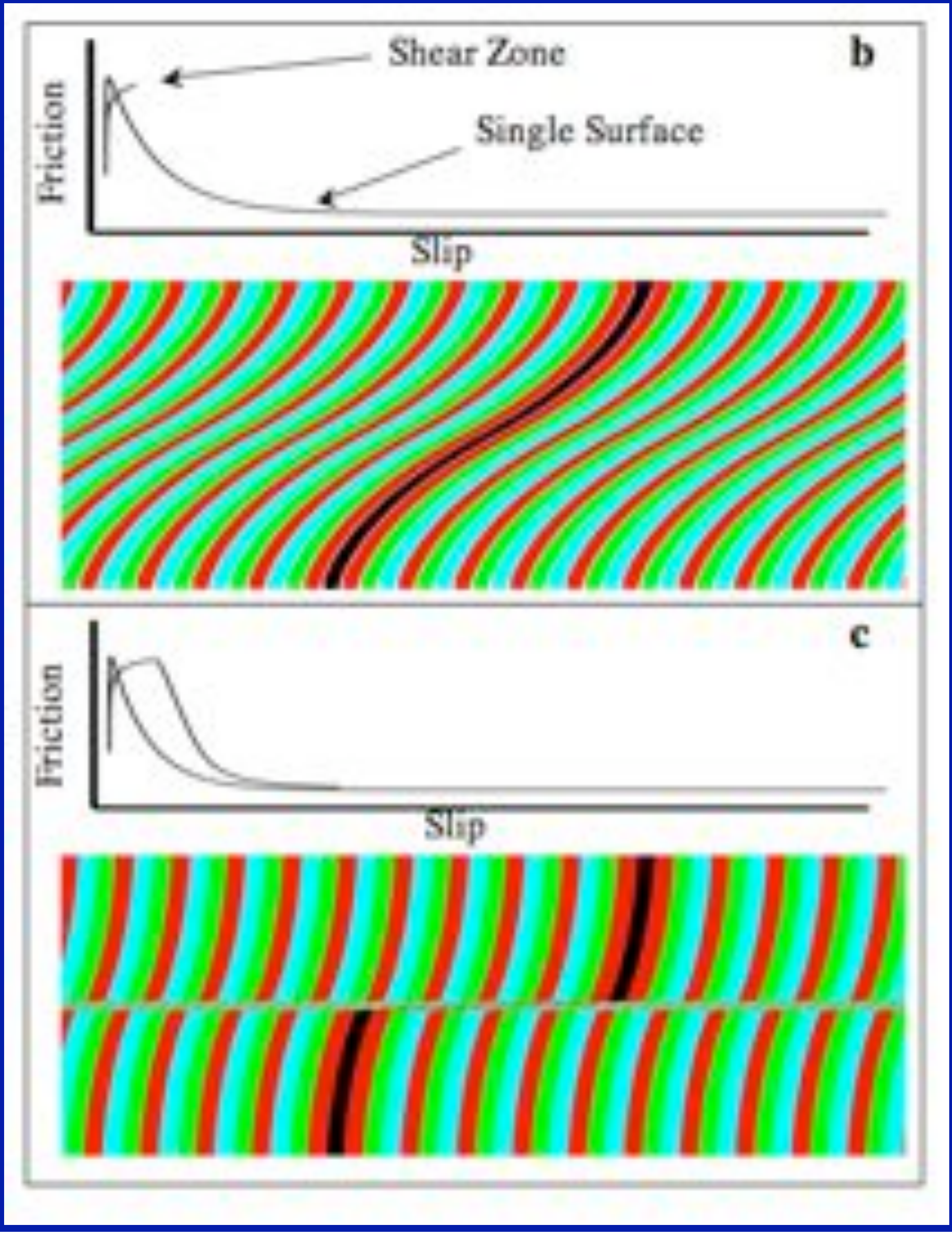


Frictional response of a shear zone of finite width





- **Parameters:**
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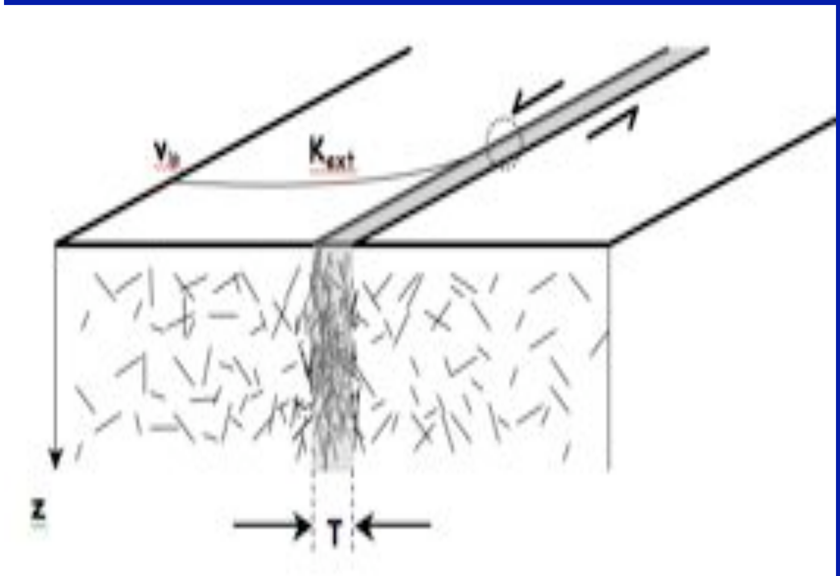

- **Parameters:**
  a=0.012, b=0.016, L=10μm
  h=6 mm, G= 30 GPa,
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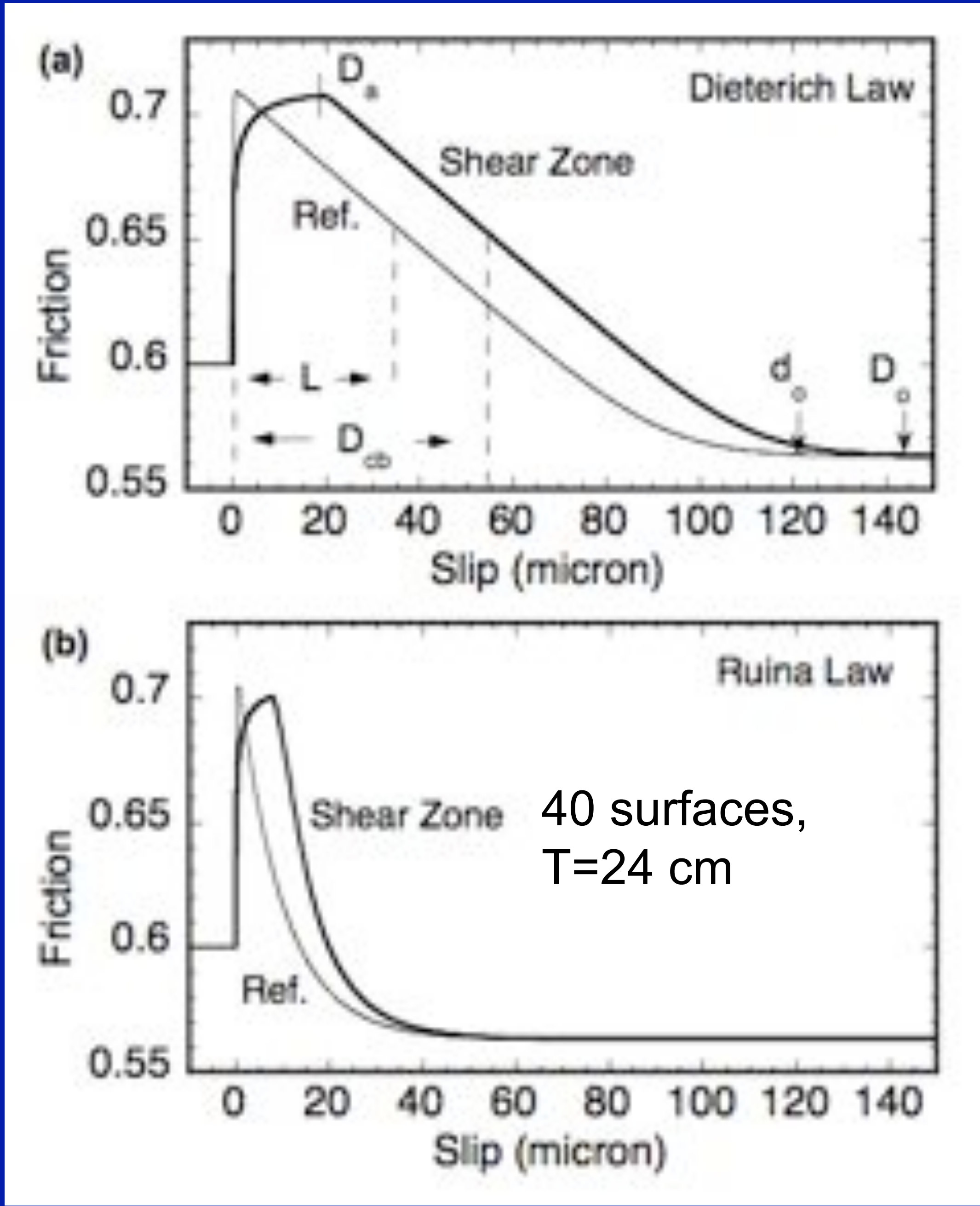
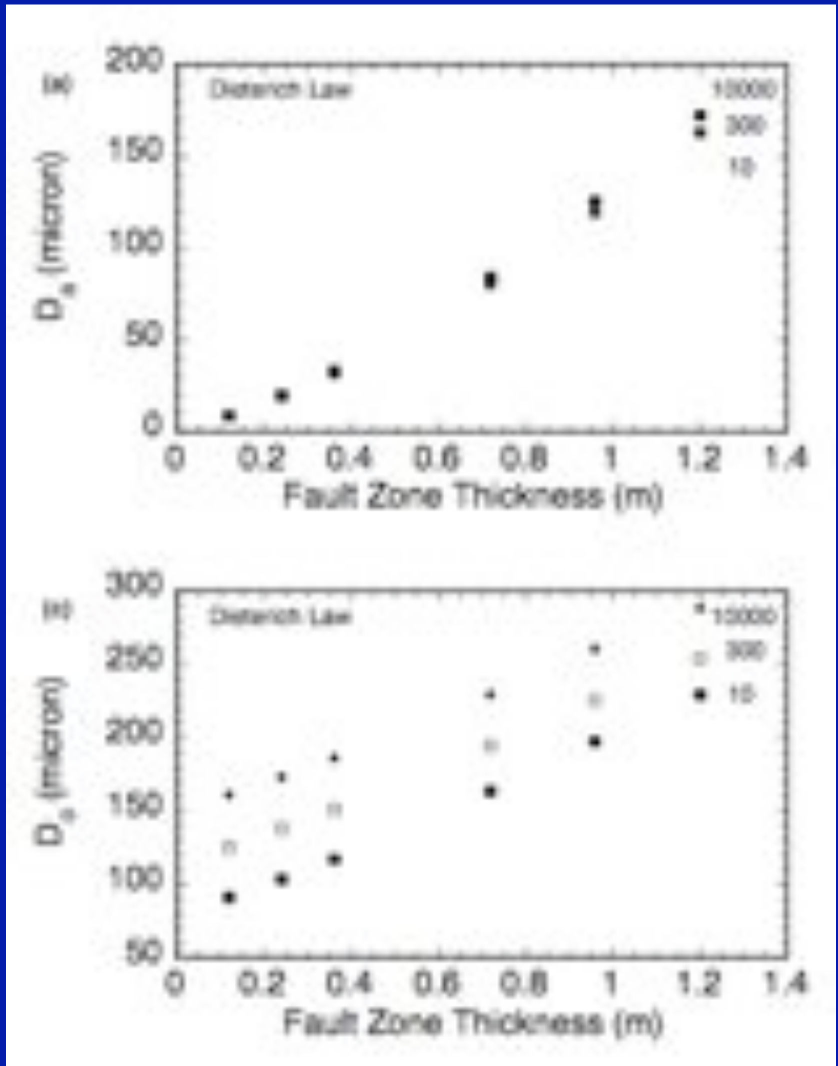
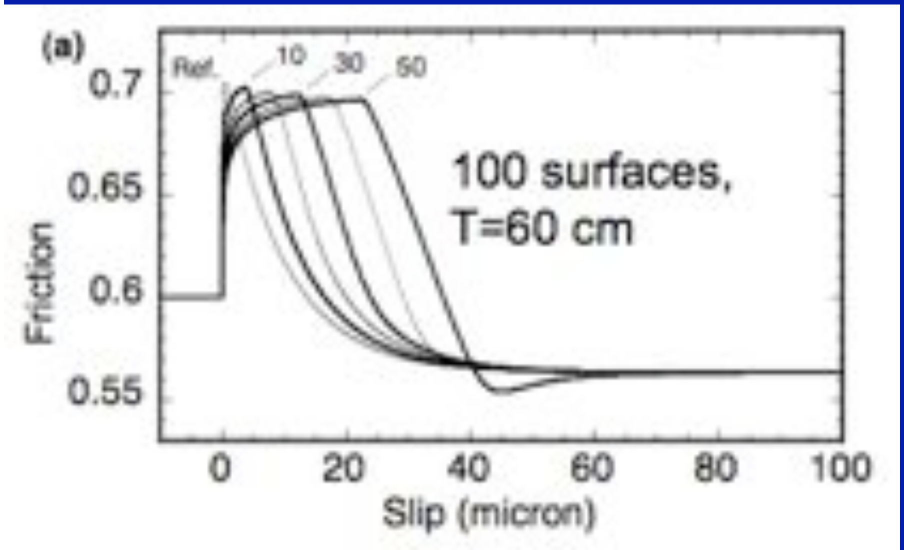


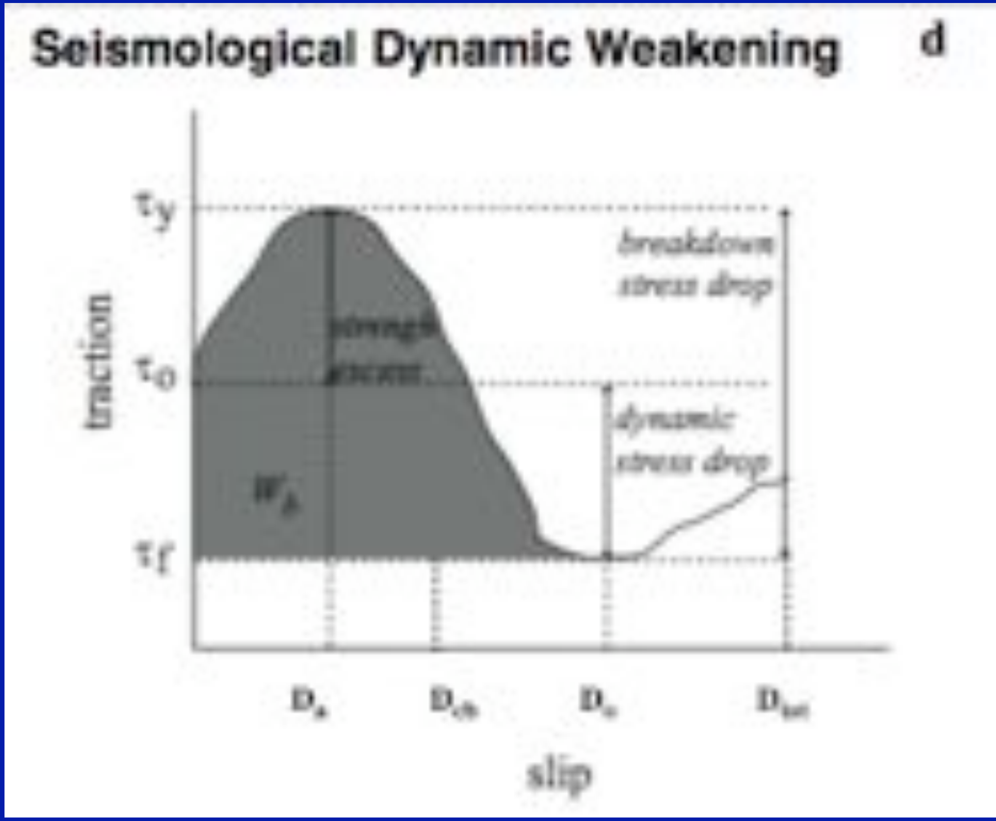
Effect of fault zone width for a few velocities

Expect: $D_o \approx D_{cb} \ln(v/v_o)$ or $D_o \approx L\ (T/h) \ln(v/v_o)$



Critical slip distance is proportional to fault zone thickness, $D_o \approx L\,(T/h)\,\ln(v/v_o)$





The Strength and Rheology of Brittle Fault Zones

Mod. Of Crust Def. Eq. Faulting: MOCDEF

1. Complex behavior from simple systems: dynamic triggering of creep and slow slip. Need a constitutive law like rate/state friction

2. Fault rocks can be very weak: Homogeneous mixtures of weak/strong materials are strong, but fabrics and clay coatings can make things extremely weak.

3. Fault Zones of finite width, dynamic complexity due to frictional response of internal slip surfaces