Friction Constitutive Laws and….

The Mechanics of Slow Earthquakes and the Spectrum of Fault Slip Behaviors

Chris Marone, The Pennsylvania State University

John Leeman, Marco Scuderi, Elisa Tinti,
Cristiano Collettini, Demian Saffer, Paul Johnson

Cargèse training school
Earthquakes: nucleation, triggering, rupture, and relationship with aseismic processes

6 Oct 2017

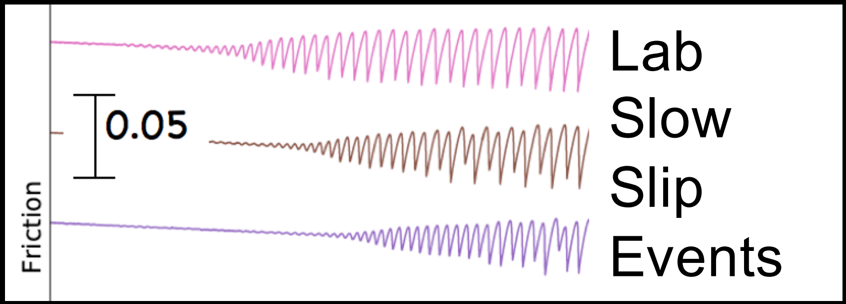
European Research Council
Seventh Framework Programme
"Ideas" Starting Grant
GLASS: 259256
European Research Council
Established by the European Commission

US NSF
IGPPS/CSES

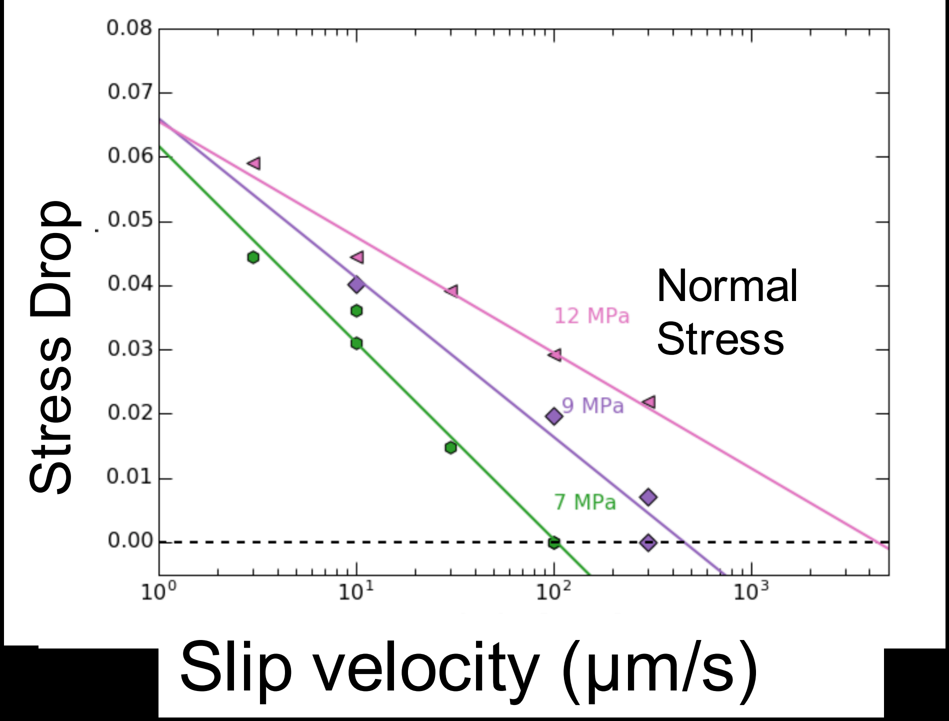
RESEARCH & INNOVATION
Marie Skłodowska-Curie actions

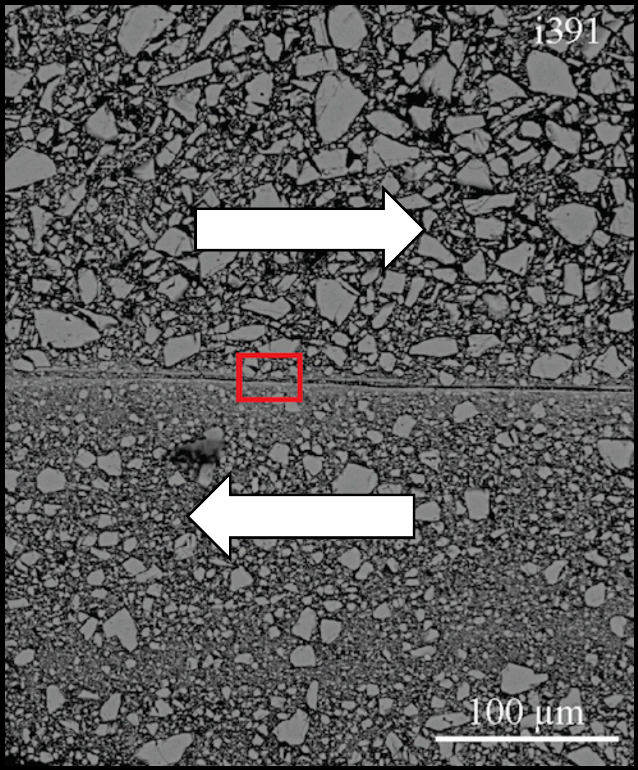
SAPIENZA
UNIVERSITÀ DI ROMA

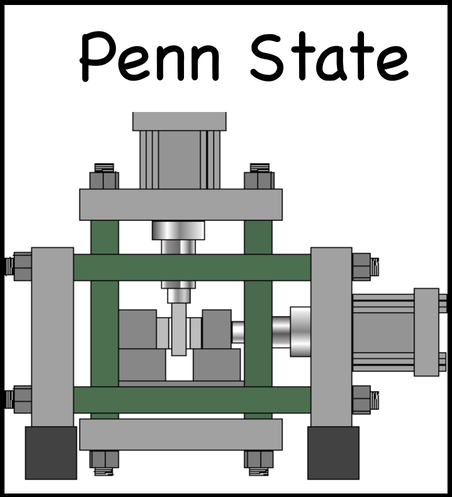
Slow Earthquakes --a view from the lab



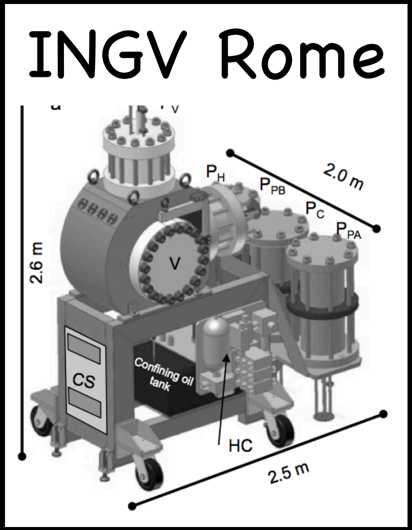
Lab Slow Slip Events







Penn State



INGV Rome

The Mechanics of Slow Earthquakes and the Spectrum of Fault Slip Behaviors

1. Friction laws: why do we need something as complex as rate/state?

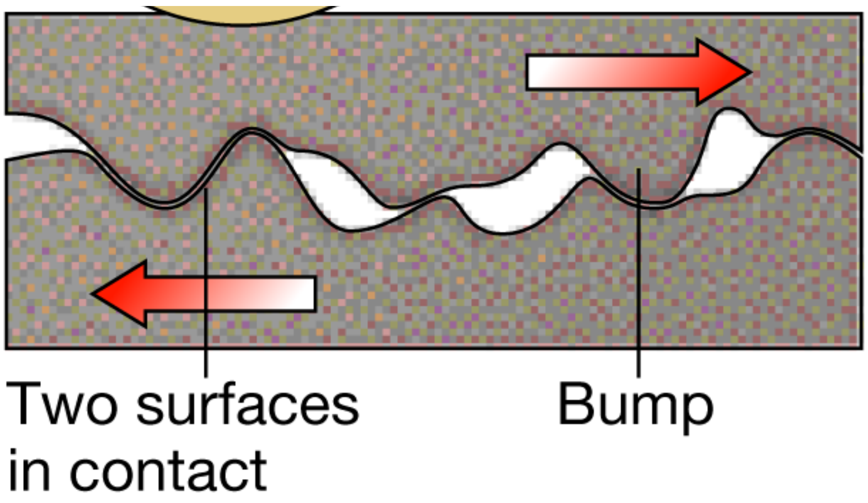
2. How do slow earthquakes work? What mechanism sets the speed limit? *Why are they slow?*

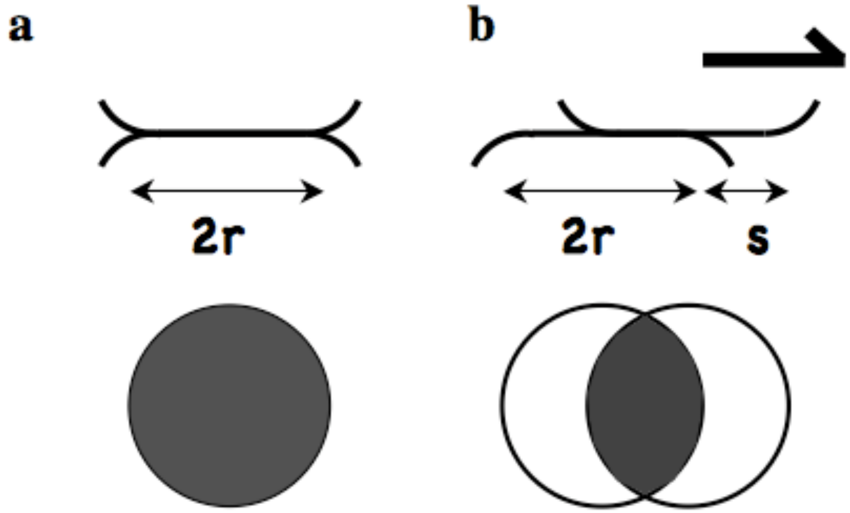
3. Speculations on how recent lab results may in apply in nature. Scaling laws for a spectrum of slip modes from slows earthquakes to super-shear rupture (SSE, LFE, tremor, VLFE, ULFE, MLFE, BB-eq, elasto-dynamic EQs) .

Minimum requirements for a friction law for faulting

Adhesive Theory of Friction (Bowden and Tabor, 1950's)

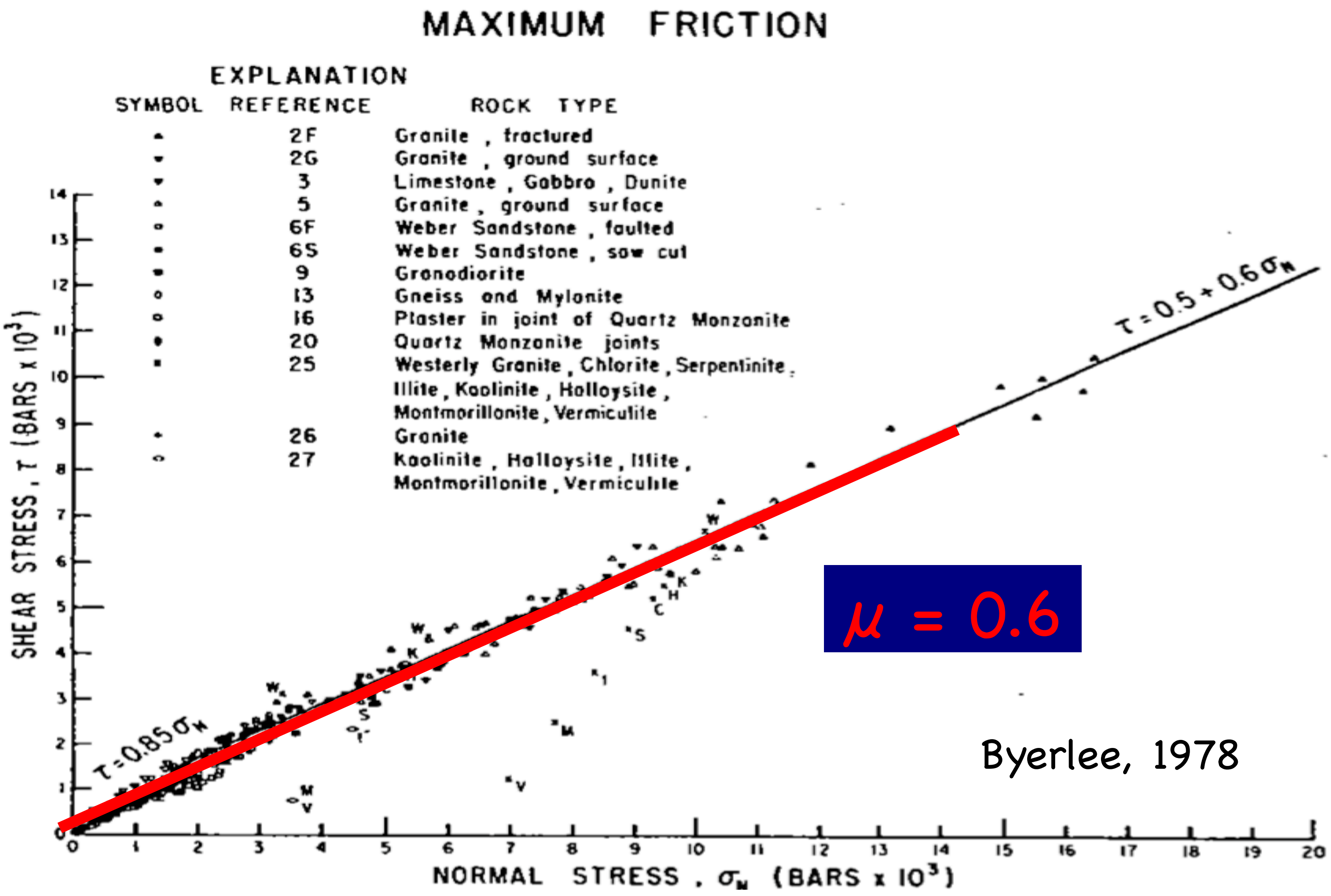
- Real contact area << nominal area
- Stress at contact junctions is at the inelastic (plastic) yield strength
- Contacts grow with "age"
- Add: Rabinowicz's observations of static/dynamic friction
- "Static" friction is higher than "Dynamic" friction because contacts are older (larger)
- -> implies that contact size decreases as slip velocity increases





Coulomb's law for shear failure $$\tau = C + \mu_i \sigma_n$$

Byerlee's Law for Rock Friction $$\tau = 50[MPa] + 0.6\sigma_n$$



MAXIMUM FRICTION

EXPLANATION

SYMBOL	REFERENCE	ROCK TYPE
▲	2F	Granite, fractured
▼	2G	Granite, ground surface
▼	3	Limestone, Gabbro, Dunite
▲	5	Granite, ground surface
○	6F	Weber Sandstone, faulted
■	6S	Weber Sandstone, saw cut
■	9	Granodiorite
○	13	Gneiss and Mylonite
○	16	Plaster in joint of Quartz Monzonite
●	20	Quartz Monzonite joints
■	25	Westerly Granite, Chlorite, Serpentinite, Illite, Kaolinite, Halloysite, Montmorillonite, Vermiculite
✦	26	Granite
○	27	Kaolinite, Halloysite, Illite, Montmorillonite, Vermiculite

$\mu = 0.6$

Byerlee, 1978

Time dependence of “static” friction
Aging of frictional contacts

Coulomb, 1785

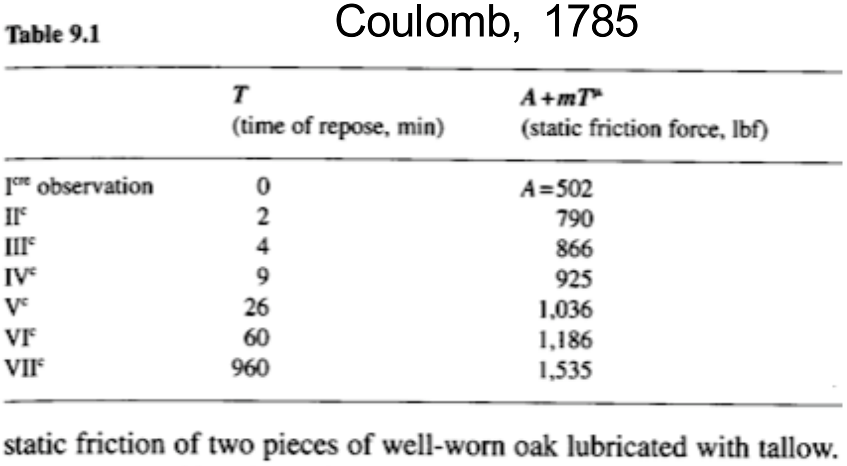
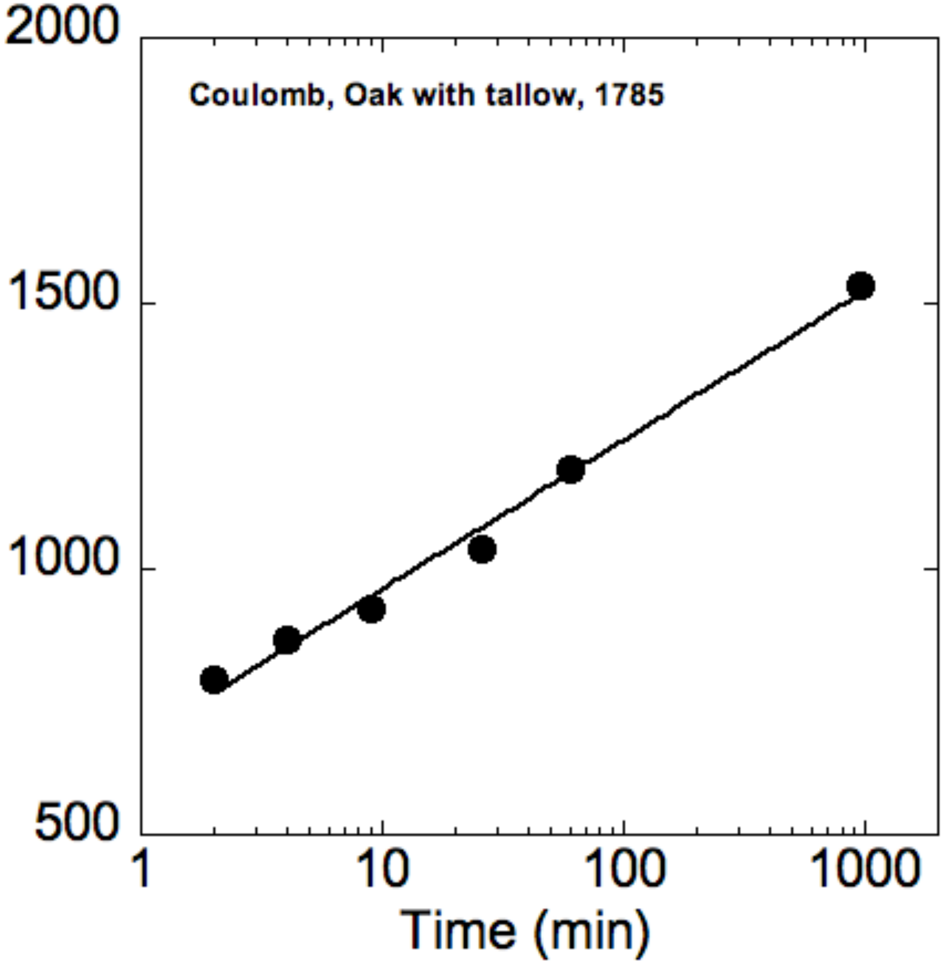


Table 9.1

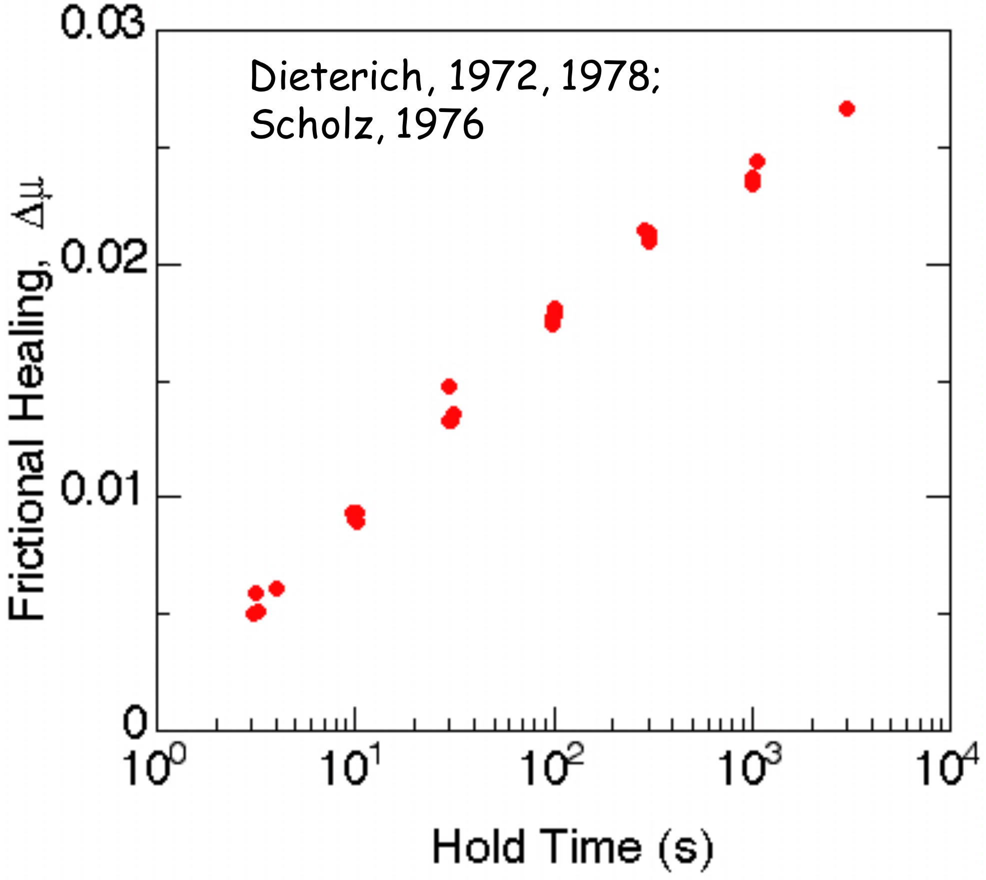
	T (time of repose, min)	$A+mT^{\mu}$ (static friction force, lbf)
I^{ere} observation	0	$A=502$
II^{e}	2	790
III^{e}	4	866
IV^{e}	9	925
V^{e}	26	1,036
VI^{e}	60	1,186
VII^{e}	960	1,535

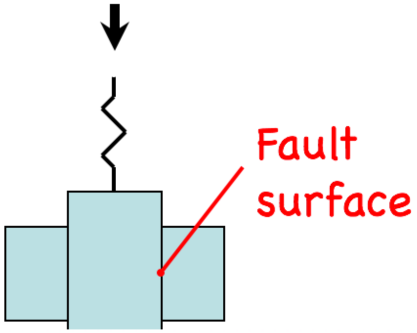
static friction of two pieces of well-worn oak lubricated with tallow.

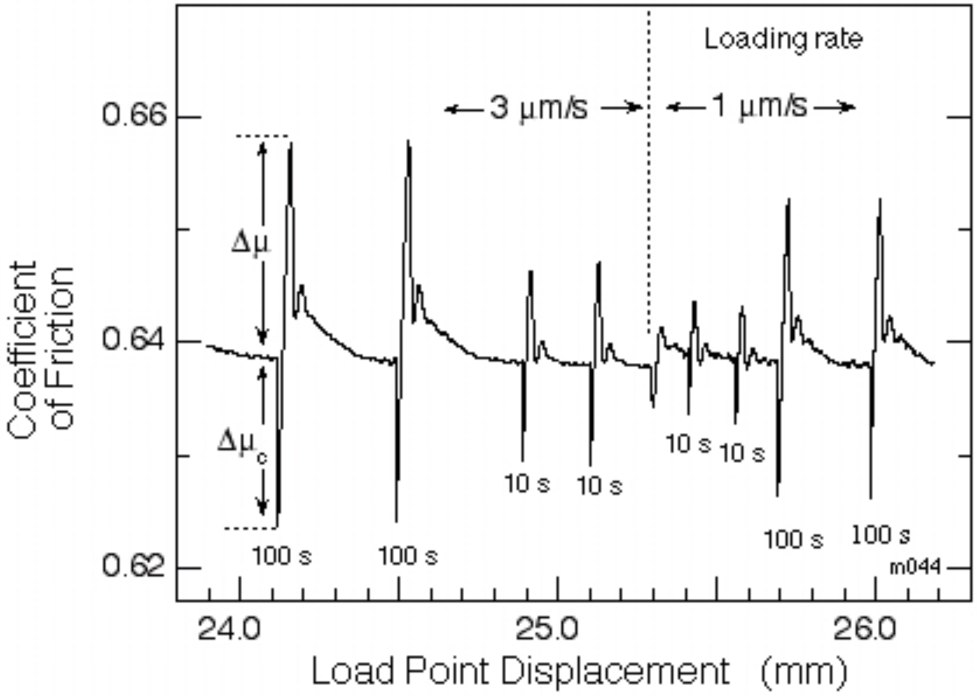
C. A. Coulomb (1736-1806)



Time dependence of friction in rocks; Aging (frictional healing)



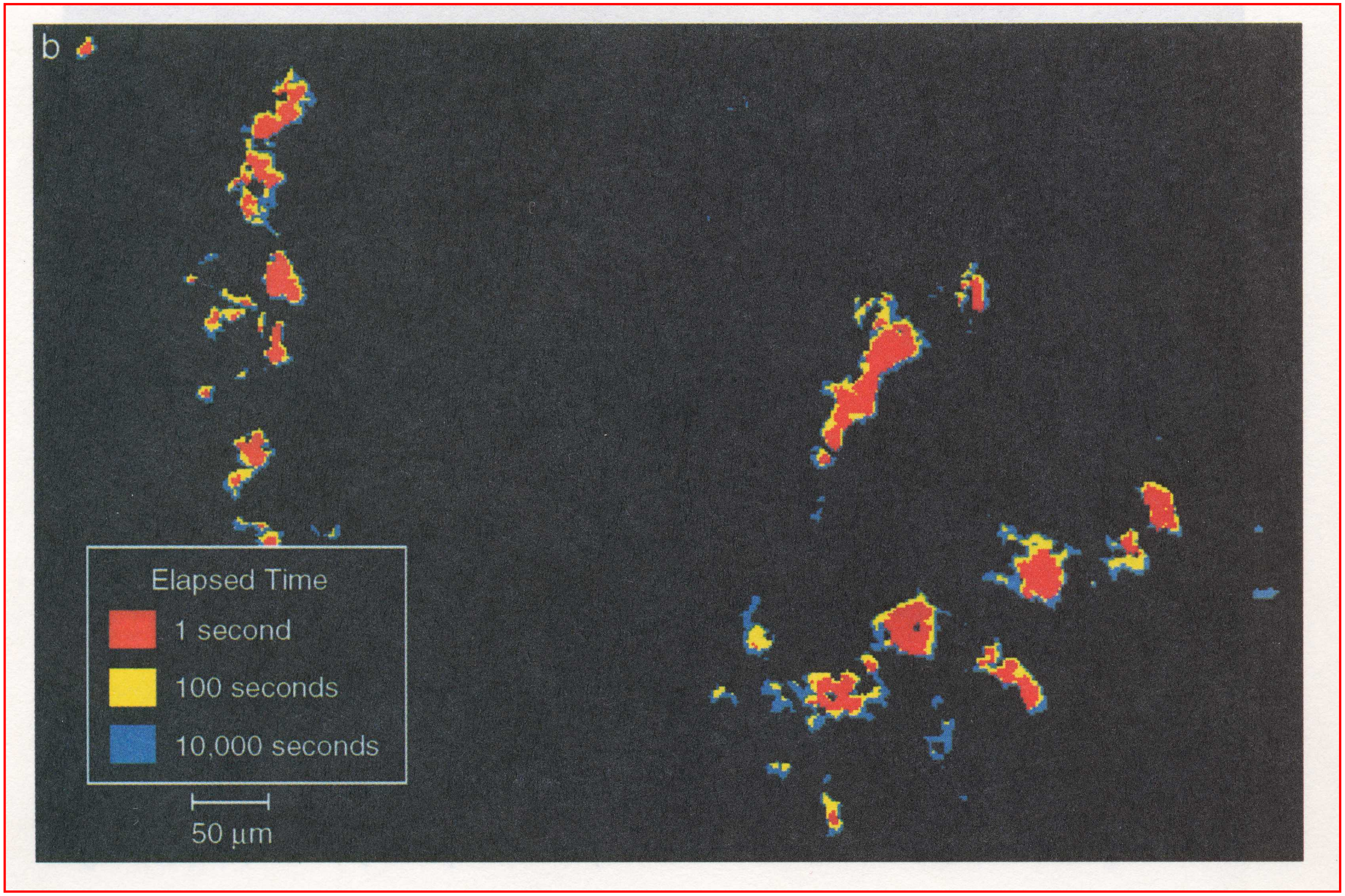




Marone, Nature, 1998

Real contact area << nominal area; Contact stresses are high

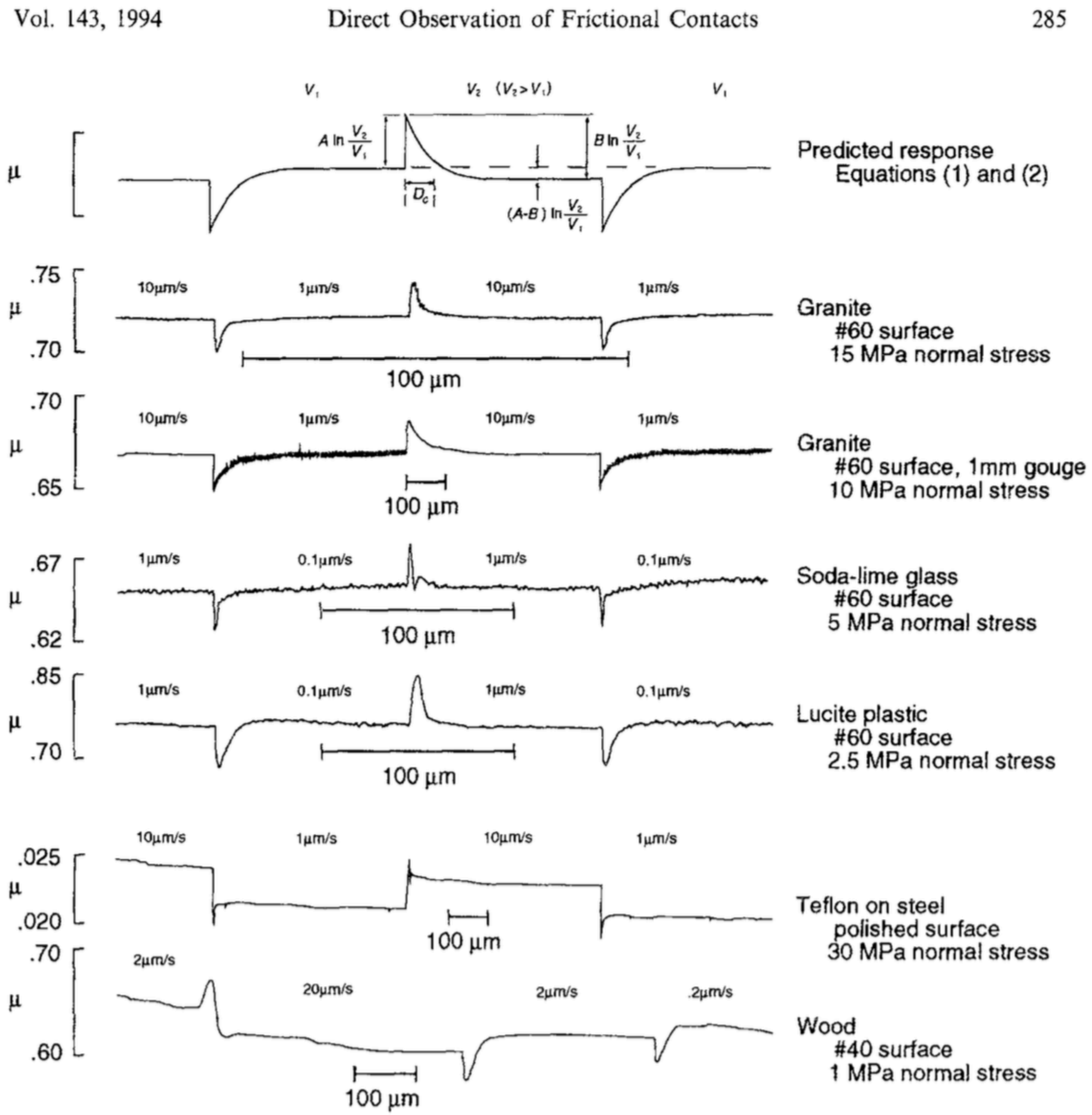
Contact junctions grow with time (age)



Dieterich and Kilgore [1994]

For many materials:

- friction varies systematically with sliding velocity and
- exhibits transient response when velocity is changed



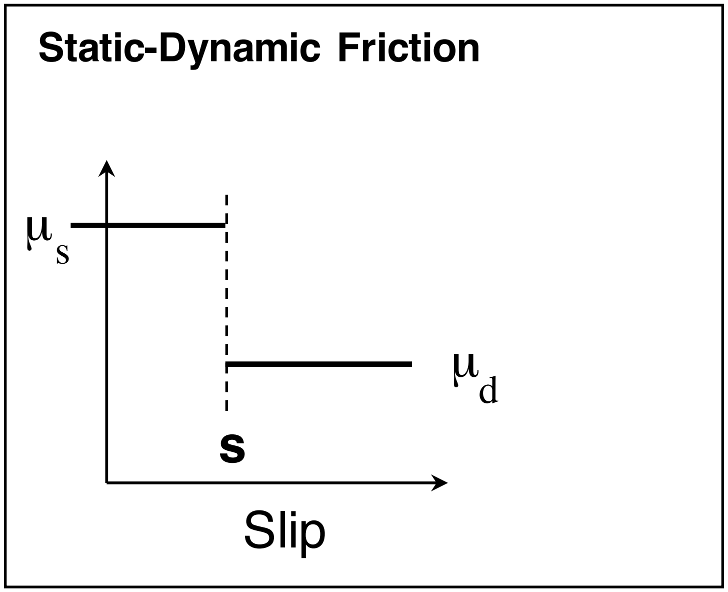
Dieterich and Kilgore, 1994

Minimum requirements for a friction law for faulting

- Aging (time dependence)
- Velocity dependence (*kinetic* friction varies systematically with sliding velocity)
- Stick-slip motion (repeated failure followed by restrengthening)

Minimum requirements for a friction law for faulting

Friction: slick-slip and stability of sliding



$$\left.\begin{array}{l}\mu = \mu_s \quad (s=0)\\ \mu = \mu_d \quad (s>0)\end{array}\right\}$$ Classical view

Rabinowicz 1951, 1956, 1958: Static vs. dynamic friction & state dependence

- Recognized that finite slip was necessary to achieve fully dynamic slip
- Experiments showed state, memory effects and that μ_d varied with slip velocity.

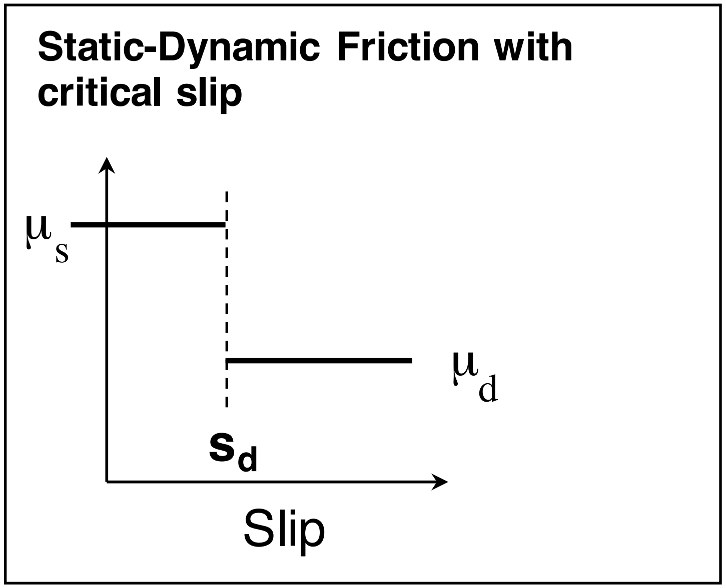
JOURNAL OF APPLIED PHYSICS VOLUME 22, NUMBER 11 NOVEMBER, 1951

The Nature of the Static and Kinetic Coefficients of Friction

ERNEST RABINOWICZ
Lubrication Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts

(Received May 23, 1951)

Experiments have been carried out to determine the transition between static and kinetic conditions when stationary metal surfaces are set into motion, a simple method being used which measures the energy that has to be given to one of the bodies to start it moving. The method is confined to cases in which the static coefficient exceeds the kinetic. Using a load of 1 kg and metal surfaces of various kinds, it is found that the static coefficient persists for distances of the order of 10^{-4} cm, and then gradually falls off to values corresponding to the kinetic coefficient. This behavior is shown to be consistent with a simple model based on the assumption that the friction force is needed to shear metallic junctions formed between the metal surfaces. The action of boundary lubricants is discussed, and it is shown that they can act either by diminishing the metallic interaction directly, or by preventing its increase during the sliding process.



Static-Dynamic Friction with critical slip

Critical slip distance for changes in friction

Friction: 2nd order variations

$$\int_{\tan\theta}^{\mu_s} s\cdot d\mu.$$

(See Fig. 6.)

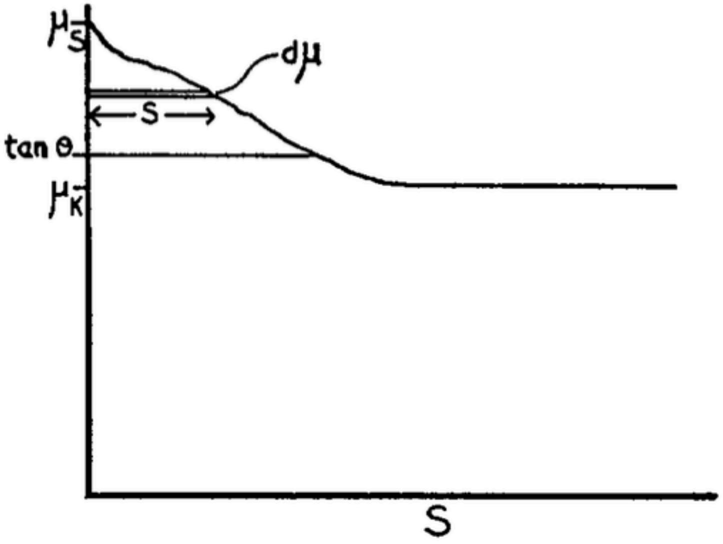
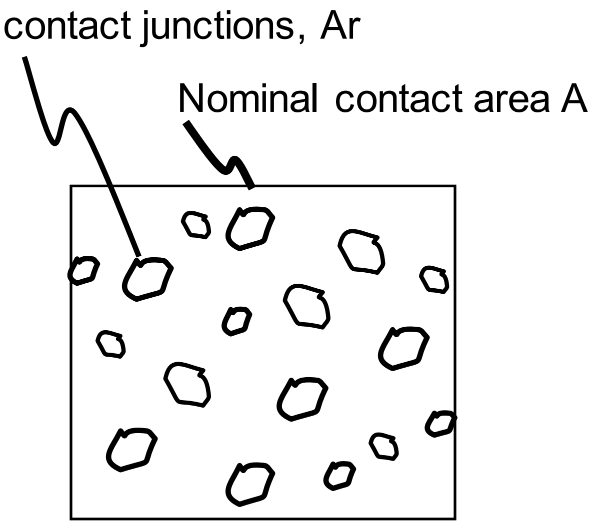


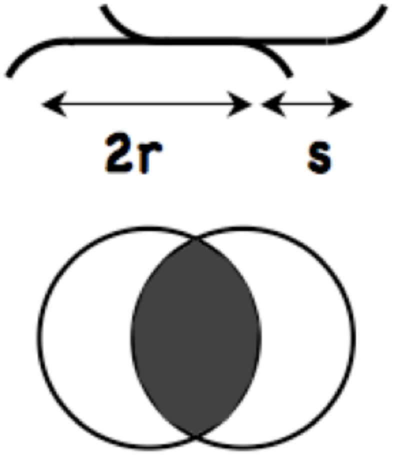
Fig. 6.

Rabinowicz 1951



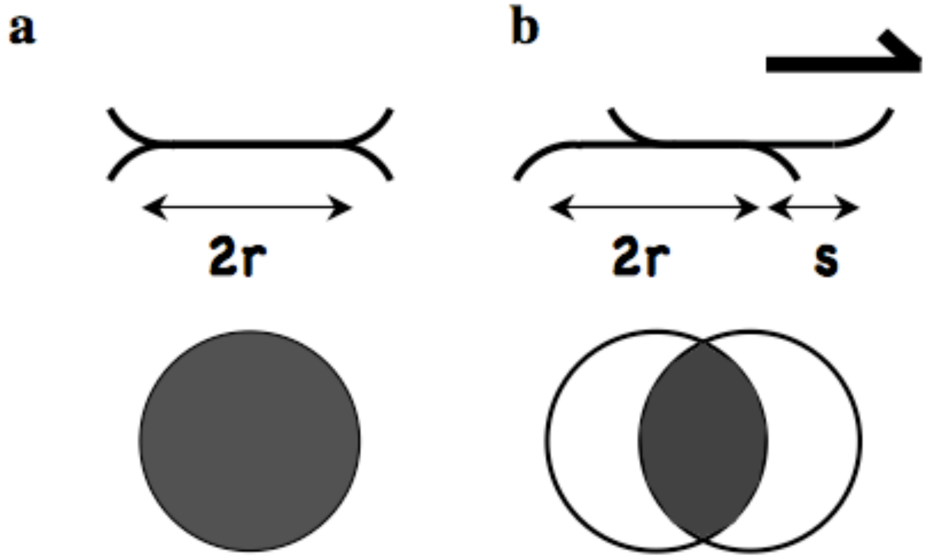
contact junctions, Ar

Nominal contact area A



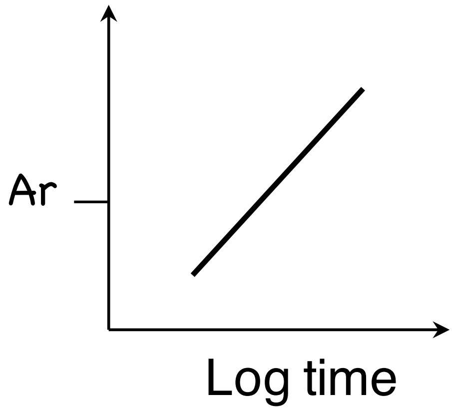
Slip weakening friction law

Adhesive asperity contacts



Bowden & Tabor, 1950's
Rabinowicz, 1951

Aging –friction increases w/ contact time



Static friction is higher than *Dynamic* friction because contacts are older (larger) in "static" state

E. Rabinowicz, Sci. Amer., 109, May 1956.

Adhesive asperity contacts
Slip weakening distance

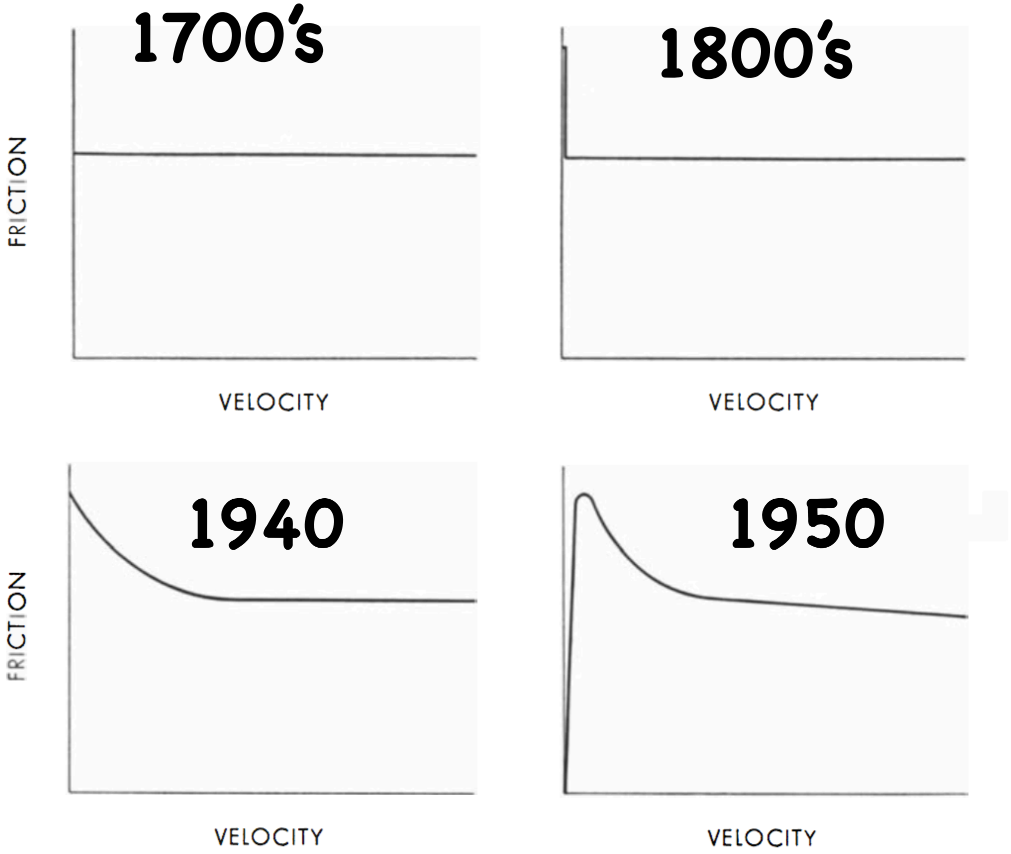
Stick and Slip

When two substances rub against each other, they frequently stick and then slip. The phenomenon accounts for the squeak of bearings, the music of violins and many other sounds of our daily experience

by Ernest Rabinowicz

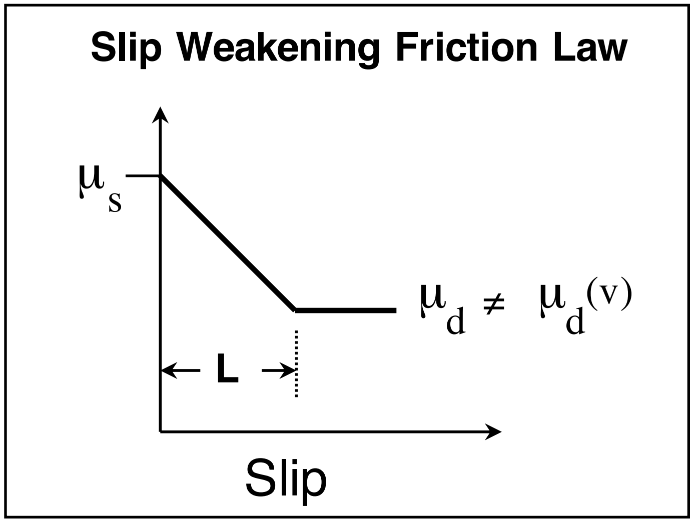
Brief History of Friction

Rabinowicz, 1956
Scientific American



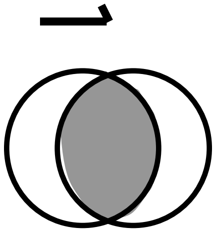
EVOLUTION OF THE FRICTION CONCEPT is illustrated. In the late 18th century it was thought that the coefficient of friction remained constant as the relative velocity of the sliding substances was increased (*upper left*). In the early 19th century it was postulated that there were two kinds of friction: static and kinetic (*upper right*). Friction was greatest when two substances were moved from a state of rest, and fell off immediately when they began to slide. Around 1940 it was shown that friction fell off gradually with the increase of velocity (*lower left*). Today it is known that friction first increases with velocity and then falls off (*lower right*). When the changing relationship between friction and velocity has the slope to the left of the peak in this curve, substances slide steadily. When it has the form of the steeper part of the slope to the right of the peak, stick-slip occurs.

Friction: 2nd order variations, slick-slip and stability of sliding



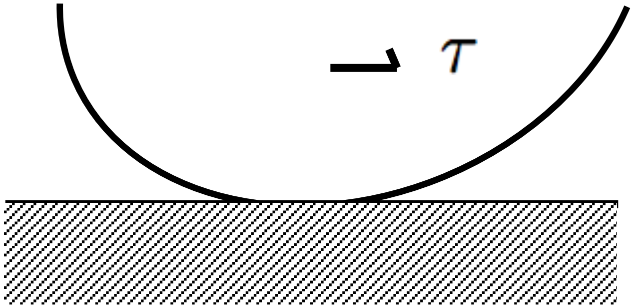
$$\mu(x) = \mu_s - \frac{x}{L}\Delta\mu \qquad (\text{for } L > x > 0)$$

$$\mu(x) = \mu_s - \Delta\mu \qquad (\text{for } x > L)$$



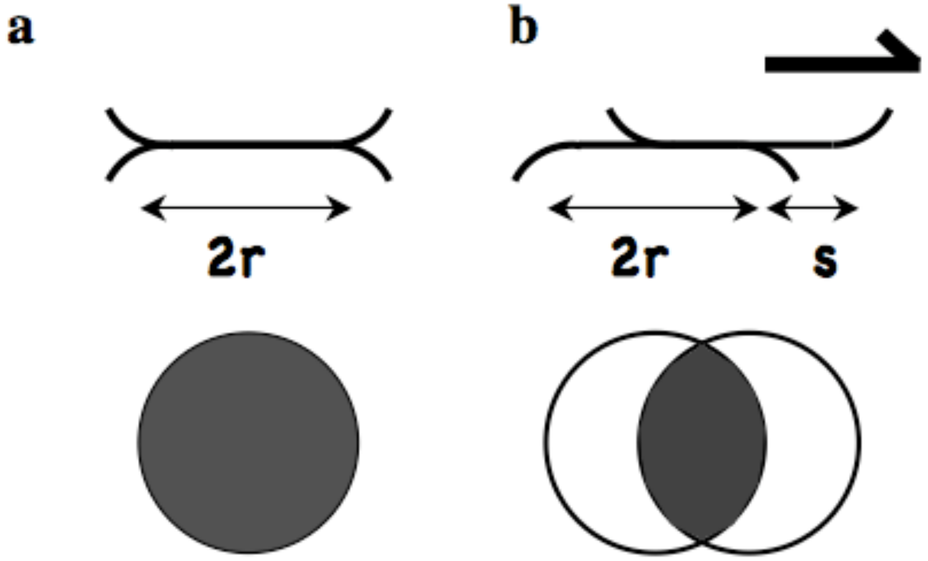
Critical friction distance represents slip necessary to erase existing contact

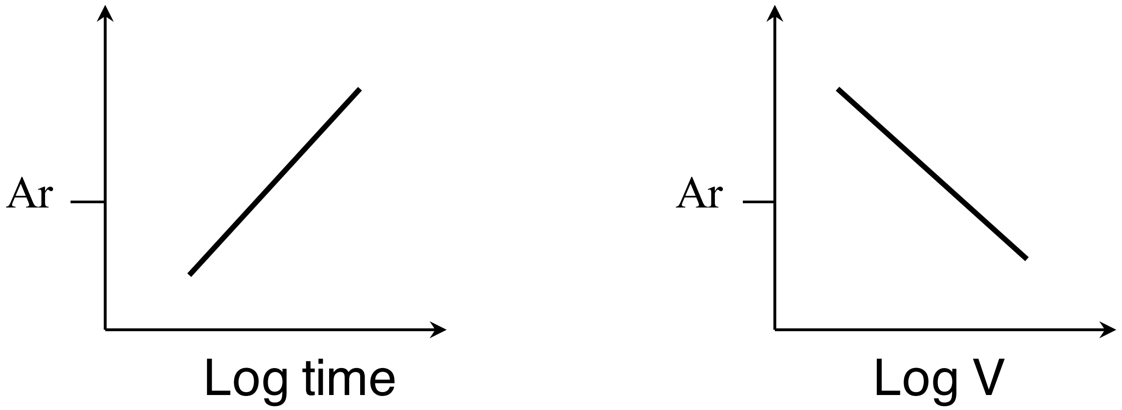
Adhesive Theory of Friction



Adhesive asperity contacts

Rabinowicz, 1951, 1956



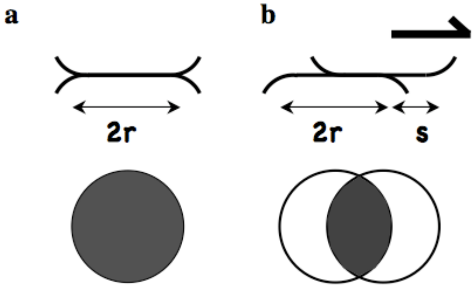


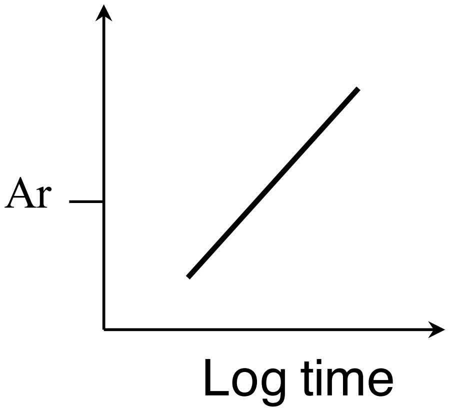
- **Contacts age (grow) with time.**
- **Young contacts are smaller than old contacts.**
- **Contact age is given by r/V**

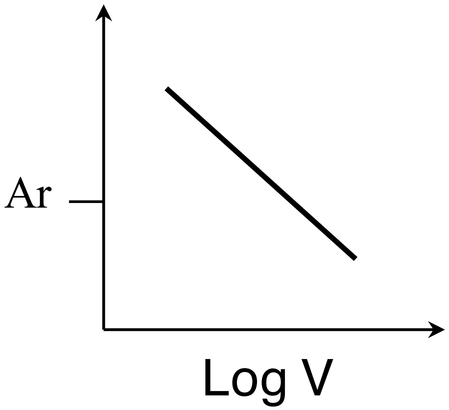
Minimum requirements for a friction law for faulting

Adhesive Theory of Friction (Bowden and Tabor, 1950's)

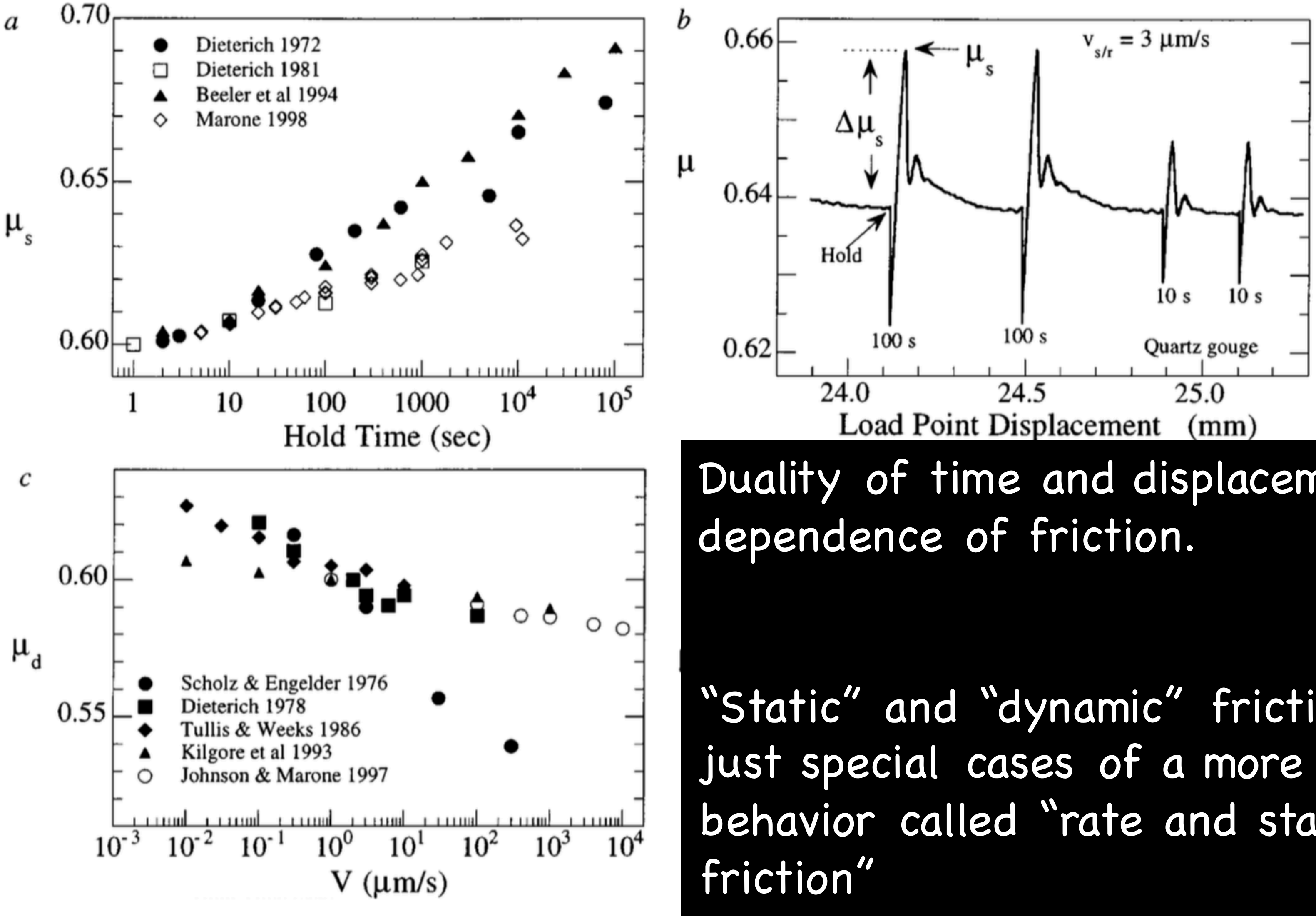
- Real contact area << nominal area
- Stress at contact junctions is at the inelastic (plastic) yield strength
- Contacts grow with "age"
- Add: Rabinowicz's observations of static/dynamic friction
- "Static" friction is higher than "Dynamic" friction because contacts are older (larger)
- -> implies that contact size decreases as slip velocity increases







Minimum requirements for a friction law for faulting

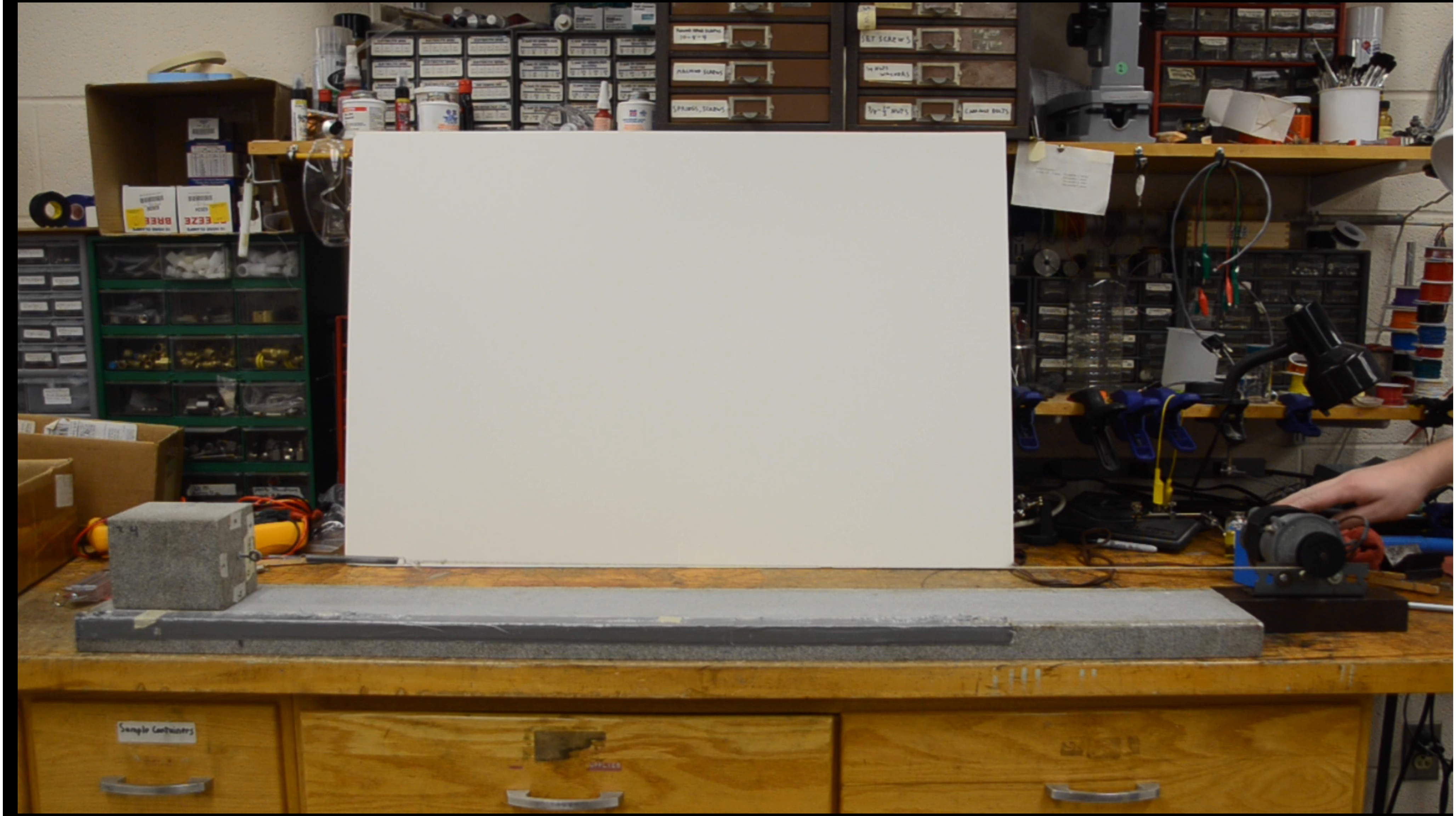


Duality of time and displacement dependence of friction.

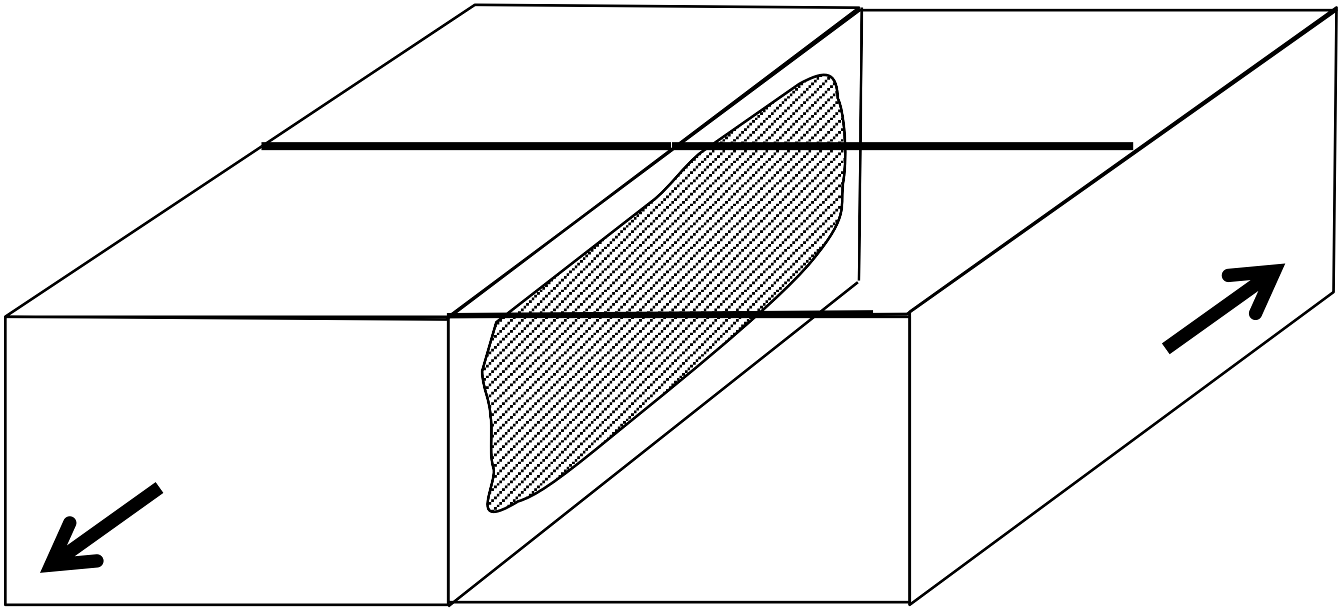
"Static" and "dynamic" friction are just special cases of a more general behavior called "rate and state friction"

(Marone, 1998) Dieterich, Scholz, Ruina, Rice

Stick-slip



Seismic cycle as repetitive stick slip instability



Brace & Byerlee, 1966

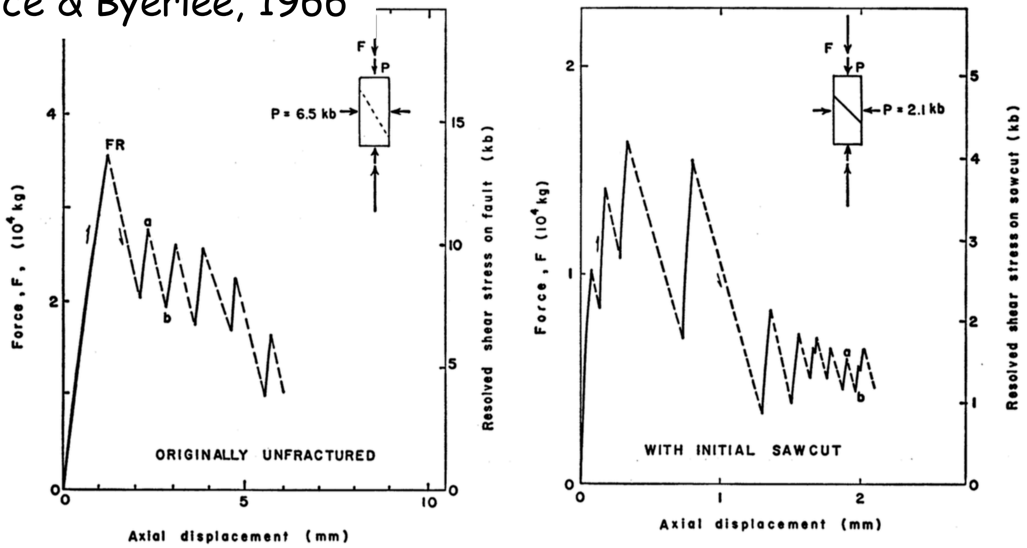
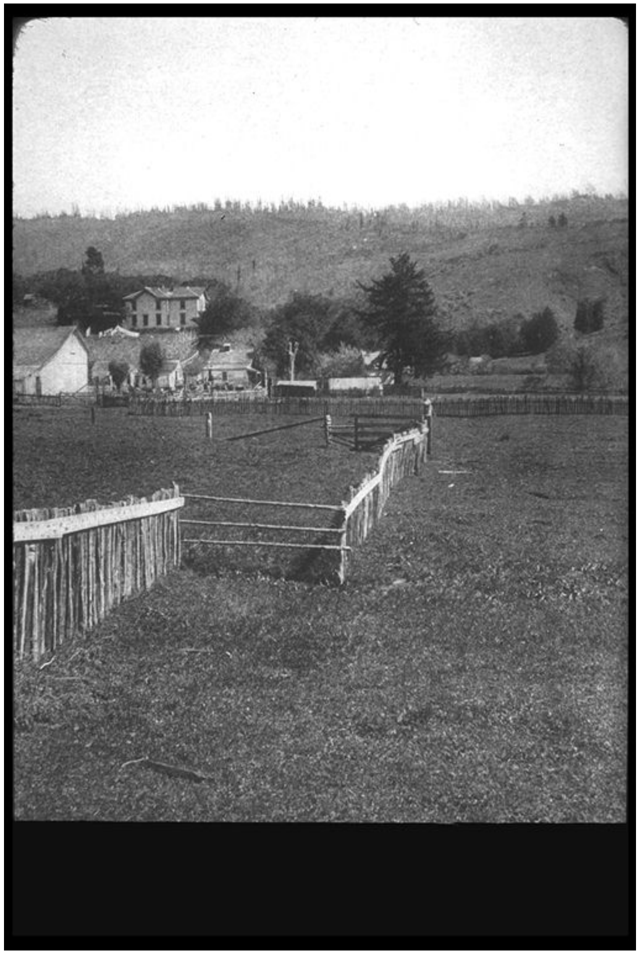


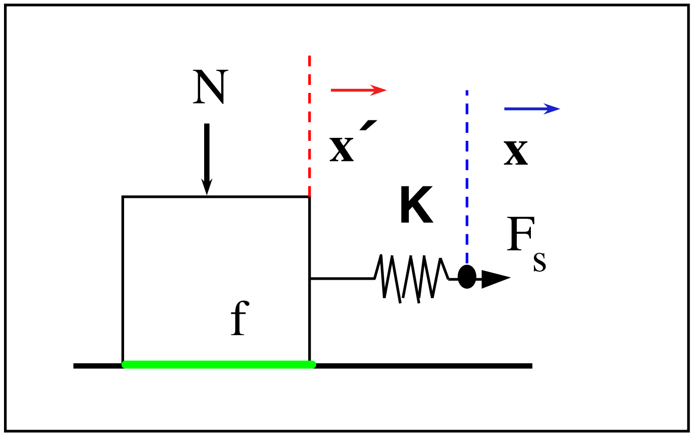
Fig. 1 (left). Force-displacement curve for the axial direction in a cylindrical sample of Westerly granite. Small diagram above the curve shows schematically how stress was applied to the sample. The sample fractured at point *FR* forming the fault which is shown as a dotted line in the small diagram. The exact shape of the curves during a stress drop (such as *ab*) is not known and is shown dotted. *P* is confining pressure. Fig. 2 (right). Same as Fig. 1 except that the sample contained a sawcut with finely ground surfaces as shown schematically (small figure) by a heavy line.

26 AUGUST 1966 991



Brittle Friction Mechanics, Stick-slip

- Stick-slip (unstable) versus stable shear

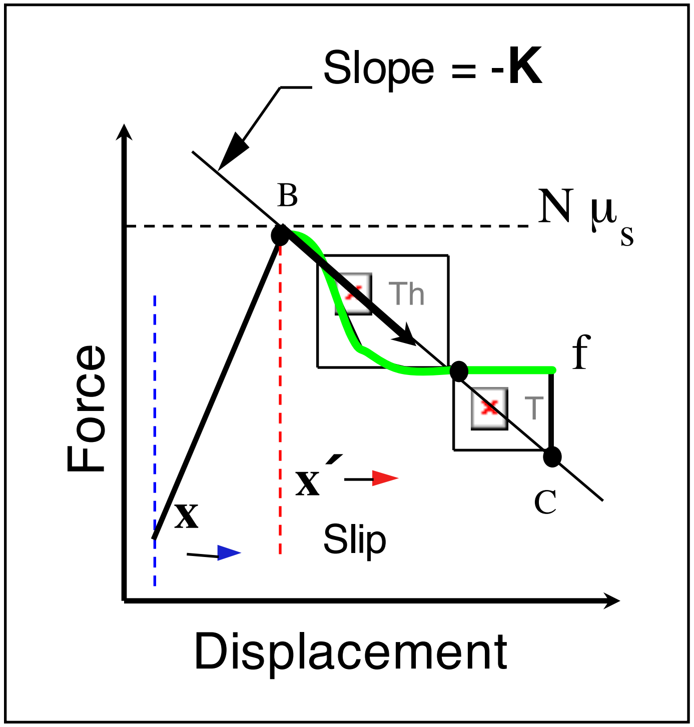


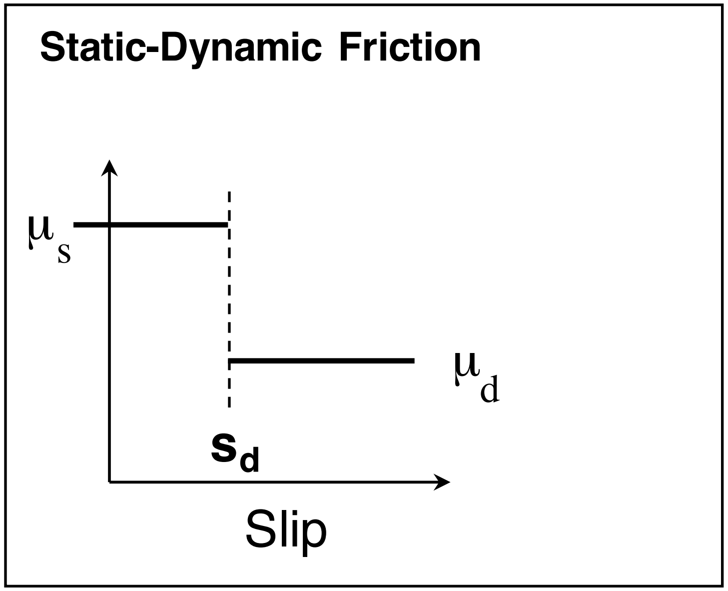
Stick-slip dynamics

$$m\ddot{x}' + \Gamma\dot{x}' + f(\dot{x}', x', t, \theta) = F_s$$

$$m\ddot{x}' + \Gamma\dot{x}' + f(\dot{x}', x't, \theta) = K(v_{lp} - v)t$$

$$m\ddot{x}' + Fx' = K(v_{lp} - v)t$$

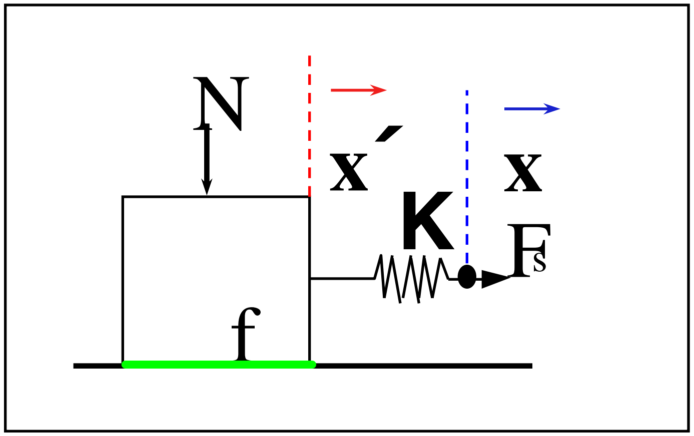




$$f = \Delta\mu N$$

Johnson and Scholz, 1976

total slip, particle velocity, and acceleration all depend on stress drop

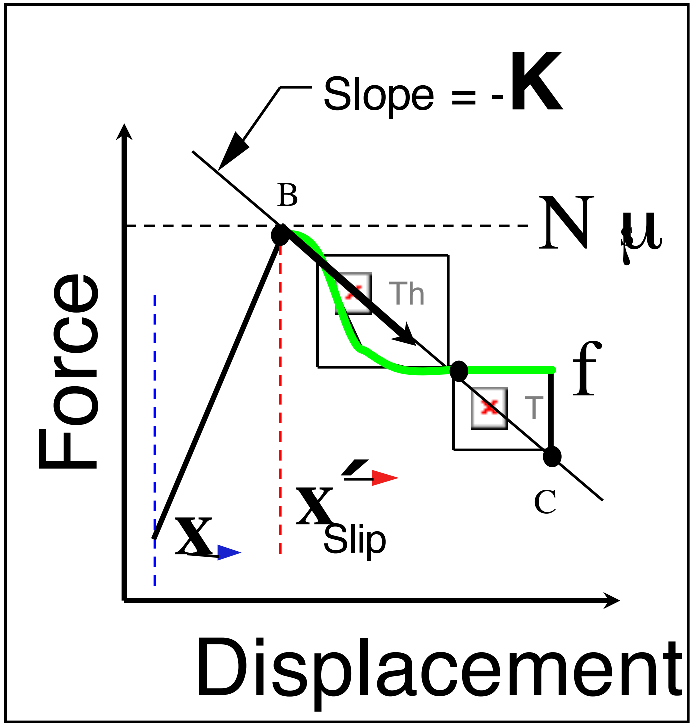


$$v(t) = \frac{\Delta\mu N}{\sqrt{Km}} sin\kappa t$$

$$\kappa = \sqrt{\frac{K}{m}}$$

$$t_r = \pi\sqrt{\frac{m}{K}}$$

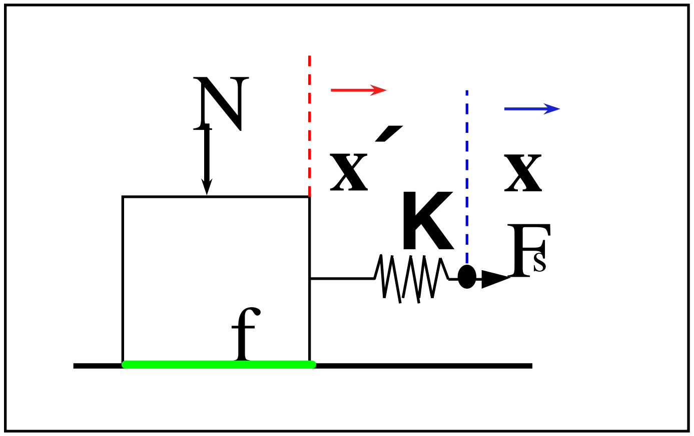
slip duration = rise time

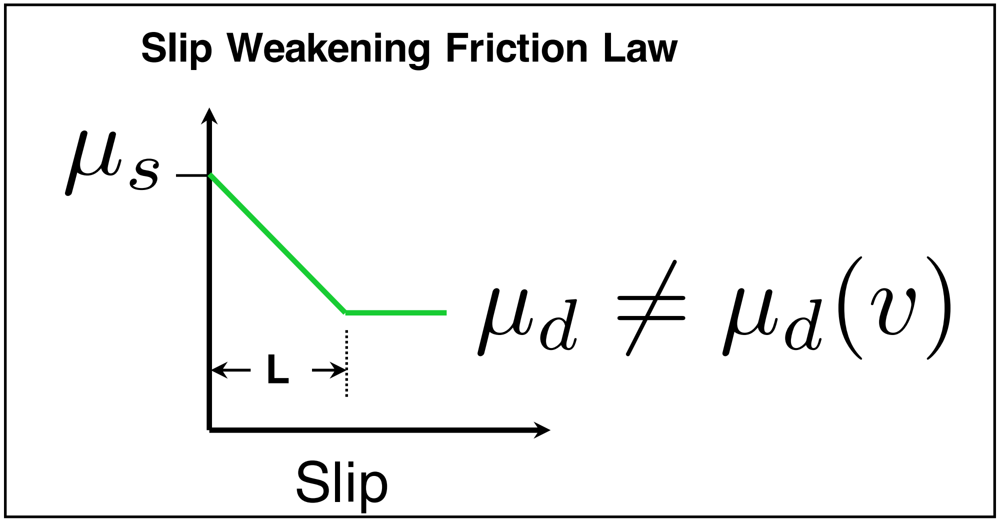


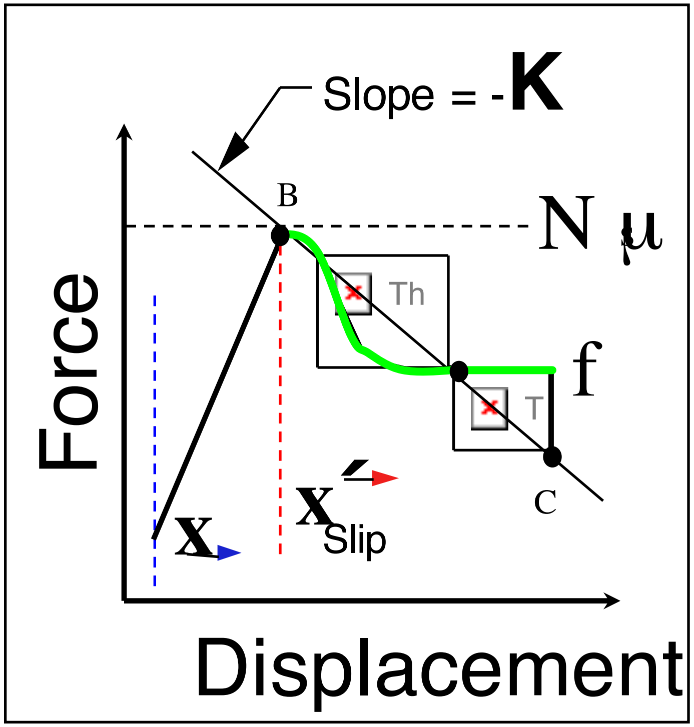
$$\Delta x' = \frac{2\Delta\mu N}{K}$$

$$\Delta\sigma = 2(\mu_s - \mu_d)\sigma_n$$

Stick-Slip Instability




Slip Weakening Friction Law



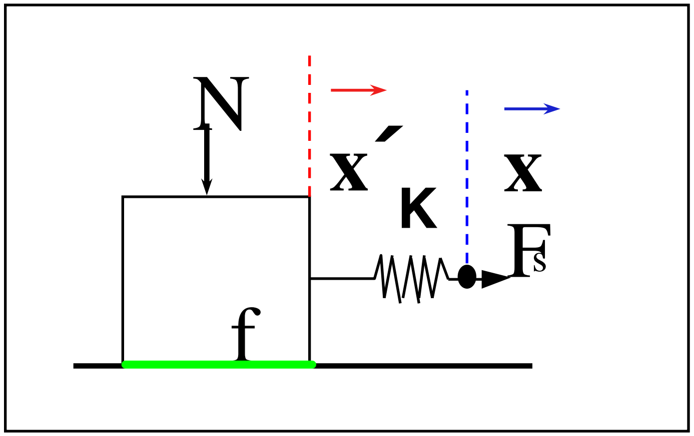
Quasistatic Stability Criterion

$$K_c = \frac{\sigma_n(\mu_s - \mu_d)}{L}$$

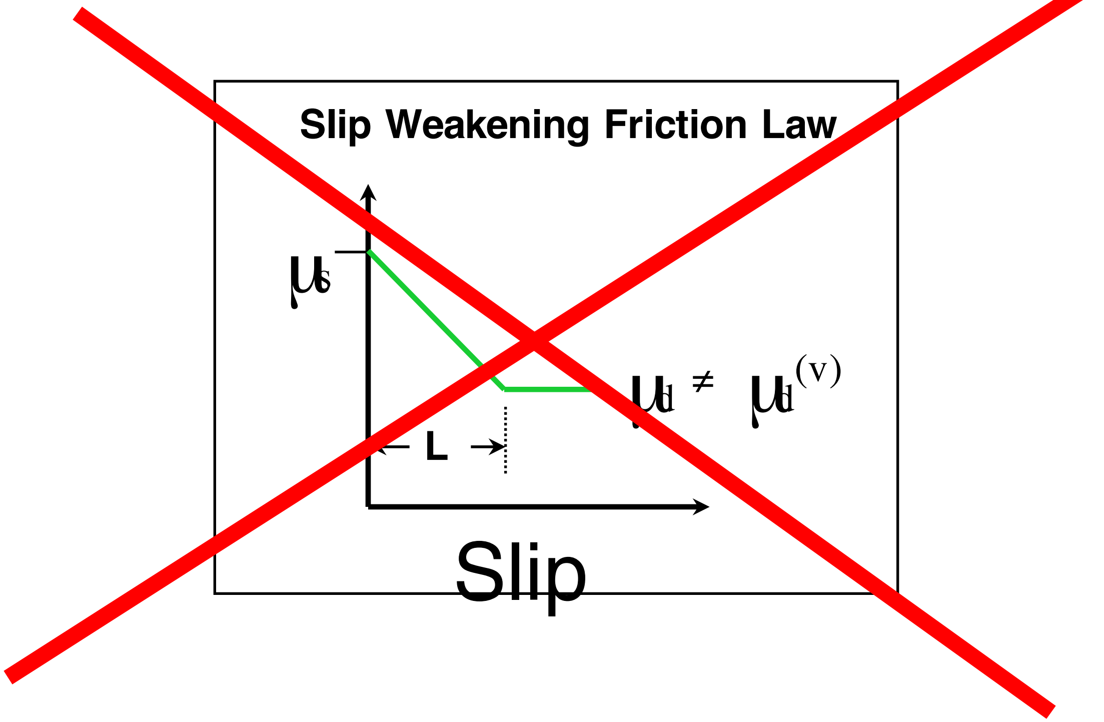
K< K_c; Unstable, stick-slip

K > K_c; Stable sliding

Laboratory Studies



But, there's a problem…….



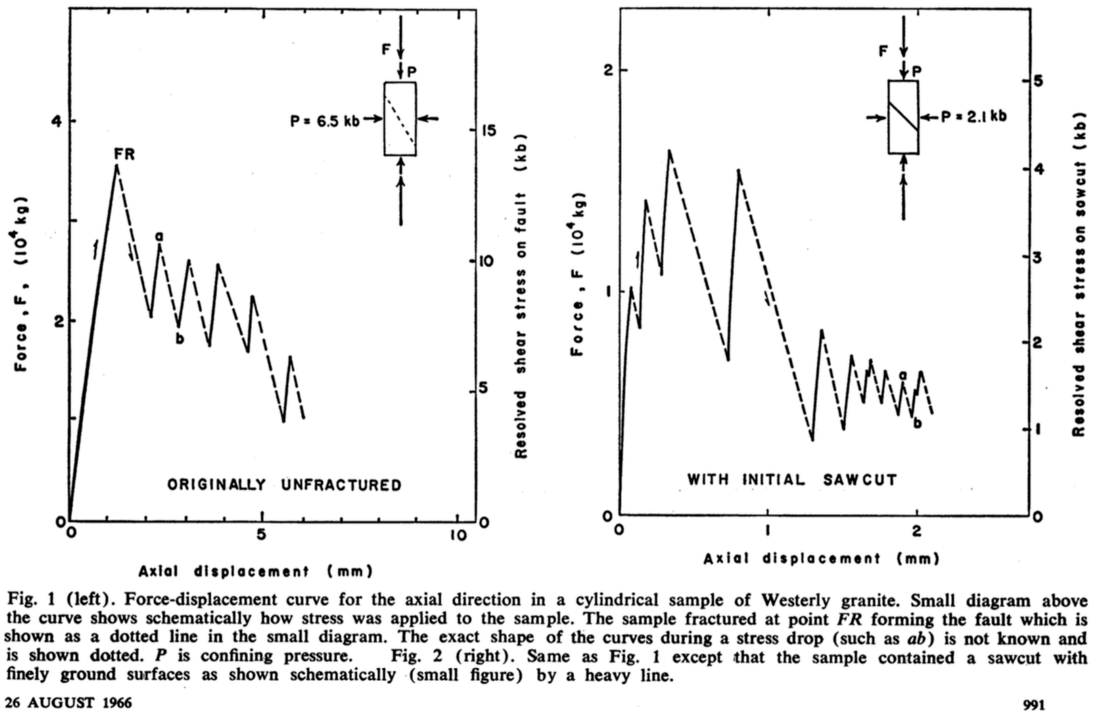


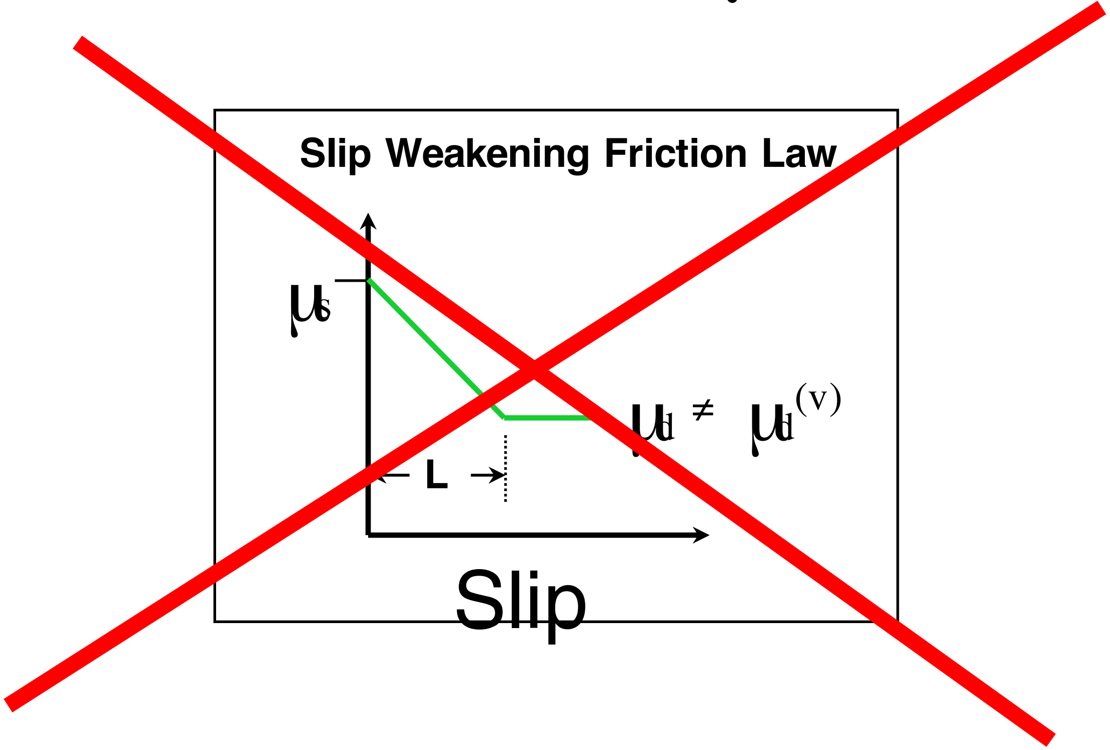
Fig. 1 (left). Force-displacement curve for the axial direction in a cylindrical sample of Westerly granite. Small diagram above the curve shows schematically how stress was applied to the sample. The sample fractured at point *FR* forming the fault which is shown as a dotted line in the small diagram. The exact shape of the curves during a stress drop (such as *ab*) is not known and is shown dotted. *P* is confining pressure. Fig. 2 (right). Same as Fig. 1 except that the sample contained a sawcut with finely ground surfaces as shown schematically (small figure) by a heavy line.

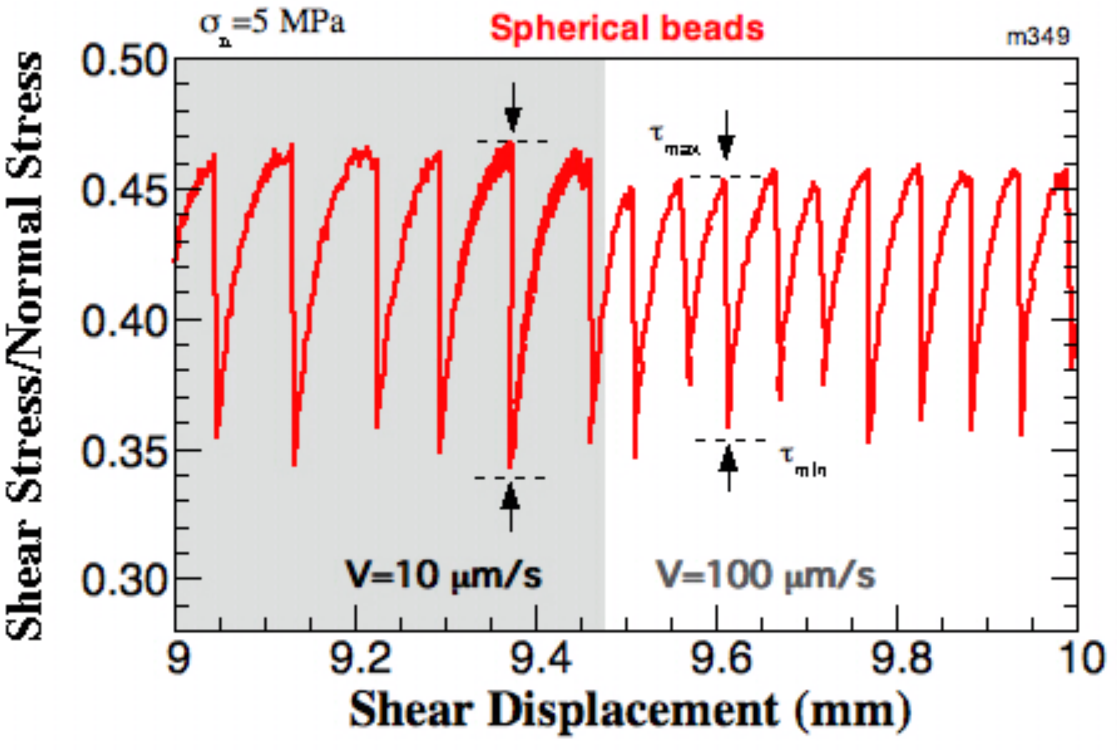
26 AUGUST 1966

991

Repetitive Stick-Slip Instability

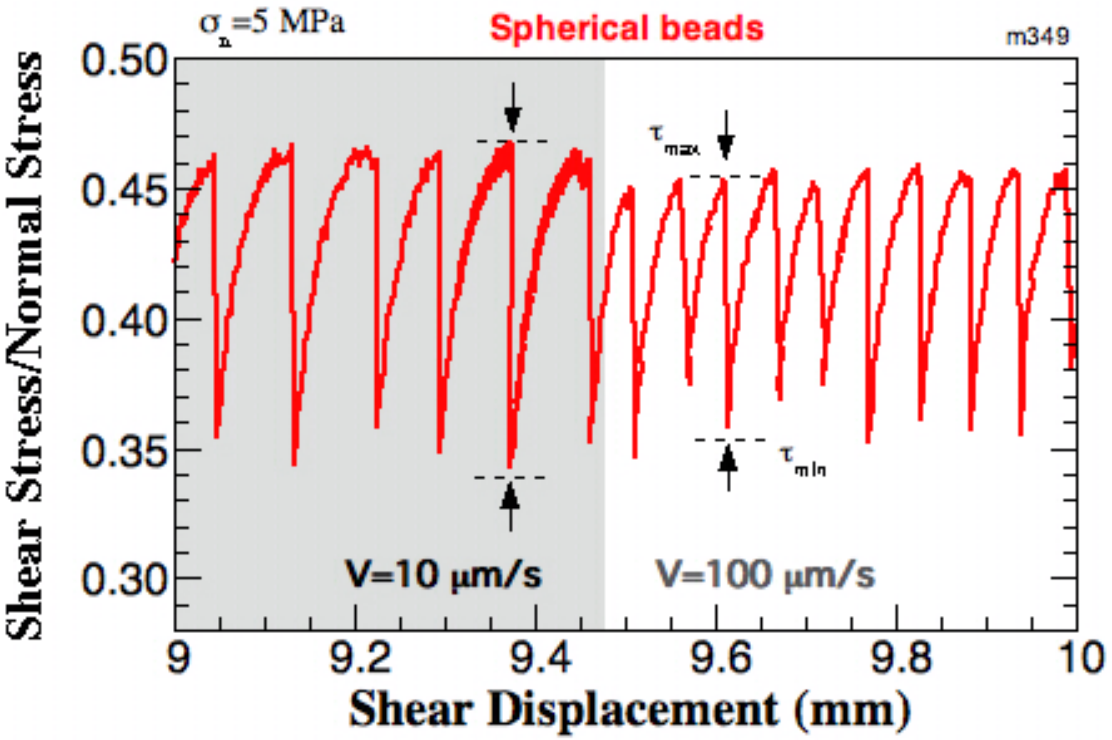
But, there's a problem……..





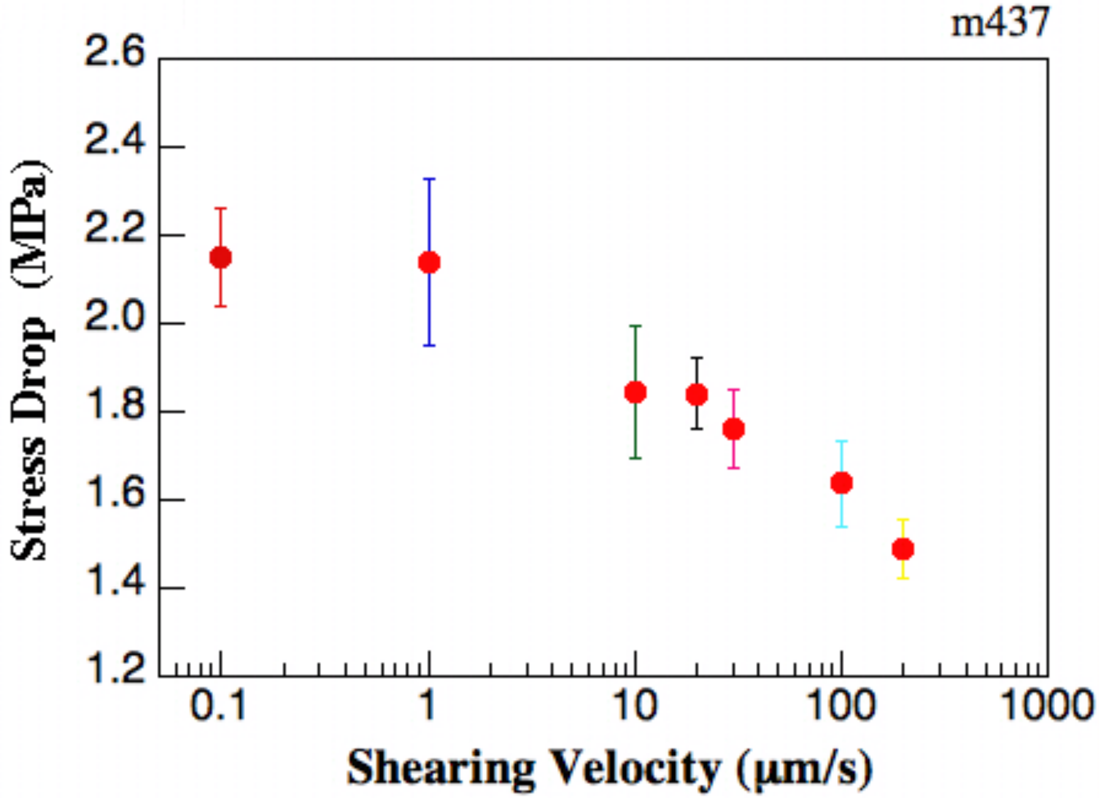
Mair, Frye and Marone, JGR 2002

Repetitive Stick-Slip Instability, like the seismic cycle



Stick-slip stress-drop varies with loading rate.

Mair, Frye and Marone, JGR 2002



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

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

state variable, characterizes physical state of surface or shearing region

critical slip distance

reference velocity

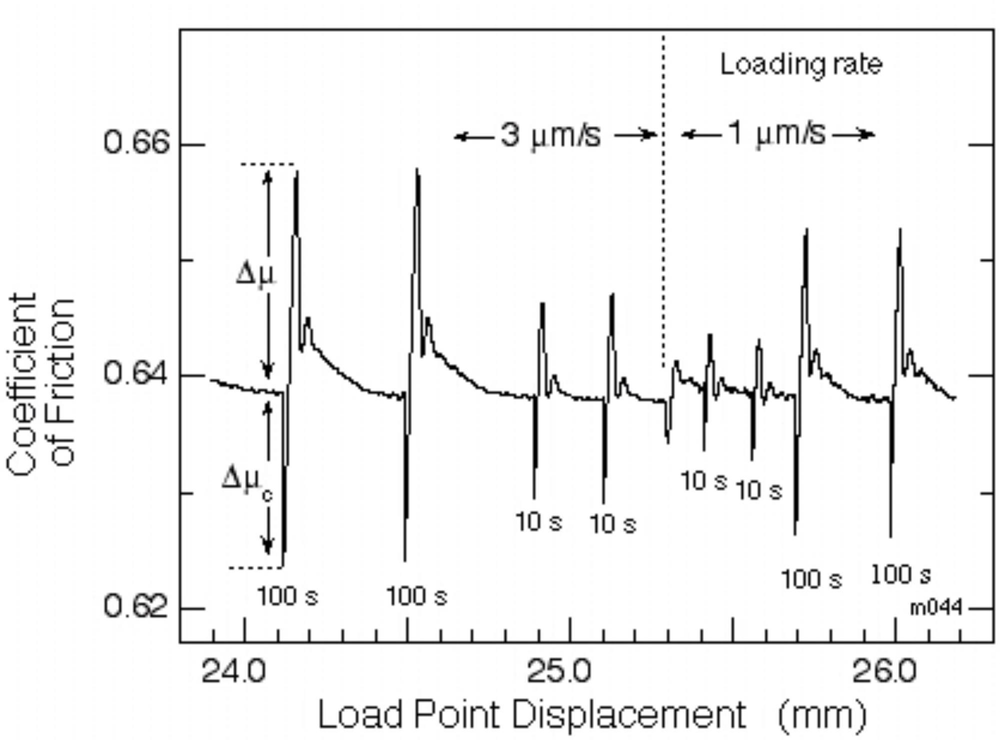
reference value of base friction

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

Dieterich, aging law

$$\frac{d\theta}{dt} = -\frac{V\theta}{D_c} ln\left(\frac{V\theta}{D_c}\right)$$

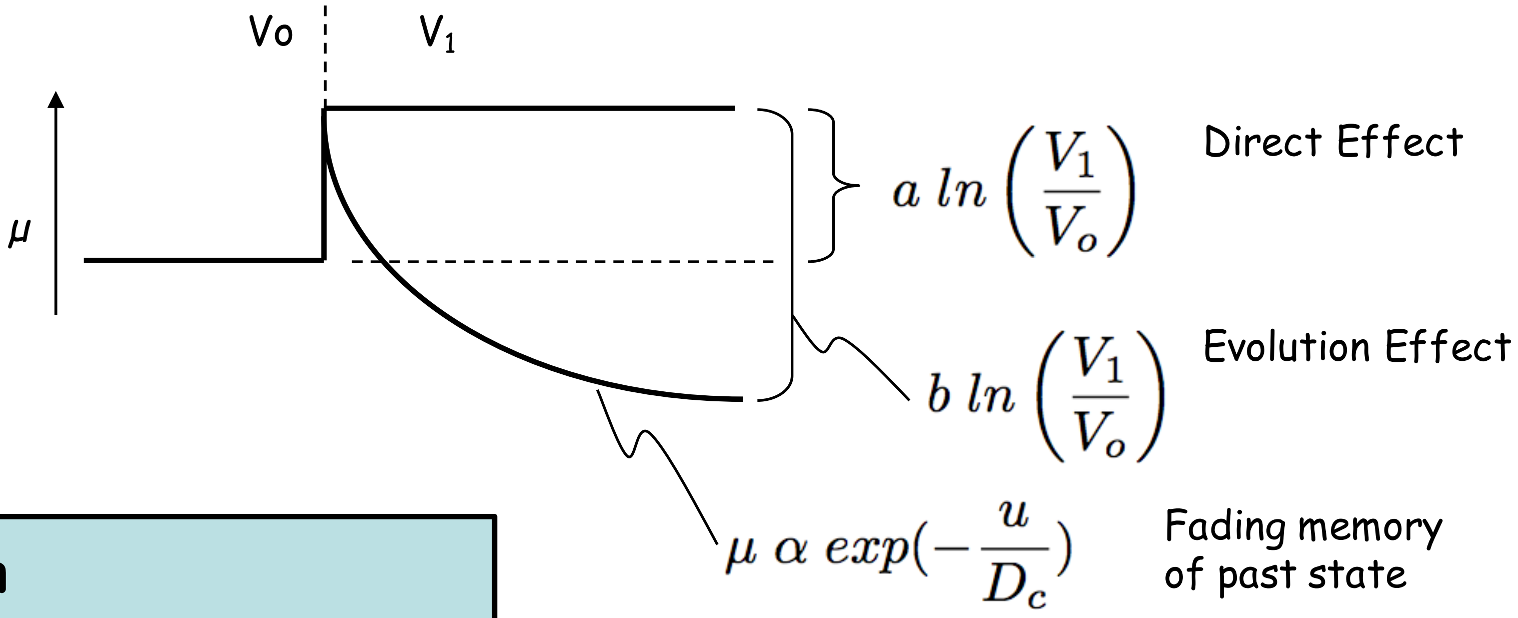
Ruina, slip law



Stick-Slip Instability Requires Some Form of Weakening:
Velocity Weakening, Slip Weakening, Thermal/hydraulic Weakening

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



Stability Criterion

$$K_c = \frac{\sigma_n (b-a)}{D_c}\left[1 + \frac{m{V_o}^2}{\sigma_n a D_c}\right]$$

(b > a), K < K_c Unstable, stick-slip

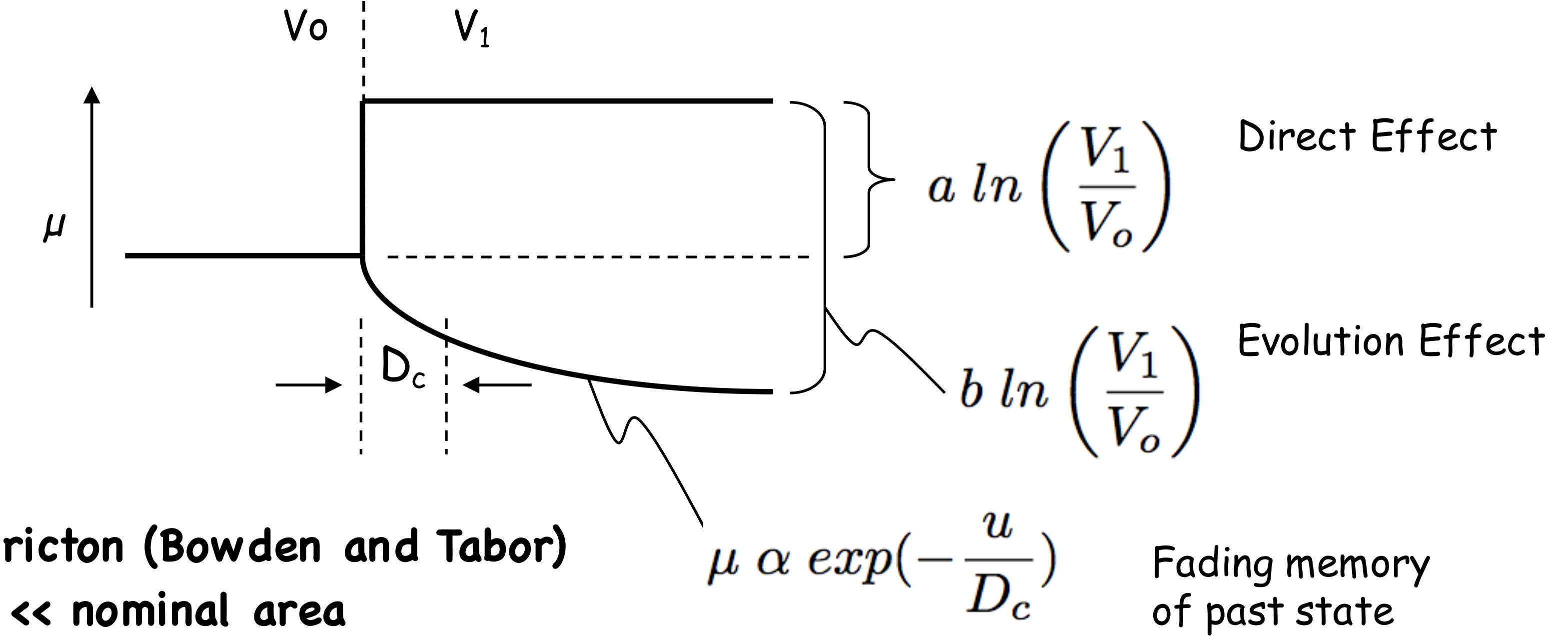
(a > b), K > K_c Stable sliding

K/K_c < 1

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

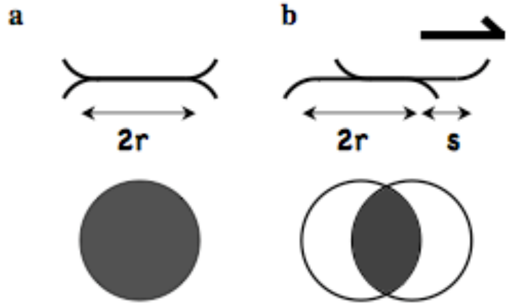
1) $\mu(\theta, V) = \mu_o + a\, ln\left(\frac{V}{V_o}\right) + b\, ln\left(\frac{V_o\theta}{D_c}\right)$

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



Adhesive Theory of Fricton (Bowden and Tabor)

- Real contact area << nominal area
- Contact junctions at inelastic (plastic) yield strength
- Contacts grow with “age”
- Add: Rabinowicz’s observations of static/dynamic friction
- “Static” friction is higher than “Dynamic” friction because contacts are older (larger)
- -> implies that contact size decreases as velocfiy increases



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

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

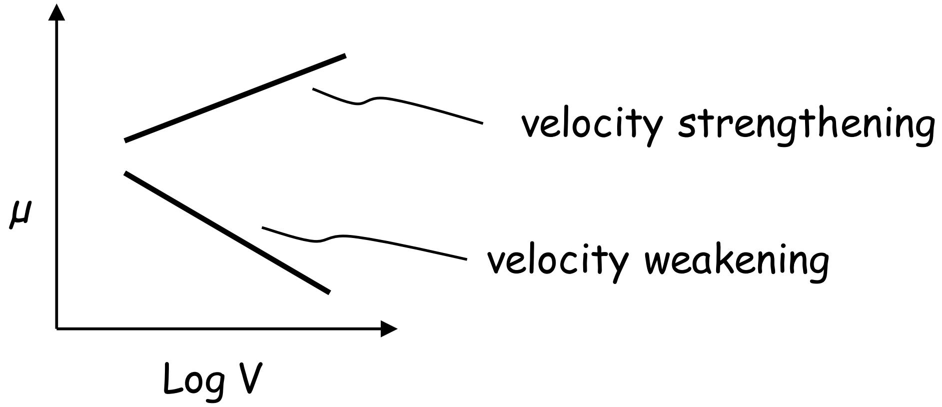
2) $$\frac{d\theta}{dt} = 1 - \frac{V\theta}{D_c}$$

Convention is to use a, b for friction and A, B for Stress

$$\tau(\theta, v) = \tau_o + A\, ln\left(\frac{V}{V_o}\right) + B\, ln\left(\frac{V_o\theta}{D_c}\right)$$

$$A - B = \frac{\Delta\tau}{\Delta lnV}$$

Steady-state velocity strengthening if a-b > 0,
velocity weakening if a-b < 0



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

Modeling experimental data

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

$$V = V_o\, exp\left[\frac{\mu - \mu_o - b\, ln(\frac{V_o\theta}{D_c})}{a}\right]$$

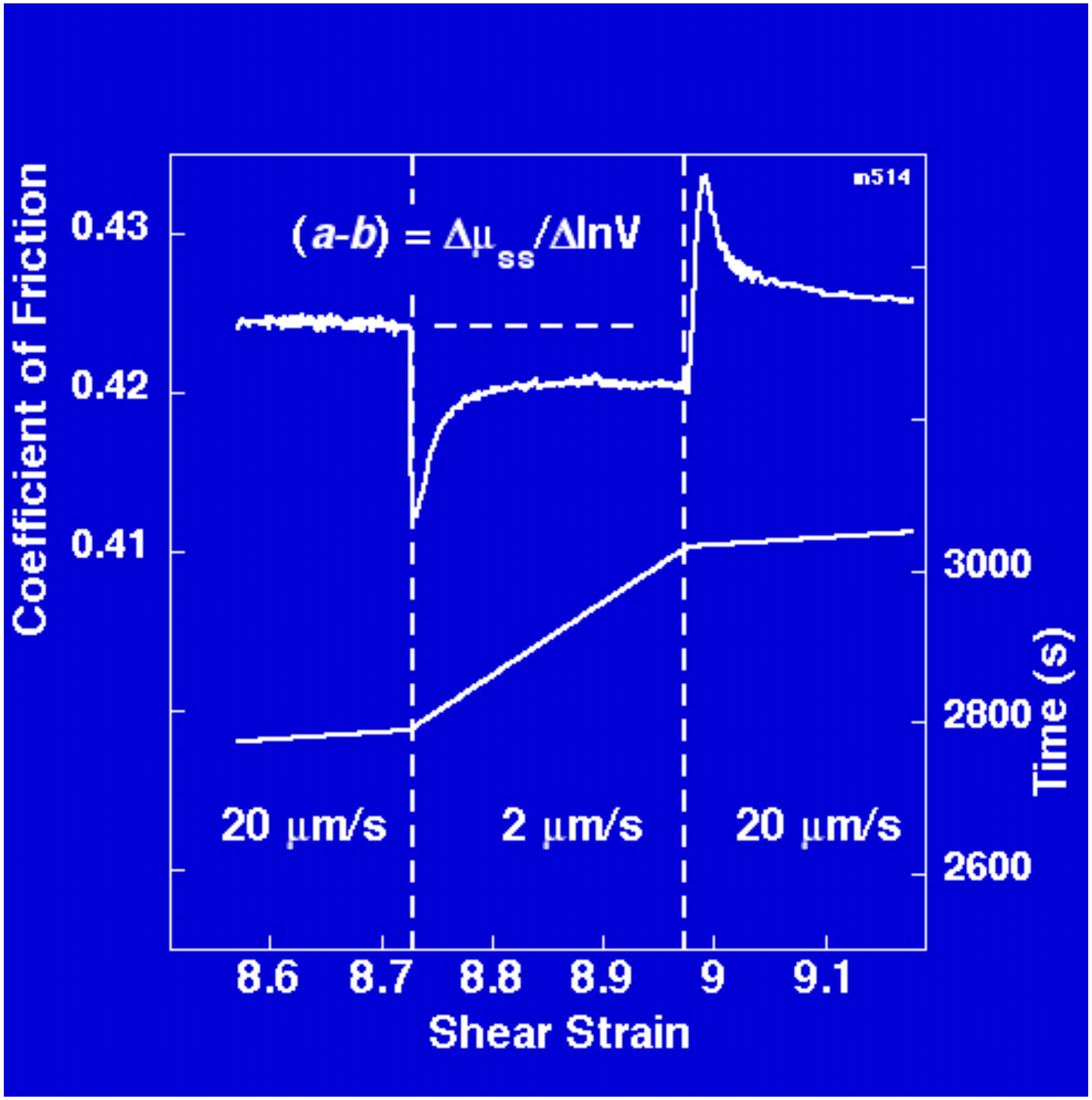
Solve:

$$\frac{d\mu}{dt} = k\left(V_{lp} - V_o\, exp\left[\frac{\mu - \mu_o - b\, ln(\frac{V_o\theta}{D_c})}{a}\right]\right)$$

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

Measuring the velocity dependence of friction

Frictional Instability
Requires (a-b) < 0



Constitutive Modelling

Rate and State Friction Law

Elastic Interaction, Testing Apparatus

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

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

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

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

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

Perturbations in normal force

Rate and State Friction Theory

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

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

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

(Linker & Dieterich, 1992)

Elastic Coupling

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

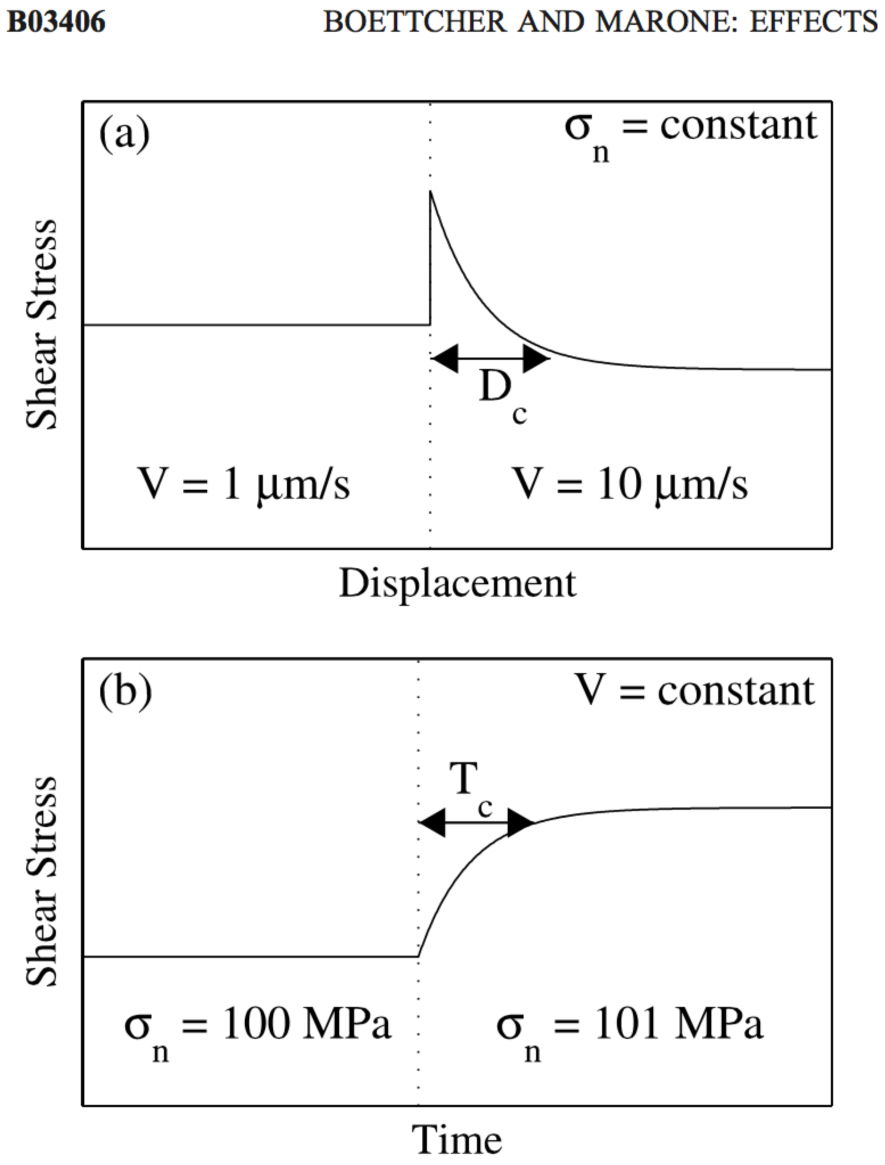
$$T_c = 2\pi \frac{D_c}{V} \sqrt{\frac{a}{b-a}}$$ *Critical Vibration Period*

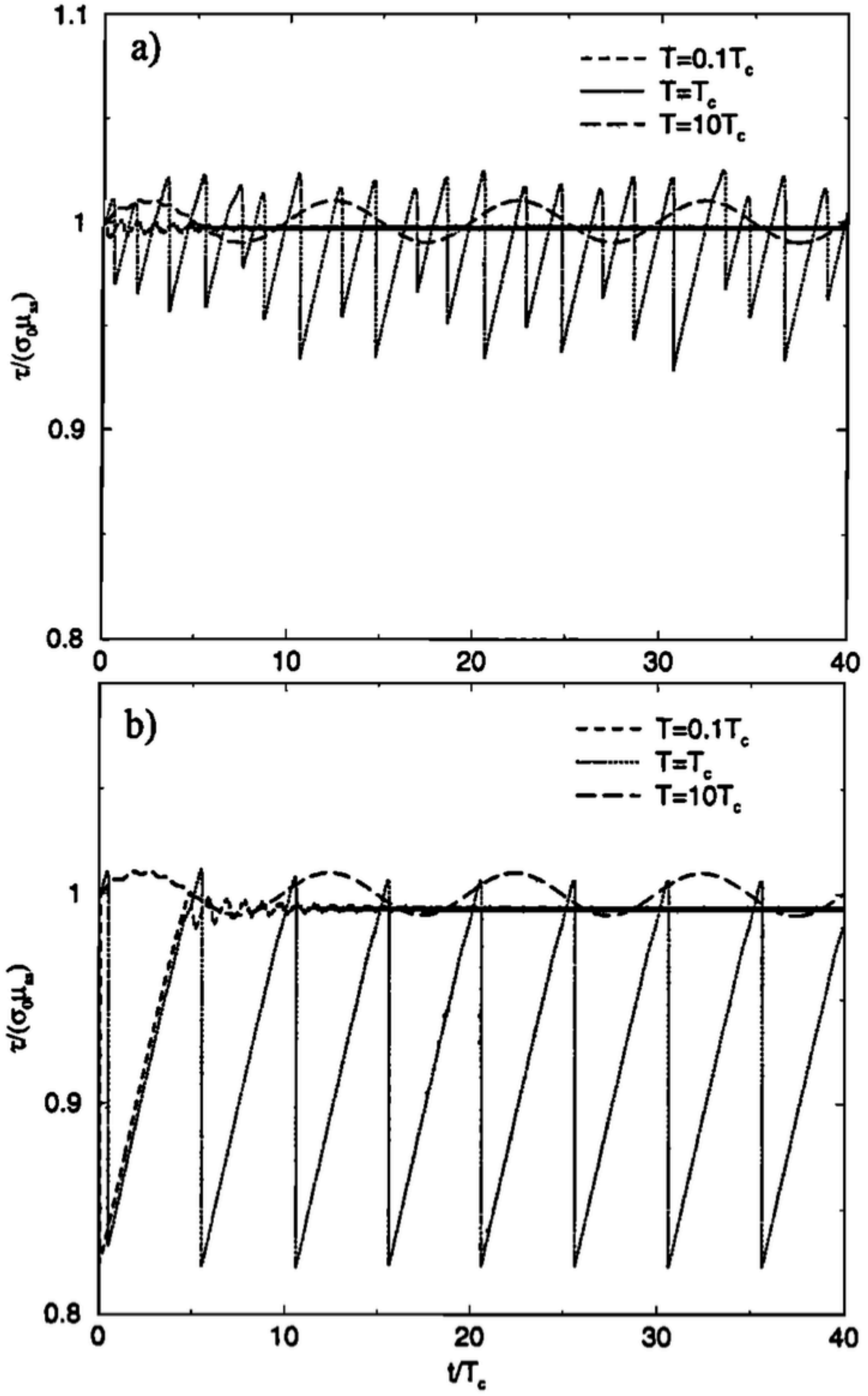
$$K_c = \sigma \frac{\left(b-a\right)}{D_c} + \frac{m v_0^2 \left(b-a\right)}{D_0^2}$$ *Critical Stiffness*

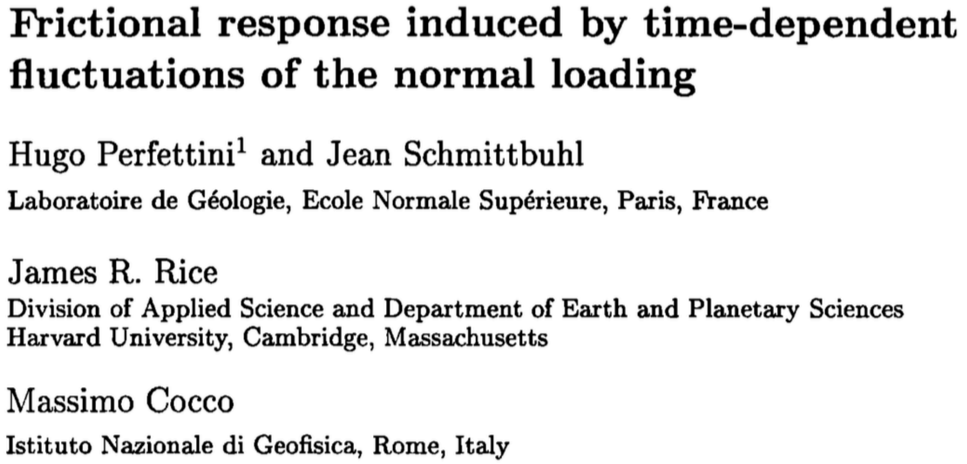
Perturbations in normal force

Rate and State Friction Theory

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







Frictional response induced by time-dependent fluctuations of the normal loading

Hugo Perfettini[1] and Jean Schmittbuhl
Laboratoire de Géologie, Ecole Normale Supérieure, Paris, France

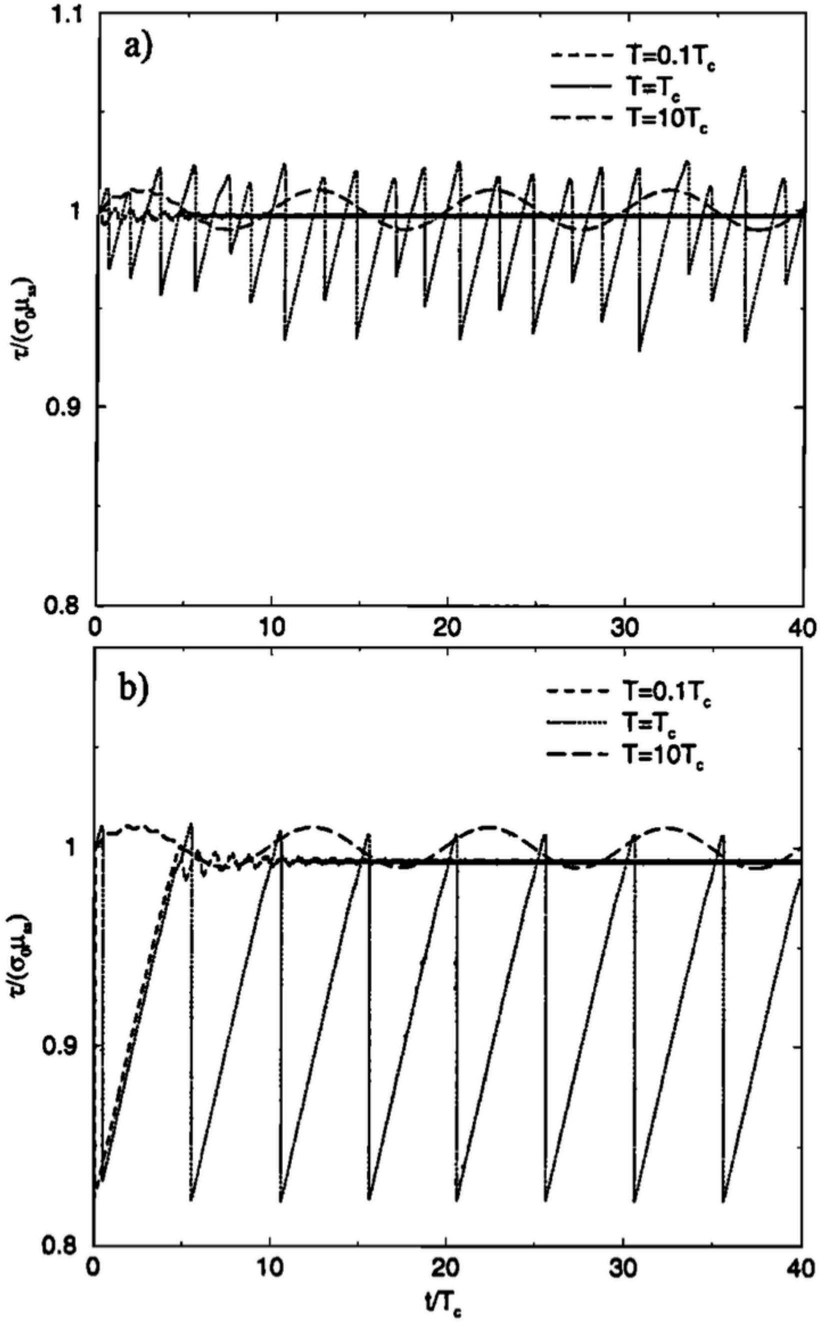
James R. Rice
Division of Applied Science and Department of Earth and Planetary Sciences
Harvard University, Cambridge, Massachusetts

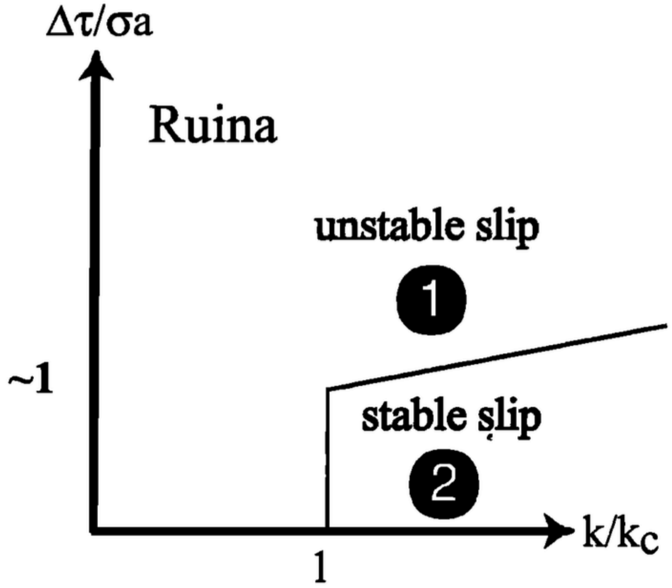
Massimo Cocco
Istituto Nazionale di Geofisica, Rome, Italy

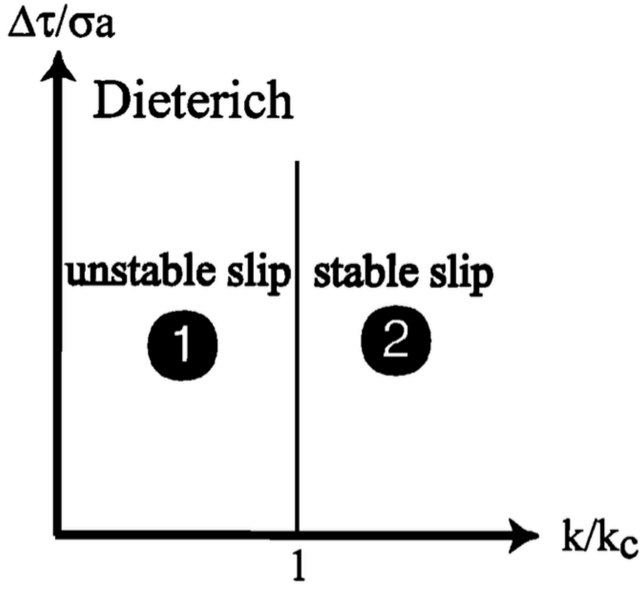
$$T_c = 2\pi \frac{D_c}{V} \sqrt{\frac{a}{b-a}}$$

Perfettini et al., 2001

Perfettini et al., 2001

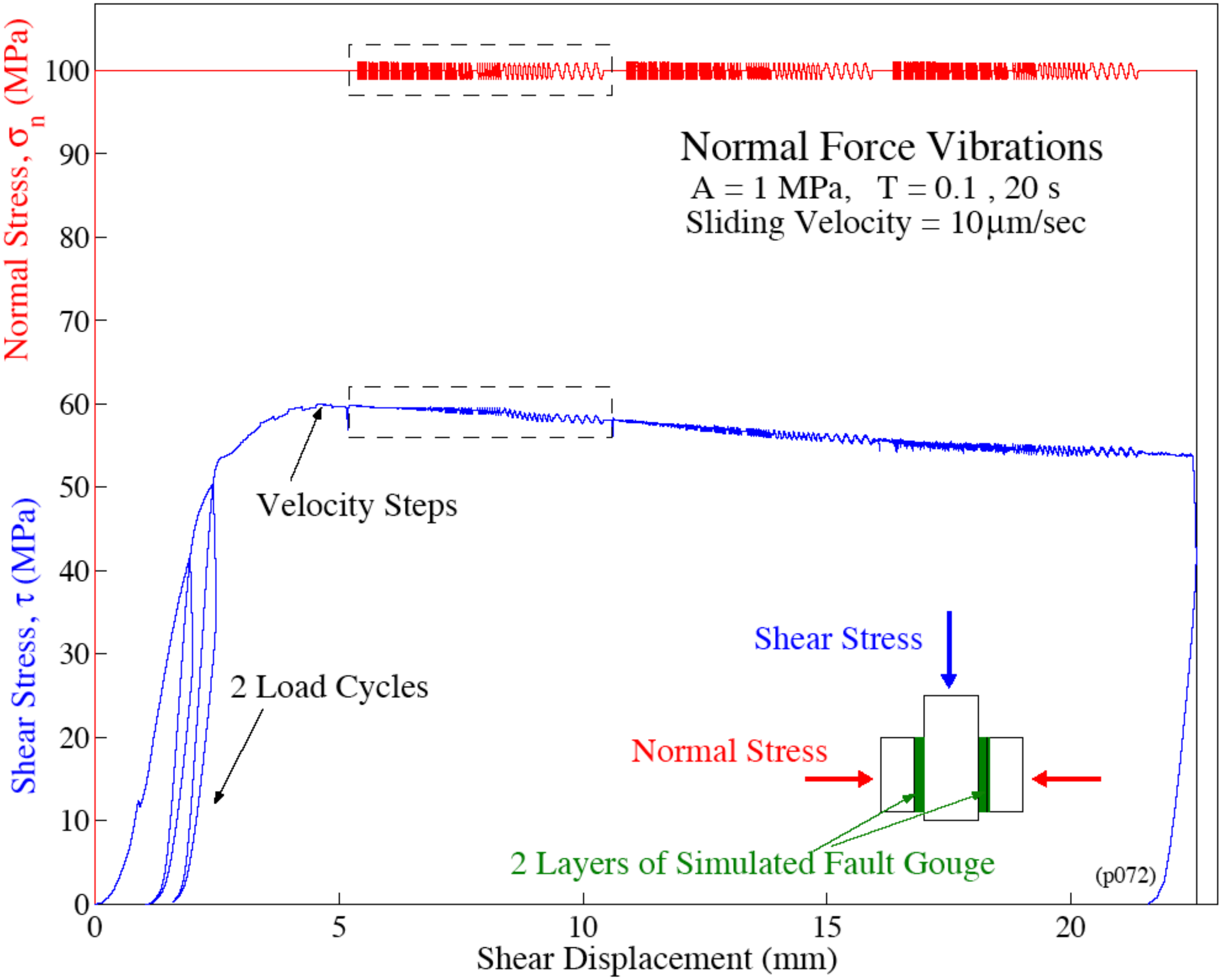




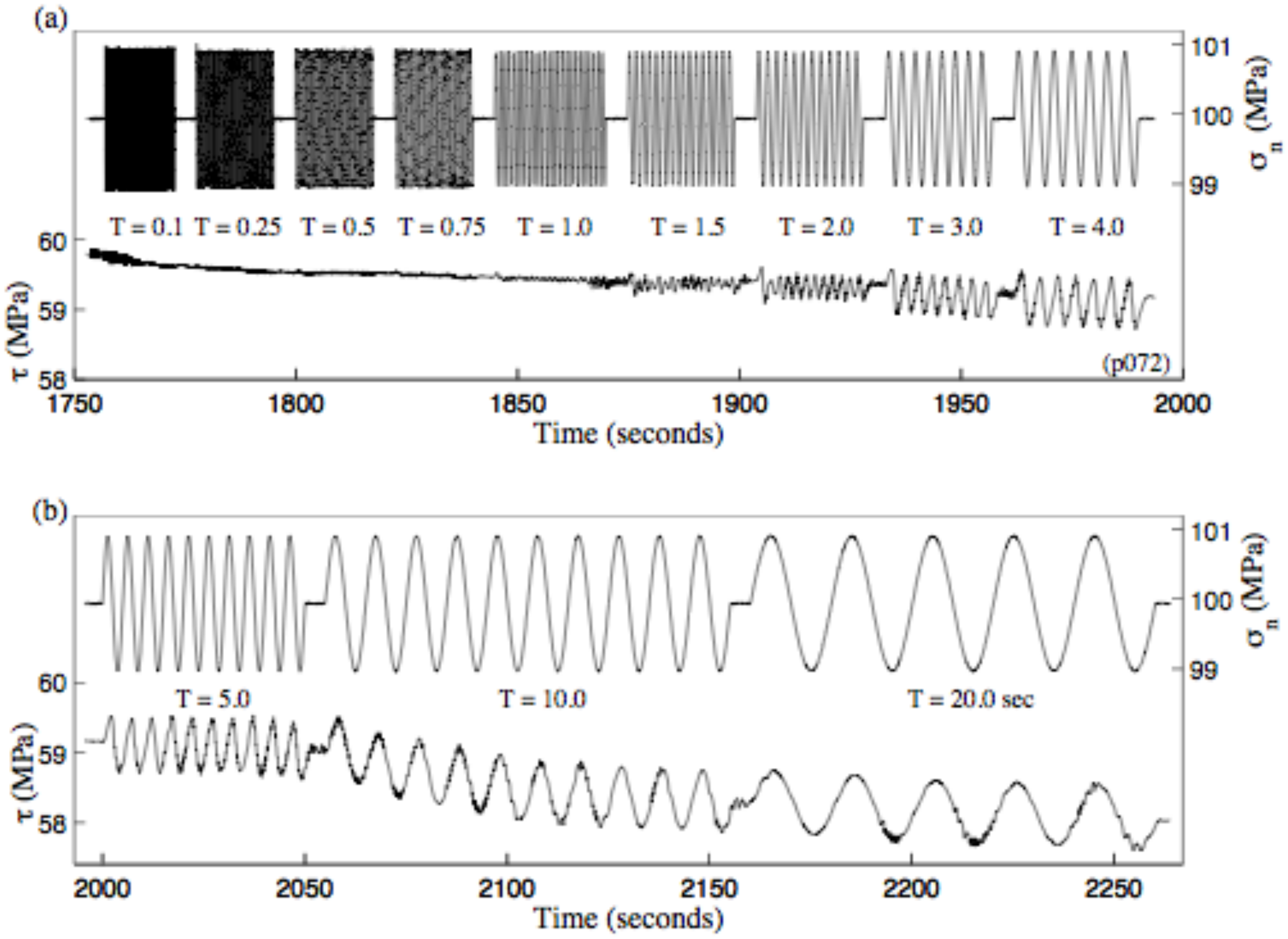


Lab: Normal Stress Vibrations
Critical period observed

Boettcher & Marone, JGR, 2004



Boettcher & Marone, JGR, 2004



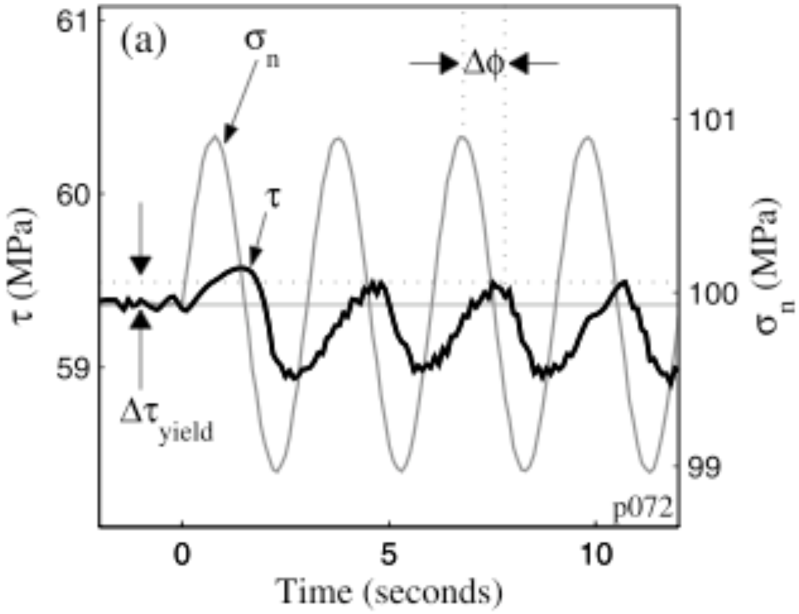
Critical period is ≈ 1 sec.

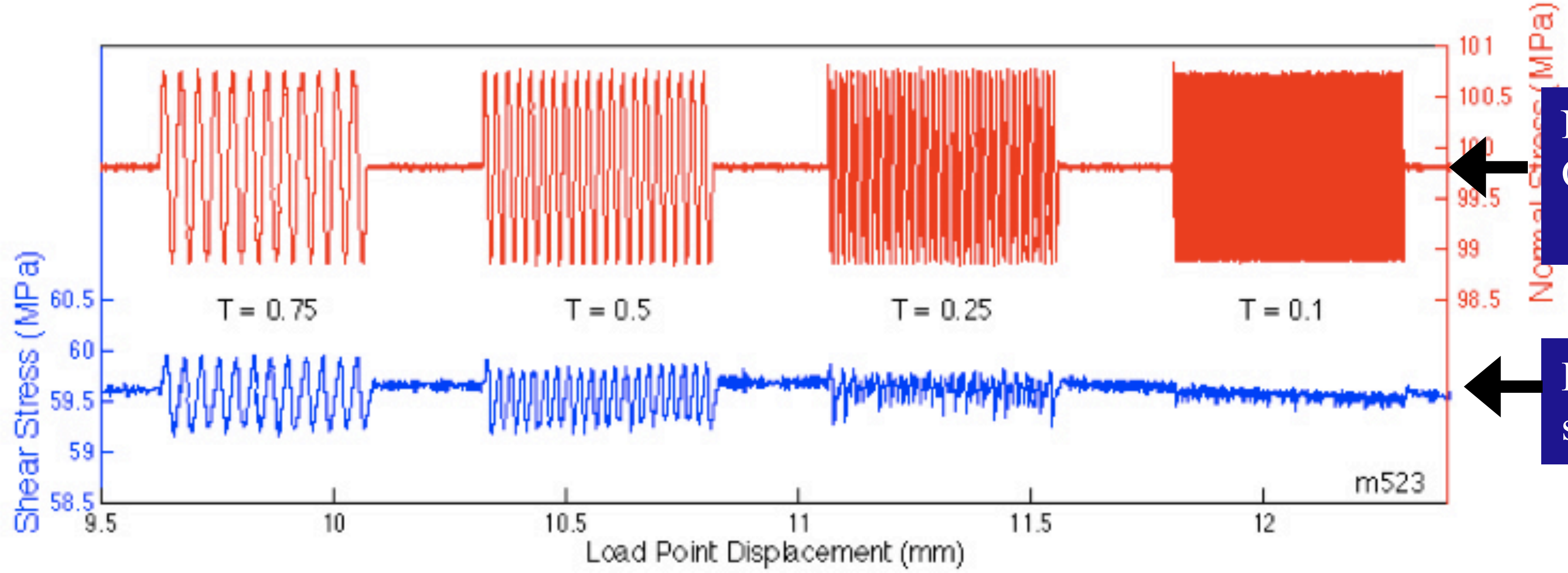
Boettcher & Marone, JGR, 2004

Also, Phase lag.

Friction response lags stressing.

Could explain delayed triggering?





Normal Stress Oscillation

Frictional strength

Rate and State Friction

Dieterich, Scholz, Ruina, Rice

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

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

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

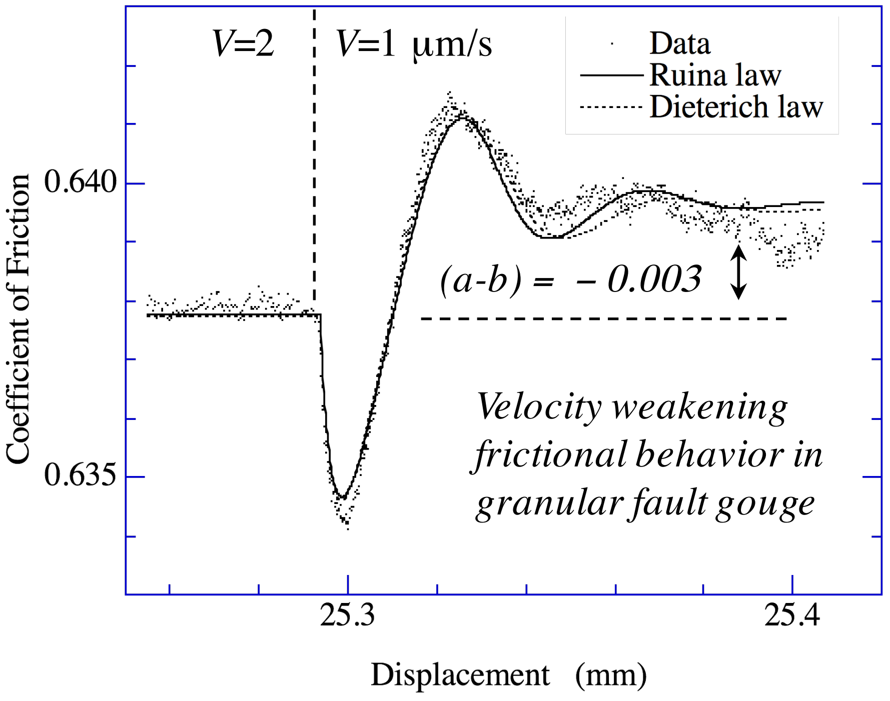
$$\theta_{ss} = \frac{D_c}{v}$$

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

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

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

Empirical laws, based on laboratory friction data



Velocity weakening frictional behavior in granular fault gouge

Thermally-activated process

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

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

The Mechanics of Slow Earthquakes and the Spectrum of Fault Slip Behaviors

1. Friction laws: why do we need something as complex as rate/state?

2. How do slow earthquakes work? What mechanism sets the speed limit? *Why are they slow?*

3. Speculations on how recent lab results may in apply in nature. Scaling laws for a spectrum of slip modes from slows earthquakes to super-shear rupture (SSE, LFE, tremor, VLFE, ULFE, MLFE, BB-eq, elasto-dynamic EQs) .

Slow Earthquakes and The spectrum of fault slip behaviors

Ordinary earthquakes, Subduction megathrust earthquakes, Creep events, Tremor, Low frequency earthquakes, Very low frequency earthquakes, Episodic tremor and slip (ETS), Long term slow slip events, Slow Precursors, Geodetic transients

LETTER

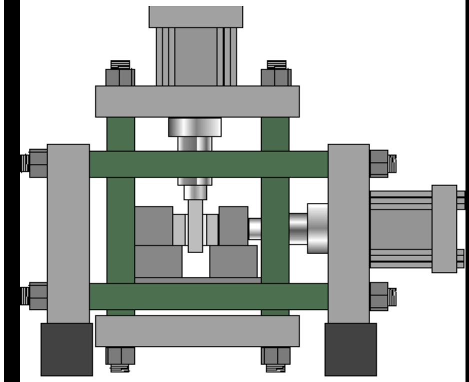
doi:10.1038/nature17190

The Parkfield tremors reveal slow and fast ruptures on the same asperity

Deepa Mele Veedu[1] & Sylvain Barbot[1]

Veedu & Barbot, 2016

PennState



John Leeman

Nature Communications 2016

ARTICLE

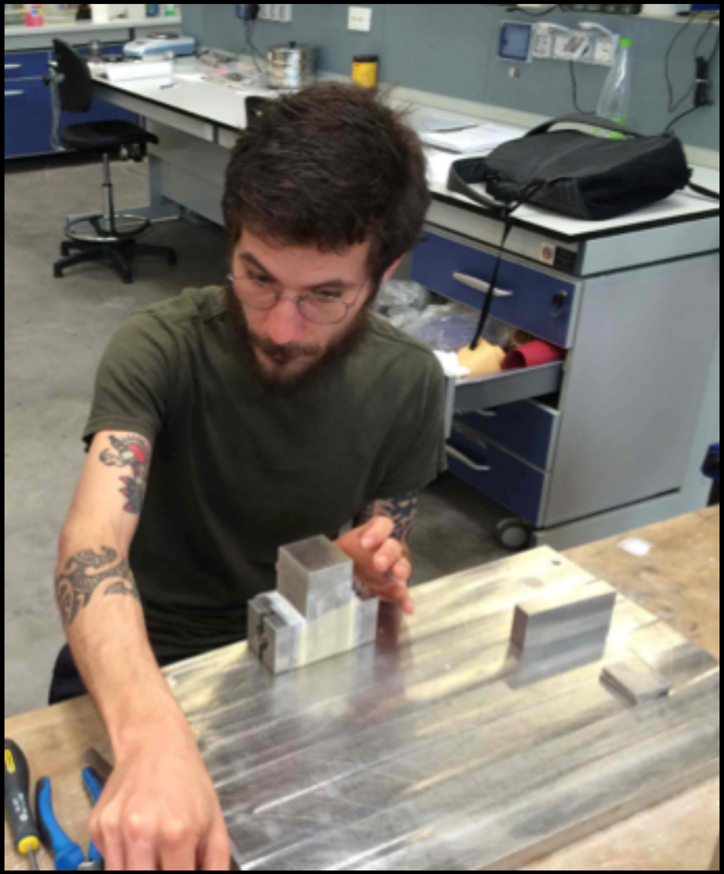
Received 4 Nov 2015 | Accepted 19 Feb 2016 | Published 31 Mar 2016

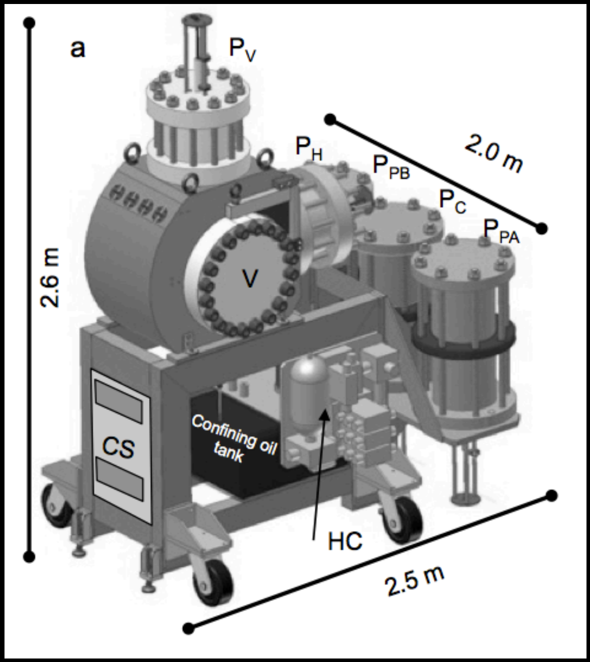
DOI: 10.1038/ncomms11104 OPEN

Laboratory observations of slow earthquakes and the spectrum of tectonic fault slip modes

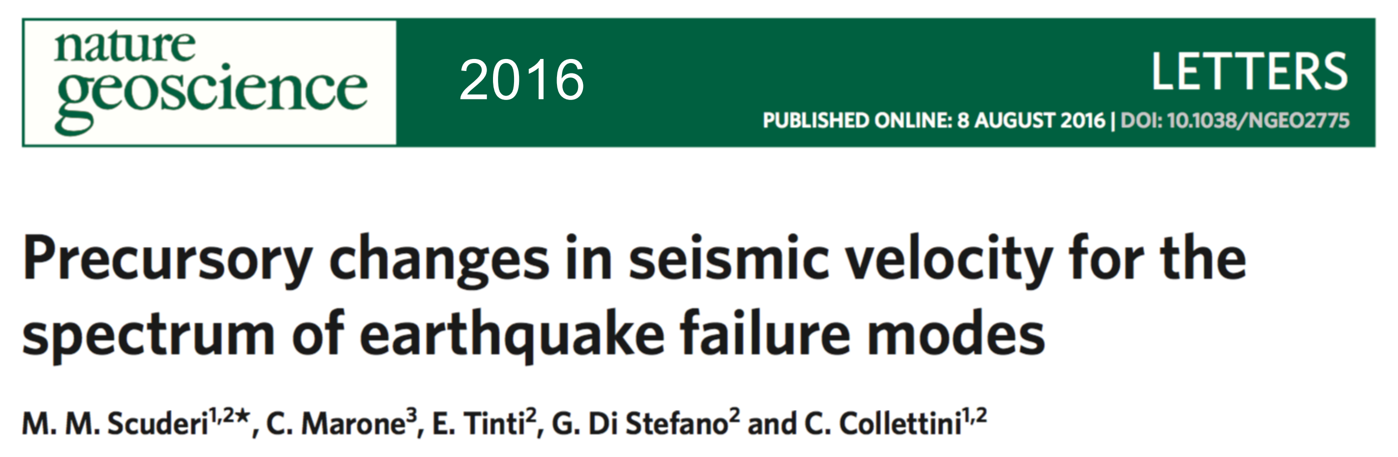
J.R. Leeman[1], D.M. Saffer[1], M.M. Scuderi[1,2] & C. Marone[1]

Marco Scuderi





SAPIENZA
UNIVERSITÀ DI ROMA

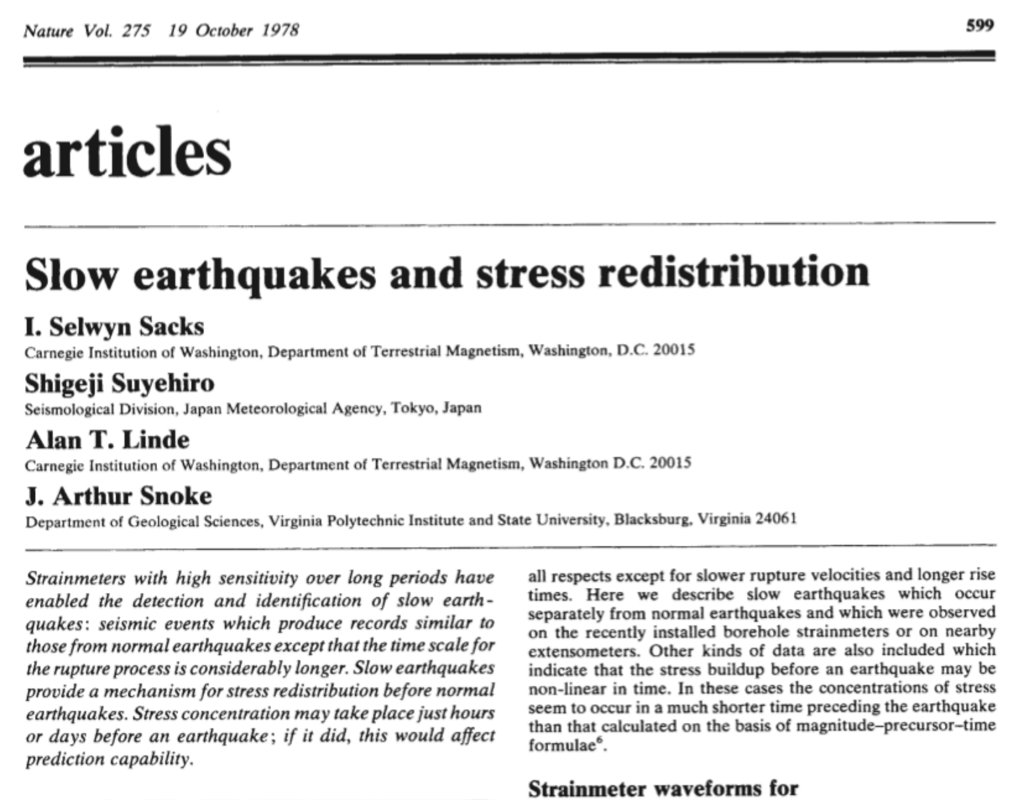


nature geoscience
2016
LETTERS

Precursory changes in seismic velocity for the spectrum of earthquake failure modes

M. M. Scuderi[1,2]*, C. Marone[3], E. Tinti[2], G. Di Stefano[2] and C. Collettini[1,2]

Slow Earthquakes and the spectrum of fault slip behavior



Nature Vol. 275 19 October 1978 599

articles

Slow earthquakes and stress redistribution

I. Selwyn Sacks
Carnegie Institution of Washington, Department of Terrestrial Magnetism, Washington, D.C. 20015
Shigeji Suyehiro
Seismological Division, Japan Meteorological Agency, Tokyo, Japan
Alan T. Linde
Carnegie Institution of Washington, Department of Terrestrial Magnetism, Washington D.C. 20015
J. Arthur Snoke
Department of Geological Sciences, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061

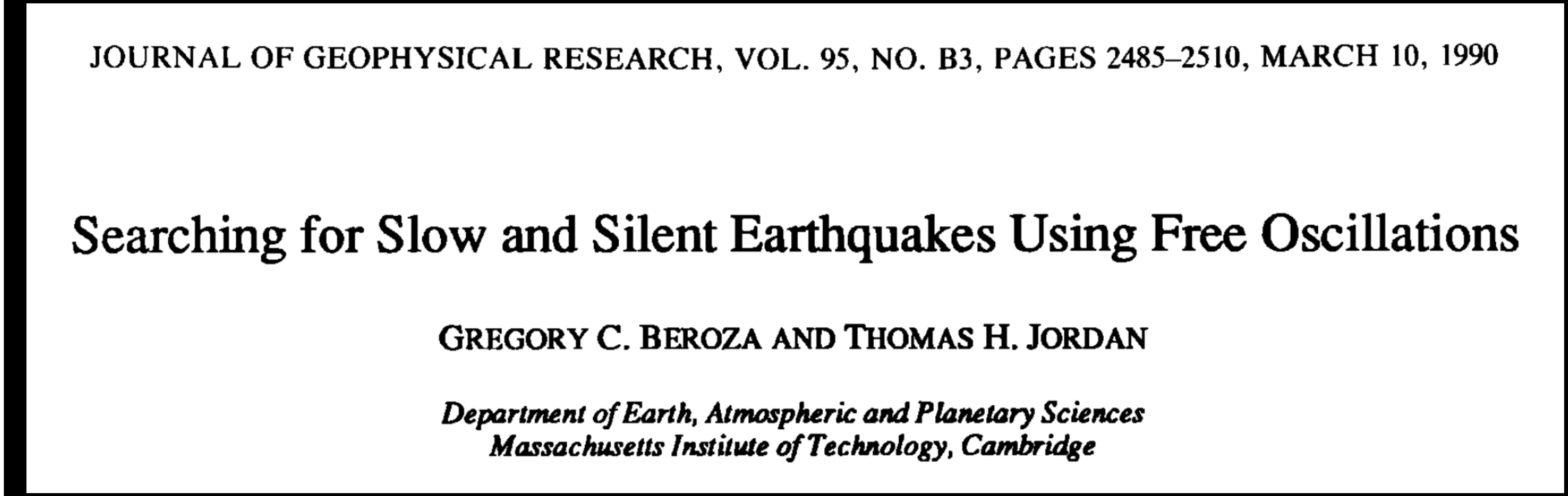
Strainmeters with high sensitivity over long periods have enabled the detection and identification of slow earthquakes: seismic events which produce records similar to those from normal earthquakes except that the time scale for the rupture process is considerably longer. Slow earthquakes provide a mechanism for stress redistribution before normal earthquakes. Stress concentration may take place just hours or days before an earthquake; if it did, this would affect prediction capability.

all respects except for slower rupture velocities and longer rise times. Here we describe slow earthquakes which occur separately from normal earthquakes and which were observed on the recently installed borehole strainmeters or on nearby extensometers. Other kinds of data are also included which indicate that the stress buildup before an earthquake may be non-linear in time. In these cases the concentrations of stress seem to occur in a much shorter time preceding the earthquake than that calculated on the basis of magnitude–precursor–time formulae[6].

Strainmeter waveforms for normal and slow earthquakes

Sacks et al., 1978

Beroza and Jordan, 1990



JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 95, NO. B3, PAGES 2485–2510, MARCH 10, 1990

Searching for Slow and Silent Earthquakes Using Free Oscillations

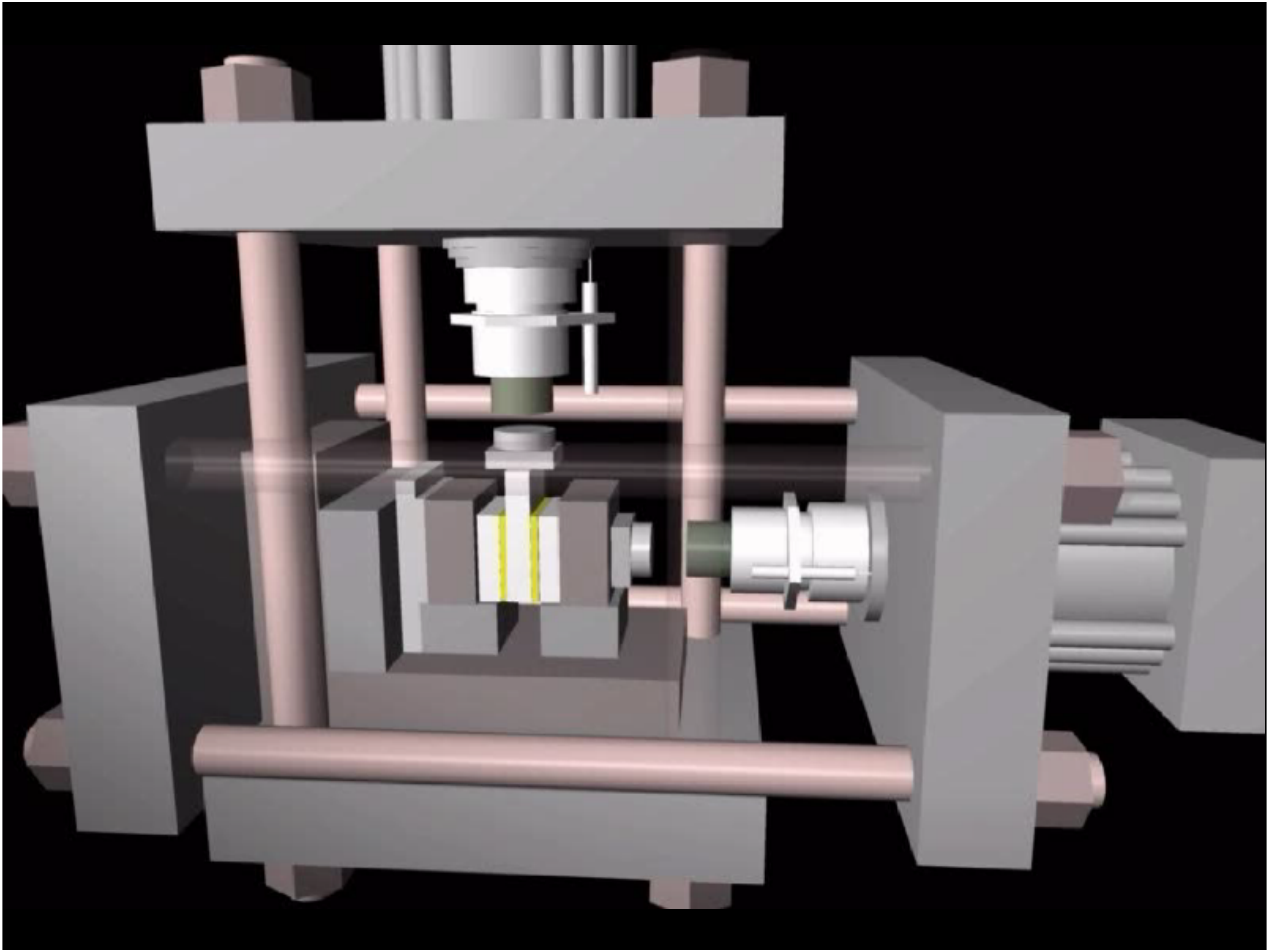
GREGORY C. BEROZA AND THOMAS H. JORDAN

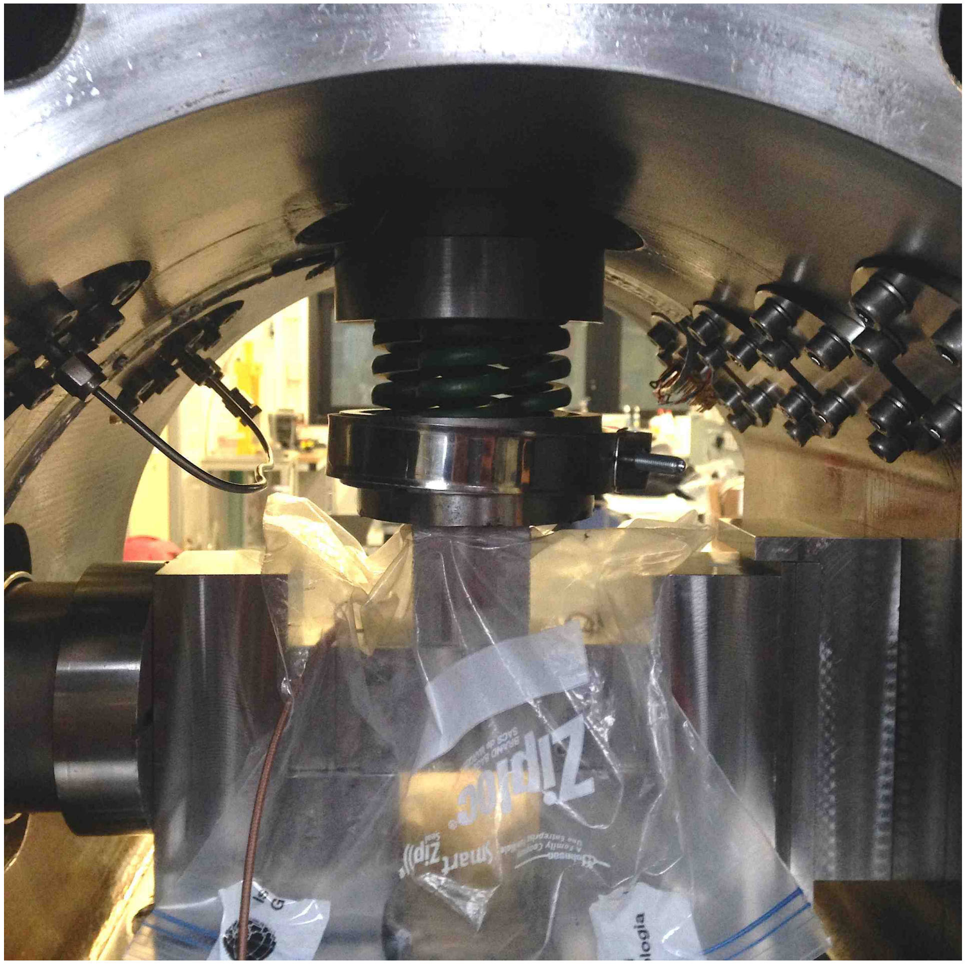
Department of Earth, Atmospheric and Planetary Sciences
Massachusetts Institute of Technology, Cambridge

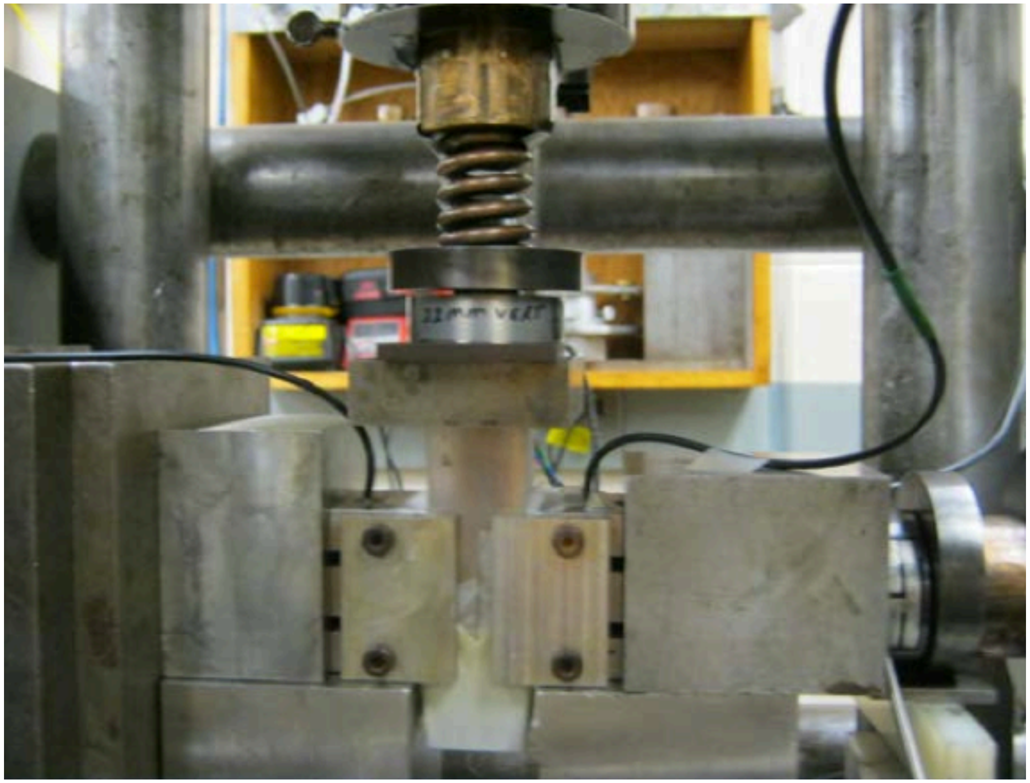
1. Slow earthquakes could represent quasi-dynamic frictional instability (positive feedback, self-driven instability)

2. Recent lab work shows repetitive stick-slip instability for the complete spectrum of slip behaviors – A new opportunity to investigate the mechanics of slow slip

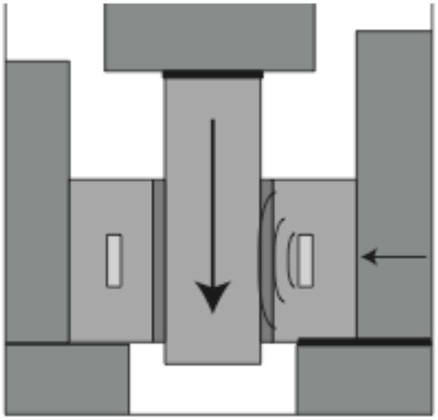
3. Mechanisms: *Why are they slow?*
    - Rate dependence of the critical rheologic stiffness Kc
    - Complex behavior near the stability boundary



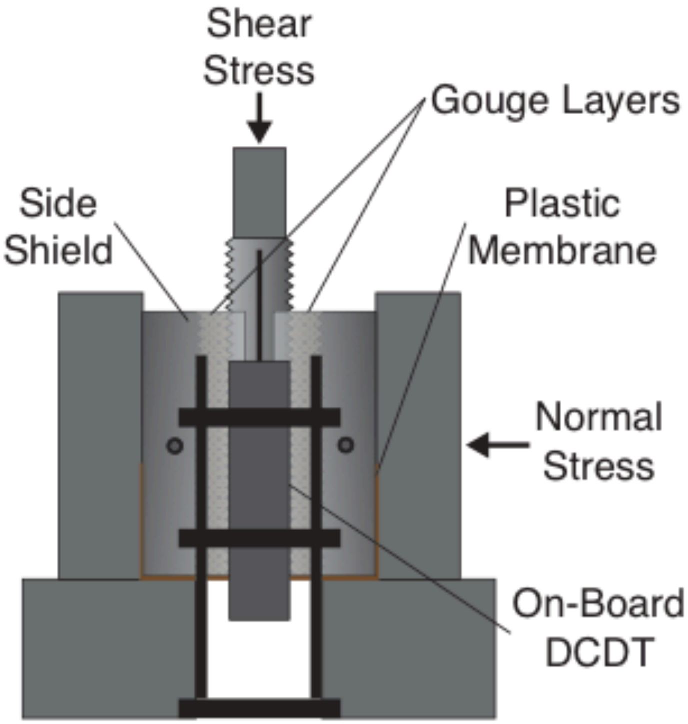

BRAVA at INGV (Rome)
Collettini Lab

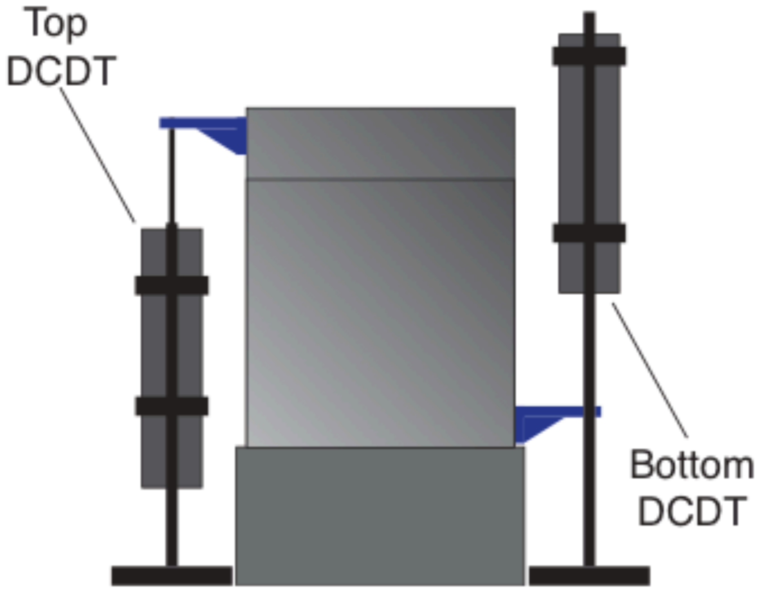

Biax at Penn State

Double direct shear with biaxial loading
and controlled loading stiffness

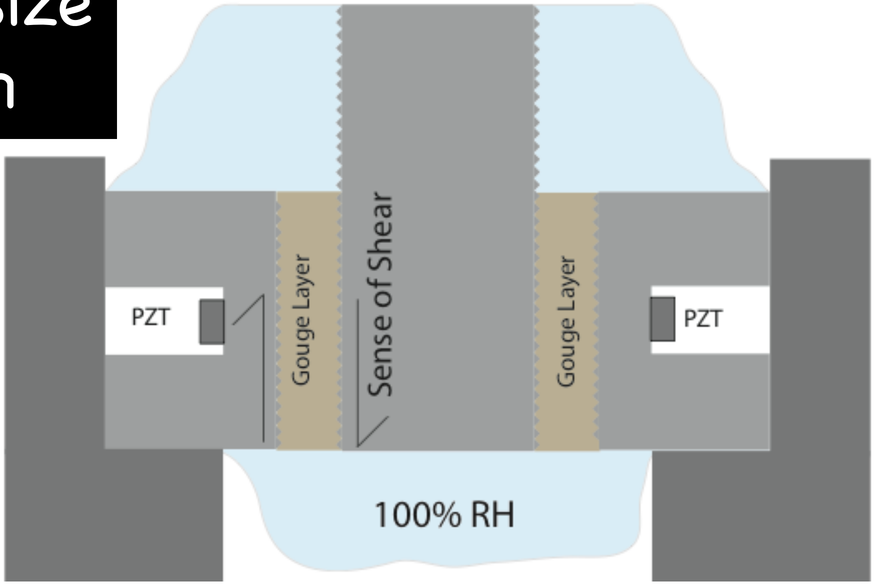


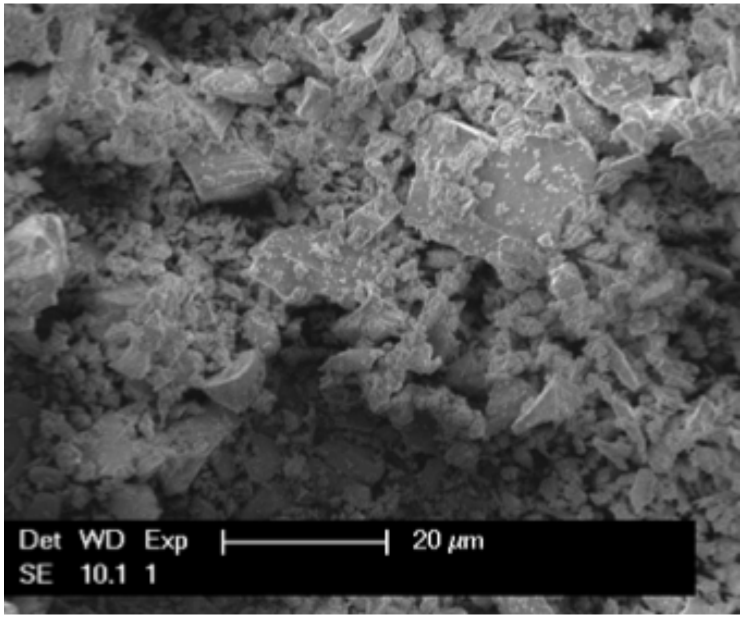
High-resolution, direct measurements of shear displacement, shear strain, normal strain, stresses





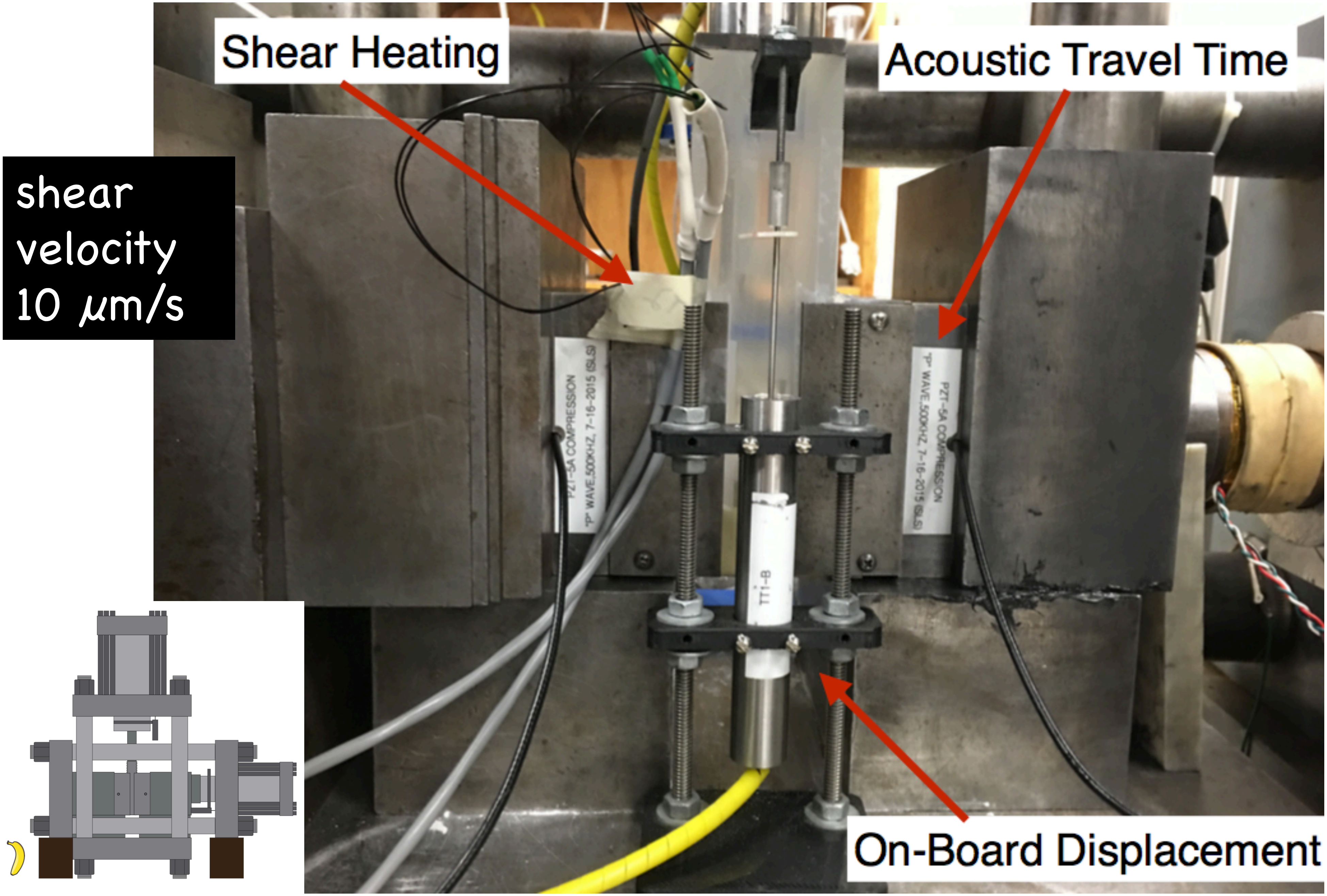
- Quartz powder
- grain size < 10μm





Biaxial testing machine at Penn State

shear
velocity
10 μm/s

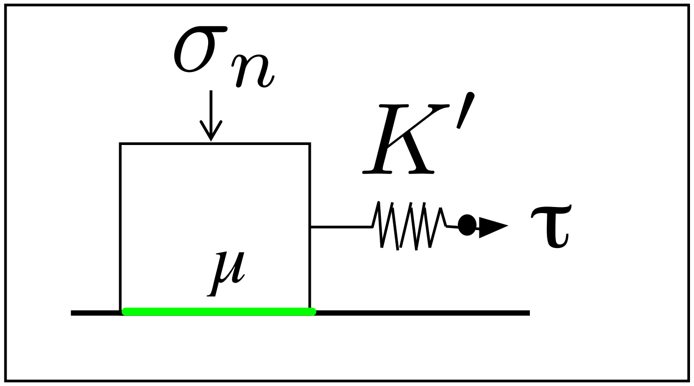


Shear Heating

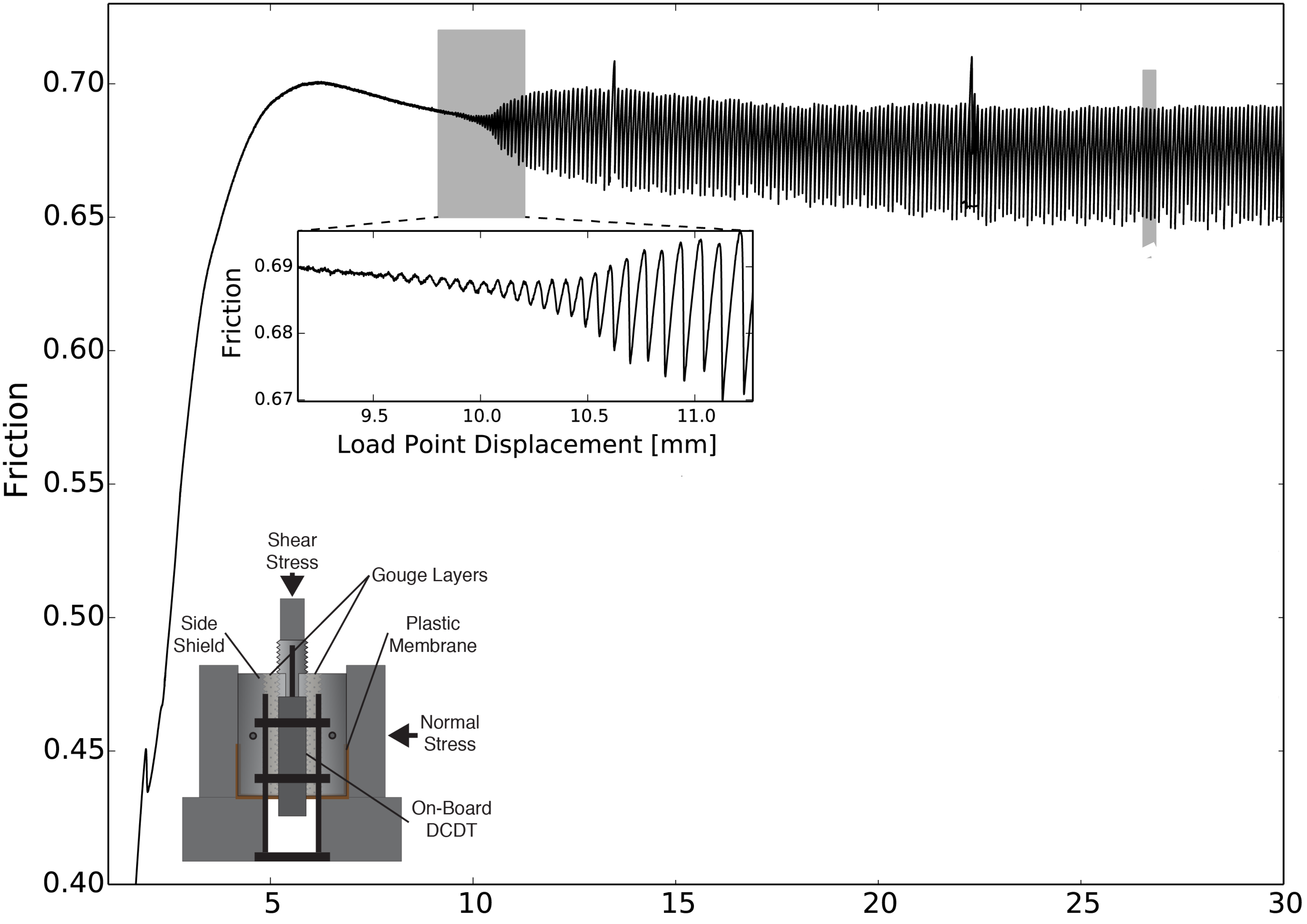
Acoustic Travel Time

On-Board Displacement

To get slow slip we modify the elastic loading stiffness and take advantage of natural variations in the frictional properties as a function of shear

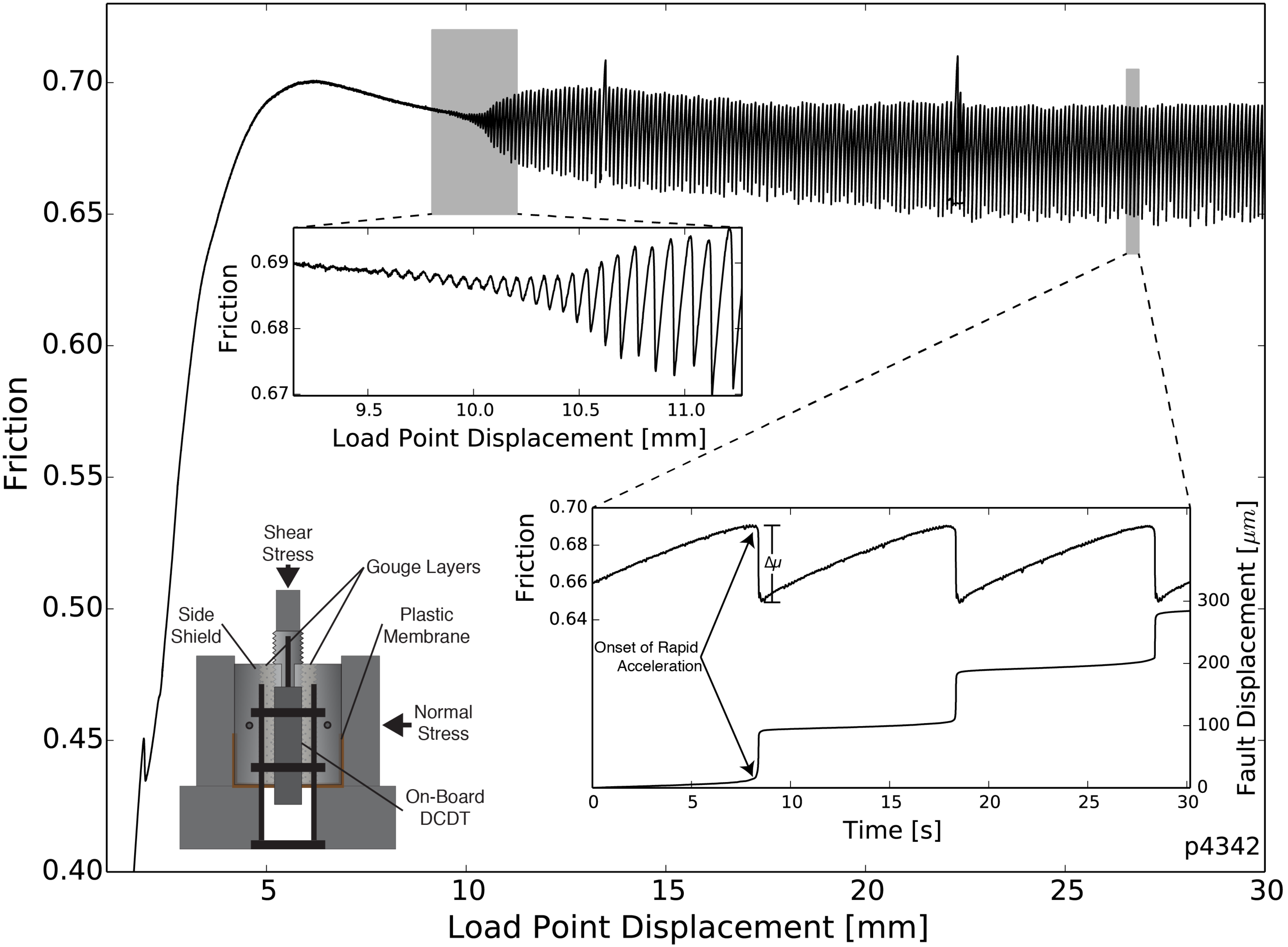


Repetitive Slow Stick-Slip



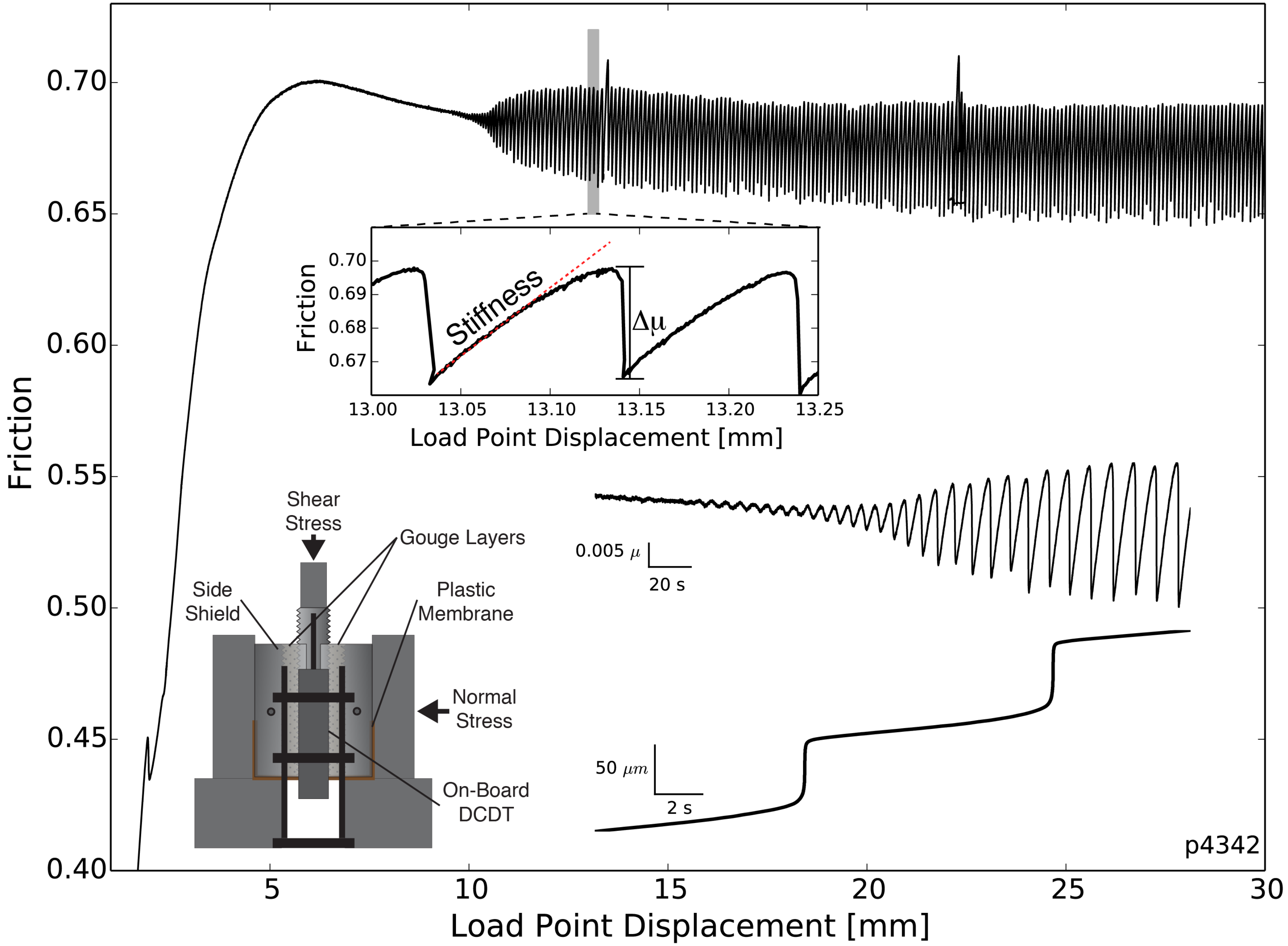
Leeman, Saffer, Scuderi & Marone, Nat. Comm. 2016

Repetitive Slow Stick-Slip



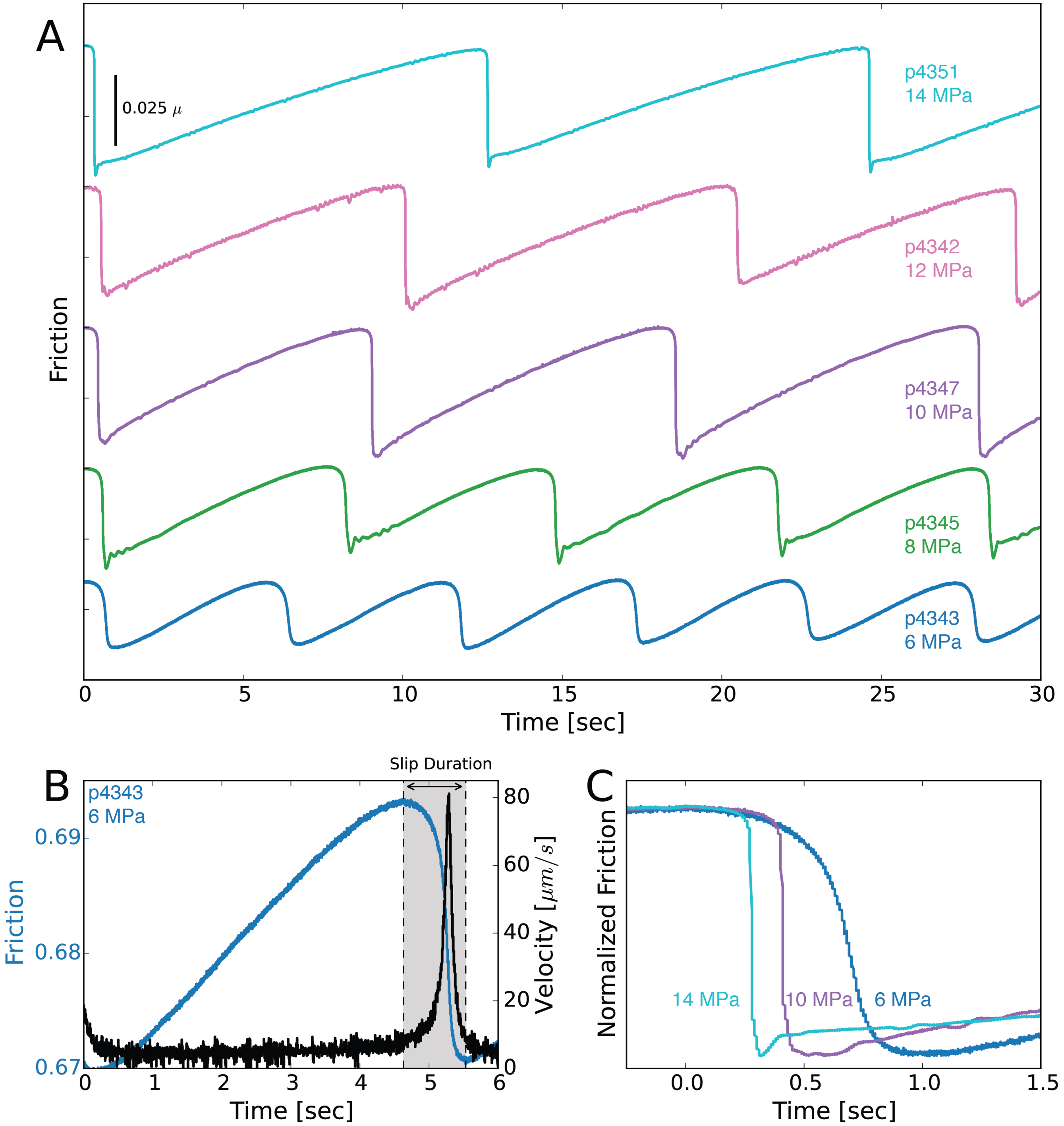
Leeman, Saffer, Scuderi & Marone, Nat. Comm. 2016

Repetitive Slow Stick-Slip

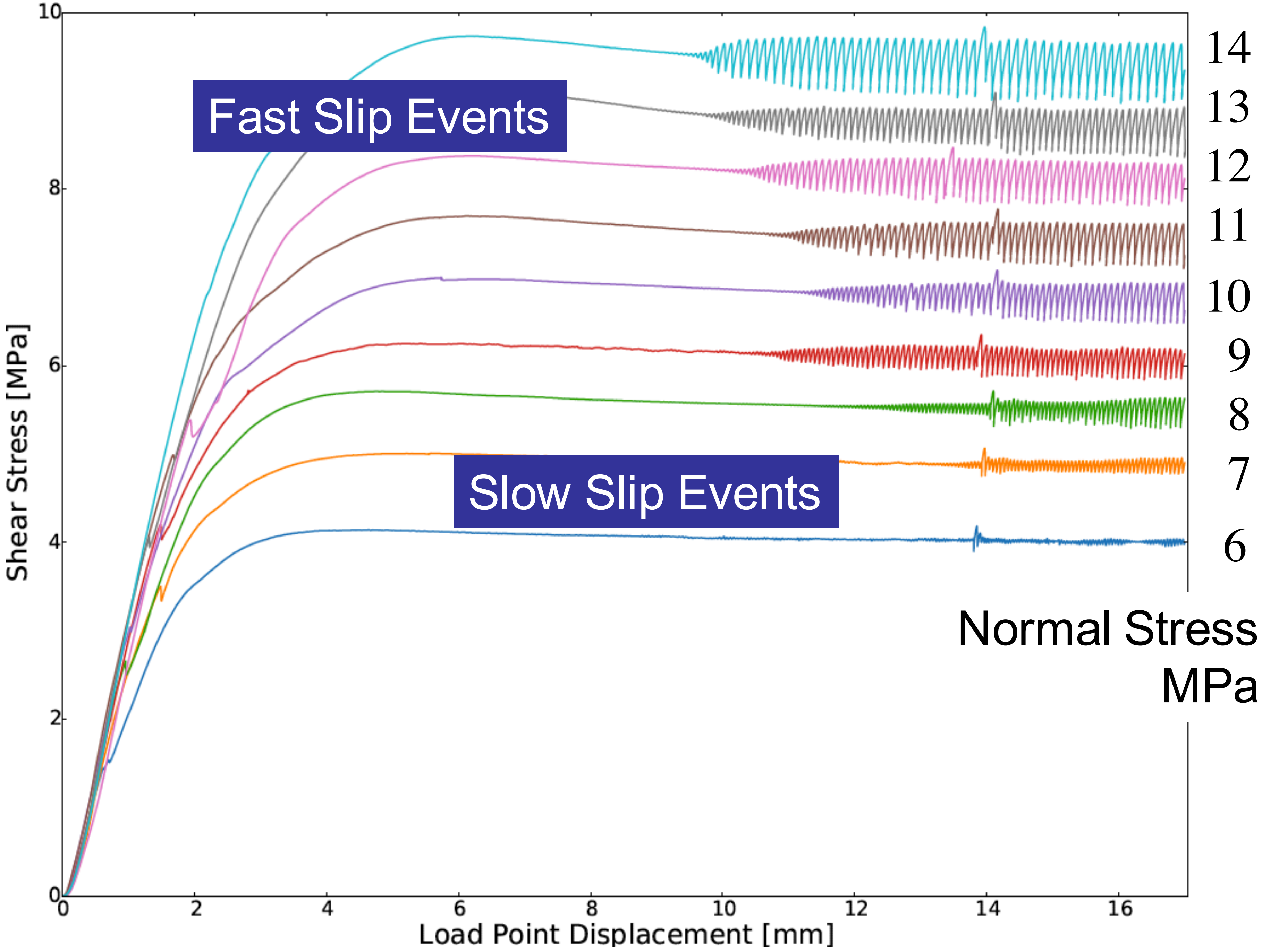


Leeman, Saffer, Scuderi & Marone, Nat. Comm. 2016

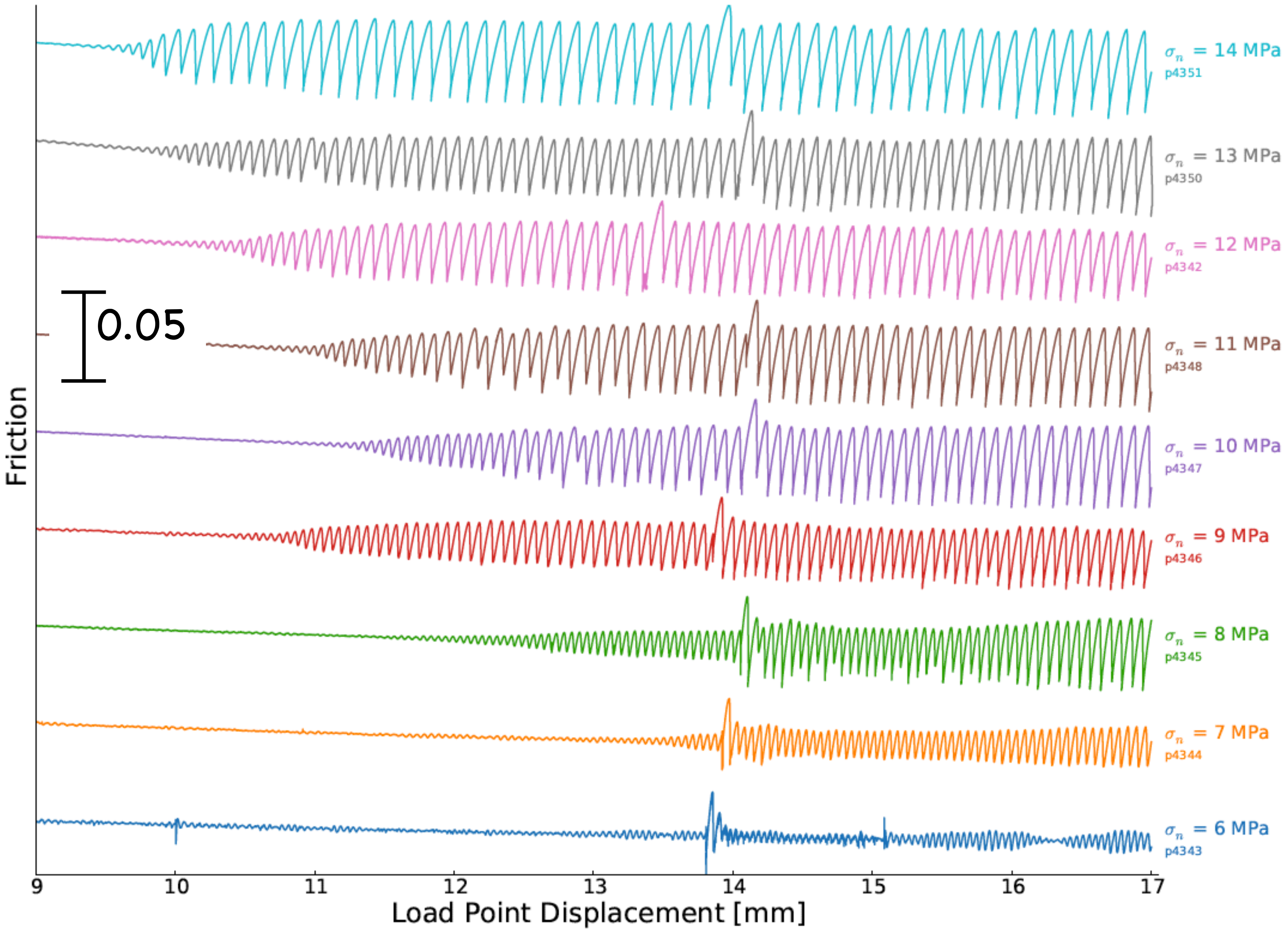
Repetitive Slow Stick-Slip



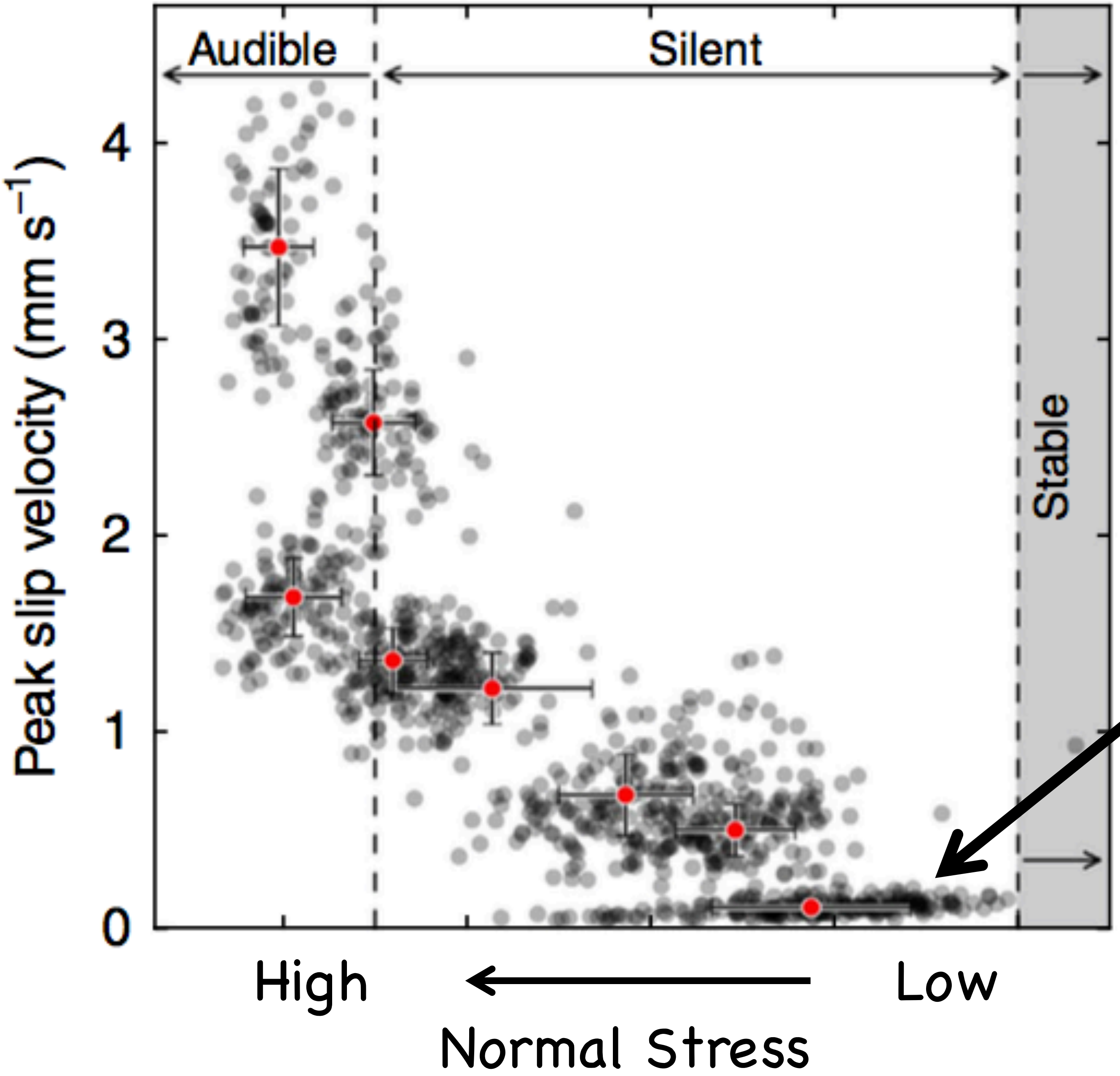
Leeman, Saffer, Scuderi & Marone, Nat. Comm. 2016



Leeman, Saffer, Scuderi & Marone, Nat. Comm. 2016



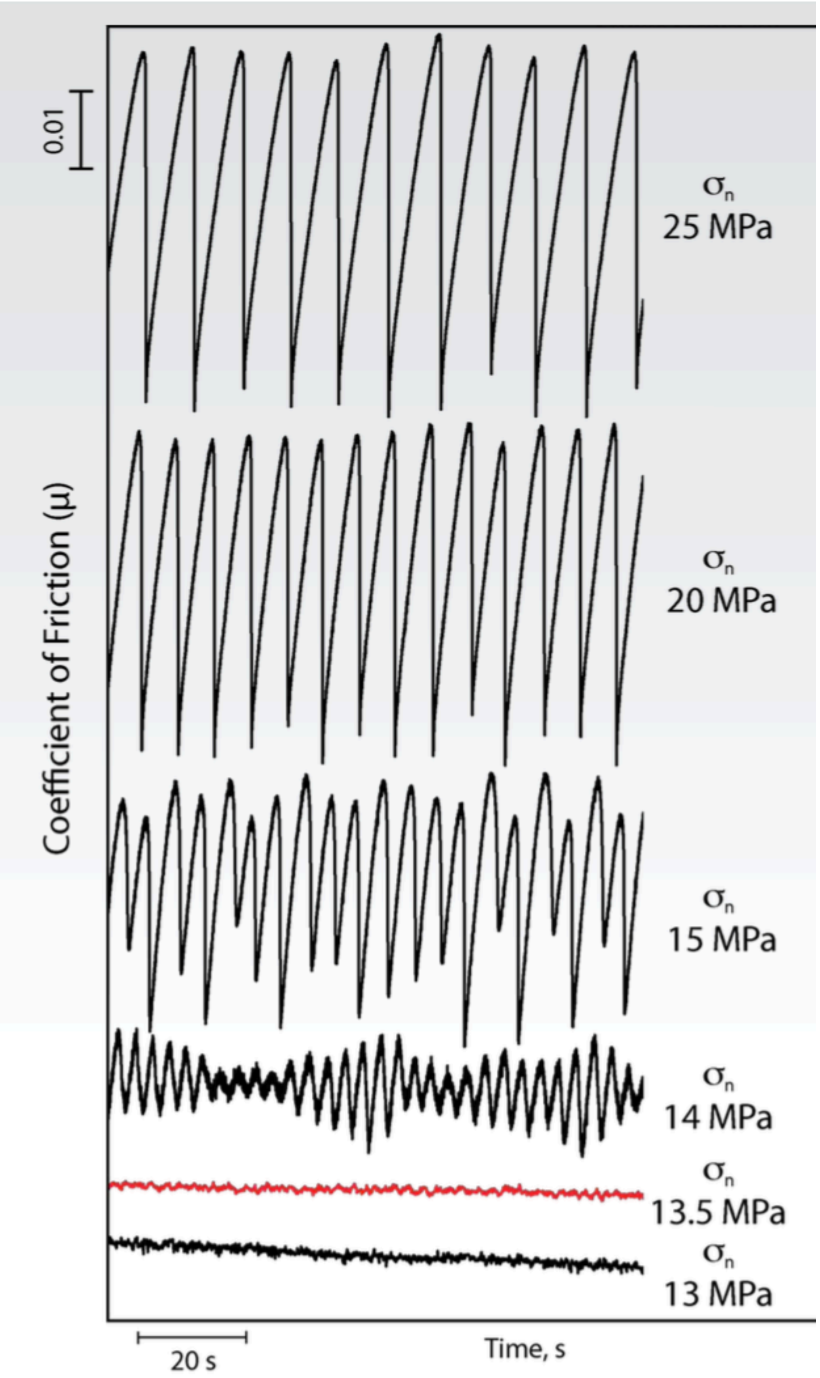
Friction
0.05
σ_n = 14 MPa
p4351
σ_n = 13 MPa
p4350
σ_n = 12 MPa
p4342
σ_n = 11 MPa
p4348
σ_n = 10 MPa
p4347
σ_n = 9 MPa
p4346
σ_n = 8 MPa
p4345
σ_n = 7 MPa
p4344
σ_n = 6 MPa
p4343
9
10
11
12
13
14
15
16
17
Load Point Displacement [mm]

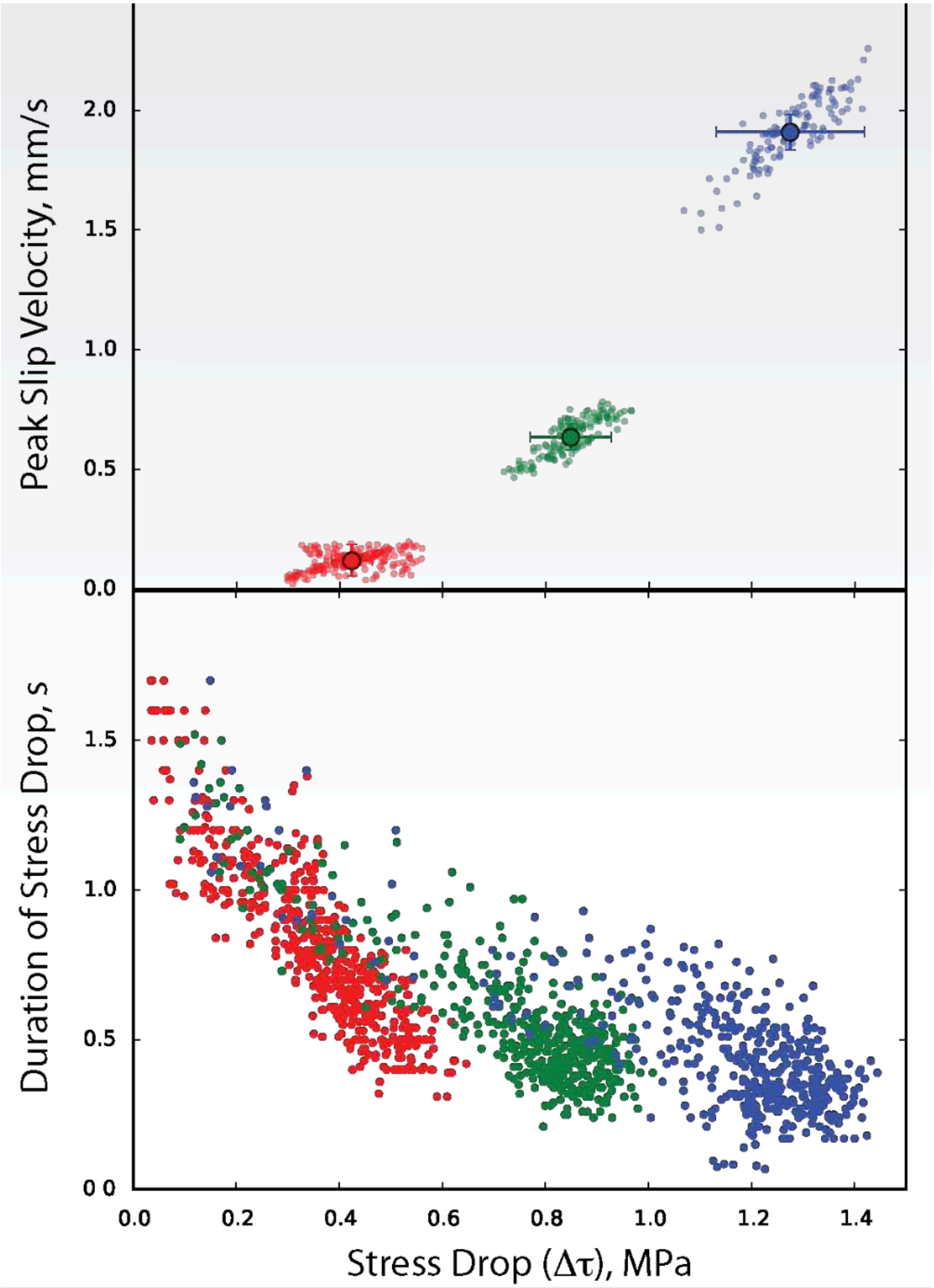


> 1000 events

60 μm/s

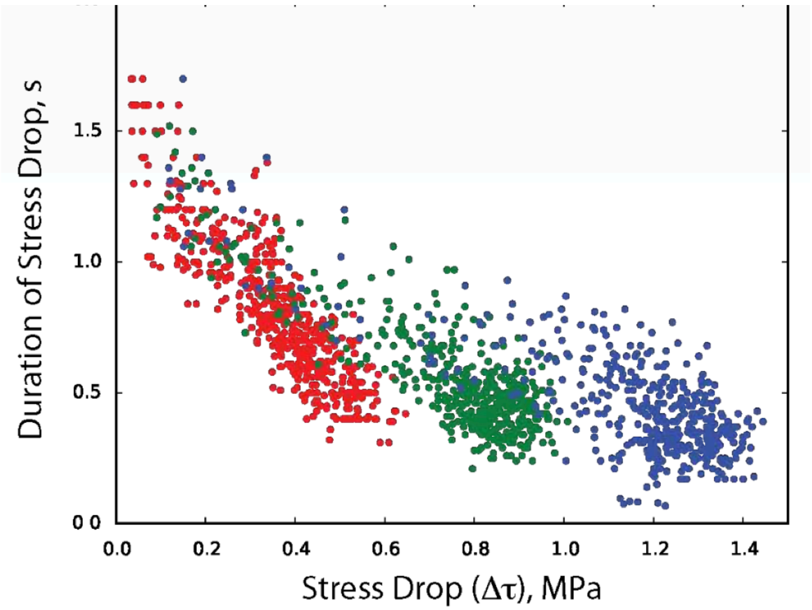
Leeman, Saffer, Scuderi & Marone, Nat. Comm. 2016



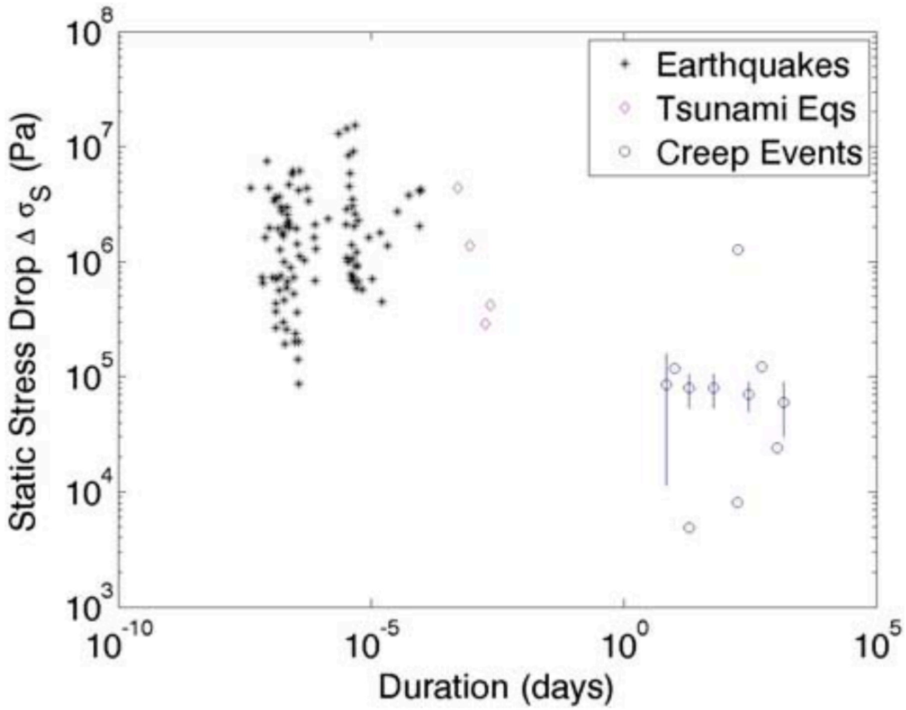


Scuderi, Marone, Tinti, Di Stefano, & Collettini, *Nature Geosc.* 2016

Stress drop decreases with event duration



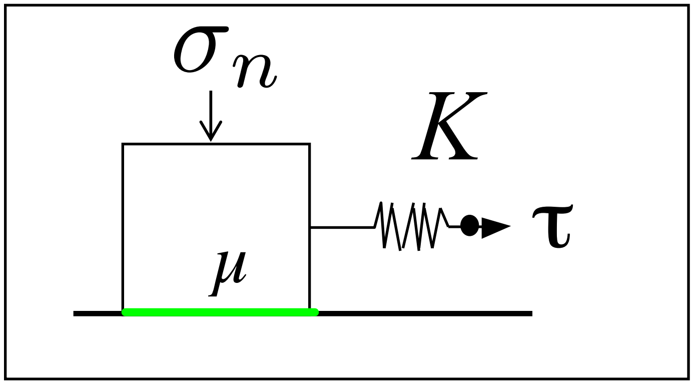
Scuderi et al., 2016



Creep events slip less than ordinary earthquakes

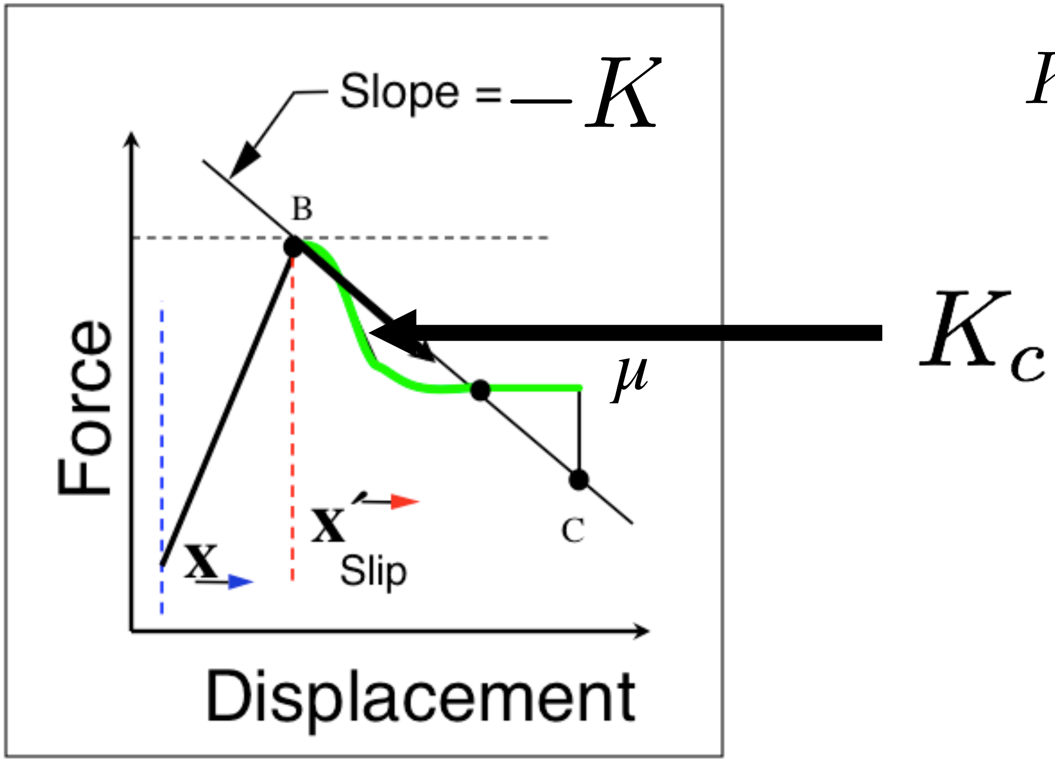
Emily E. Brodsky[1] and James Mori[2]

Mechanics of Frictional Sliding: Stick-slip

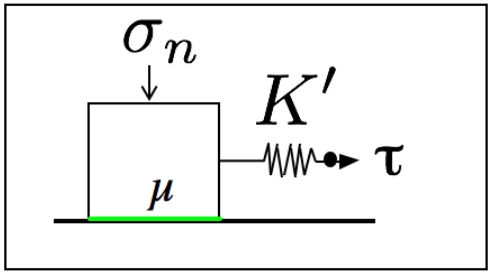


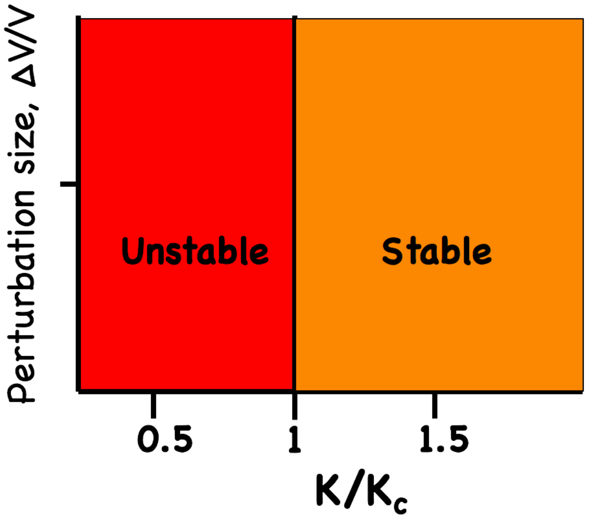
Unstable if $K < K_c$

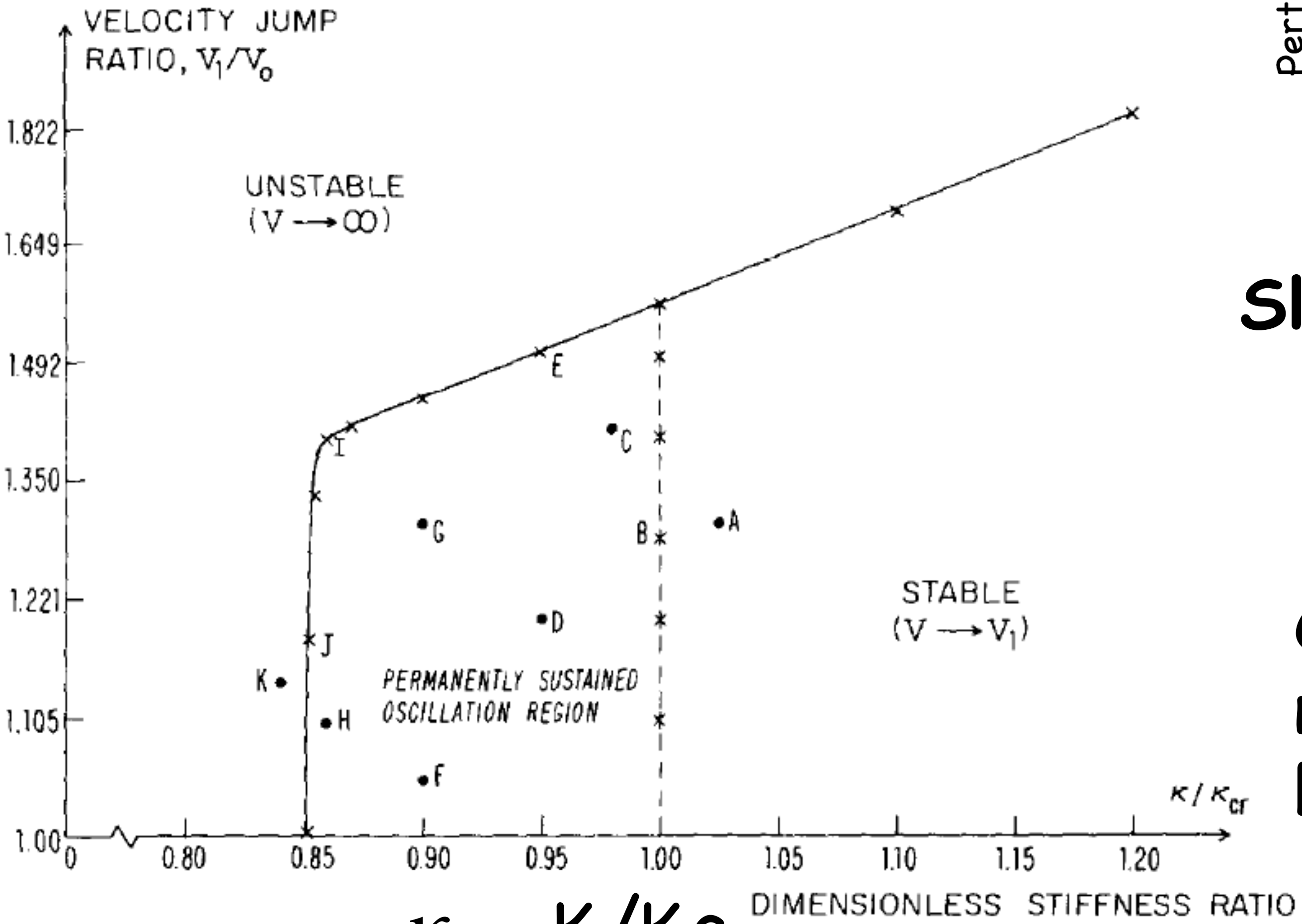
$$K_c = \frac{\sigma_n(b-a)}{D_c}\left[1 + \frac{mV_o^{\,2}}{\sigma_n a D_c}\right]$$



Stability transition from stable to unstable sliding.







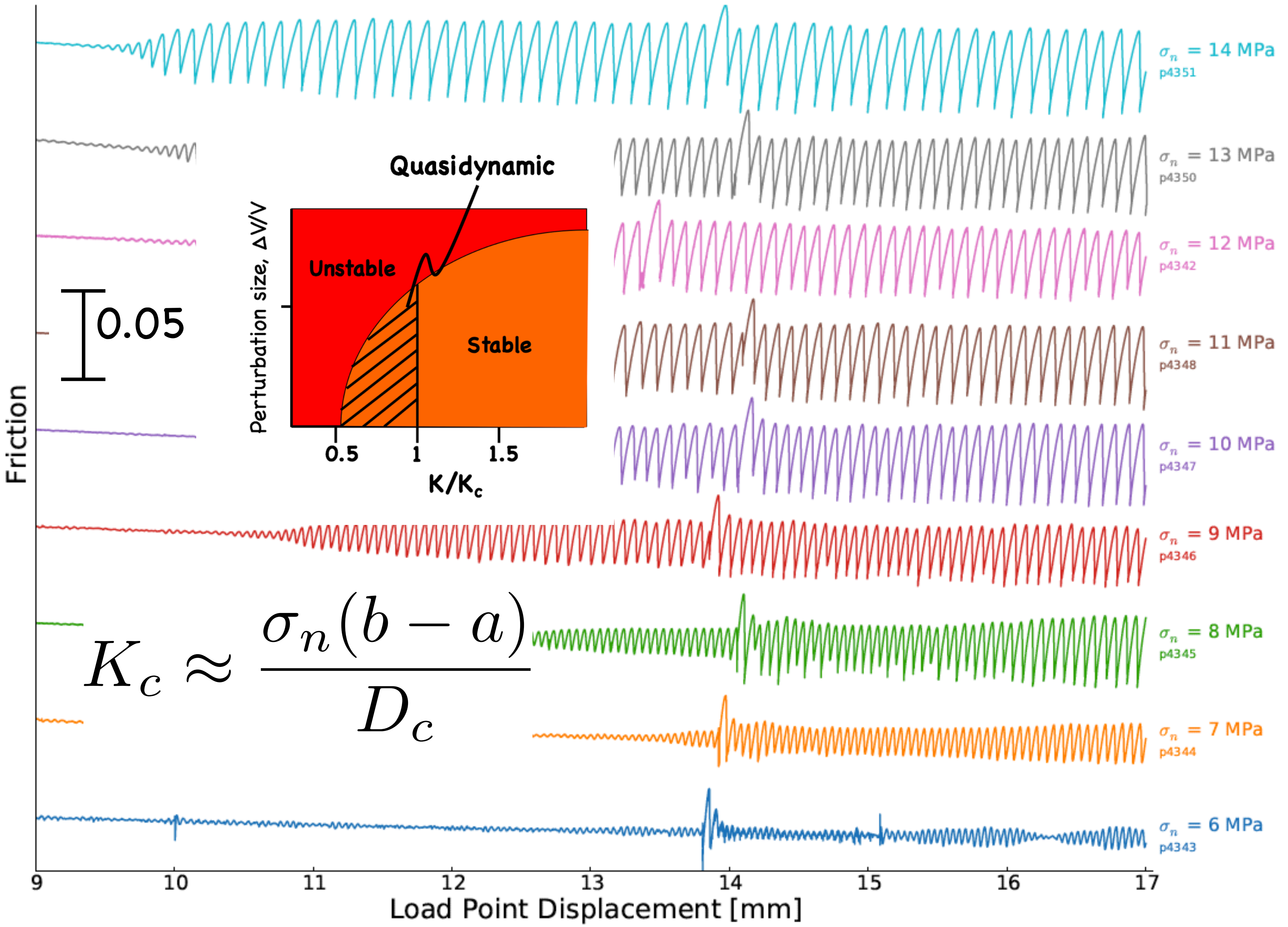
κ = K/Kc

Slip is unstable if

$$K < K_c$$

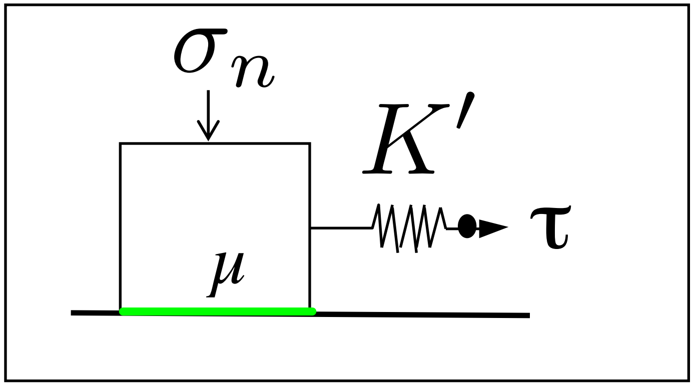
Complex behavior near the stability boundary

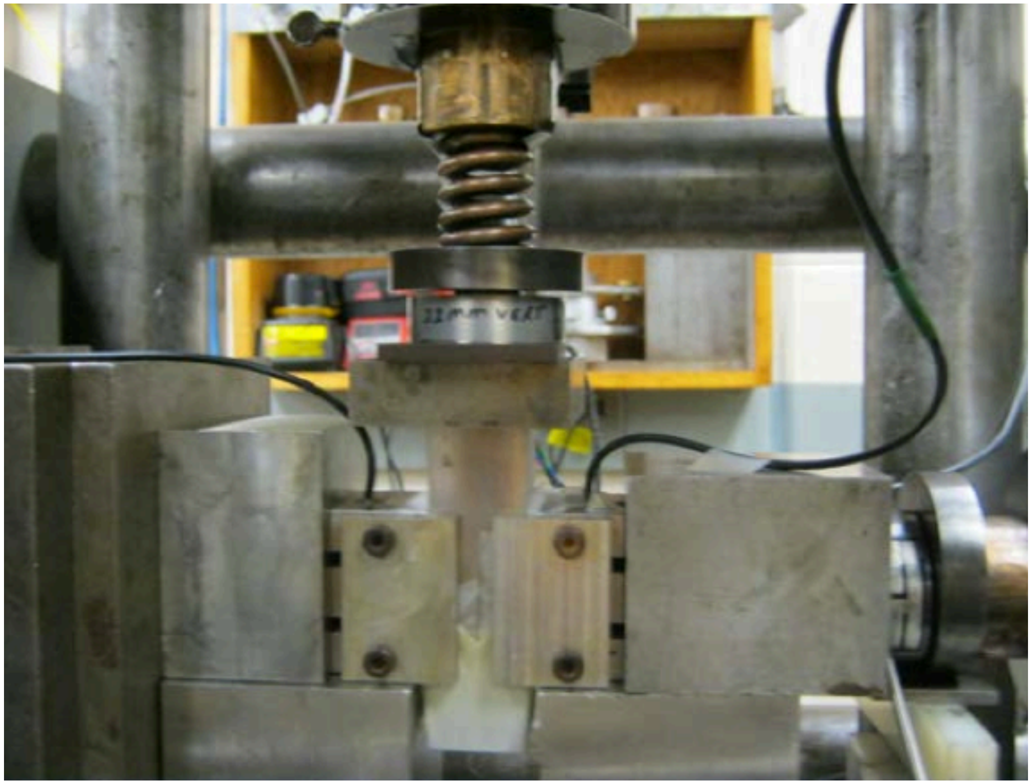
Gu et al., 1984

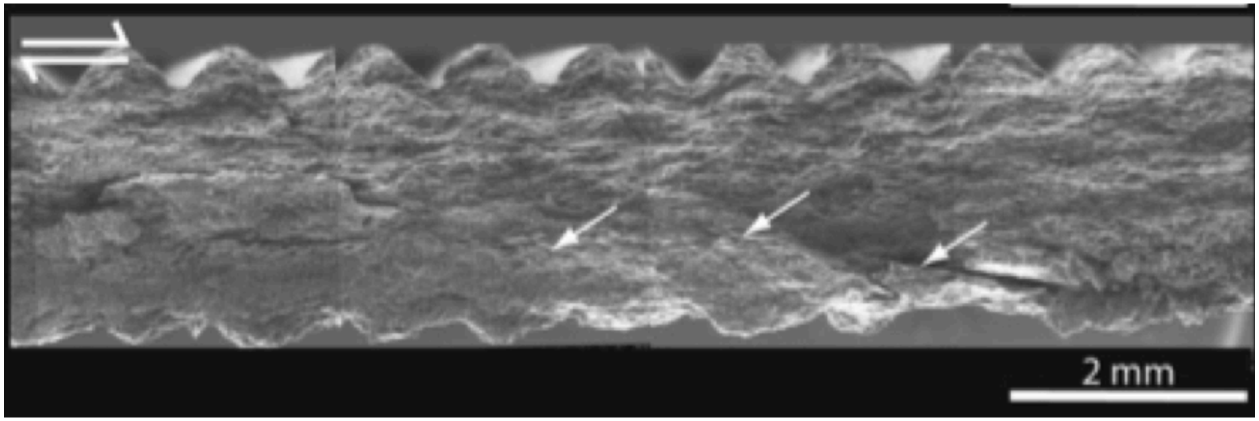


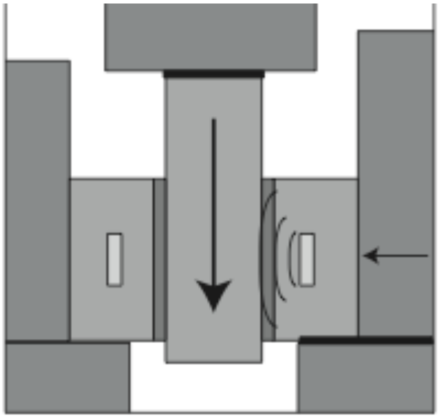
$$K_c \approx \frac{\sigma_n (b-a)}{D_c}$$

elastic loading stiffness



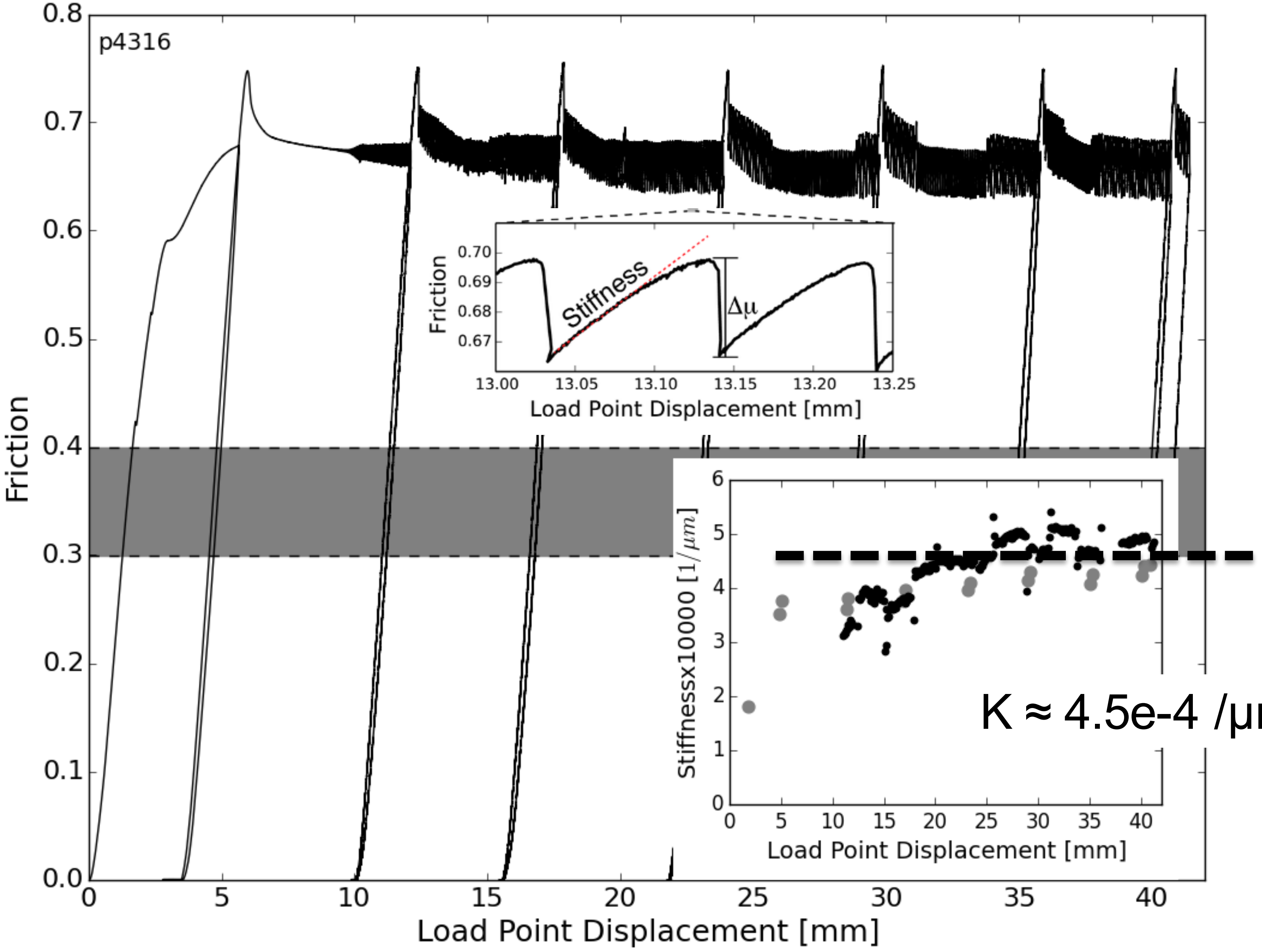






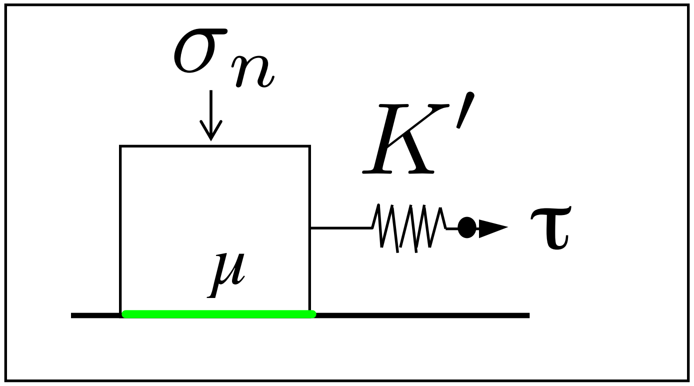
Double direct shear with biaxial loading

We measure elastic loading stiffness using 2 methods

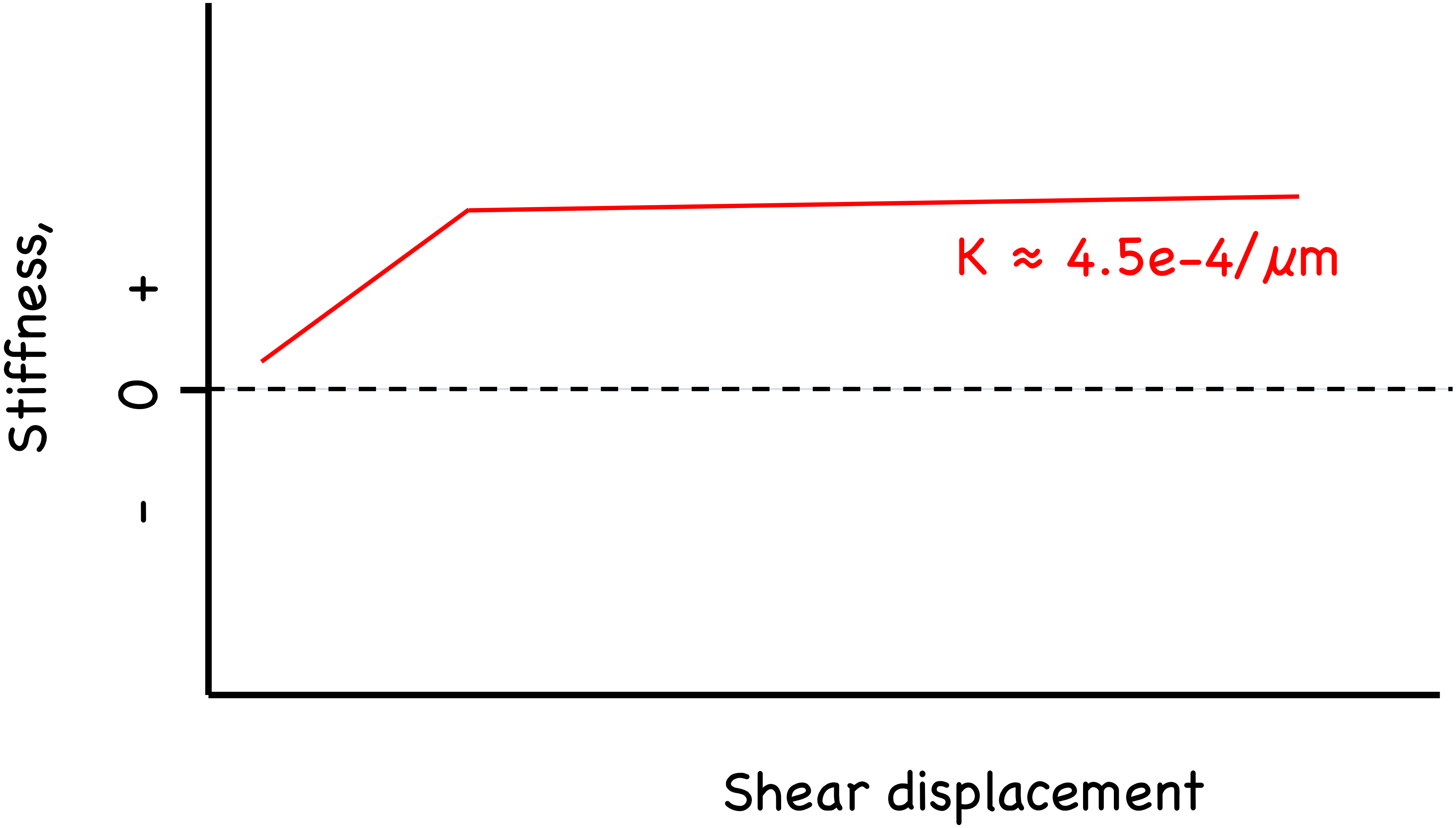


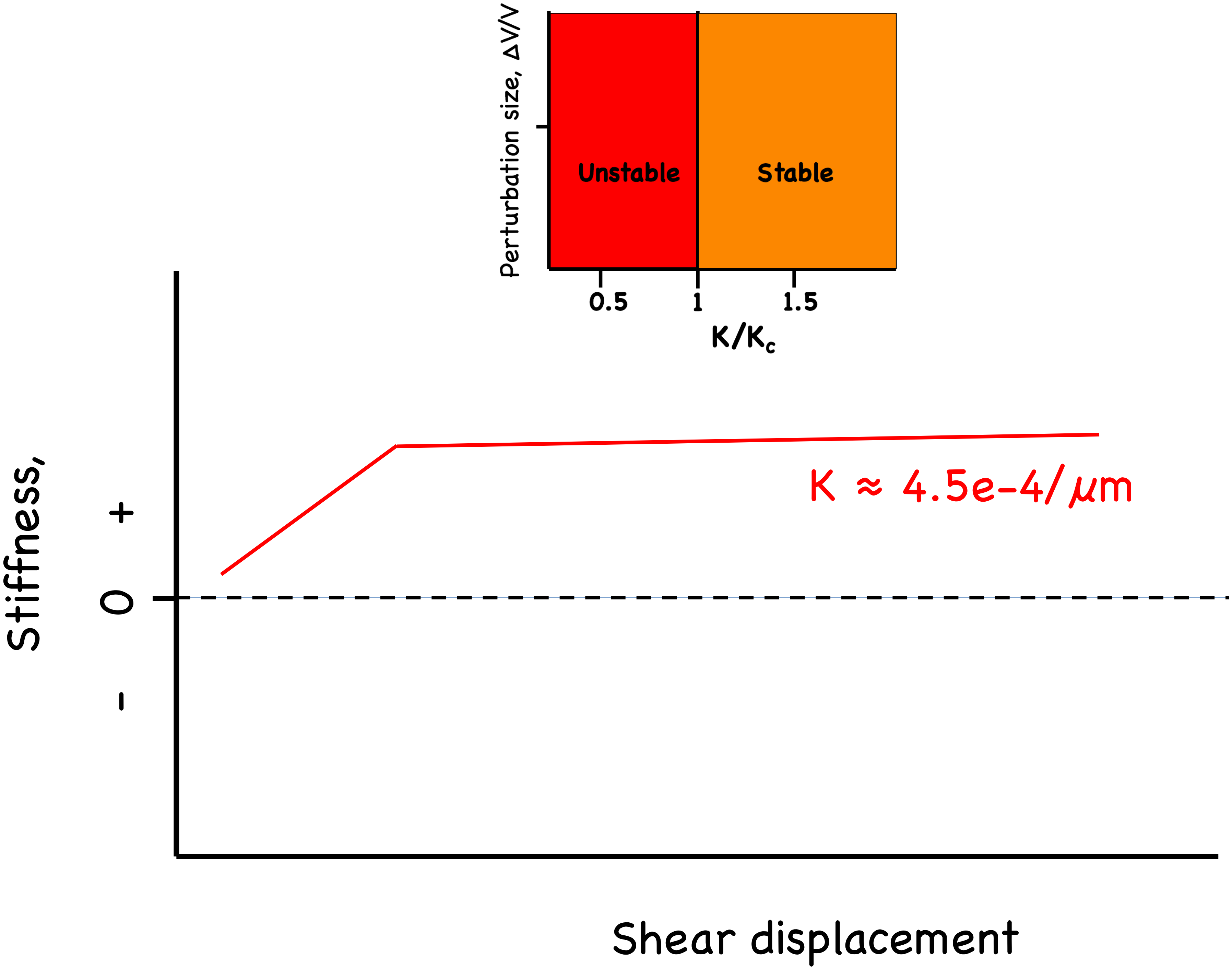
K ≈ 4.5e-4 /μm

Leeman, Saffer, Scuderi & Marone



$$K = \frac{K'}{\sigma_n}$$



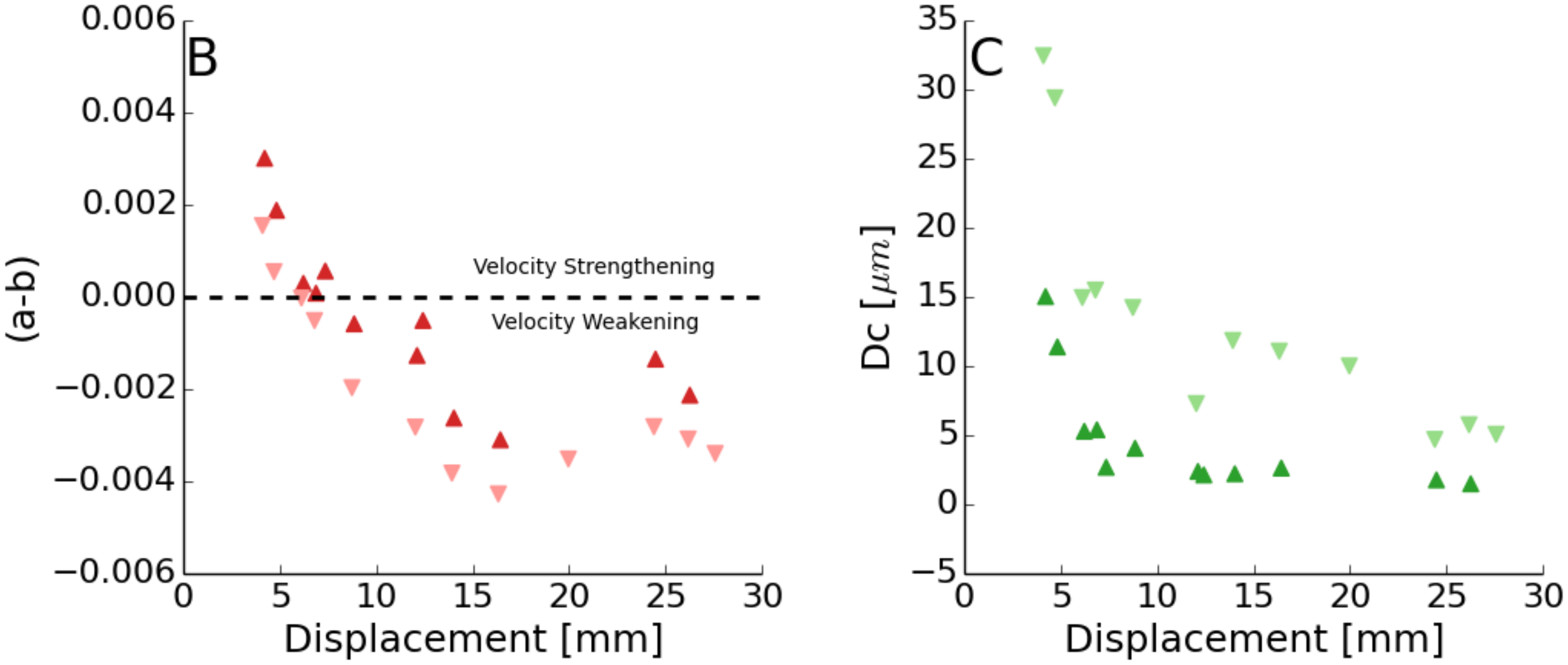

Perturbation size, ΔV/V
Unstable
Stable
0.5
1
1.5
K/K$_c$
Stiffness,
+
0
-
K ≈ 4.5e-4/μm
Shear displacement

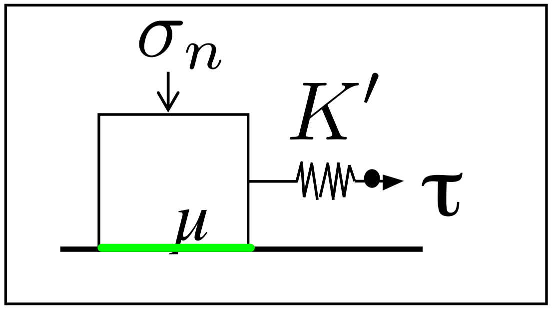
1) $\mu(\theta, V) = \mu_o + a\ ln\left(\frac{V}{V_o}\right) + b\ ln\left(\frac{V_o\theta}{D_c}\right)$

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

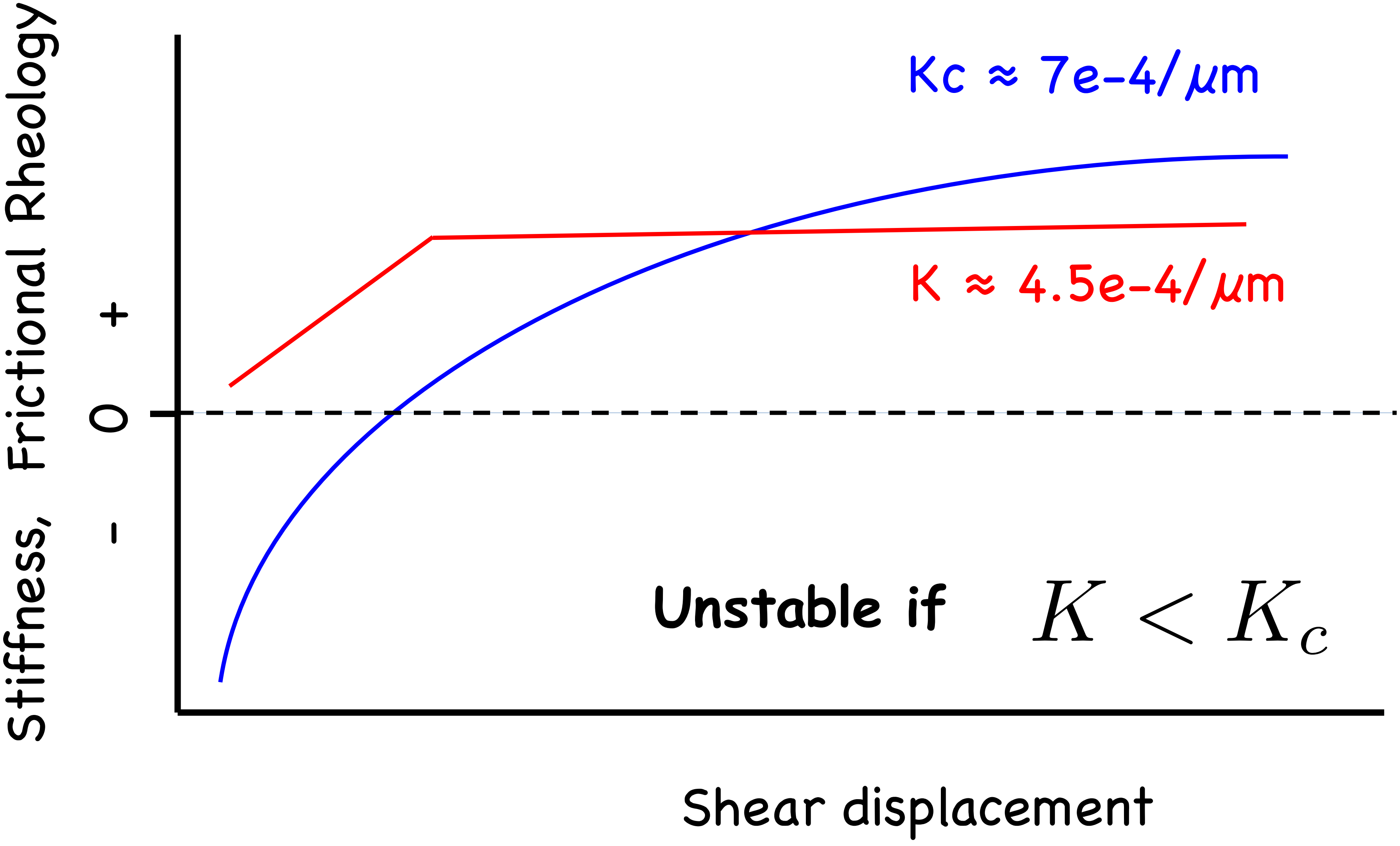
Stability Criterion

$$K_c = \frac{(b-a)}{D_c}$$



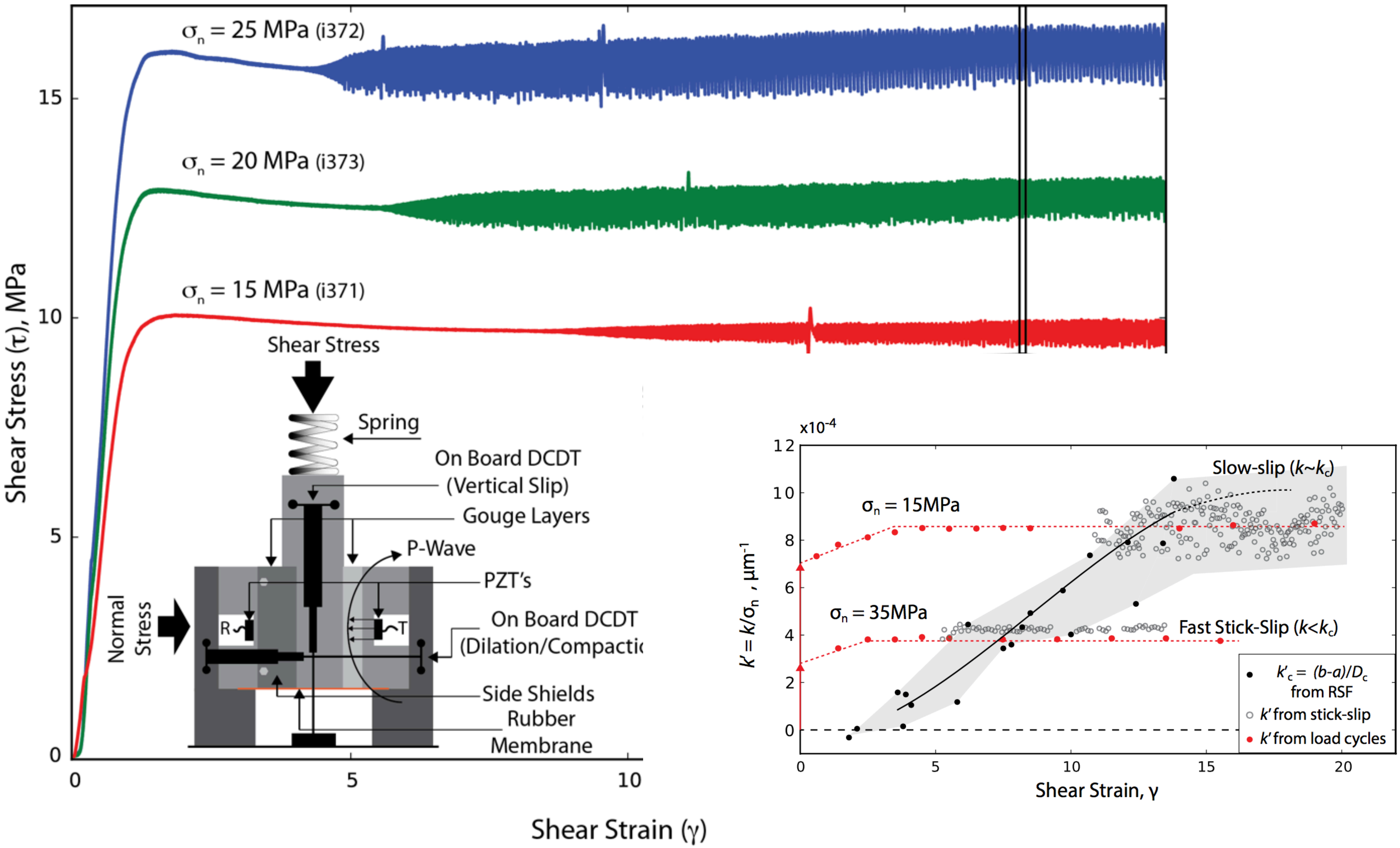


$$\frac{K'}{\sigma_n} < K_c = \frac{(b-a)}{D_c}$$

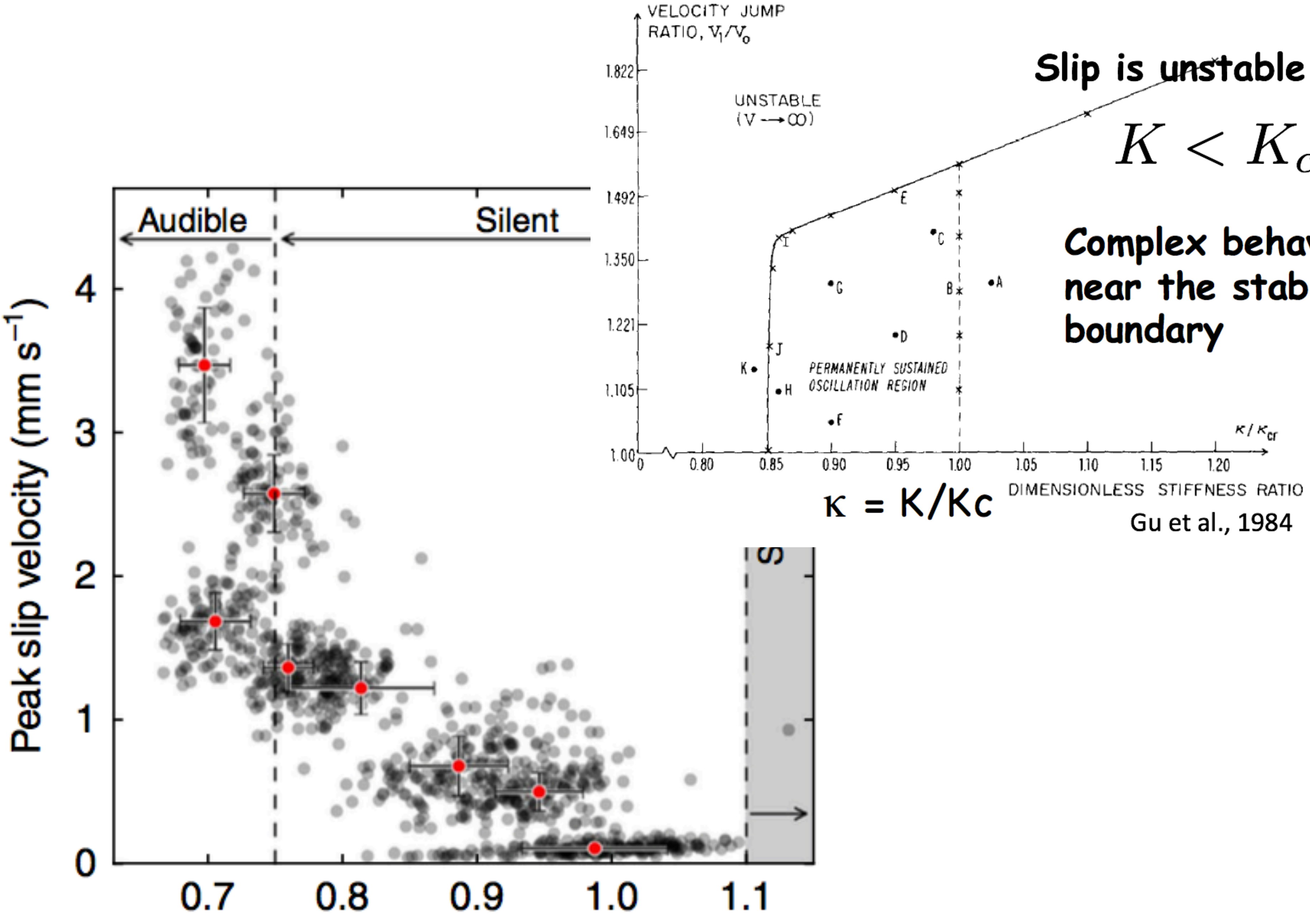


Unstable if $K < K_c$

Repetitive Slow Stick-Slip



Scuderi et al., *Geology*, 2017



Slip is unstable if

$$K < K_c$$

Complex behavior near the stability boundary

κ = K/Kc

Gu et al., 1984

κ = K/Kc

Leeman, Saffer, Scuderi & Marone, *Nature Comm. 2016.*

We have studied simple conditions (room temp., quartz powder as fault gouge, etc.)

Thinking is that the results illuminate a mechanism that may apply under more general conditions.

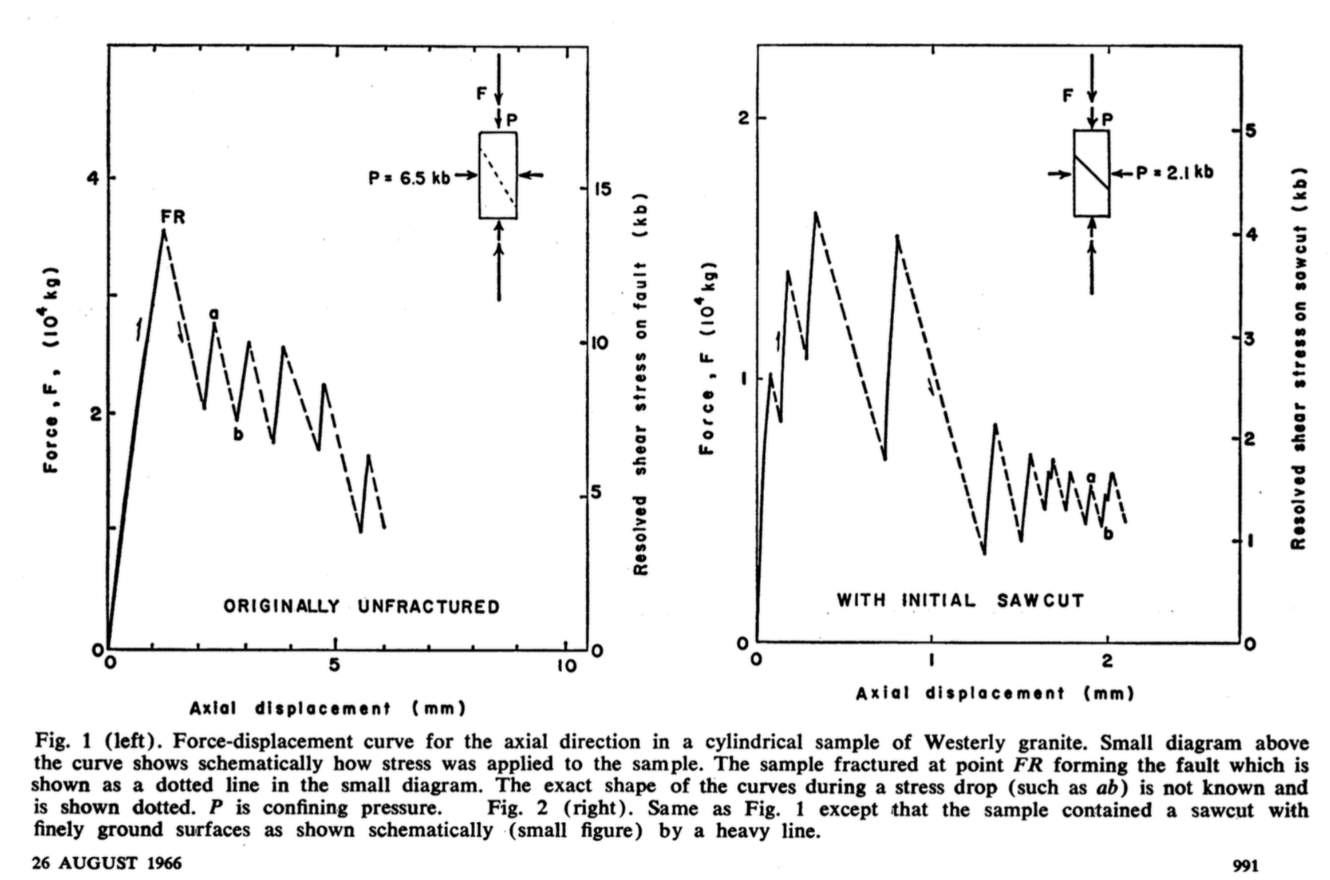


Fig. 1 (left). Force-displacement curve for the axial direction in a cylindrical sample of Westerly granite. Small diagram above the curve shows schematically how stress was applied to the sample. The sample fractured at point *FR* forming the fault which is shown as a dotted line in the small diagram. The exact shape of the curves during a stress drop (such as *ab*) is not known and is shown dotted. *P* is confining pressure. Fig. 2 (right). Same as Fig. 1 except that the sample contained a sawcut with finely ground surfaces as shown schematically (small figure) by a heavy line.

26 AUGUST 1966 991

Stick-slip as a Mechanism for Earthquakes,
Brace and Byerlee, *Science* 1966

Fault Slip Behavior

Stick-slip and stable sliding

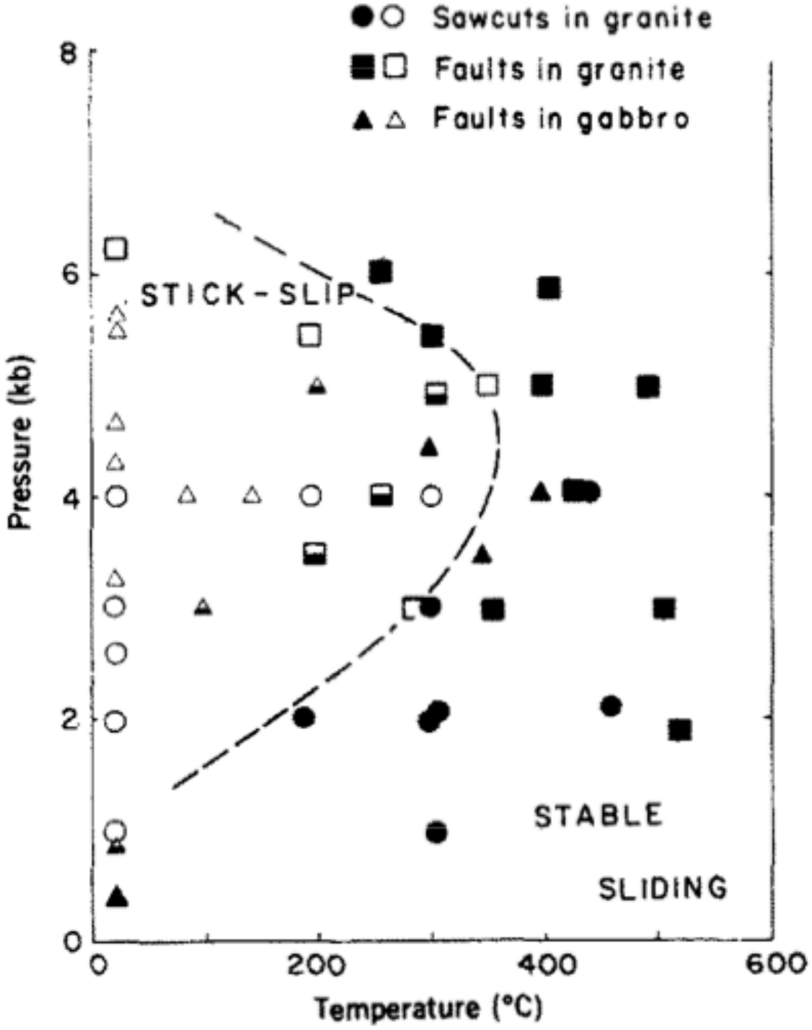
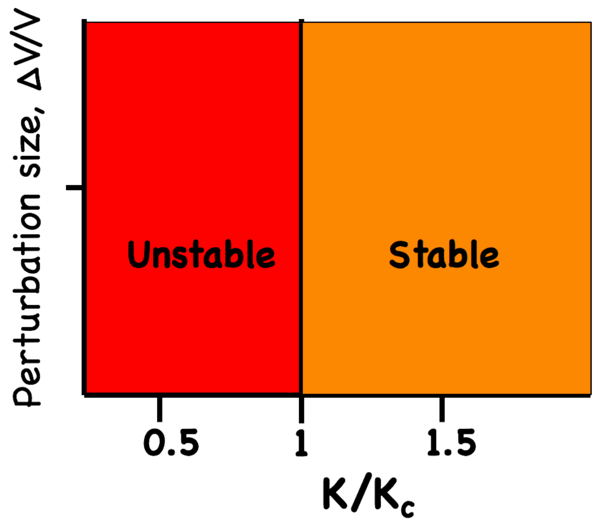
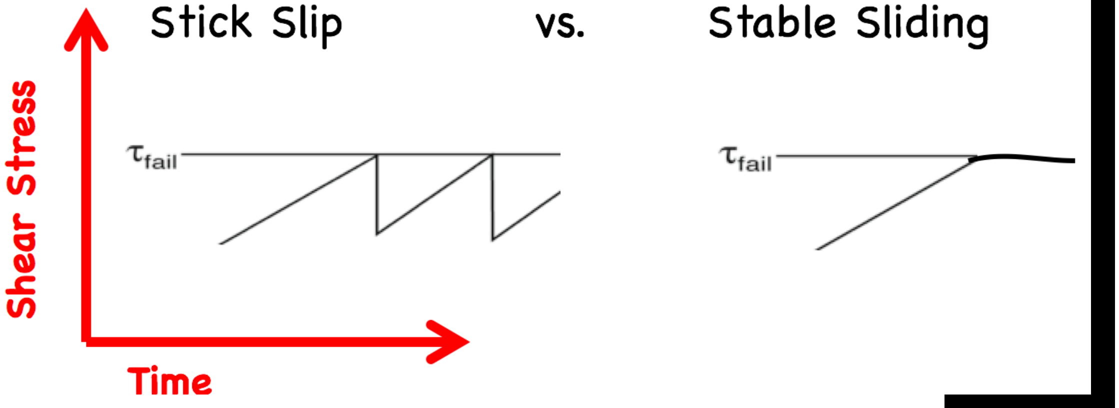


Fig.6. Effect of pressure and temperature on sliding stability for granite and gabbro (Brace and Byerlee, 1970 with some new data).





1. Slow earthquakes as a quasi-dynamic frictional instability

2. Mechanisms: *Why are they slow?*
   - Rate dependence of the critical rheologic stiffness Kc
   - Slow frictional stick-slip near the stability boundary

   Fault zone energy release rate equals frictional weakening rate

   Stress drop is quasidynamic because the dynamic force imbalance is negligible

The Mechanics of Slow Earthquakes and the Spectrum of Fault Slip Behaviors

1. Friction la … plex as
   rate/s

How are we doing on
time? $t > t_o + 60$?

2. How do … anism sets the
   speed limit? *Wh*

3. Speculations on how recent lab results may in apply in nature. Scaling laws for a spectrum of slip modes from slows earthquakes to super-shear rupture (SSE, LFE, tremor, VLFE, ULFE, MLFE, BB-eq, elasto-dynamic EQs) .

Speculations on how recent lab results may in apply in nature.

Where should slow earthquakes occur?

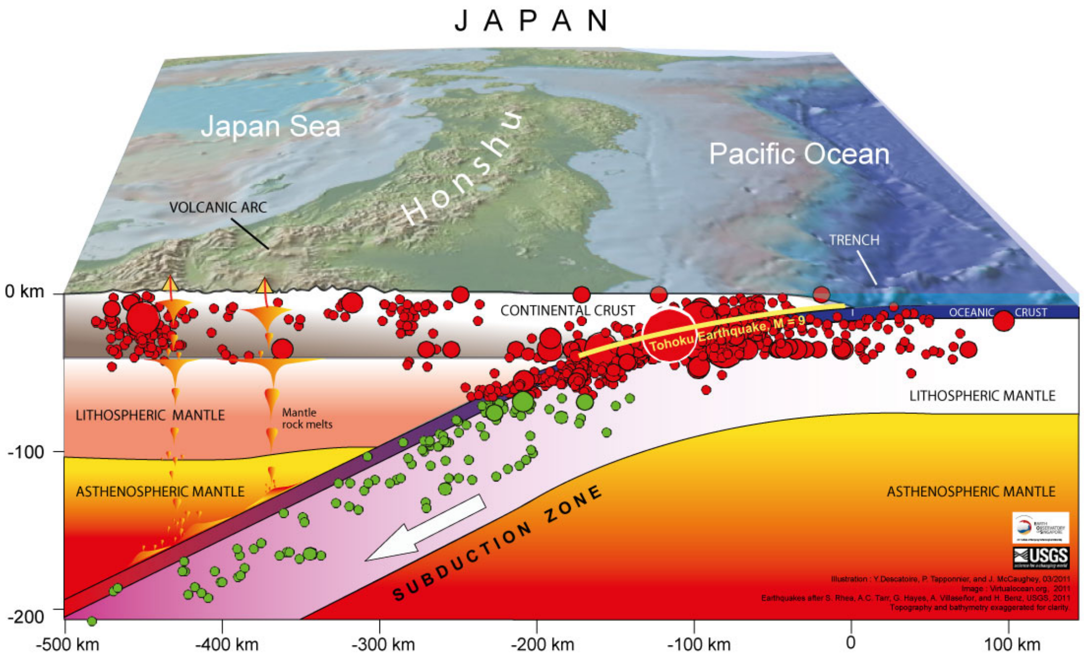


Illustration : Y.Descatoire, P. Tapponnier, and J. McCaughey, 03/2011
Image : Virtualocean.org, 2011
Earthquakes after S. Rhea, A.C. Tarr, G. Hayes, A. Villaseñor, and H. Benz, USGS, 2011
Topography and bathymetry exaggerated for clarity.

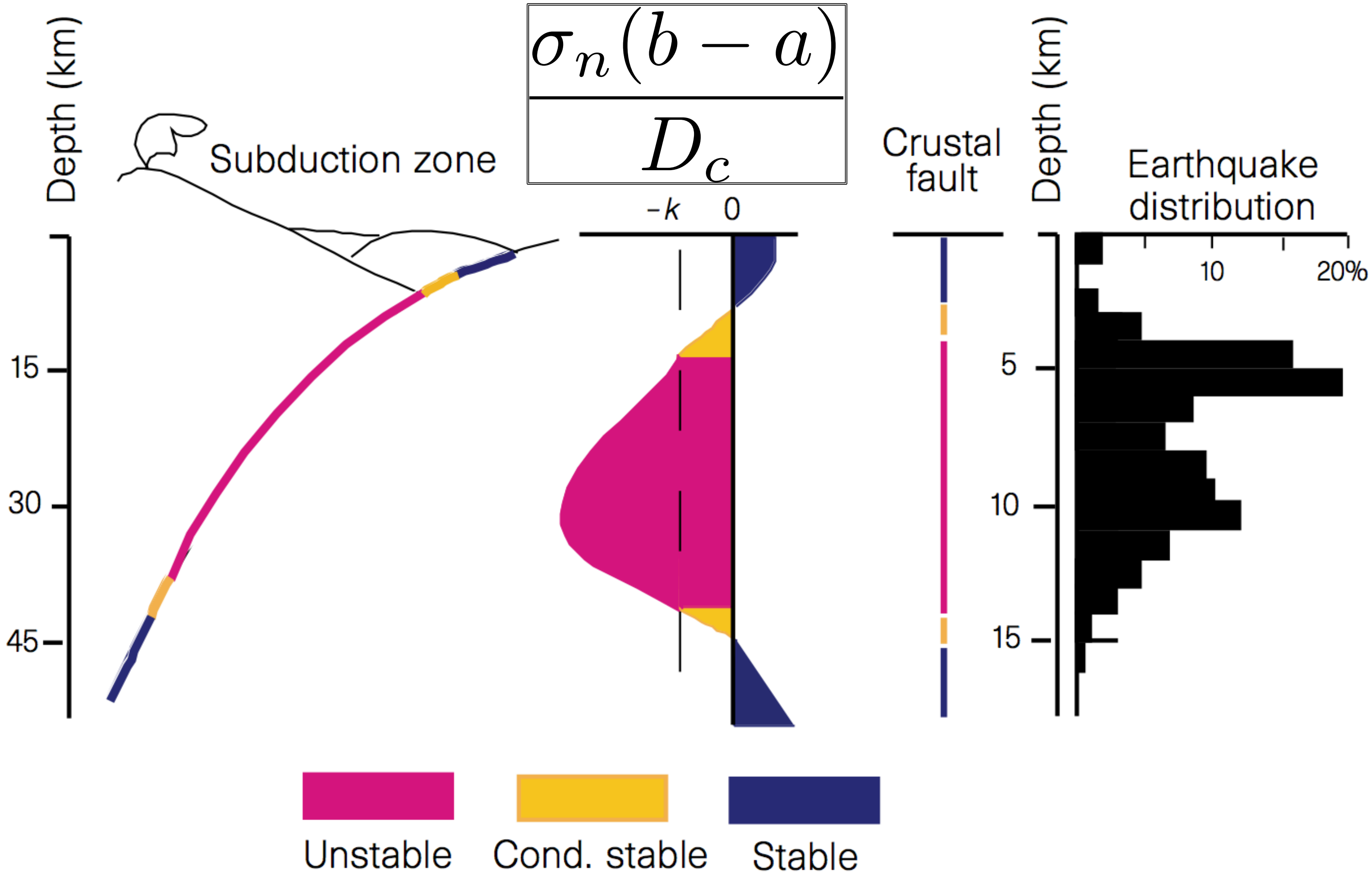
tohoku2-bloc_diagramme_japan_earthquakes

Slip is unstable if

$$K < K_c$$

Complex behavior near the stability boundary

$$\boxed{\frac{\sigma_n(b-a)}{D_c}}$$

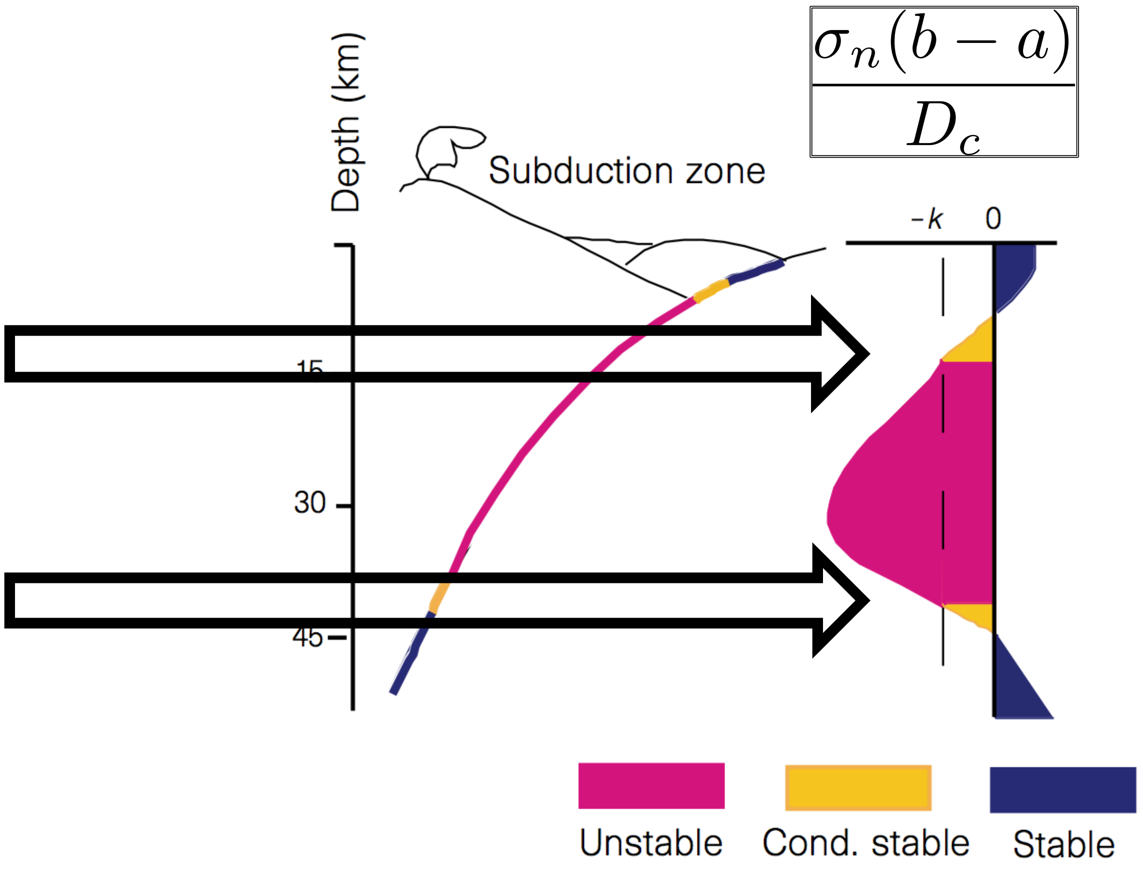


Scholz, 1998

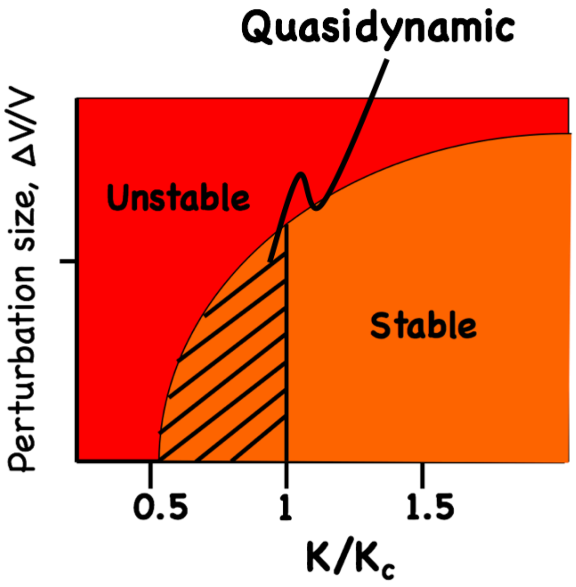
$$K_c \approx \frac{\sigma_n(b-a)}{D_c}$$

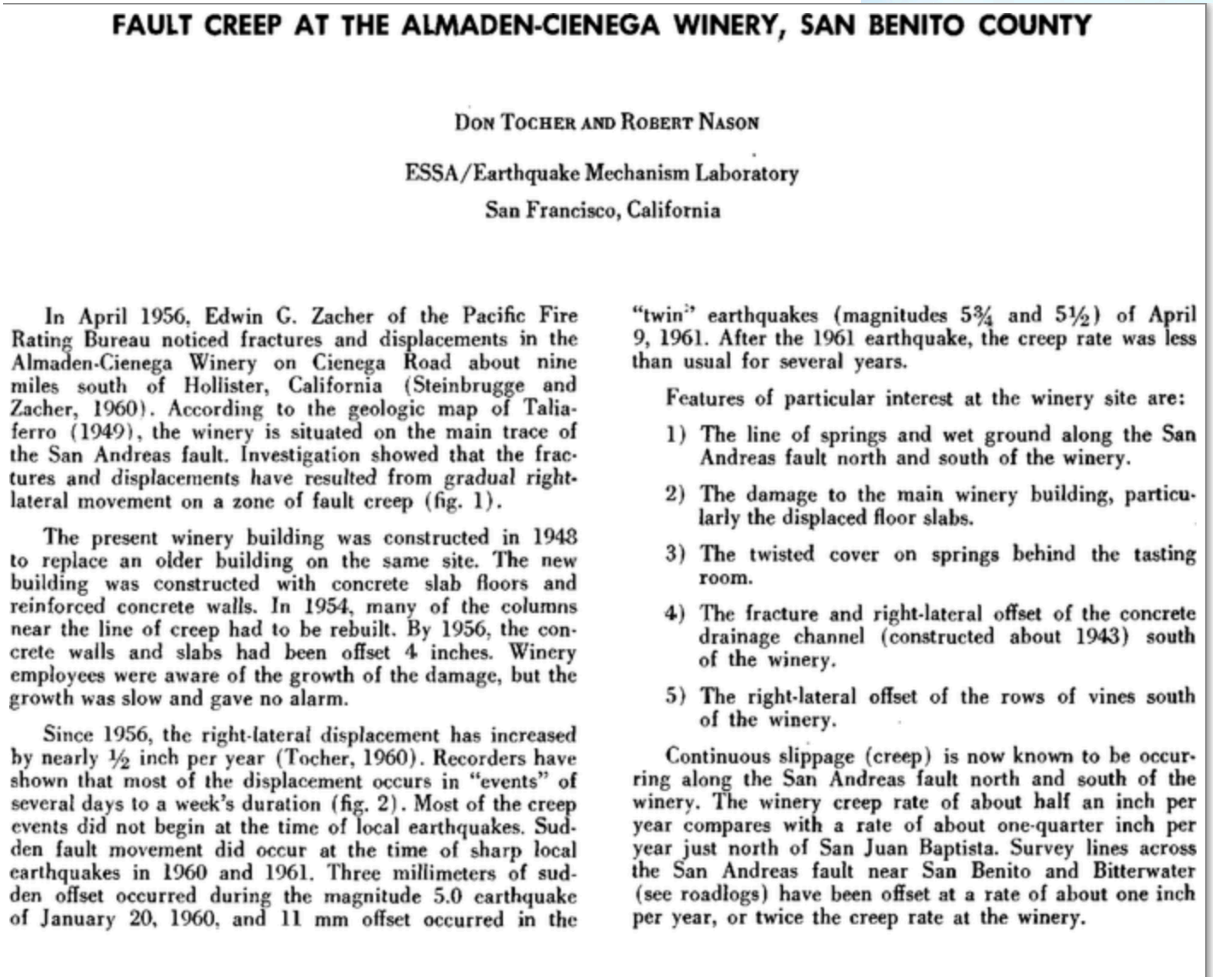
- **Complex slip modes near the stability boundary**

- **Slow slip should occur at the updip and downdip limits of the seismogenic zone**



$$\frac{\sigma_n(b-a)}{D_c}$$





FAULT CREEP AT THE ALMADEN-CIENEGA WINERY, SAN BENITO COUNTY

DON TOCHER AND ROBERT NASON

ESSA/Earthquake Mechanism Laboratory
San Francisco, California

In April 1956, Edwin G. Zacher of the Pacific Fire Rating Bureau noticed fractures and displacements in the Almaden-Cienega Winery on Cienega Road about nine miles south of Hollister, California (Steinbrugge and Zacher, 1960). According to the geologic map of Taliaferro (1949), the winery is situated on the main trace of the San Andreas fault. Investigation showed that the fractures and displacements have resulted from gradual right-lateral movement on a zone of fault creep (fig. 1).

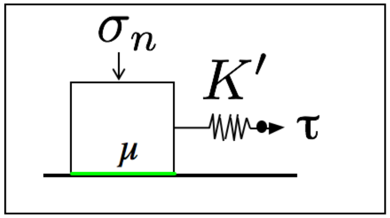
The present winery building was constructed in 1948 to replace an older building on the same site. The new building was constructed with concrete slab floors and reinforced concrete walls. In 1954, many of the columns near the line of creep had to be rebuilt. By 1956, the concrete walls and slabs had been offset 4 inches. Winery employees were aware of the growth of the damage, but the growth was slow and gave no alarm.

Since 1956, the right-lateral displacement has increased by nearly ½ inch per year (Tocher, 1960). Recorders have shown that most of the displacement occurs in "events" of several days to a week's duration (fig. 2). Most of the creep events did not begin at the time of local earthquakes. Sudden fault movement did occur at the time of sharp local earthquakes in 1960 and 1961. Three millimeters of sudden offset occurred during the magnitude 5.0 earthquake of January 20, 1960, and 11 mm offset occurred in the "twin" earthquakes (magnitudes 5¾ and 5½) of April 9, 1961. After the 1961 earthquake, the creep rate was less than usual for several years.

Features of particular interest at the winery site are:

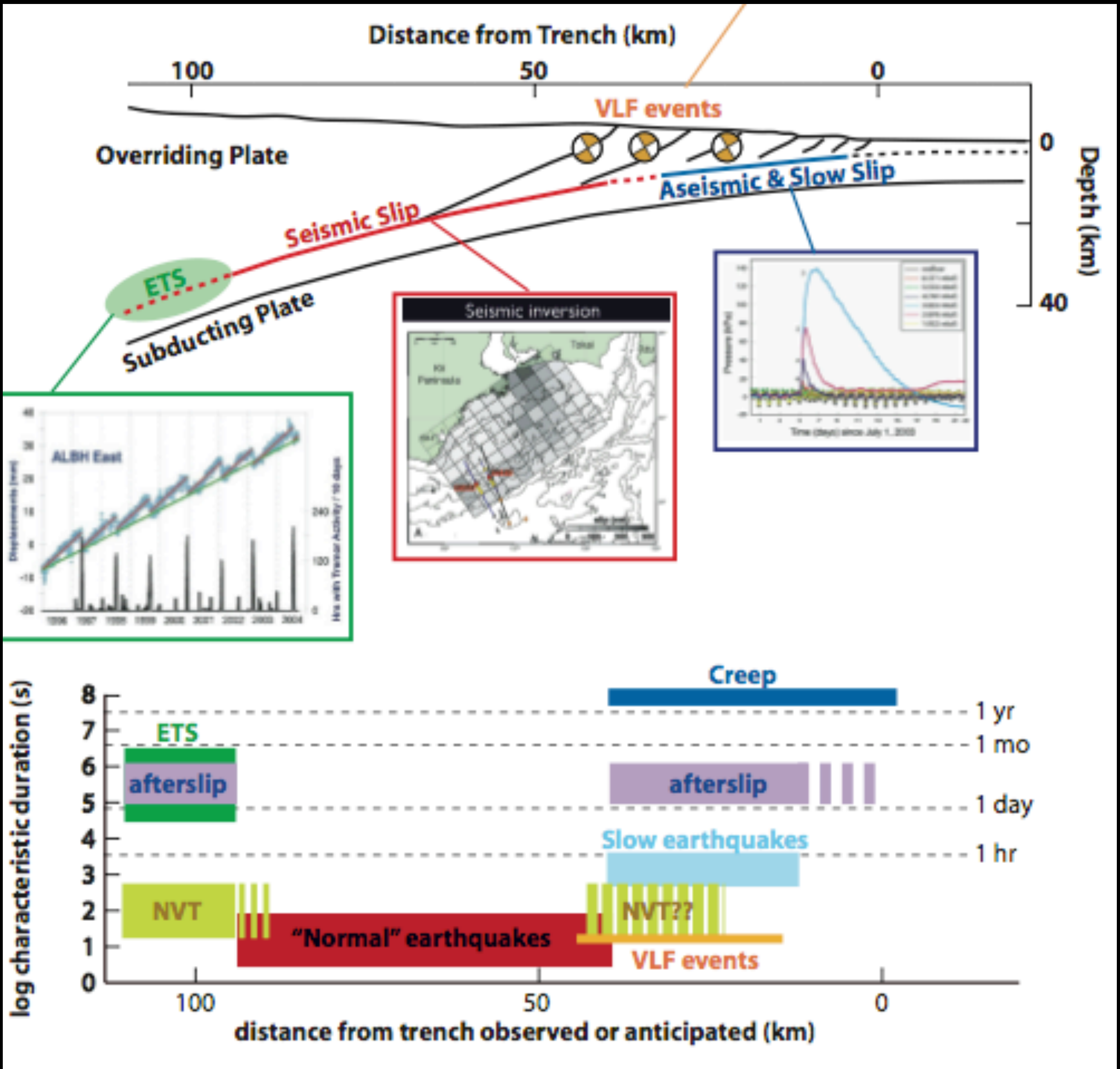
1) The line of springs and wet ground along the San Andreas fault north and south of the winery.
2) The damage to the main winery building, particularly the displaced floor slabs.
3) The twisted cover on springs behind the tasting room.
4) The fracture and right-lateral offset of the concrete drainage channel (constructed about 1943) south of the winery.
5) The right-lateral offset of the rows of vines south of the winery.

Continuous slippage (creep) is now known to be occurring along the San Andreas fault north and south of the winery. The winery creep rate of about half an inch per year compares with a rate of about one-quarter inch per year just north of San Juan Baptista. Survey lines across the San Andreas fault near San Benito and Bitterwater (see roadlogs) have been offset at a rate of about one inch per year, or twice the creep rate at the winery.



AAPG, 1967
Gabilan Range & Adjacent San Andreas Fault Guidebook

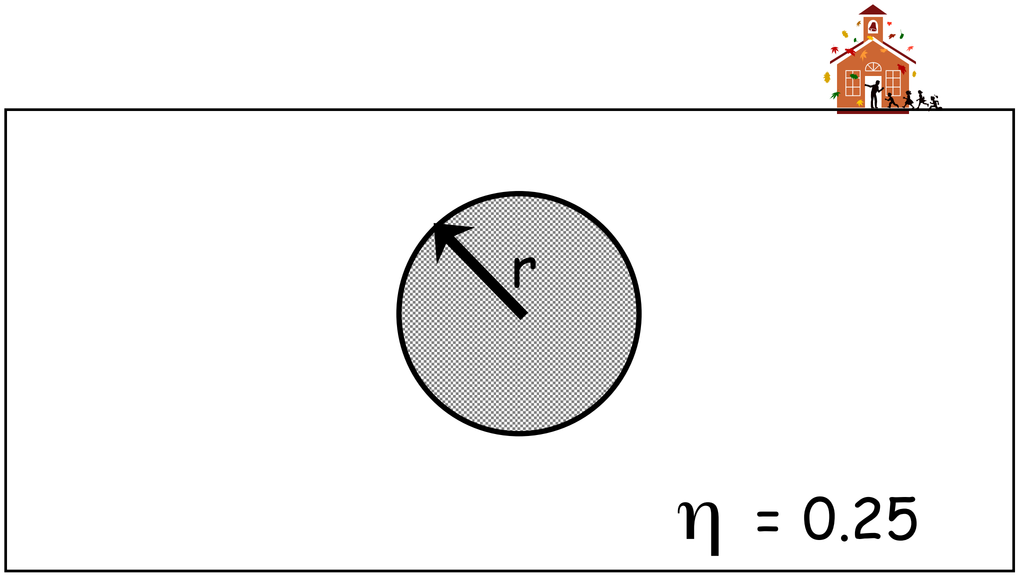
The Spectrum of Fault Slip Behaviors



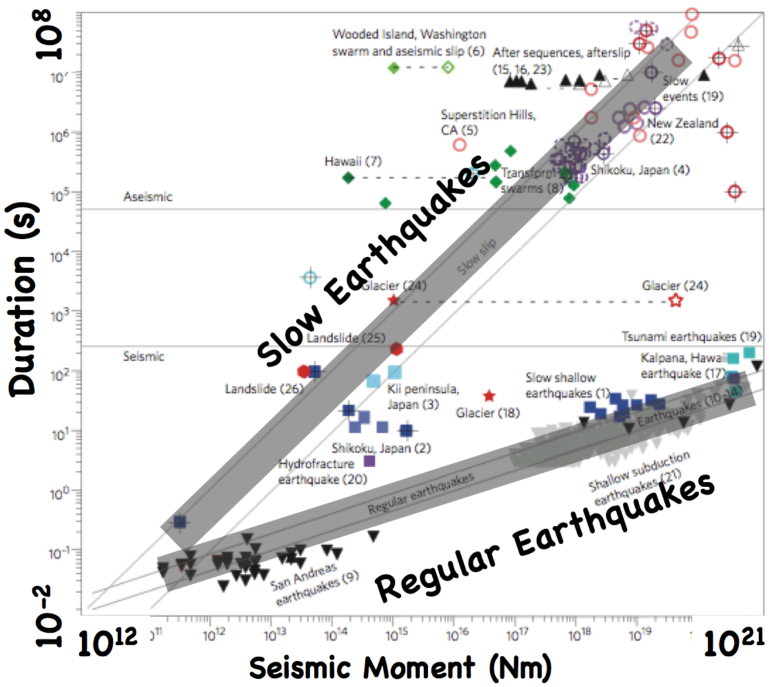
Marone & Saffer, 2008

Speculations on how lab results may in apply in nature.

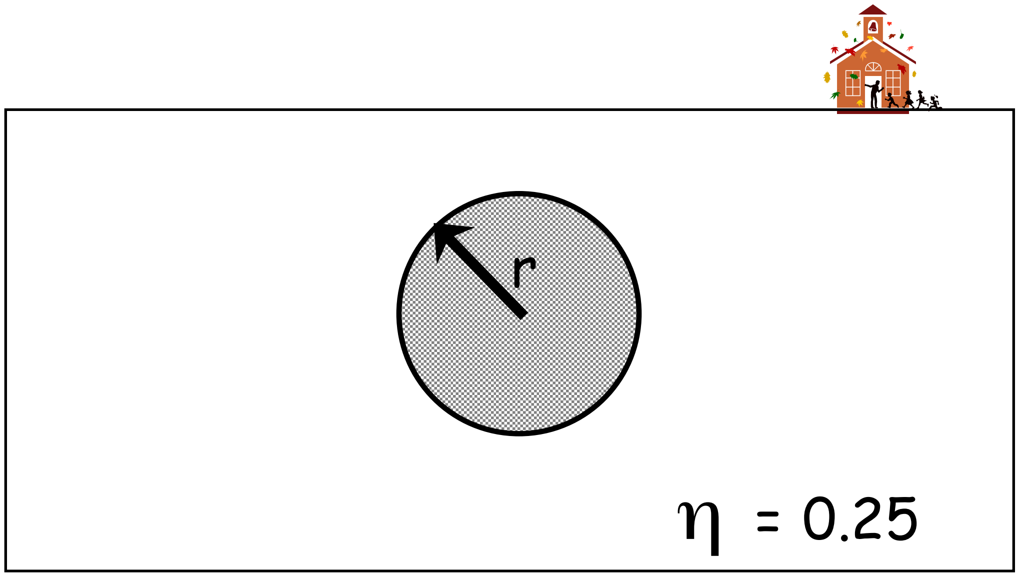
Source Parameter and Scaling Relations



Dislocation model for fault slip and earthquake rupture



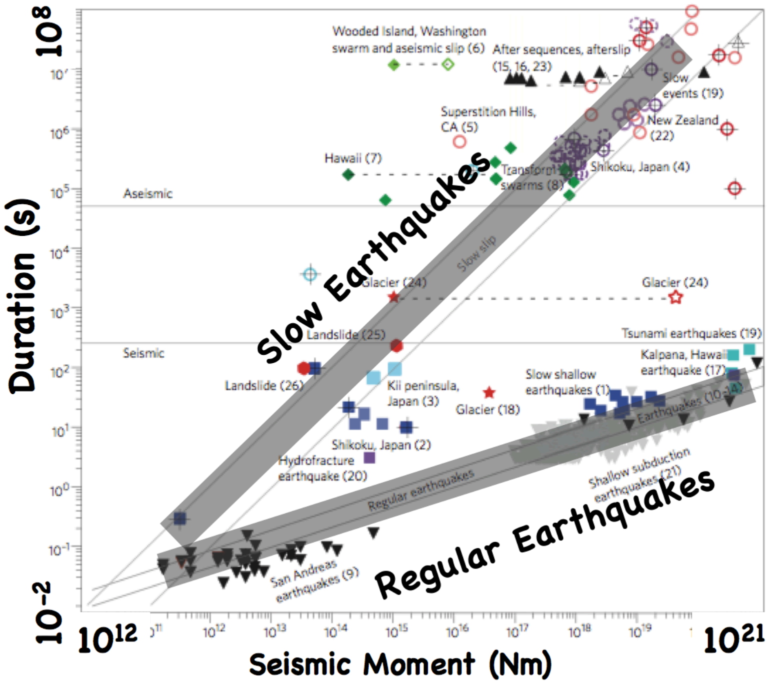
Source Parameter and Scaling Relations for Ordinary Earthquakes



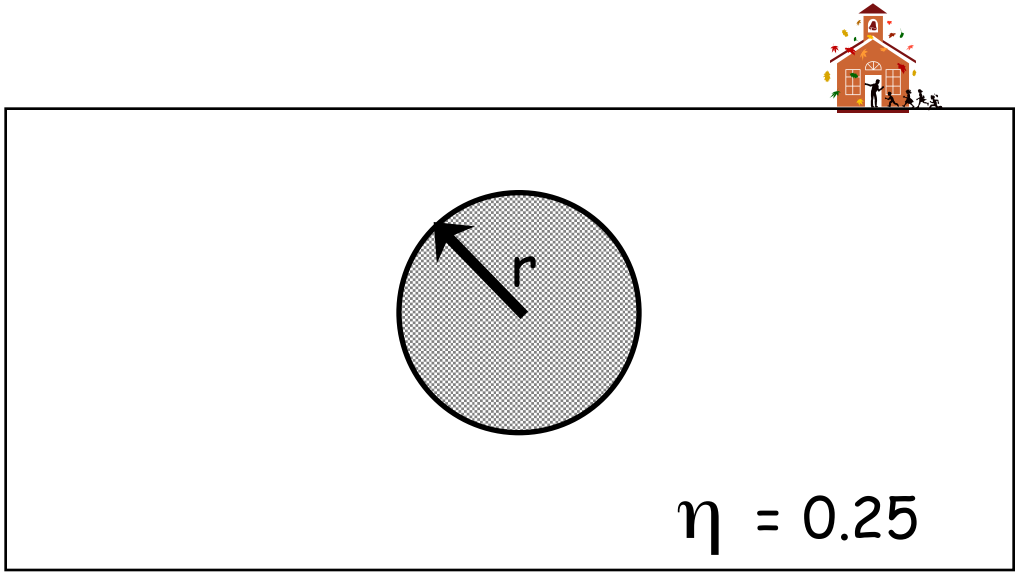
$$\Delta\sigma = \frac{7\pi}{16} G \frac{\bar{u}}{r}$$

$$M_o = G\bar{u}A$$

Dislocation model for fault slip and earthquake rupture



Source Parameter and Scaling Relations for Ordinary Earthquakes



Dislocation model for fault slip and earthquake rupture

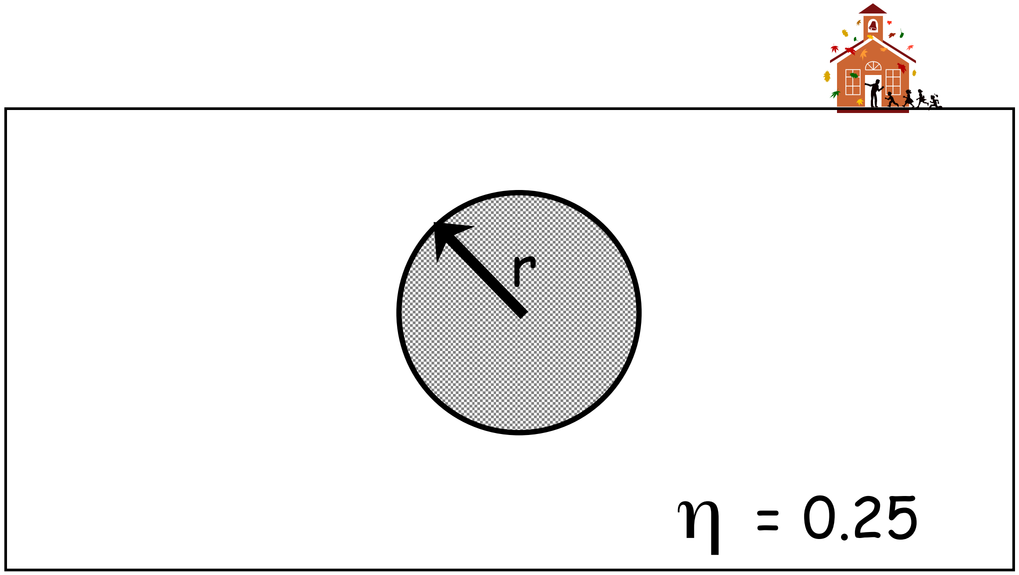
$$\Delta\sigma = \frac{7\pi}{16} G \frac{\bar{u}}{r}$$

$$M_o = G\bar{u}A$$

$$M_o = C\Delta\sigma r^3$$

"Brune" Stress Drop

Source Parameter and Scaling Relations for Ordinary Earthquakes



Dislocation model for fault slip and earthquake rupture

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

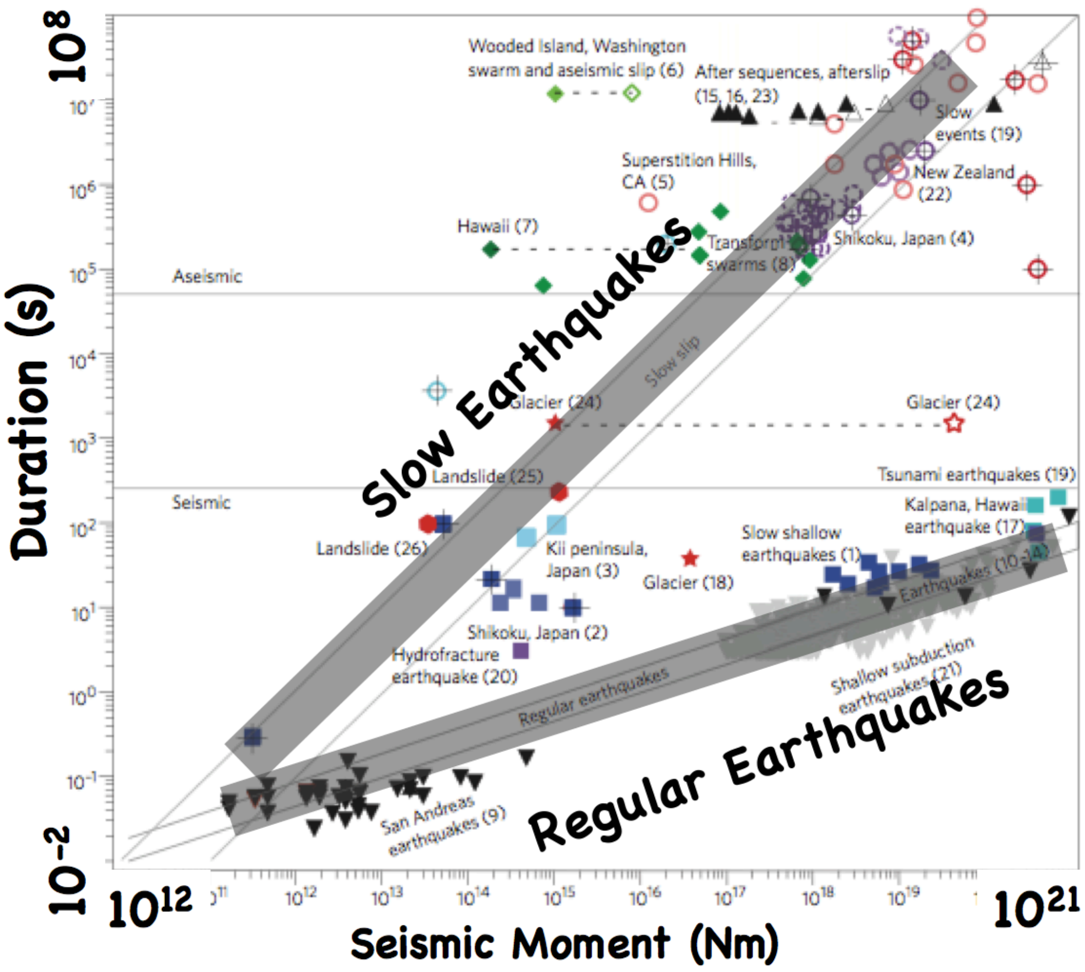
$$M_o = G\bar{u}A$$

$$M_o = C\Delta\sigma r^3$$

$$V_r = \frac{r}{T}$$

$$M_o = C\Delta\sigma V_r^3 T^3$$

Source Parameter and Scaling Relations for Ordinary Earthquakes



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

$$M_o = G\bar{u}A$$

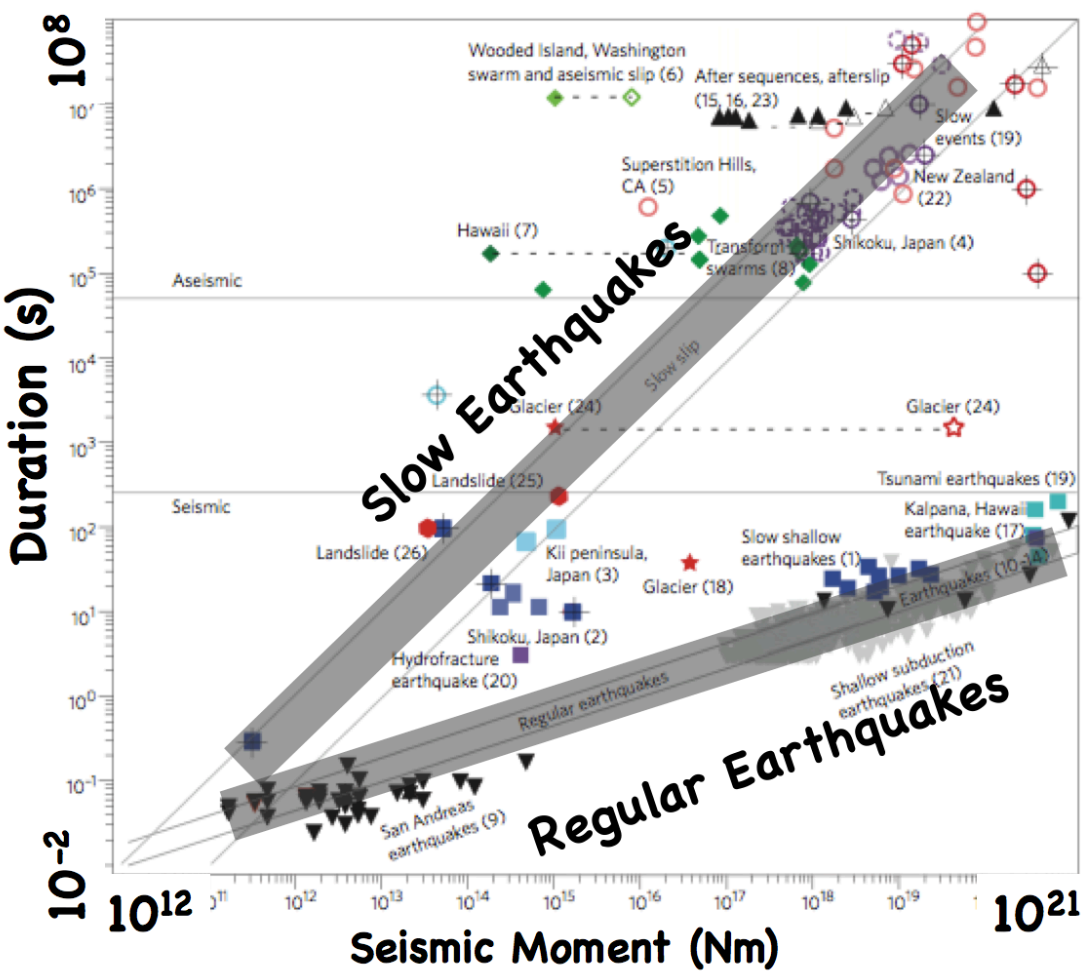
$$M_o = C\Delta\sigma r^3$$

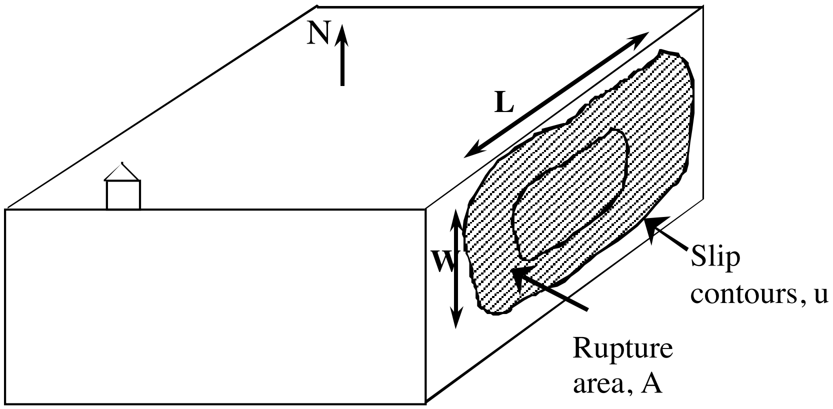
$$V_r = \frac{r}{T}$$

$$M_o = C\Delta\sigma V_r^3 T^3$$

Ide et al., 2007; Peng and Gomberg, 2010

Ordinary Earthquakes V_r is a few km/s





$$M_o = C\Delta\sigma V_r^3 T^3$$

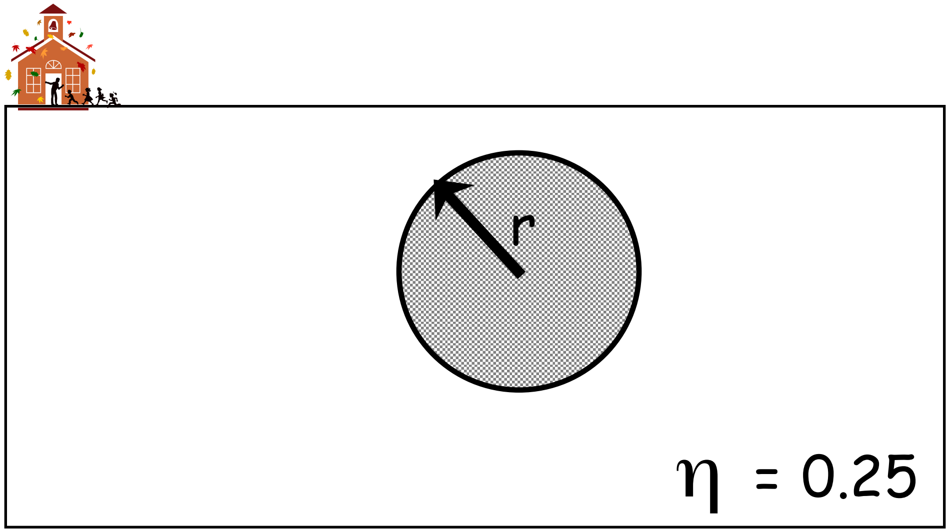
Ide et al., 2007; Peng and Gomberg, 2010

Nucleation Size for Regular Earthquakes

Unstable slip if

$$K < K_c$$

$$K = \frac{\Delta\sigma}{\bar{u}} = \frac{7\pi}{16}\frac{G}{r}$$

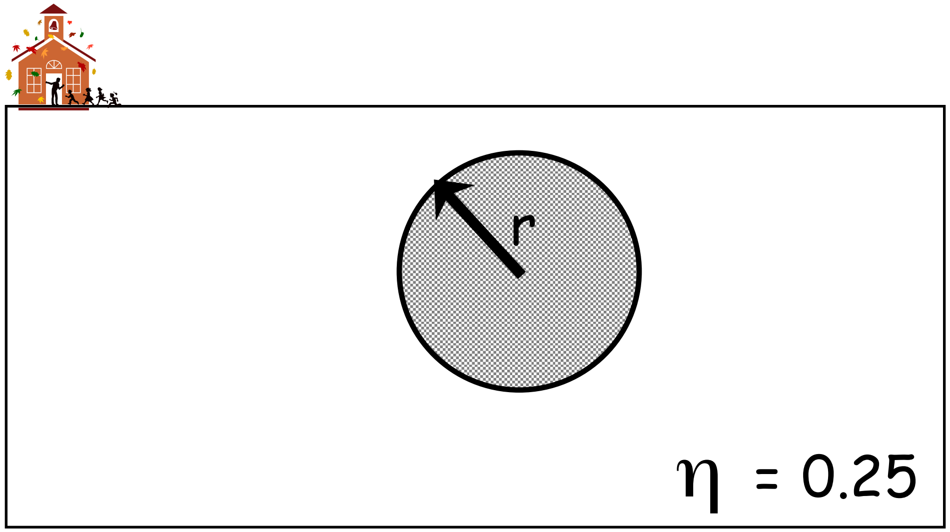


Nucleation Size for Regular Earthquakes

Unstable slip if

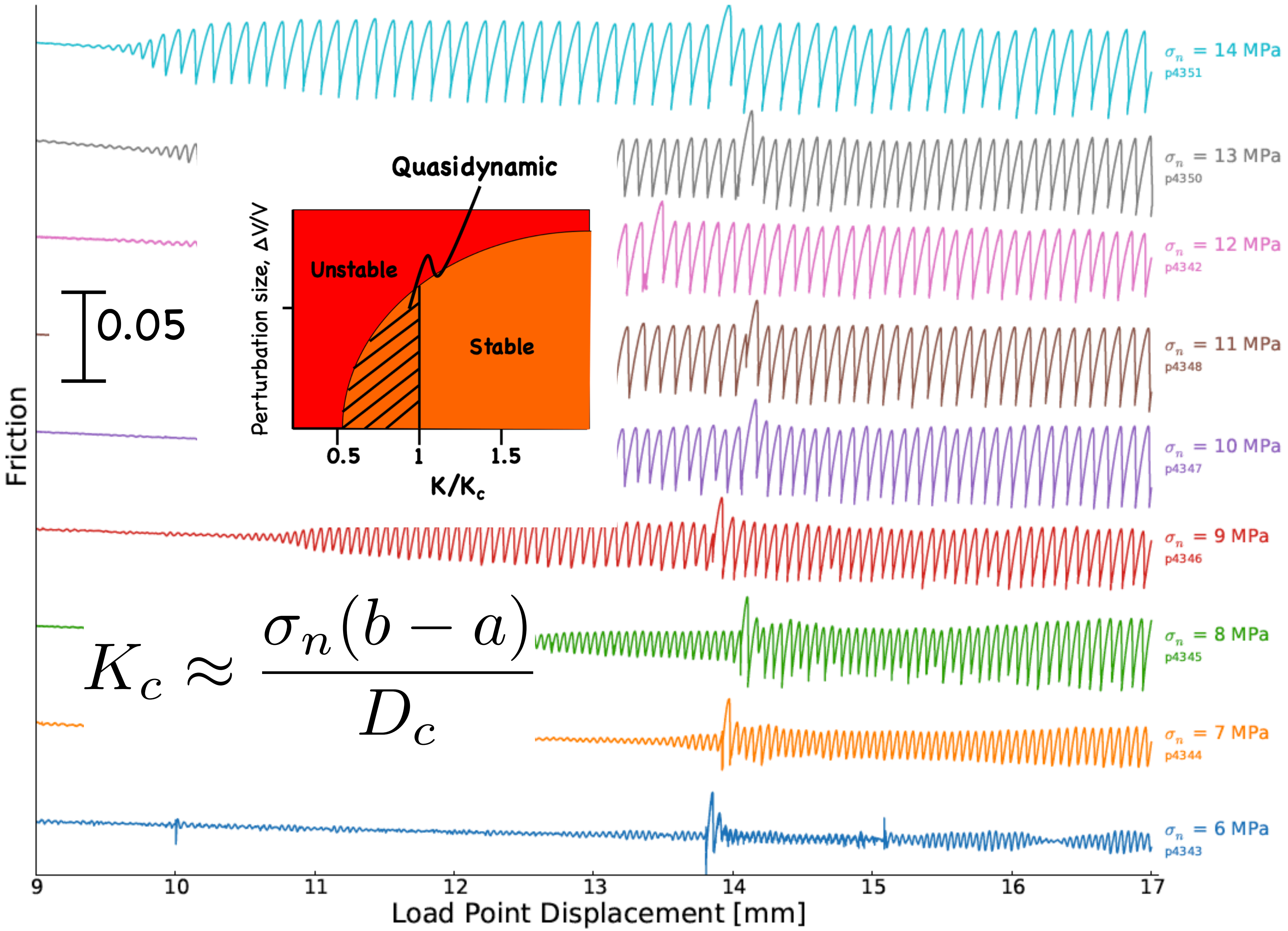
$$K < K_c$$

$$K = \frac{\Delta\sigma}{\bar{u}} = \frac{7\pi}{16}\frac{G}{r}$$



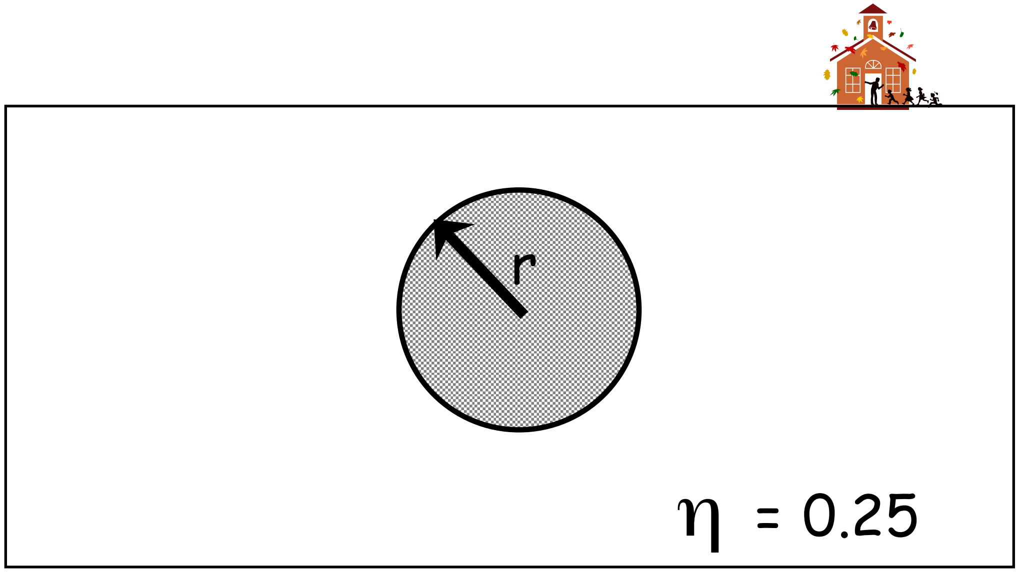
$$K_c \approx \frac{\sigma_n(b-a)}{D_c}$$

$$h^* = \frac{GD_c}{\sigma_n(b-a)}$$



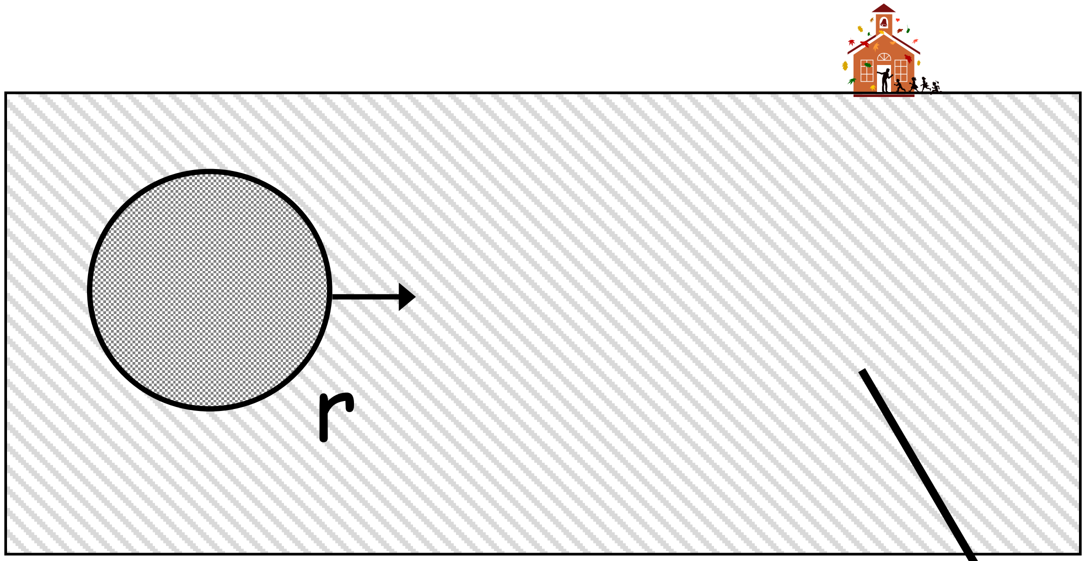
$$K_c \approx \frac{\sigma_n(b-a)}{D_c}$$

Rupture Patch Size for Slow Earthquakes?



Slow earthquake nucleation when $\frac{K}{K_c} \approx 1.0$

$$h^* = r_c = \frac{GD_c}{\sigma_n(b-a)}$$

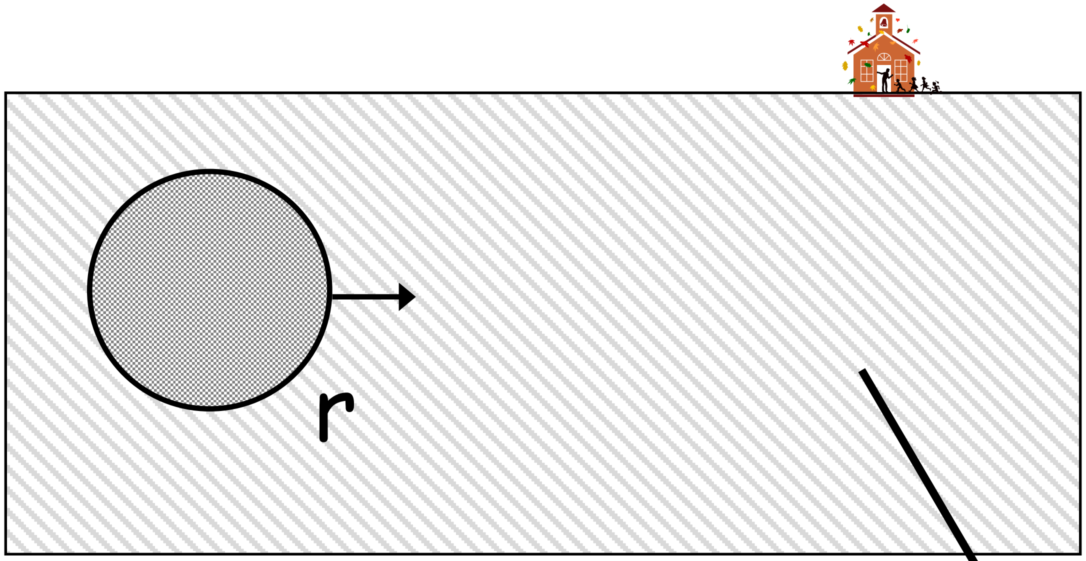


Do slow slip events propagate at fixed size?

$$M_o^{patch} = G\bar{u}r^2$$

~~$M_o = C\Delta\sigma r^3$~~

$$M_o \approx V_r T$$

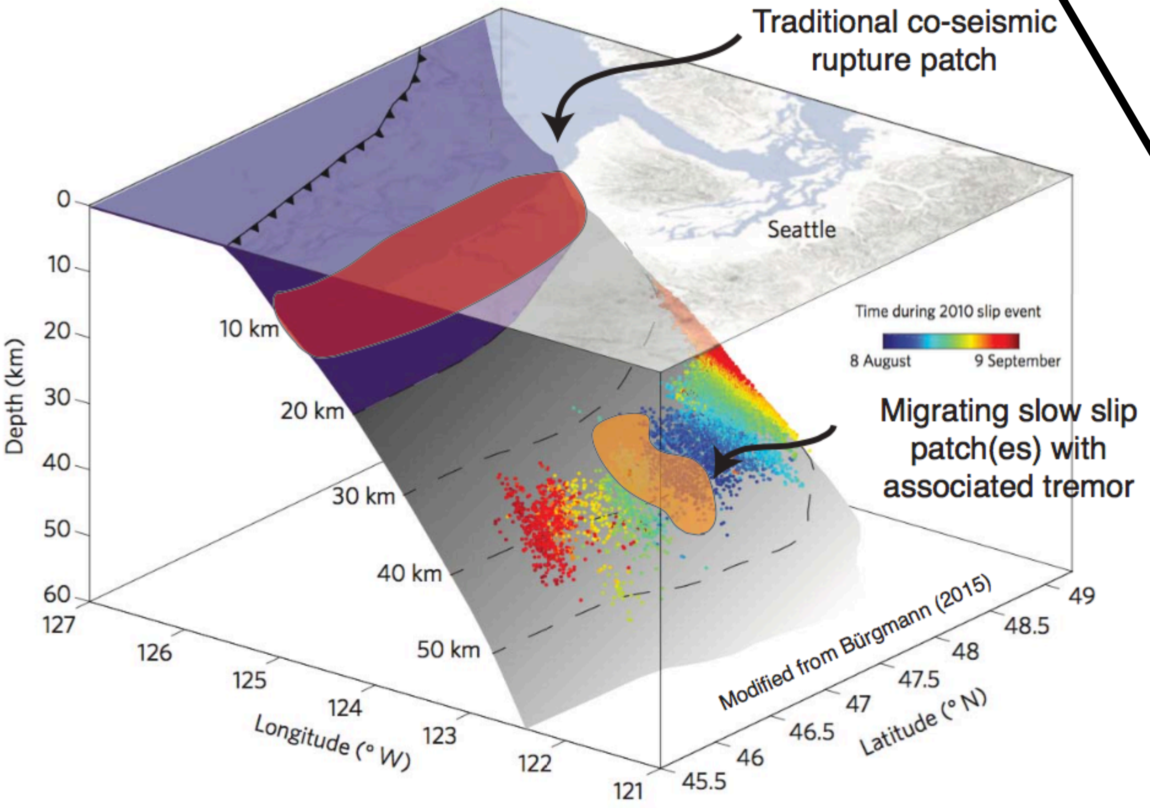


Do slow slip events propagate at fixed size?

$$M_o{}^{patch} = G\bar{u}r^2$$

$$\cancel{M_o = C\Delta\sigma r^3}$$

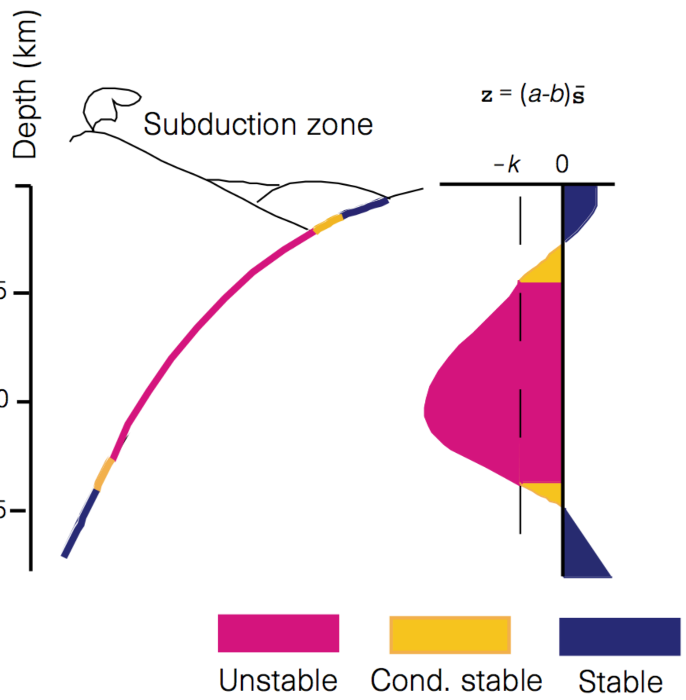
$$M_o \approx V_r T$$



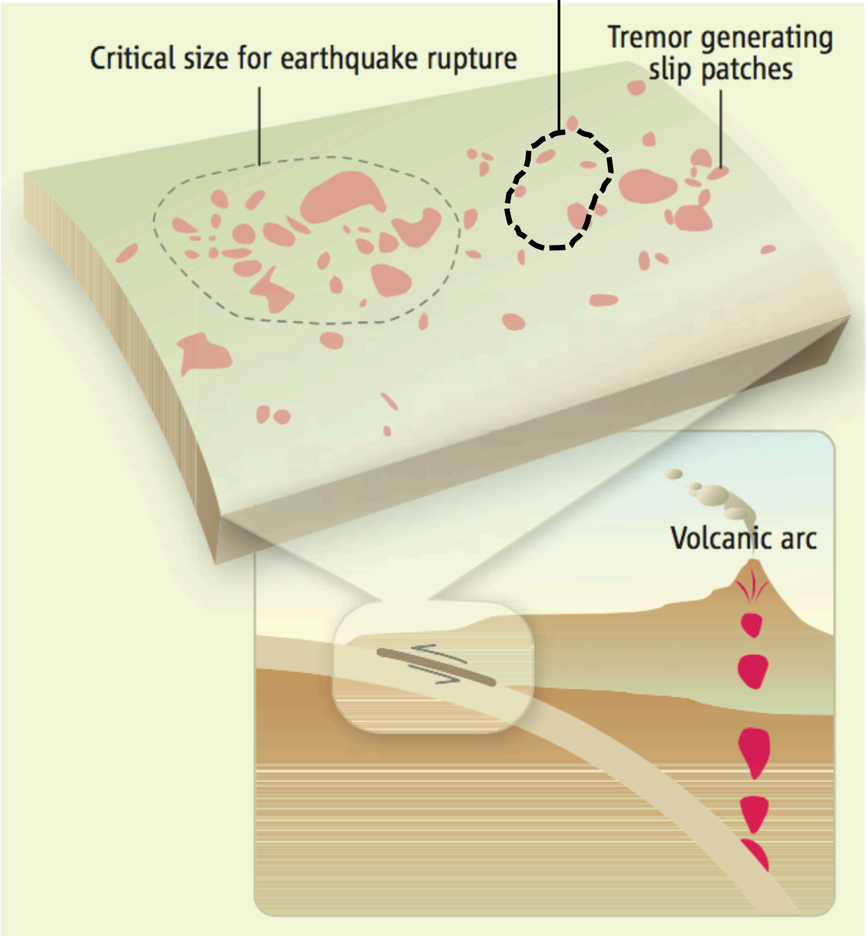
Bürgmann, 2015; Houston, 2015

Slow slip events propagate at size r < h*

$$h^* = \frac{G D_c}{\sigma_n (b - a)}$$



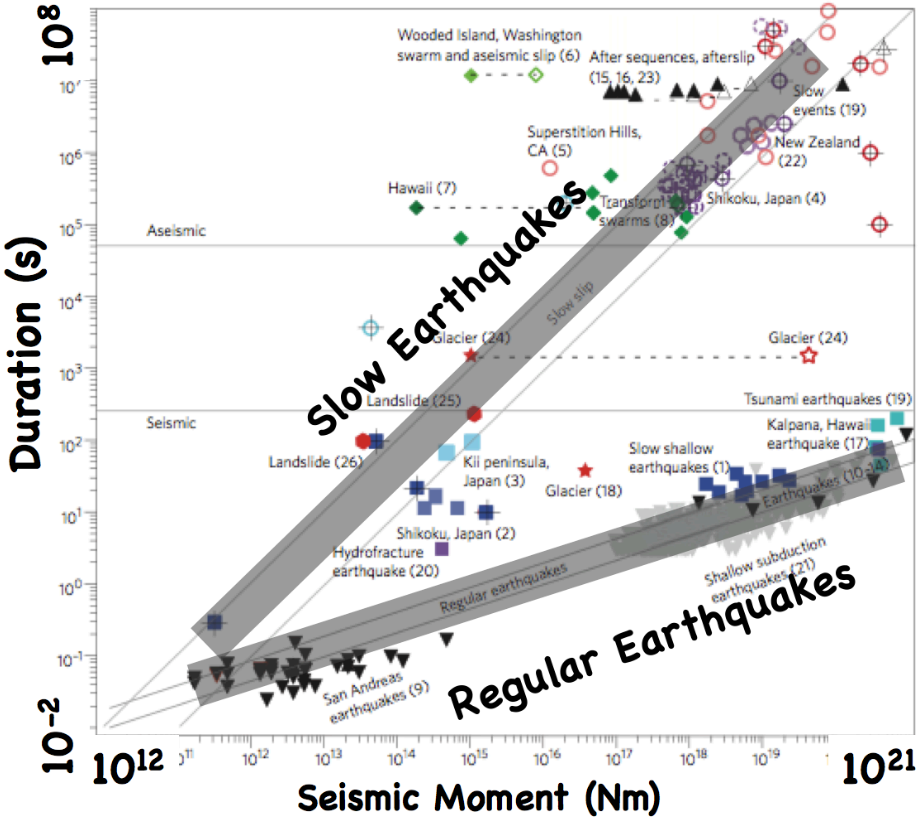
Slow slip patch size



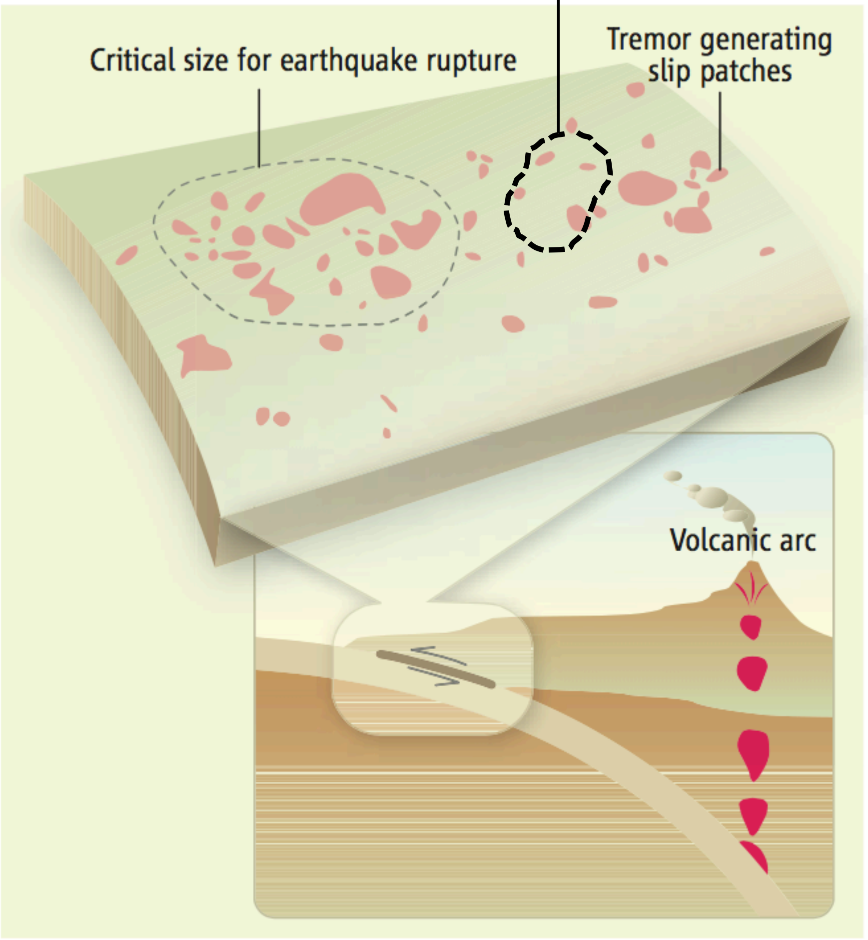
Richardson and Marone, 2008

Slow slip events propagate at size r < h*

$$h^* = \frac{GD_c}{\sigma_n(b-a)}$$



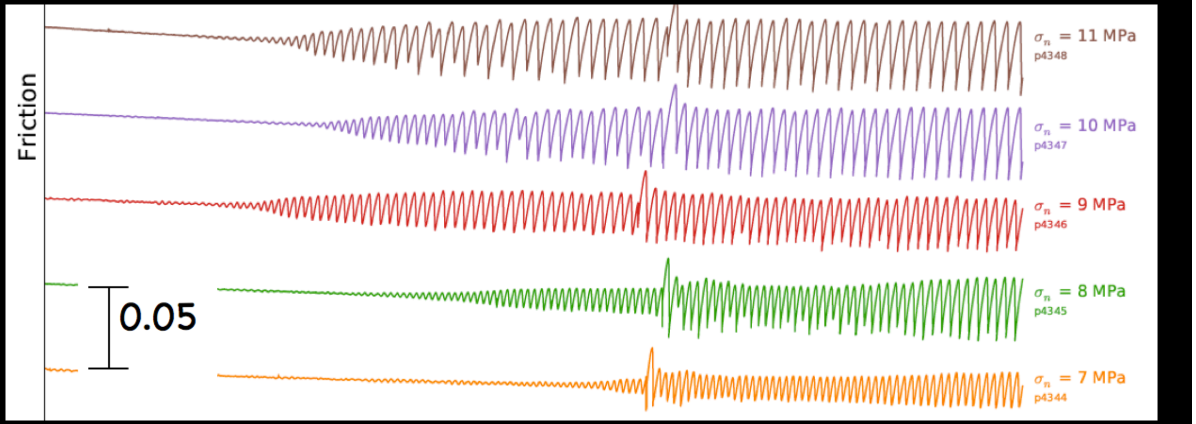
Slow slip patch size



Richardson and Marone, 2008

Summary

1. Slow earthquakes and fast, normal earthquakes are part of the spectrum of fault slip behaviors (slip modes)
2. We produce lab slow earthquakes by matching loading stiffness and frictional rheology
3. We observe the full spectrum of slip rates from fast to slow, near the stability boundary
4. Stick-slip stress drop is lower for slower events and decreases with slip event speed – the same as for slow vs. regular earthquakes



The Mechanics of Slow Earthquakes and the Spectrum of Fault Slip Behaviors

Thank You