Mechanics of Earthquakes and Faulting

Lecture 15 , 23 Mar. 2021

www.geosc.psu.edu/Courses/Geosc508

- 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)

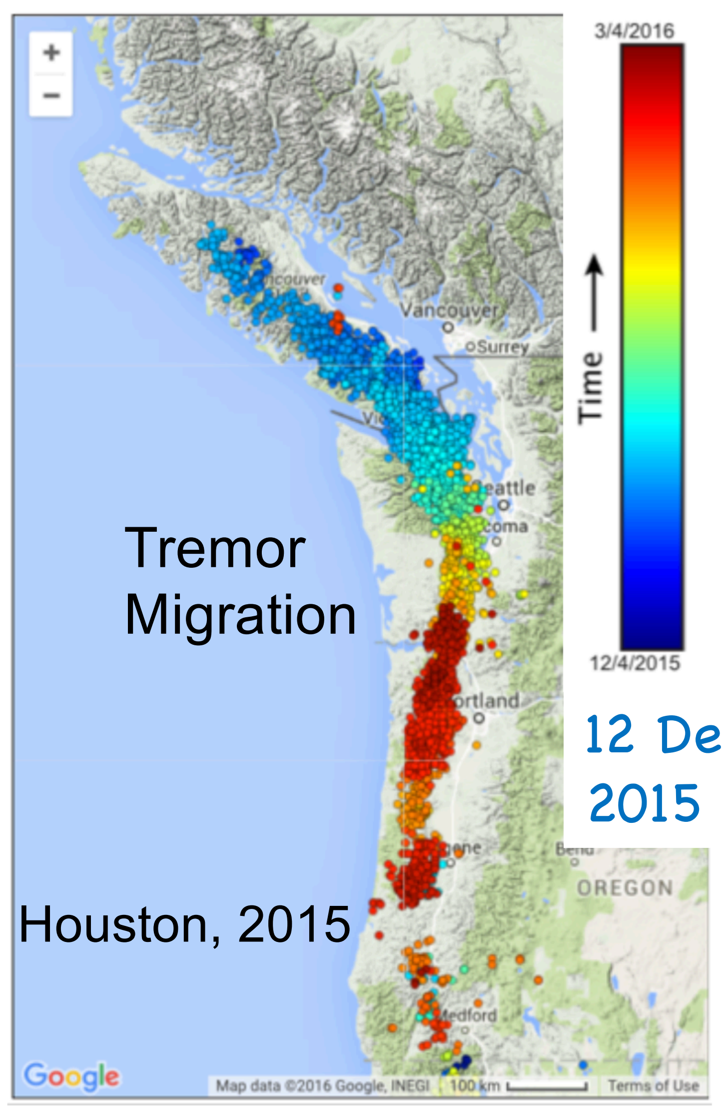
The spectrum of fault slip behaviors

- Ordinary earthquakes
- Tsunamigenic earthquakes
- Tectonic Tremor
- Episodic tremor and slip (ETS)
- Low frequency earthquakes
- Very low frequency earthquakes
- Long term slow slip events
- Slow precursors

Slow Earthquakes

- Aseismic slip

4 Mar. 2016



Tremor Migration

Houston, 2015

12 Dec. 2015

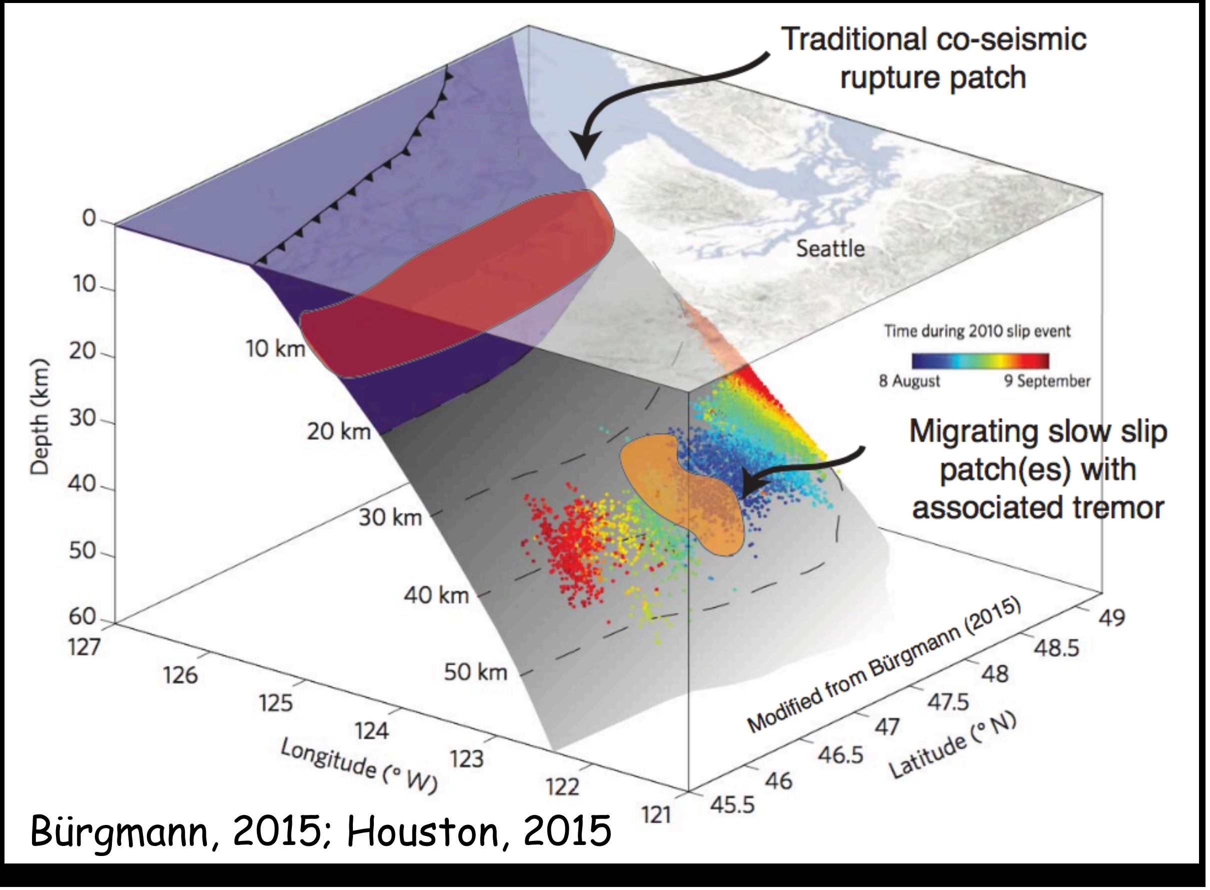
Slow Earthquakes are self-propagating ruptures

Slip on the fault patch elevates the crack-tip stresses to the levels necessary for continued fracture

Slow Earthquakes

V_r is a few km/day

One Month in 2010



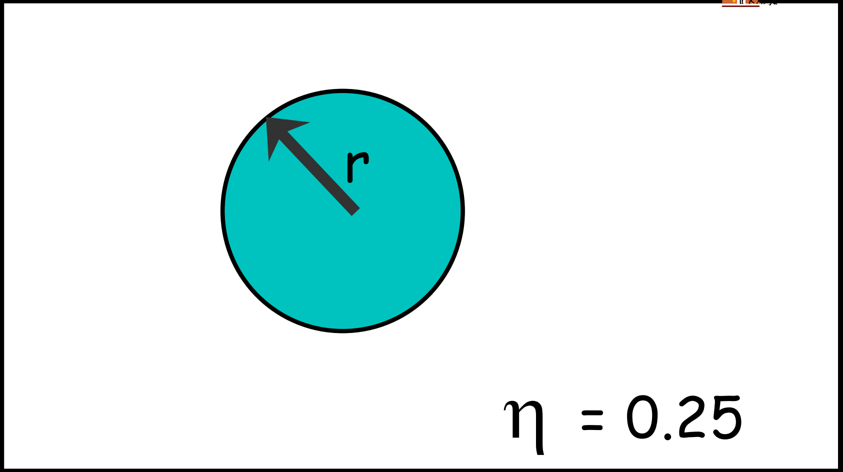
Traditional co-seismic rupture patch

Migrating slow slip patch(es) with associated tremor

Bürgmann, 2015; Houston, 2015

Ordinary Earthquakes

Seismic waves are created by rapid acceleration at the rupture front



Ordinary (fast) Earthquakes

V_r is a few km/s

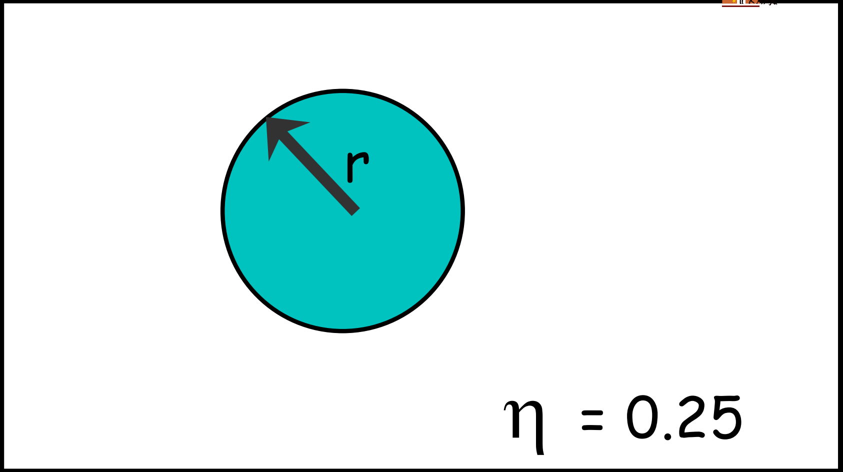
Images from the aftermath of the Anchorage earthquake

M7.1 2018 Anchorage Earthquake

Slow Earthquakes are also self-propagating ruptures

They don't radiate elastic energy

But they obey Fracture Mechanics

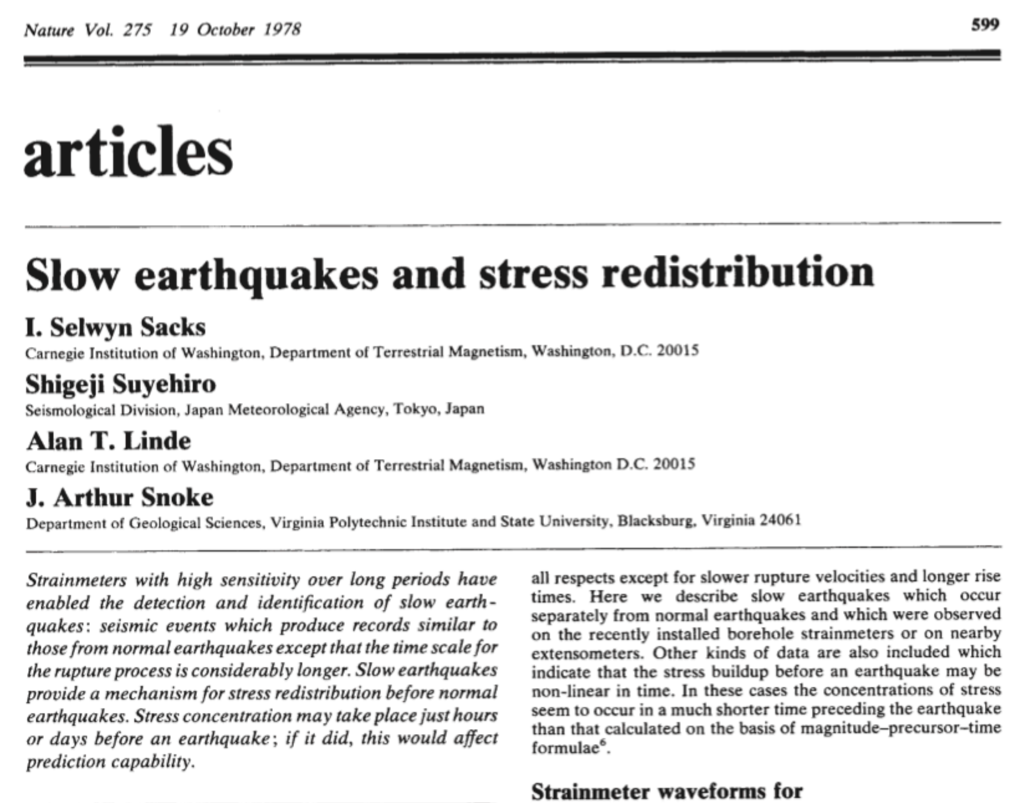


Slip on the fault patch elevates the crack-tip stresses to the levels necessary for continued fracture
-the energy release rate equals the fracture energy

Slow Earthquakes

V_r is a few km/day

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

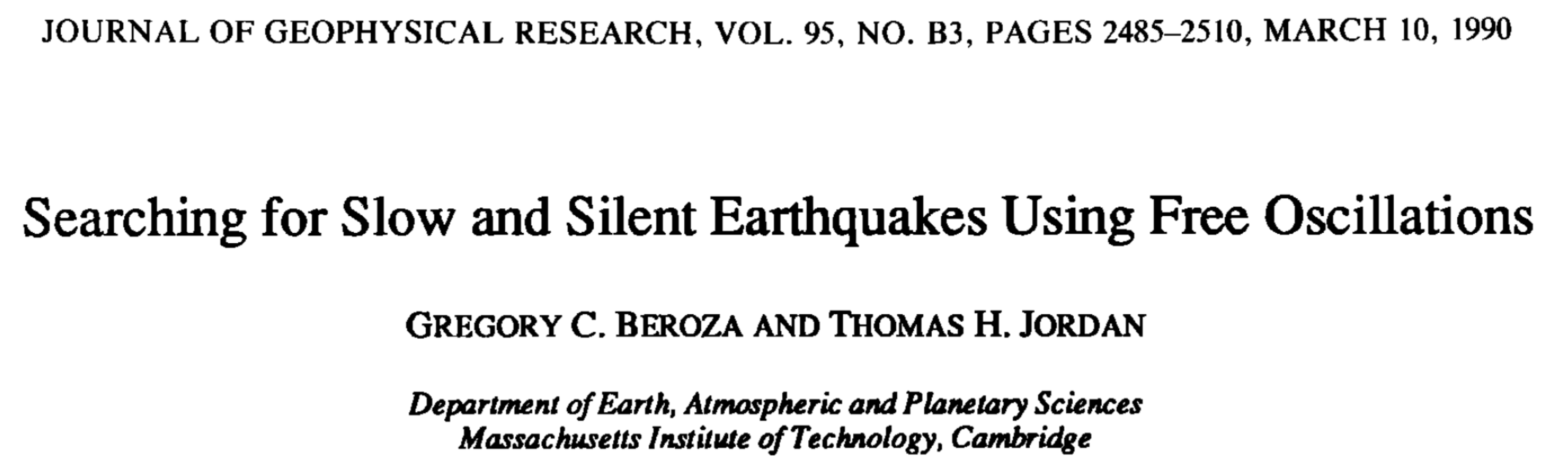
Strainmeters with high sensitivity over long periods have enabled the detection and identification of slow earthquakes: seismic events which produce records similar to those from normal earthquakes except that the time scale for the rupture process is considerably longer. Slow earthquakes provide a mechanism 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

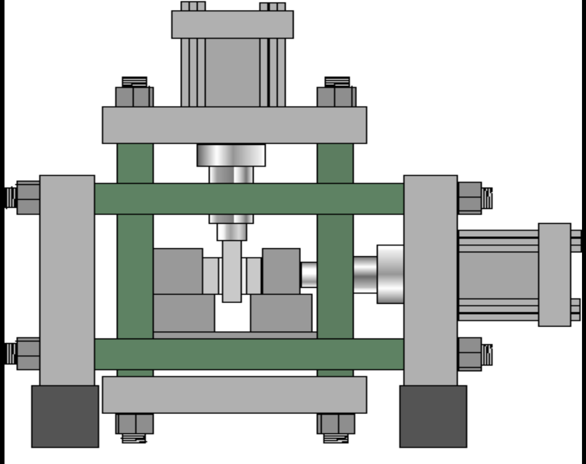
1. Slow earthquakes could represent quasi-dynamic frictional instability (positive feedback, self-driven instability)

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

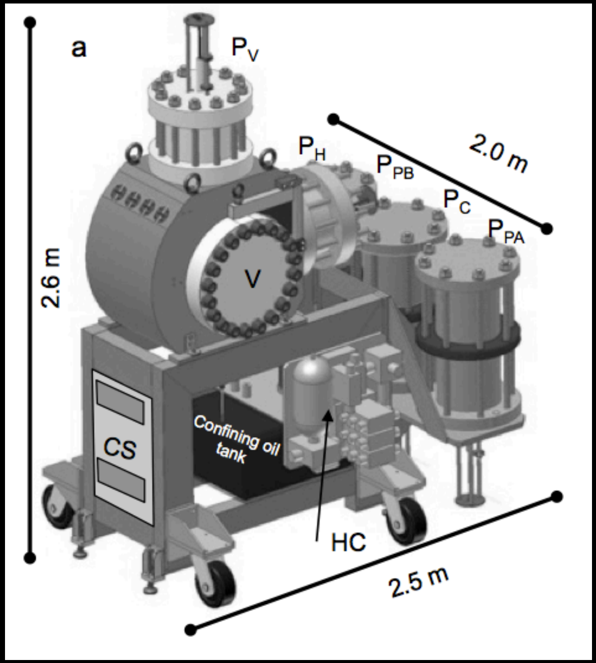
PennState

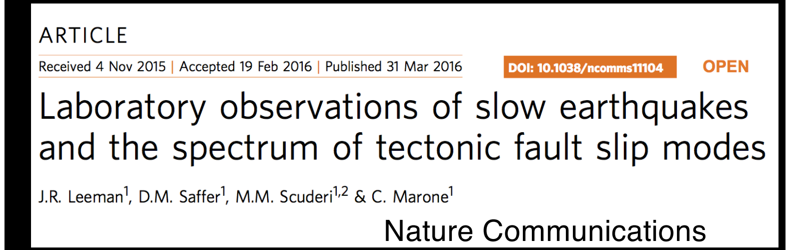
SAPIENZA
UNIVERSITÀ DI ROMA



John Leeman

Marco Scuderi





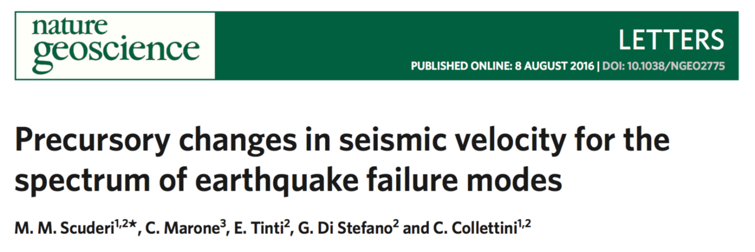
ARTICLE

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]

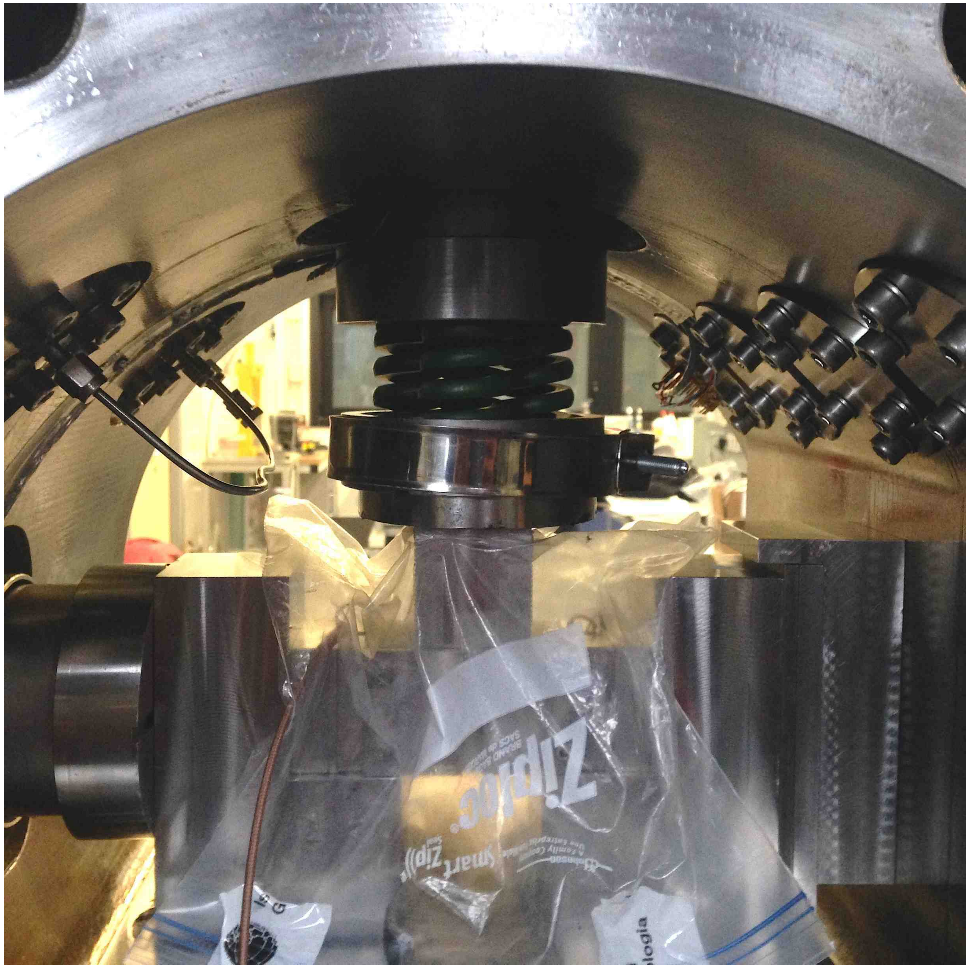
Nature Communications



nature geoscience LETTERS
PUBLISHED ONLINE: 8 AUGUST 2016 | DOI: 10.1038/NGEO2775

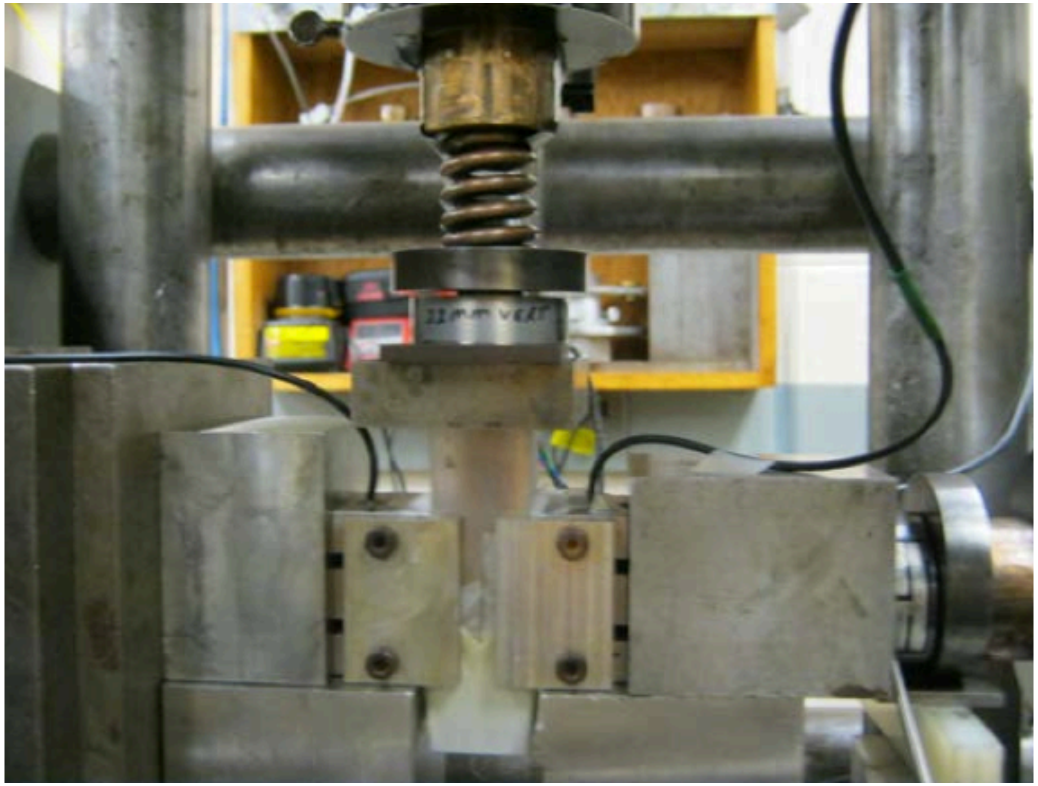
Precursory changes in seismic velocity for the spectrum of earthquake failure modes

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



BRAVA at INGV (Rome)

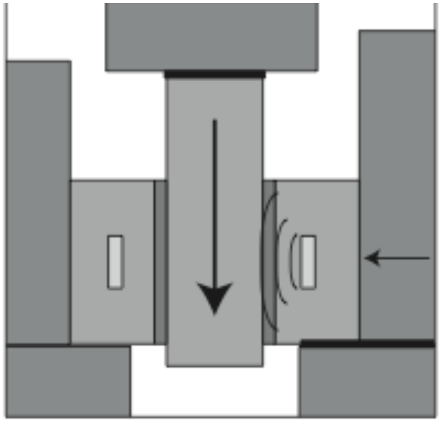
Collettini Lab



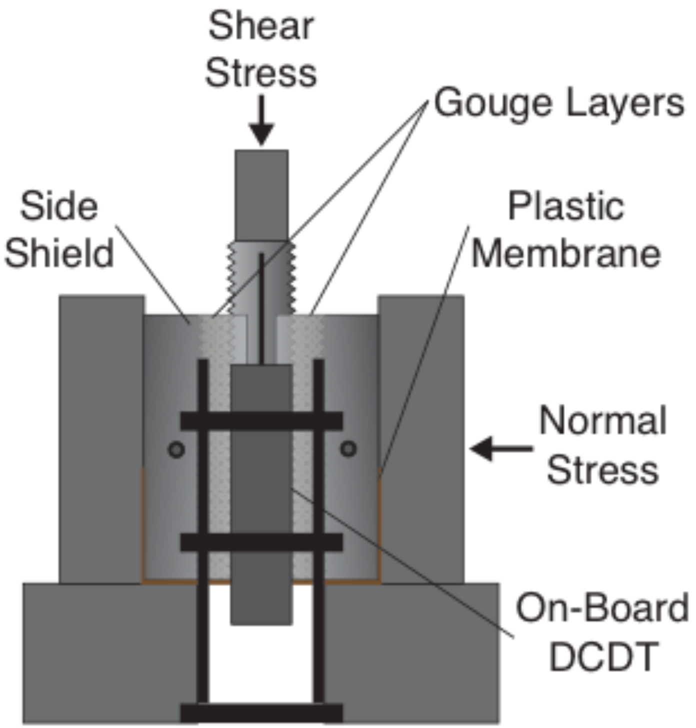
Biax at Penn State

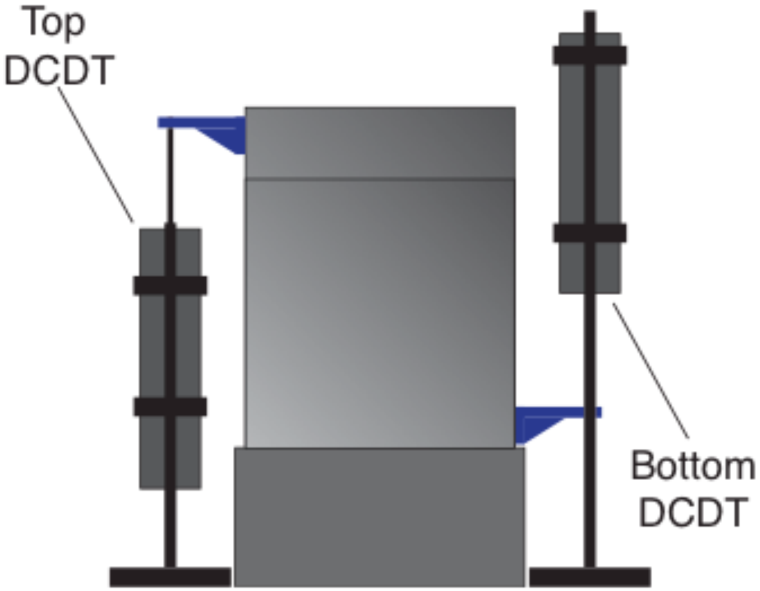
Double direct shear with biaxial loading

and controlled loading stiffness

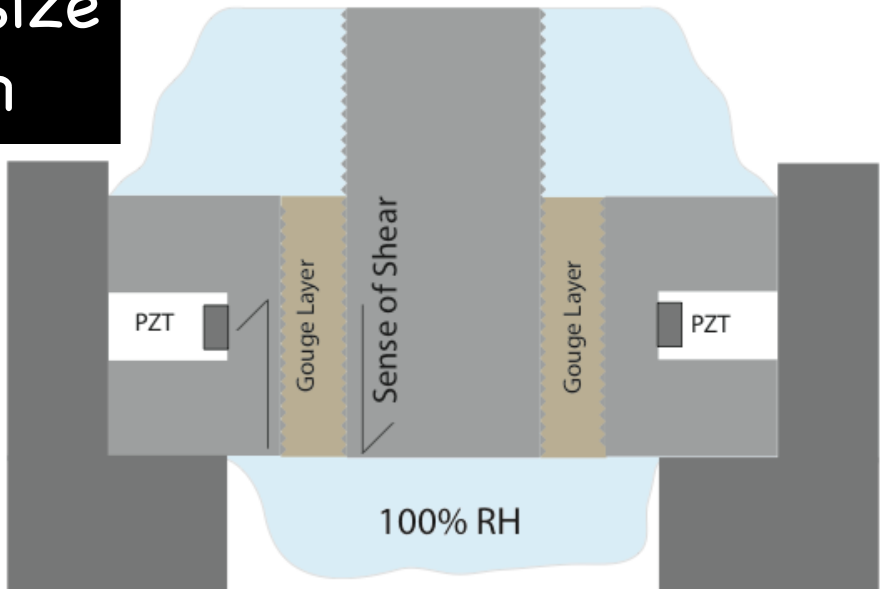


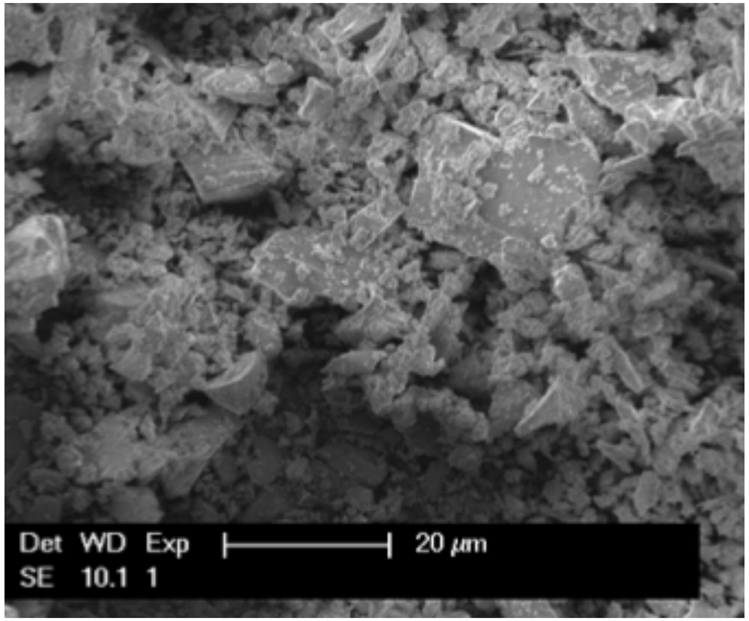
High-resolution, direct measurements of shear displacement, shear strain, normal strain, stresses



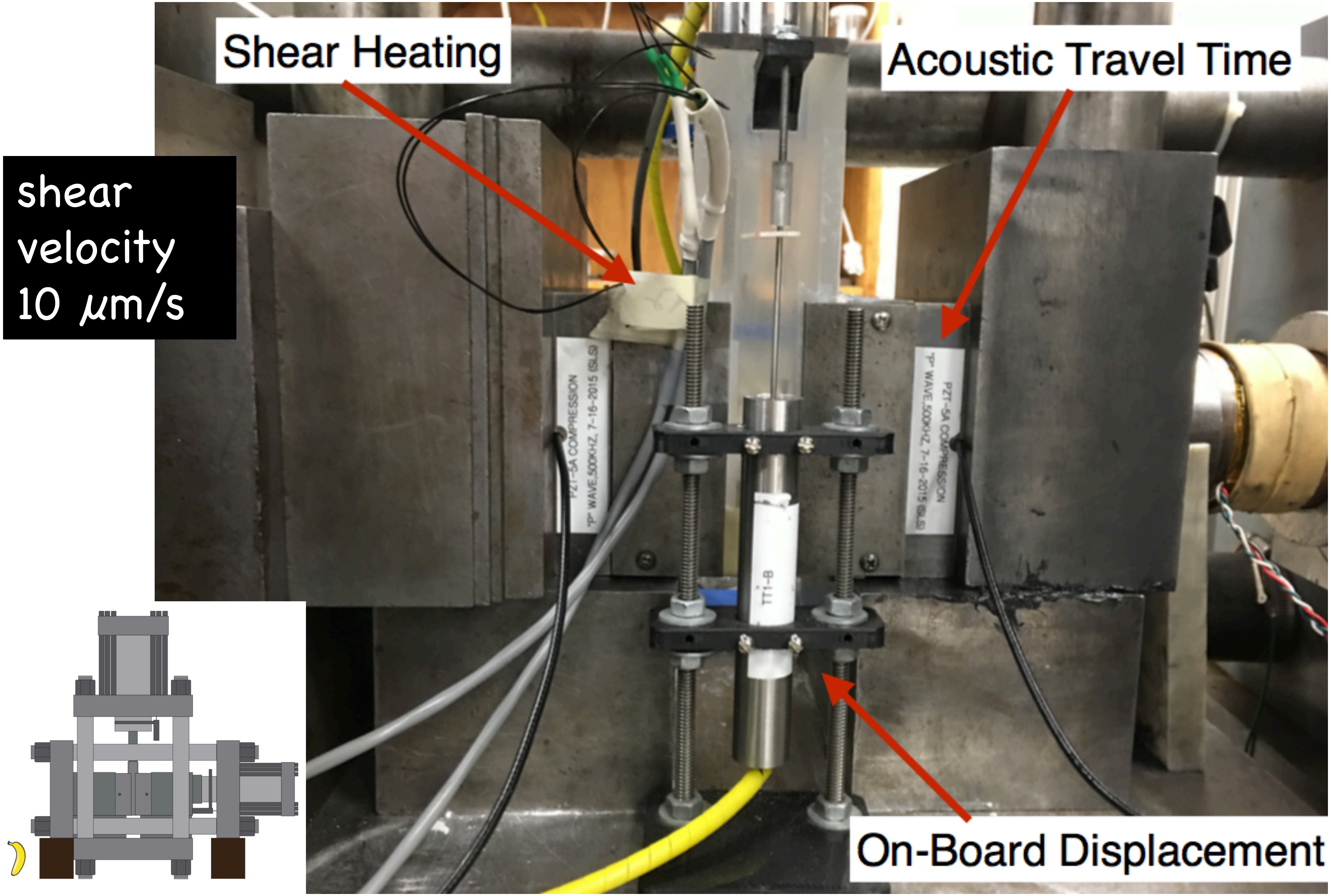


- Quartz powder
- grain size < 10μm





Biaxial testing machine at Penn State



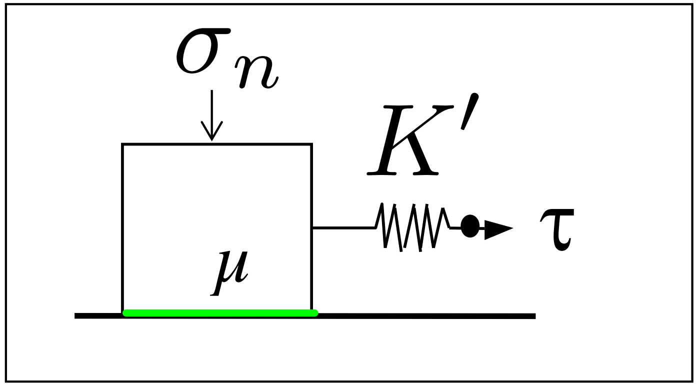
shear
velocity
10 μm/s

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



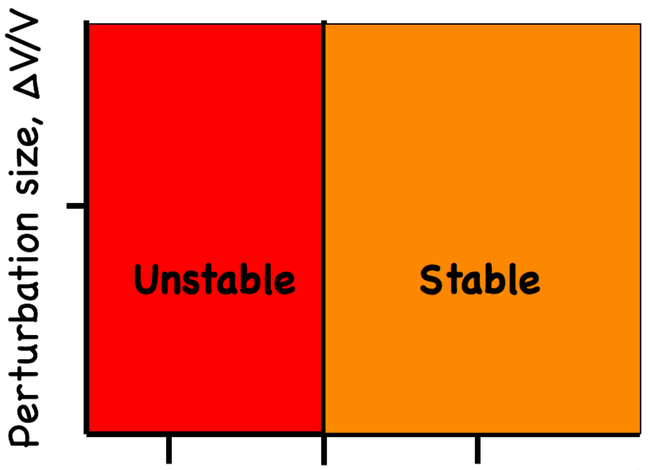
How do we produce slow slip?

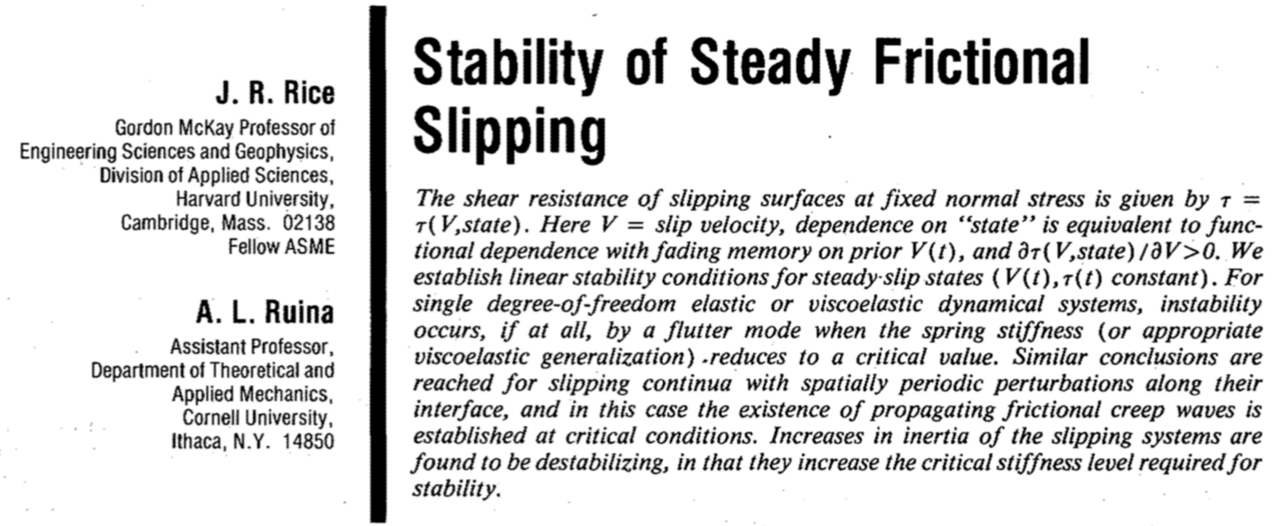
Rate and State Friction

$$\frac{\tau(\theta, v)}{\sigma_n} = \mu_o + a\, ln\left(\frac{v}{v_o}\right) + b\, ln\left(\frac{v_o\theta}{D_c}\right)$$

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

Dieterich, 1979; Ruina, 1983





J. R. Rice
Gordon McKay Professor of
Engineering Sciences and Geophysics,
Division of Applied Sciences,
Harvard University,
Cambridge, Mass. 02138
Fellow ASME

A. L. Ruina
Assistant Professor,
Department of Theoretical and
Applied Mechanics,
Cornell University,
Ithaca, N.Y. 14850

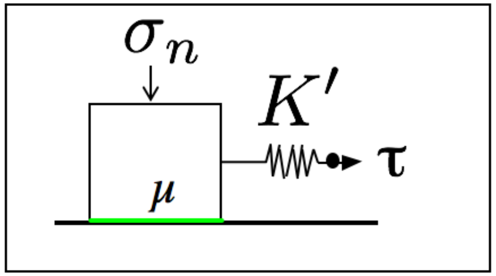
Stability of Steady Frictional Slipping

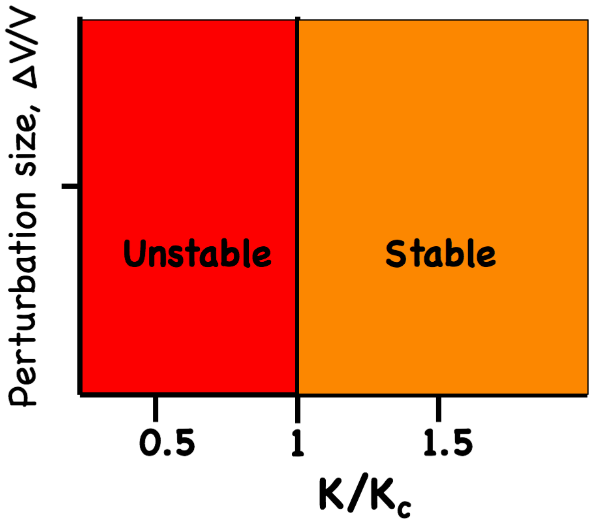
The shear resistance of slipping surfaces at fixed normal stress is given by $\tau = \tau(V,state)$. Here V = slip velocity, dependence on "state" is equivalent to functional dependence with fading memory on prior $V(t)$, and $\partial\tau(V,state)/\partial V>0$. We establish linear stability conditions for steady-slip states ($V(t)$, $\tau(t)$ constant). For single degree-of-freedom elastic or viscoelastic dynamical systems, instability occurs, if at all, by a flutter mode when the spring stiffness (or appropriate viscoelastic generalization) reduces to a critical value. Similar conclusions are reached for slipping continua with spatially periodic perturbations along their interface, and in this case the existence of propagating frictional creep waves is established at critical conditions. Increases in inertia of the slipping systems are found to be destabilizing, in that they increase the critical stiffness level required for stability.

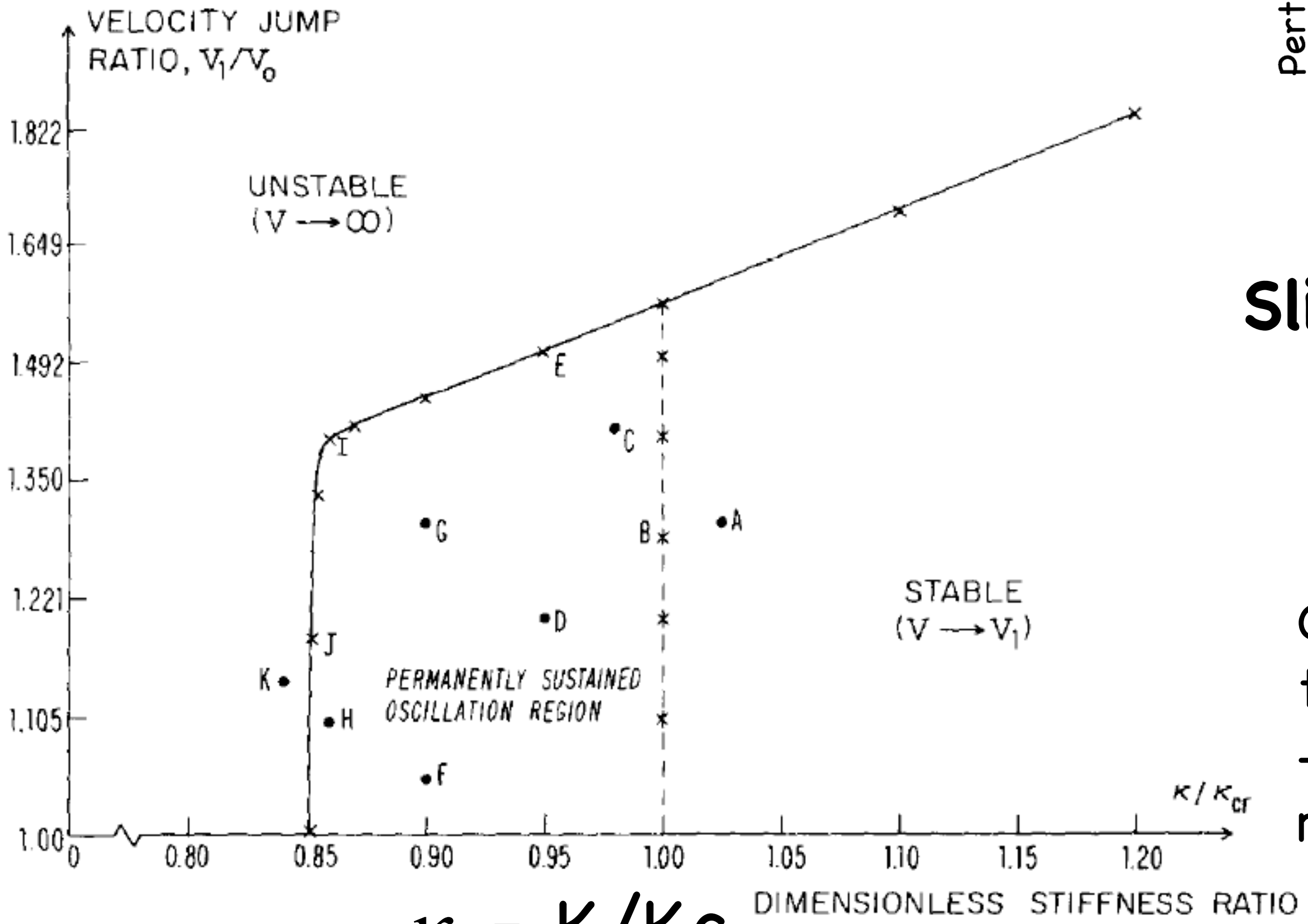
Journal of Applied Mechanics, vol. 50, pp. 343-349, 1983

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

Stability transition from stable to unstable sliding.







Slip is unstable if

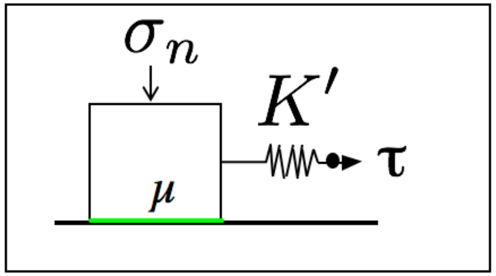
$$K < K_c$$

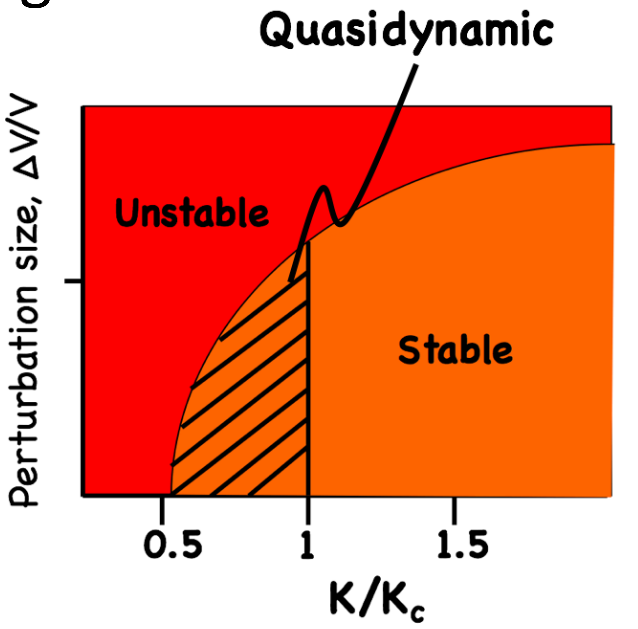
Complex behavior near the stability boundary, --but not for 1 sv rsf model

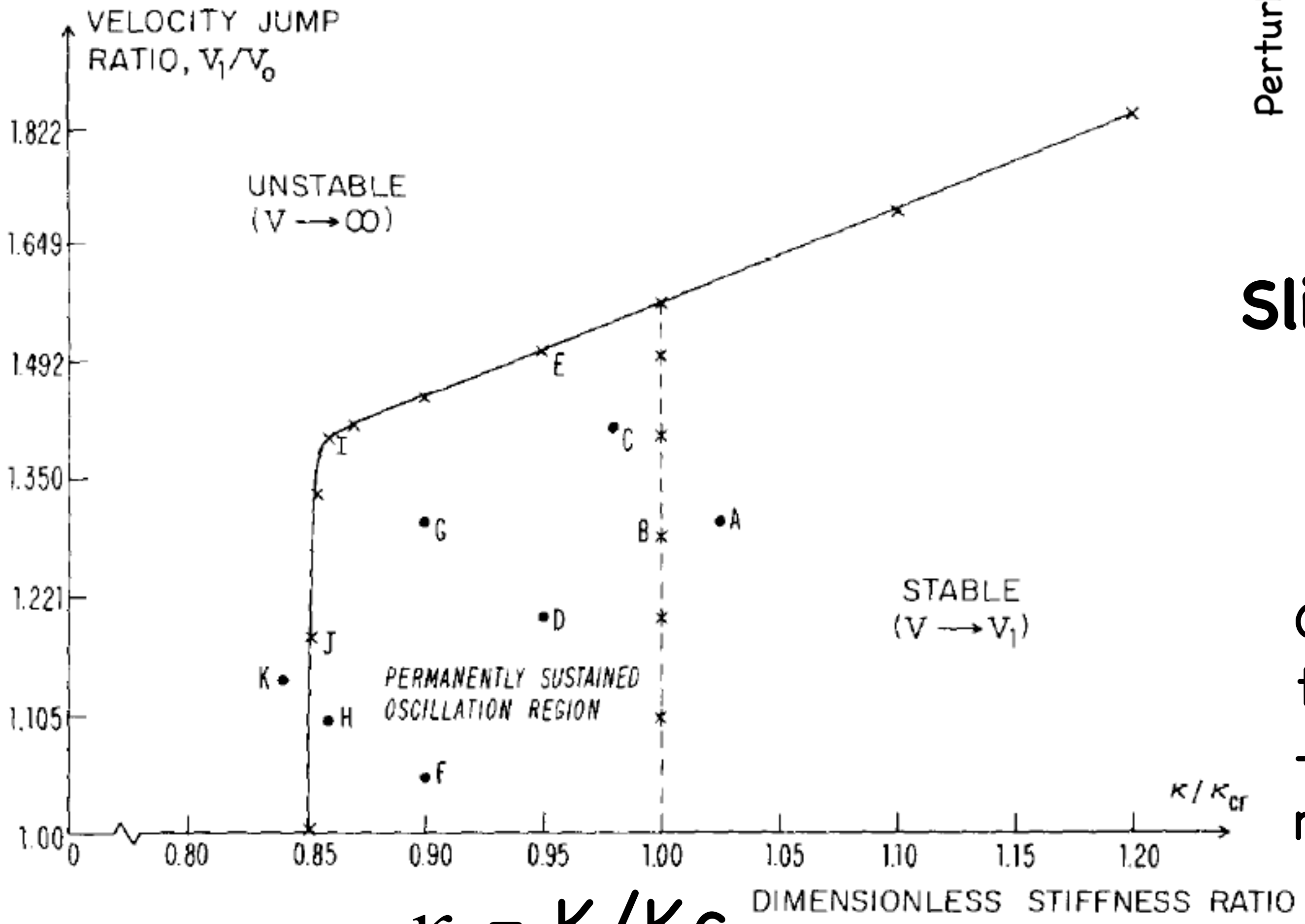
κ = K/Kc

Gu et al., 1984

Stability transition from stable to unstable sliding.







$\kappa = K/Kc$

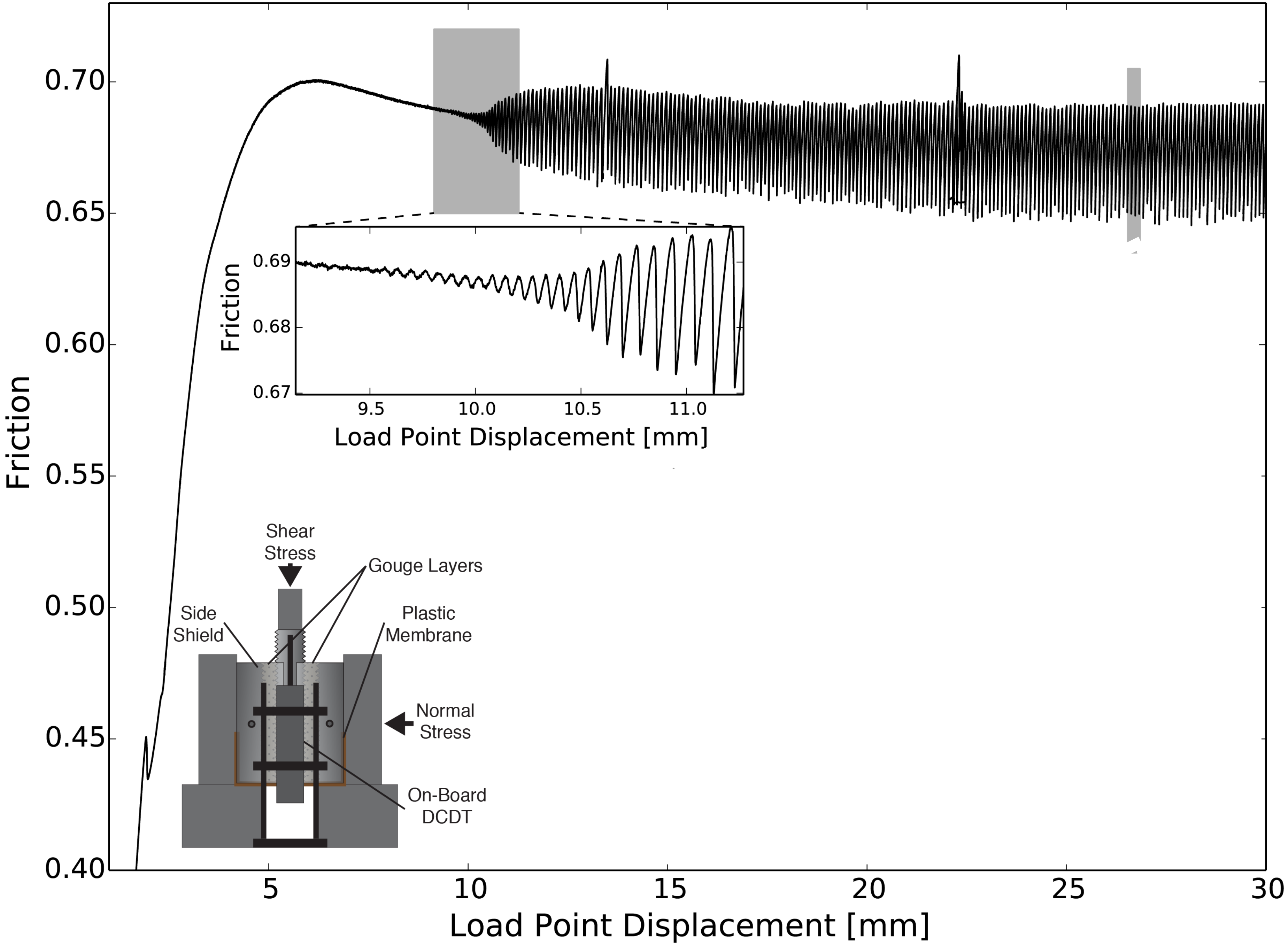
Gu et al., 1984

Slip is unstable if

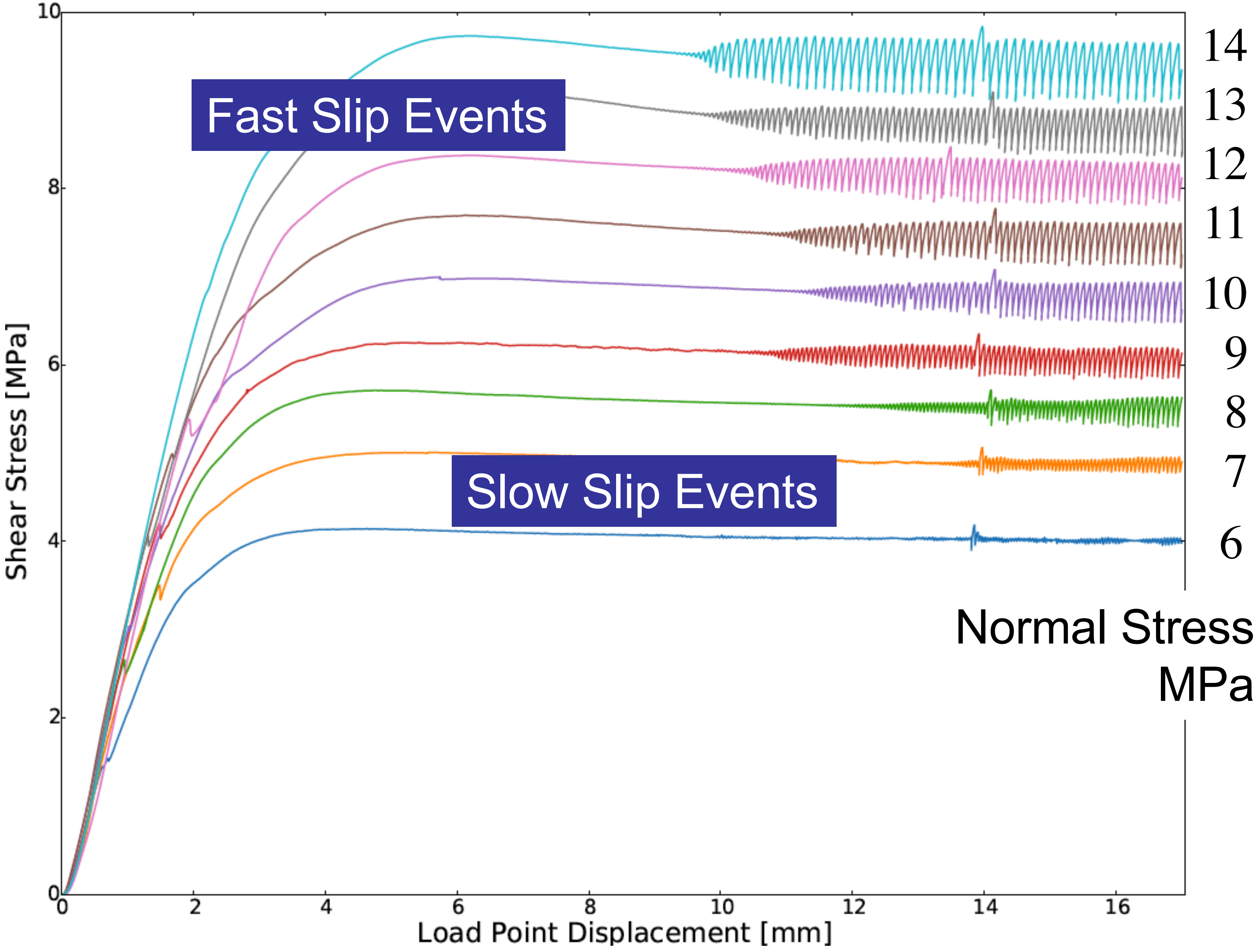
$$K < K_c$$

Complex **behavior** near the stability boundary, --**but not for 1 sv rsf model**

Repetitive Slow Stick-Slip



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

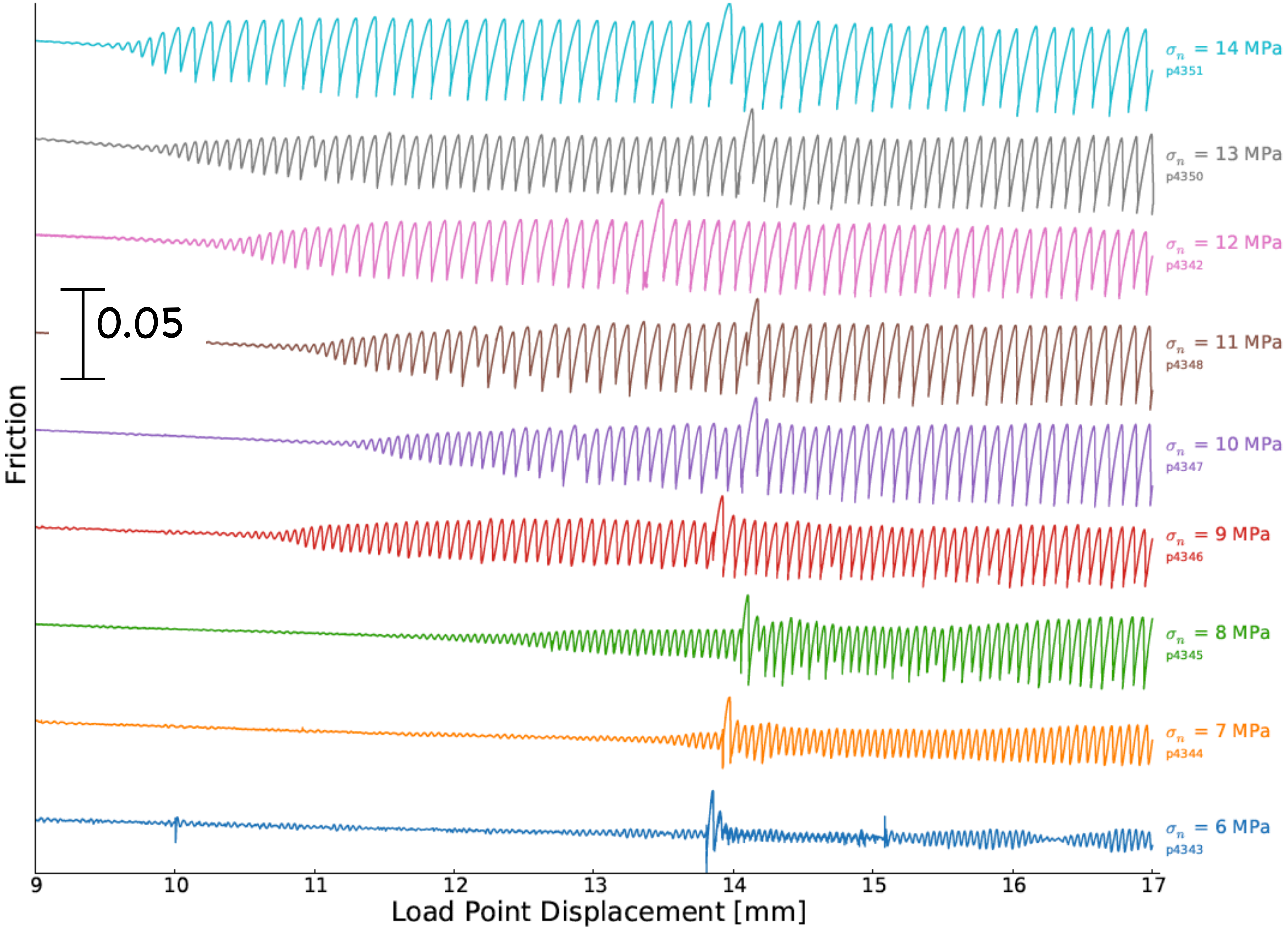


Fast Slip Events

Slow Slip Events

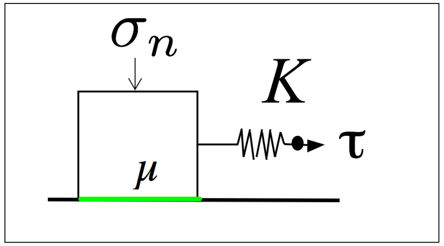
Normal Stress
MPa

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


Friction
0.05
Load Point Displacement [mm]
9
10
11
12
13
14
15
16
17
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

Mechanics of Faulting

Frictional Sliding: Stick-slip

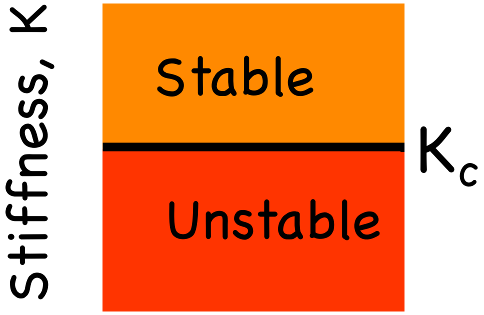


$$k = \frac{K}{\sigma_n} \qquad \mu = \frac{\tau}{\sigma_n}$$

$$\frac{\tau(\theta, v)}{\sigma_n} = \mu_o + a\, ln\left(\frac{v}{v_o}\right) + b\, ln\left(\frac{v_o\theta}{D_c}\right)$$

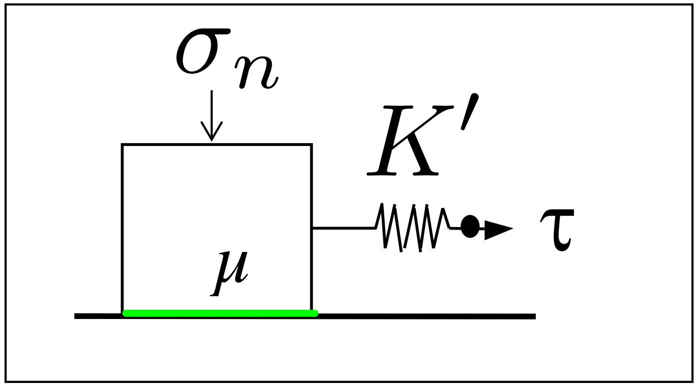
$$\frac{d\theta}{dt} = -\frac{V\theta}{D_c} ln(\frac{V\theta}{D_c})$$

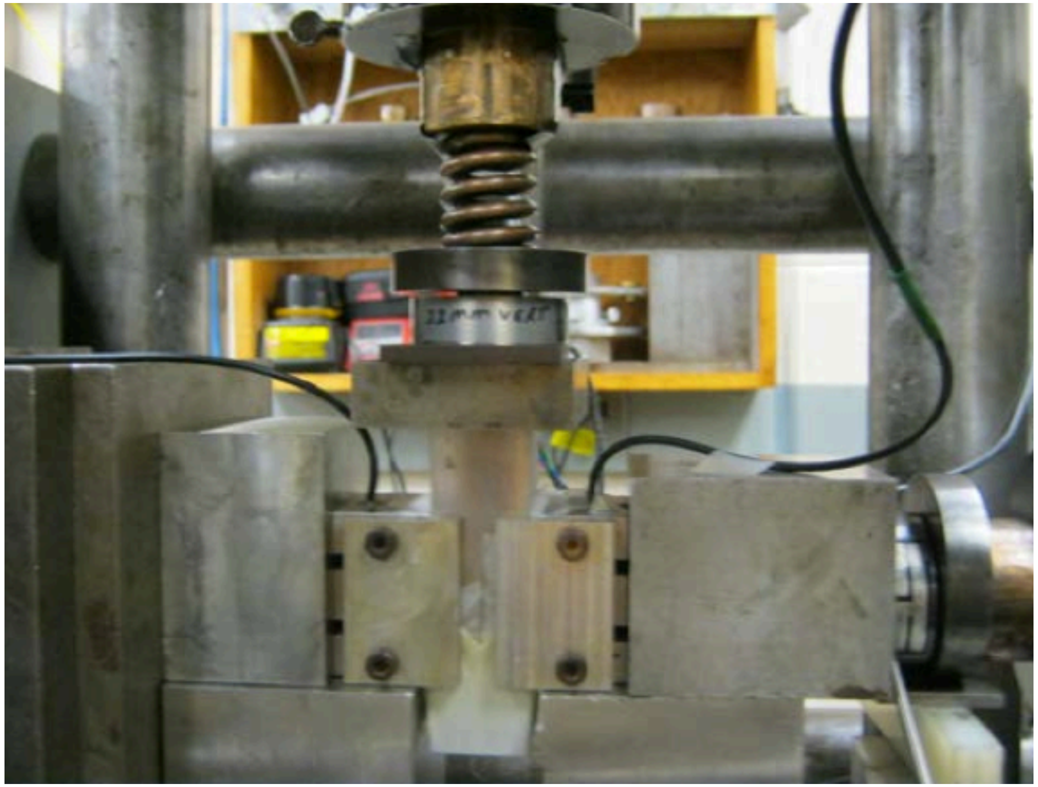
$$\frac{d\mu}{dt} = k(V_{lp} - V)$$

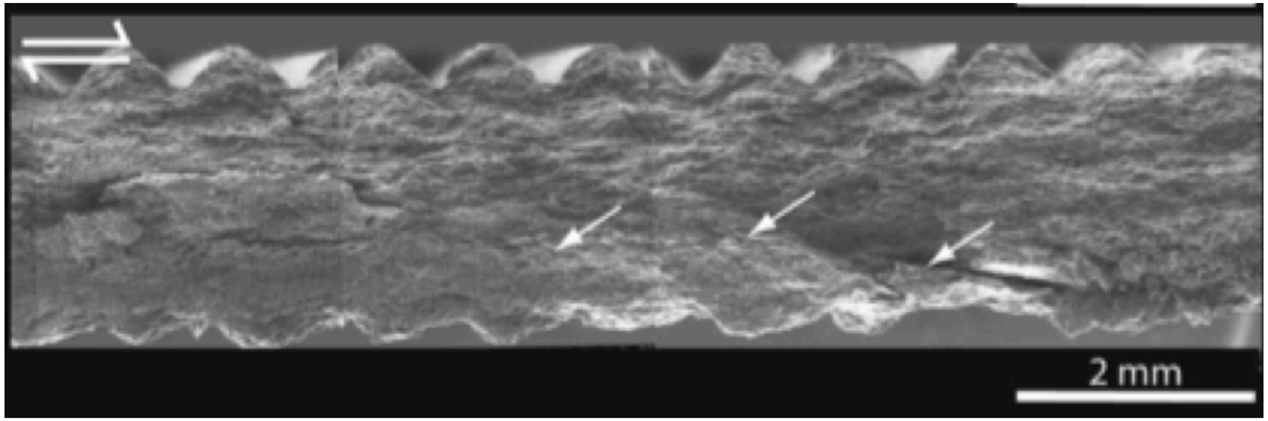


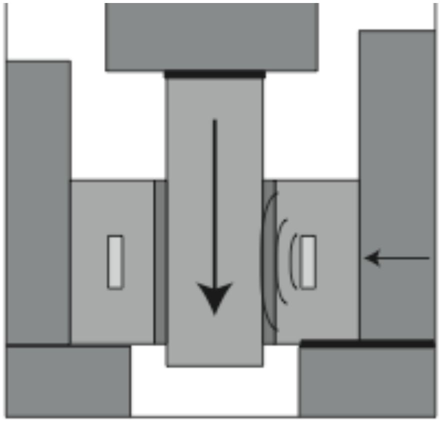
$$K_c = \frac{\sigma_n(b-a)}{D_c}[1 + \frac{m{V_o}^2}{\sigma_n a D_c}]$$

Dieterich, 1979; Ruina, 1983; Rice & Ruina, 1983; Gu et al., 1984 elastic loading stiffness

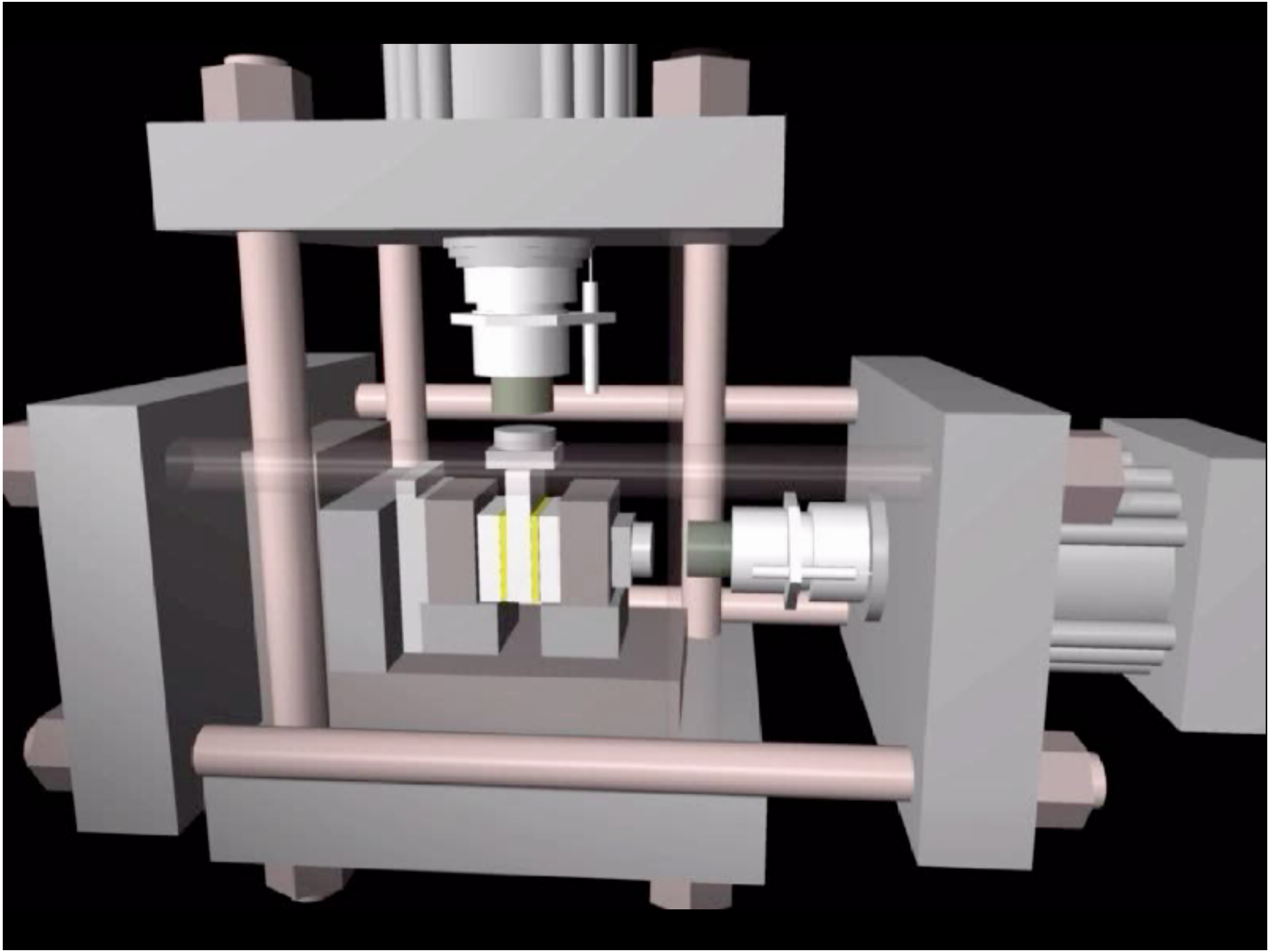




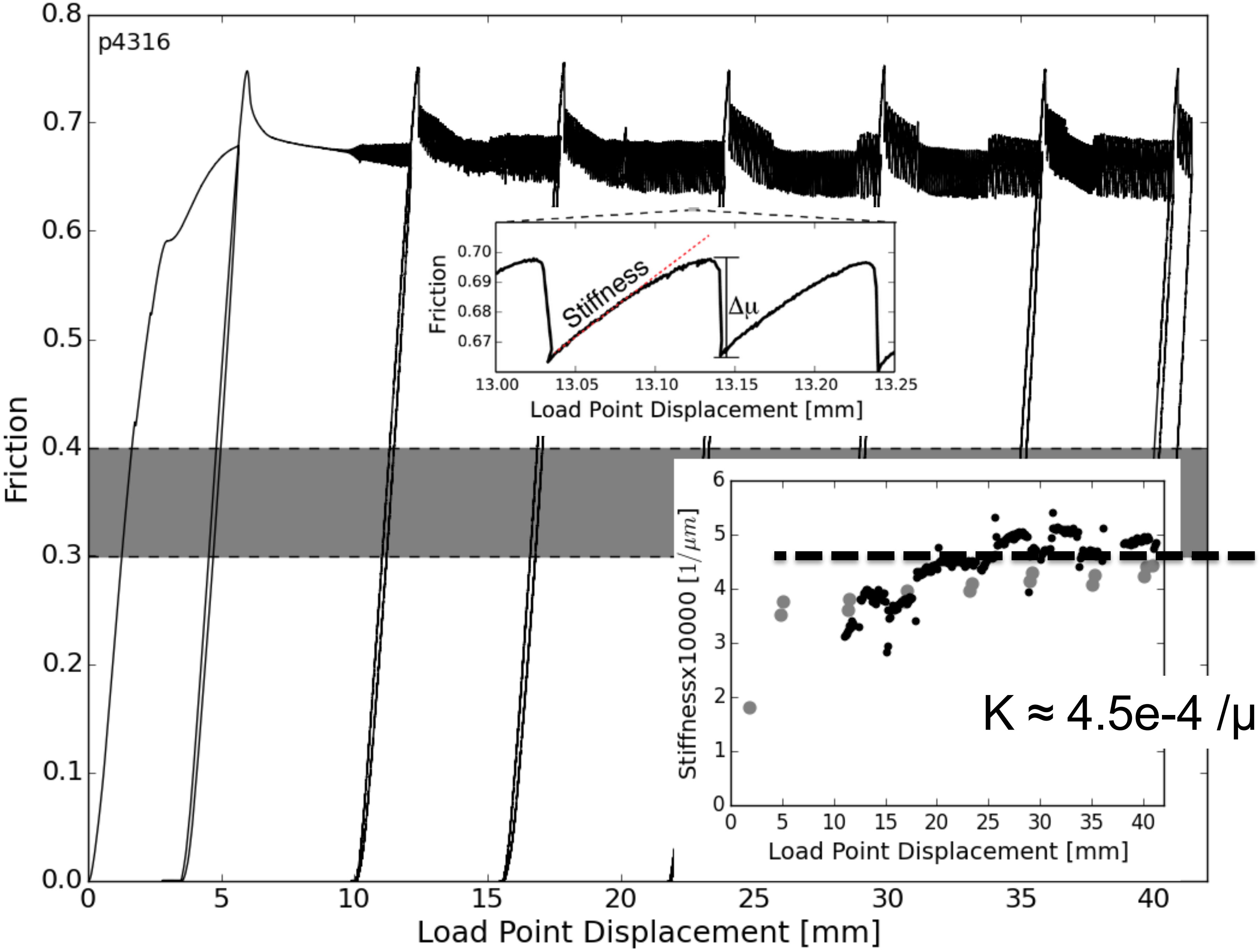




Double direct shear with biaxial loading



We measure elastic loading stiffness using 2 methods



K ≈ 4.5e-4 /μm

Leeman, Saffer, Scuderi & Marone

AGU100 ADVANCING EARTH AND SPACE SCIENCE

JGR

Journal of Geophysical Research: Solid Earth

RESEARCH ARTICLE

10.1029/2018JB015768

Special Section:
Slow Slip Phenomena and
Plate Boundary Processes

Frictional Mechanics of Slow Earthquakes

J. R. Leeman[1], C. Marone[1], and D. M. Saffer[1]

[1]Department of Geosciences and Center for Geomechanics, Geofluids, and Geohazards, The Pennsylvania State University, University Park, PA, USA

Slip is unstable if

$$K < K_c$$

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

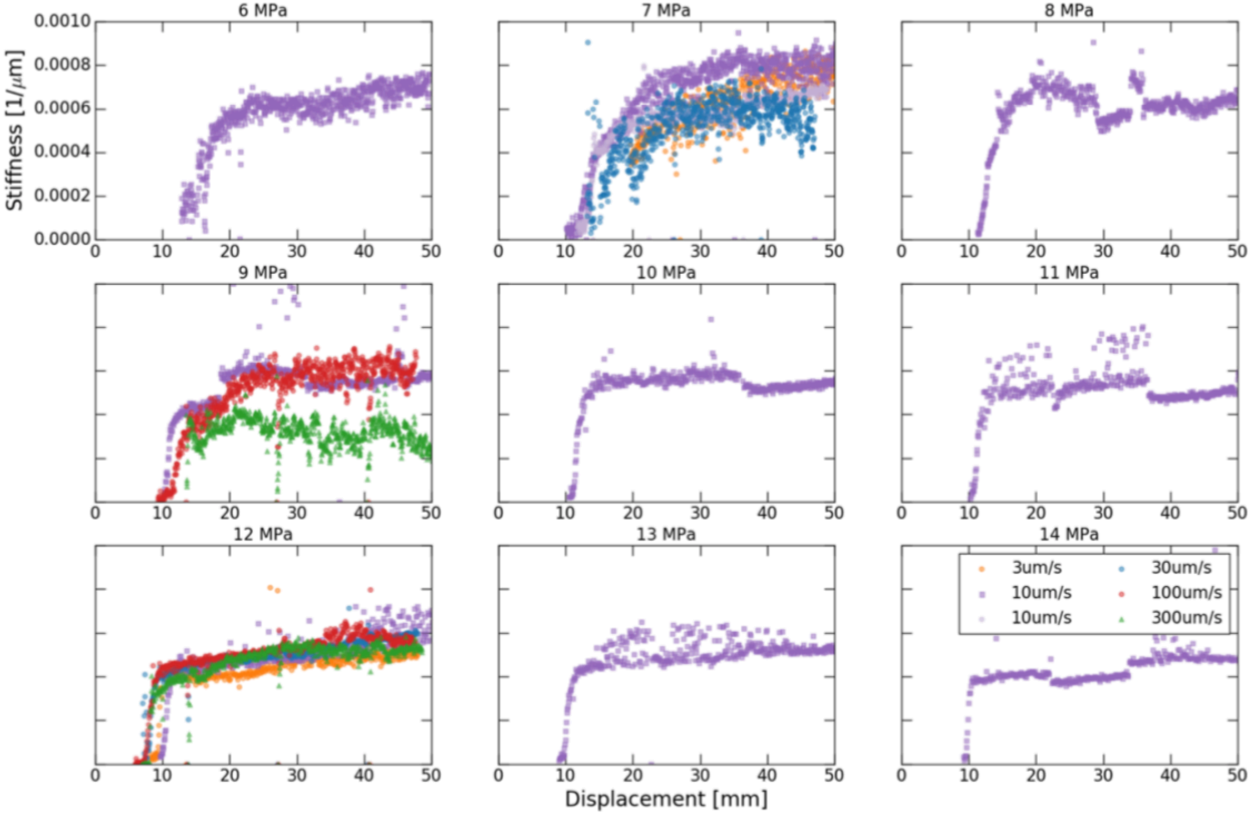
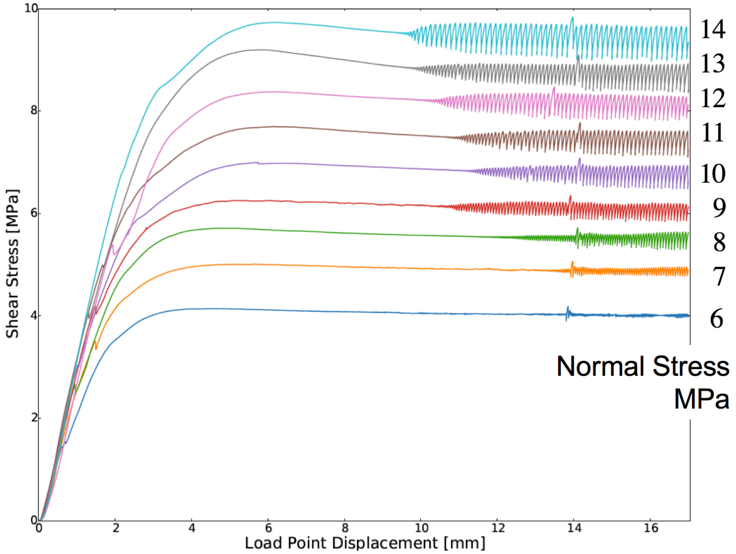
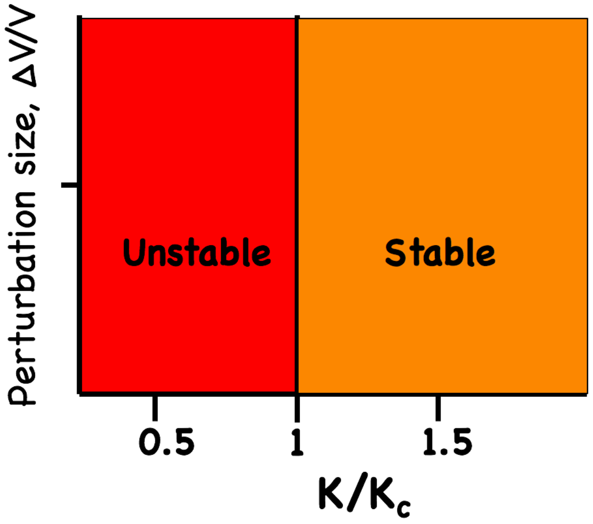


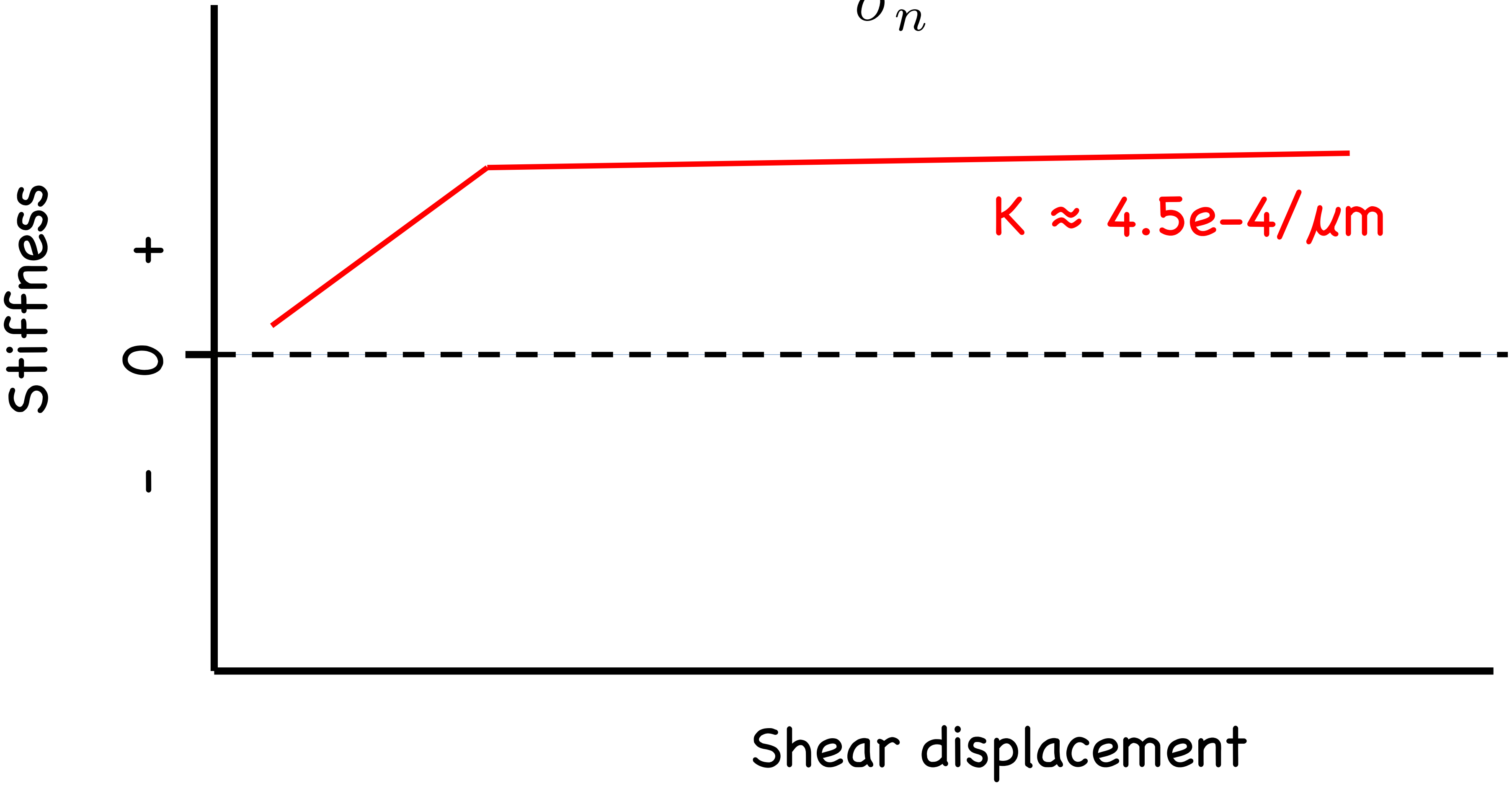
Figure S6. The effective stiffness of each stick-slip event at a given normal stress as a function of displacement. Notice the quick rise once events begin and asymptotic approach of a final steady-state value.



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

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





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

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

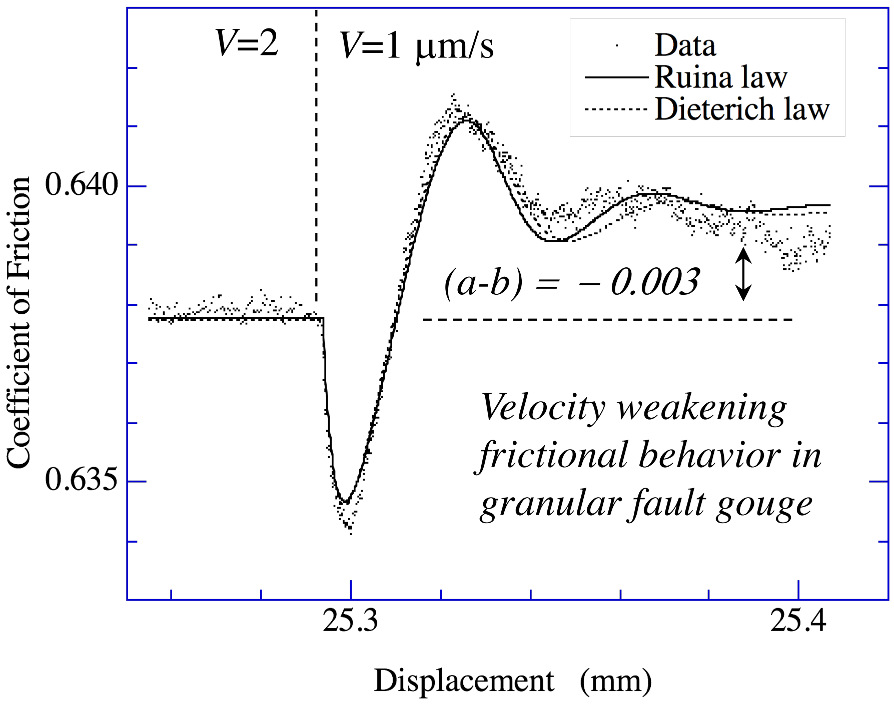
$$\theta_{ss} = \frac{D_c}{v}$$

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

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

$$K_c = \sigma\frac{(b-a)}{D_c} + \frac{mv_0^2(b-a)}{D_c^{\,2}}$$

Empirical laws, based on laboratory friction data

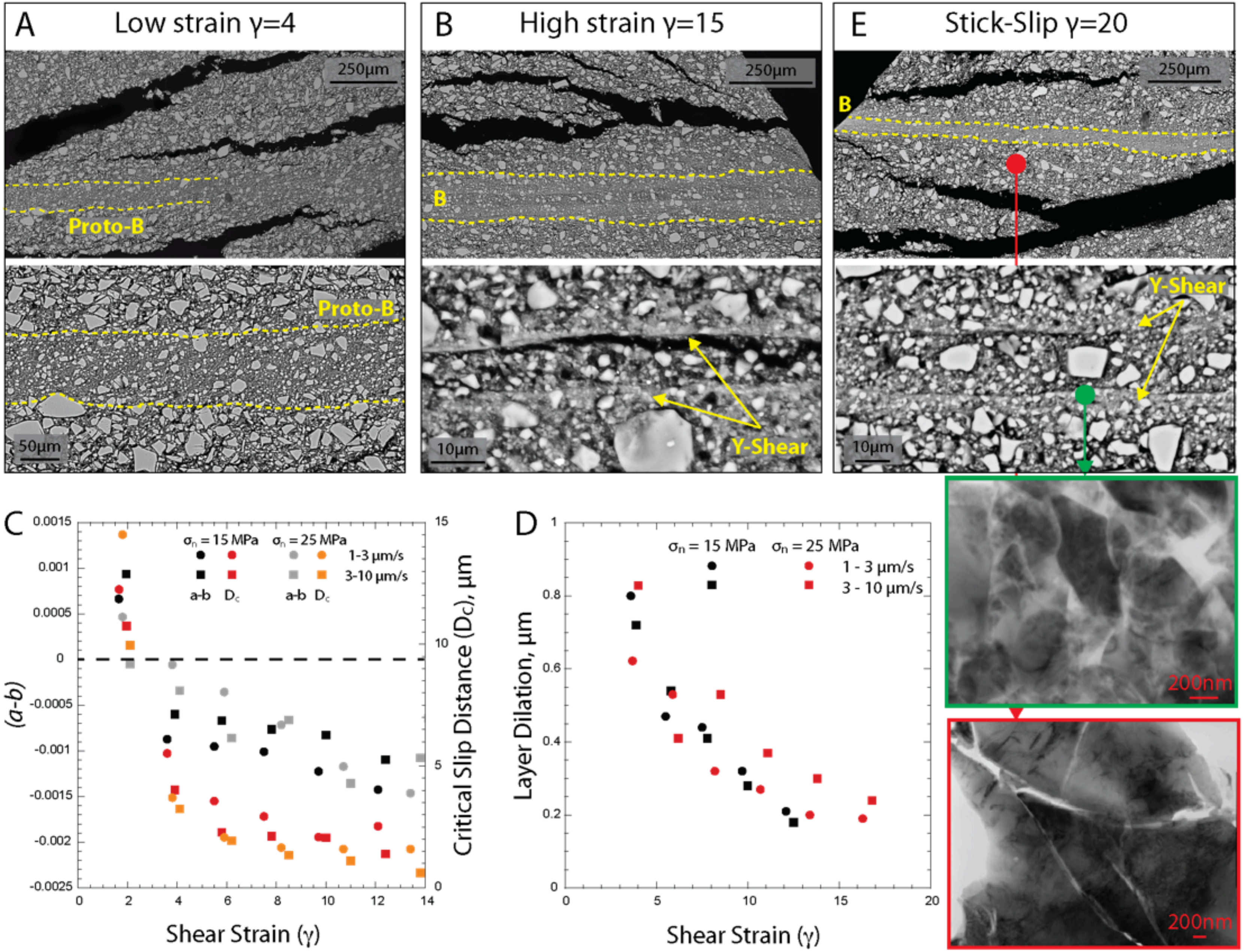


Thermally-activated process

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

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

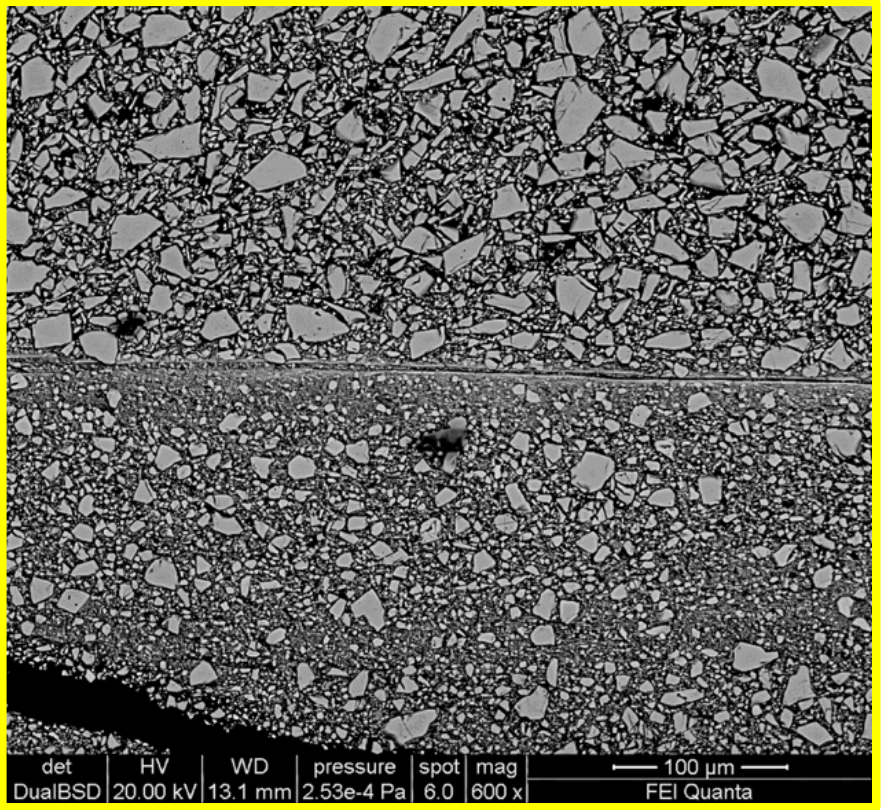
Fault Zone Microstructure

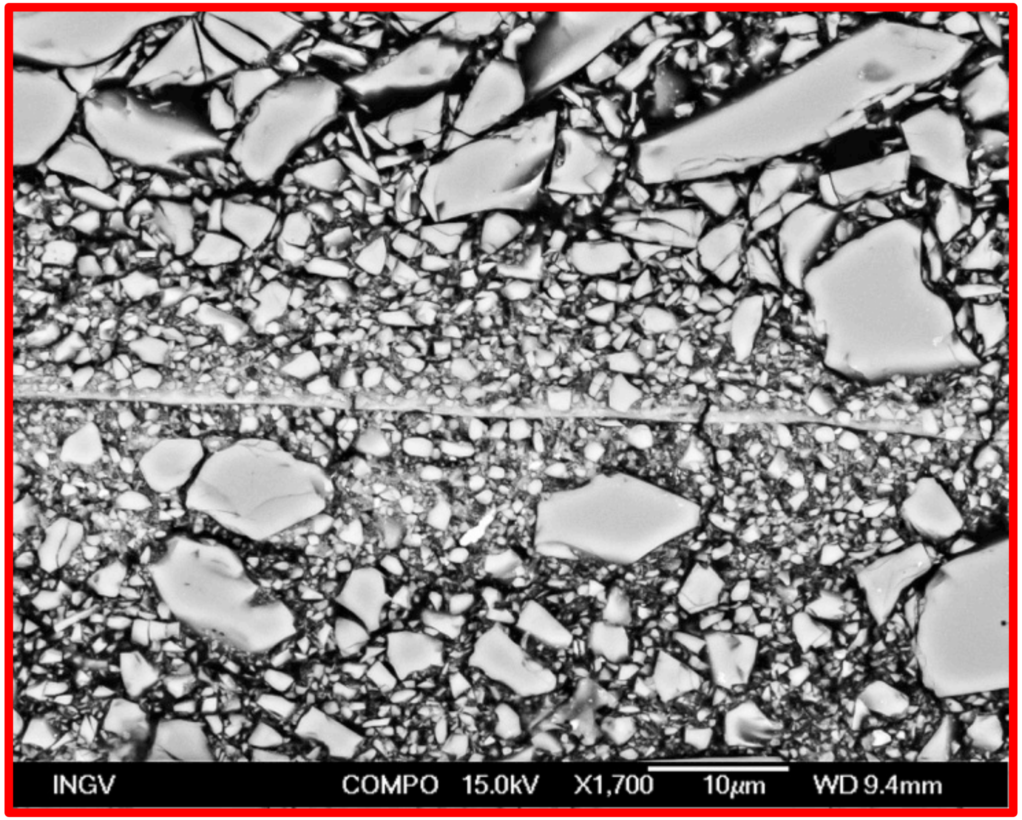


Scuderi, Viti, Tinti, Collettini, and Marone, *Geology*, 2017

Fault Zone Microstructures

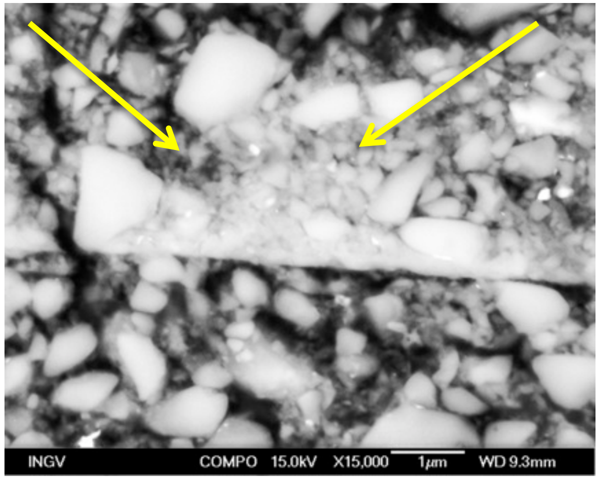
- Fault zone microstructure and shear fabric has a clear signature in friction constitutive properties.
- As shear localizes the fault zone becomes more unstable.

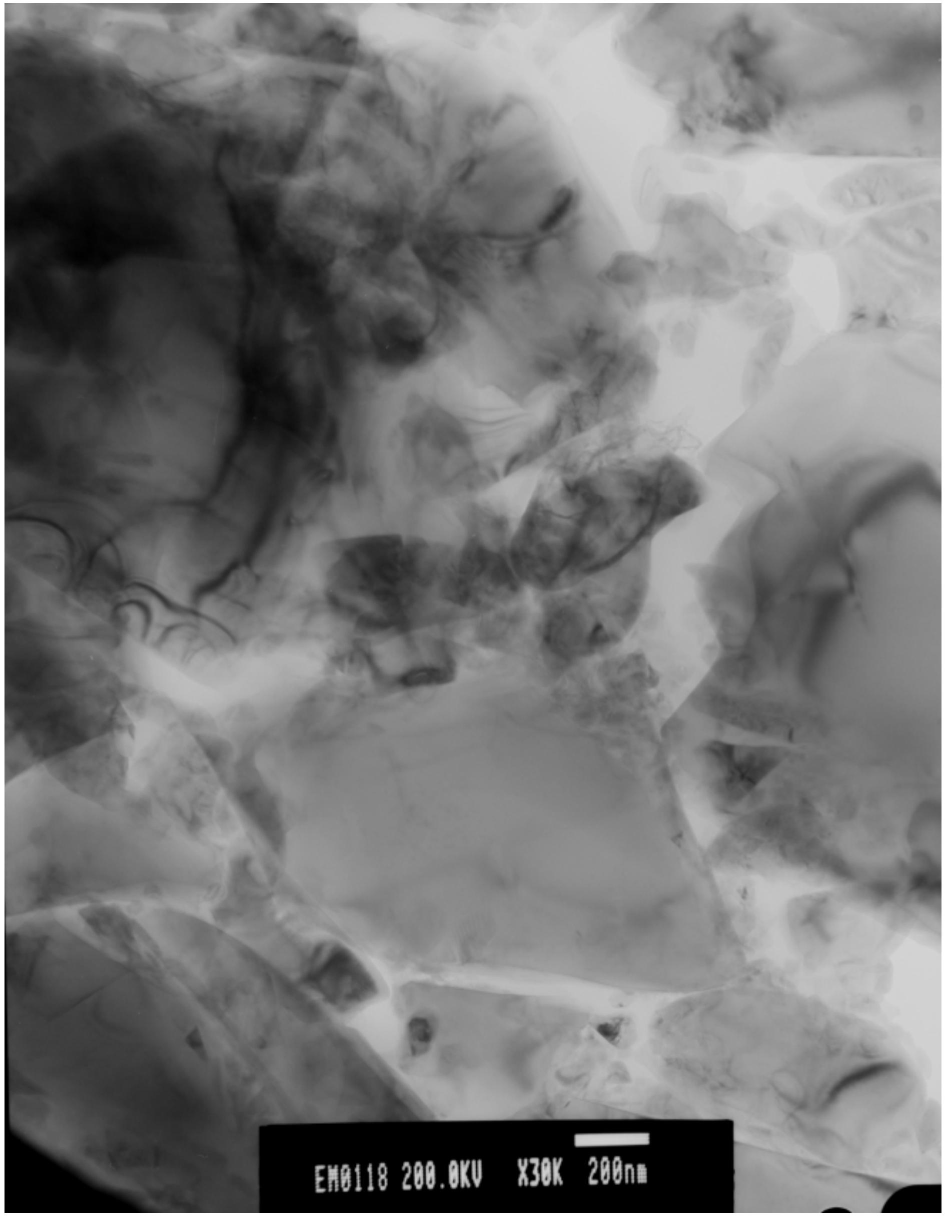


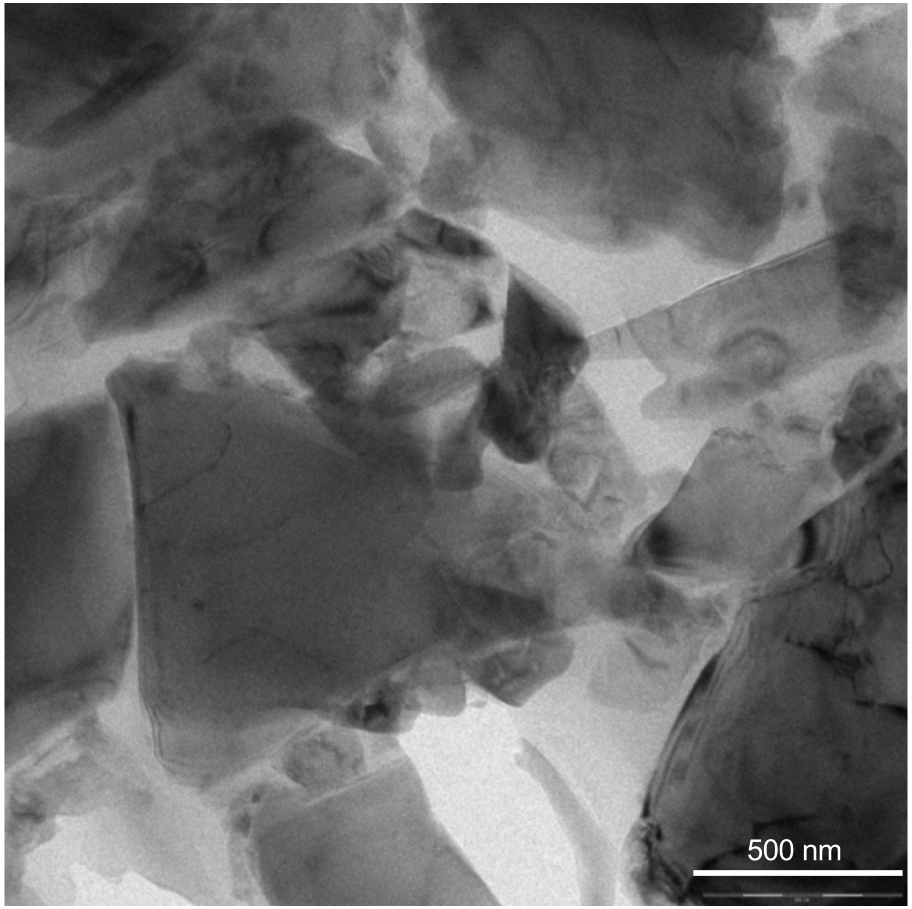


Stick & slip: nano-structures NEAR the slipping plane.

Some fractured Q grains (1 μm-300 nm) with sharp grain-boundaries. Dislocations with sub-grains development.

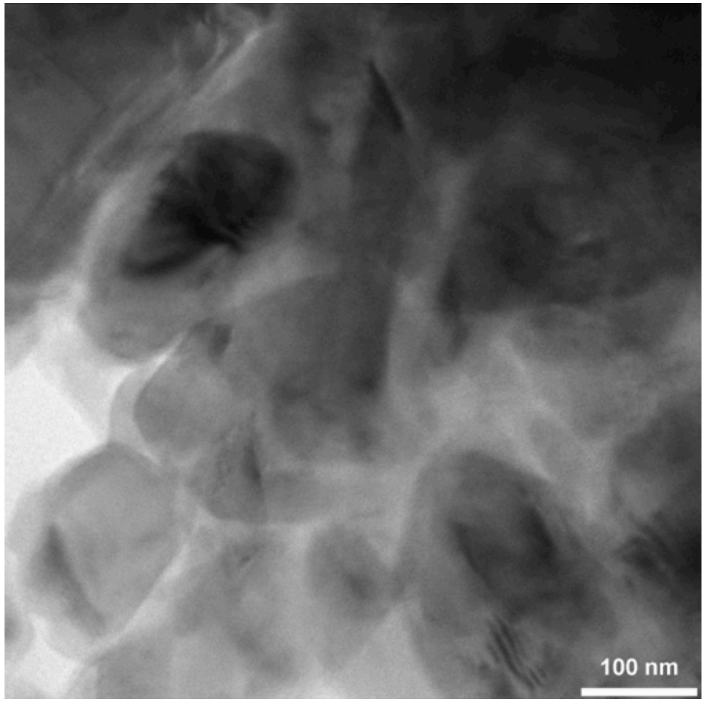


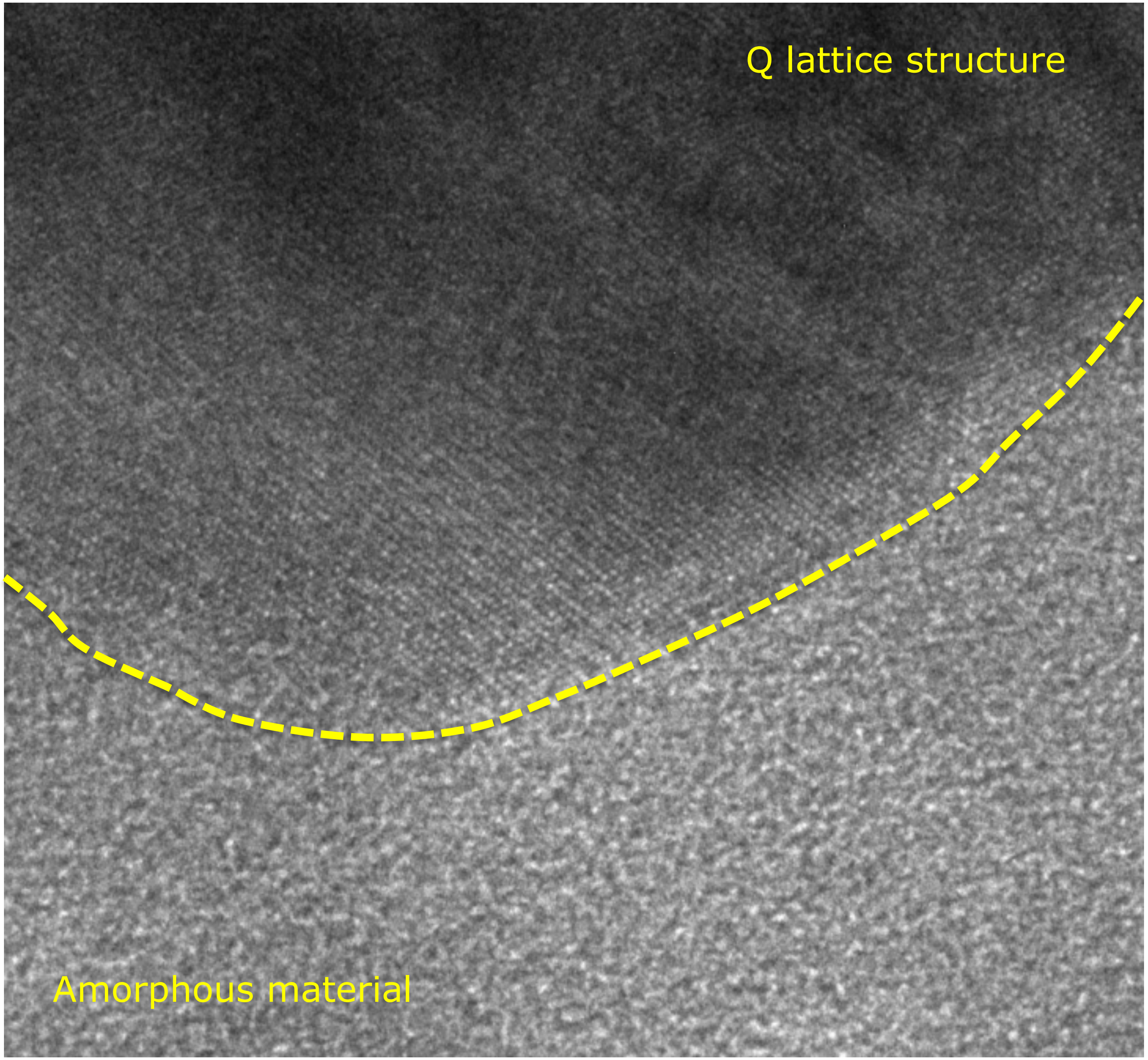


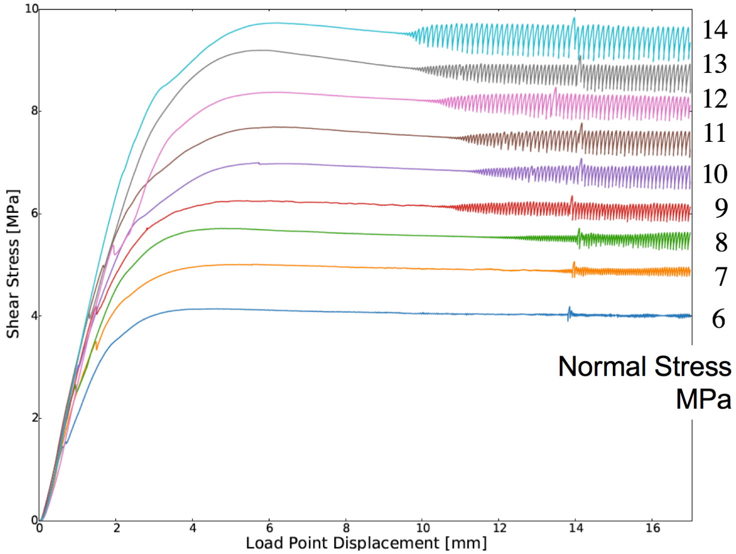


Stick & slip: nano-structures INTO the slipping plane.

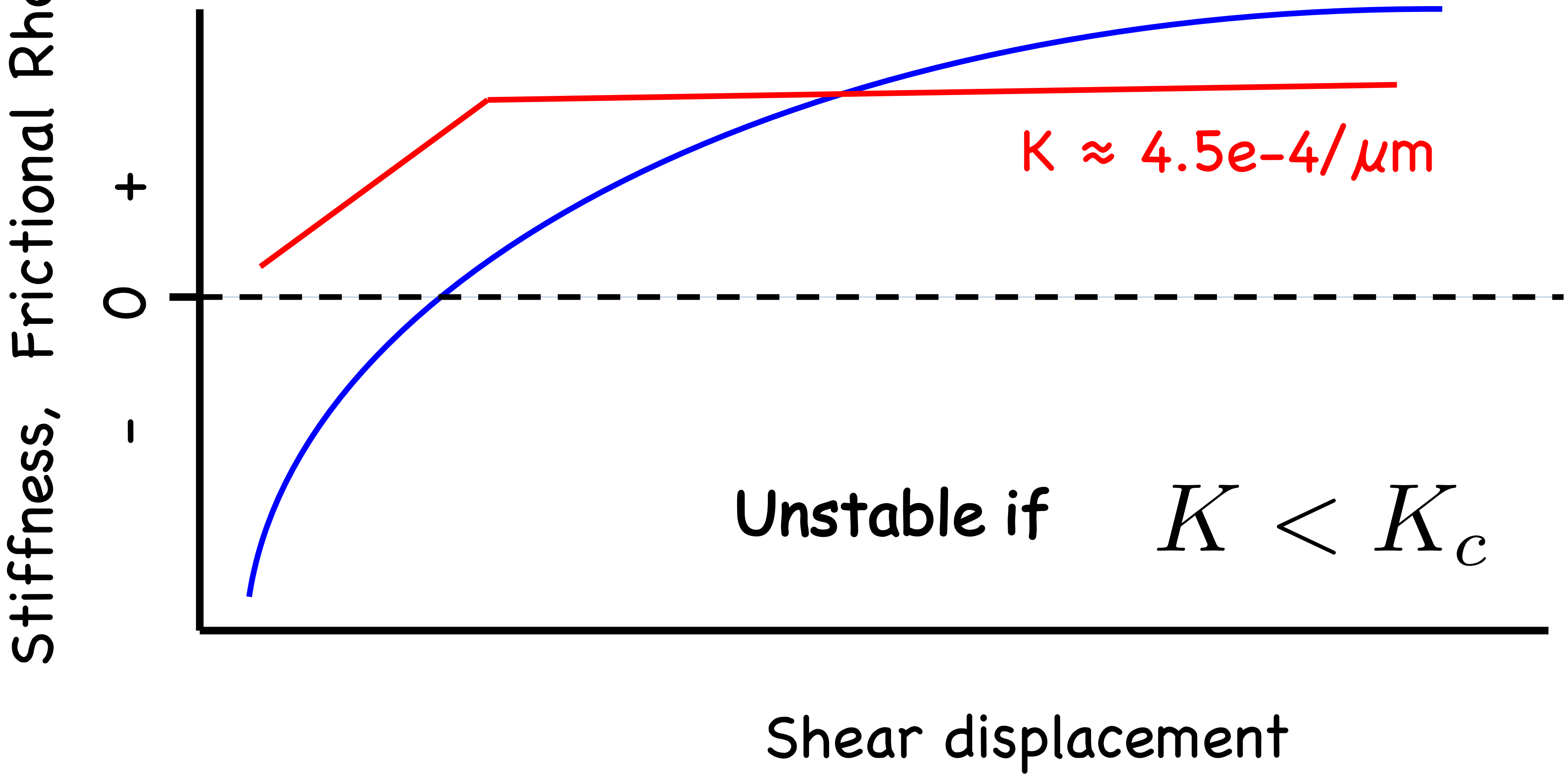
Smaller grains surrounded by an amorphous film.







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

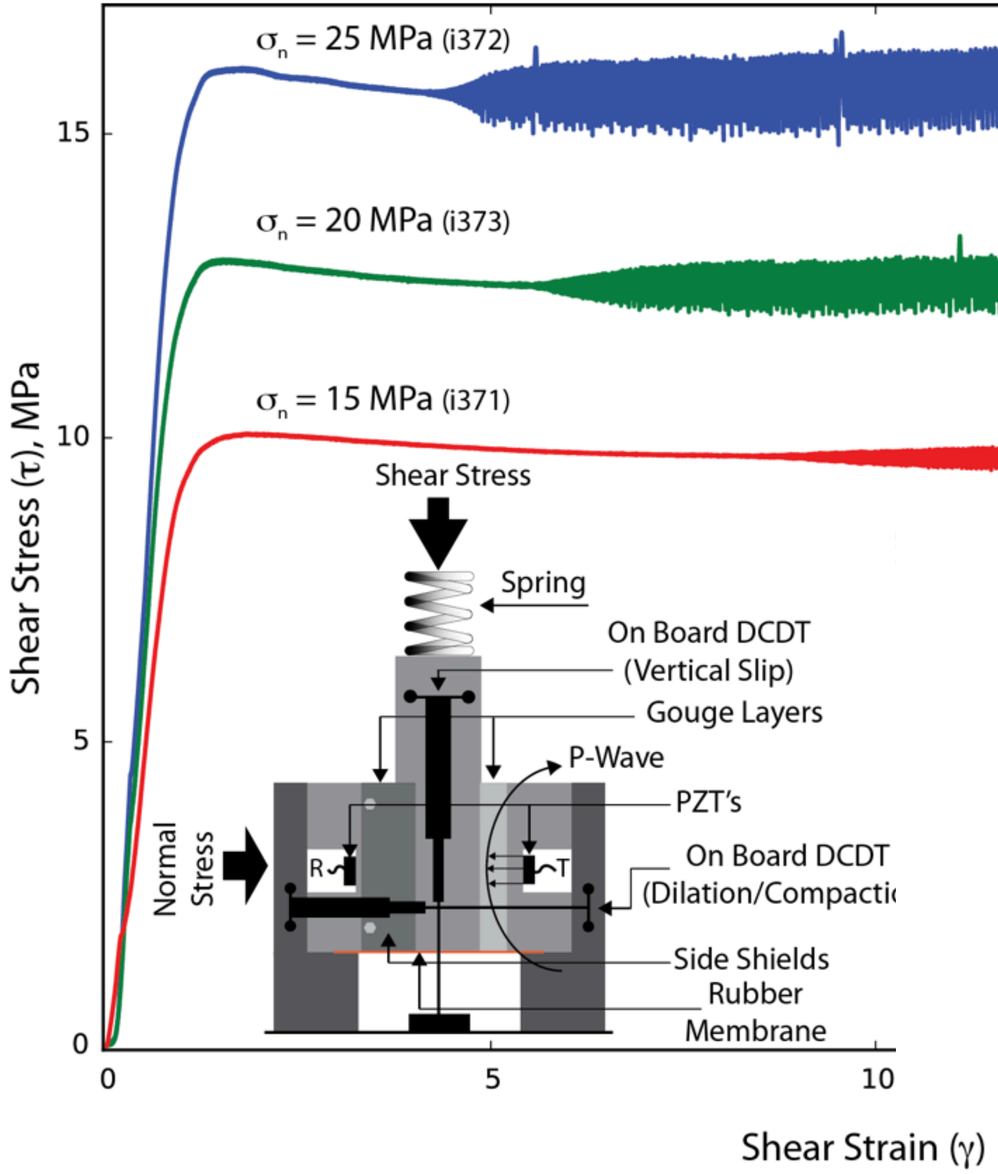


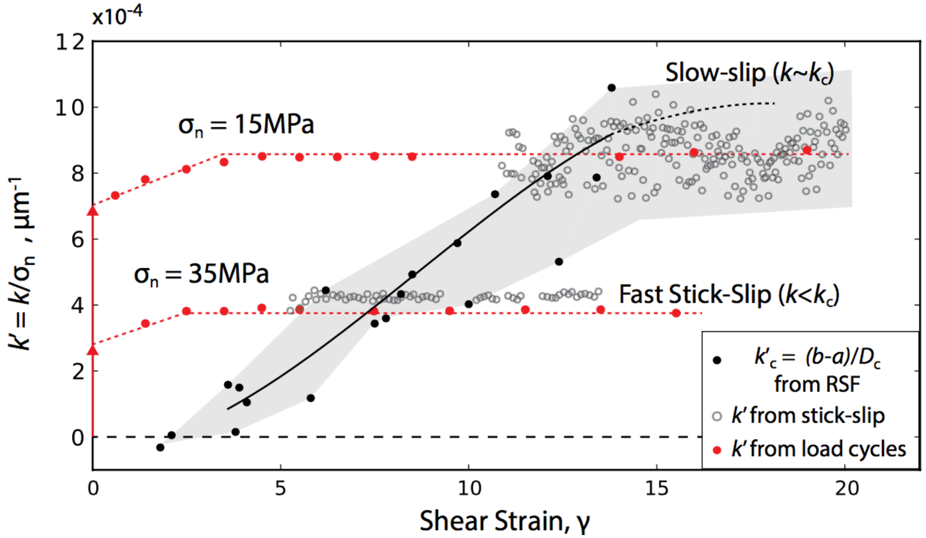
Kc ≈ 7e-4/μm

K ≈ 4.5e-4/μm

Unstable if $K < K_c$

Repetitive Slow Stick-Slip





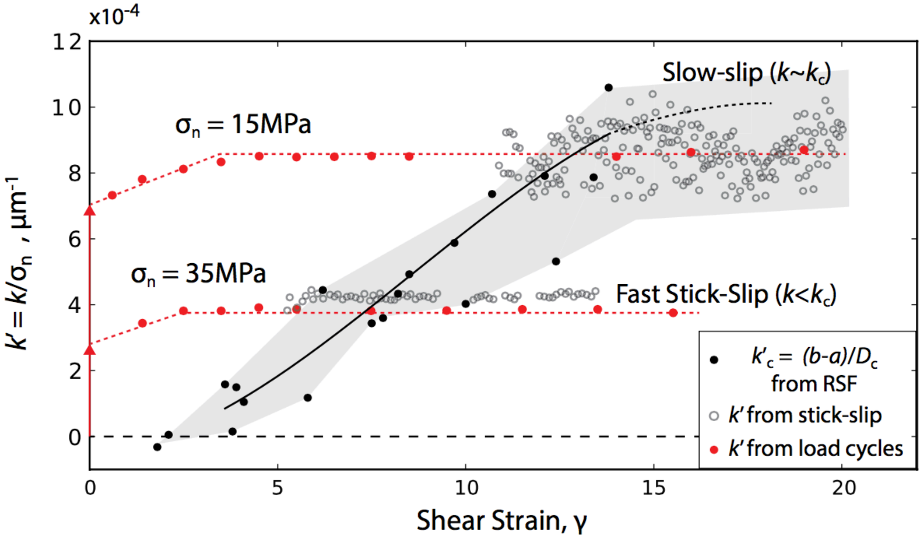
$$\frac{K'}{\sigma_n} < K_c = \frac{(b-a)}{D_c}$$

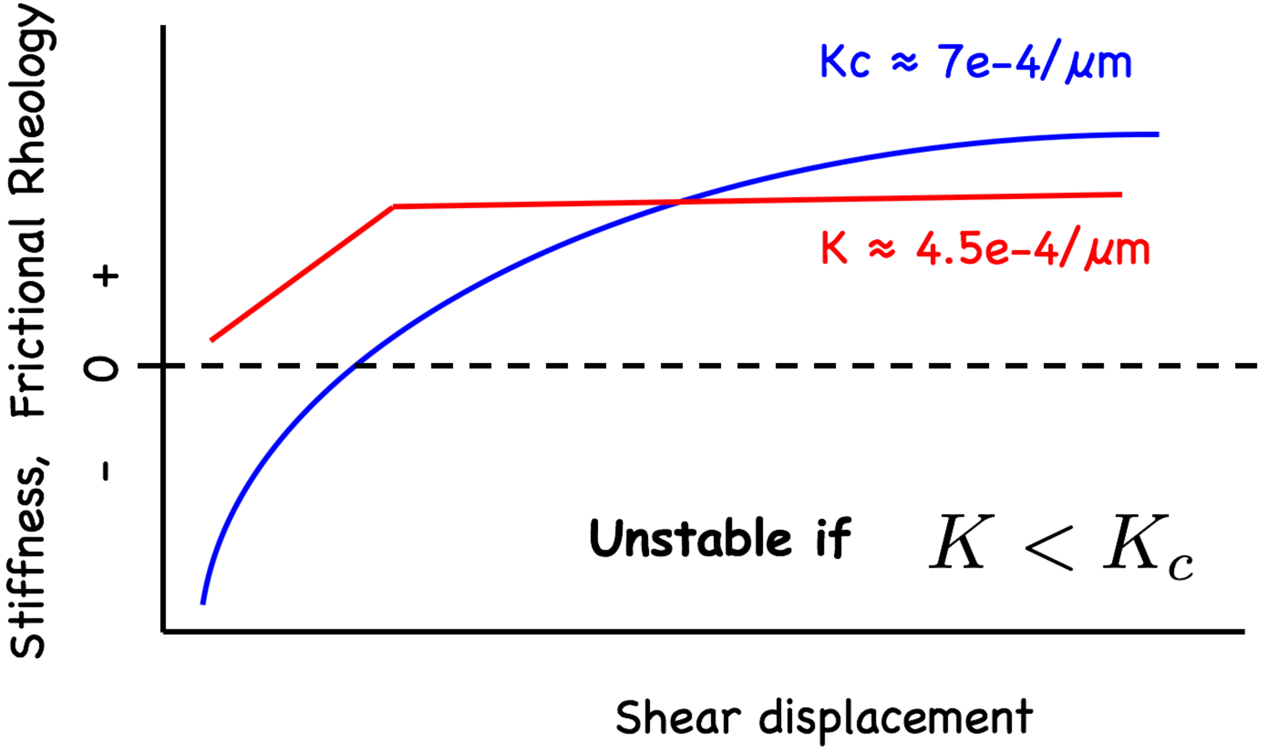
Scuderi et al., *Geology*, 2017

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

Control Parameters

Rheology (weakening rate)

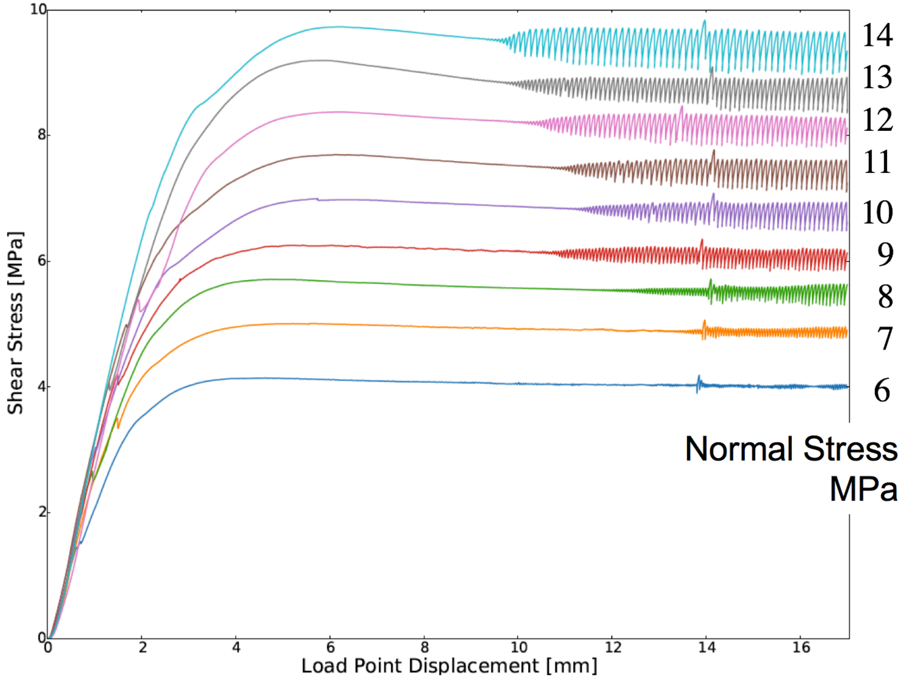


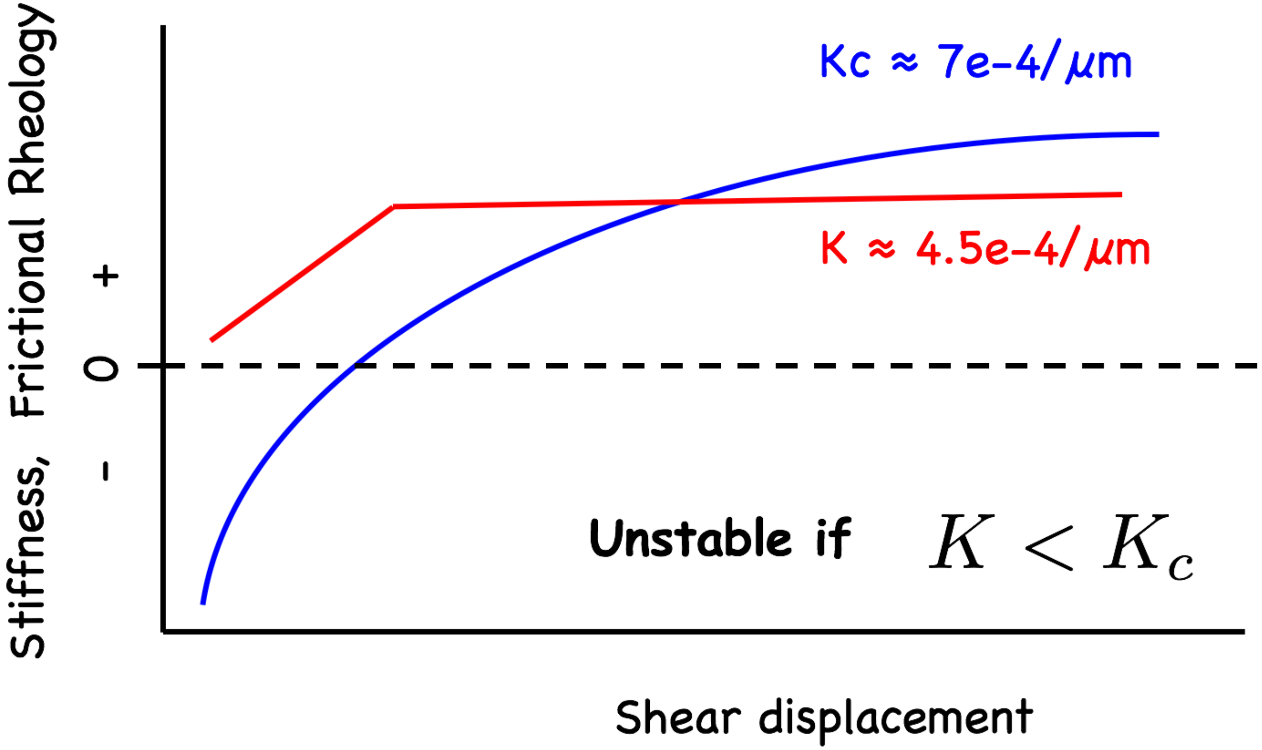


$$\boxed{\frac{K'}{\sigma_n}} < K_c = \boxed{\frac{(b-a)}{D_c}}$$

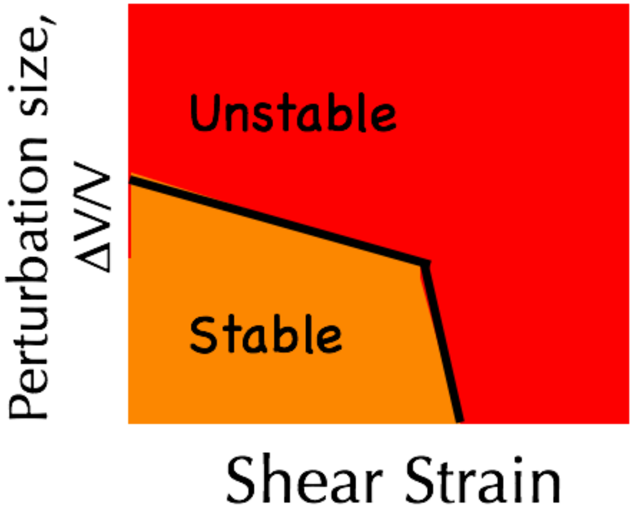
Control Parameters

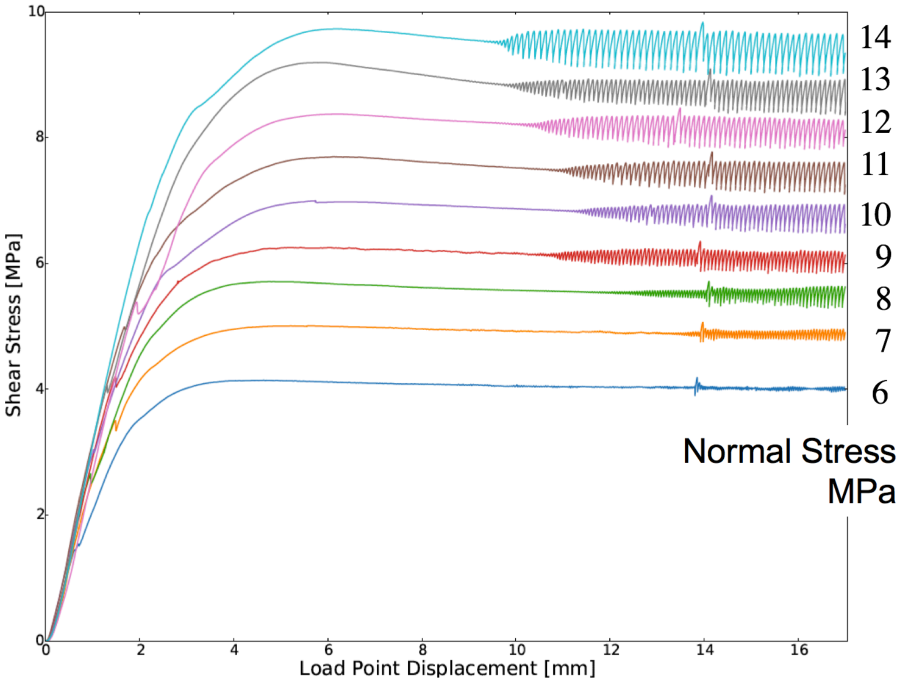
Rheology (weakening rate)

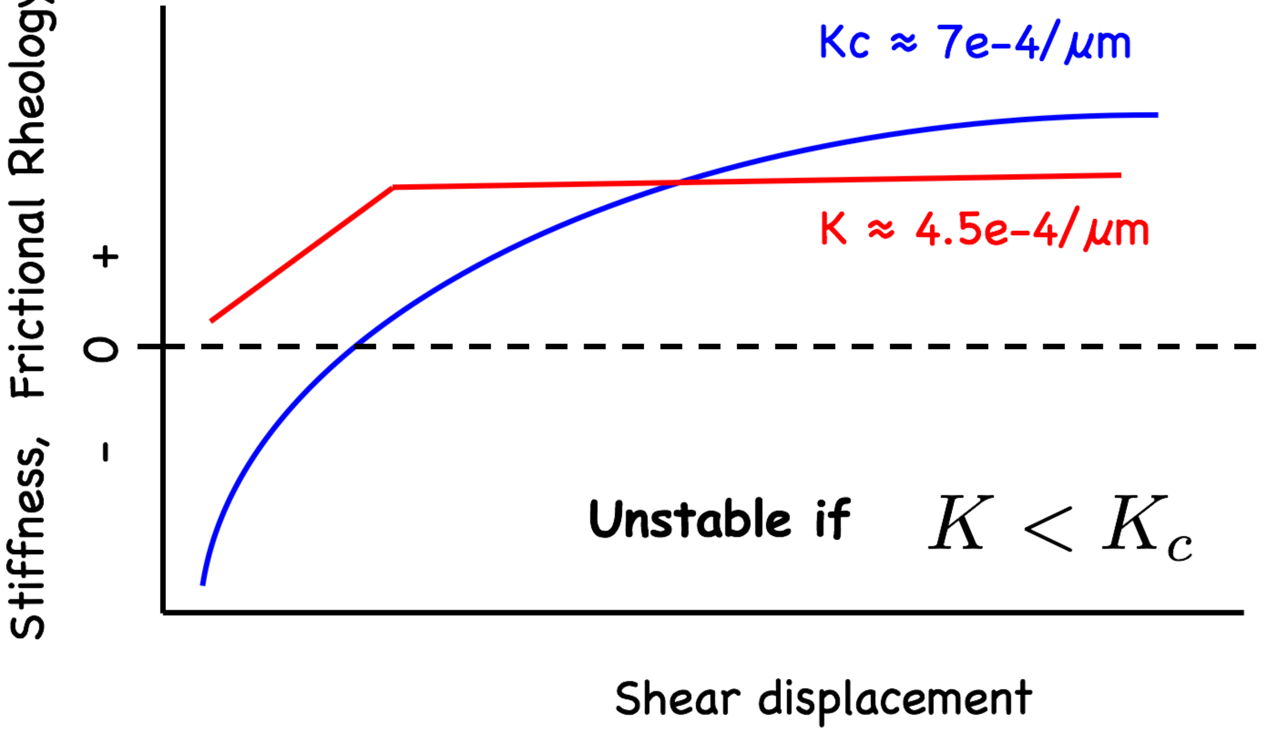




Unstable if $K < K_c$







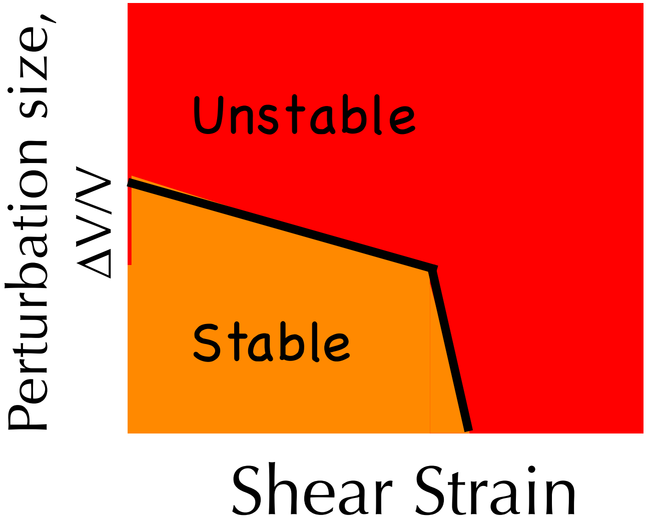
Unstable if $K < K_c$

Frictional Sliding: Stability transition depends on strain (shear displacement) and slip velocity)

$$\frac{\tau(\theta, v)}{\sigma_n} = \mu_o + a\,ln\left(\frac{v}{v_o}\right) + b\,ln\left(\frac{v_o\theta}{D_c}\right)$$

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

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



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

$$K_c(V, \gamma)$$

Frictional Sliding: Stability transition depends on strain (shear displacement) and slip velocity)

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 104, NO. B12, PAGES 28,899–28,914, DECEMBER 10, 1999

Friction of simulated fault gouge for a wide range of velocities and normal stresses

Karen Mair and Chris Marone

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

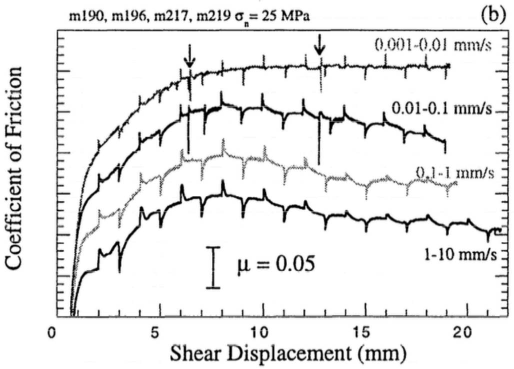


Figure 3. (a) Coefficient of friction and layer thickness as a function of shear displacement for a "fast" velocity test carried out at 1-10 mm/s and σ_n = 25 MPa. The velocity steps are indicated by dashed lines, and alpha is shown schematically. (b) Friction as a function of shear displacement for a range of tests at σ_n = 25 MPa with velocity ranging between 0.001-10 mm/s (all velocity steps are factor of 10 increases and decreases). Curves are offset for clarity since friction levels are comparable. Arrows indicate short holds required for linear variable displacement transducer (lvdt) range offset in the slower tests. Note the decrease in $\Delta\mu_{direct}$ with slip at high velocity.

changes in $\Delta\mu_{direct}$. Changes in $\Delta\mu_{evol}$ therefore are not solely responsible for the transition in (a-b) with increasing slip.

In Figure 8b we plot $\Delta\mu_{direct}$ for discrete ranges of shear displacement. At low velocity, data for all shear displacements plot together as expected from Figure 8a. However, at high ve-

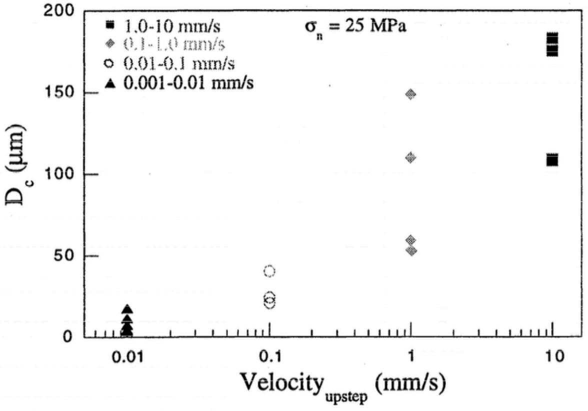
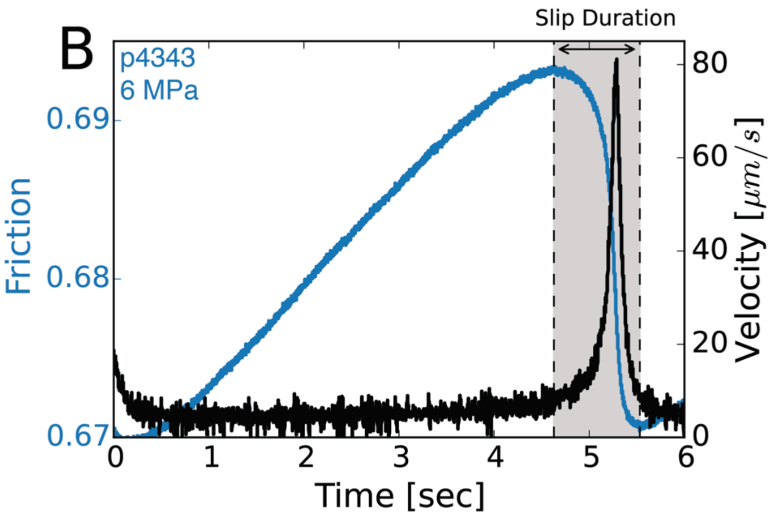
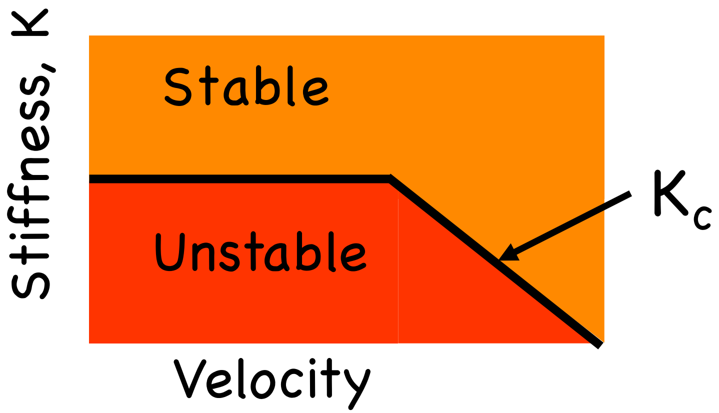
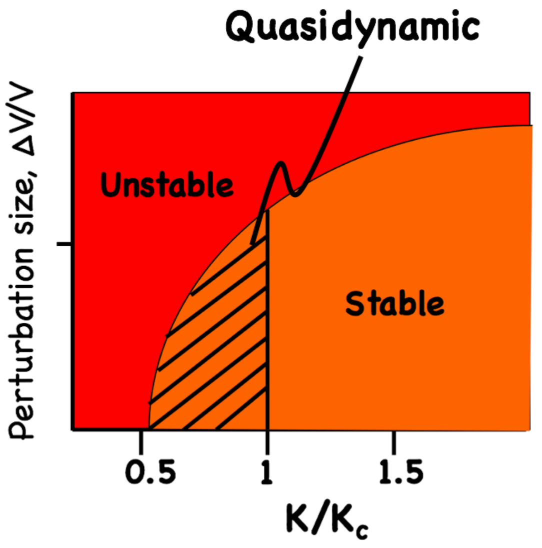


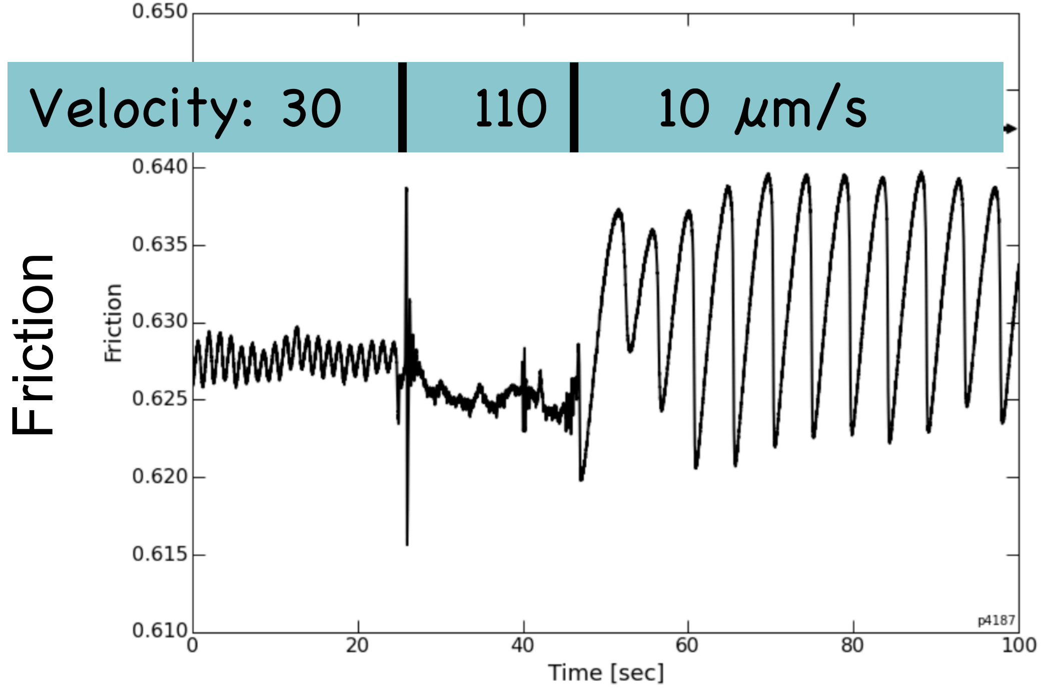
Figure 4. Critical slip displacement (D_c) as a function of upstep velocity for a range of experiments at σ_n = 25 MPa. D_c is systematically larger as a function of increasing velocity.





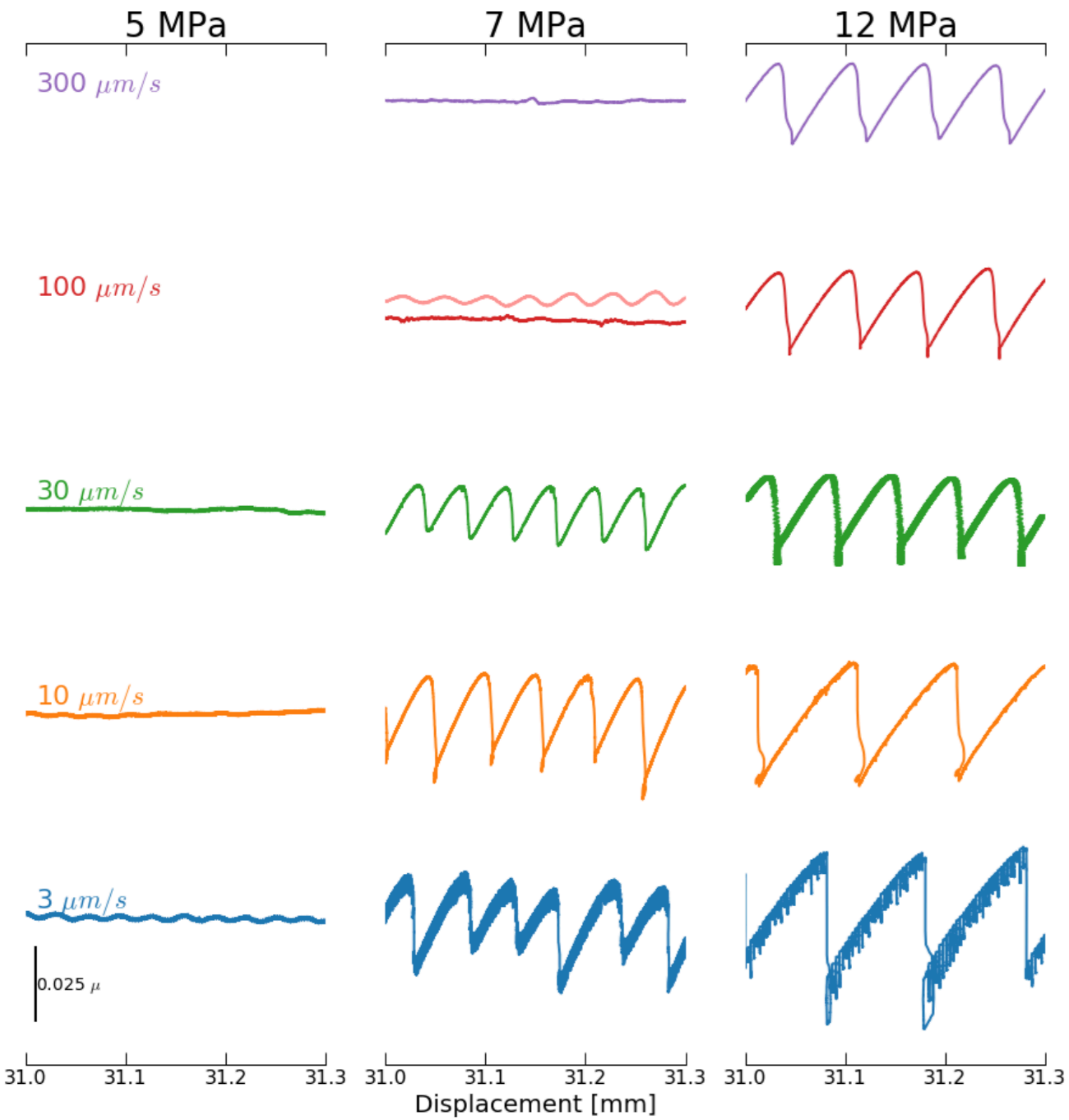


Gu et al., 1984



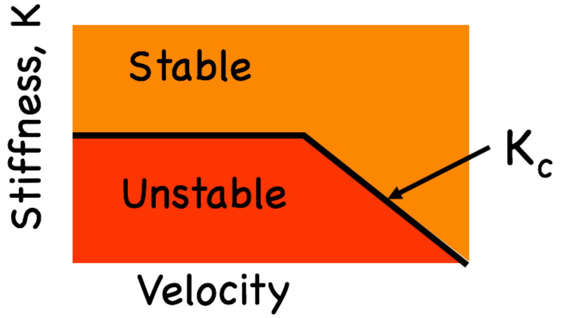
Leeman, Marone & Saffer *JGR*, 2018

Slow Slip

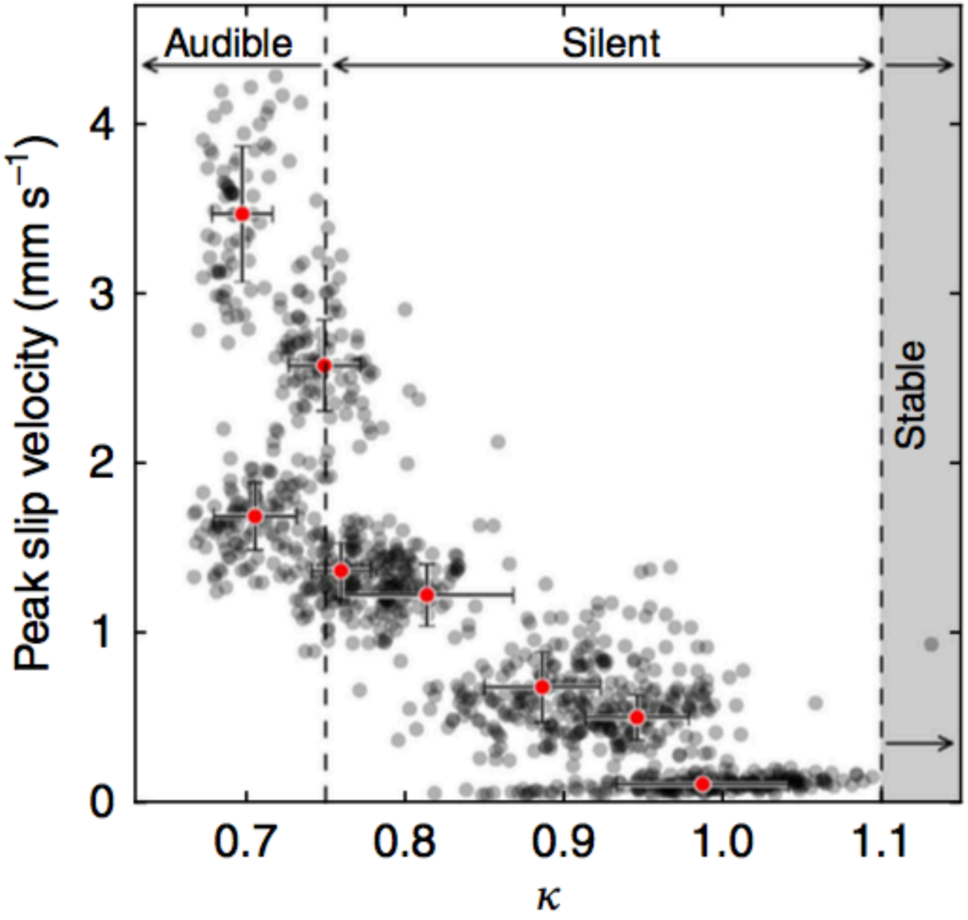


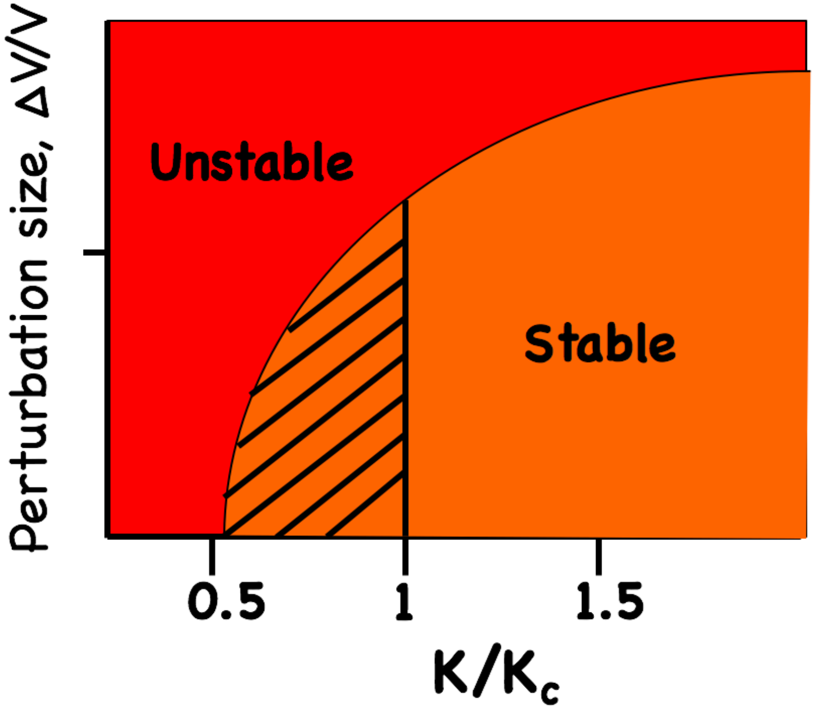
Kc is a function of slip velocity, normal stress, and the friction parameters

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



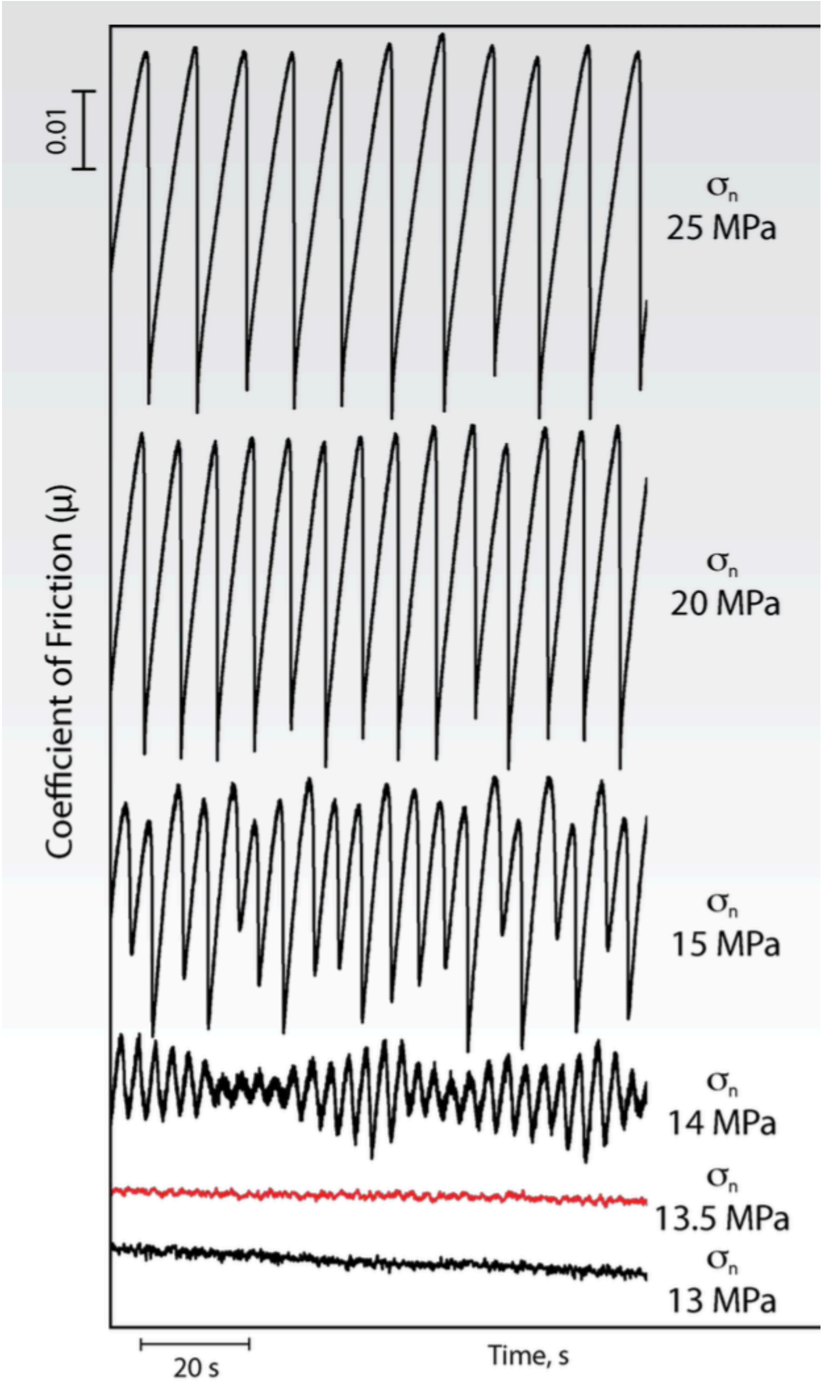
Leeman, Marone & Saffer JGR, 2018





Unstable slip if

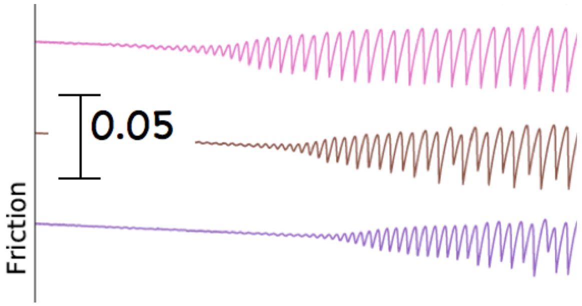
$$K < K_c \approx \frac{\sigma_n(b-a)}{D_c}$$



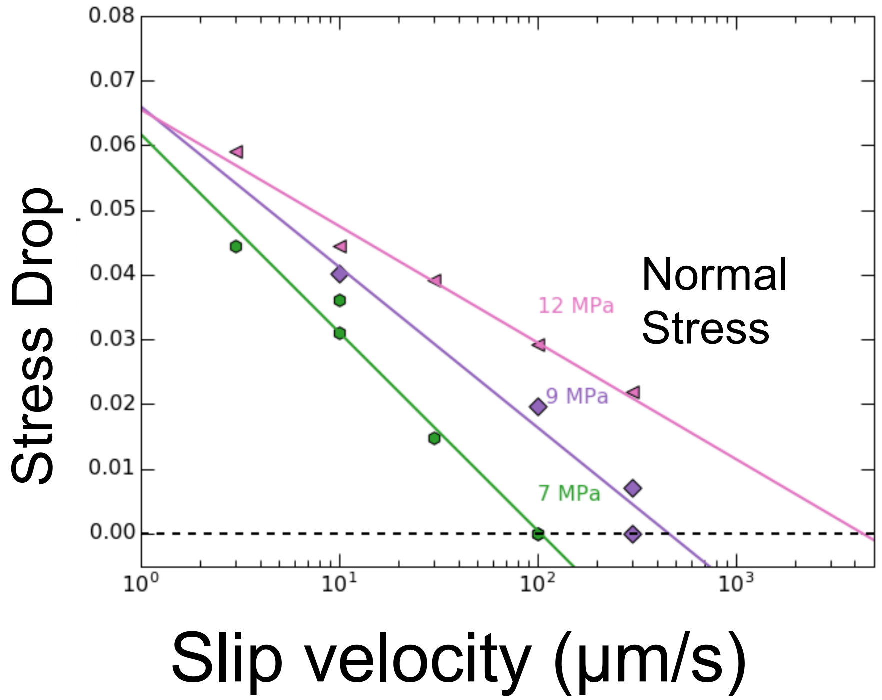
Period Doubling Near The Stability Boundary

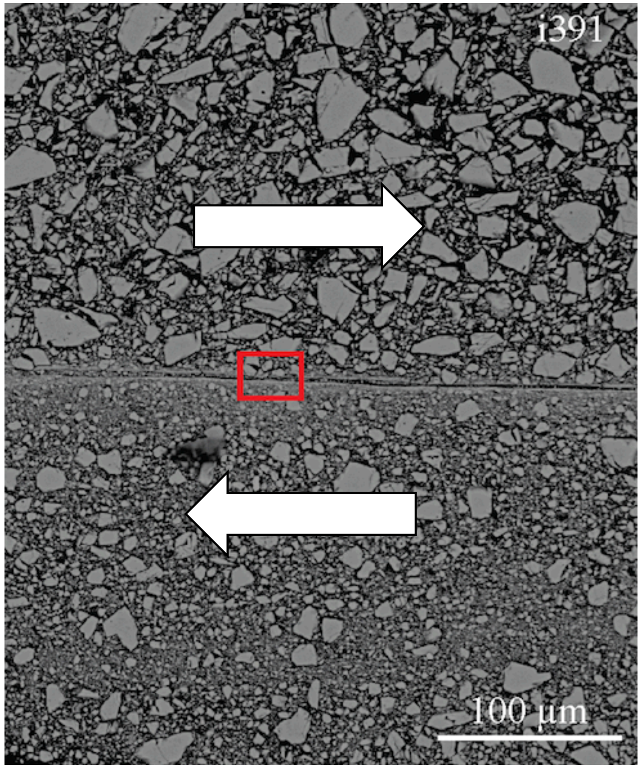
Scuderi, Marone, Tinti, Di Stefano, & Collettini, *Nature Geosc.* 2016

Slow Earthquakes --a view from the lab

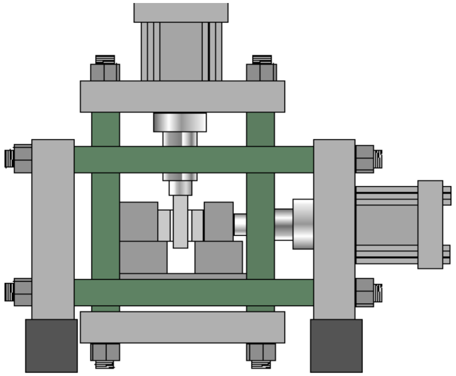


Lab
Slow
Slip
Events

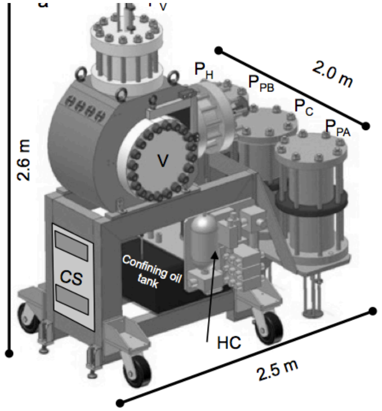




Penn State



INGV Rome



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?*
   1. Quasi-dynamic frictional instability (positive feedback, self-driven instability)
   2. Rate dependence of the critical rheologic weakening rate, $K_c(V)$
   3. Fracture mechanics: energy release rate equals frictional weakening rate, stress drop is quasidynamic because the dynamic force imbalance is negligible