Mechanics of Earthquakes and Faulting

Lecture 14 , 18 Mar. 2021

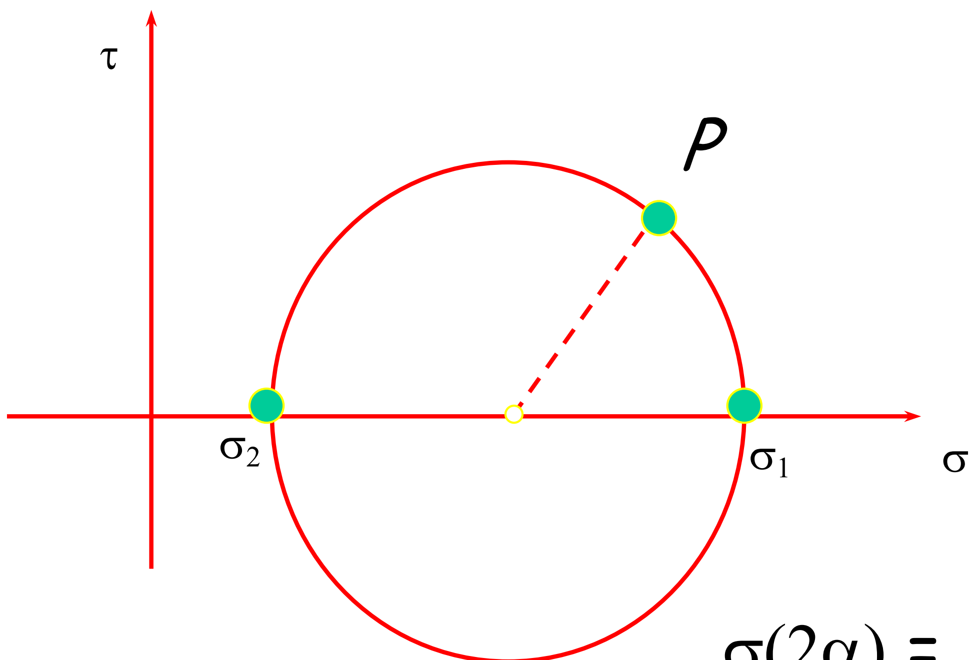
www.geosc.psu.edu/Courses/Geosc508

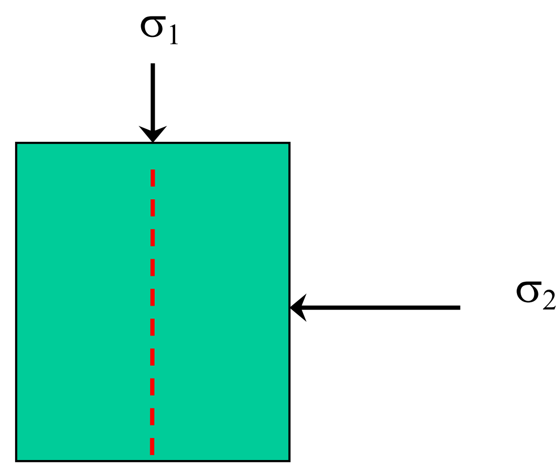
- Role of healing for connecting friction to fracture mechanics
- Earthquake nucleation and frictional instability; Nucleation size
- Slow earthquakes and the opportunity to further investigate the application of rate state friction laws to instability.
- Recent lab work showing repetitive stick-slip 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)

Imagine that you're in a restaurant with some friends. The owner stops by to say hello and after hearing that you're a geophysicist she challenges you to write down the Shear and Normal Stress on a Plane of Arbitrary Orientation given the principal stresses.

She calls the waiter over and he gives you a couple extra napkins and a pencil and says, don't worry about the third dimension because that's always in the fault plane for simple (Andersonian) faulting. So you know that you can just use two principal stresses. The maximum and minimum stress. Go ahead and call them σ_1 and σ_2

Ok, get to work! You've got to finish before he brings the drinks



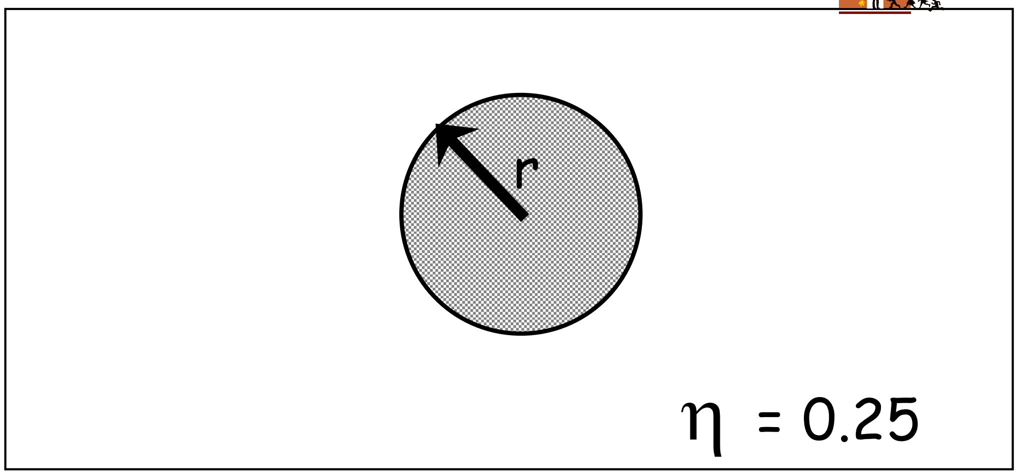


Sketch in plane P

$\sigma(2\alpha) =$

$\tau(2\alpha) =$

Rupture Patch Size for Earthquake Nucleation



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

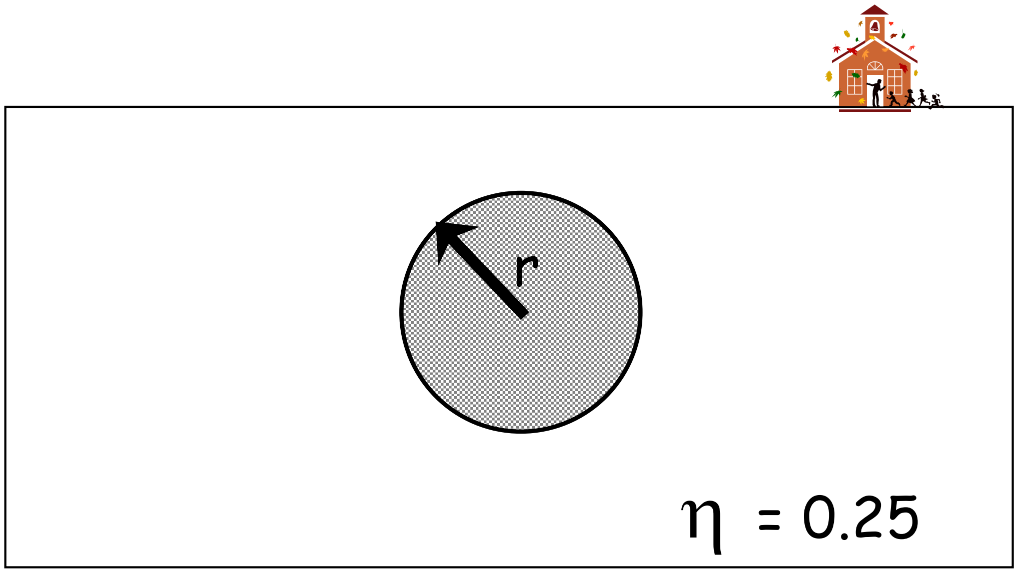
$$\Delta u(x,y) = \frac{24}{7\pi}\frac{\Delta\sigma}{\mu}\sqrt{c^2 - \left(x^2 + y^2\right)}$$

$$\Delta\sigma = \frac{7\pi}{24} G \frac{\Delta u_{max}}{r}$$

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

$$h^* = r_c$$

Rupture Patch Size for Earthquake Nucleation



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

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

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

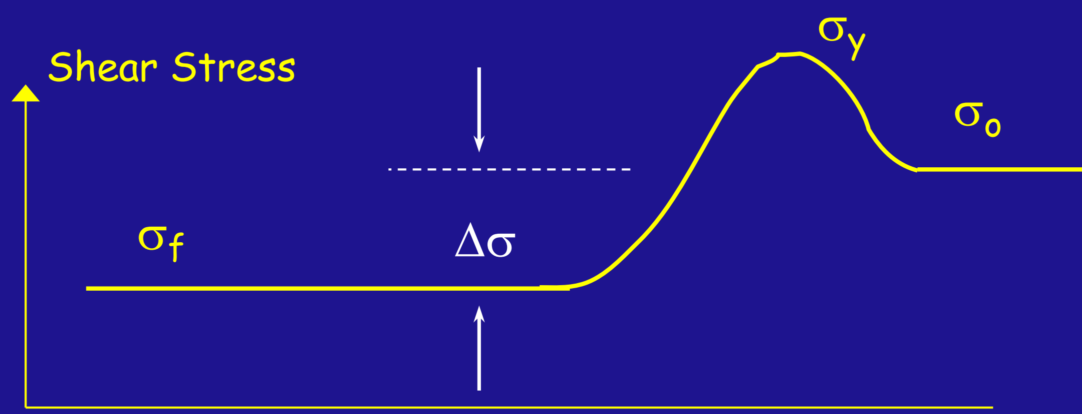
$$h^* = r_c \approx C\frac{GD_c}{\sigma_n(b-a)}$$

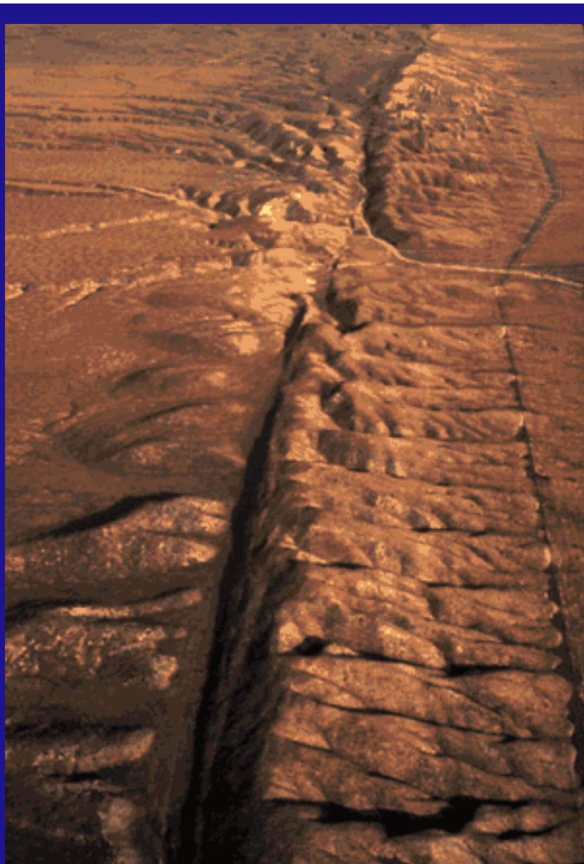
See also: Earthquake nucleation on rate and state faults – Aging and slip laws, Ampuero & Rubin, JGR 2008

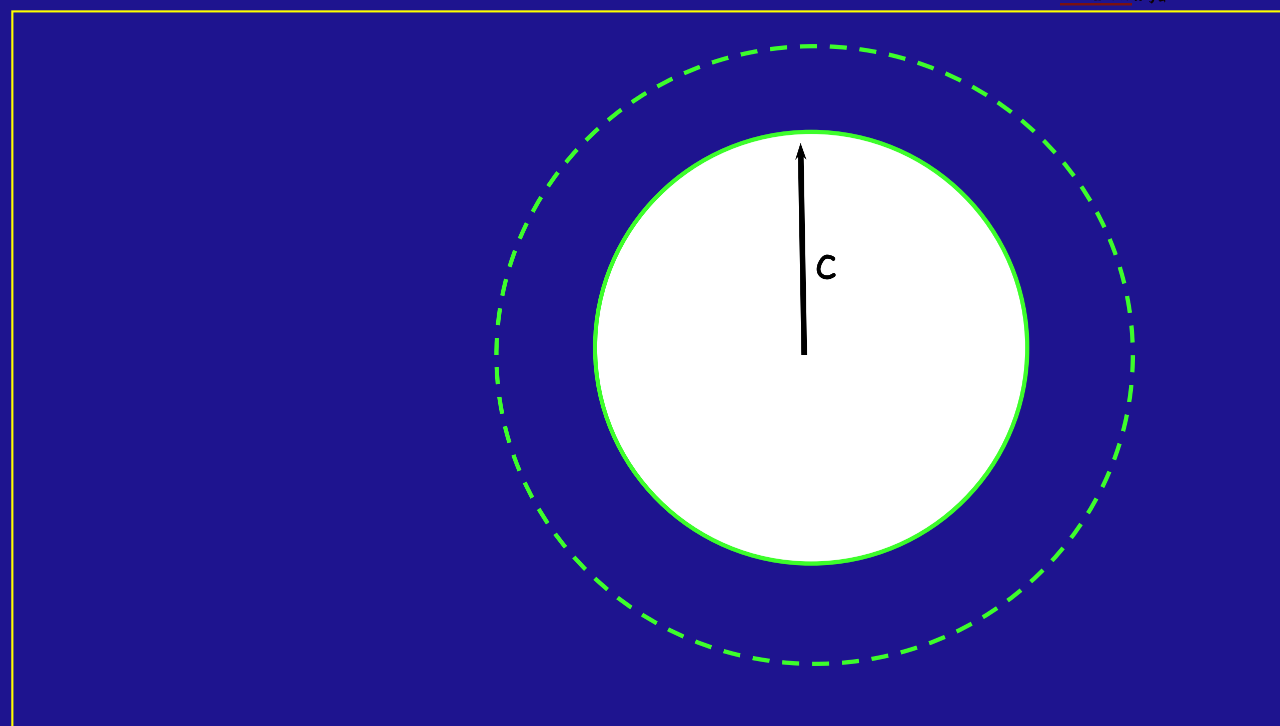
Dislocation model, circular crack

$\Delta\sigma = (\sigma_o - \sigma_f)$

$$\Delta u(x,y) = \frac{24}{7\pi}\frac{\Delta\sigma}{\mu}\sqrt{c^2 - \left(x^2 + y^2\right)}$$

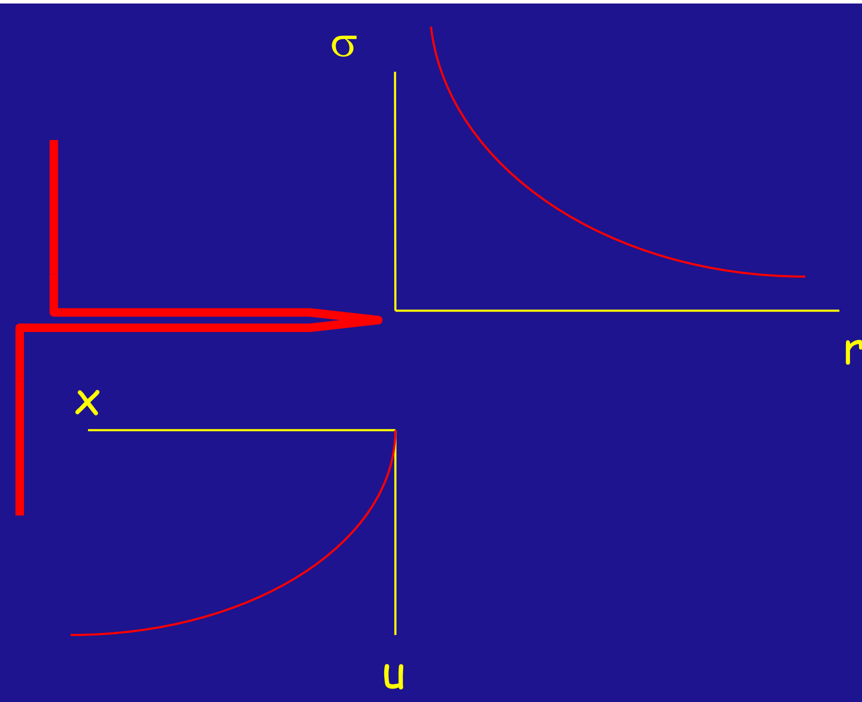






Crack tip stress field, real materials

- Singular crack (Eshelby)

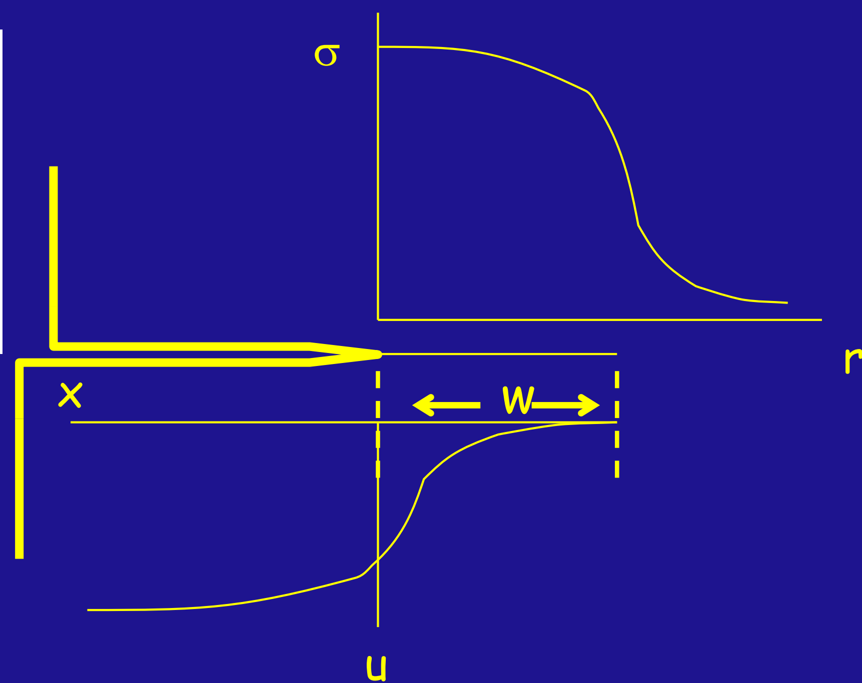


- Dugdale (Barenblatt)
  - Assume a yield criterion, σ_y, within a crack tip region

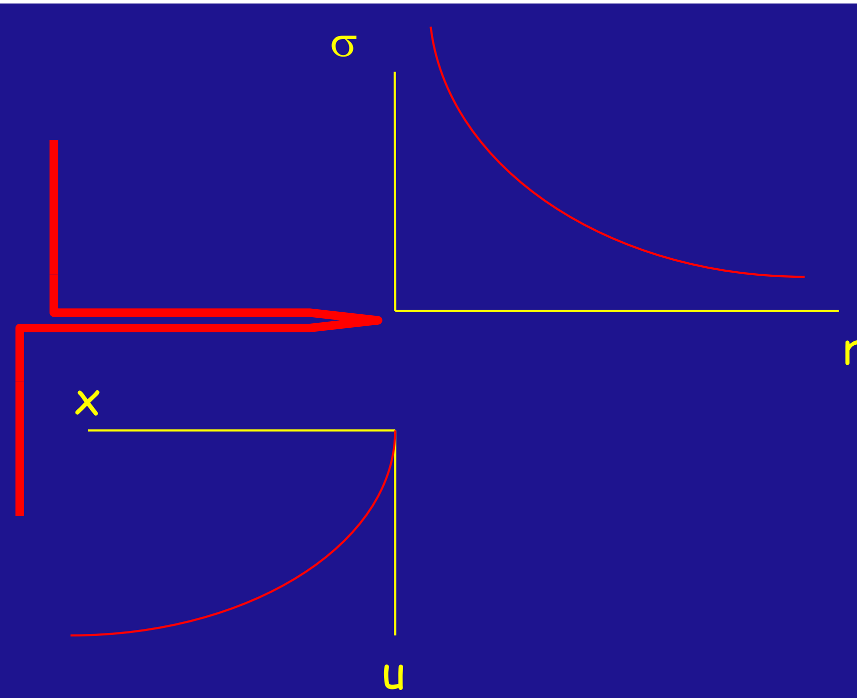
s = w

$$\Delta u = \frac{(1-\eta)(\sigma_o - \sigma_f)\ c}{2\pi\mu}\ f(\theta,\ \theta_2),\ see\ \ 1.30$$

$$\theta = \cos^{-1}\left(\frac{2x}{c}\right)\ \ for\ |x| < \frac{c}{2}\ \ and\ \ \theta_2 = \cos^{-1}\left(\frac{c-2s}{c}\right)$$



Crack tip stress field, real materials



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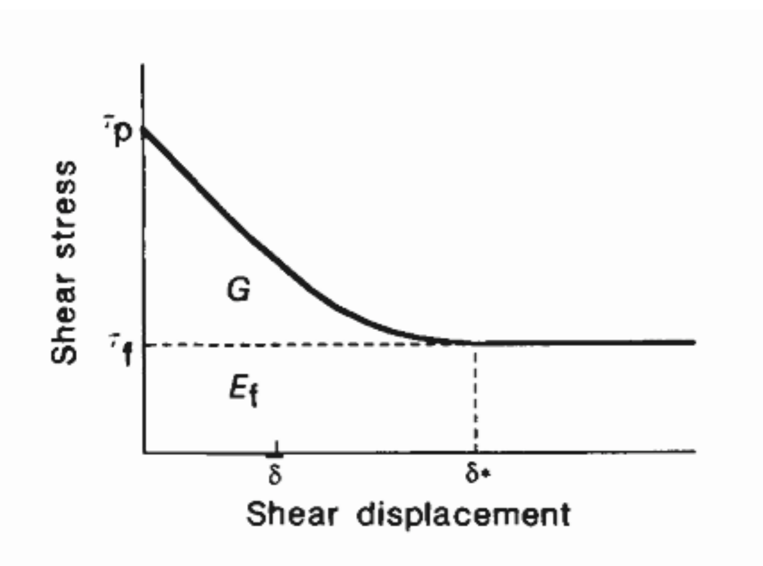
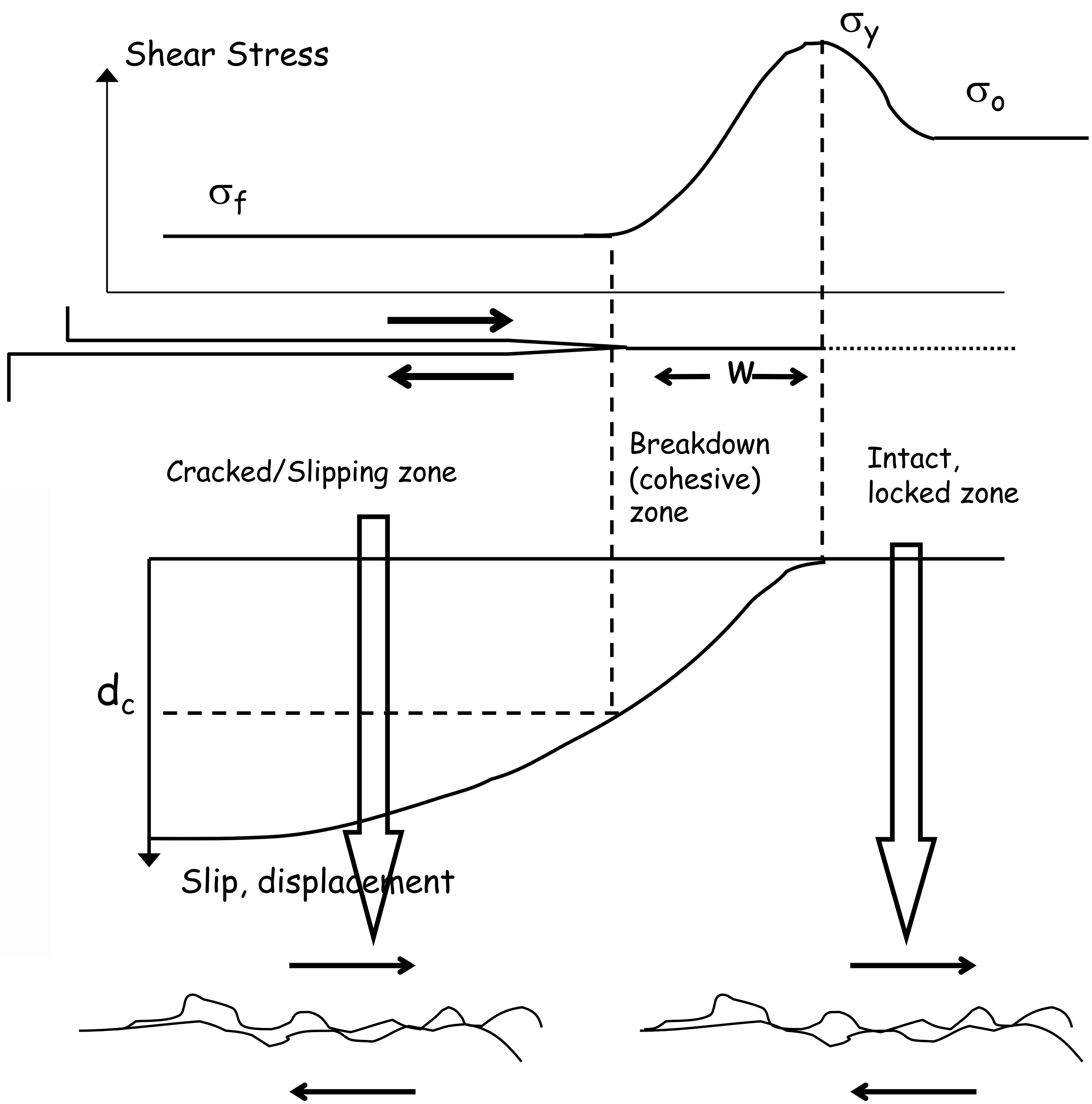
- e.g., can we 'read' the state of stress in the crust from earthquake (fault) data

Barenblatt, G. I., 1959, The formation of brittle cracks during brittle fracture. General ideas and hypotheses. Axially-symmetric cracks. Appl. Math. Mech. 23, 1273 – 1282.
Barenblatt, G. (1962). The mathematical theory of equilibrium cracks in brittle fracture. Advances in Applied Mechanics, 7, 55–129.
Dugdale, D. (1960). Yielding of steel sheets containing slits. Journal of the Mechanics and Physics of Solids, 8, 100–104.

Cohesive zone, slip weakening crack model for friction





Cohesive zone crack model, applies to fracture and/or friction

- Dugdale (Barenblatt)

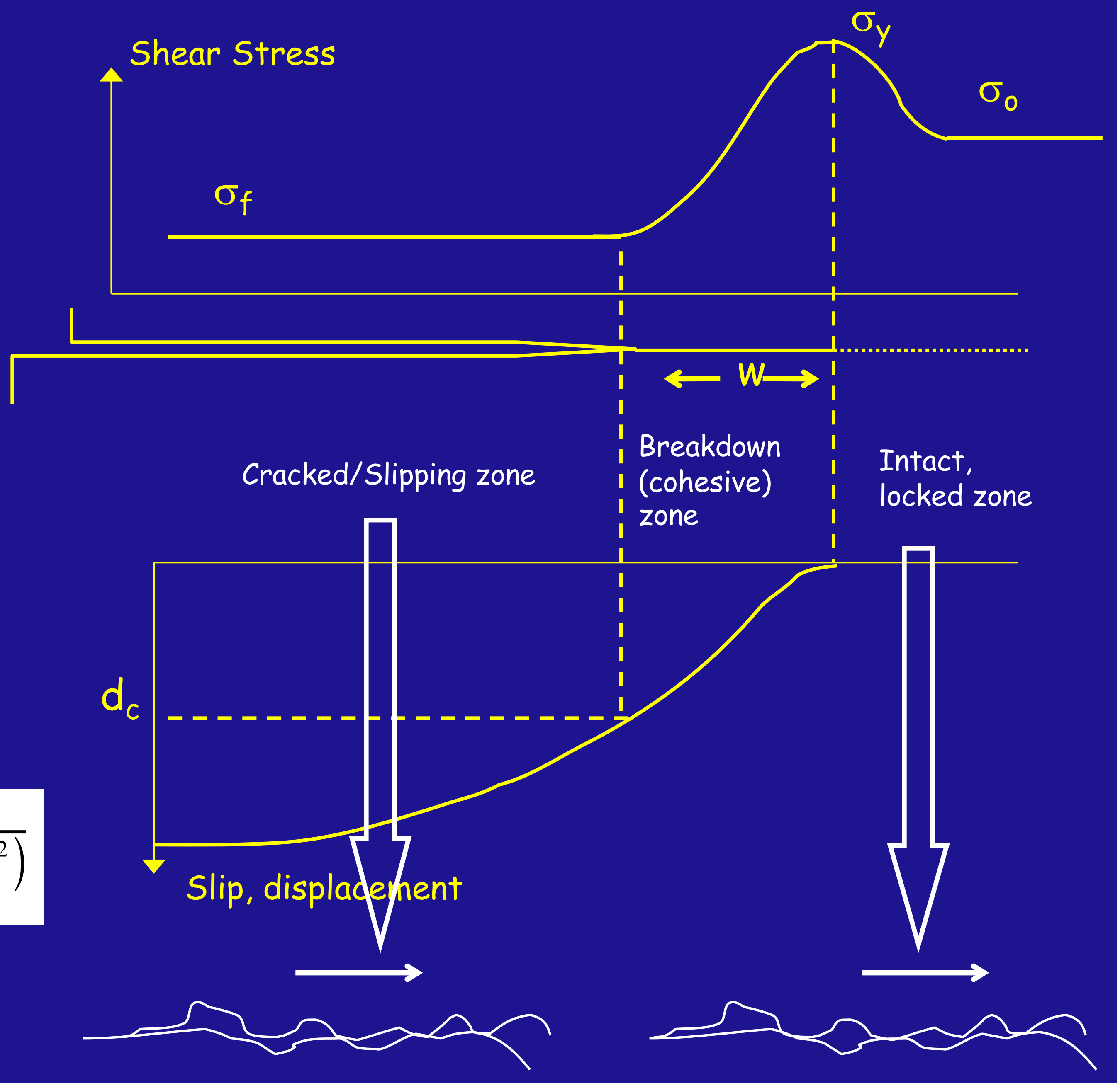
$$\Delta u = \frac{(1-\eta)(\sigma_o - \sigma_f)\ c}{2\pi\mu}\ f(\theta,\ \theta_2),\ see\ 1.30$$

$$\theta = \cos^{-1}\left(\frac{2x}{c}\right)\ \ for\ |x| < \frac{c}{2}\ \ and\ \ \theta_2 = \cos^{-1}\left(\frac{c-2s}{c}\right)$$

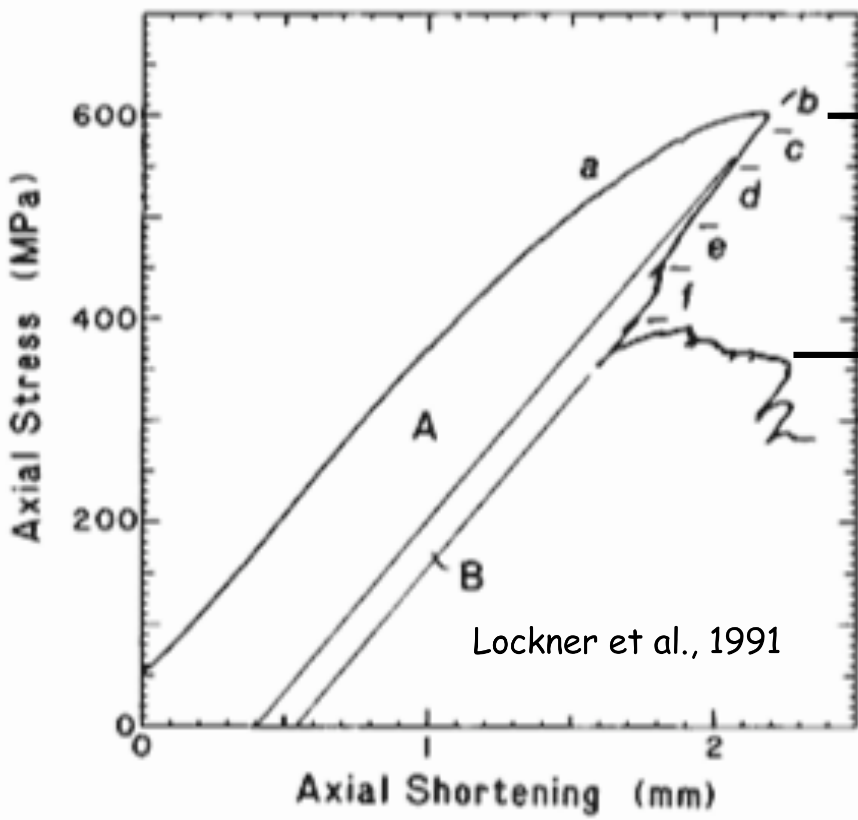
Dislocation model, circular crack

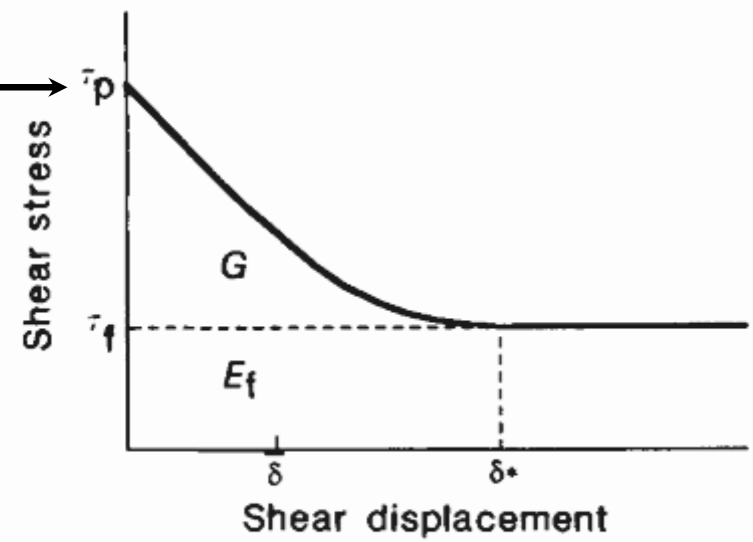
$\Delta\sigma = (\sigma_o - \sigma_f)$

$$\Delta u(x,y) = \frac{24}{7\pi}\ \frac{\Delta\sigma}{\mu}\sqrt{c^2 - (x^2 + y^2)}$$



Shear Fracture Energy from Postfailure Behavior



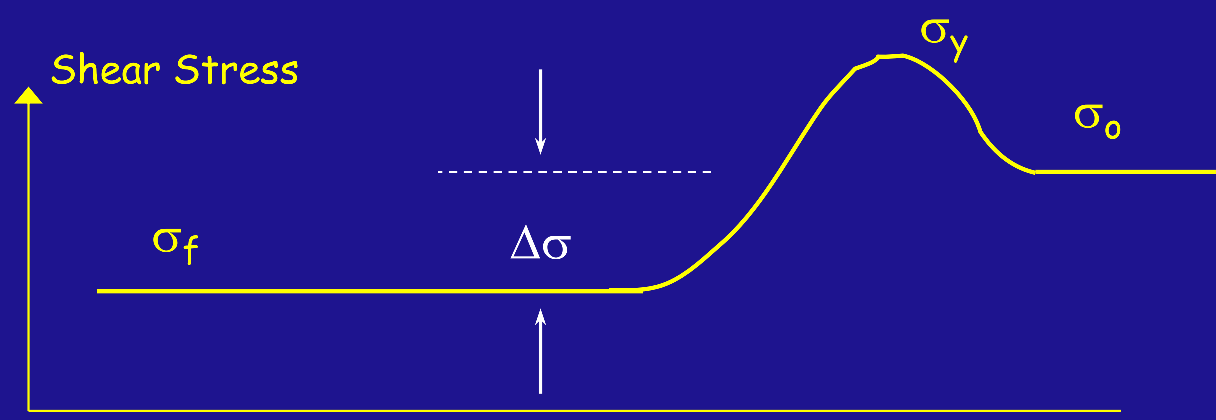


Inferred shear stress vs. slip relation for slip-weakening model. (based on Wong, 1982)

Wong, 1982, found that shear stress dropped ~ 0.2 GPa over a slip distance of ~50 microns.

Exercise: Estimate G from this data and compare it to the values reported in Scholz (Table 1.1) and Wong, 1982.

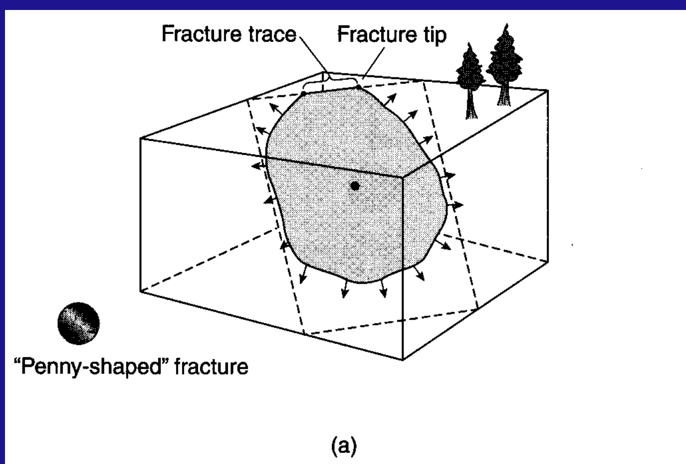
Dislocation model for fracture and earthquake rupture

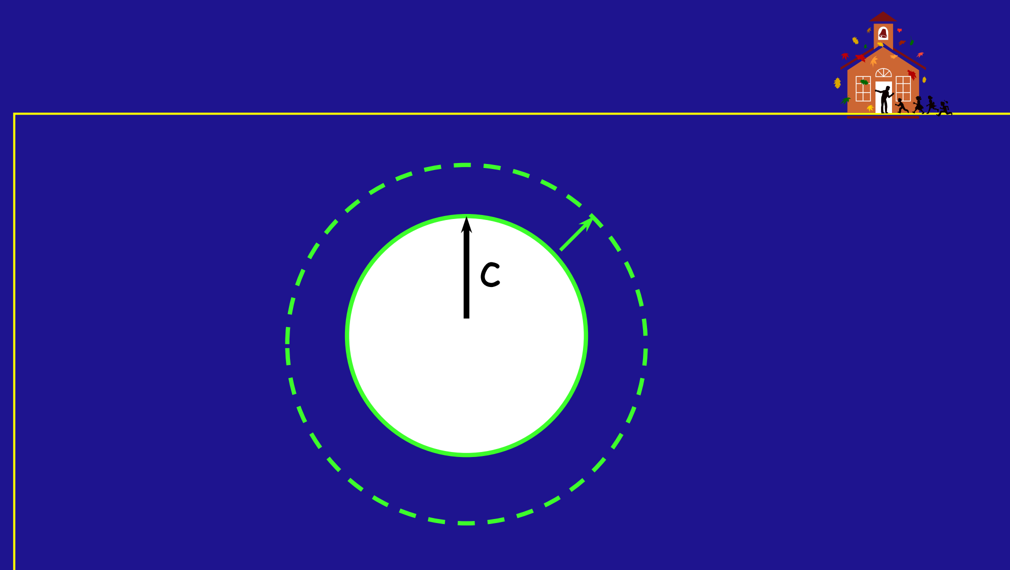


Dislocation model, circular crack

$\Delta\sigma = (\sigma_o - \sigma_f)$

$$\Delta u(x,y) = \frac{24}{7\pi}\frac{\Delta\sigma}{\mu}\sqrt{c^2 - \left(x^2 + y^2\right)}$$





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

Relation between stress drop and slip for a circular dislocation (crack) with radius r

For η=0.25, Chinnery (1969)

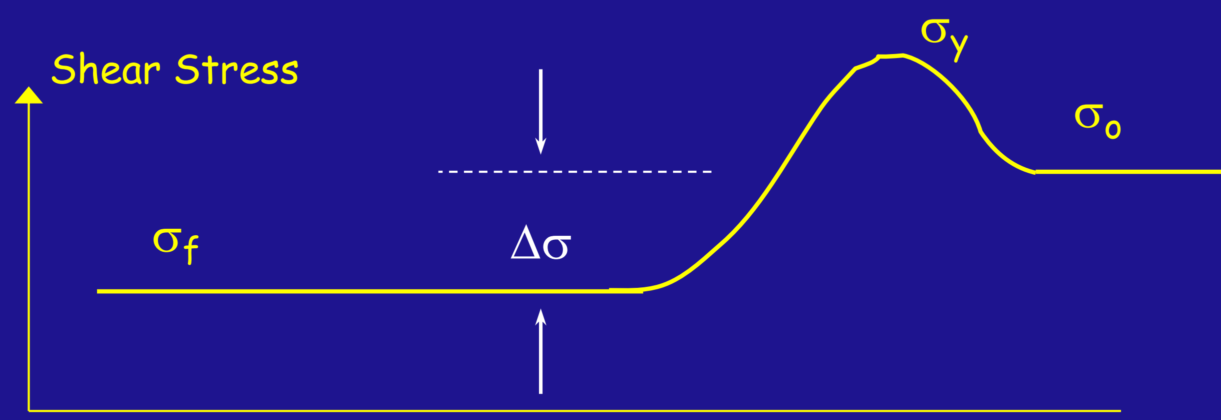
- Importance of slip: e.g., $M_o = \mu A u$

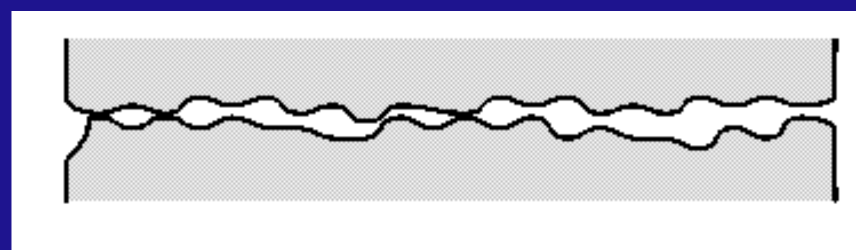
Dislocation model for fracture and earthquake rupture

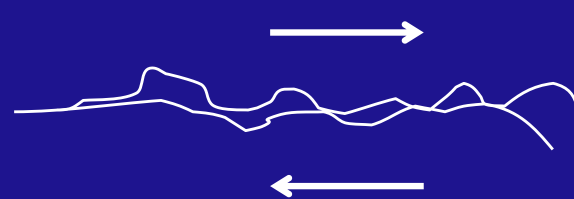
Dislocation model, circular crack

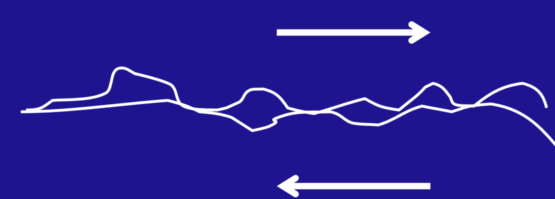
$\Delta\sigma = (\sigma_o - \sigma_f)$

$$\Delta u(x,y) = \frac{24}{7\pi}\,\frac{\Delta\sigma}{\mu}\sqrt{c^2 - \left(x^2 - y^2\right)}$$



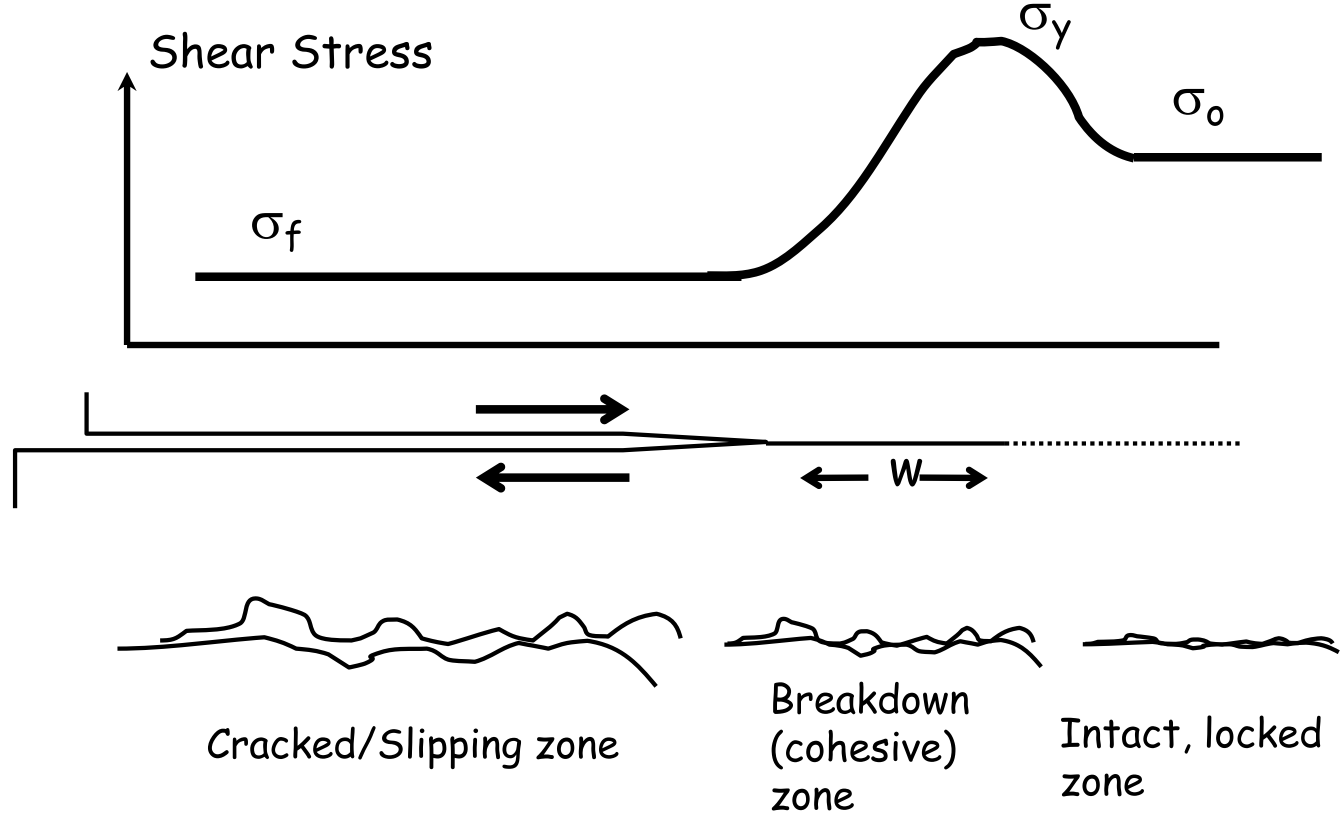


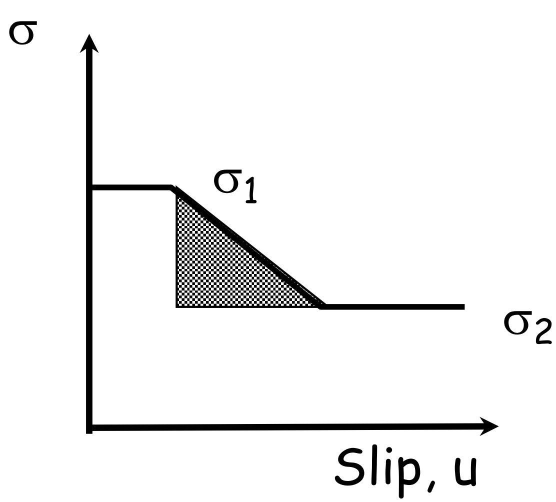


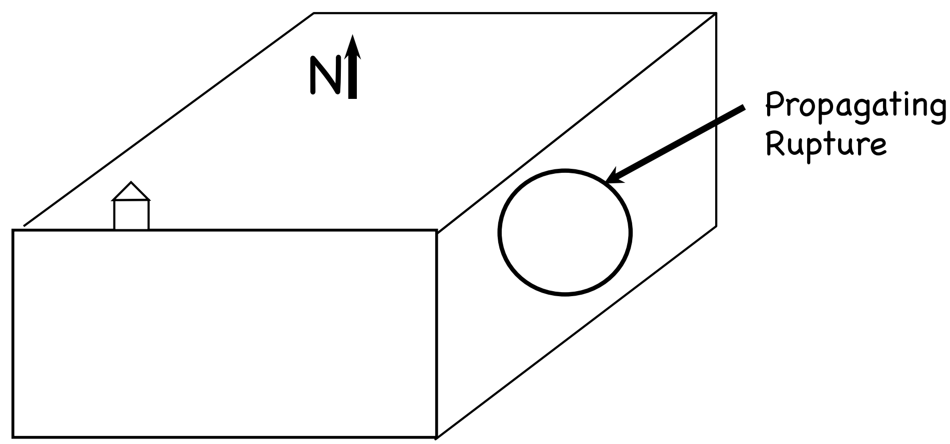


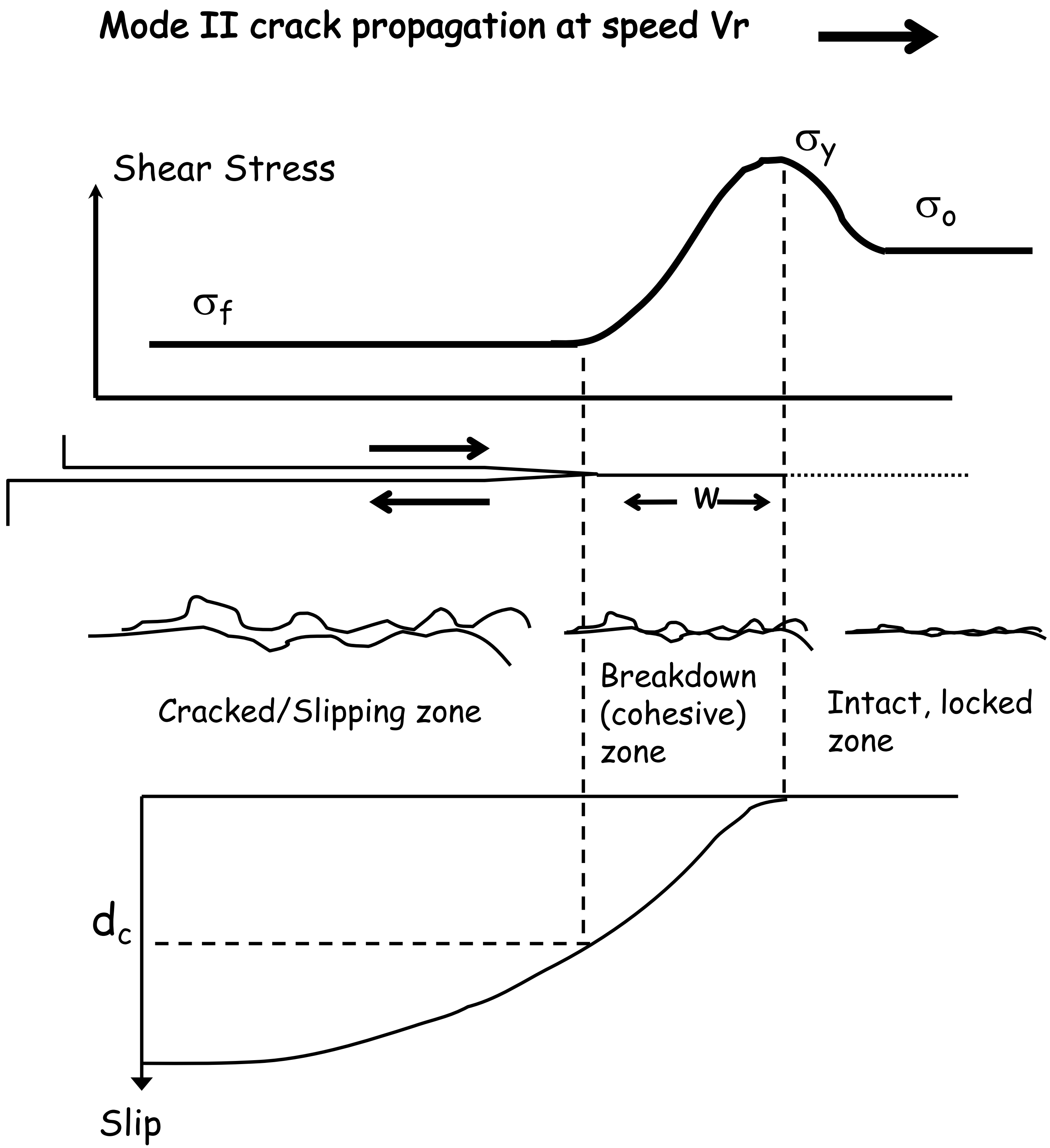
Mode II crack propagation at speed Vr

cohesive zone/slip weakening crack model for friction









cohesive zone/slip weakening crack model for friction

f_{max} scales as:

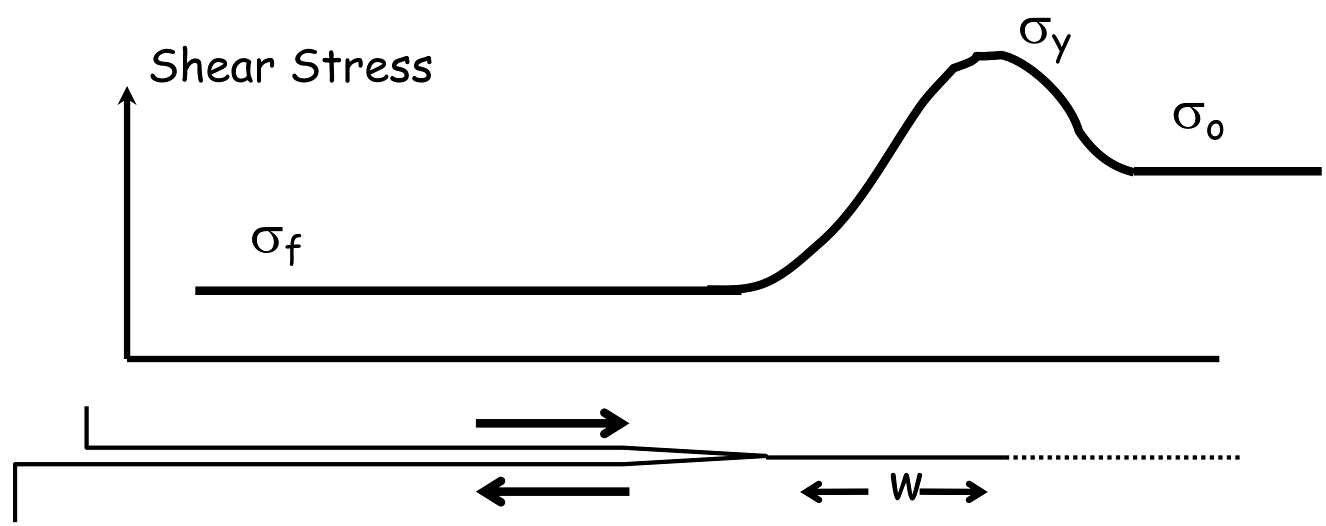
f_{max} = **w/Vr**

$$\Delta\sigma = \frac{7\pi}{24} G \frac{u_{max}}{r}$$

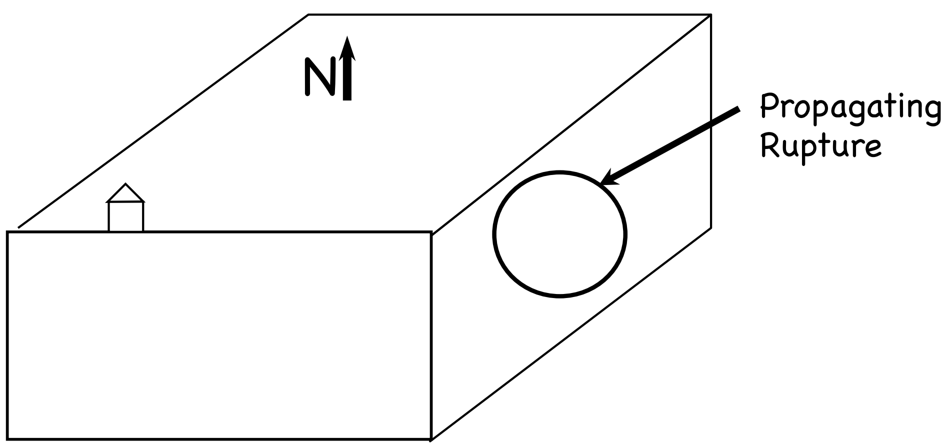
$$\Delta\sigma = \frac{7\pi}{24} G \frac{D_c}{w}$$

$$D_c = \frac{24}{7\pi} \frac{\Delta\sigma}{G} w$$

Mode II crack propagation



Cohesive zone length w scales as:



$$w \approx C \frac{D_c G}{\Delta\sigma}$$

$$\frac{w}{D_c} \approx C \frac{G}{\Delta\sigma}$$

Slip weakening model (Ida, 1972, 1973)

$$R_c = \frac{CGD_c}{\sigma_n (b-a)} \quad or \quad L_c = \frac{E \; D_c}{2(1-\nu^2)\sigma_n \Delta\mu}$$

Recall the derivation of this result:

Frictional Instability

Requires $K < K_c$

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

$$\Delta\sigma = \frac{7\pi}{24} G \frac{u_{max}}{r}$$

Relation between stress drop and slip for a circular dislocation (crack) with radius r

For ν =0.25, Chinnery (1969)

$$\Delta\sigma = \frac{7\pi}{24} G \frac{D_c}{w}$$

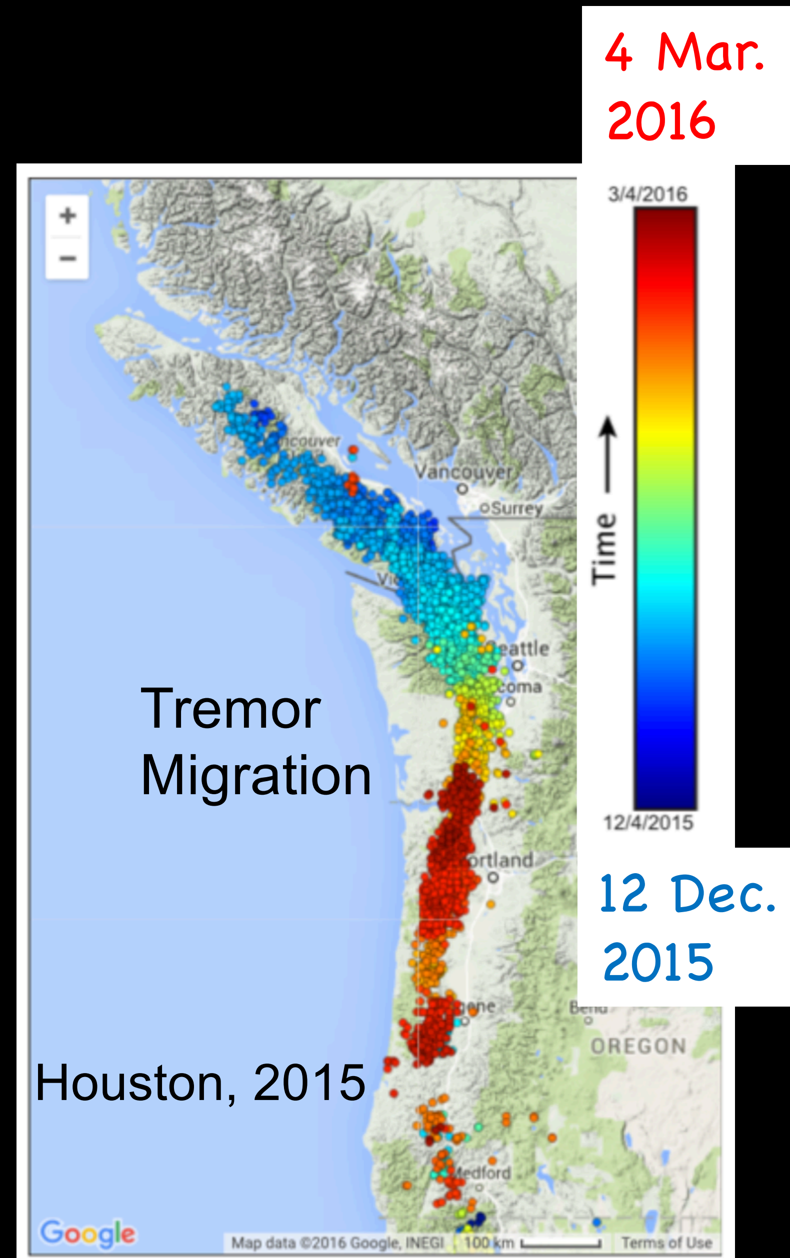
$$D_c = \frac{24}{7\pi} \frac{\Delta\sigma}{G} w$$

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

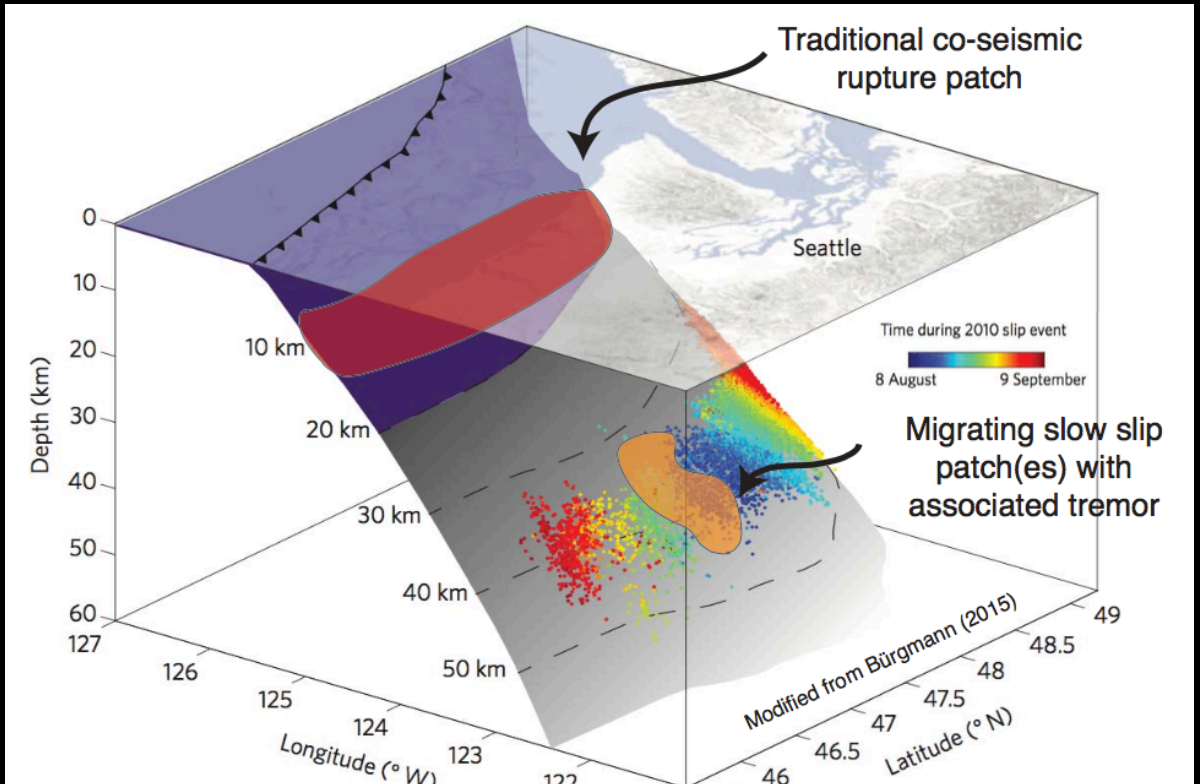
- Aseismic slip



Slow Earthquakes are self-propagating ruptures

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

One Month in 2010



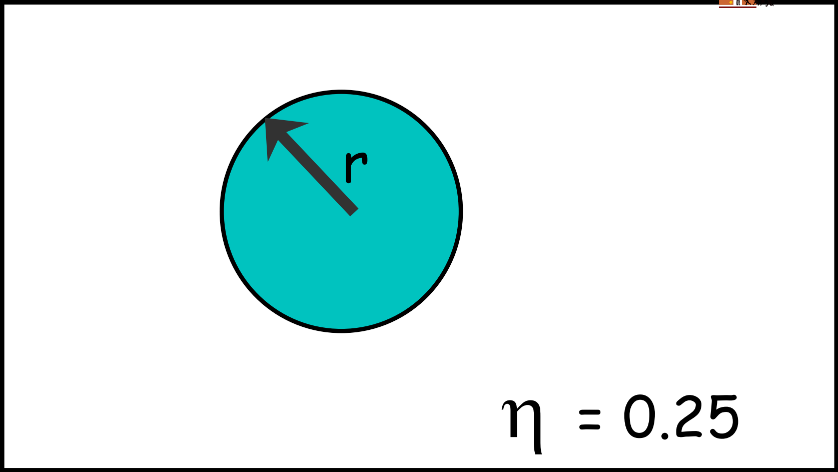
Bürgmann, 2015; Houston, 2015

Slow Earthquakes

V_r is a few km/day

Ordinary Earthquakes

Seismic waves are created by rapid acceleration at the rupture front



Ordinary (fast) Earthquakes

V_r is a few km/s

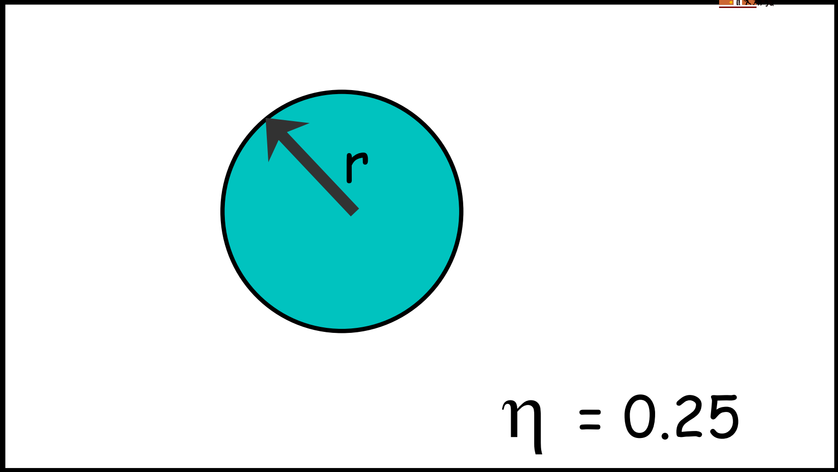
Images from the aftermath of the Anchorage earthquake

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
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Shigeji Suyehiro
Seismological Division, Japan Meteorological Agency, Tokyo, Japan
Alan T. Linde
Carnegie Institution of Washington, Department of Terrestrial Magnetism, Washington D.C. 20015
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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

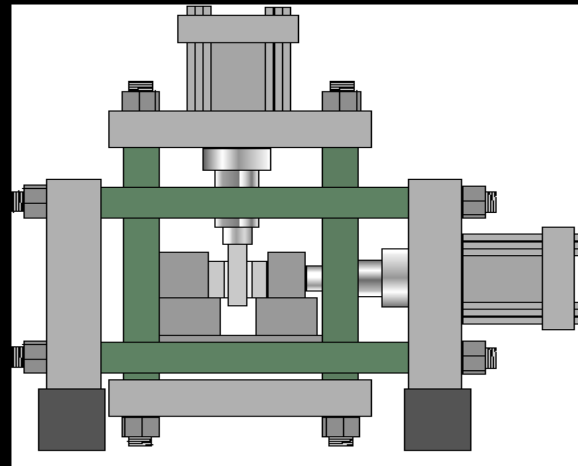
1. Slow earthquakes could represent quasi-dynamic frictional instability (positive feedback, self-driven instability)

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

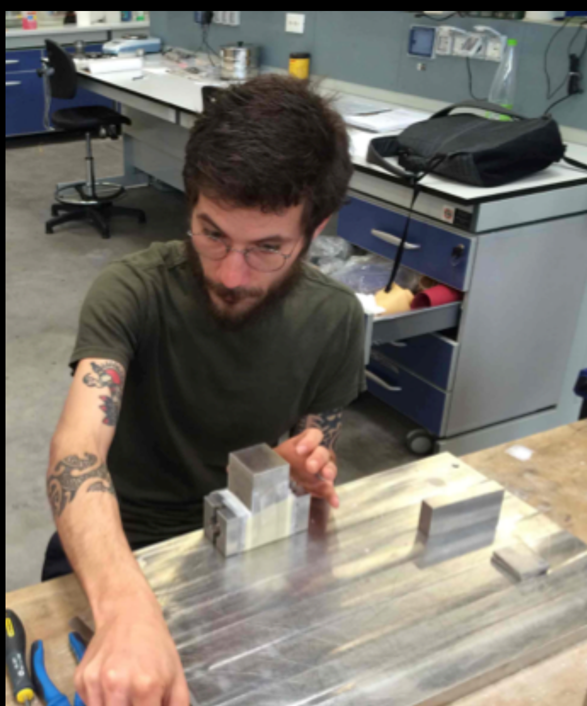
PennState

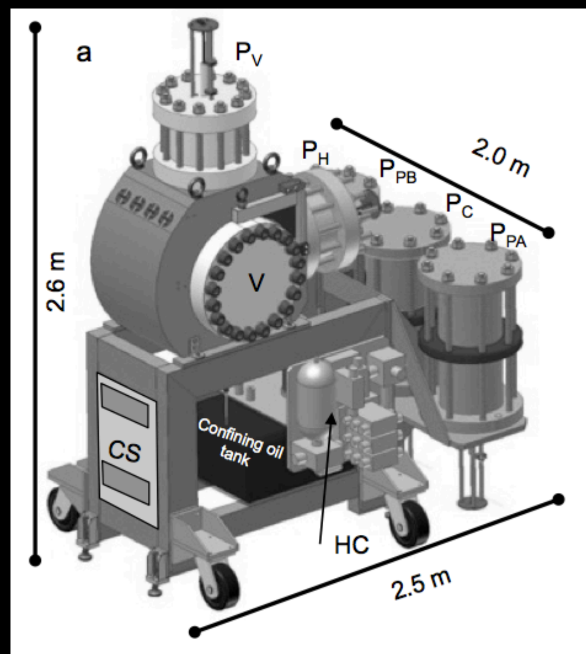
SAPIENZA
UNIVERSITÀ DI ROMA



John Leeman

Marco Scuderi





ARTICLE

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

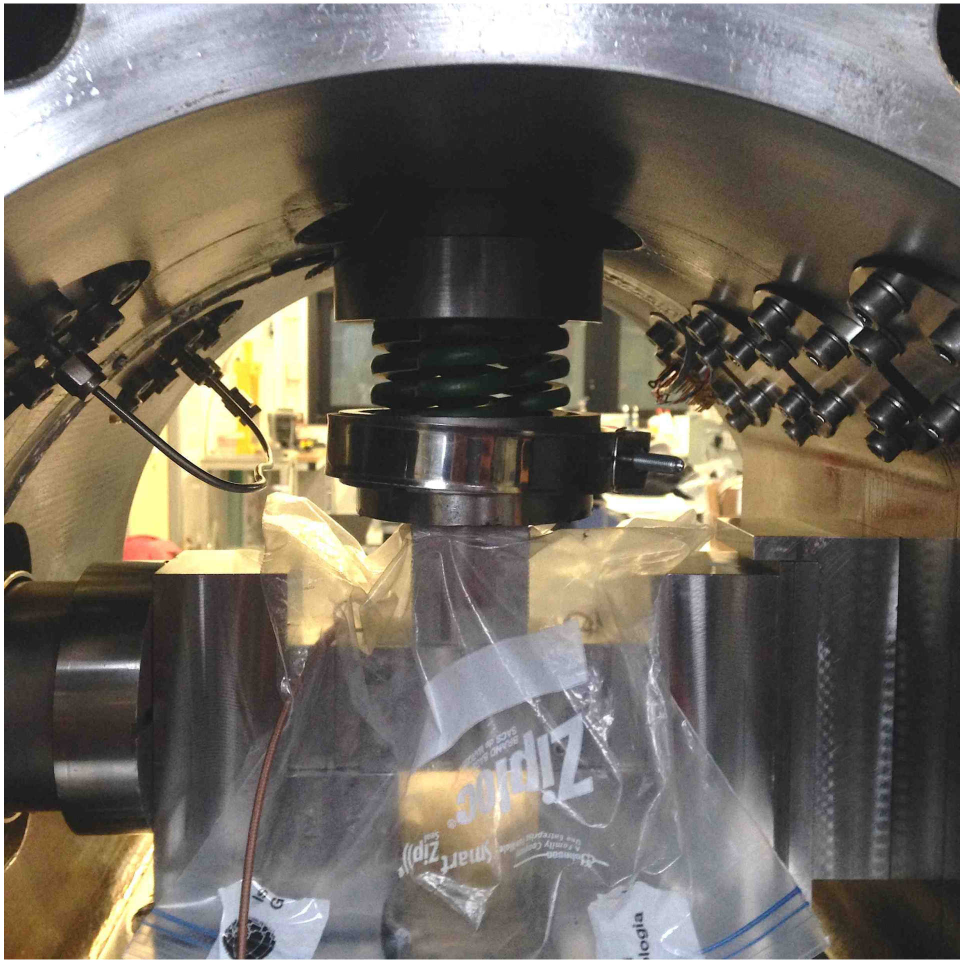
J.R. Leeman[1], D.M. Saffer[1], M.M. Scuderi[1,2] & C. Marone[1]

Nature Communications

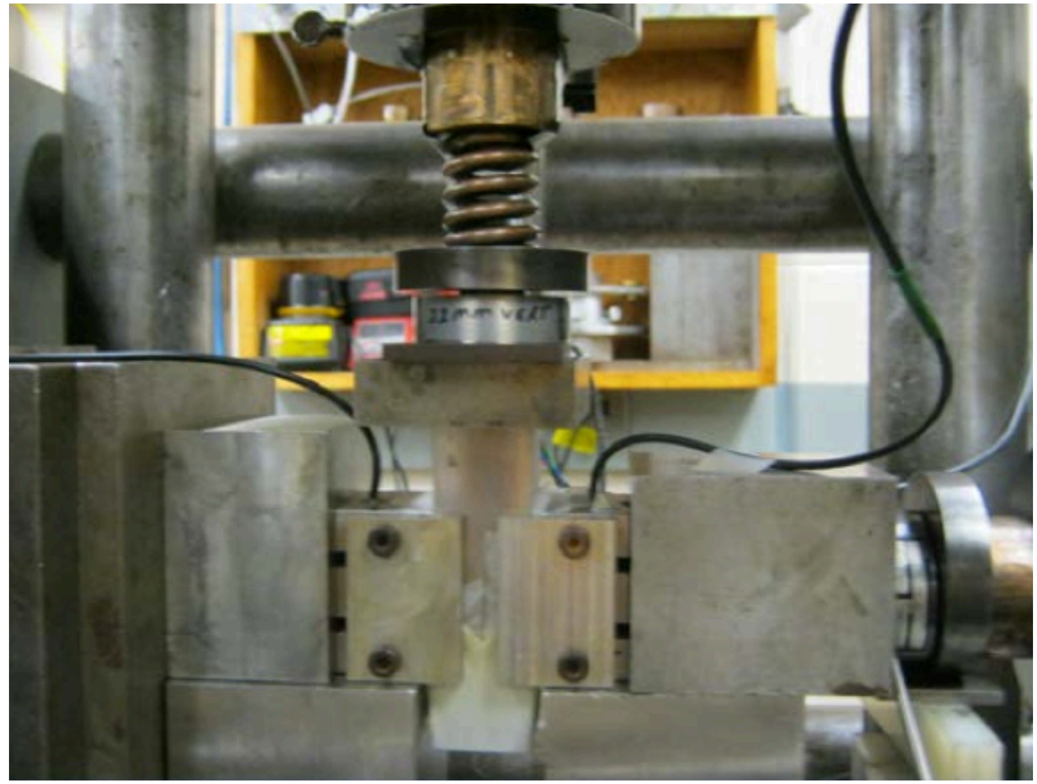
nature geoscience LETTERS
PUBLISHED ONLINE: 8 AUGUST 2016 | DOI: 10.1038/NGEO2775

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]

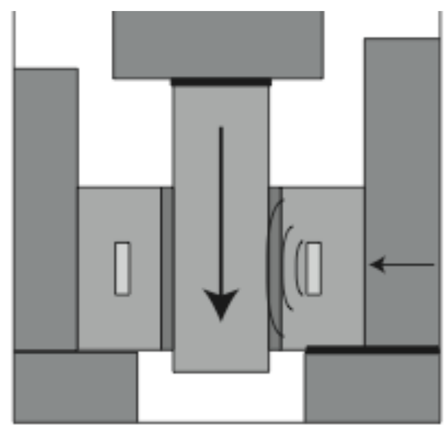


BRAVA at INGV (Rome)
Collettini Lab

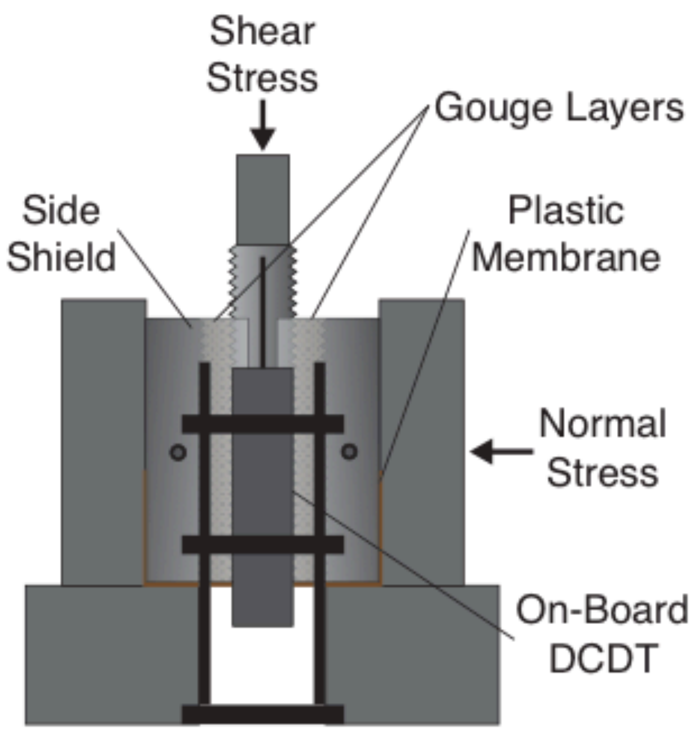


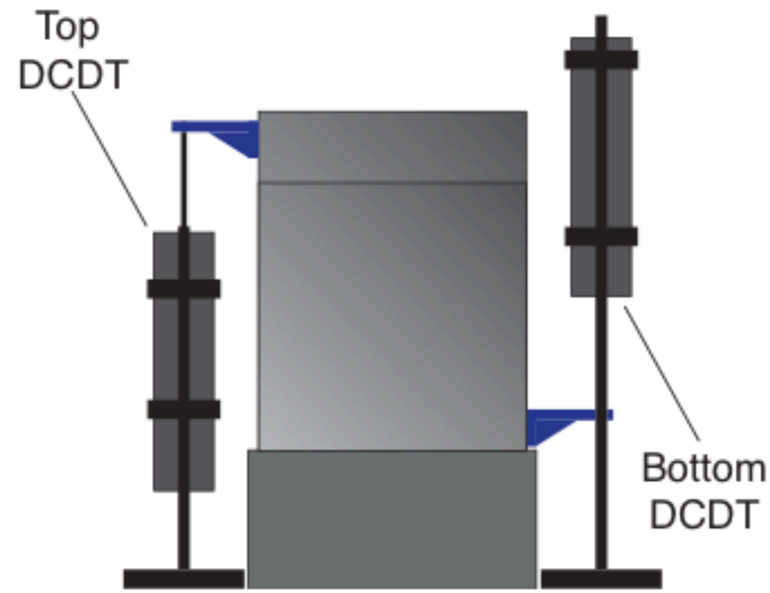
Biax at Penn State

Double direct shear with biaxial loading
and controlled loading stiffness

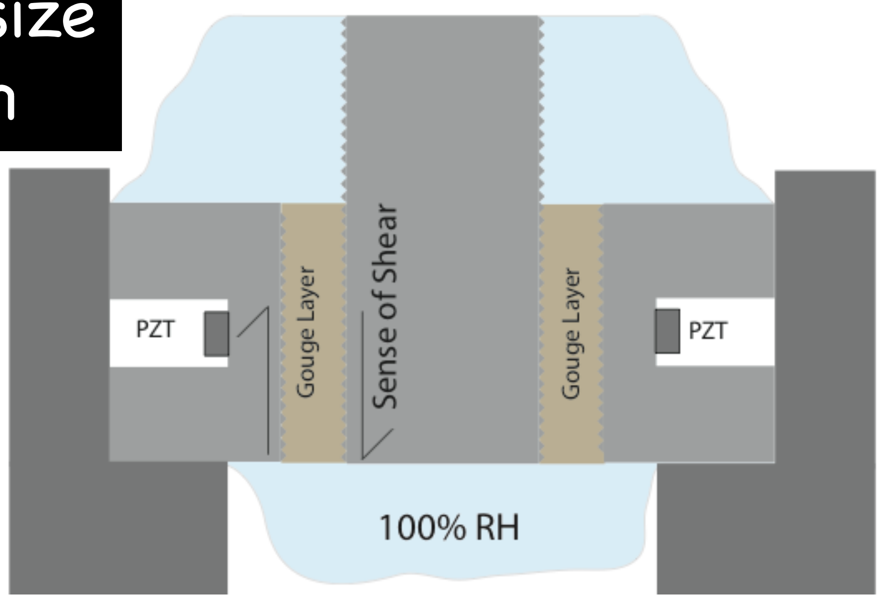


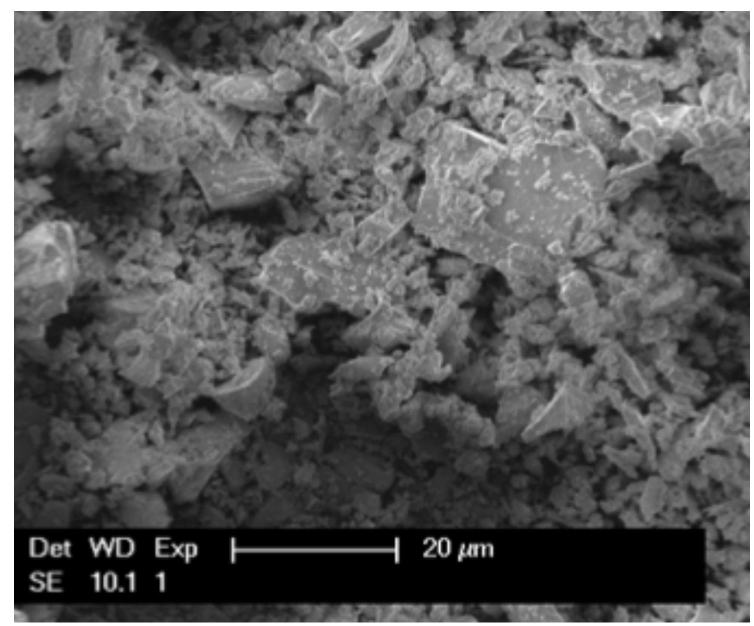
High-resolution, direct measurements of shear displacement, shear strain, normal strain, stresses





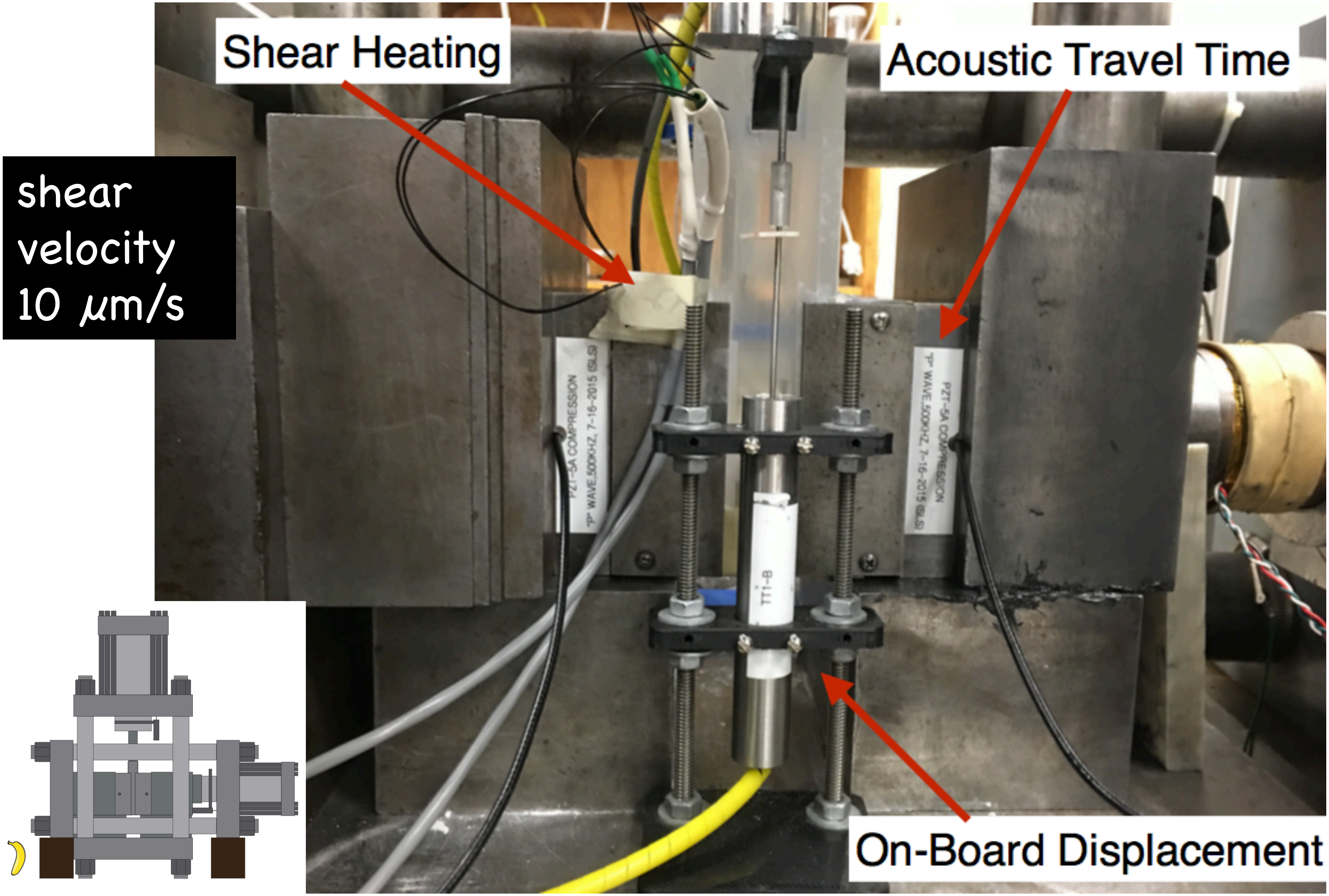
- Quartz powder
- grain size < 10μm



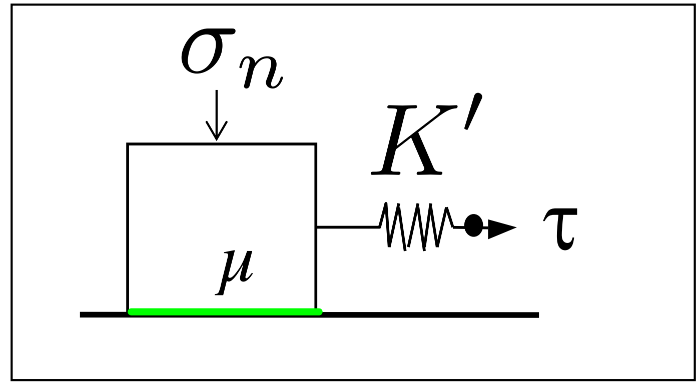


Biaxial testing machine at Penn State

shear velocity 10 μm/s



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

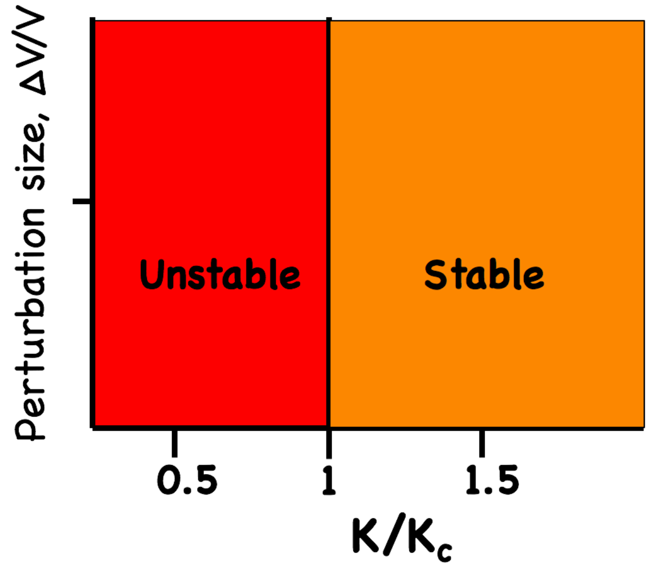


How do we produce slow slip?

Rate and State Friction

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

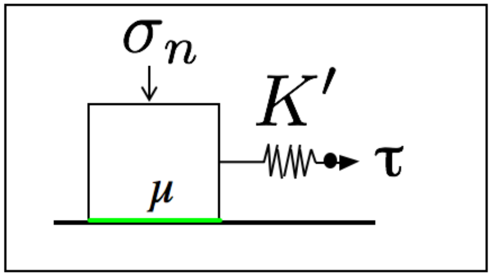
$$\frac{d\theta}{dt} = -\frac{V\theta}{D_c} ln(\frac{V\theta}{D_c})$$

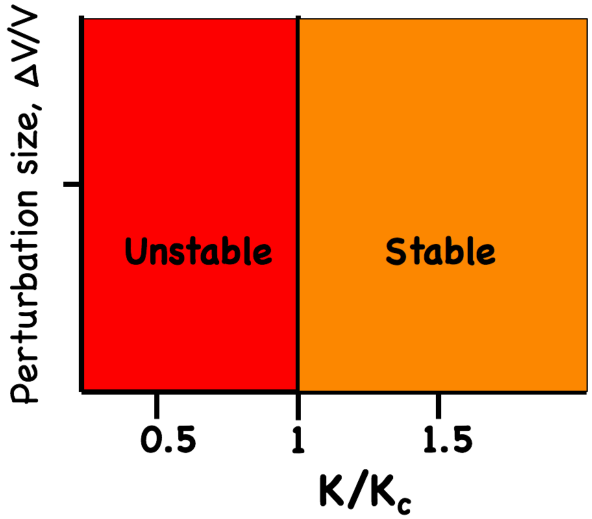


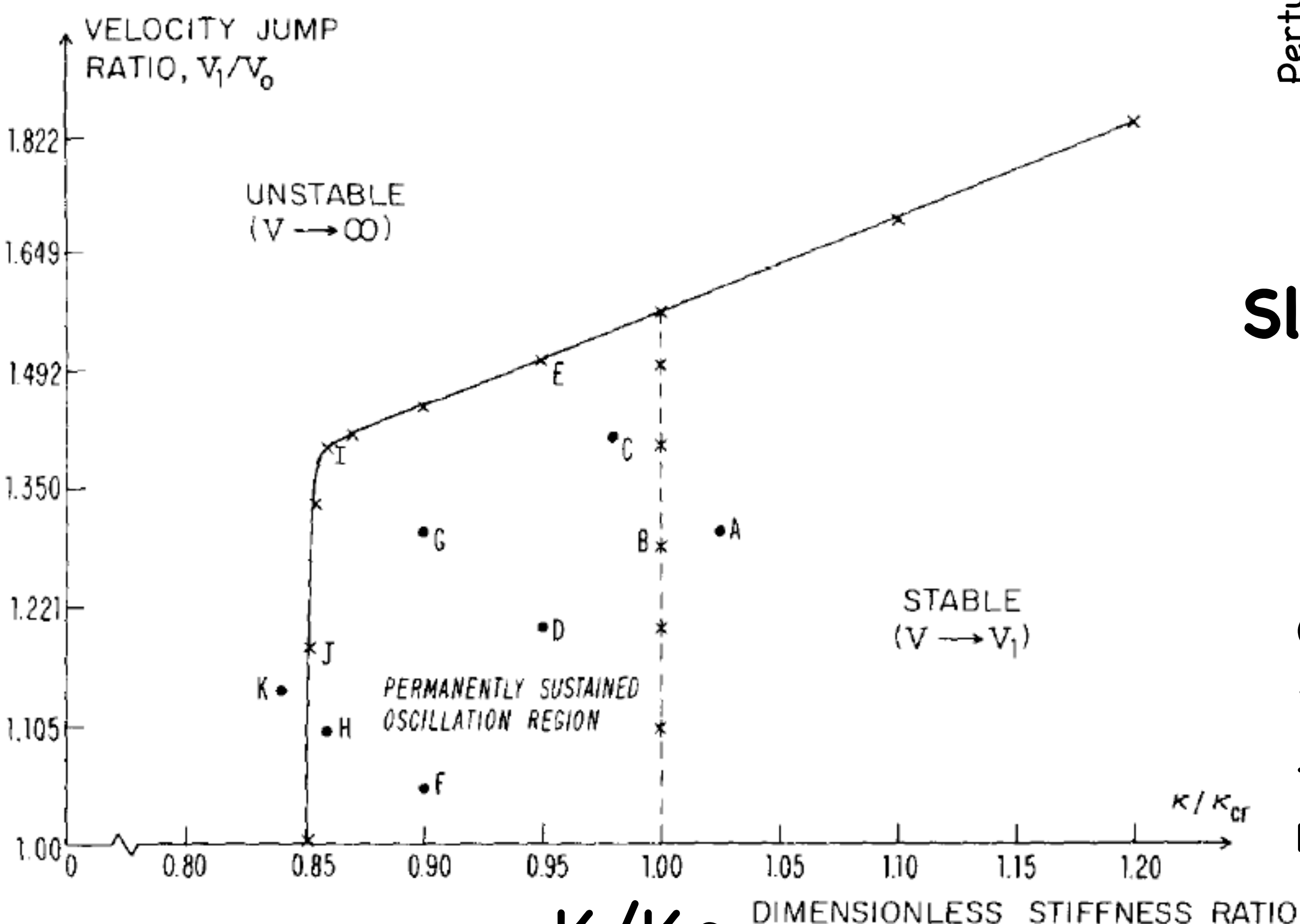
$$K_c = \frac{\sigma_n(b-a)}{D_c}[1 + \frac{m{V_o}^2}{\sigma_n a D_c}]$$

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

Stability transition from stable to unstable sliding.







κ = K/Kc

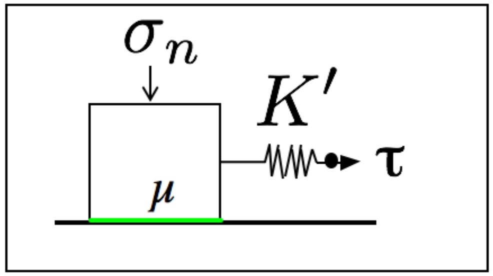
Gu et al., 1984

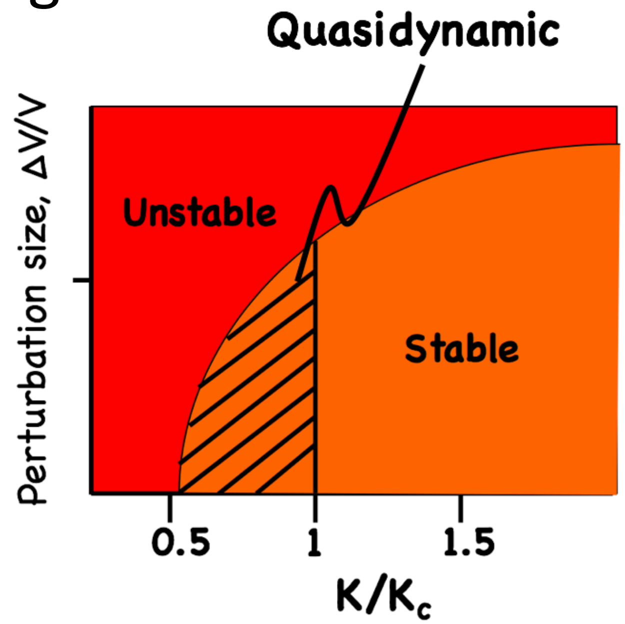
Slip is unstable if

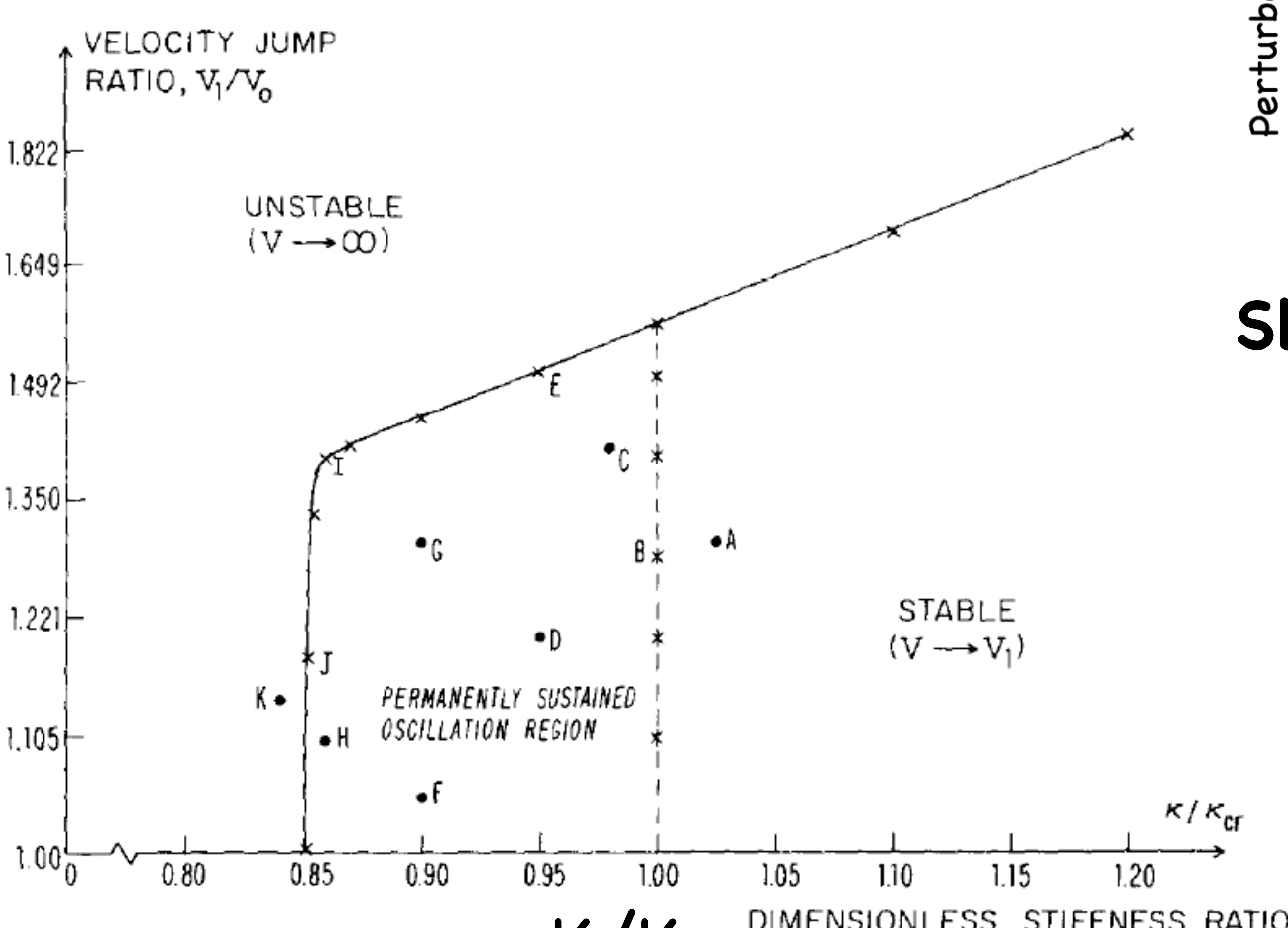
$$K < K_c$$

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

Stability transition from stable to unstable sliding.







Slip is unstable if

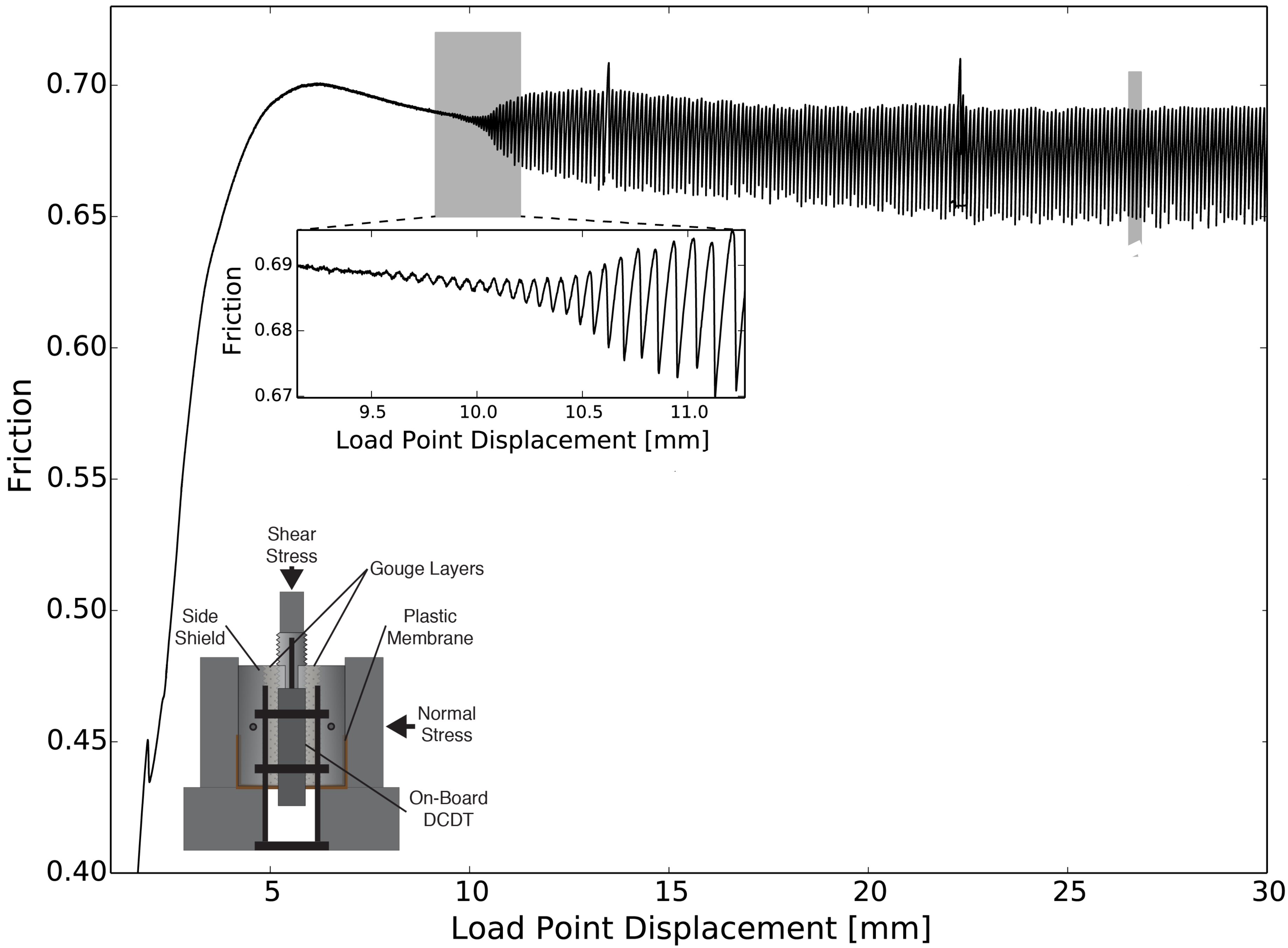
$$K < K_c$$

κ = K/Kc

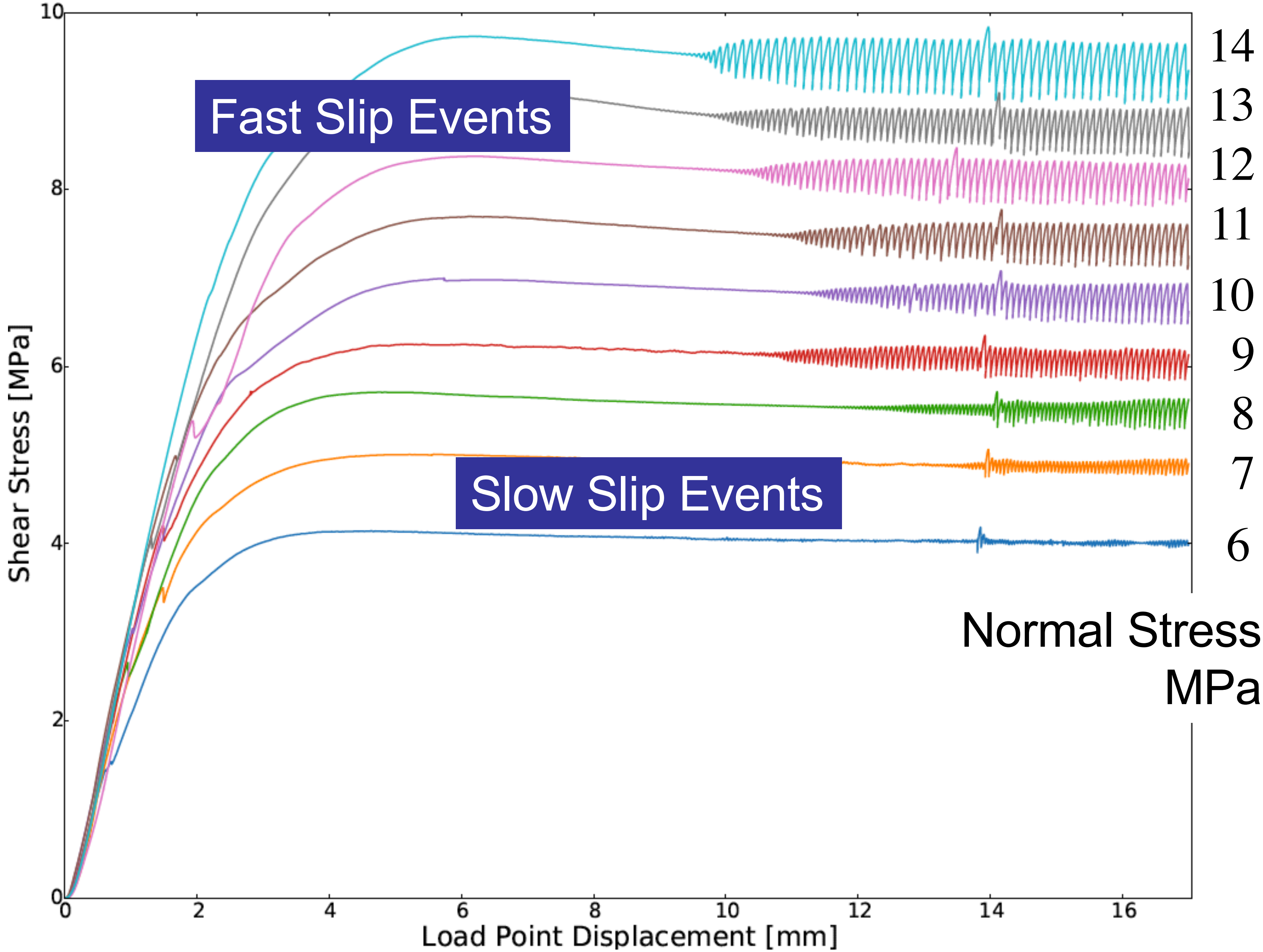
Complex behavior near the stability boundary, --but not for 1 sv rsf model

Gu et al., 1984

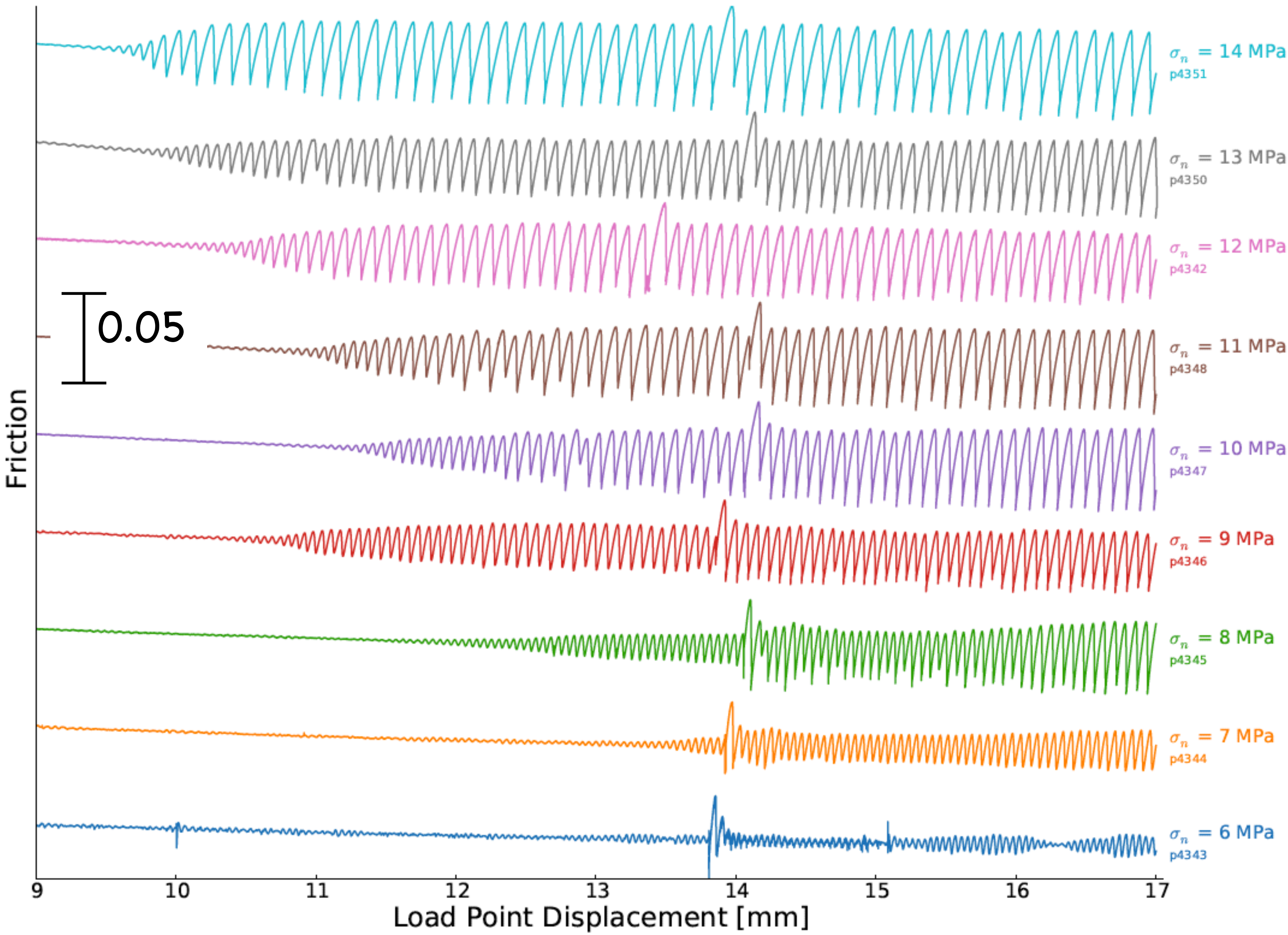
Repetitive Slow Stick-Slip



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



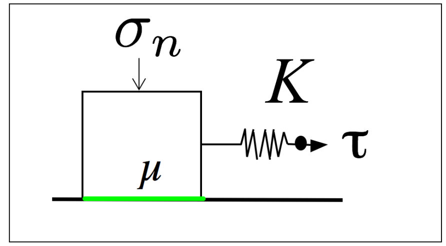
Leeman, Saffer, Scuderi & Marone, Nat. Comm. 2016



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

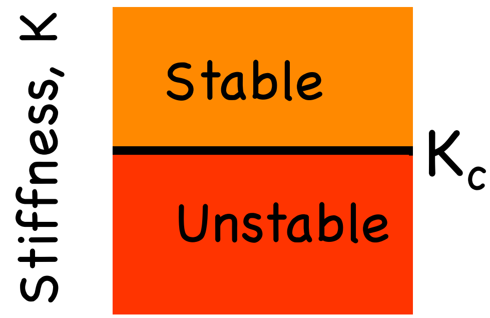


$$k = \frac{K}{\sigma_n} \qquad \mu = \frac{\tau}{\sigma_n}$$

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

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

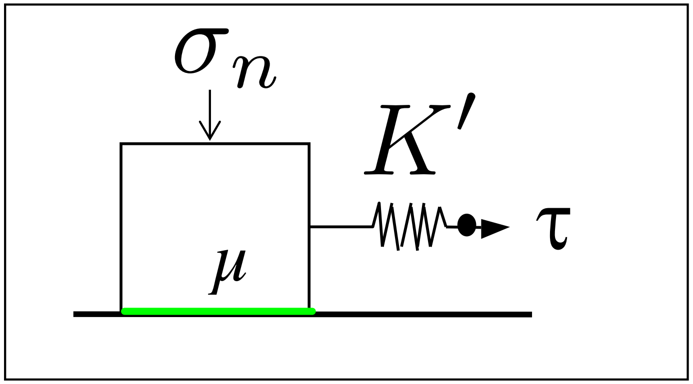
$$\frac{d\mu}{dt} = k(V_{lp} - V)$$

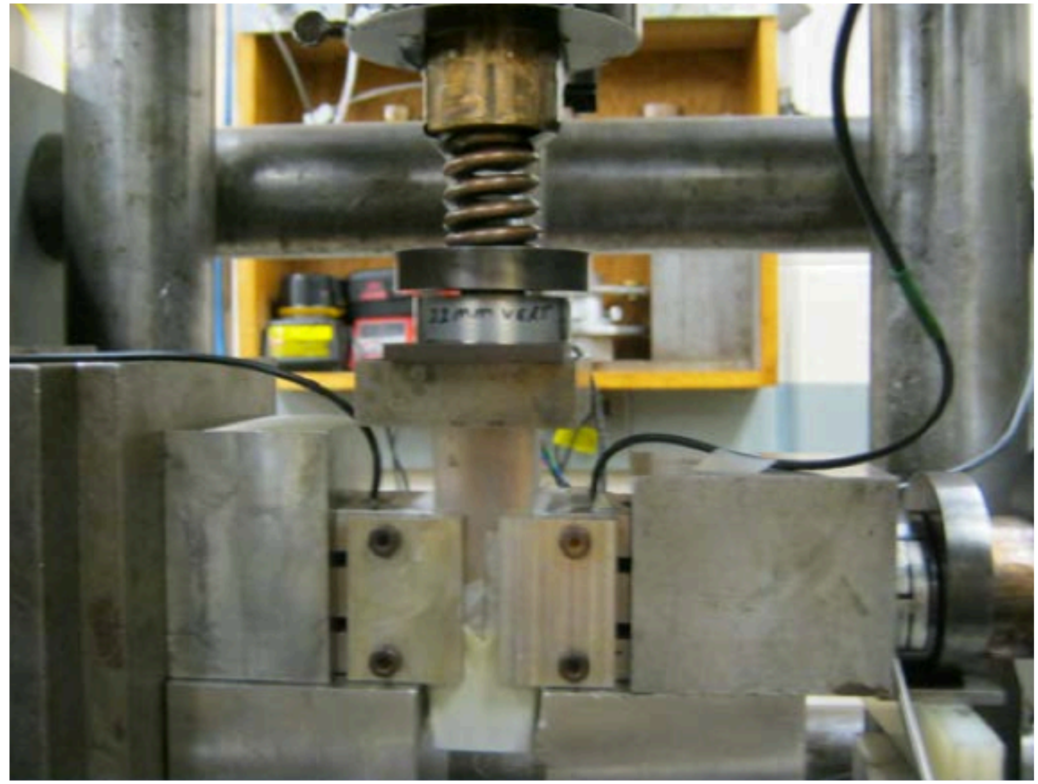


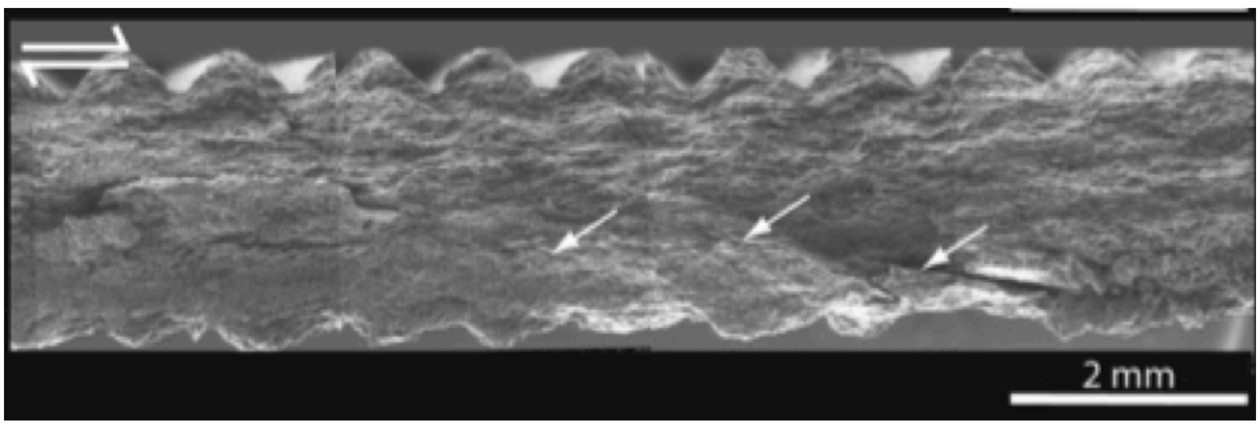
$$K_c = \frac{\sigma_n(b-a)}{D_c}[1 + \frac{m{V_o}^2}{\sigma_n a D_c}]$$

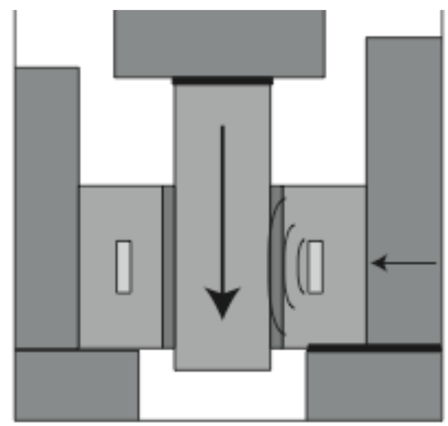
Dieterich, 1979; Ruina, 1983; Rice & Ruina, 1983; Gu et al., 1984

elastic loading stiffness

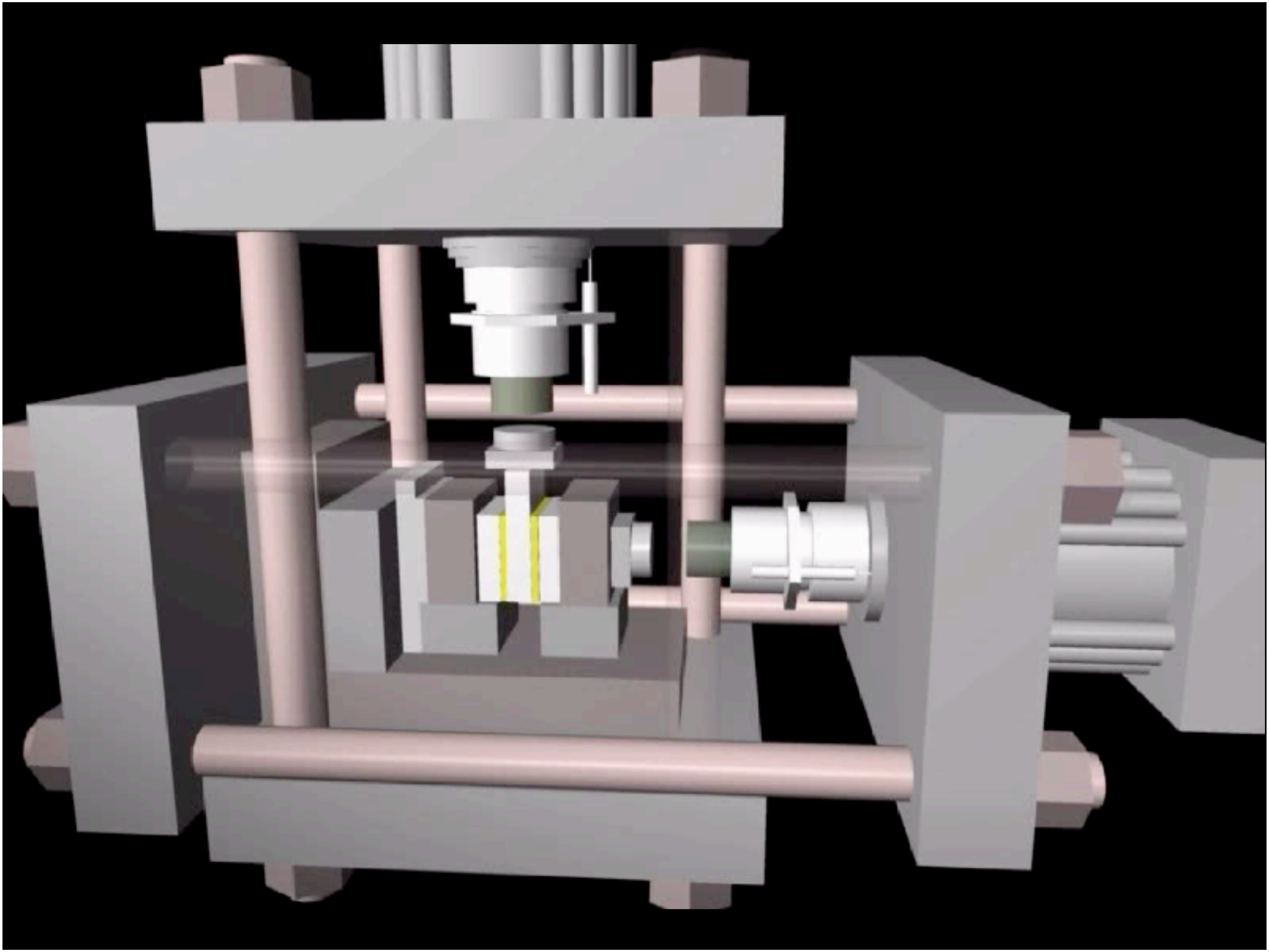




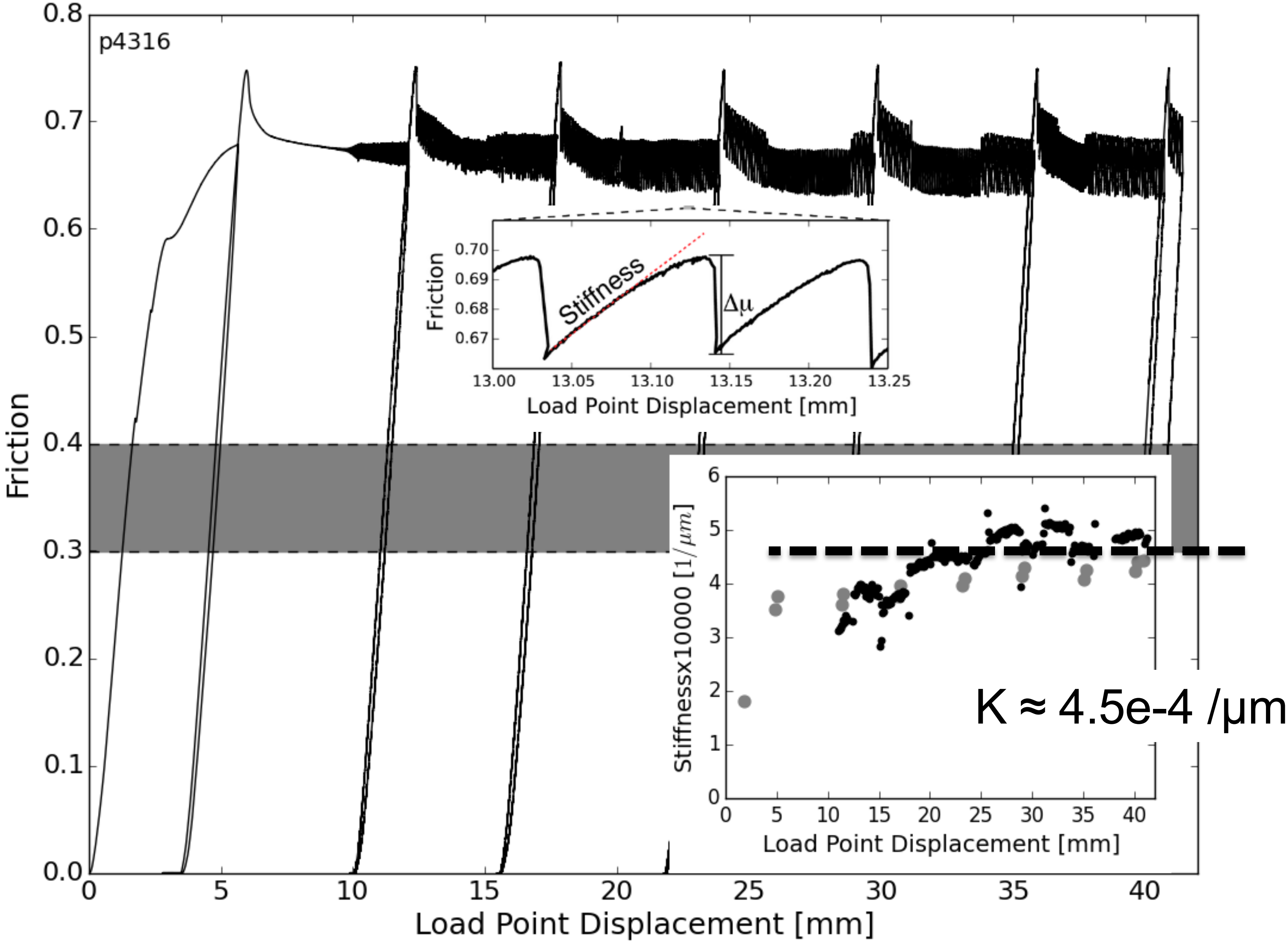




Double direct shear with biaxial loading



We measure elastic loading stiffness using 2 methods



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

$$K < K_c$$

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

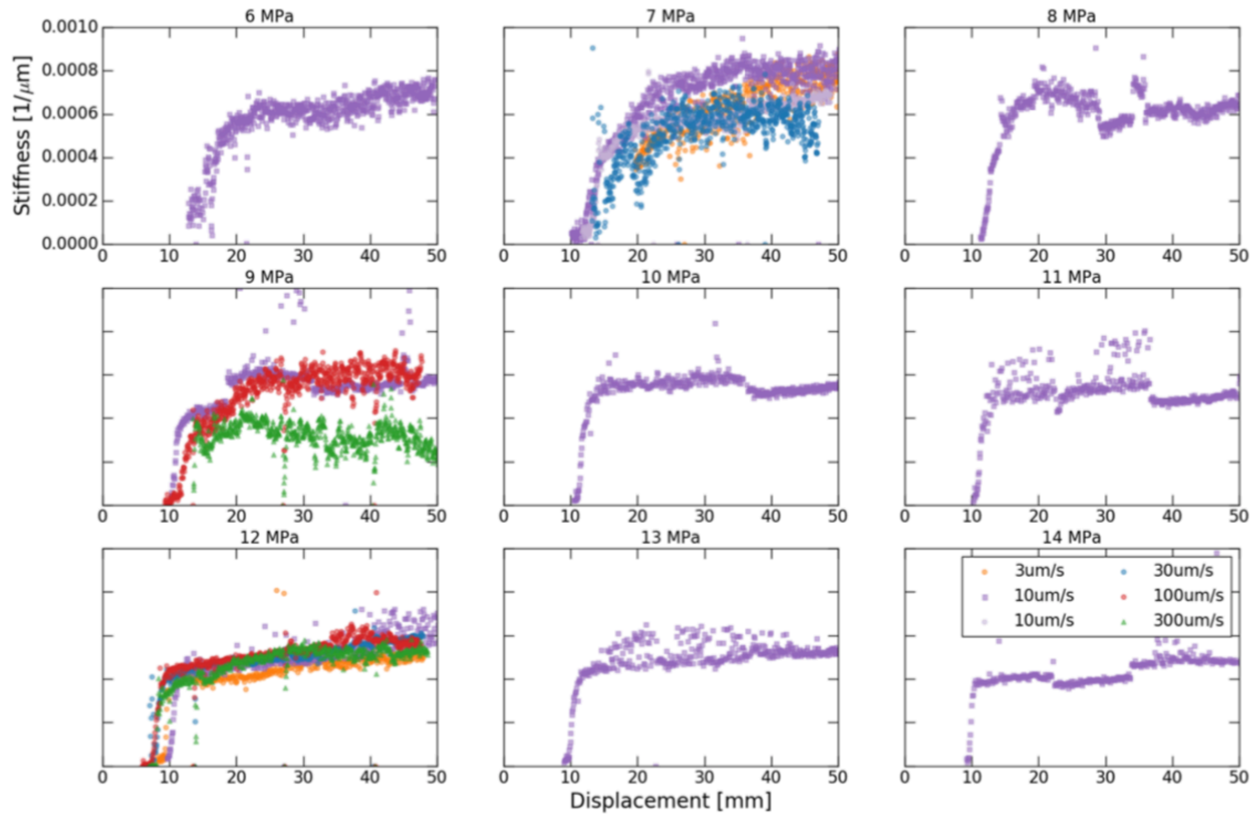
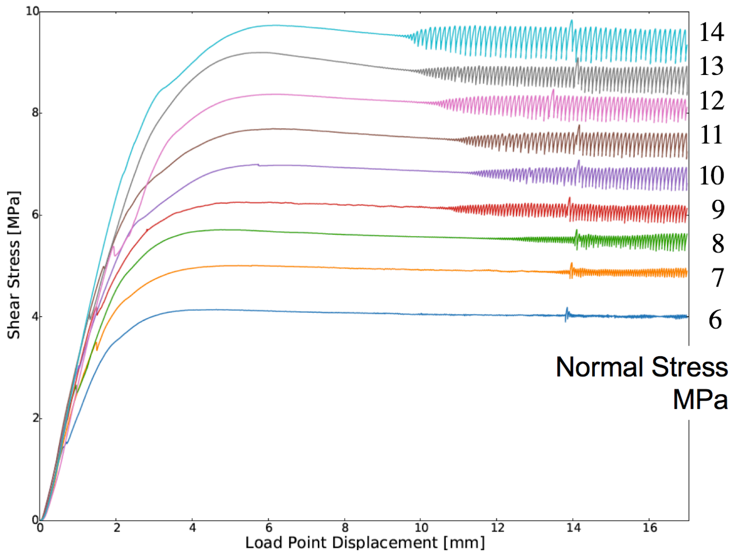
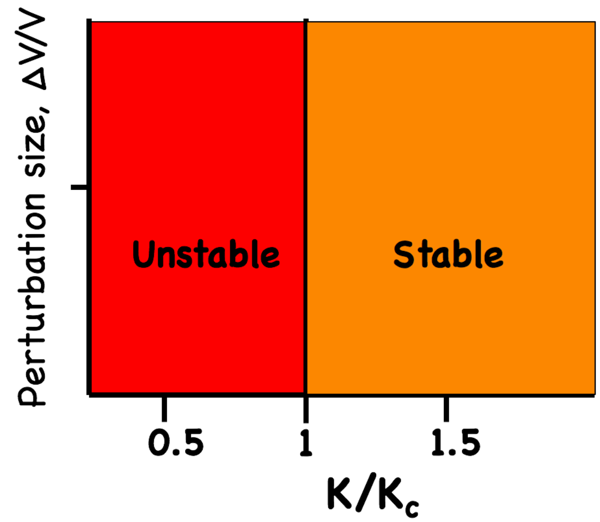


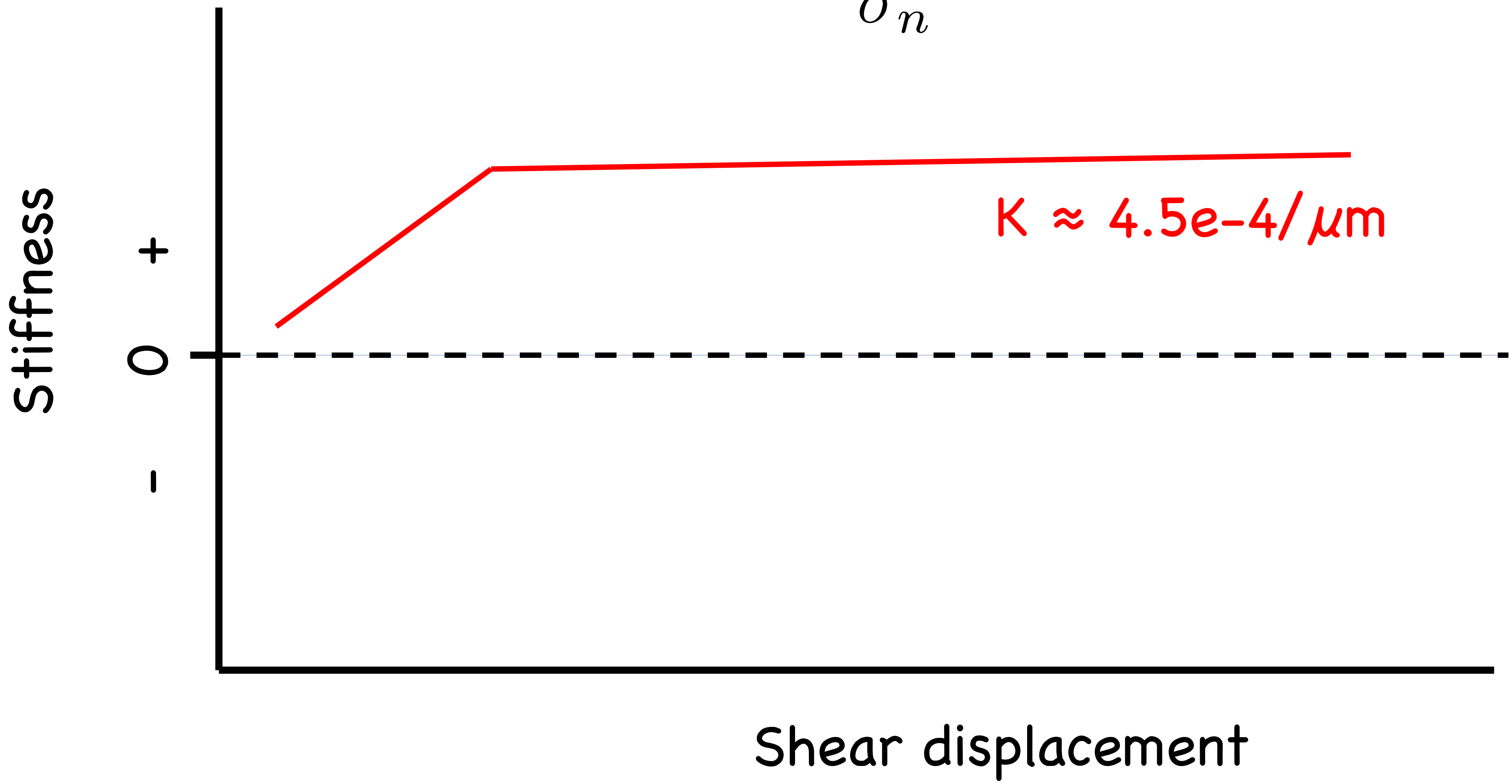
Figure S6. The effective stiffness of each stick-slip event at a given normal stress as a function of displacement. Notice the quick rise once events begin and asymptotic approach of a final steady-state value.



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

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





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

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

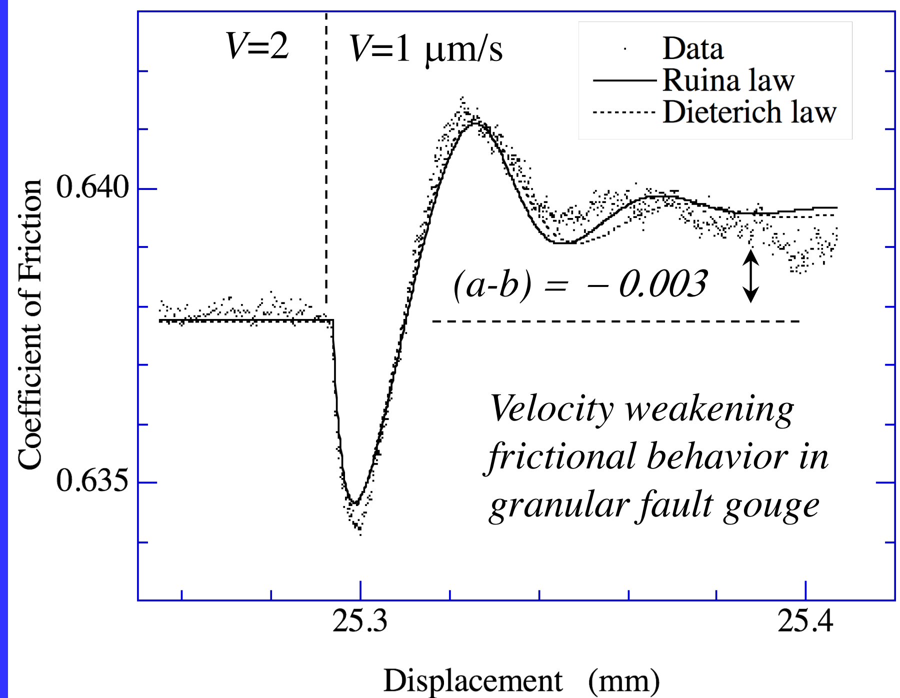
$$\theta_{ss} = \frac{D_c}{v}$$

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

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

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

Empirical laws, based on laboratory friction data

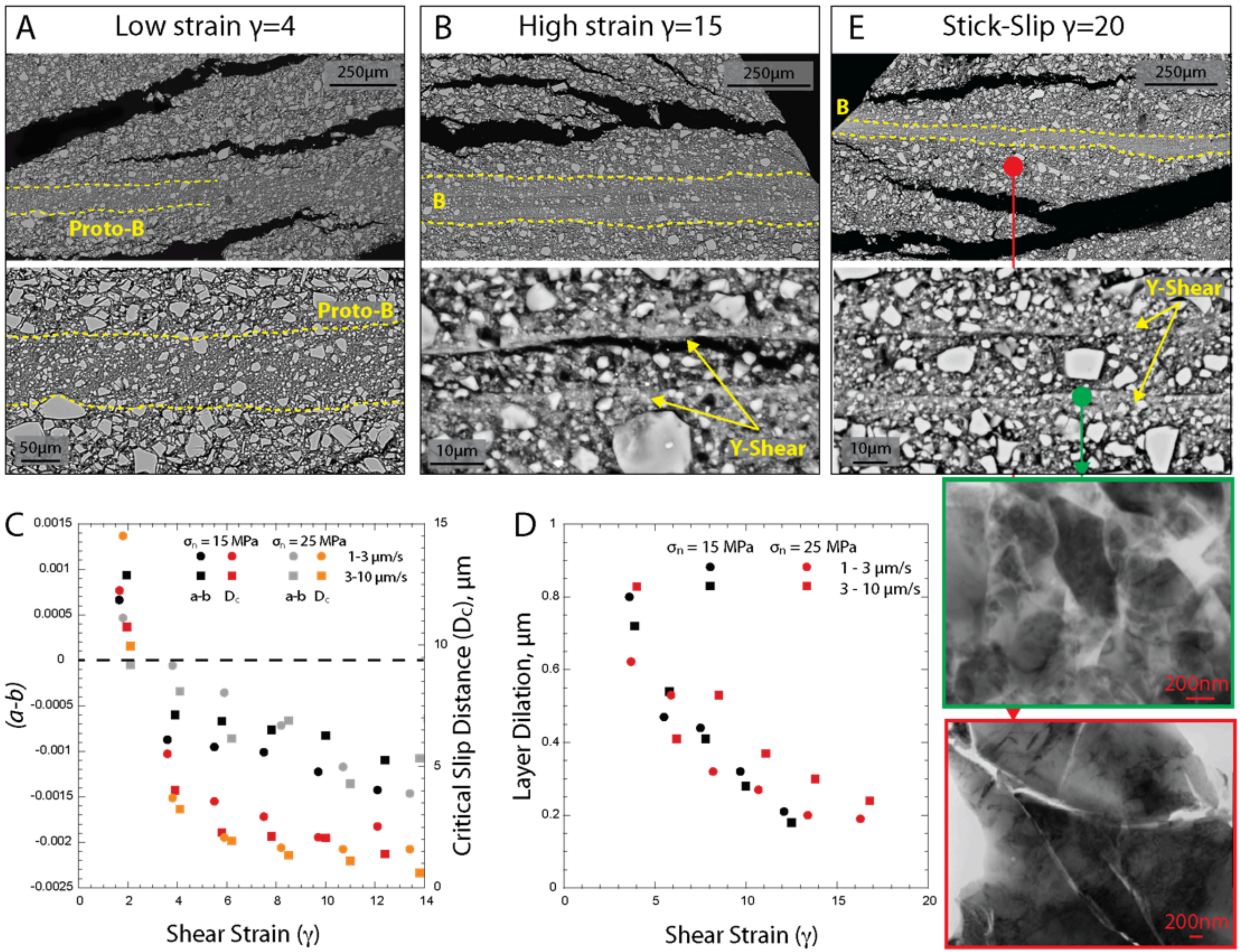


Thermally-activated process

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

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

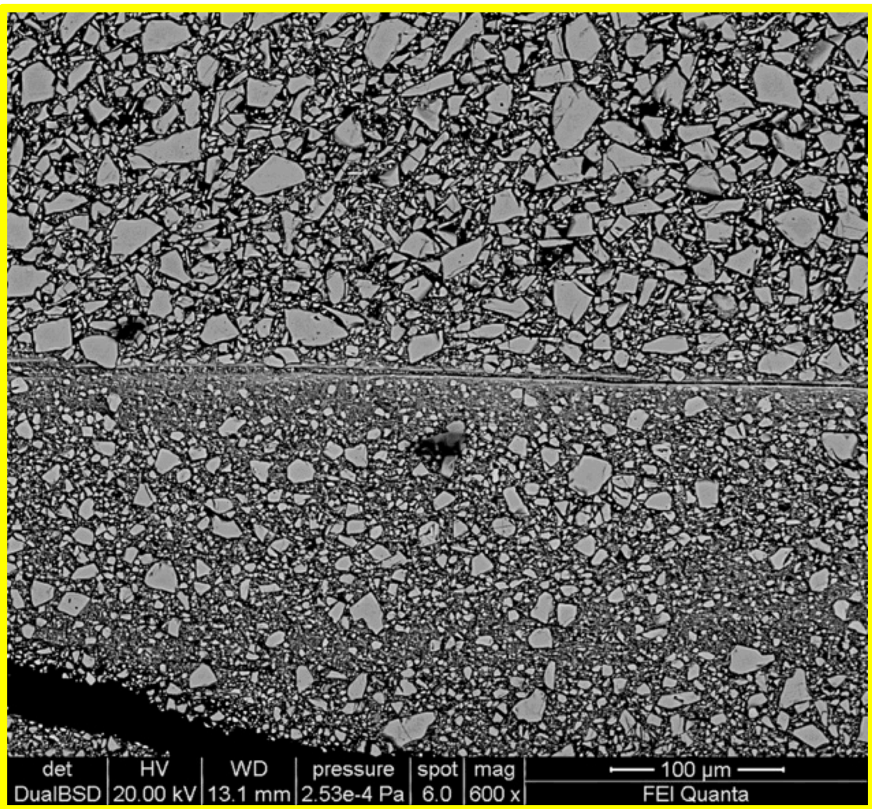
Fault Zone Microstructure

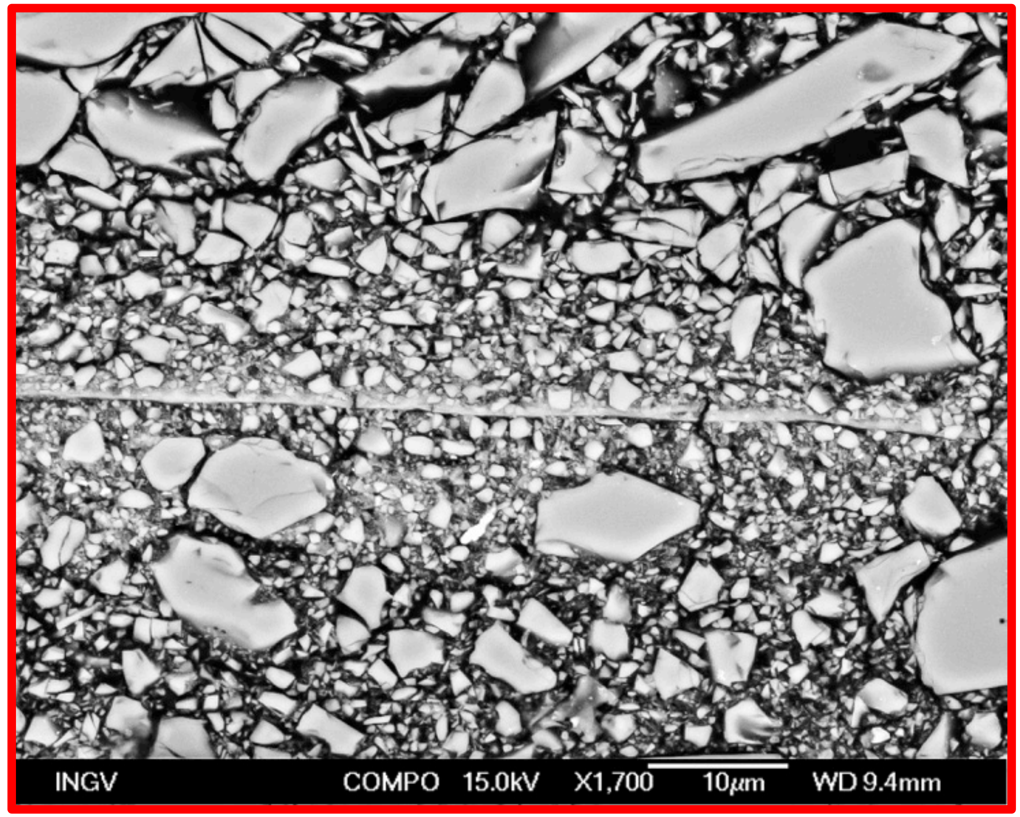


Scuderi, Viti, Tinti, Collettini, and Marone, *Geology*, 2017

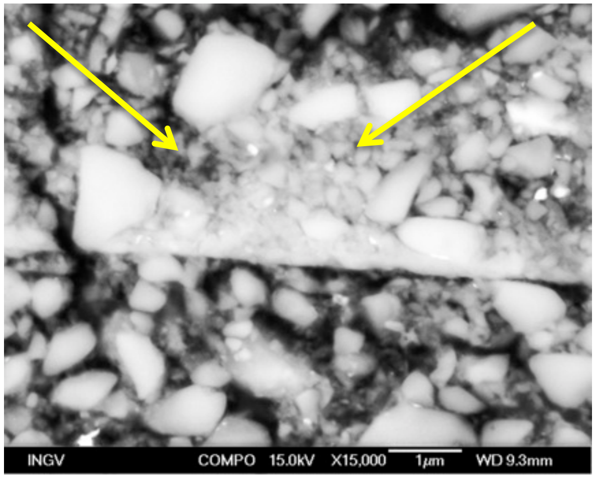
Fault Zone Microstructures

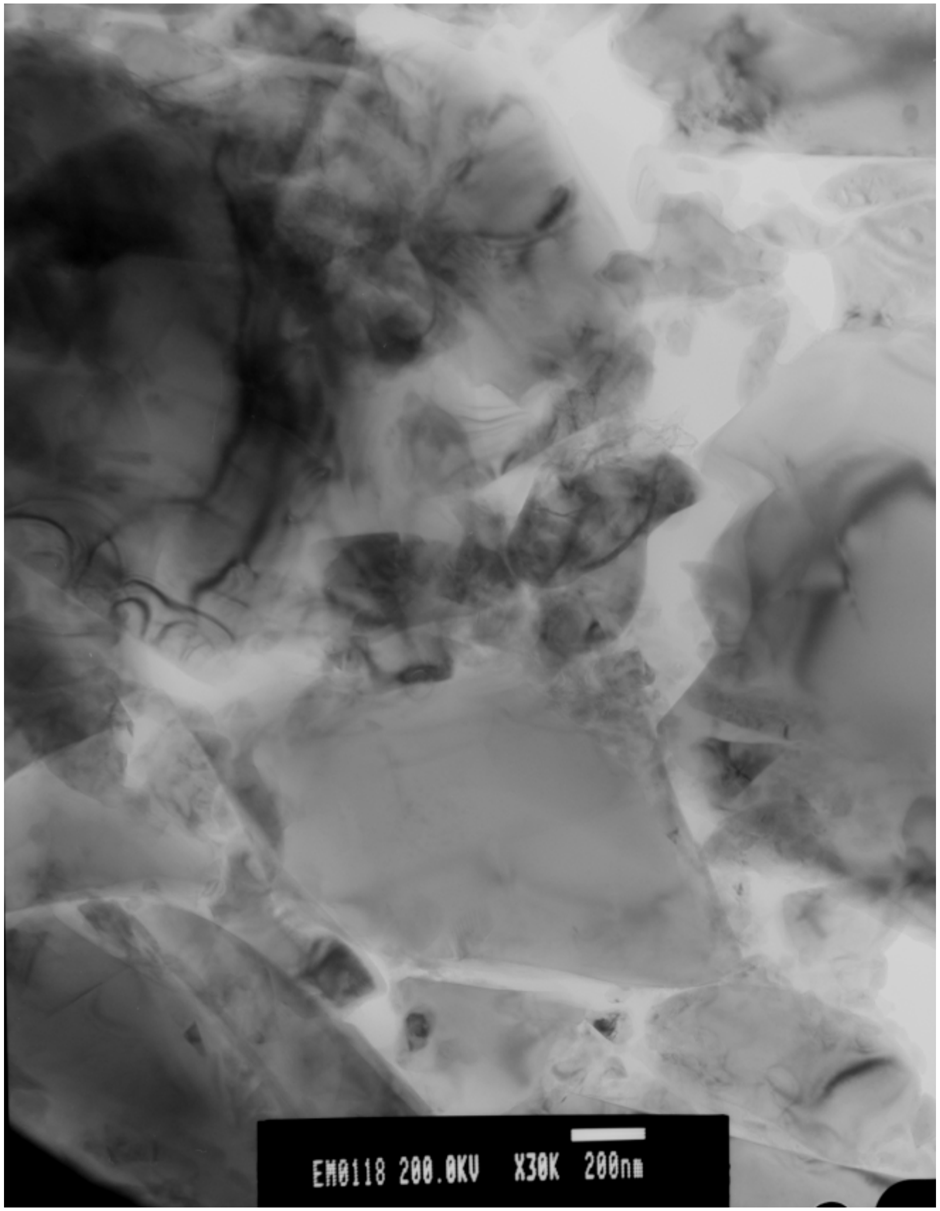
- Fault zone microstructure and shear fabric has a clear signature in friction constitutive properties.
- As shear localizes the fault zone becomes more unstable.

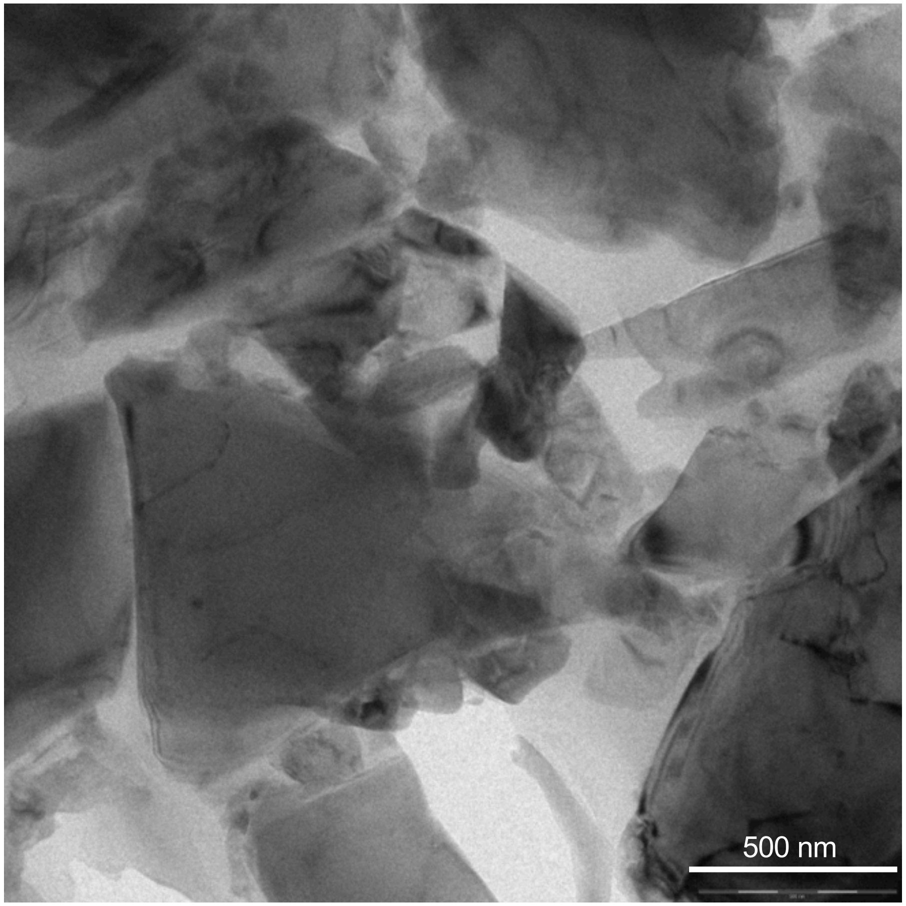




Stick & slip: nano-structures NEAR the slipping plane.
Some fractured Q grains (1 μm-300 nm) with sharp grain-boundaries. Dislocations with sub-grains development.

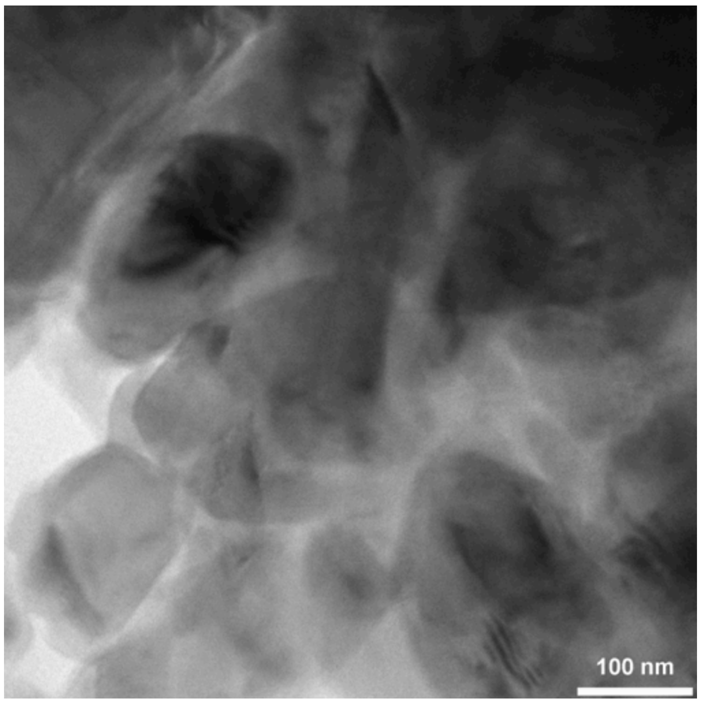


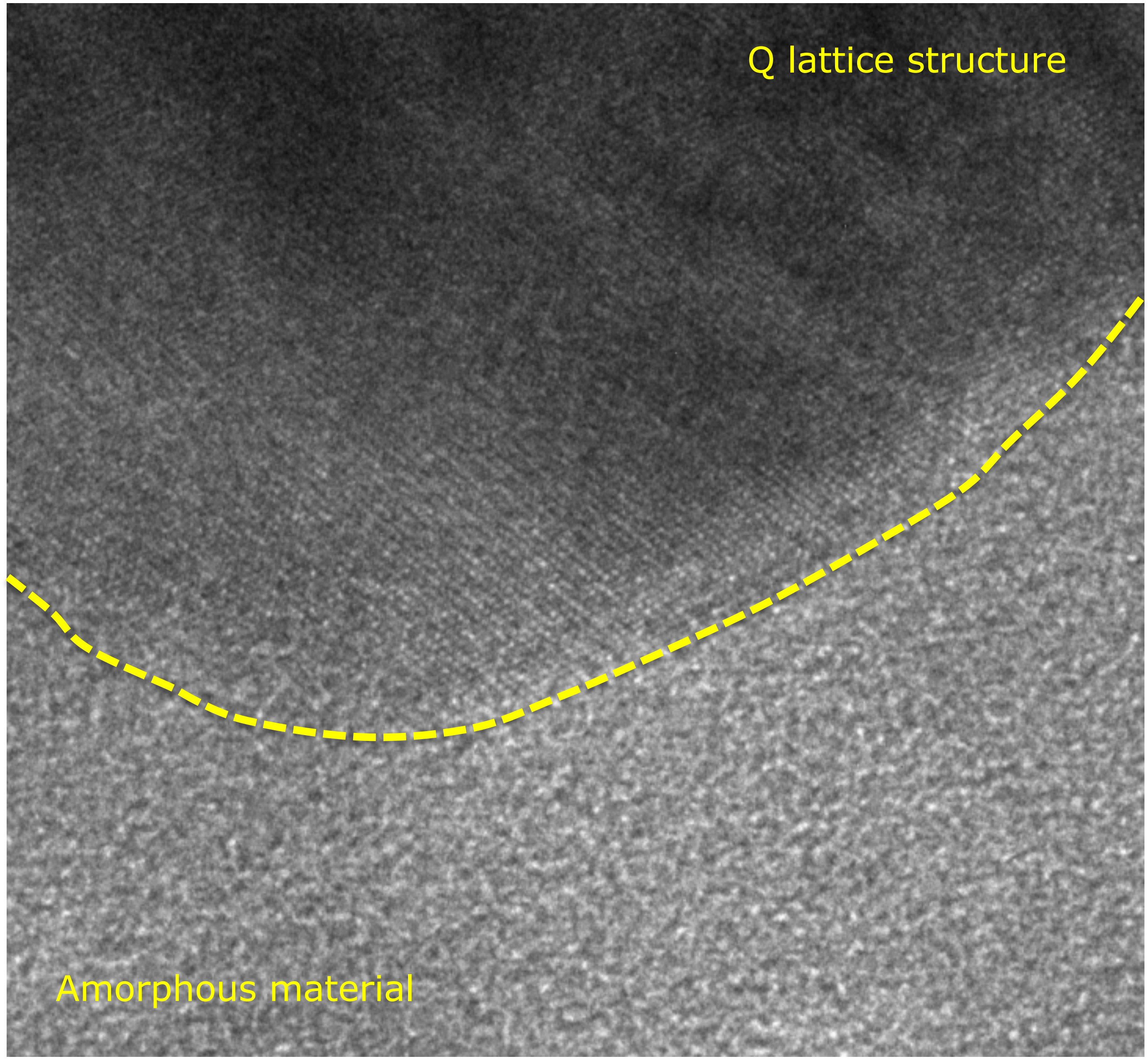


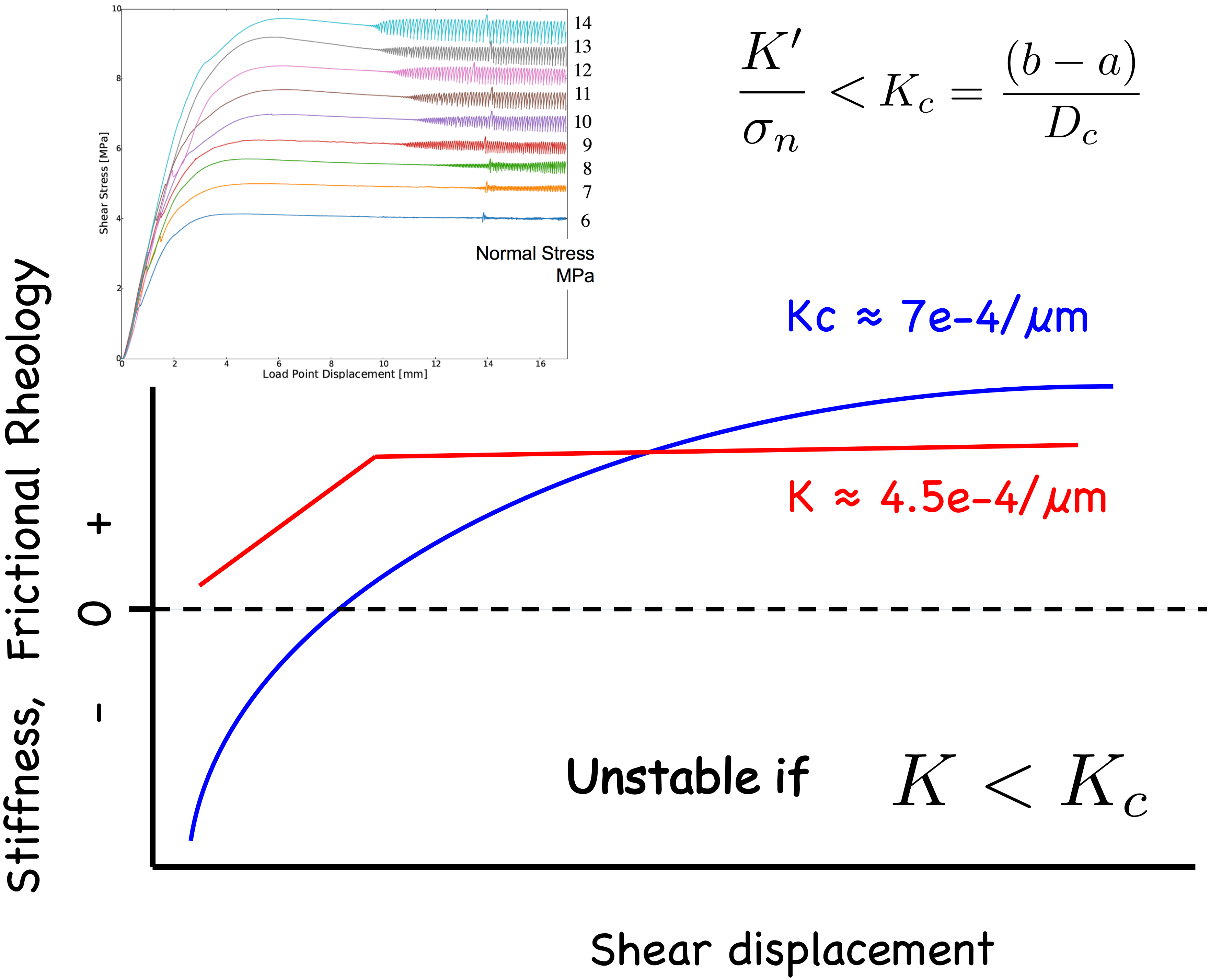


Stick & slip: nano-structures INTO the slipping plane.

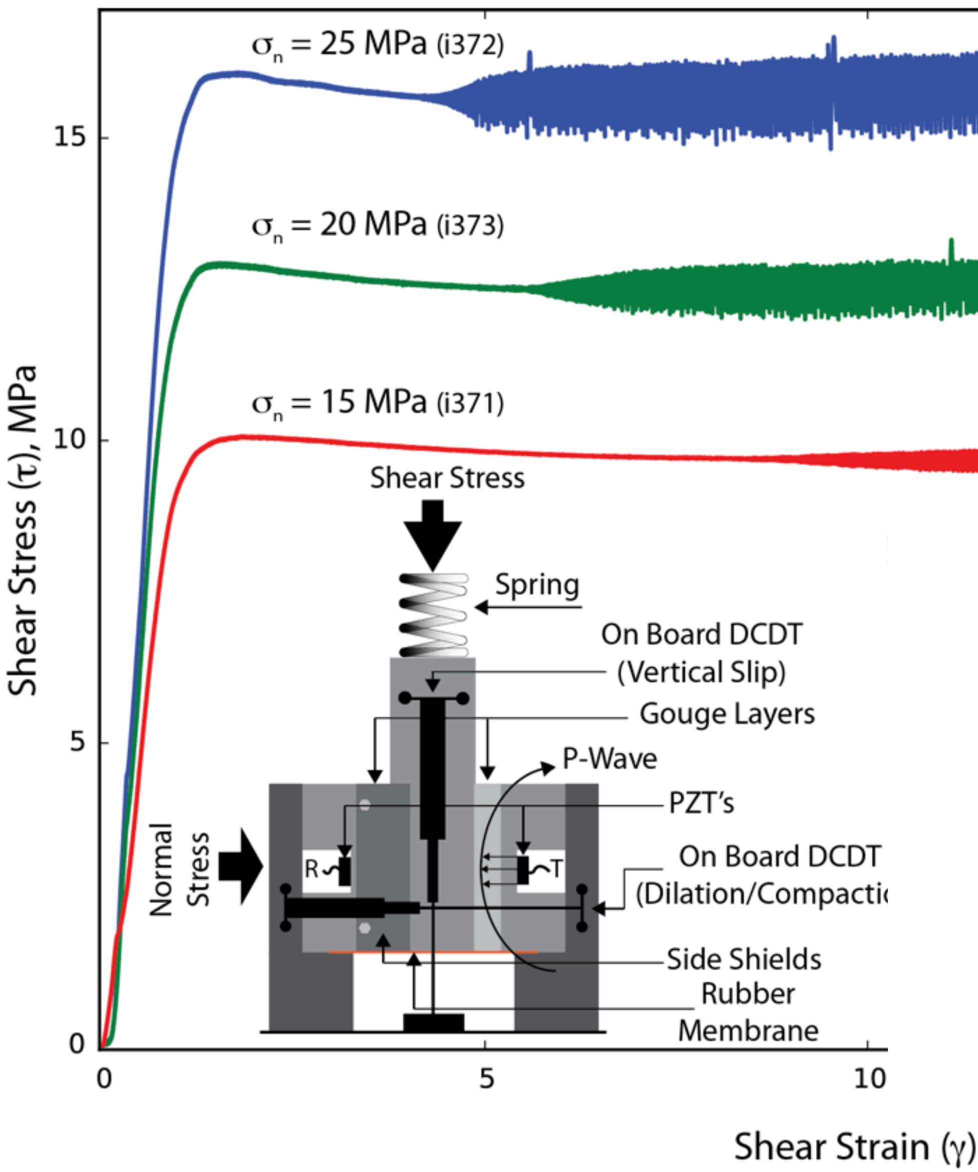
Smaller grains surrounded by an amorphous film.

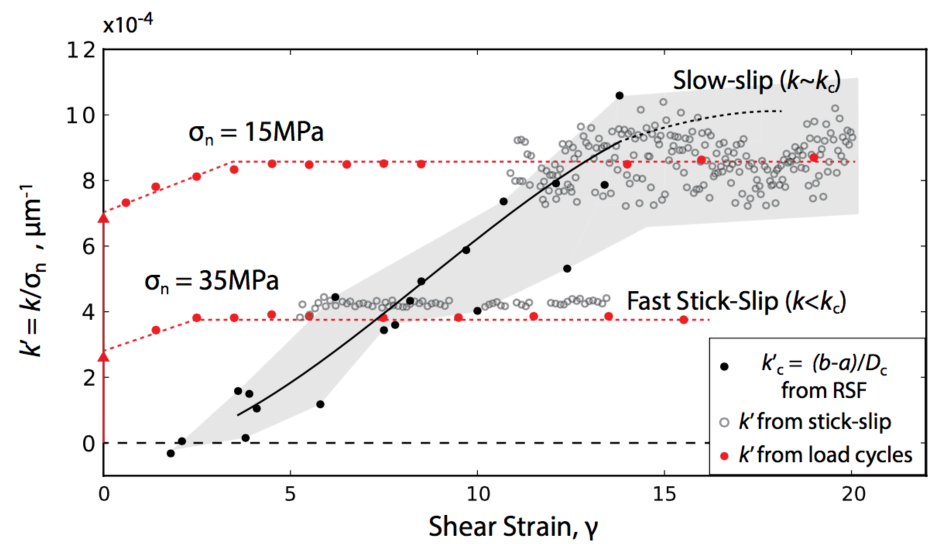





$$\frac{K'}{\sigma_n} < K_c = \frac{(b-a)}{D_c}$$
Shear Stress [MPa]
Load Point Displacement [mm]
14
13
12
11
10
9
8
7
6
Normal Stress
MPa
Kc ≈ 7e-4/μm
K ≈ 4.5e-4/μm
Stiffness, Frictional Rheology
+
0
-
Unstable if $K < K_c$
Shear displacement

Repetitive Slow Stick-Slip





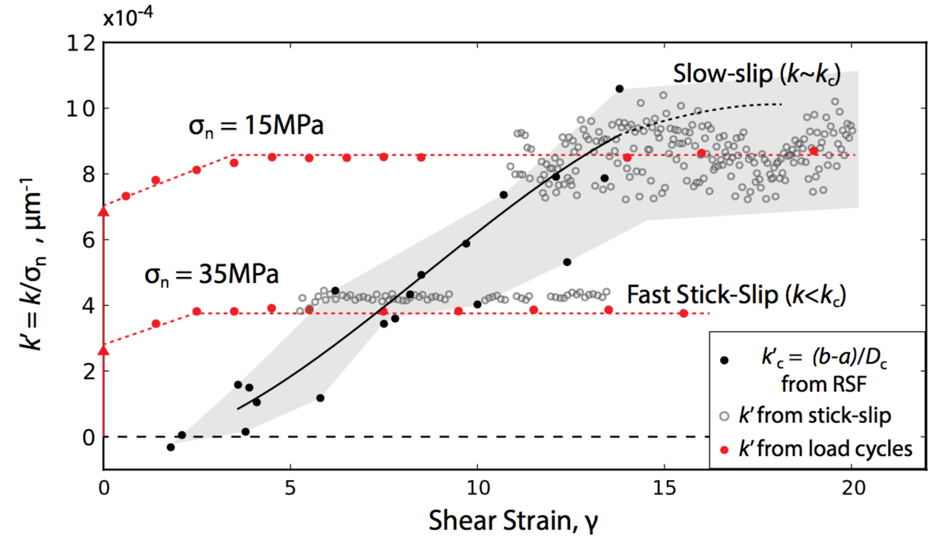
Scuderi et al., *Geology*, 2017

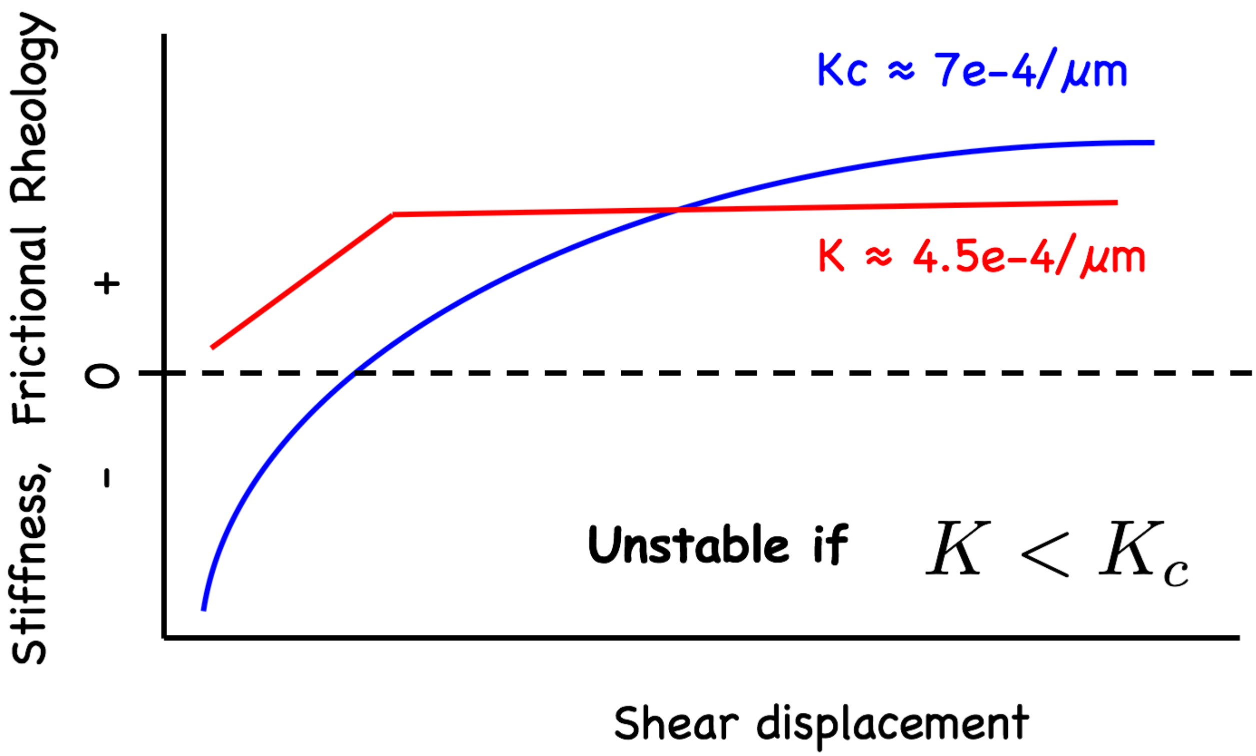
$$\frac{K'}{\sigma_n} < K_c = \frac{(b-a)}{D_c}$$

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

Control Parameters

Rheology (weakening rate)

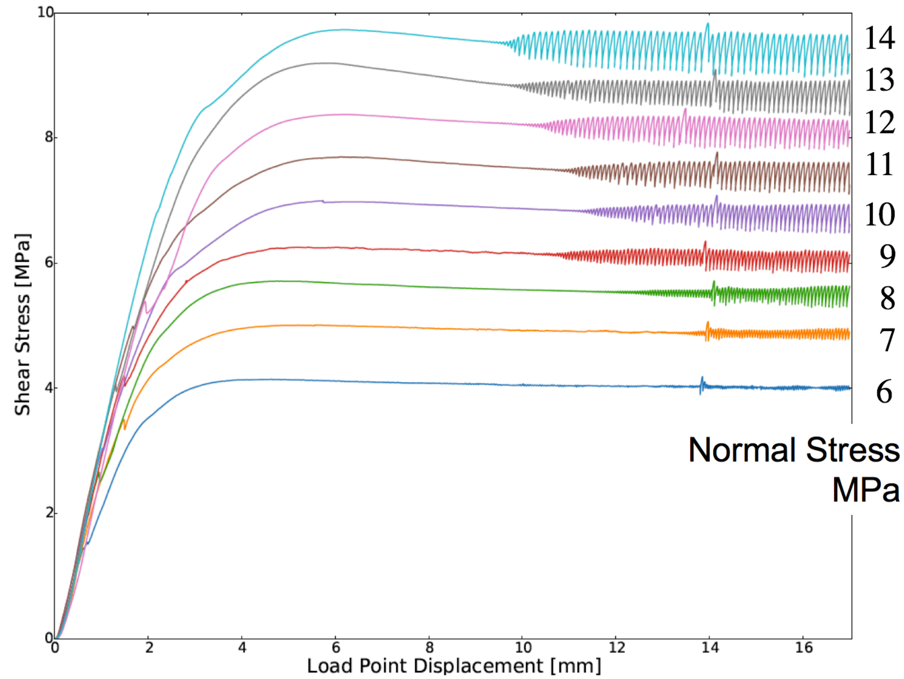


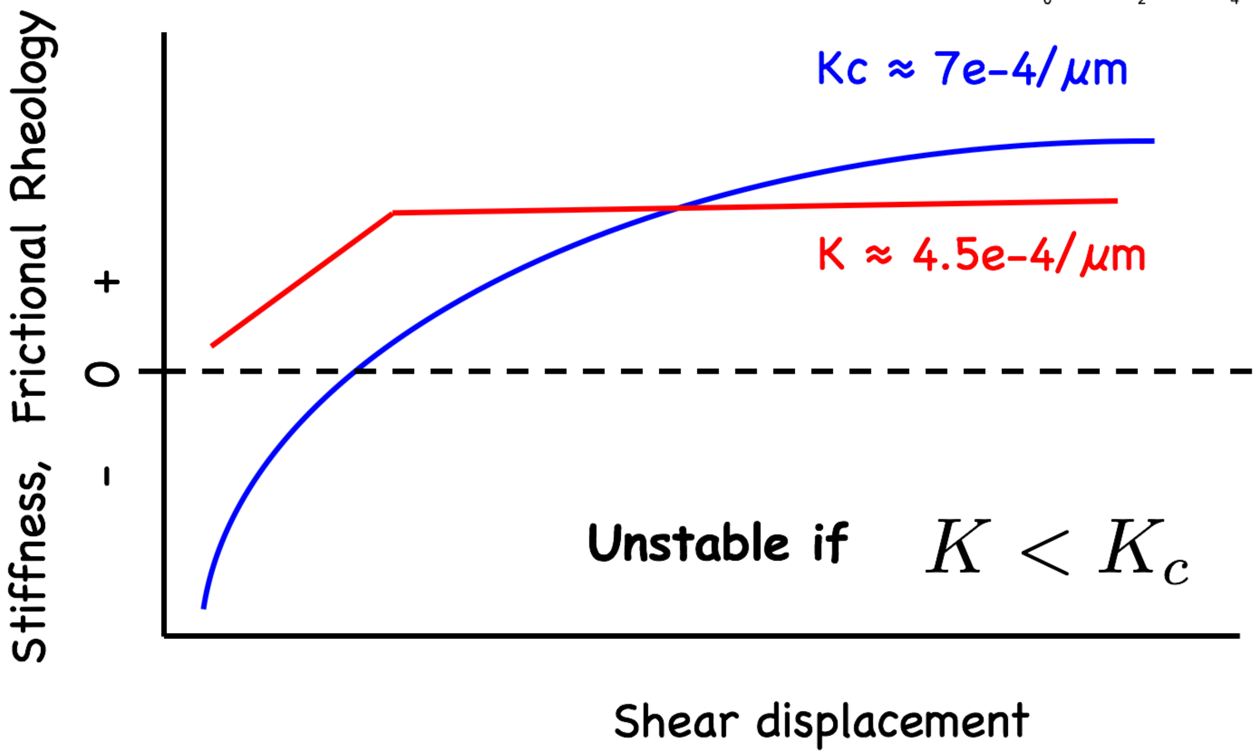


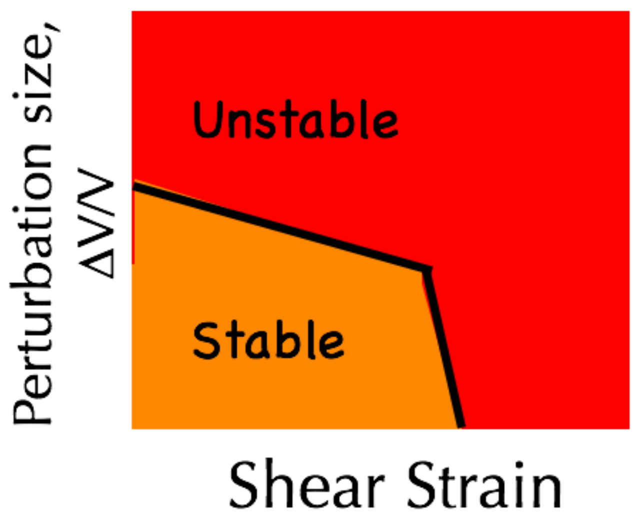
$$\boxed{\frac{K'}{\sigma_n}} < K_c = \boxed{\frac{(b-a)}{D_c}}$$

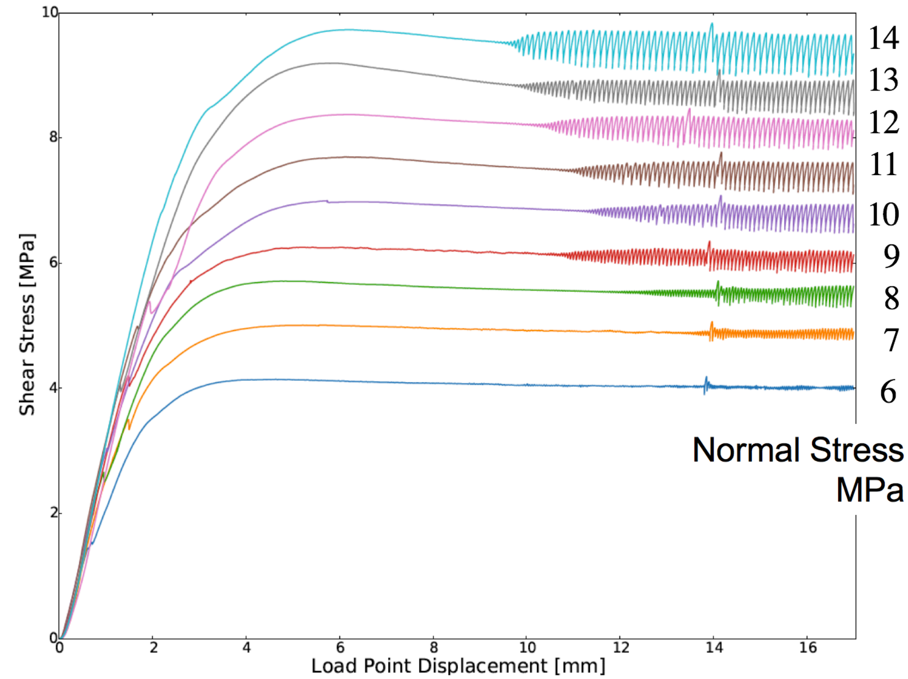
Control Parameters

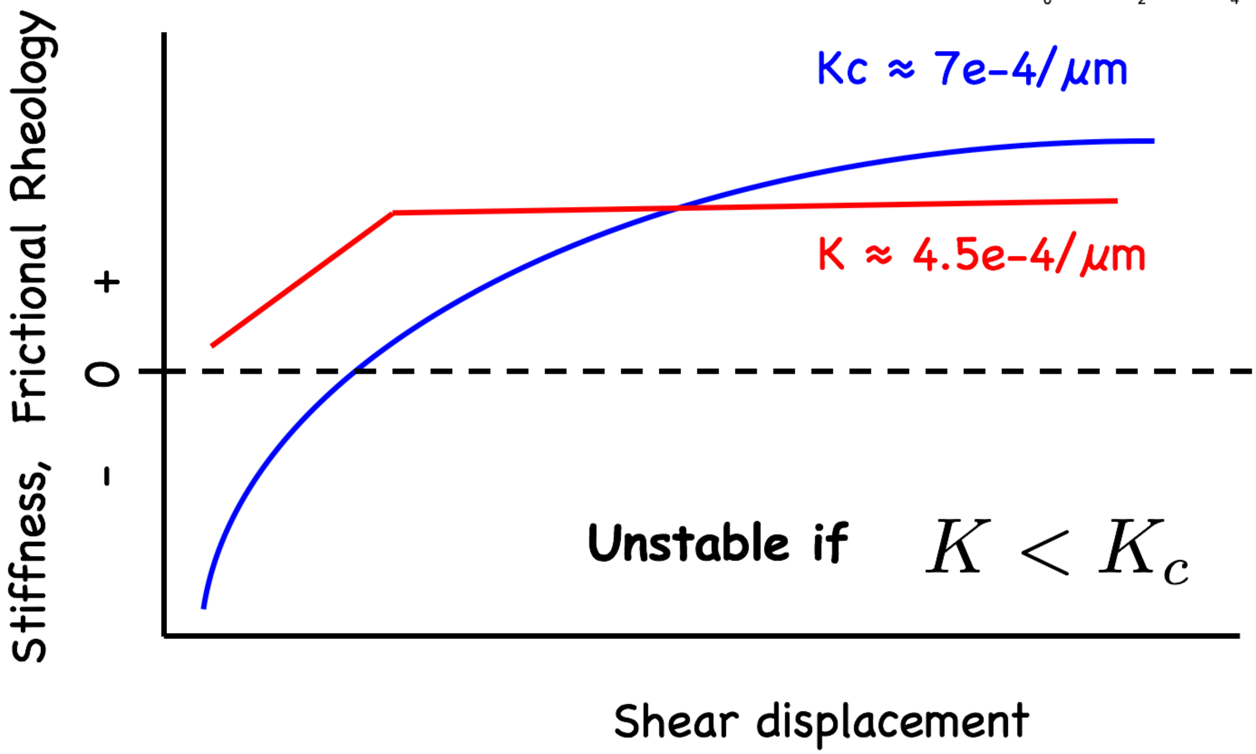
Rheology (weakening rate)






Perturbation size, ΔV/V
Unstable
Stable
Shear Strain


Shear Stress [MPa]
Load Point Displacement [mm]
14
13
12
11
10
9
8
7
6
Normal Stress
MPa

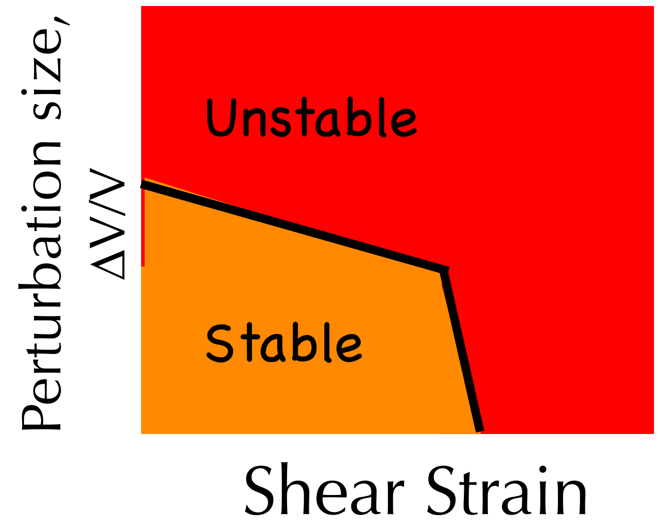

Kc ≈ 7e-4/μm
K ≈ 4.5e-4/μm
Stiffness, Frictional Rheology
+
0
-
Unstable if $K < K_c$
Shear displacement

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

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

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

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



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

$$K_c(V, \gamma)$$

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

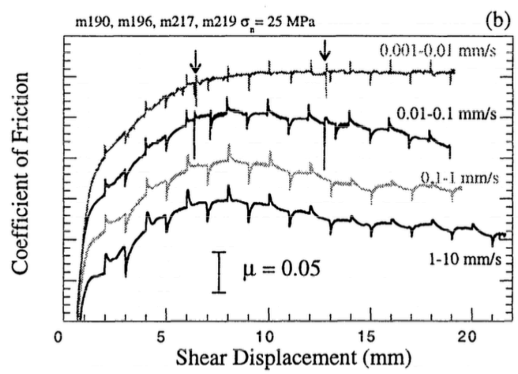


Figure 3. (a) Coefficient of friction and layer thickness as a function of shear displacement for a "fast" velocity test carried out at 1-10 mm/s and σ_n = 25 MPa. The velocity steps are indicated by dashed lines, and alpha is shown schematically. (b) Friction as a function of shear displacement for 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-

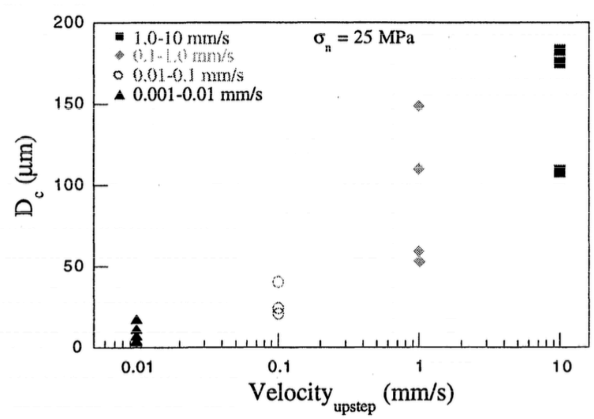
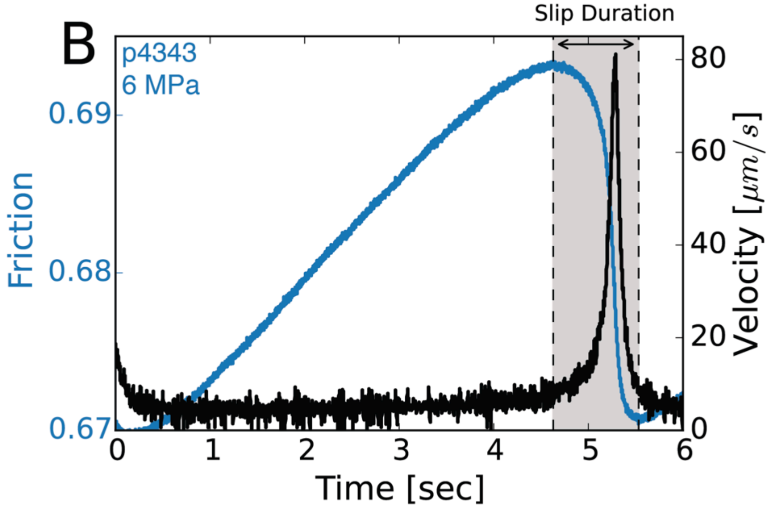
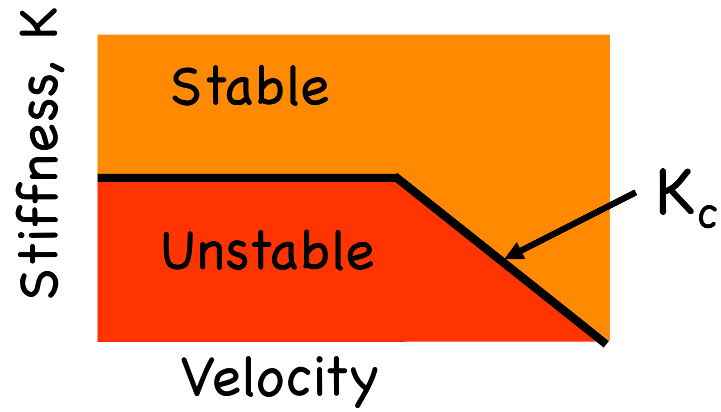
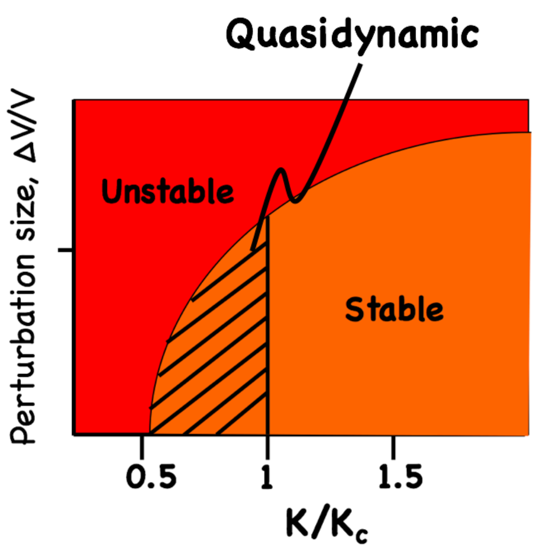


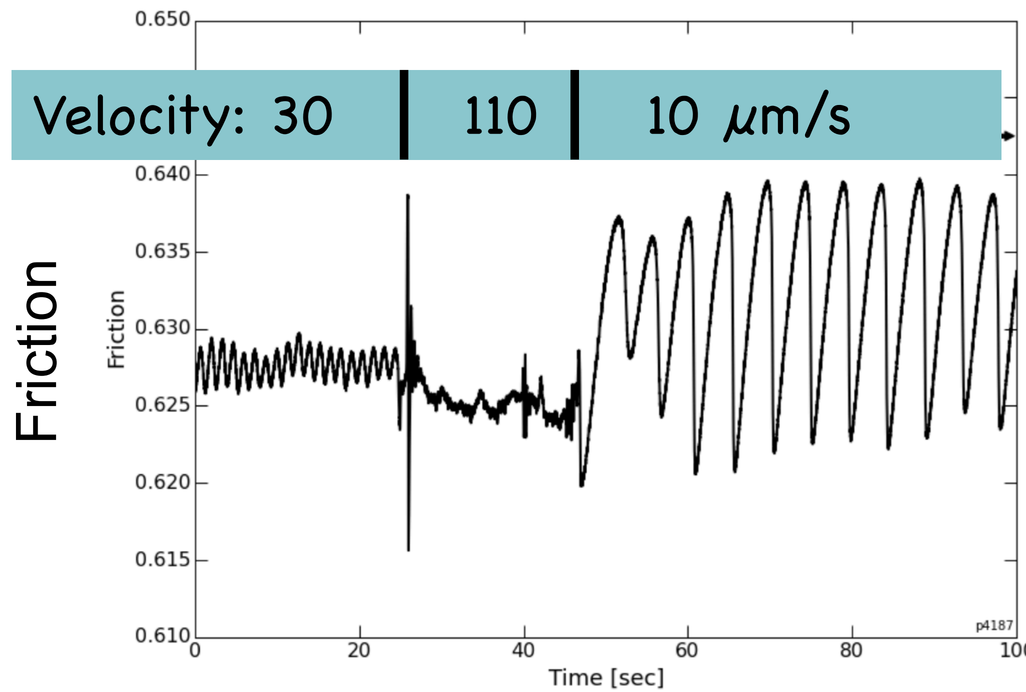
Figure 4. Critical slip displacement (D_c) as a function of upstep velocity for a range of experiments at σ_n = 25 MPa. D_c is systematically larger as a function of increasing velocity.





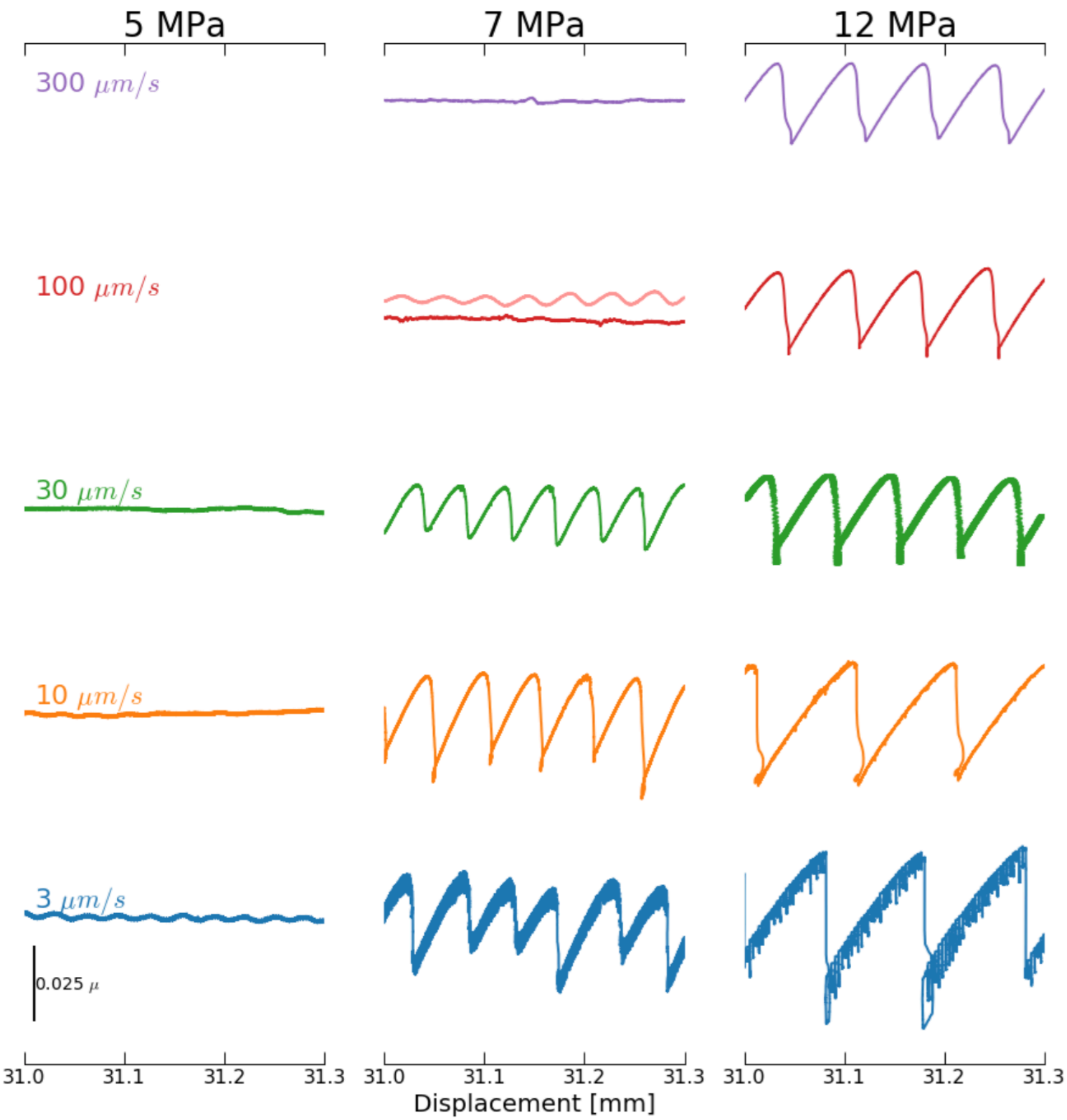


Gu et al., 1984



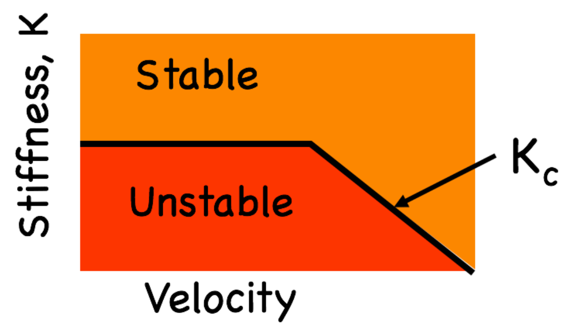
Leeman, Marone & Saffer *JGR*, 2018

Slow Slip

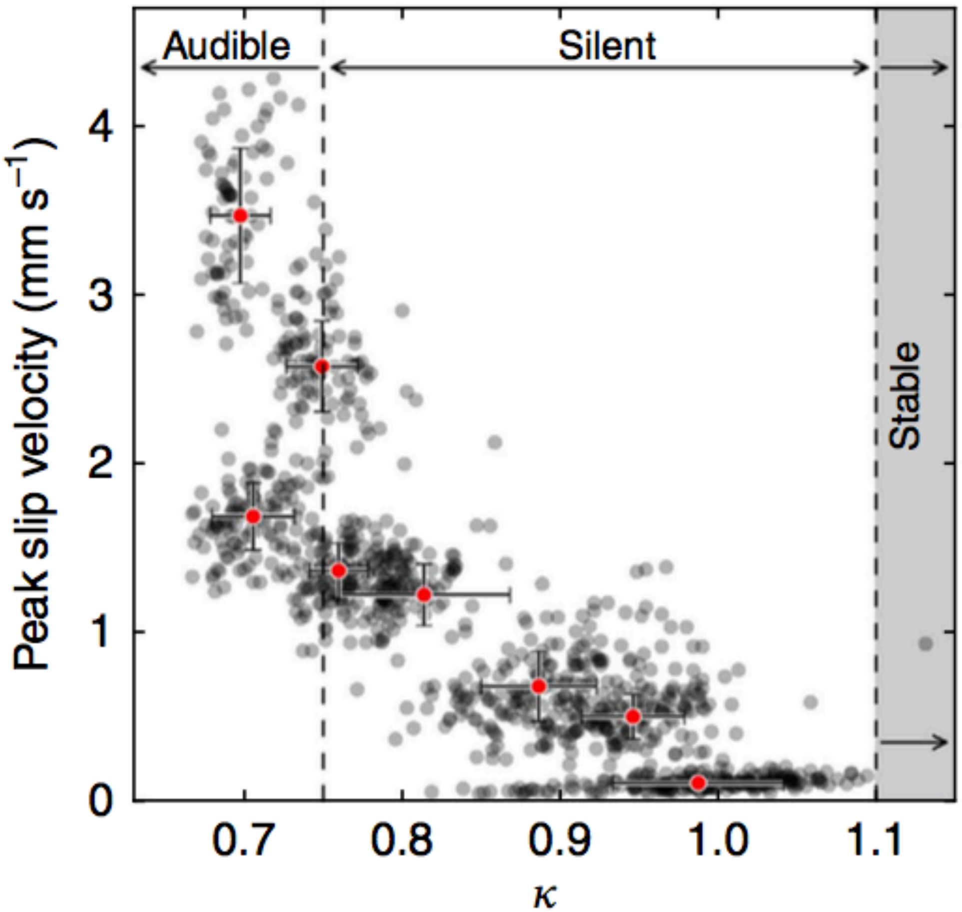


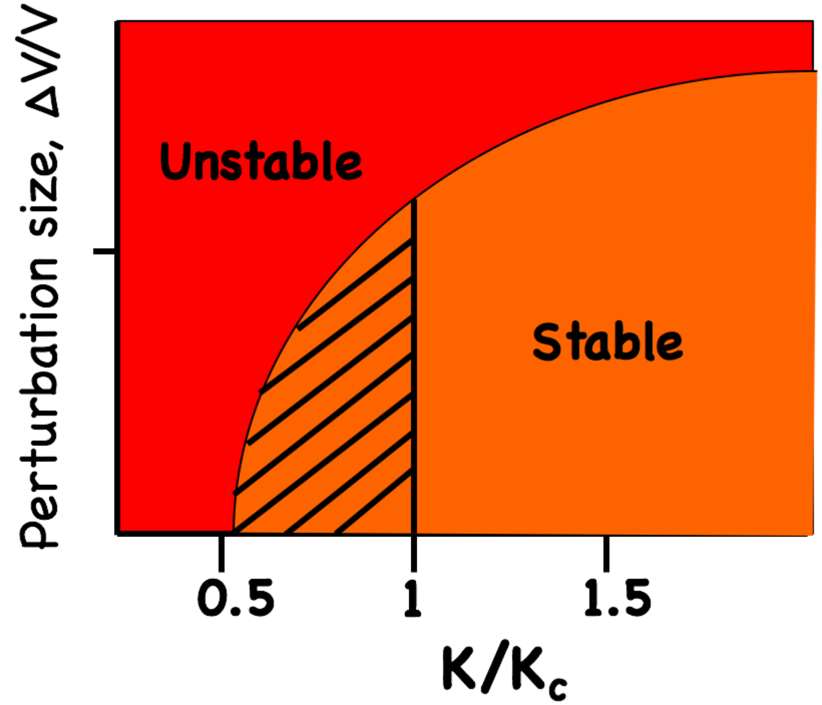
Kc is a function of slip velocity, normal stress, and the friction parameters

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



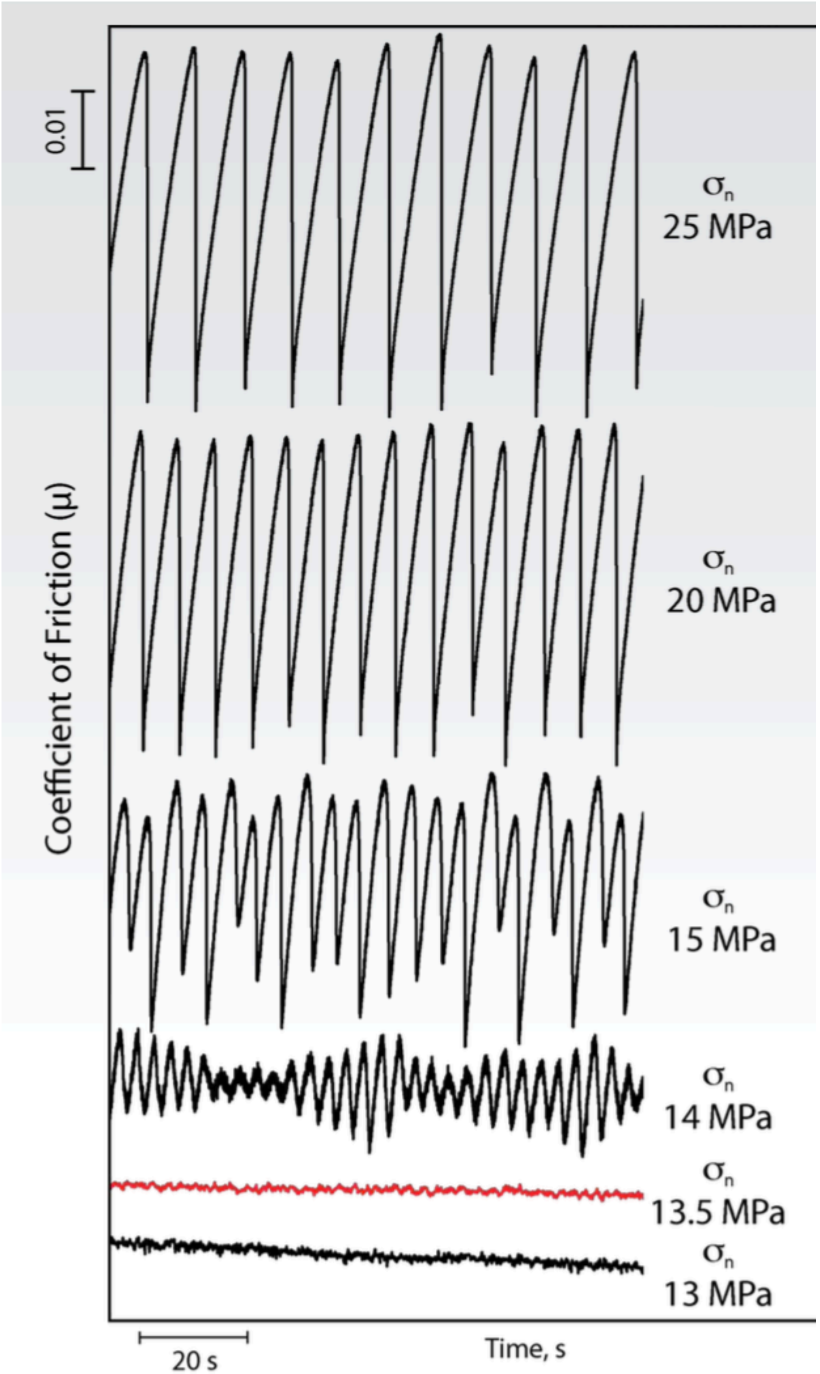
Leeman, Marone & Saffer JGR, 2018





Unstable slip if

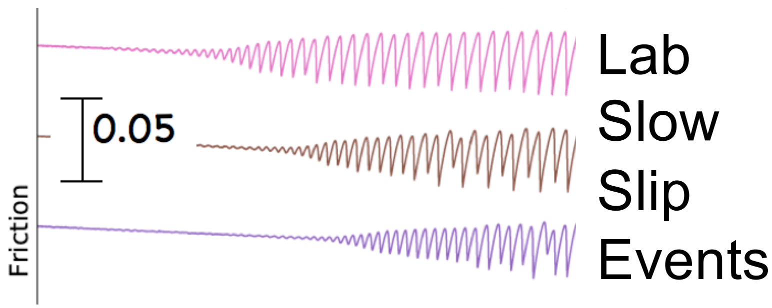
$$K < K_c \approx \frac{\sigma_n(b-a)}{D_c}$$

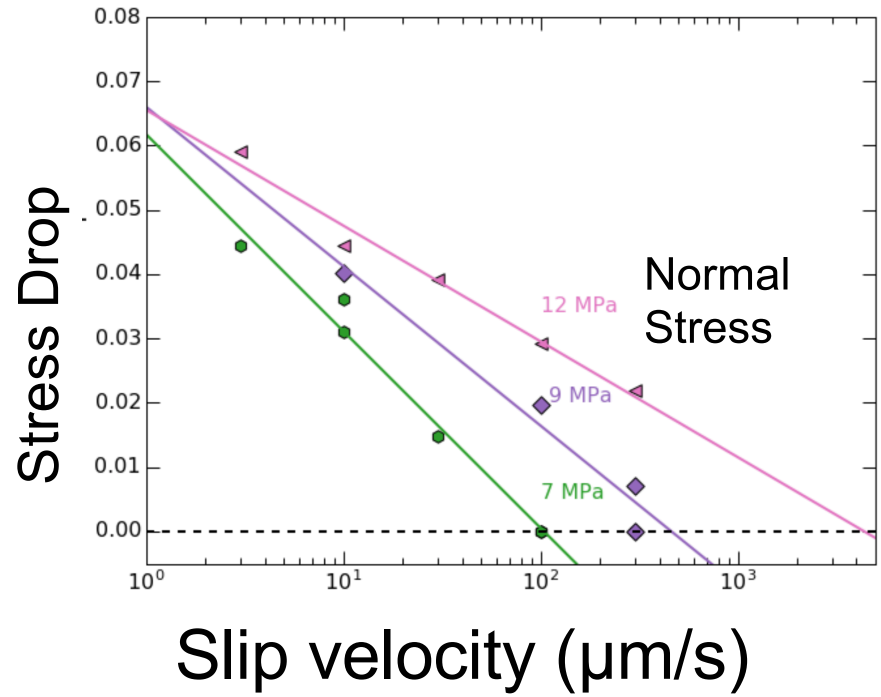


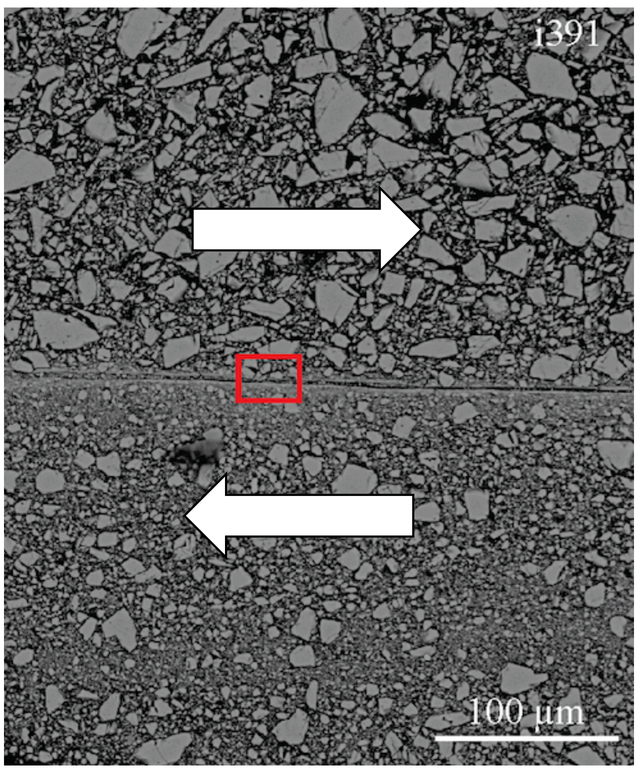
Period Doubling Near The Stability Boundary

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

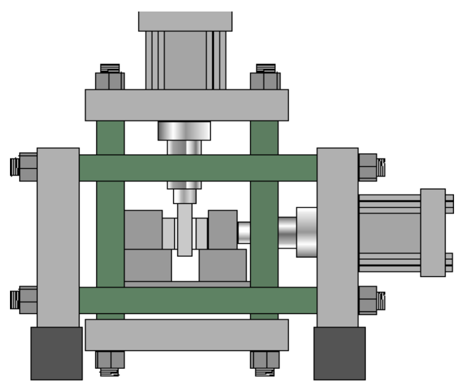
Slow Earthquakes --a view from the lab



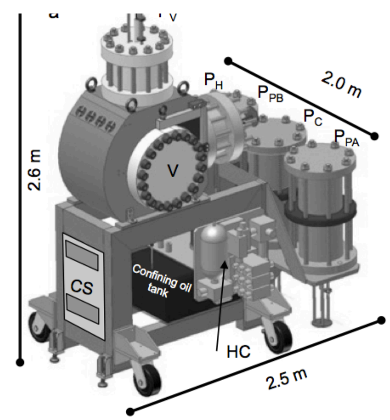




Penn State



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?*

   A. Quasi-dynamic frictional instability (positive feedback, self-driven instability)

   B. Rate dependence of the critical rheologic weakening rate, $K_c(V)$

   C. Fracture mechanics: energy release rate equals frictional weakening rate, stress drop is quasidynamic because the dynamic force imbalance is negligible