Mechanics of Earthquakes and Faulting

Lecture 16 , 25 Mar. 2021

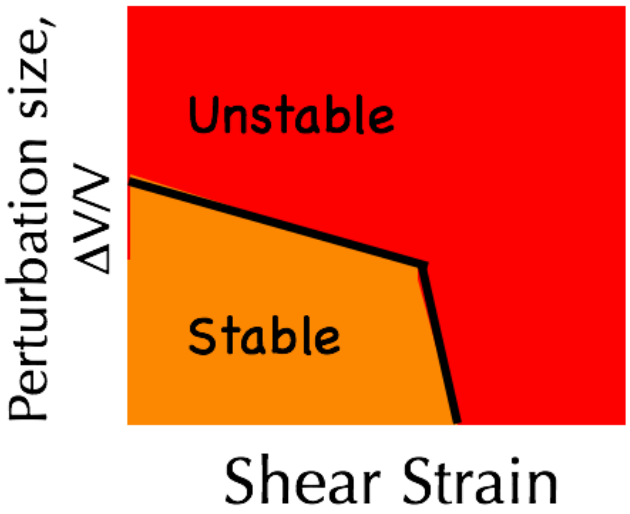
www.geosc.psu.edu/Courses/Geosc508

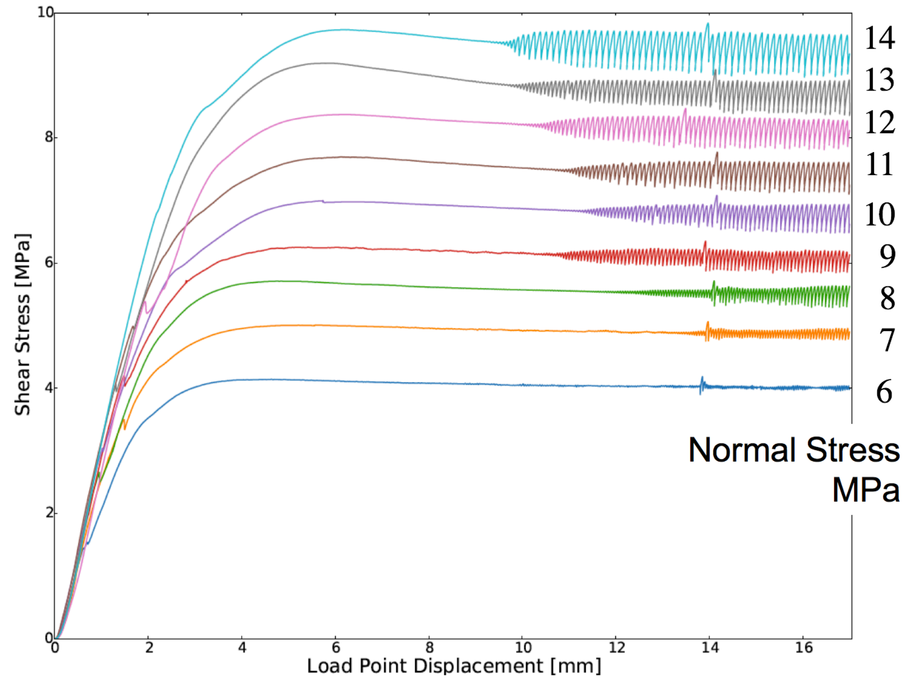
- Slow earthquakes and the opportunity to further investigate the application of rate state friction laws to instability.

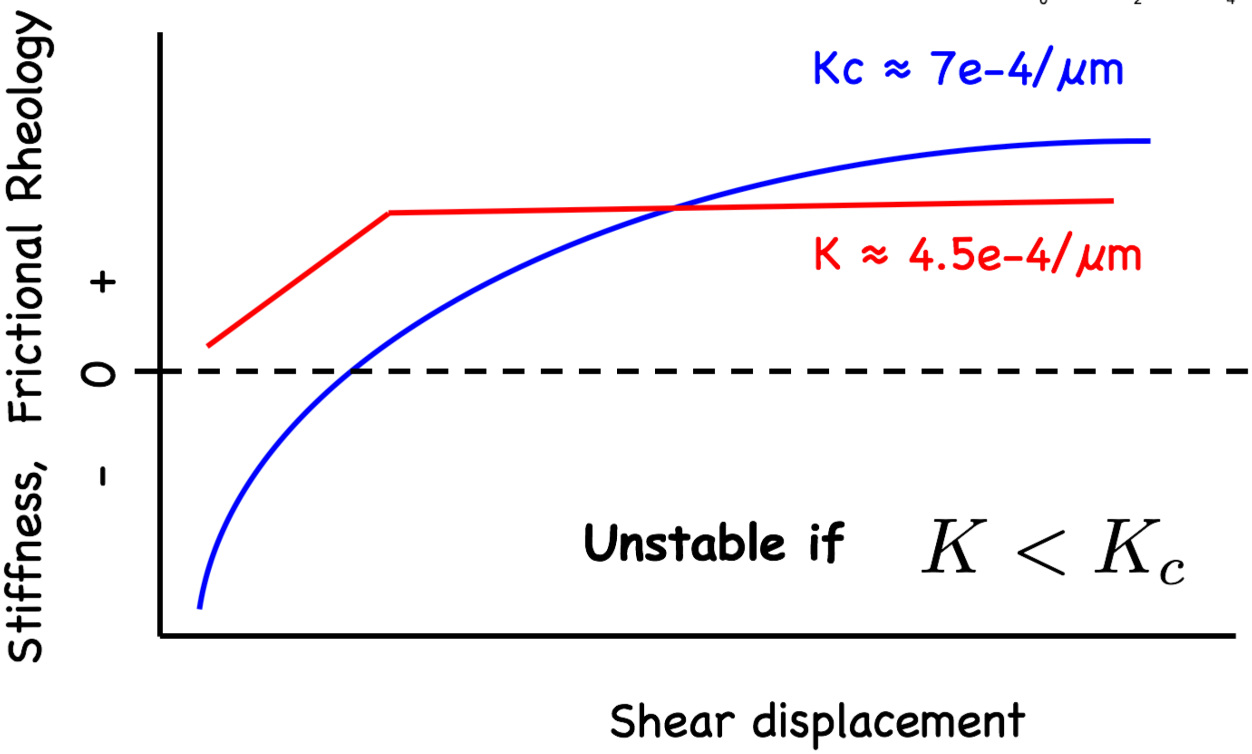
- Mechanisms: Why are they slow?

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

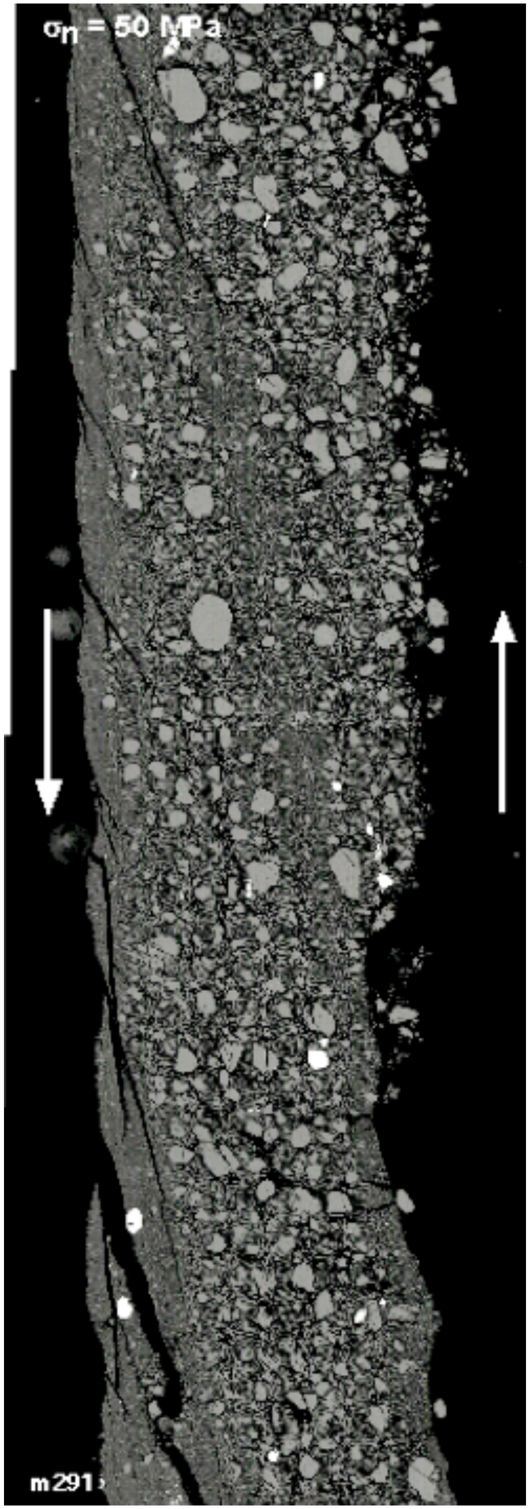
- Precursory changes in fault zone (elastic) properties prior to failure for the spectrum of fault slip rates

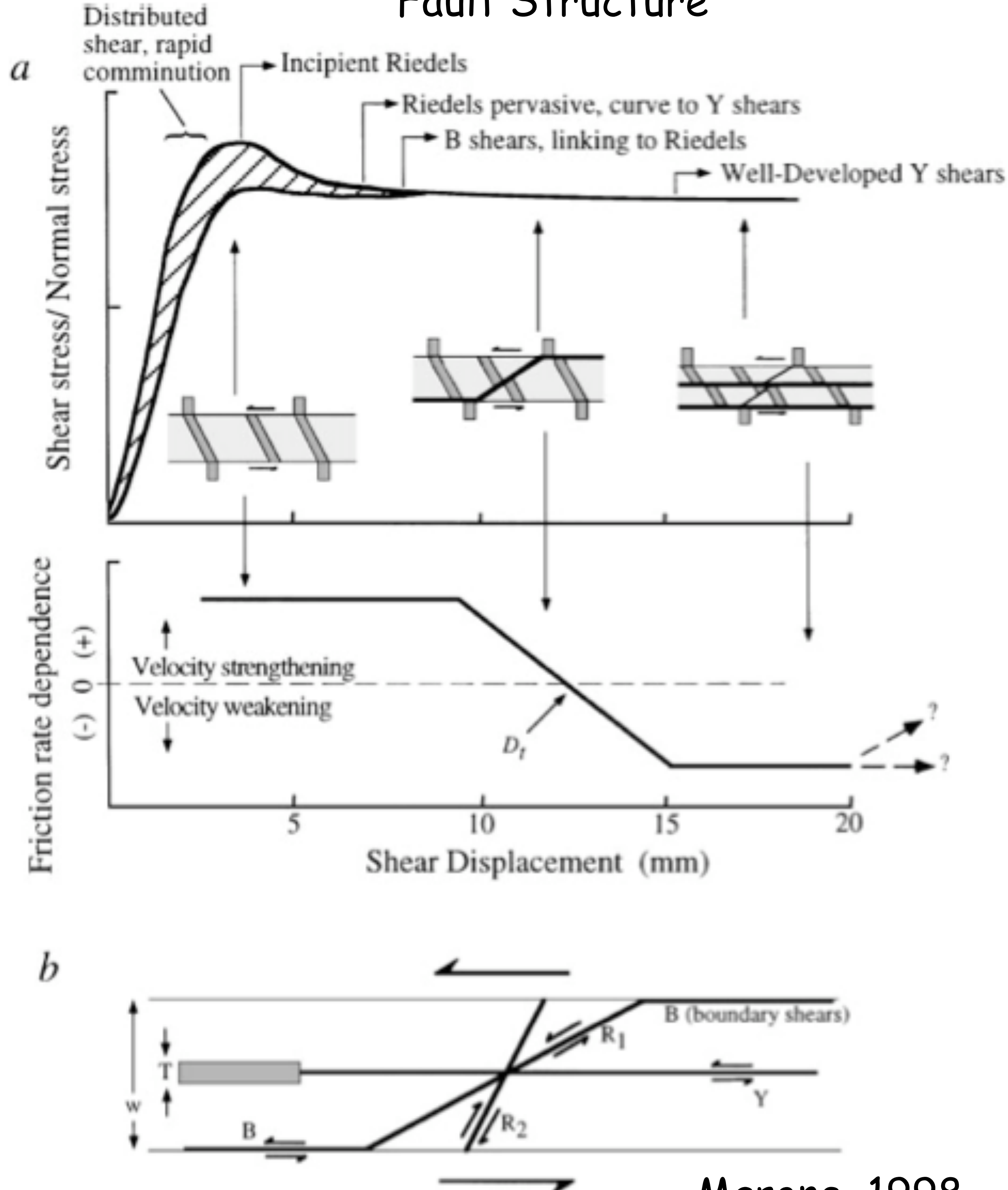

Unstable
Stable
Perturbation size, ΔV/V
Shear Strain


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

Fault Structure





Marone, 1998

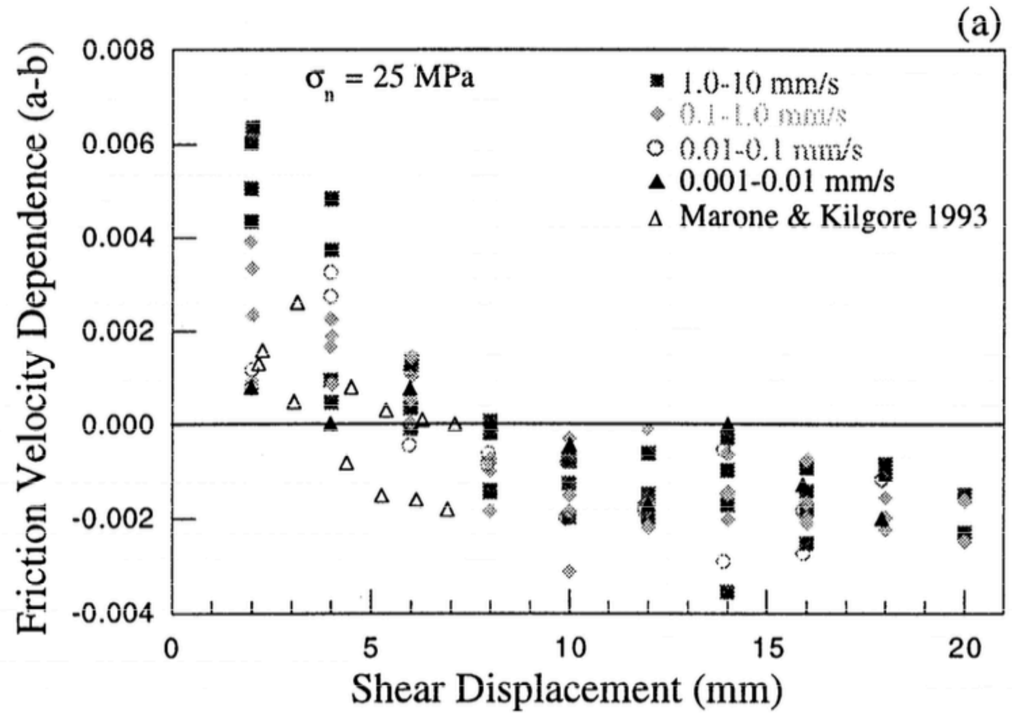
Frictional Sliding: Stability transition depends on strain (shear displacement) and slip velocity)

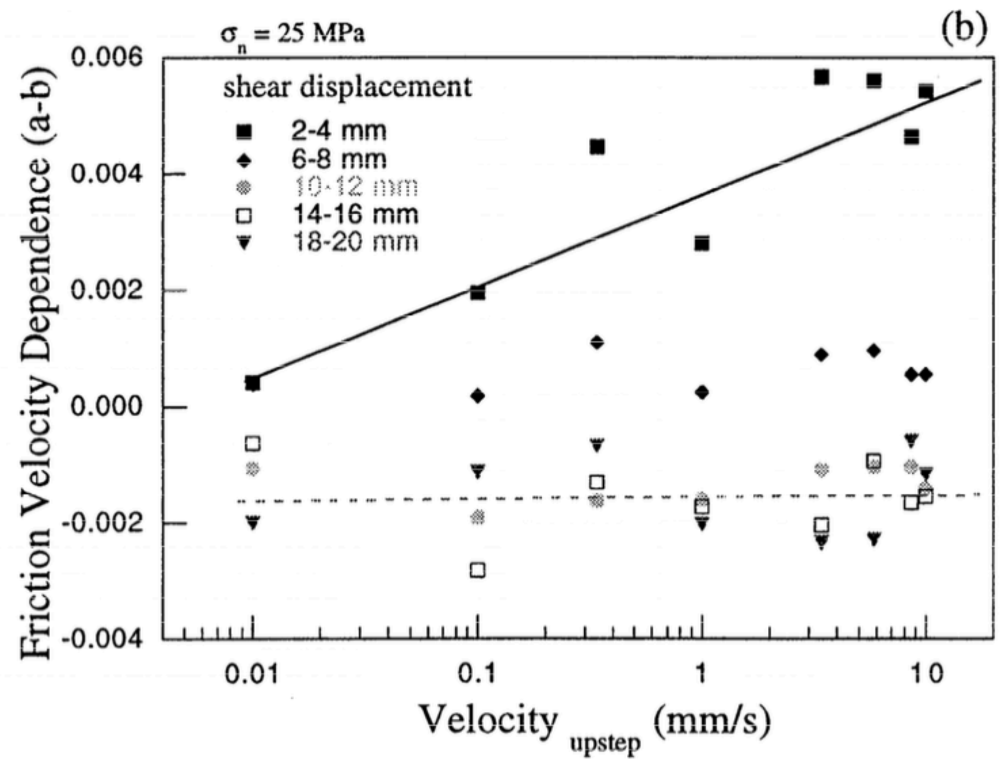
JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 104, NO. B12, PAGES 28,899–28,914, DECEMBER 10, 1999

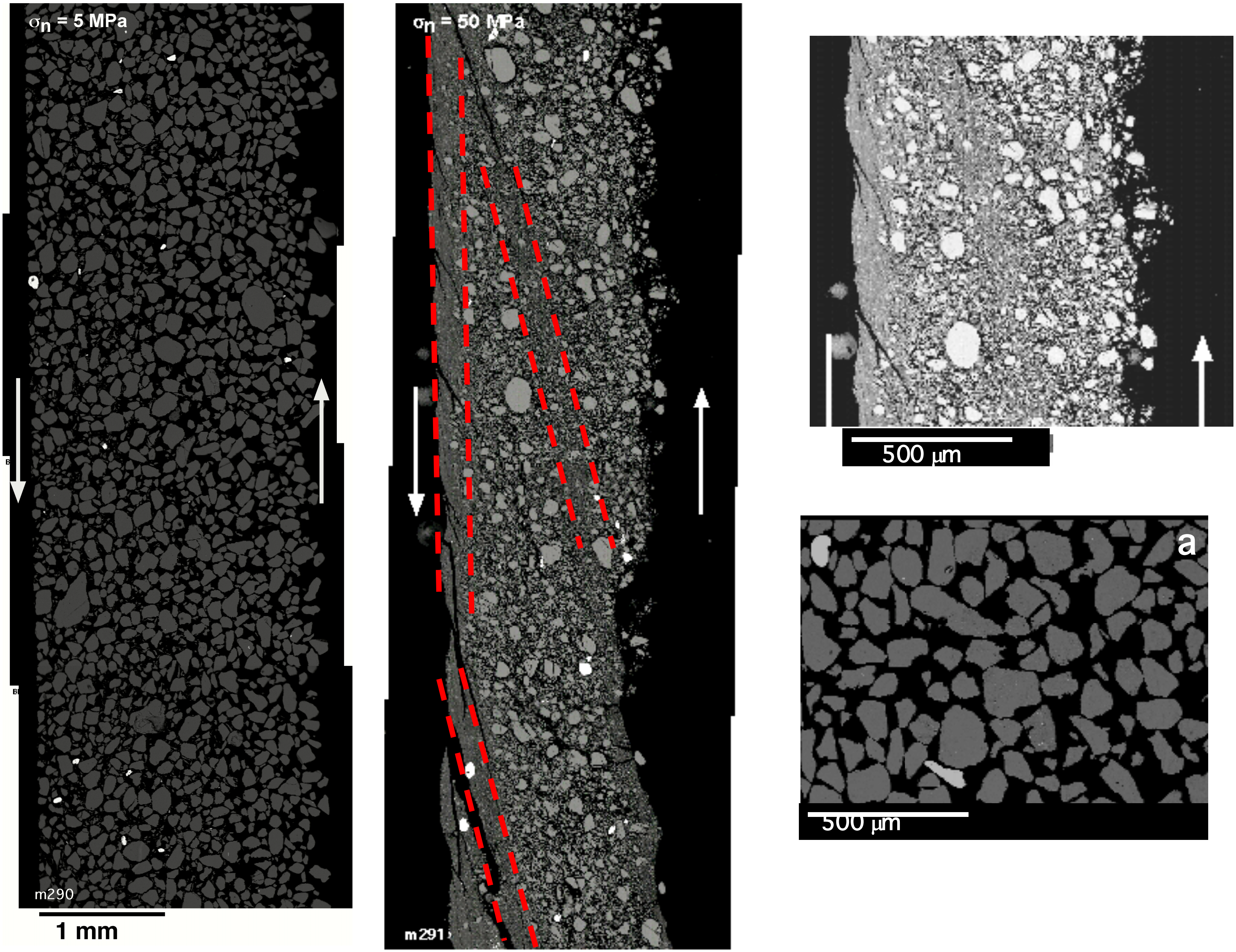
Friction of simulated fault gouge for a wide range of velocities and normal stresses

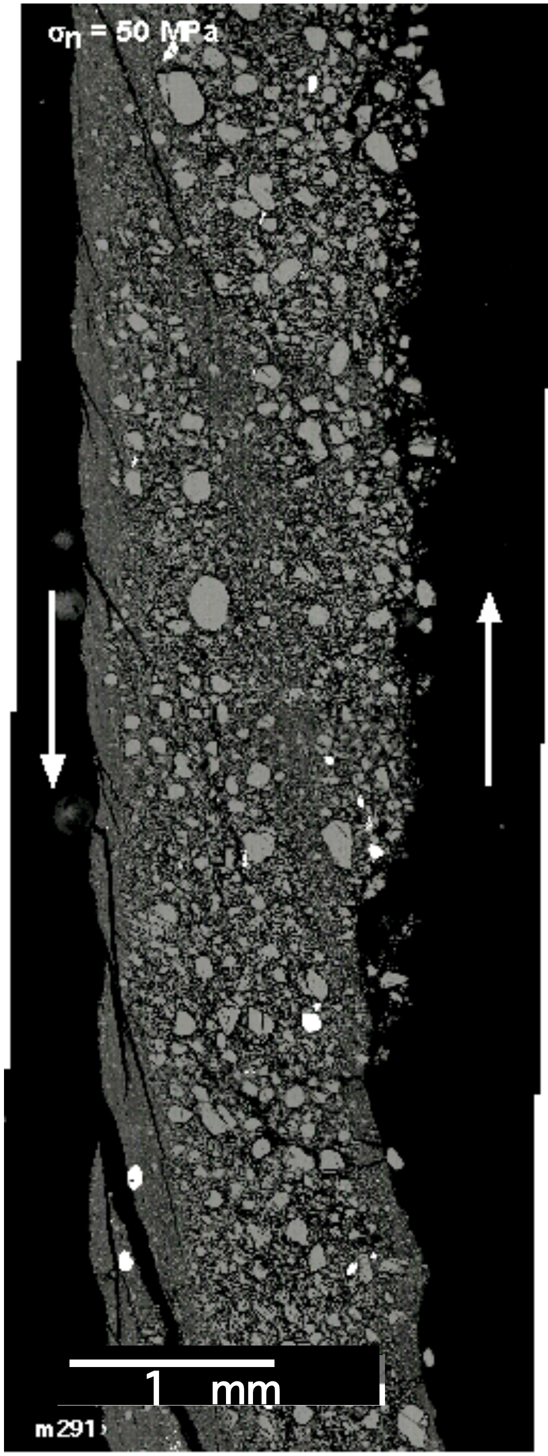
Karen Mair and Chris Marone

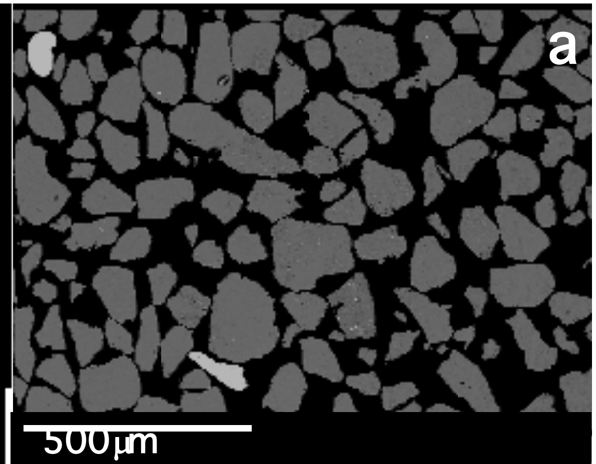
Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge

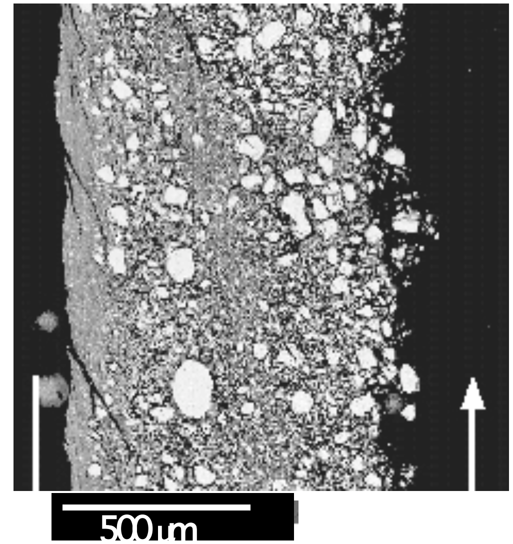


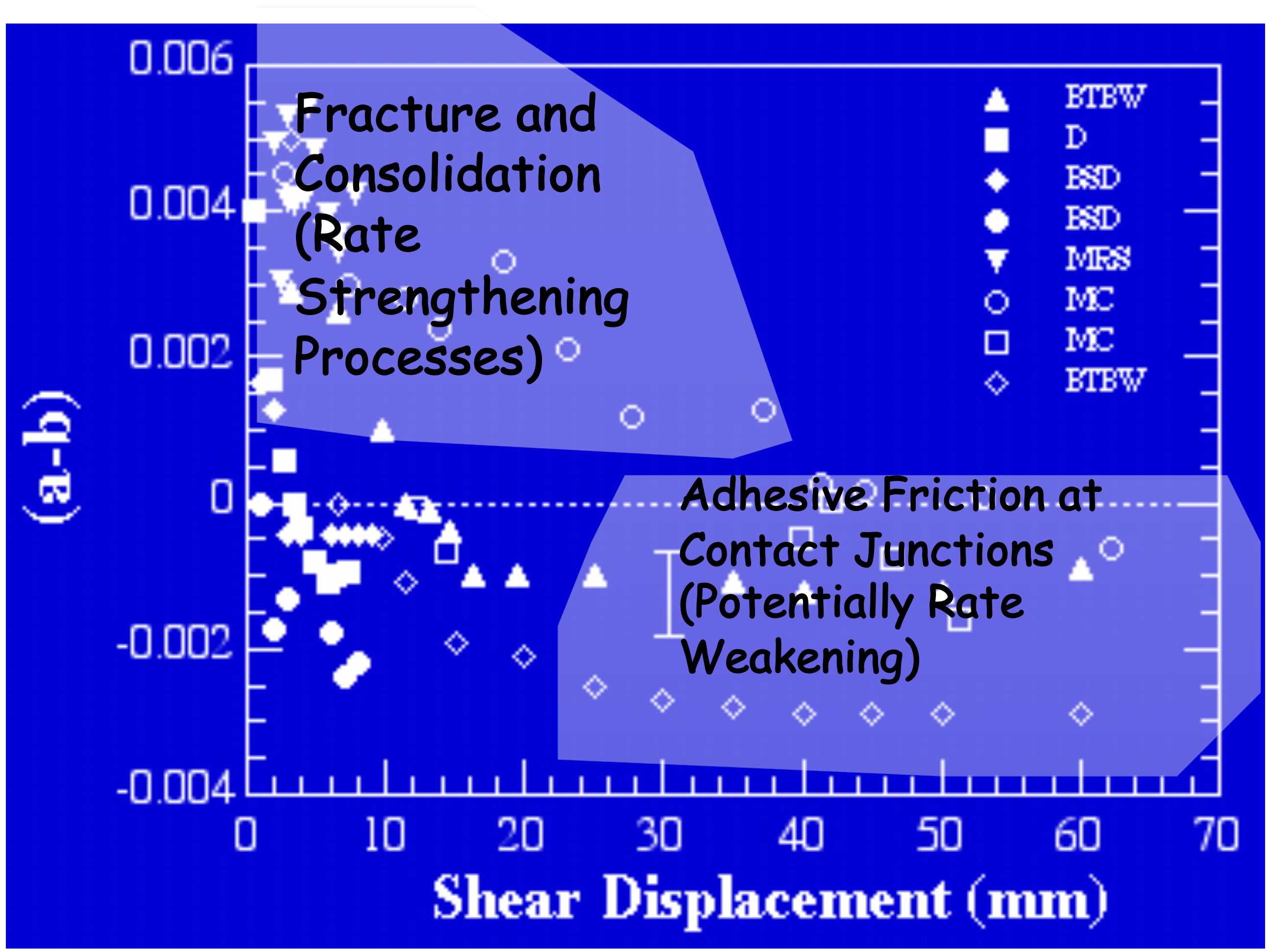



σn = 5 MPa
m290
1 mm
σn = 50 MPa
m291
500 µm
a
500 µm


σn = 50 MPa
1 mm
m291


a
500µm


500µm


Fracture and Consolidation (Rate Strengthening Processes)
Adhesive Friction at Contact Junctions (Potentially Rate Weakening)
BTBW
D
BSD
BSD
MRS
MC
MC
BTBW
0.006
0.004
0.002
0
-0.002
-0.004
(a-b)
0
10
20
30
40
50
60
70
Shear Displacement (mm)

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

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

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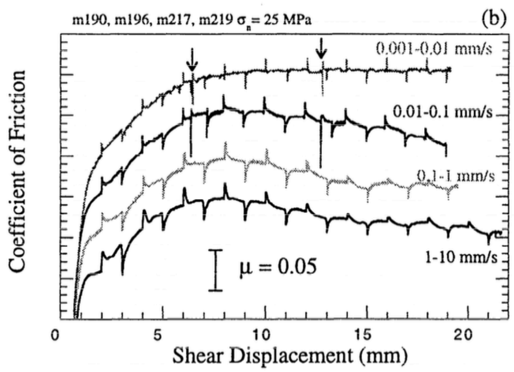


Figure 3. (a) Coefficient of friction and layer thickness as a function of shear displacement for a "fast" velocity test carried out at 1-10 mm/s and σ_n = 25 MPa. The velocity steps are indicated by dashed lines, and alpha is shown schematically. (b) Friction as a function of shear displacement for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

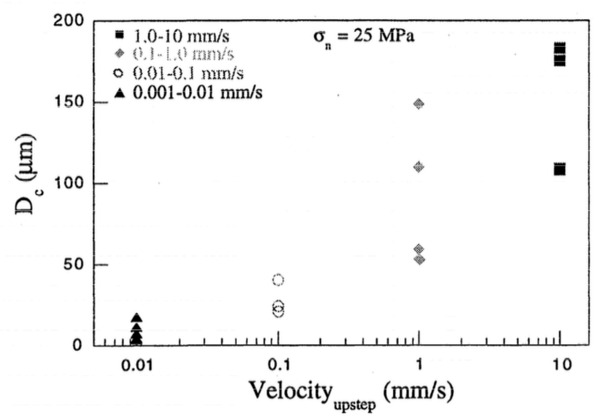
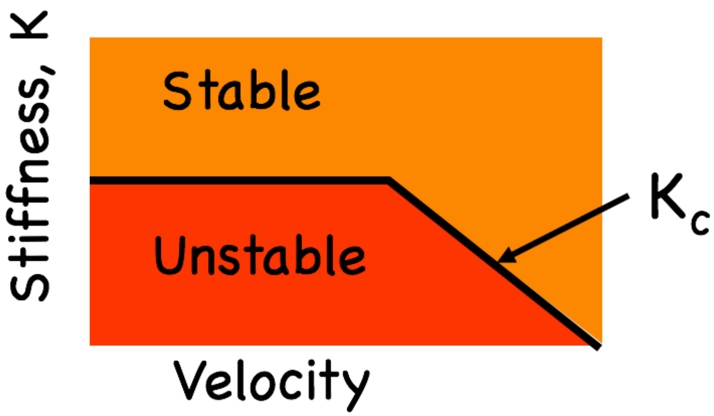
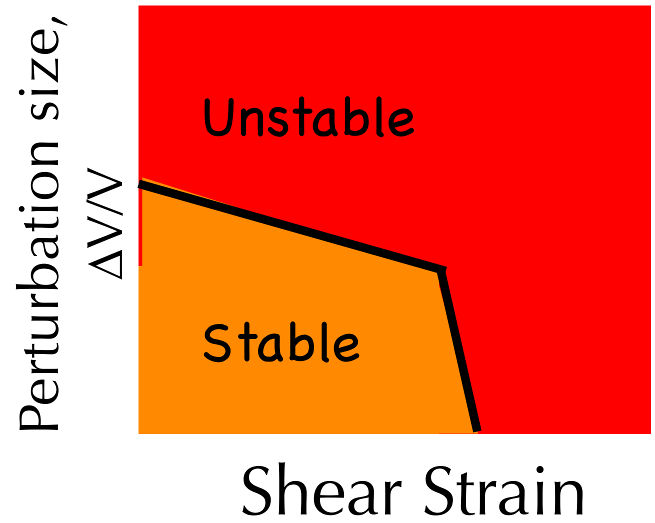


Figure 4. Critical slip displacement (D_c) as a function of upstep velocity for a range of experiments at σ_n = 25 MPa. D_c is systematically larger as a function of increasing velocity.

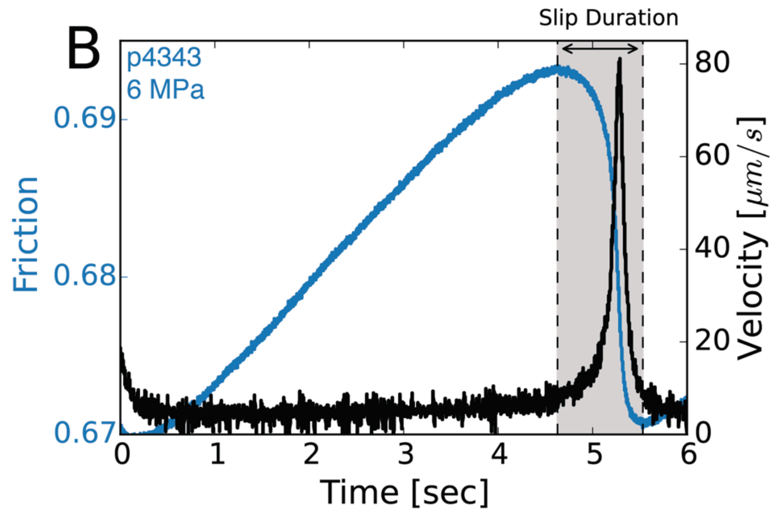
Frictional Sliding: Stability transition depends on strain (shear displacement) and slip velocity)

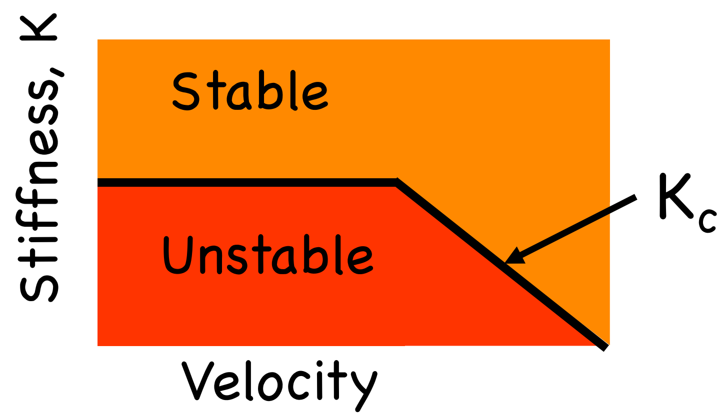


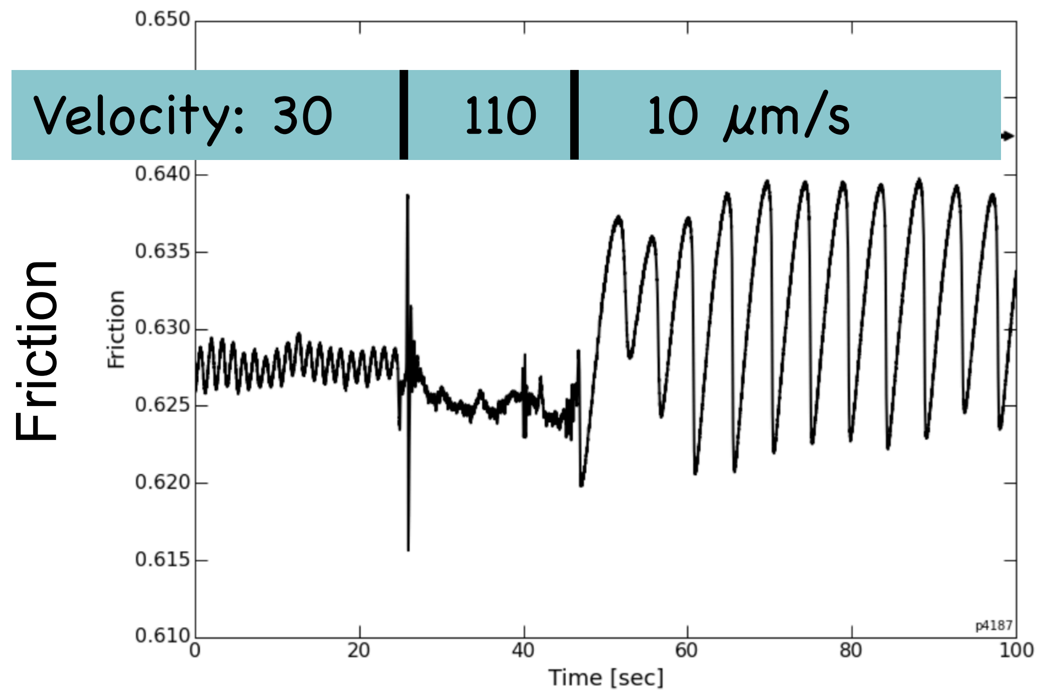


$$K_c \approx \frac{\sigma_n(b-a)}{D_c}$$

$$K_c(V,\gamma)$$

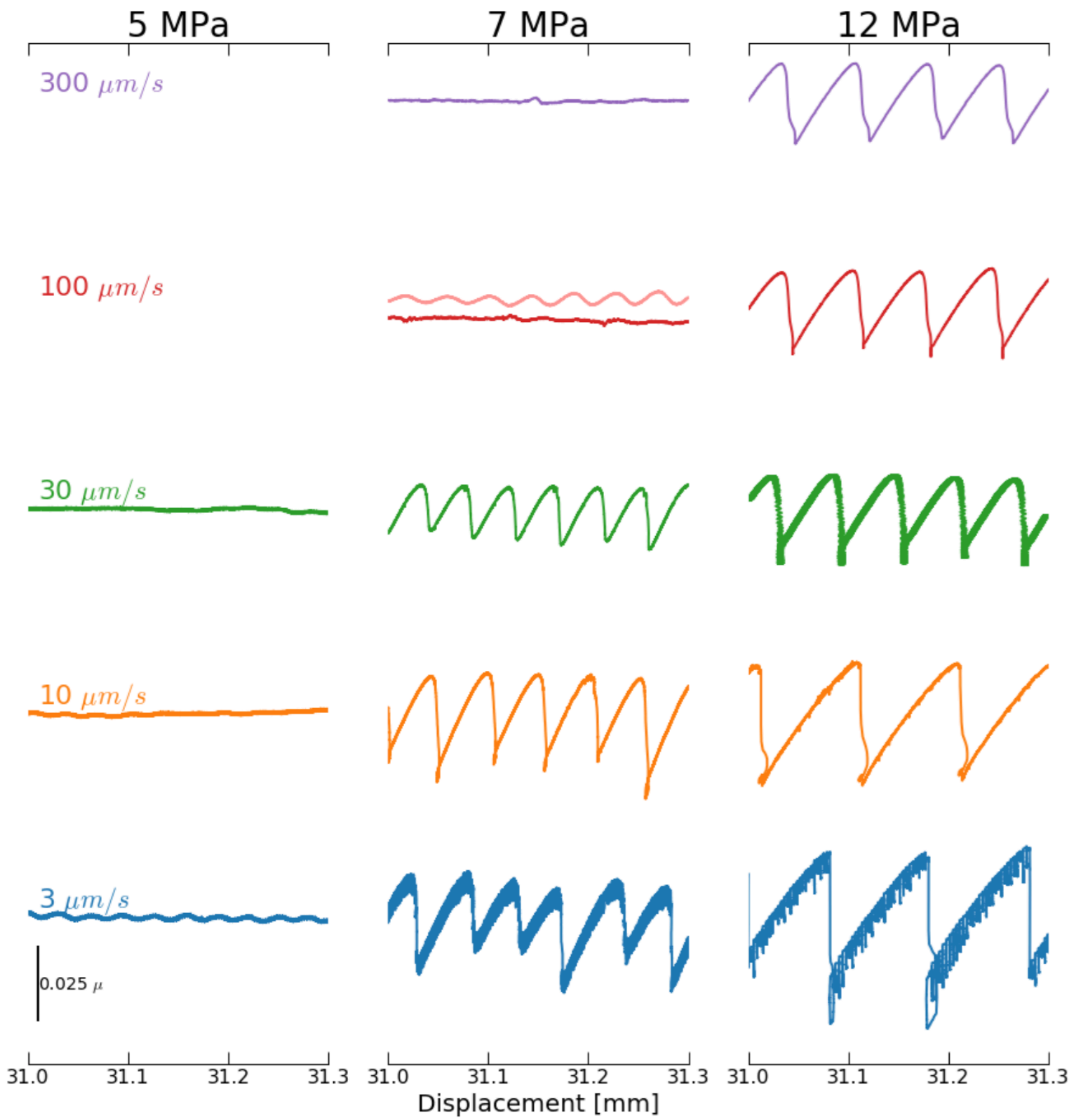






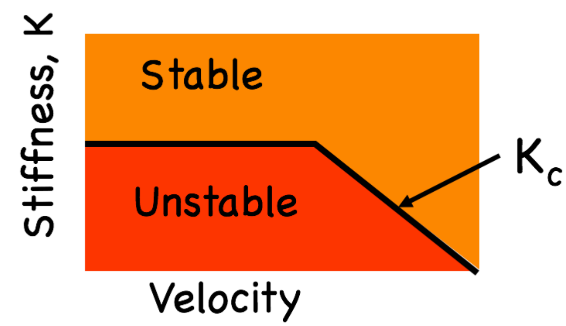
Leeman, Marone & Saffer *JGR*, 2018

Slow Slip



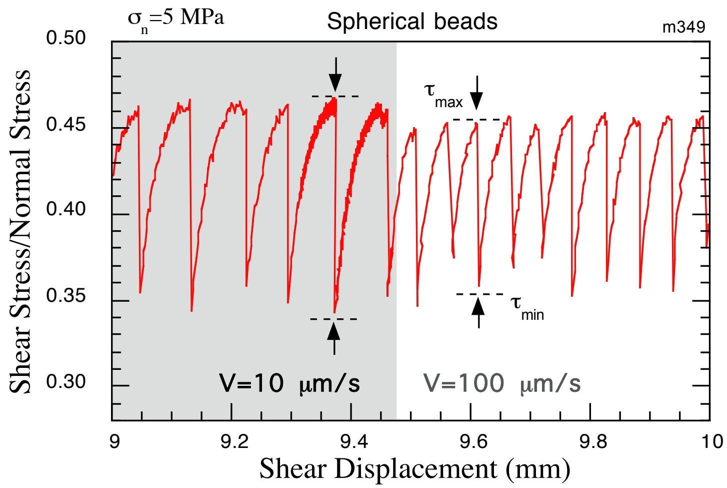
Kc is a function of slip velocity, normal stress, and the friction parameters

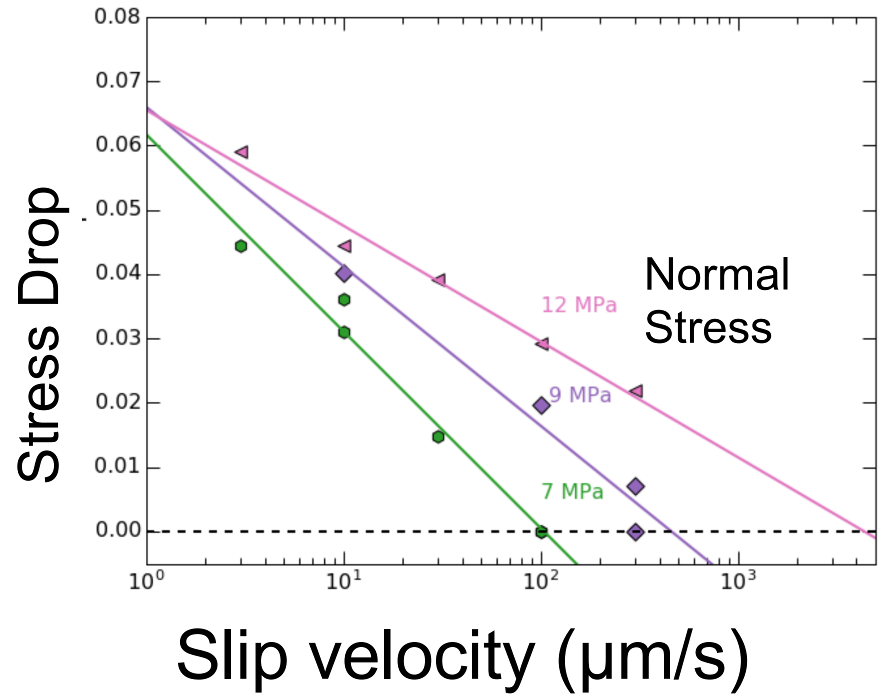
$$\frac{K'}{\sigma_n} < K_c = \frac{(b-a)}{D_c}$$

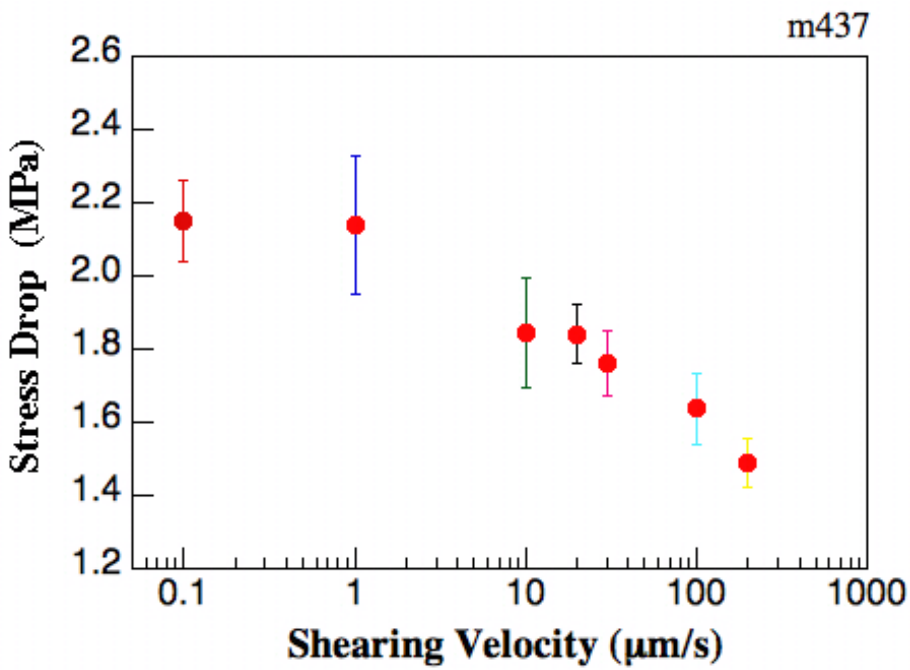


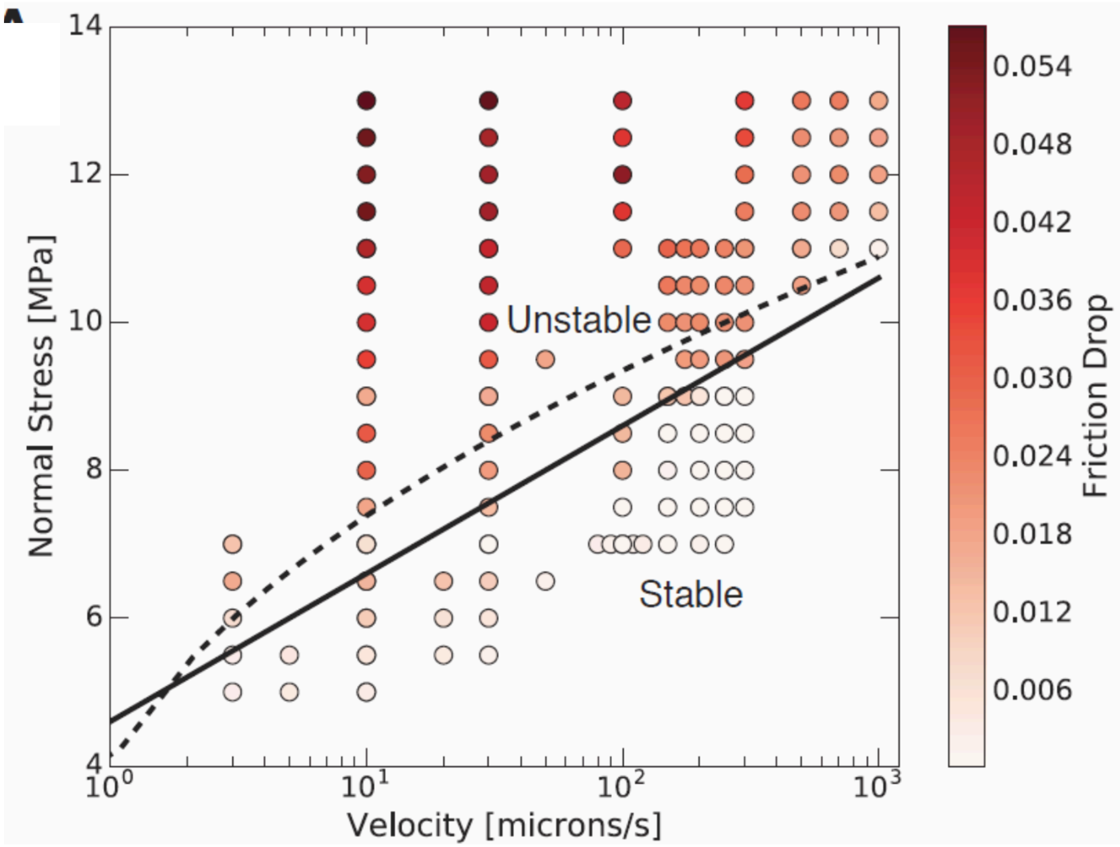
Leeman, Marone & Saffer JGR, 2018

Slow Earthquakes --a view from the lab







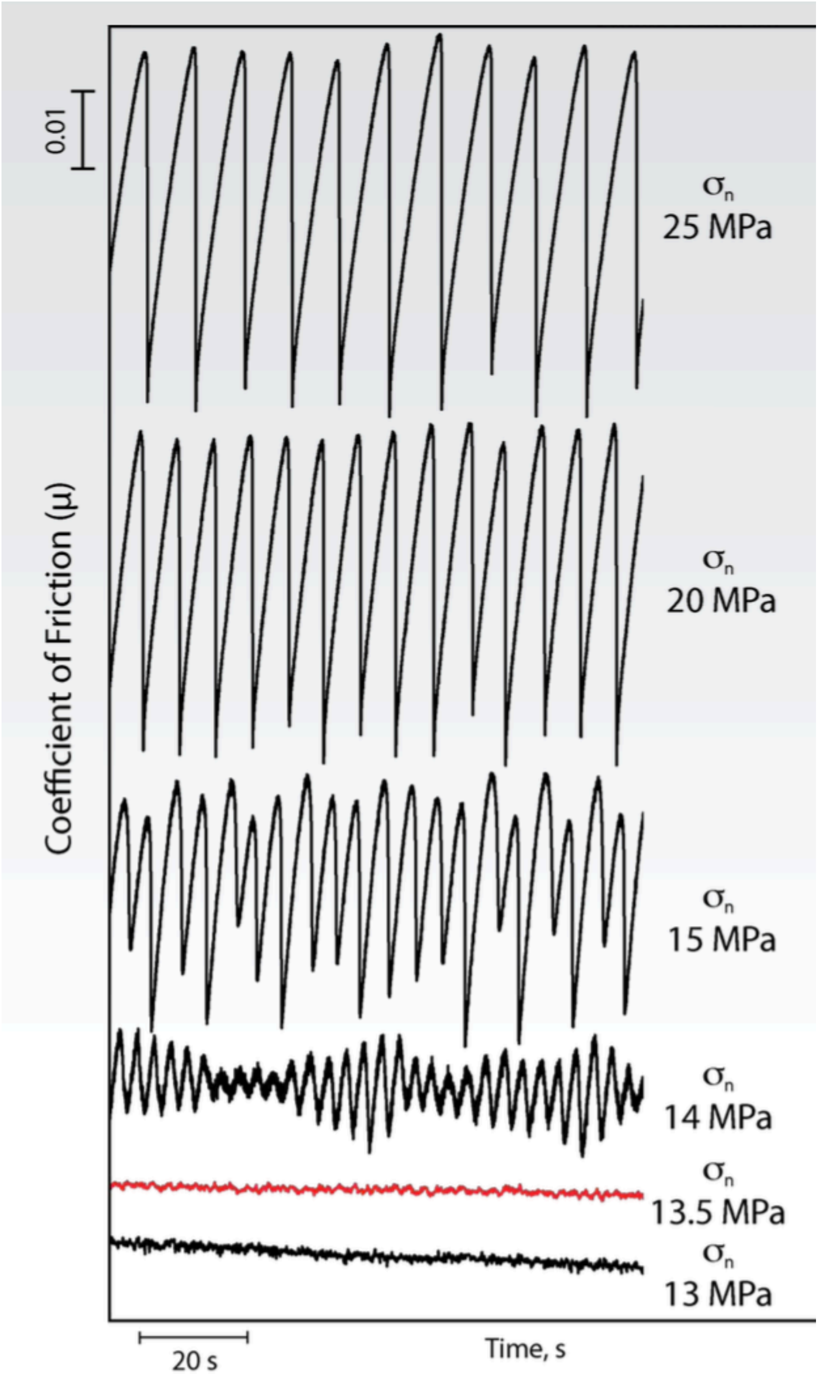


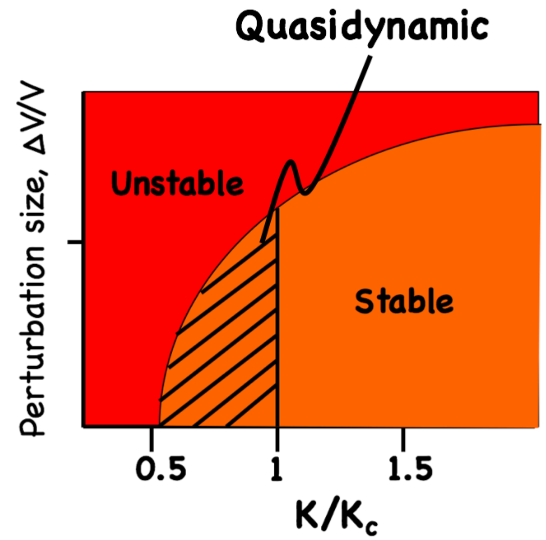
$$K = K_c = \sigma_n \frac{(b-a)}{D_c}$$

$$\sigma_n = \frac{(K d_c ln(V/V_{ref})}{(b-a)}$$

$d_c = 100$ µm, b-$a = 0.005$

Leeman, Marone & Saffer JGR, 2018

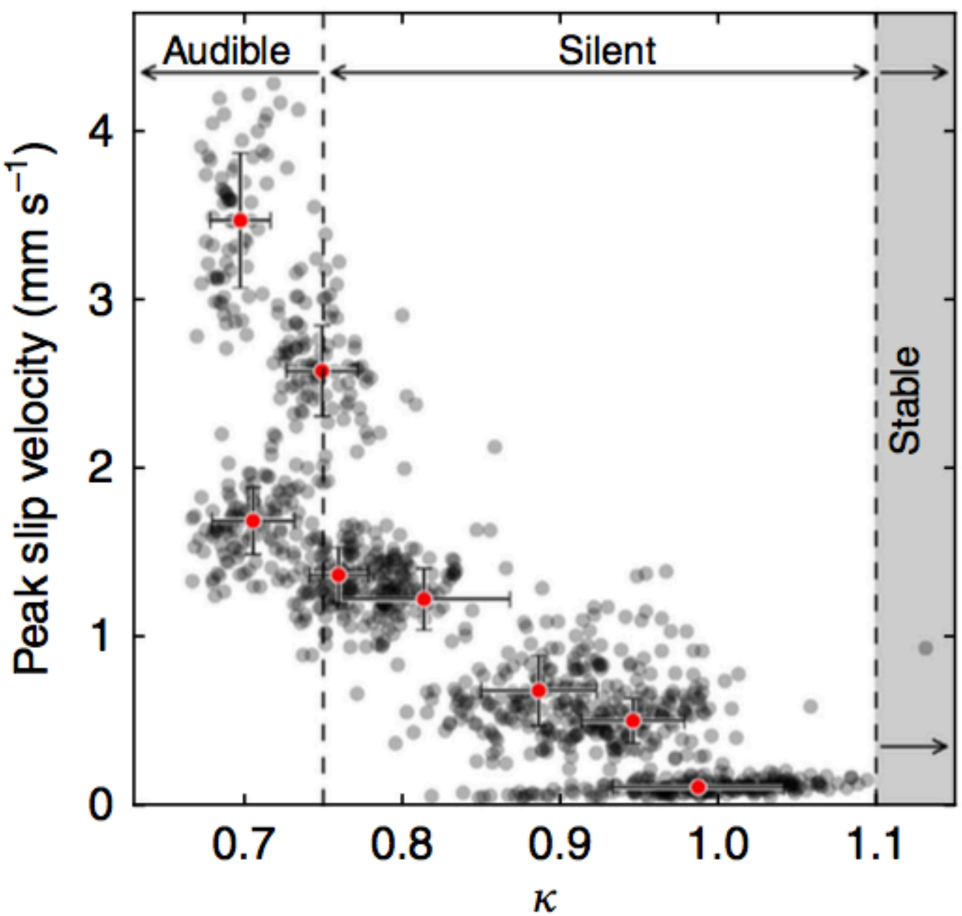


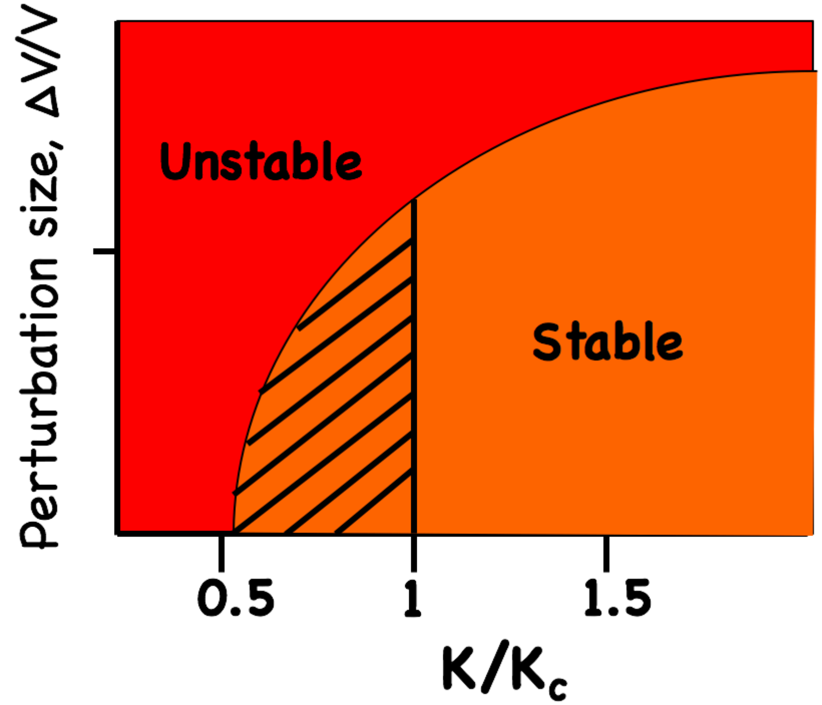


Gu et al., 1984

Period Doubling Near The Stability Boundary

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





Unstable slip if

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

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?*

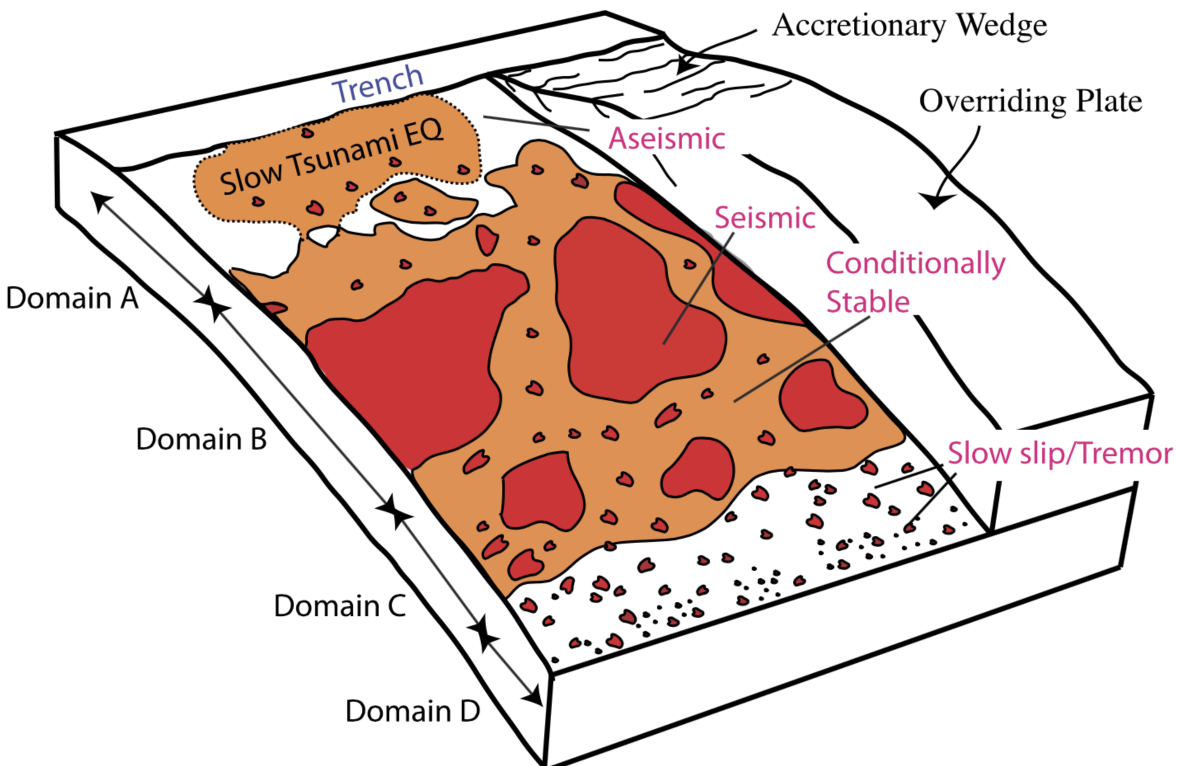
   A. Quasi-dynamic frictional instability (positive feedback, self-driven instability)

   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

Speculations on how the results may apply in nature

A. Where should slow earthquakes occur?
B. How could we get slow and fast slip on the same fault segment?



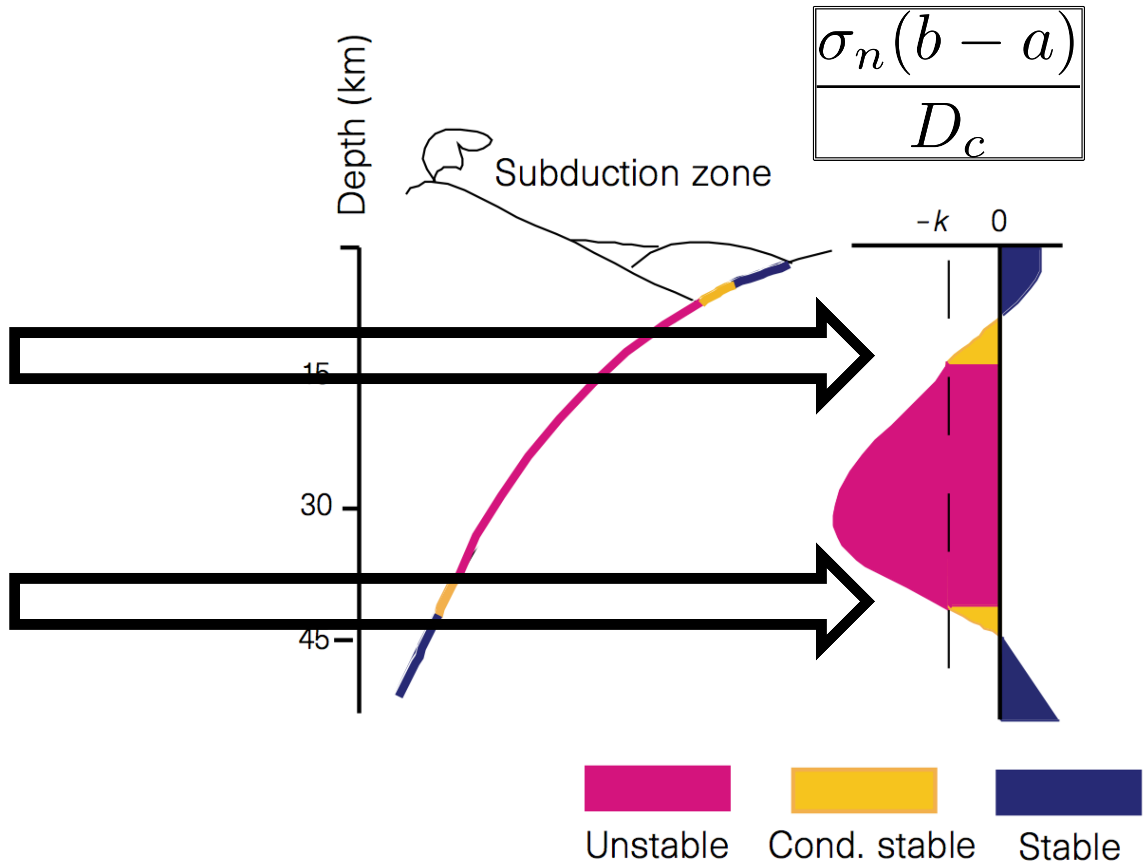
Lay, 2015

Lab guidance

Slow slip and complex behavior near the stability boundary, defined by: $K \approx K_c$

- Complex slip modes near the stability boundary

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

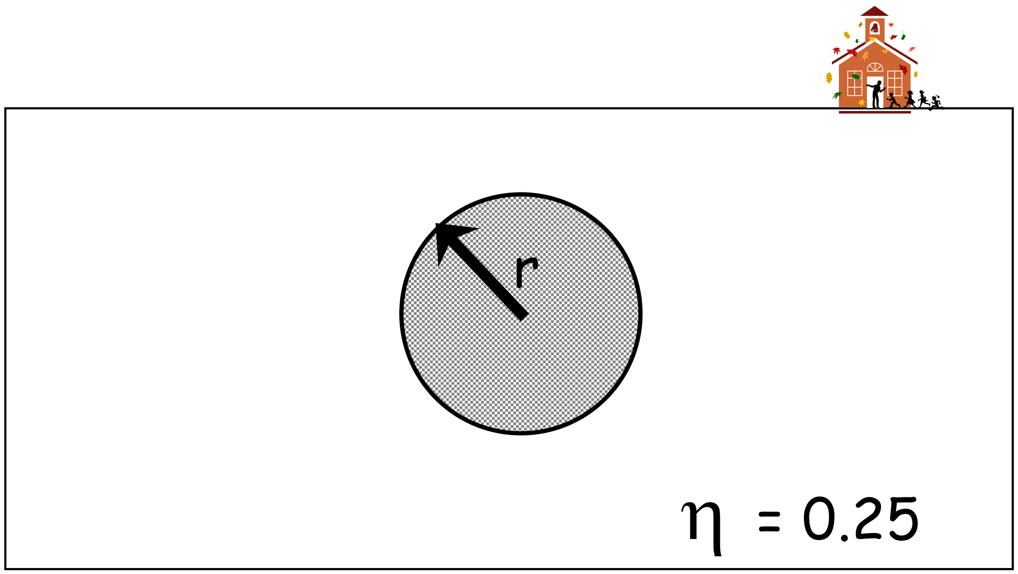


Unstable slip if

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

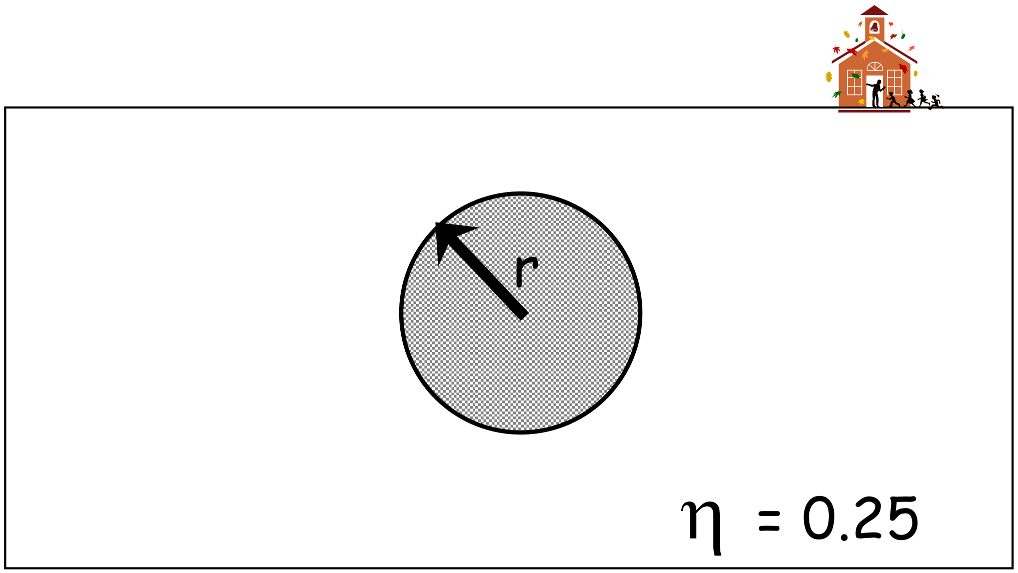
Speculations on how the results may in apply in nature

B. Source Parameters and Scaling Relations for Slow Earthquakes



Dislocation model for fault slip and earthquake rupture

Earthquakes nucleate when the fault slip patch exceeds a certain size, related to local stiffness and friction



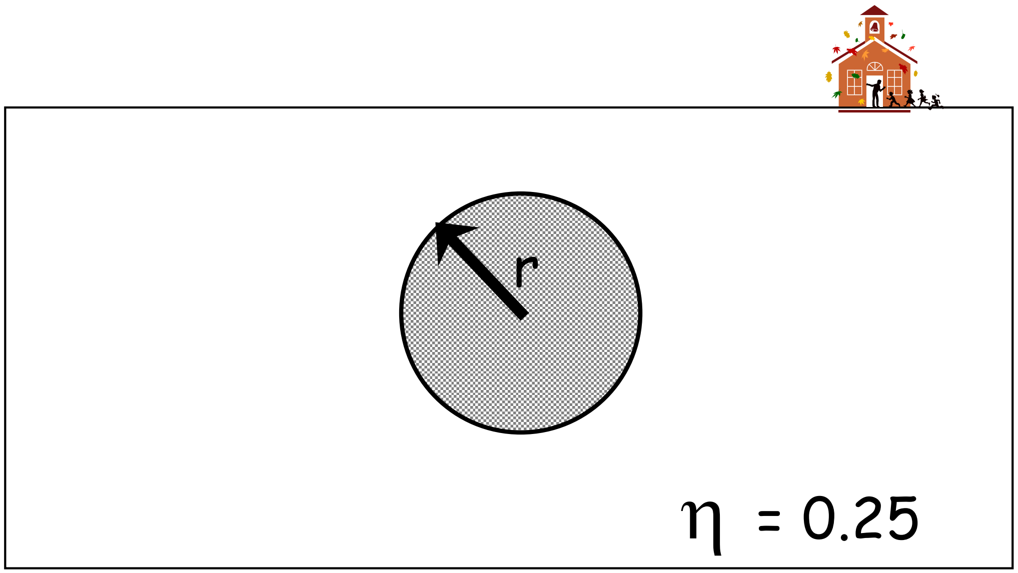
Unstable if

$$K < K_c$$

Critical weakening rate with slip

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

Earthquakes nucleate when the fault slip patch exceeds a certain size, related to local stiffness and friction



Unstable if

$$K < K_c$$

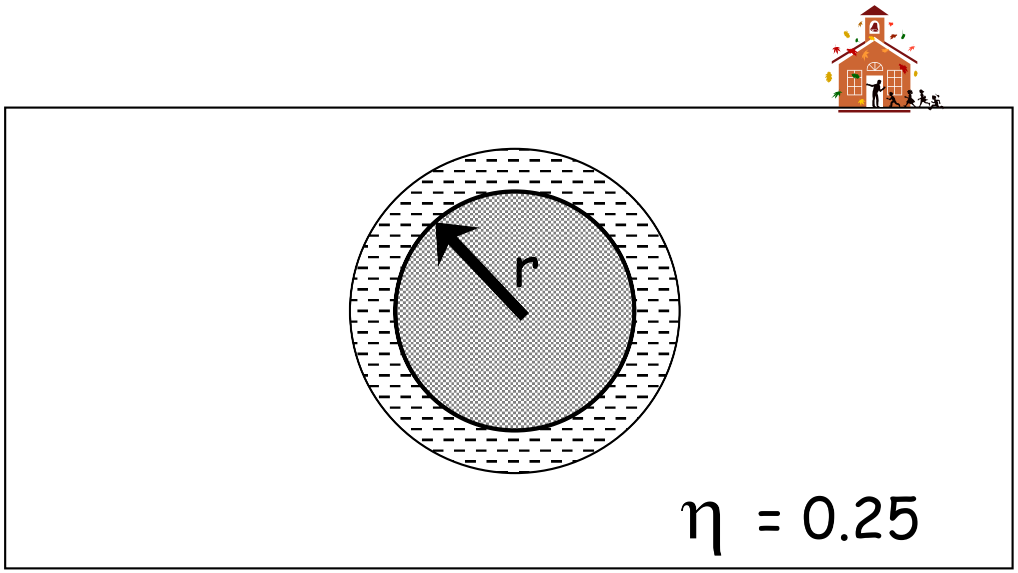
Local stiffness

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

Critical weakening rate with slip

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

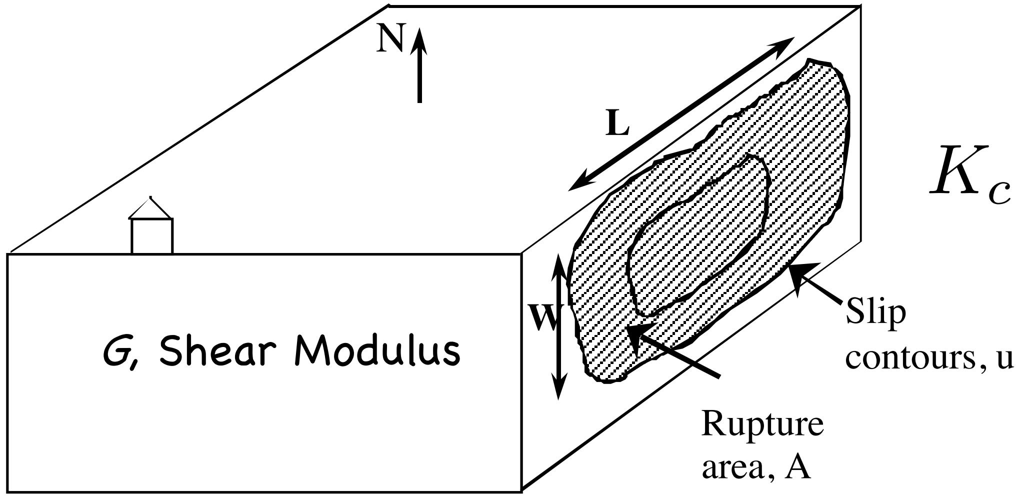
Earthquakes nucleate when the fault slip patch exceeds a certain size, related to local stiffness and friction



Precursory phenomena should occur in the nucleation zone

Earthquakes occur on faults

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



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

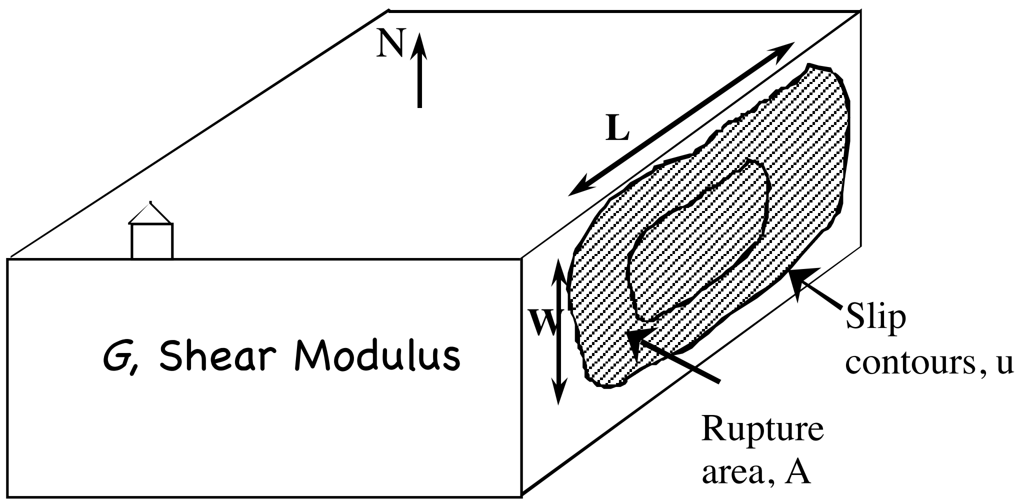
$$K = \frac{\Delta\sigma}{\bar{u}} = \frac{7\pi}{16}\frac{G}{r}$$

1. Earthquake Source properties are reasonably well described as propagating elastodynamic rupture

2. Earthquake Nucleation occurs when the patch size exceeds *h**

*h**

Earthquakes occur on faults



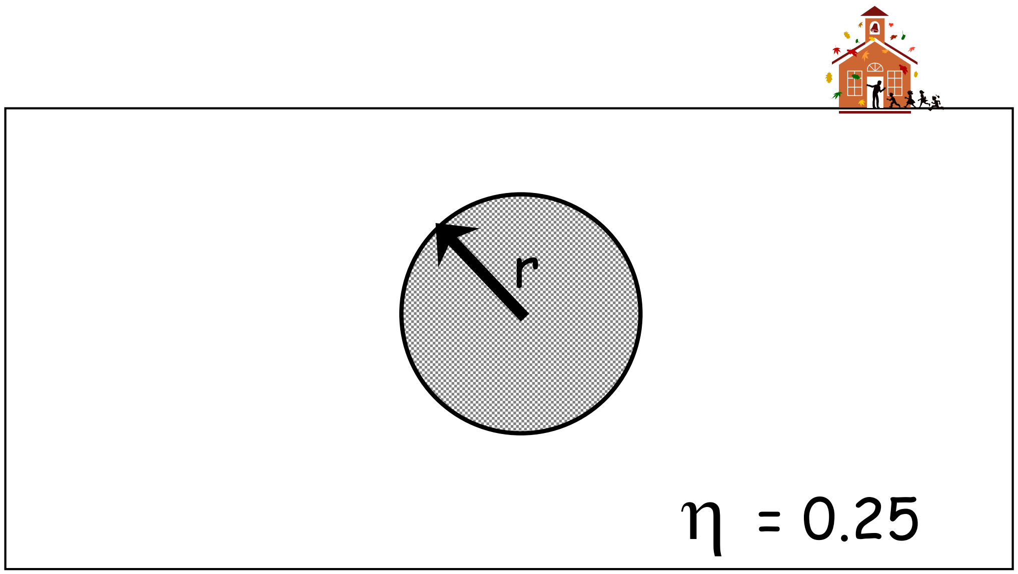
$$M_o = G\bar{u}A$$

1. Earthquake Source properties are reasonably well described as propagating elastodynamic rupture

2. Earthquake Nucleation occurs when the patch size exceeds *h**

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

Earthquake Source Parameters and Scaling Relations



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

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

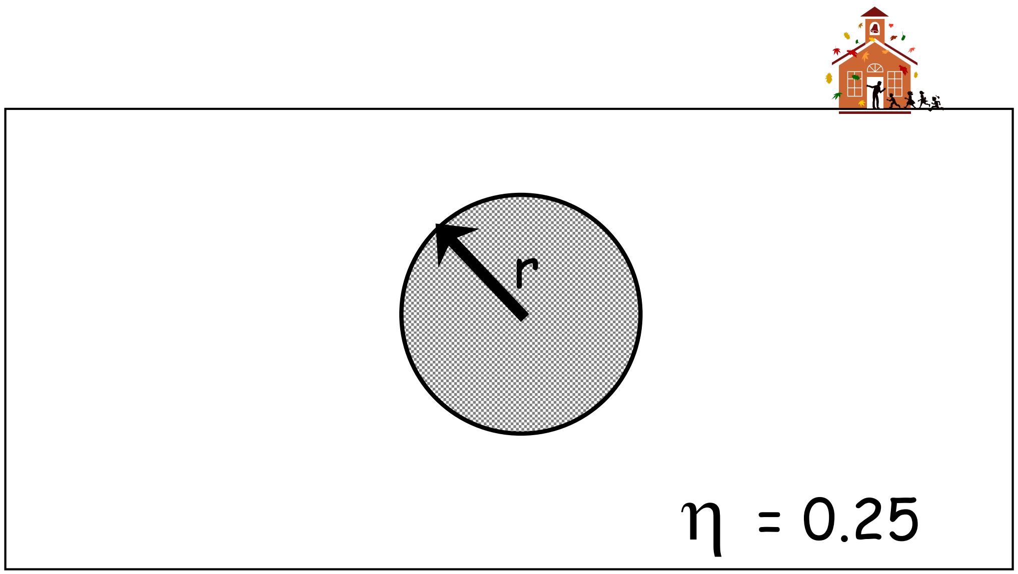
$$M_o = C\Delta\sigma r^3$$

Dislocation model for fault slip and earthquake rupture

Rupture Patch Size for Slow Earthquakes

Unstable if

$$K < K_c$$



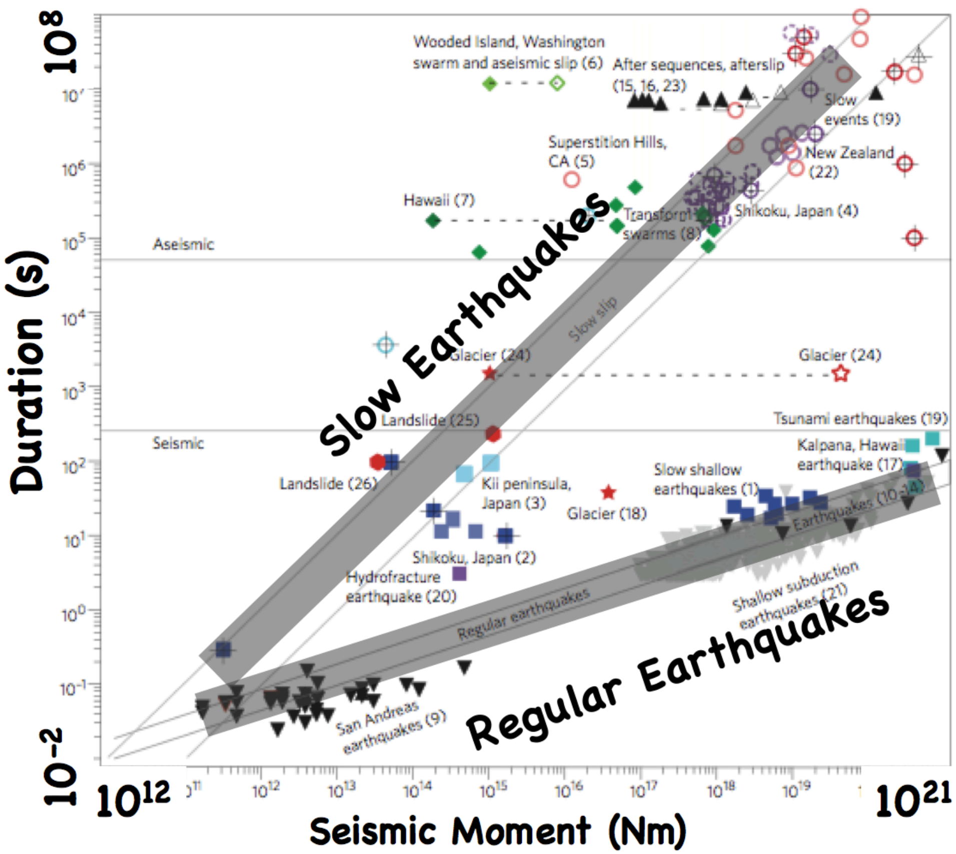
$$K = \frac{\Delta\sigma}{\bar{u}} = \frac{7\pi}{16}\frac{G}{r}$$

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

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

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

Earthquake Source Parameters and Scaling Relations



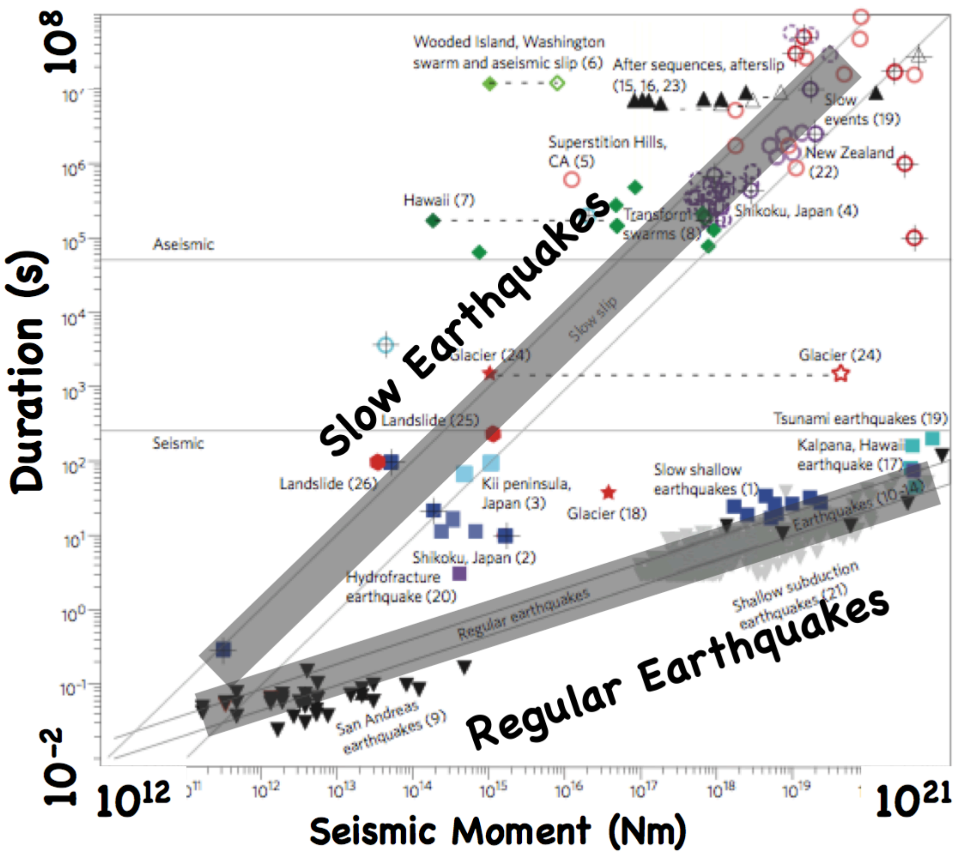
Ide et al., 2007; Peng and Gomberg, 2010

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

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

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

Earthquake Source Parameters and Scaling Relations



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

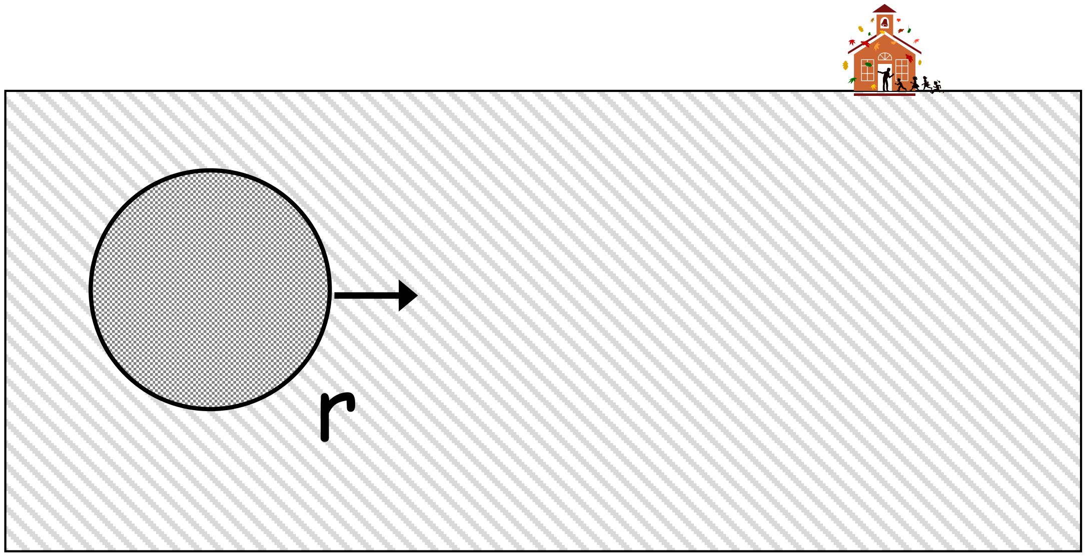
$$\Delta\sigma = \frac{7\pi}{16} G \frac{\bar{u}}{r}$$

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

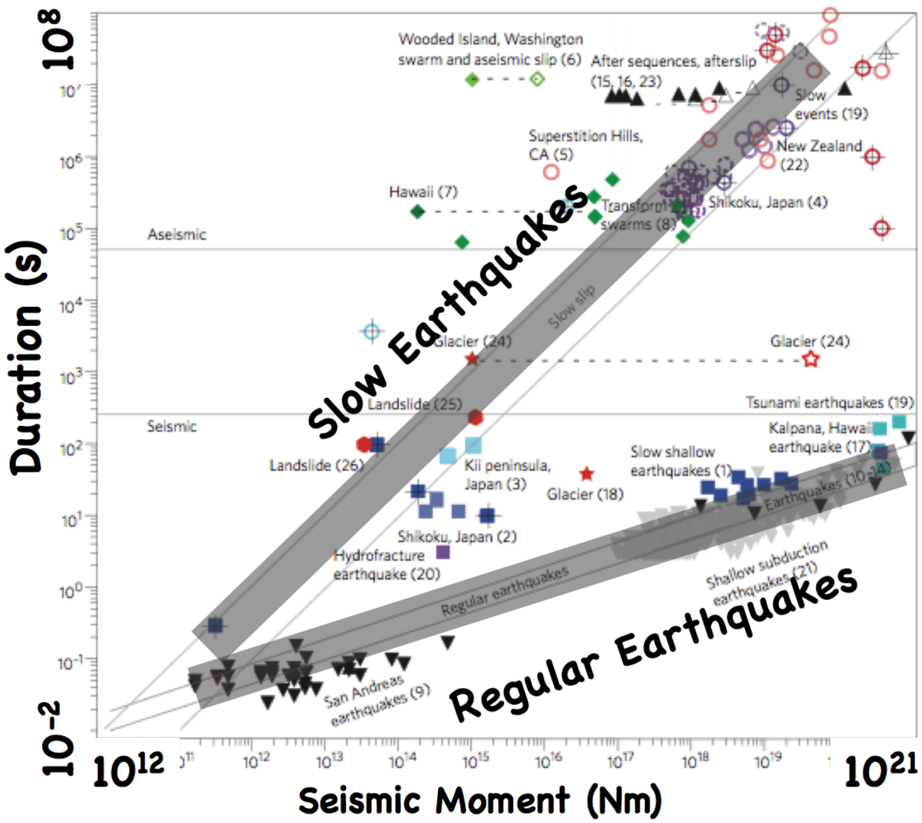
$$M_o = C\Delta\sigma r^3$$

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

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



Slow slip when effective rupture patch size is limited by heterogeneity

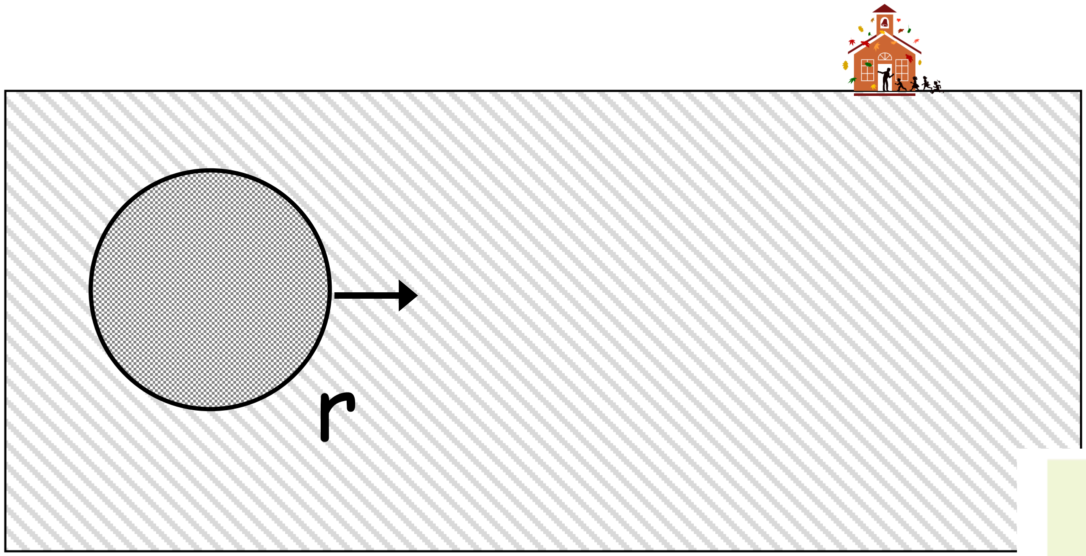


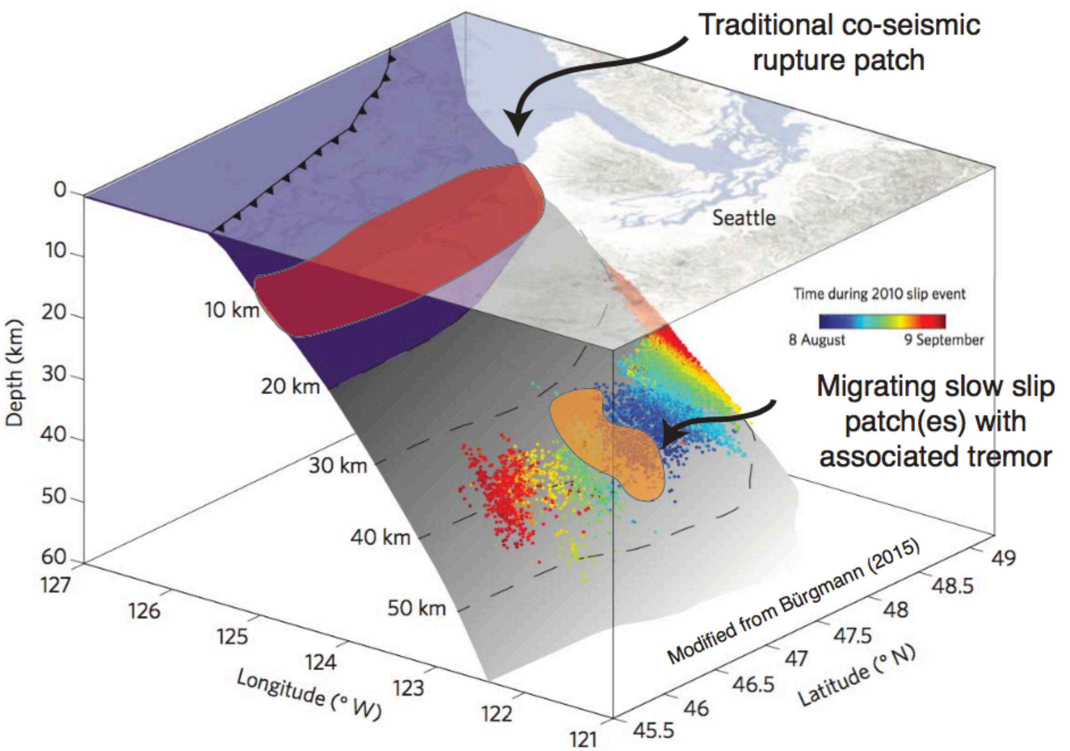
$$M_o{}^{patch} = G\bar{u}r^2$$

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

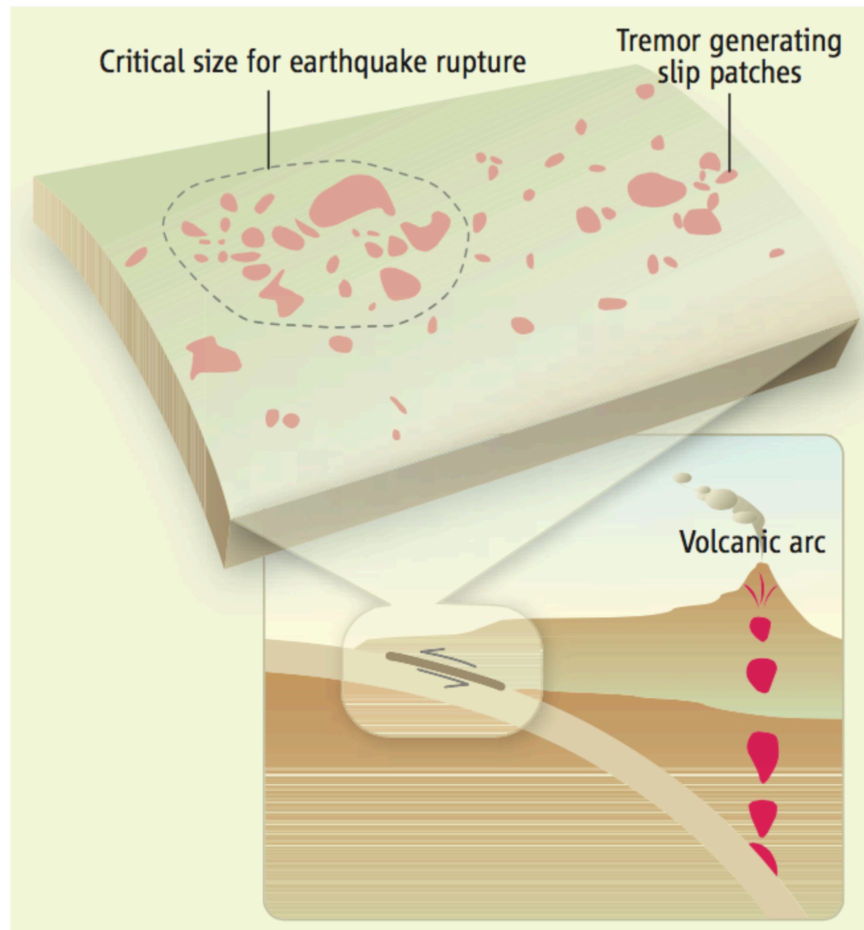
$$M_o \approx V_r T$$

Slow slip when effective rupture patch size is limited by heterogeneity





Bürgmann, 2015; Houston, 2015



Richardson and Marone, 2008