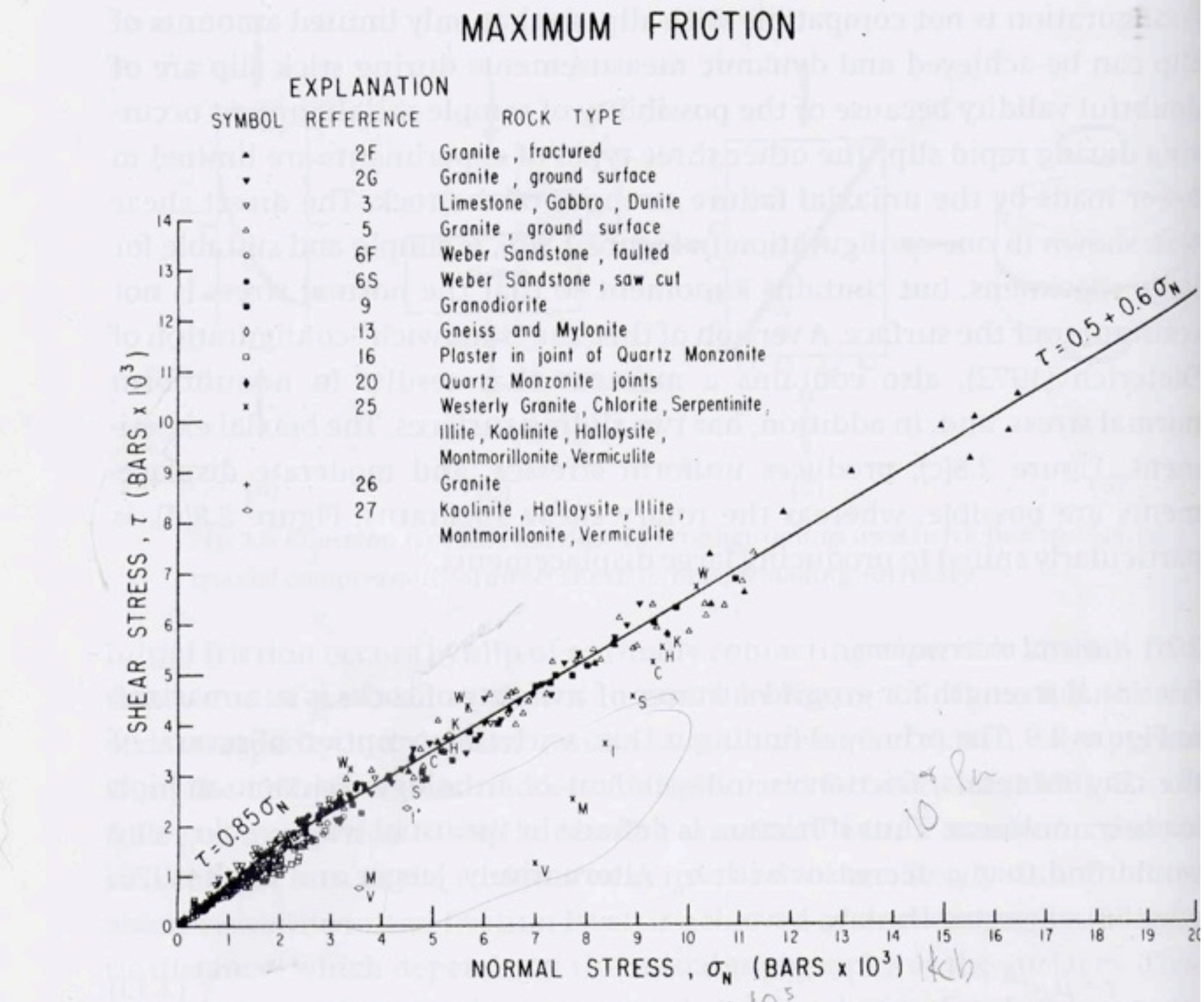


Fig. 2.9. Frictional strength for a wide variety of rocks plotted as a function of normal load. The lettered data points refer to clay minerals as indicated in the key. (From Byerlee, 1978.)

$$\tau = \mu_s \sigma_n$$

Byerlee's Law (1978)

Does rock type matter?

This works at T less than 350-400° C

For Wednesday: read Moore and Rymer, Nature, 2007

new evidence for weak mineral (talc) along the SAF

Short and sweet. Who wants to present it?

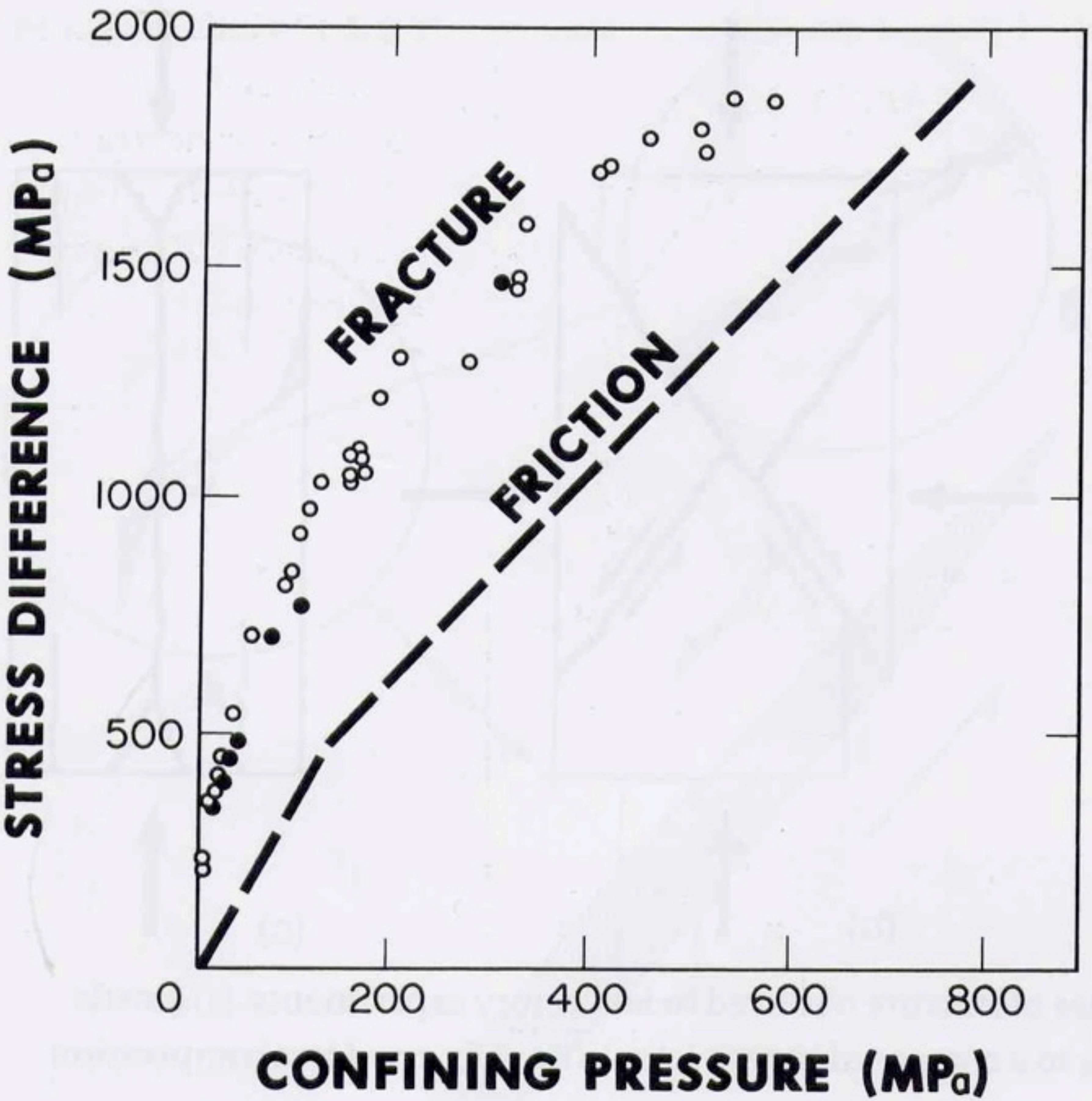


Fig. 1.13. The strength of Westerly granite as a function of confining pressure. Also shown, for reference, is the frictional strength for sliding on an optimally oriented plane. Data sources are: open circles, Brace *et al.* (1966) and Byerlee (1967a); closed circles, Hadley (1975); friction, Byerlee (1978). Stress difference is $\sigma_1 - \sigma_3$.

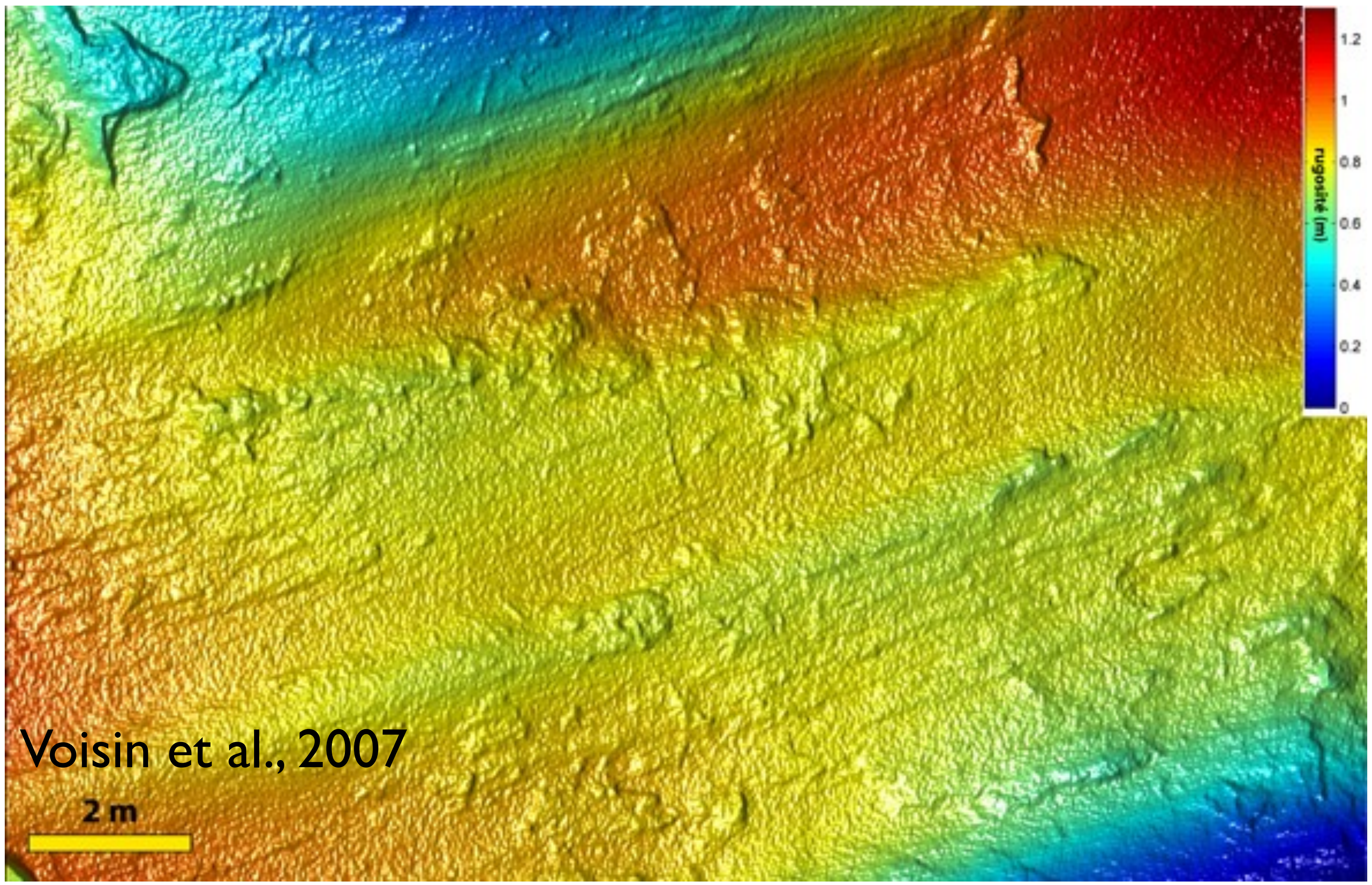
Friction force is independent of the size of MACROSCOPIC areas in contact

Amonton's First Law

Friction is proportional to normal stress

Amonton's Second Law

High-precision Lidar scan (topography) of an exposed fault surface



Asperities at a wide array of spatial scales

"smoother" profile in the slip direction

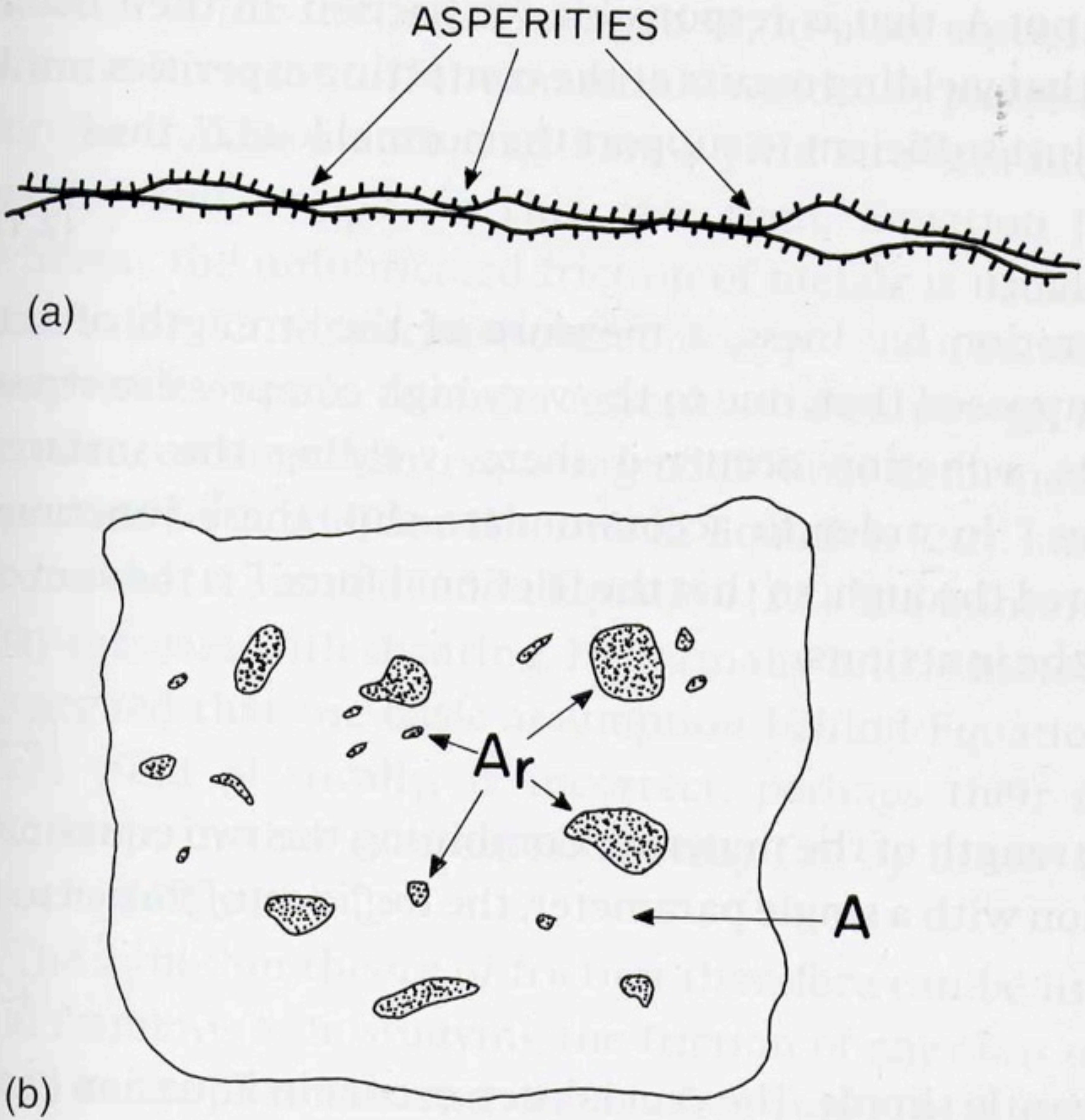


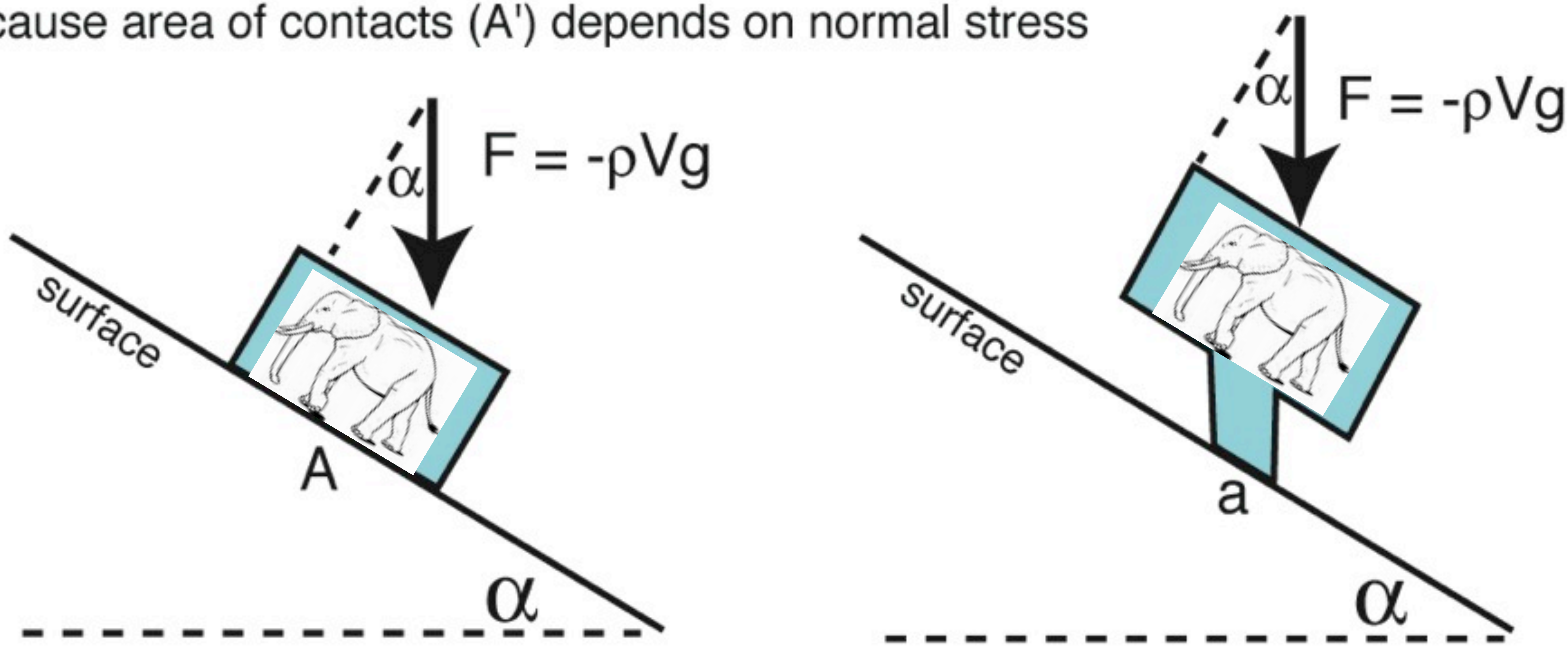
Fig. 2.1. Schematic diagram, in section and plan view, of contacting surface. The stippled regions in plan view represent the areas of asperity contact, which together comprise the real contact area A_r.

at each asperity, shear stress must exceed frictional strength for sliding to occur

Amonton's First Law

friction force is insensitive to **macroscopic** area

because area of contacts (A') depends on normal stress



Same real contact area Ar for both cases.

If macroscopic contact area is small, normal stress = N/area is larger, asperities squash, and Ar is a larger % of macroscopic contact area

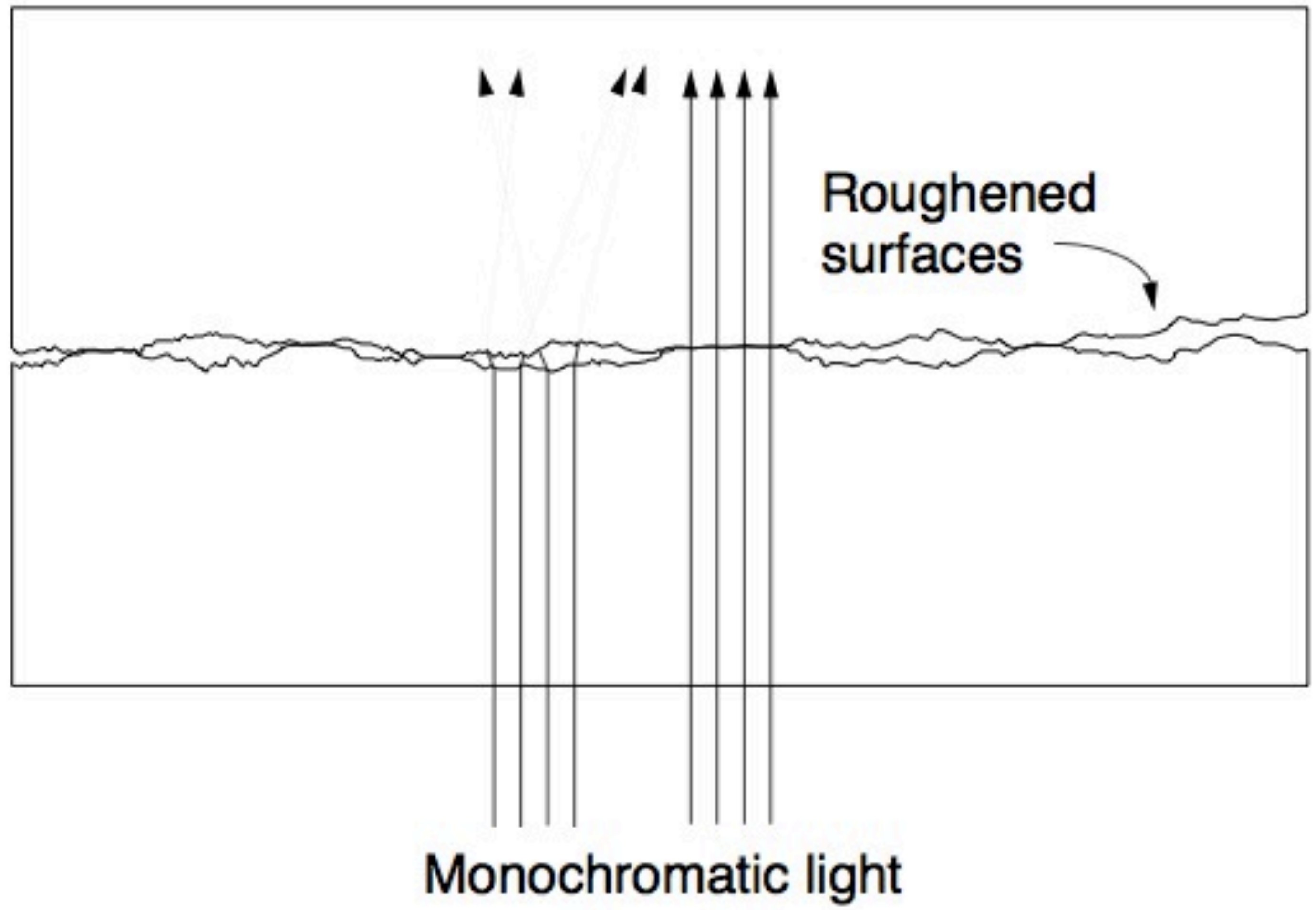
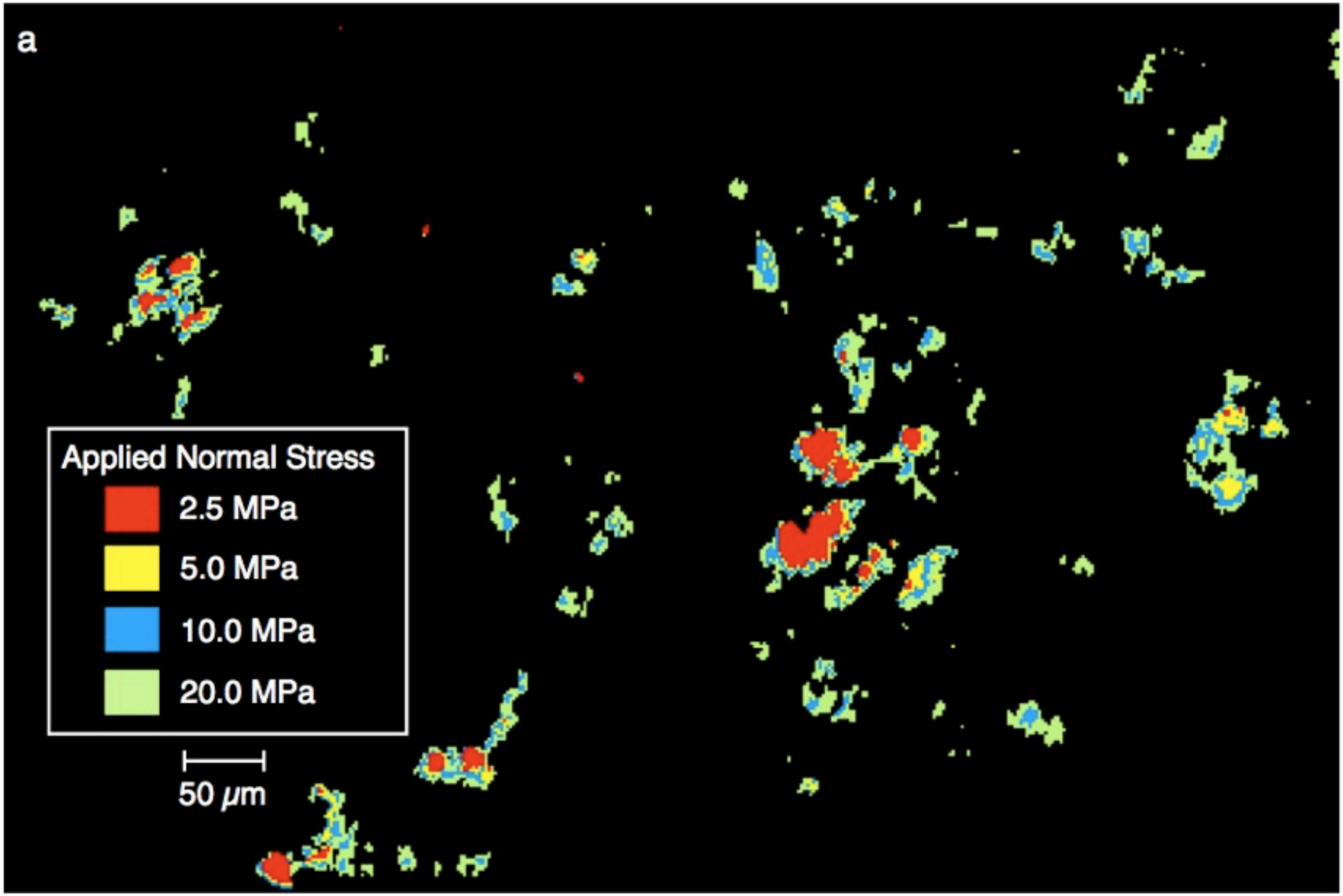


Figure 2
Schematic representation of roughened sliding surfaces. Light transmitted through the sliding blocks is scattered except at contacts.

Dieterich and Kilgore, 1994

Dieterich and Kilgore, 1994



Asperity contact area increases with (macroscopic) normal stress

At the contacts, this affects shear and normal stress the same way

So ratio (mu) does not change with normal stress

from Dieterich and Kilgore, 1994

We observe that **total (real - EHH) contact area increases linearly with applied normal stress** for both the acrylic plastic and glass. **Hence, average contact normal stress, obtained from the product of applied normal stress and total contact area/unit area, is independent of applied stress.** In addition, we observe a linear correlation between normal stress and sliding resistance. These results conform to the usual view of unlubricated roughened surfaces which holds that **friction (that is friction coeff times applied normal stress - EHH) is proportional to real area of contact which in turn is controlled by contact yielding in response to the applied normal stress.**

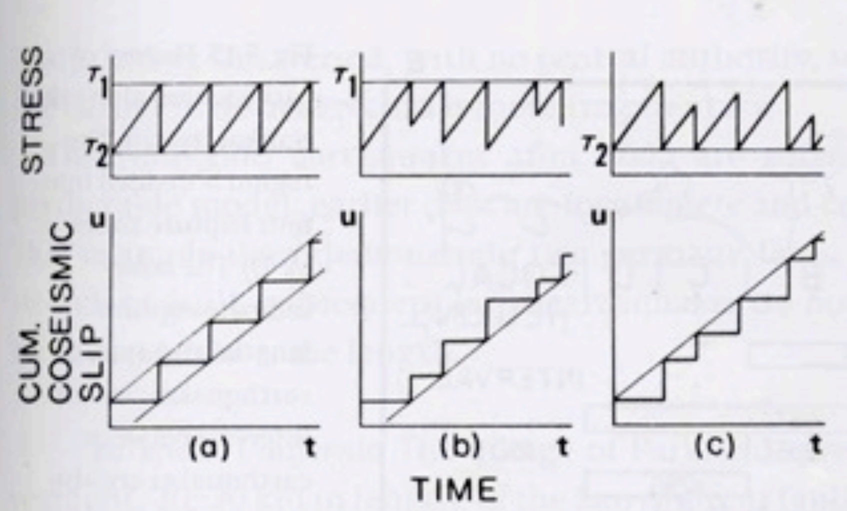


Fig. 5.13. Simple earthquake recurrence models: (a) Reid's perfectly periodic model; (b) time-predictable model; (c) slip-predictable model. The time-predictable model is motivated by the observation of the Nankaido earthquakes. (From Shimazaki and Nakata, 1980.)

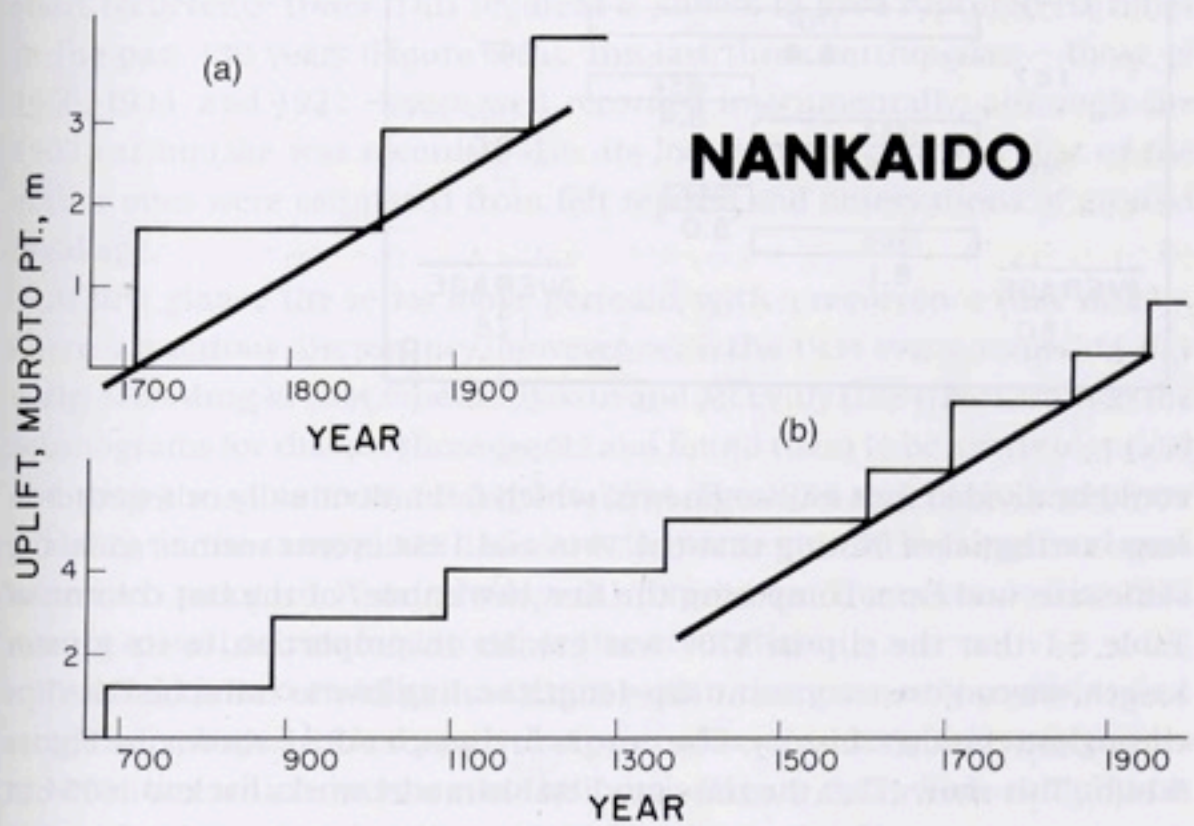


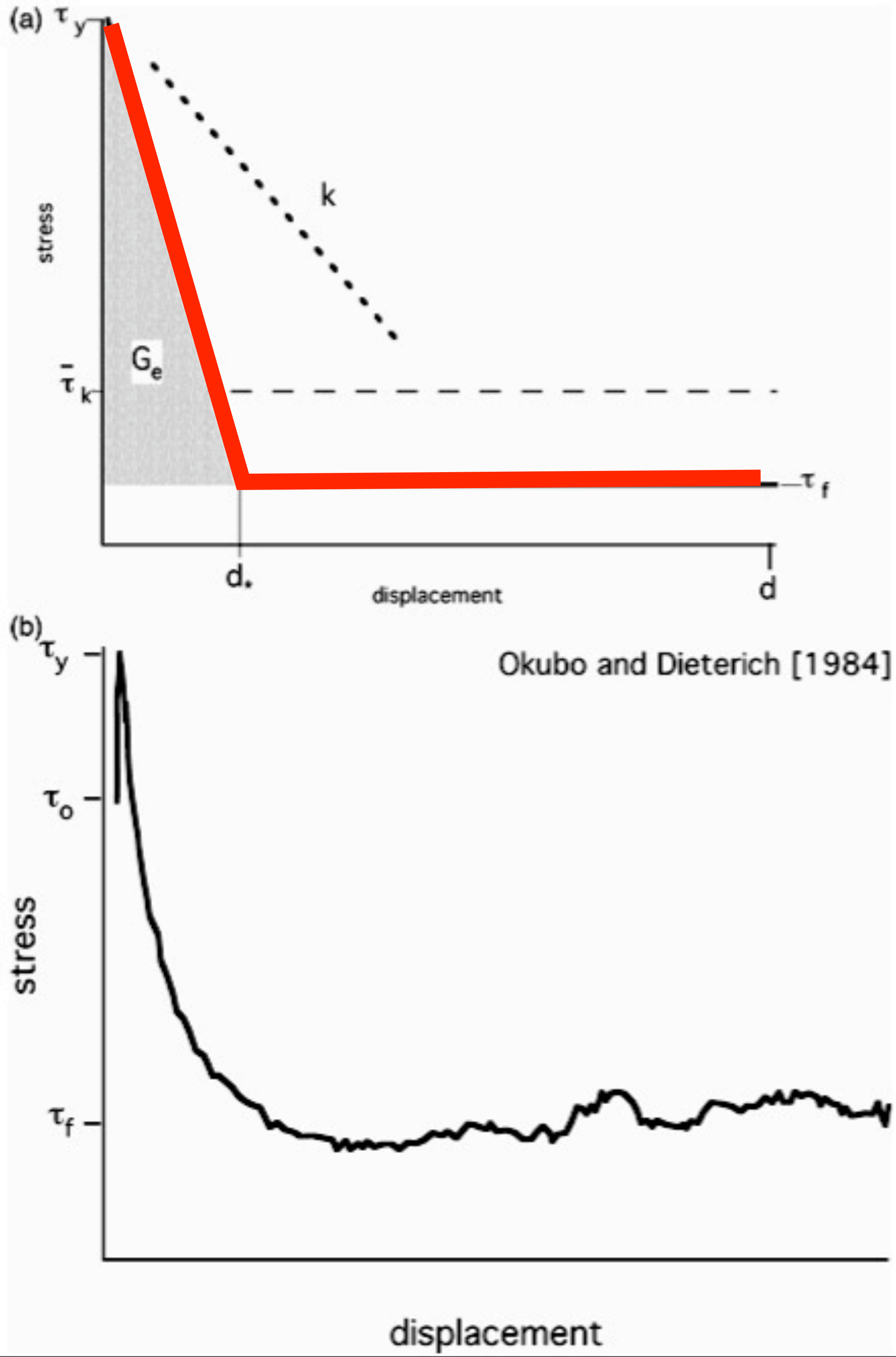
Fig. 5.14. History of uplift at Muroto Point in response to Nankaido earthquakes compared with the time-predictable model: (a) data since 1707, when measurements are available; (b) an extrapolation further back in time, using Ando's history (Figure 5.15) and a scaling law to determine uplift. Bold line is the interpretation with the time-predictable model.

From Scholz (2002)

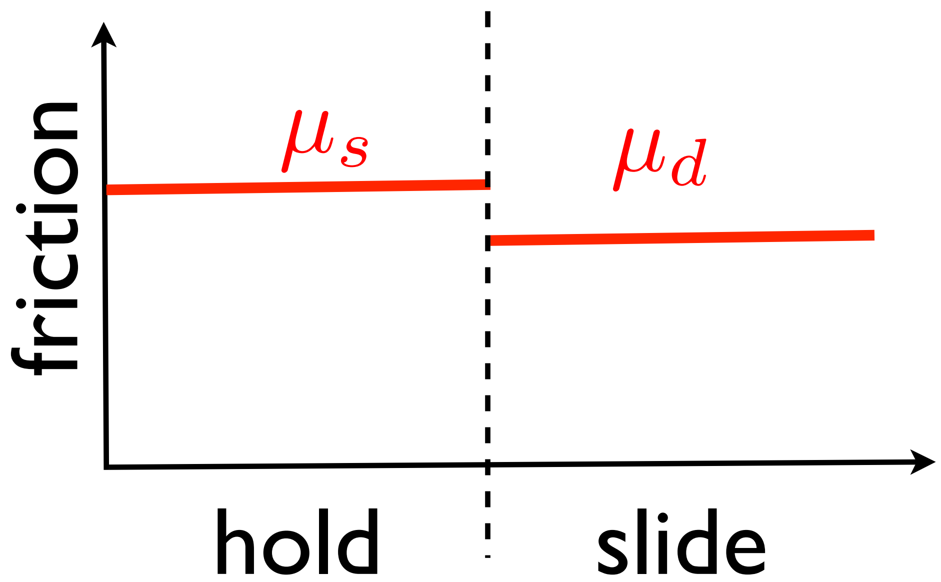
stress drops are small relative to background stress

Brace and Byerlee (1966) addressed this problem with stick-slip.

Slip weakening law (still used in many computer models of spontaneous earthquake generation)



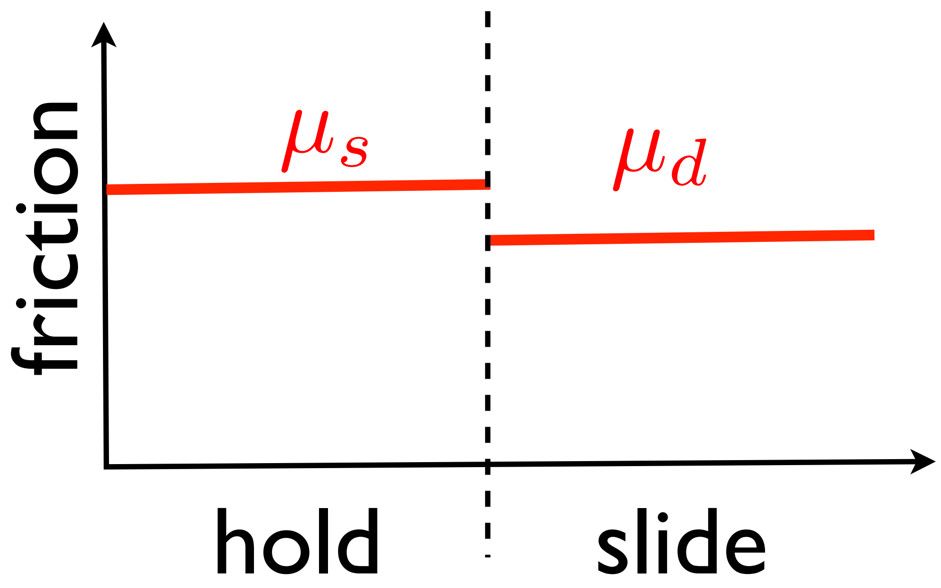
Some ideas about static vs. dynamic friction



slip occurs if $\tau \geq \mu_s \sigma_n$

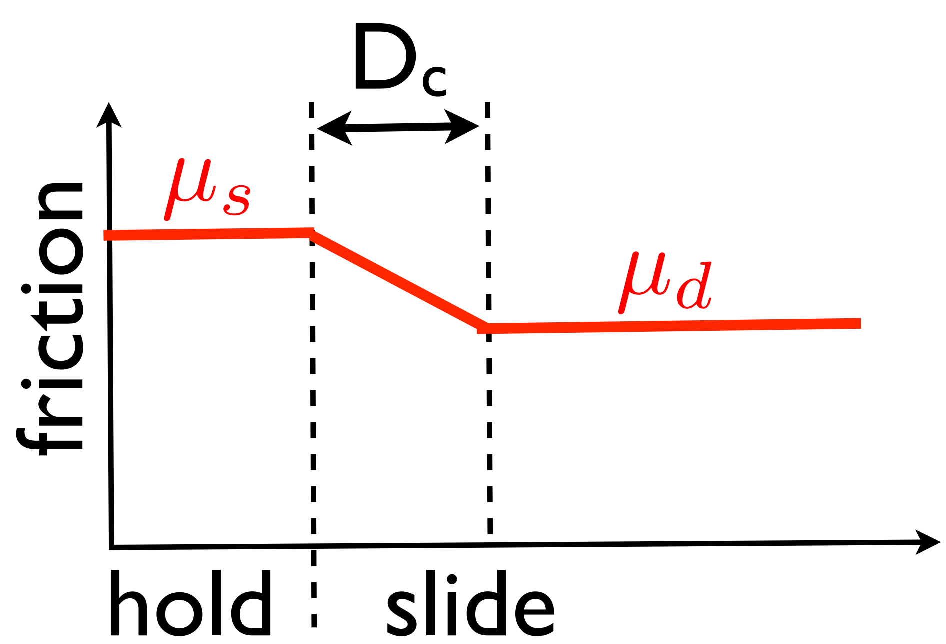
$$\Delta\tau = (\mu_s - \mu_d)\sigma_n$$

Some ideas about static vs. dynamic friction



slip occurs if $\tau \geq \mu_s \sigma_n$

$$\Delta\tau = (\mu_s - \mu_d)\sigma_n$$

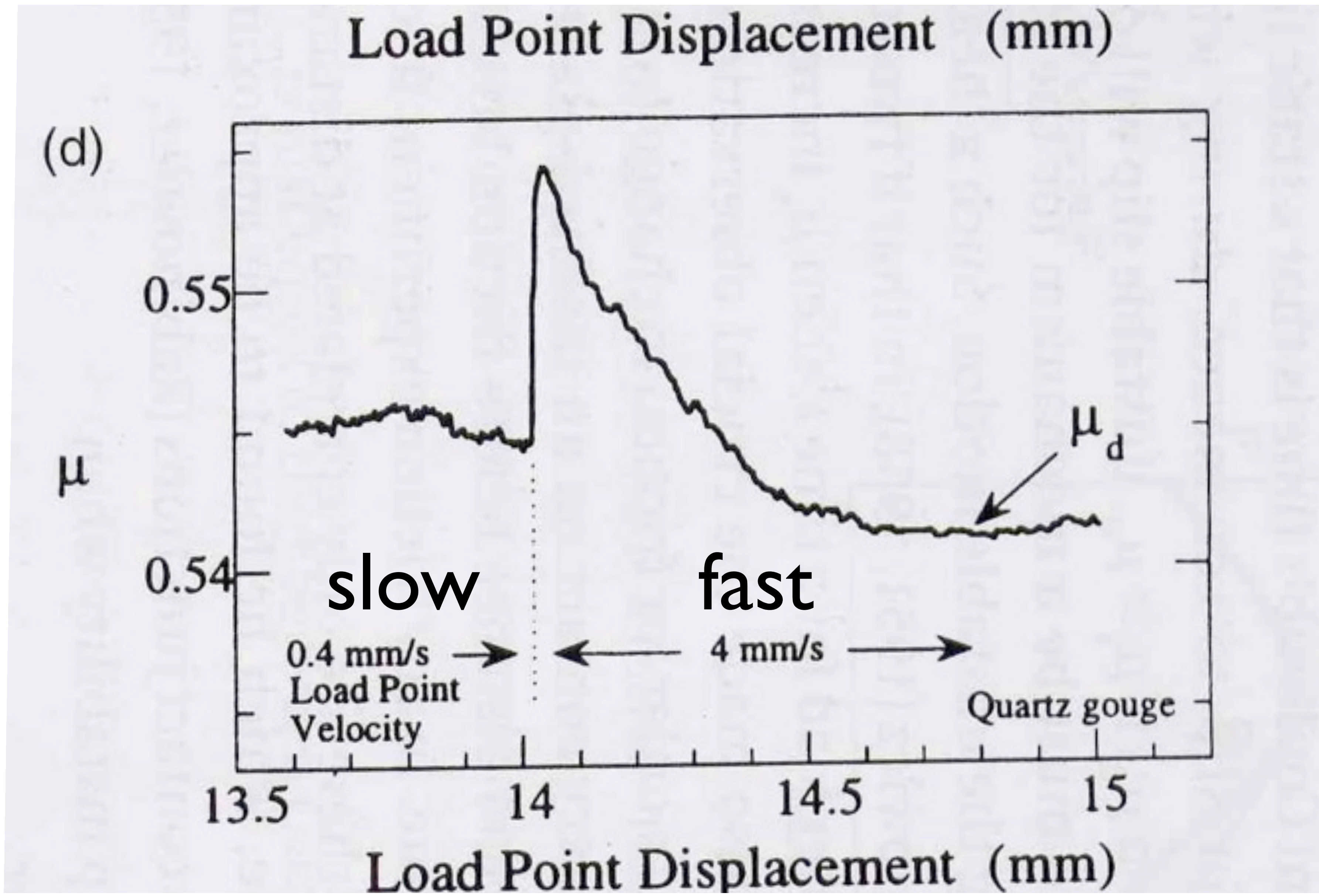


slip may occur.

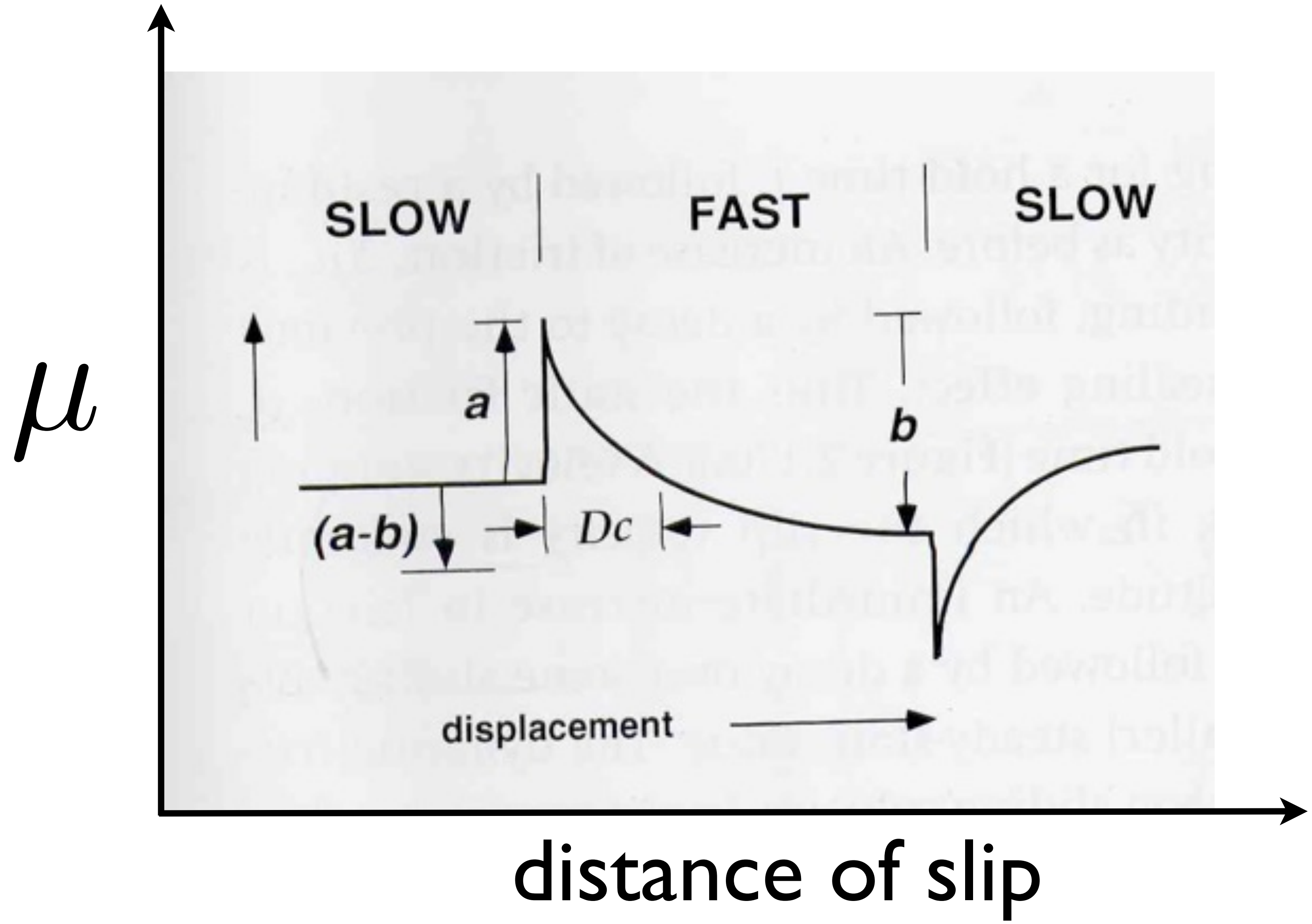
It depends on the "stiffness" of the fault, which is a function of the shear modulus and the size of the fault patch where $\tau \geq \mu_s \sigma_n$

$$\Delta\tau = (\mu_s - \mu_d)\sigma_n$$

What friction data look like when slip velocity is changed suddenly



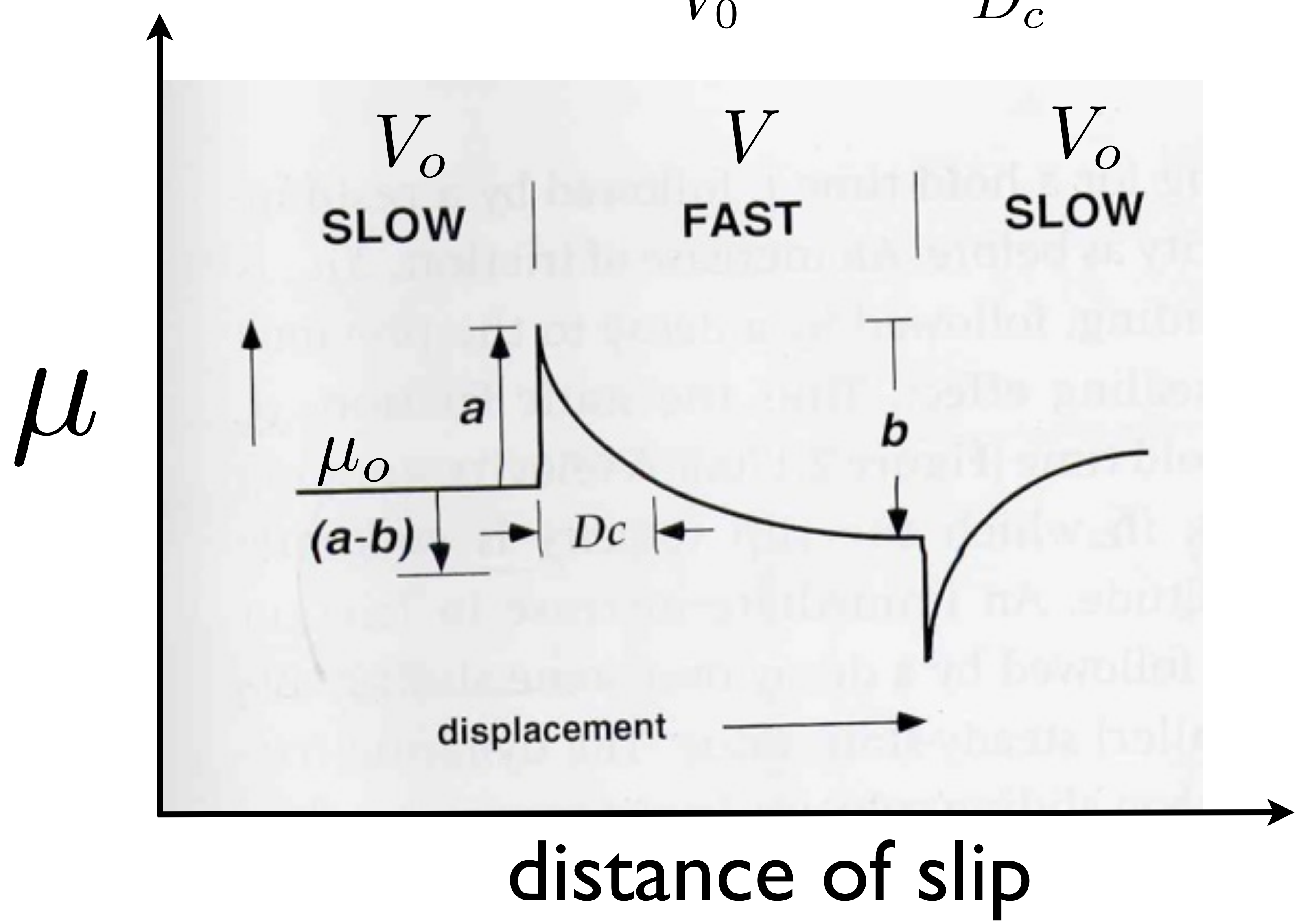
Rate- and state- dependent friction (empirical description of these observations)



$$\mu = \mu_o + a ln(\frac{V}{V_0}) + b ln(\frac{V_o \theta}{D_c})$$

(Dieterich 1981; Ruina 1983)

$$\mu = \mu_o + a ln(\frac{V}{V_0}) + b ln(\frac{V_o \theta}{D_c})$$



$$\theta_o = \frac{D_c}{V_o}$$

The mysterious state variable θ
What is it? (it has units of time...)

It is a healing parameter: allows faults to restrengthen after earthquakes

Dieterich (1981)

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

Ruina (1983)

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

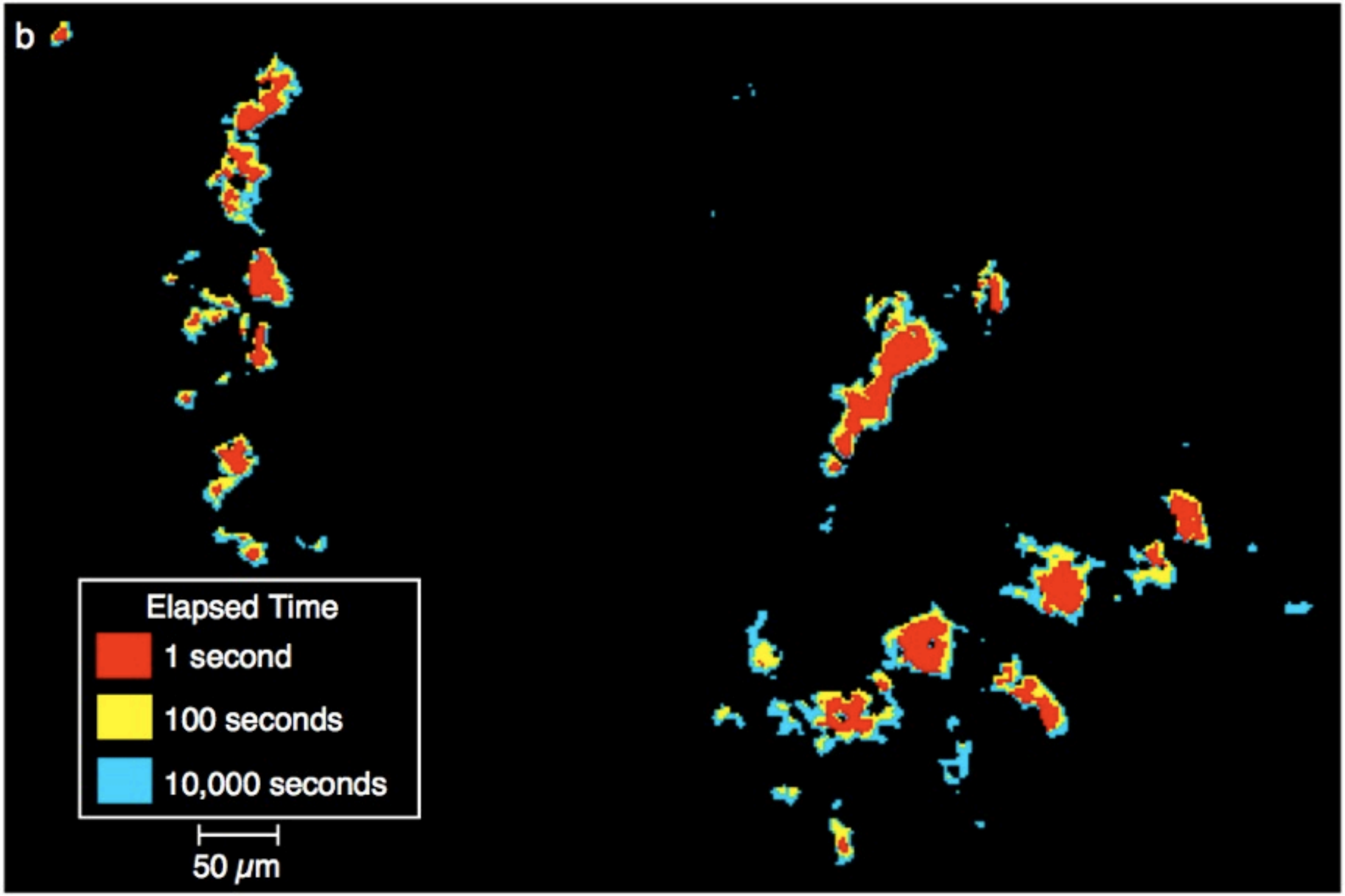
Dieterich law

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

If slip after a rate change >> D_c then $\theta \rightarrow \frac{D_c}{V}$

and we can simplify the above equation to: $\mu = \mu_o + (a-b)ln(\frac{V}{V_o})$

Dieterich and Kilgore, 1994



Asperity contact area also increases with hold time thanks to state variable (healing). This is increasing the frictional strength (mu times normal stress - nut normal stress is constant here)

from Dieterich and Kilgore, 1994

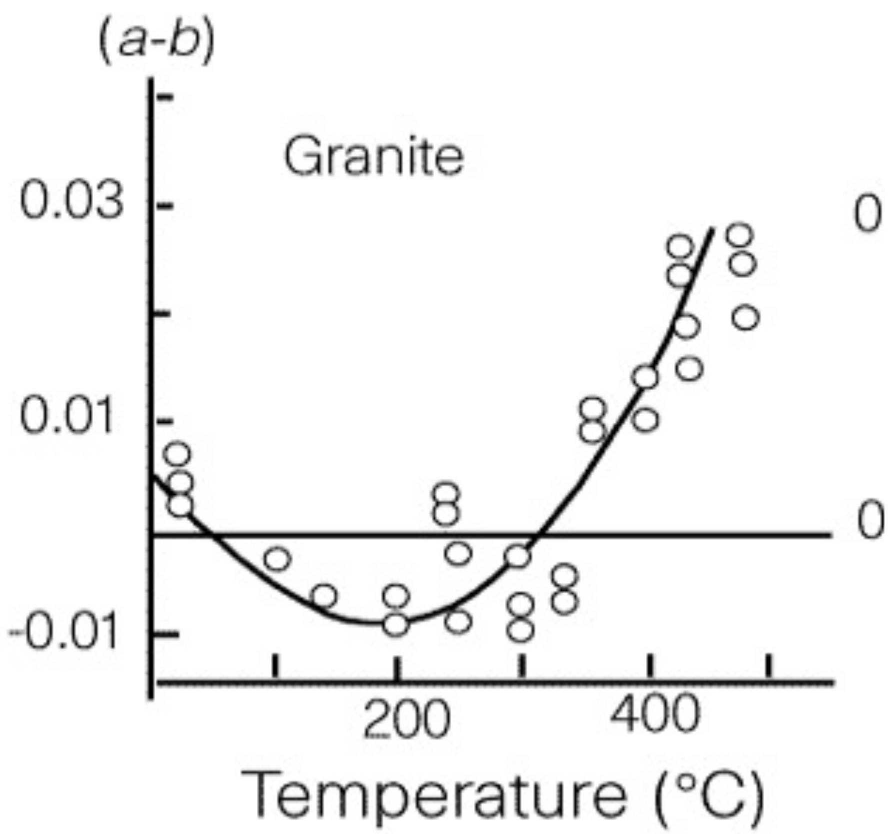
Video images at increasing times of contact confirm increase of contact area with time. Figure 6b illustrates time- dependent contact growth in acrylic. The three processes observed to increase contact area with normal stress also operate to increase contact area with time (contact growth, coalescence and formation of new contacts).

...

We find (Figures 6b and 7) an approximately logarithmic increase of contact area during the hold

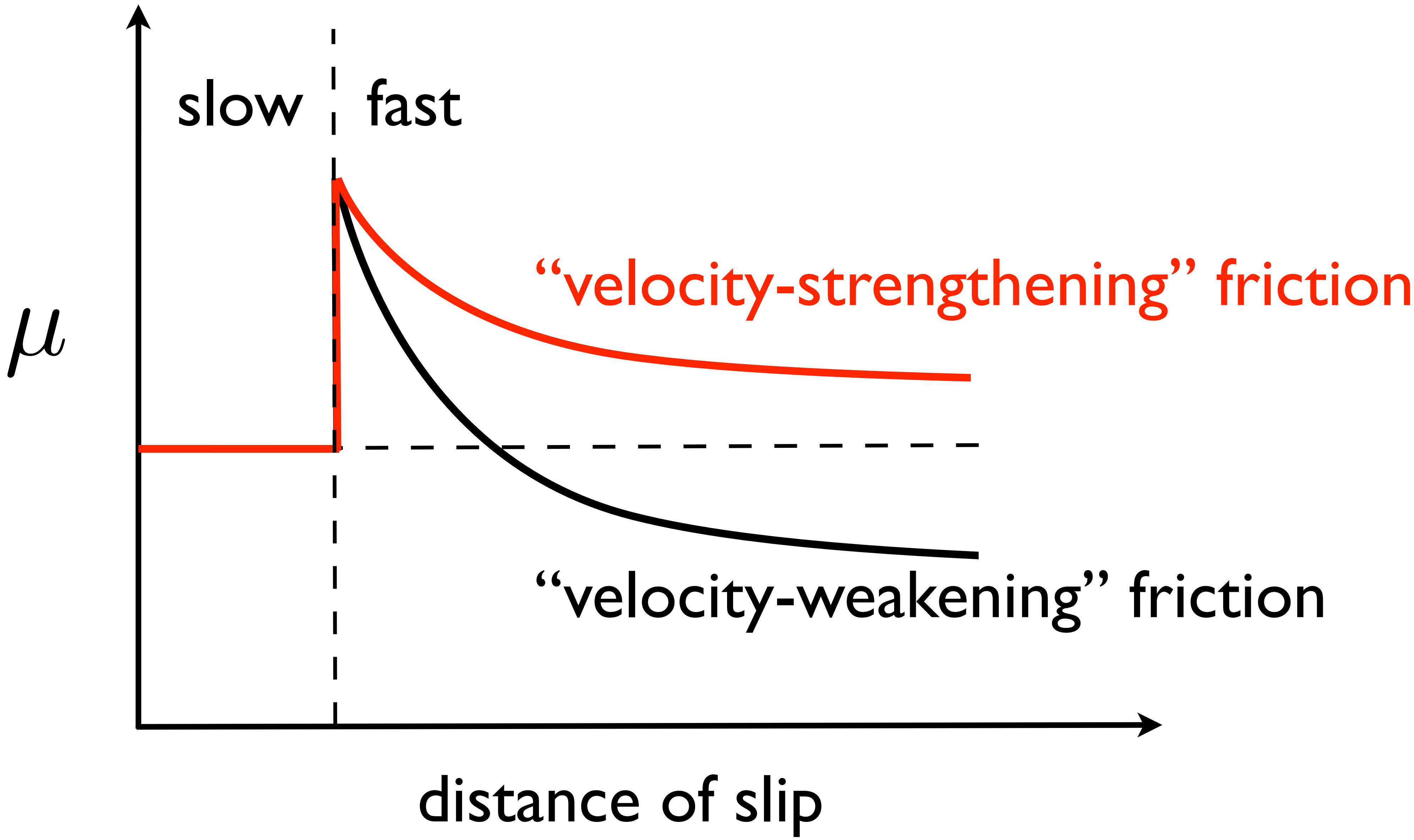
...

Effect of temperature on (a-b)



(*a* - *b*) vs. temperature for granite
(Scholz, 1998 and 2003)

Laboratory experiments show that (a-b) is positive at temperatures higher than about 300°C for most crustal rocks.



$$\mu = \mu_o + (a - b)ln(\frac{V}{V_o})$$

if positive then ____

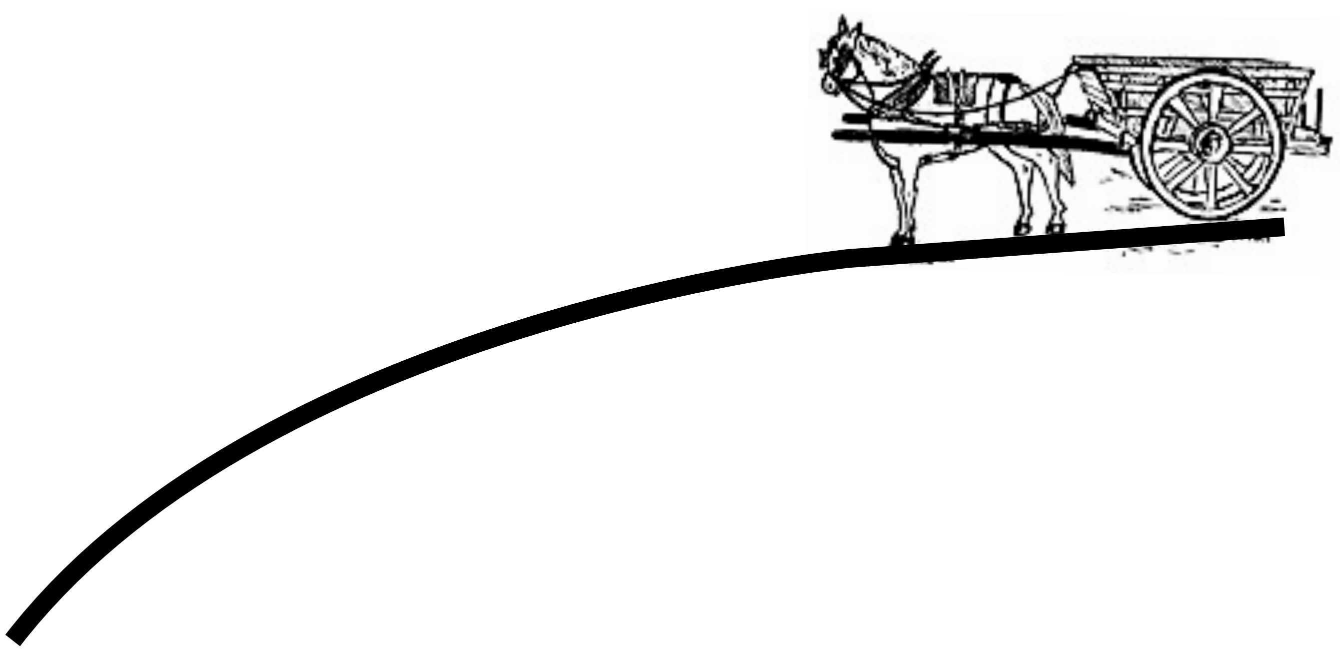
if negative then _____

velocity-strengthening friction:

faster sliding -->
stronger fault -->
slows sliding

<u>velocity-strengthening friction:</u>

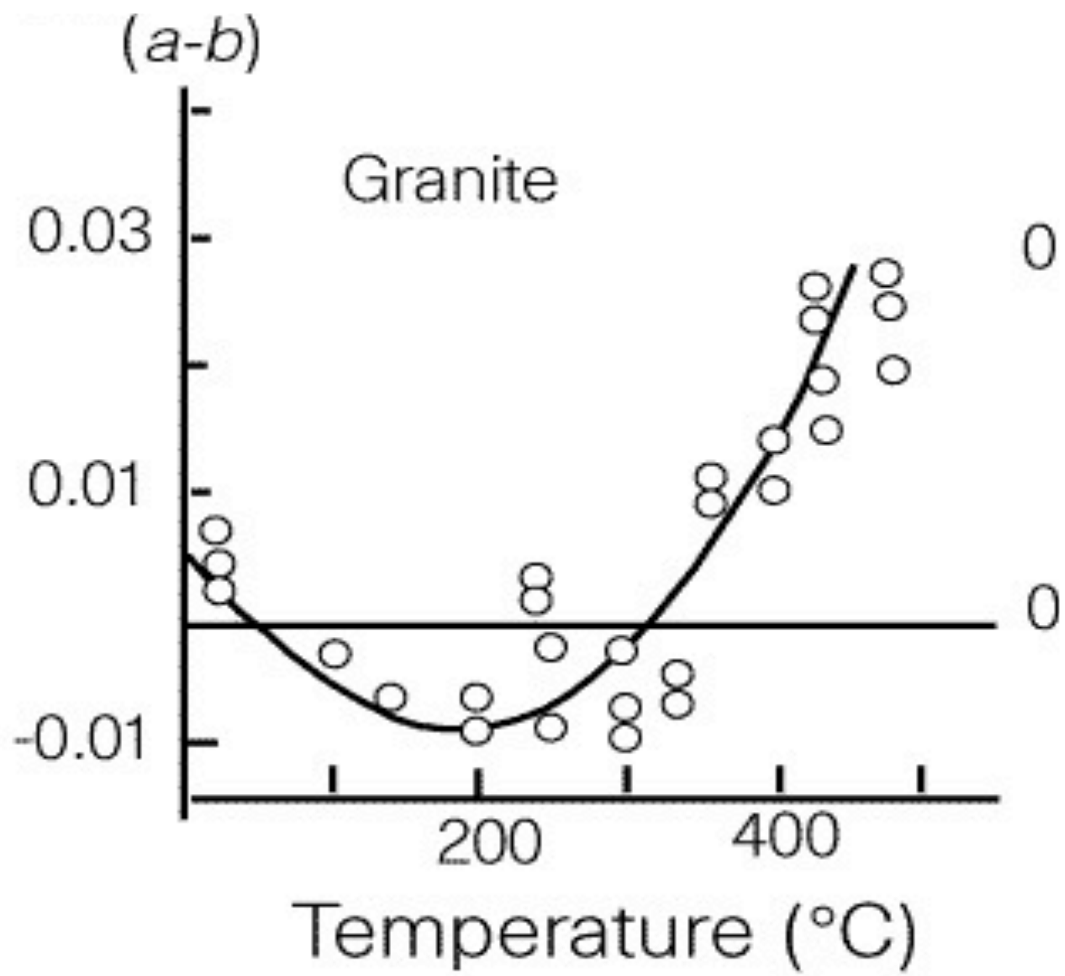
faster sliding -->
stronger fault -->
slows sliding



<u>velocity weakening friction:</u>

faster sliding -->
weaker fault -->
even faster sliding

Effect of temperature on friction



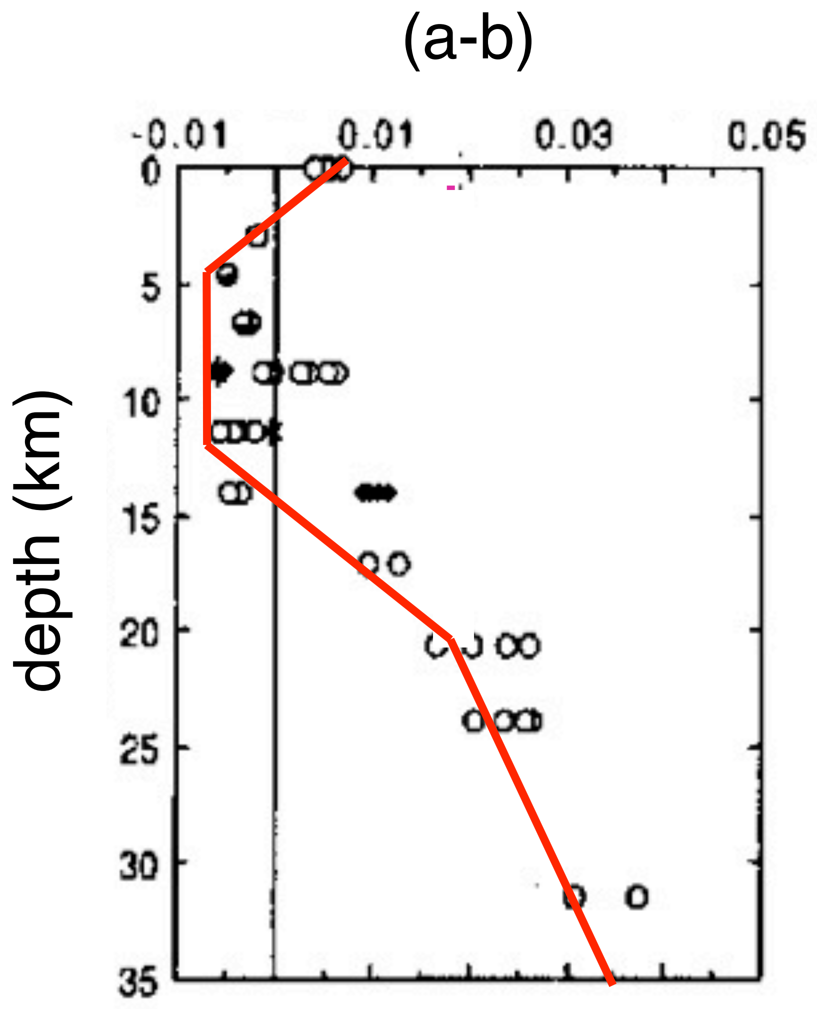
(a - b) vs. temperature for granite (Scholz, 1998 and 2003)

Stable frictional sliding is promoted at temperatures higher than about 300°C for most crustal rocks (at depths exceeding about 12-15 km).

This stops downward propagation of earthquake ruptures.

This prevents nucleation of earthquakes below 12-15 km.

How (a-b) varies with depth



(Blanpied et al, 1991)

T < 300-350°C
a-b<0
Sliding can be unstable

T > 300-350°C
a-b>0
Sliding is stable

μ has NOTHING to do with stability!
Only the **change** in μ with sliding velocity matters.

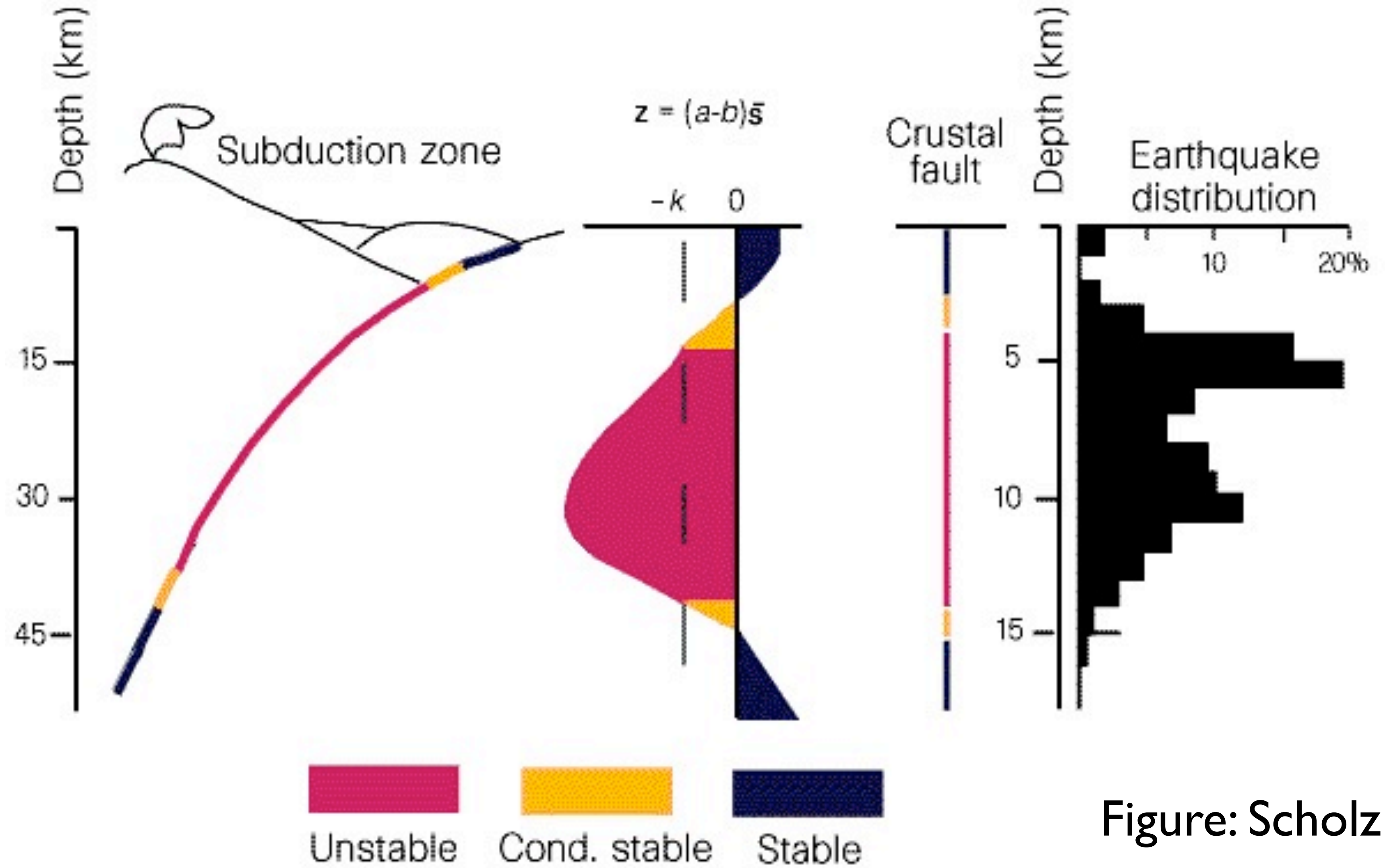


Figure: Scholz 1998

Why velocity-strengthening friction?

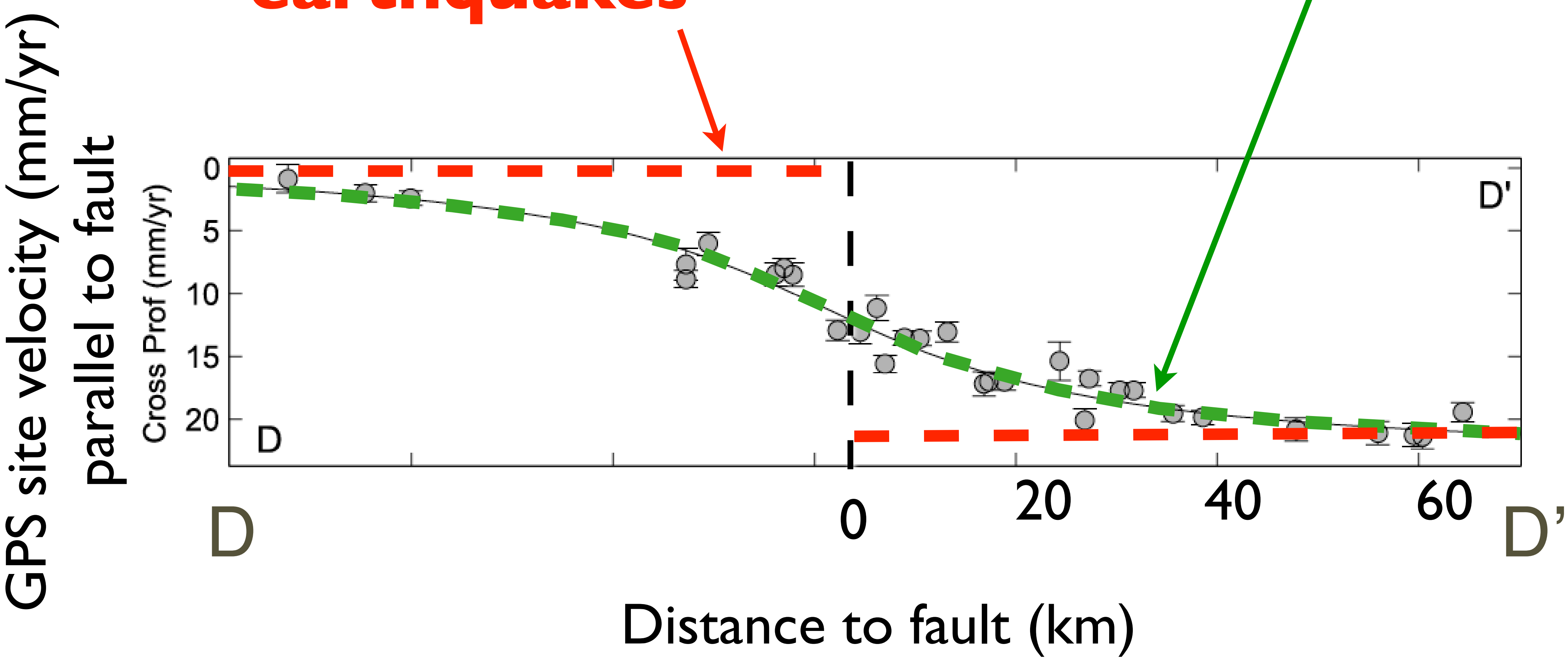
• shallow: granular gouge. particles must move around each other to allow relative motion of two sides of the fault. This requires volume increase with increased sliding rate, which requires energy input.

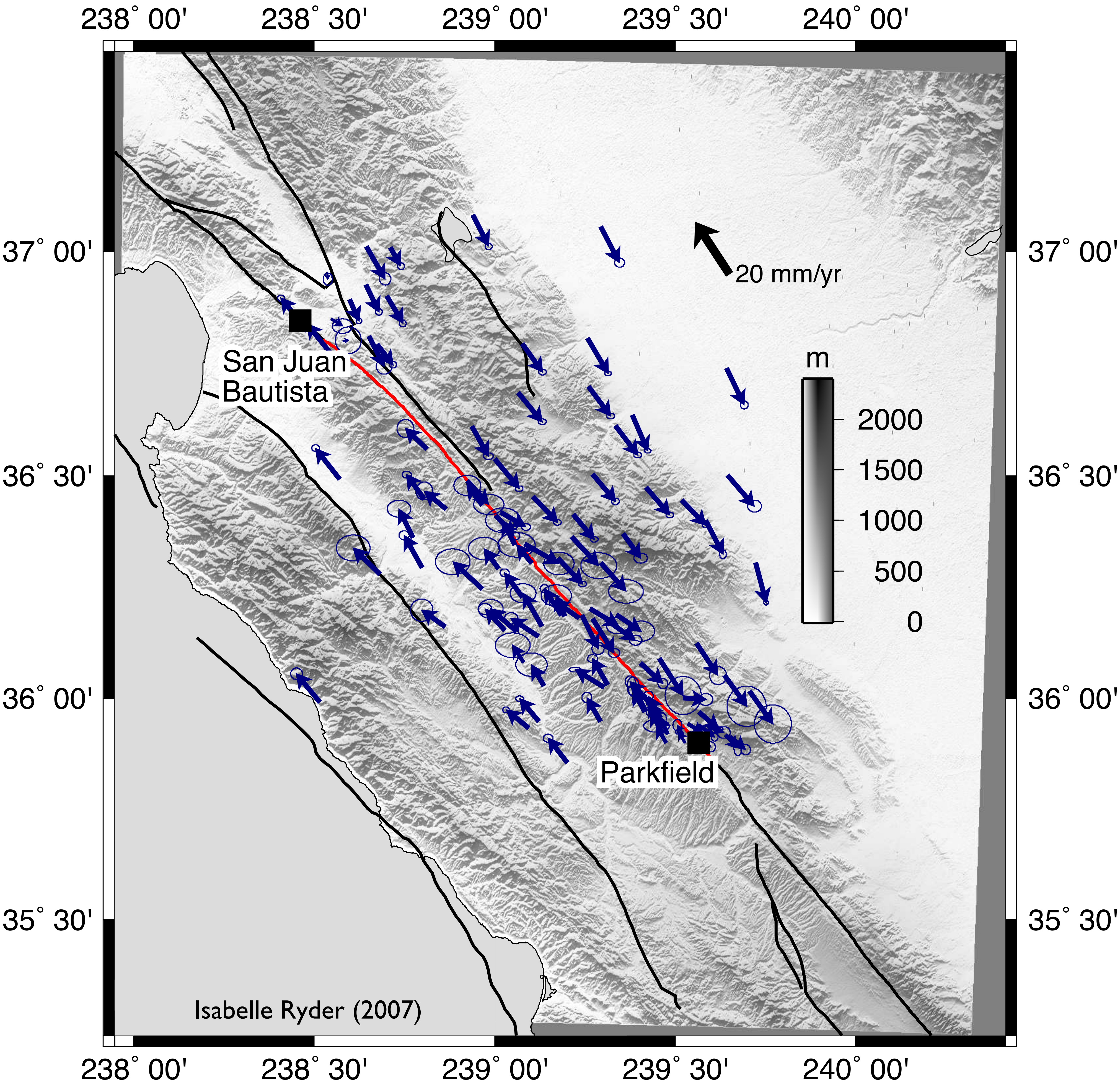
• deep: Big a. Hotter. Asperities deform viscously to some extent before breaking, and with viscous flow, higher shear stress is required for a higher slip velocity (strain rate across the fault)

Wouldn't it be great if ALL faults were velocity-strengthening?

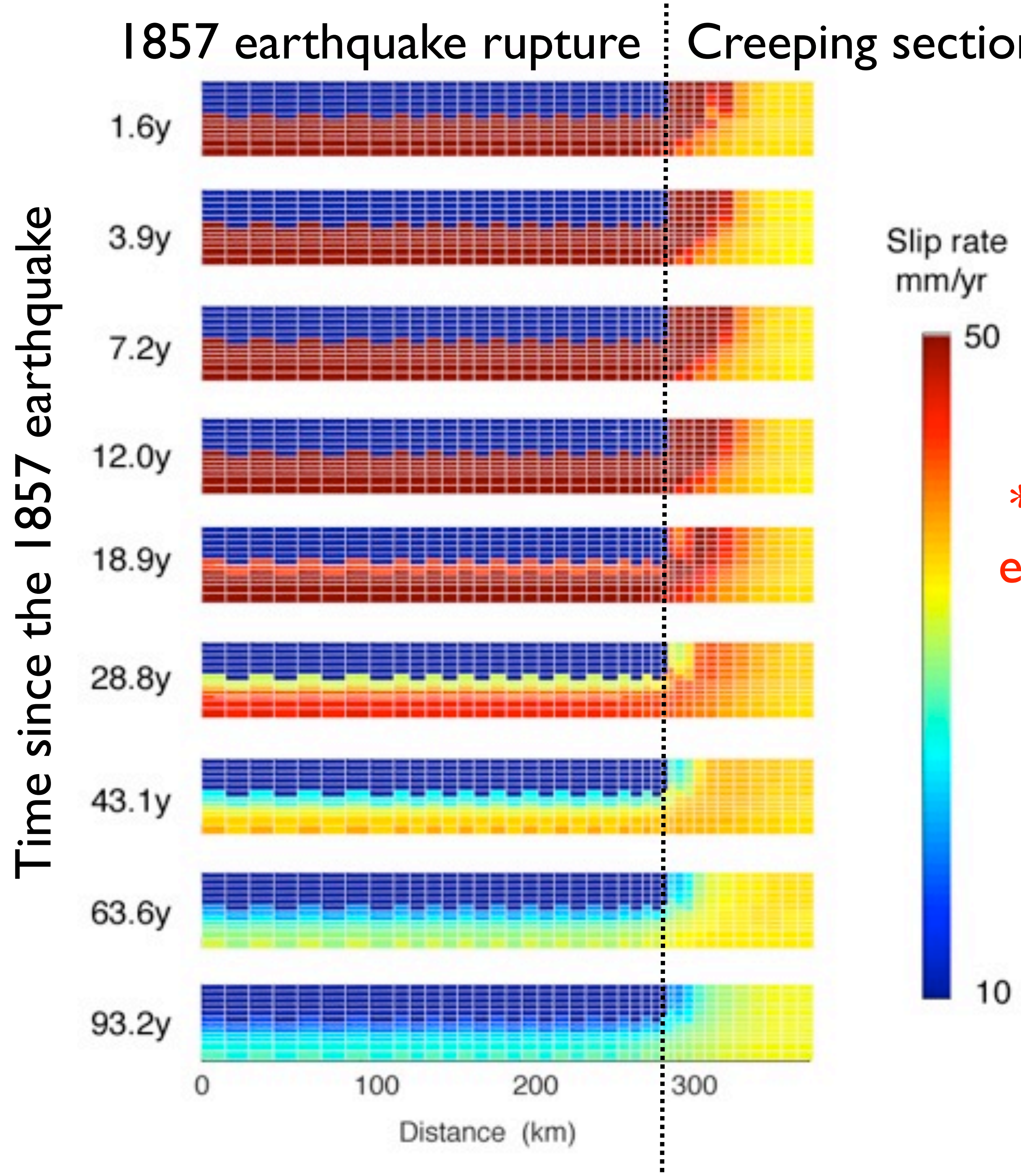
creeping fault: strain and stress are both constant. Aseismic creep and **no earthquakes**

ordinary fault: crust warps around the fault (arctangent profile). strain and elastic stress build up between earthquakes




238° 00'
238° 30'
239° 00'
239° 30'
240° 00'
37° 00'
36° 30'
36° 00'
35° 30'
20 mm/yr
m
2000
1500
1000
500
0
San Juan
Bautista
Parkfield
Isabelle Ryder (2007)

Creeping section of the San Andreas Fault has velocity-strengthening friction

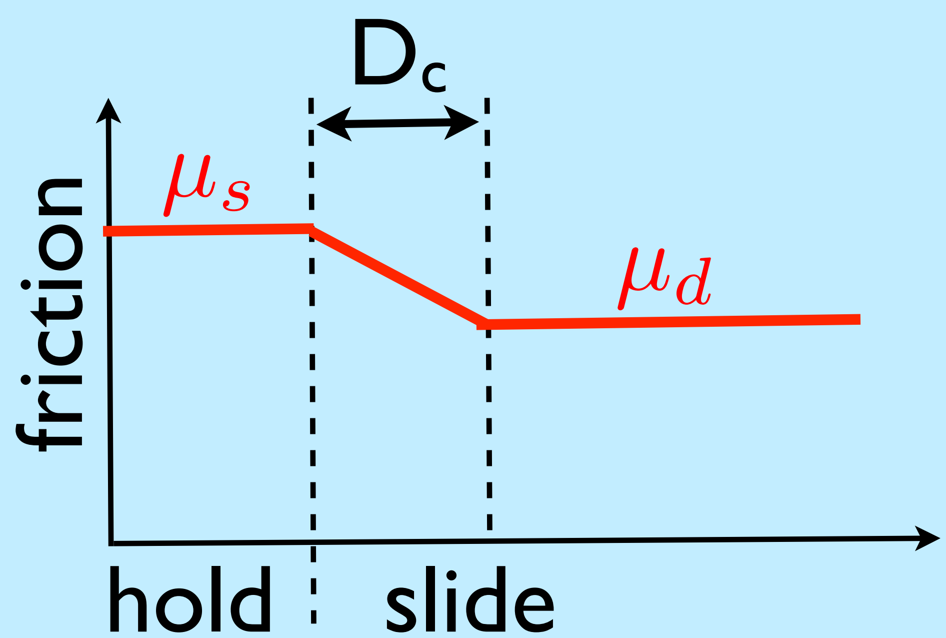


*if the fault is “kicked” by an earthquake nearby, creep and speed up or slow down.

Velocity-weakening or slip-weakening friction:
fault is still not <u>always</u> unstable
Scholz (1998) gives required conditions for instability

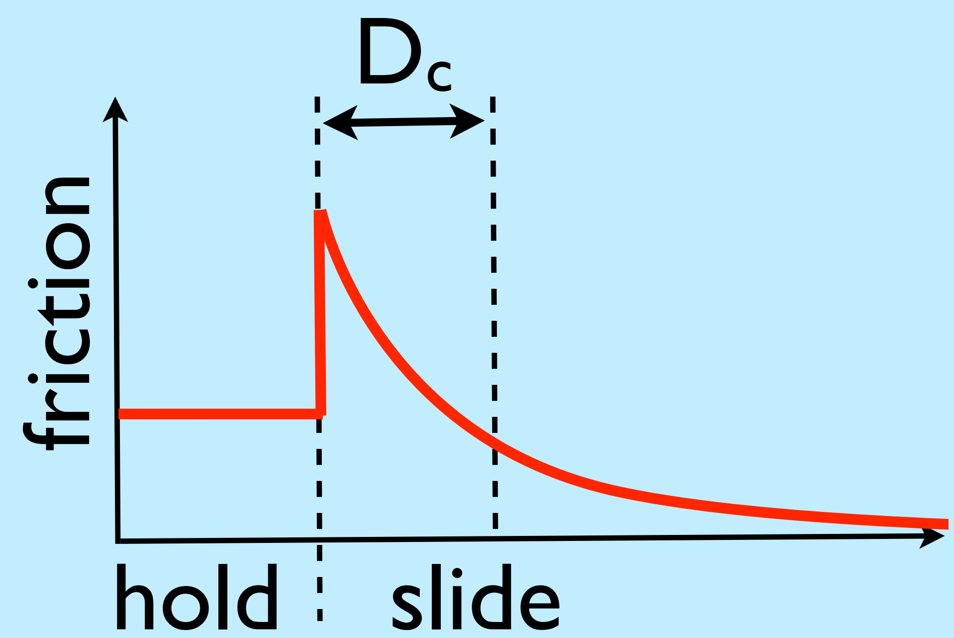
Slip-weakening

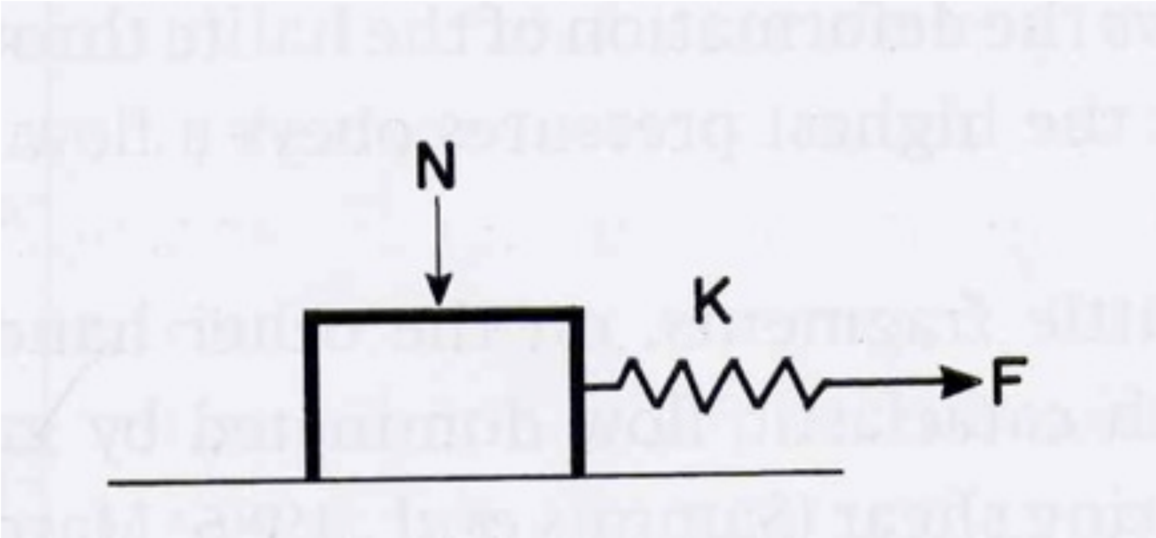
slip <u>may</u> occur if $\tau \geq \mu_s \sigma_n$



Velocity-weakening

slip <u>may</u> occur if $\tau \geq \mu_s \sigma_n$





This is a battle between the shear force pulling the block and the friction force resisting it

$$\tau \times A = k \times x = F_{spring} =$$

$$\sigma_n \times A \times \mu = N \times \mu = F_{friction}$$

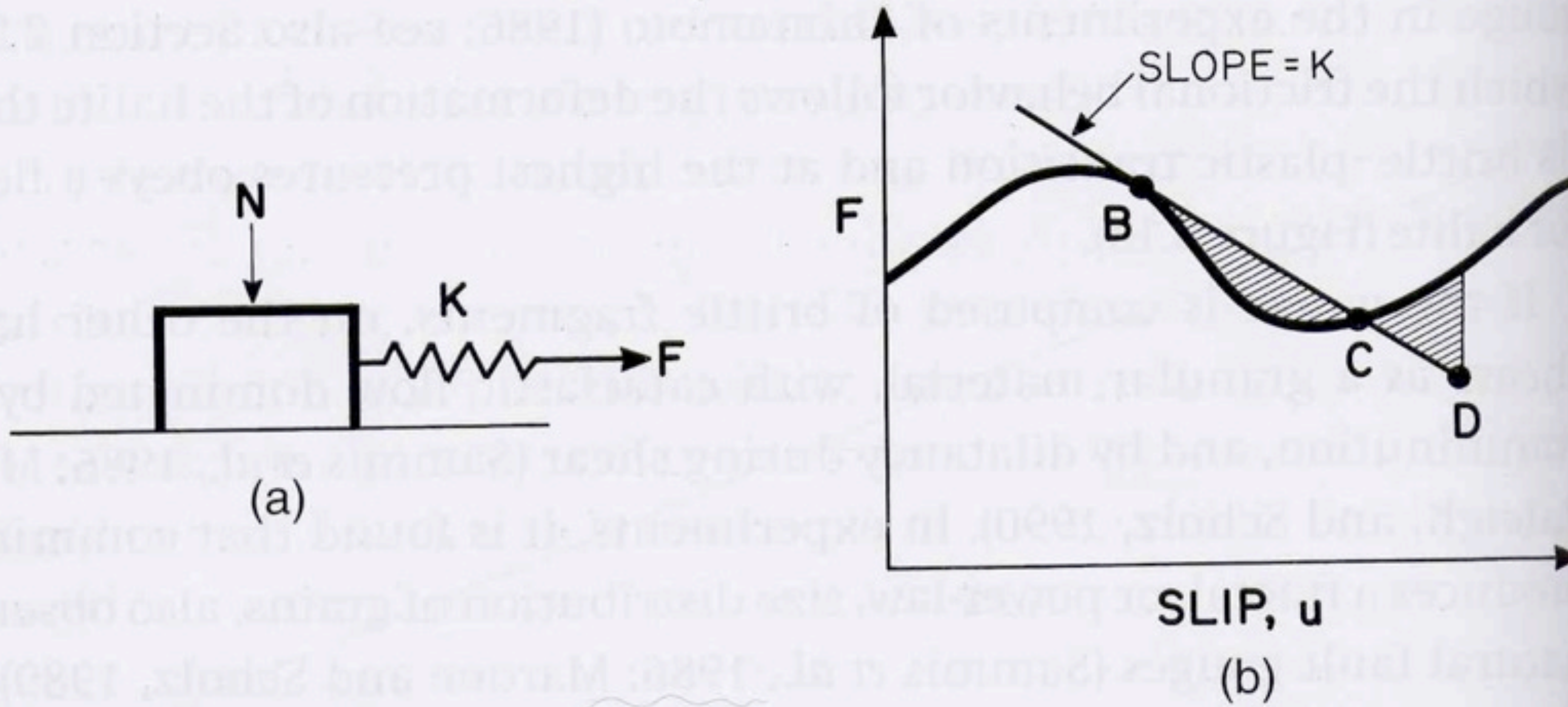
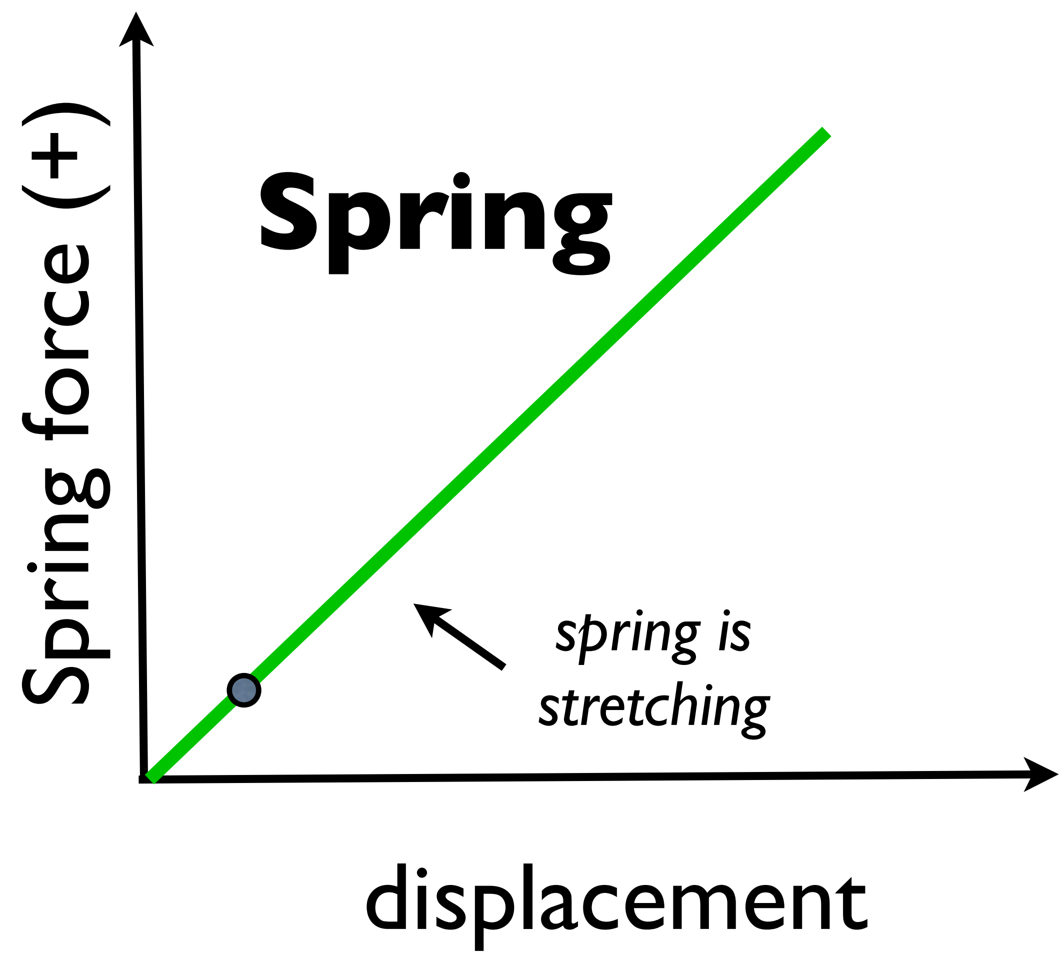
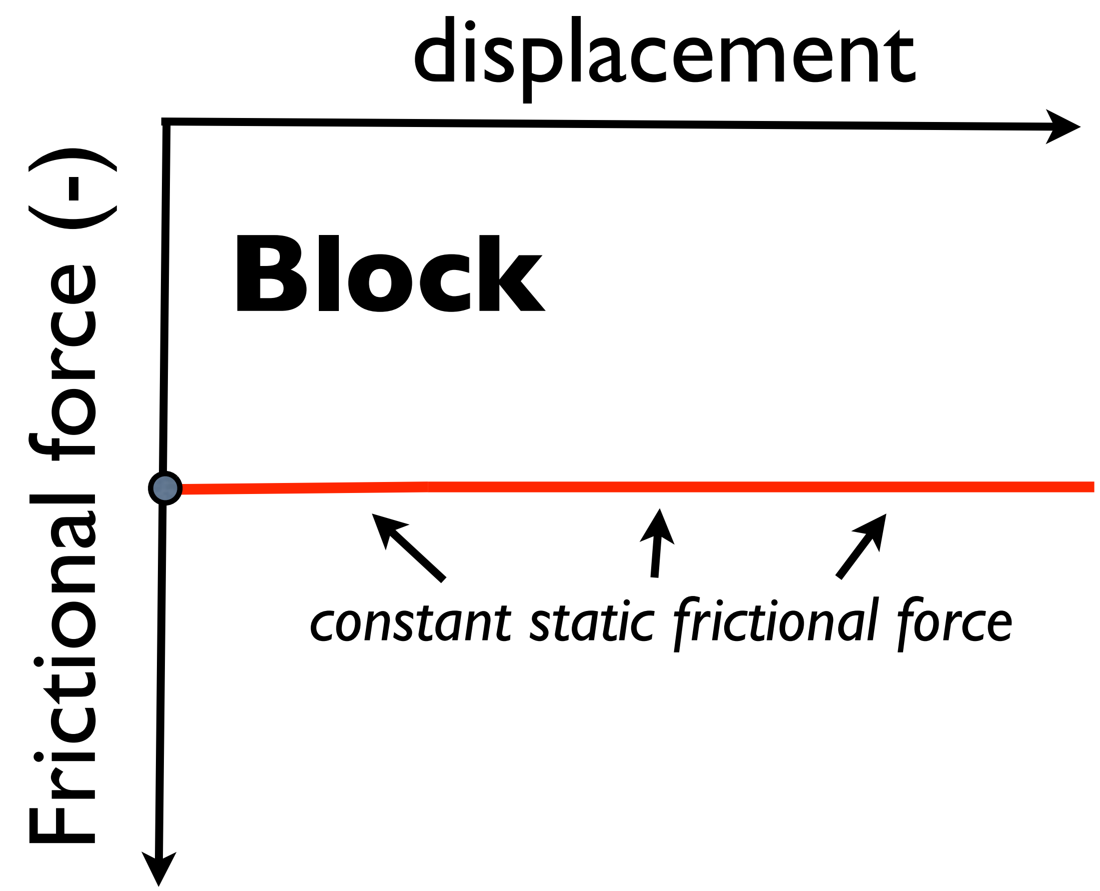
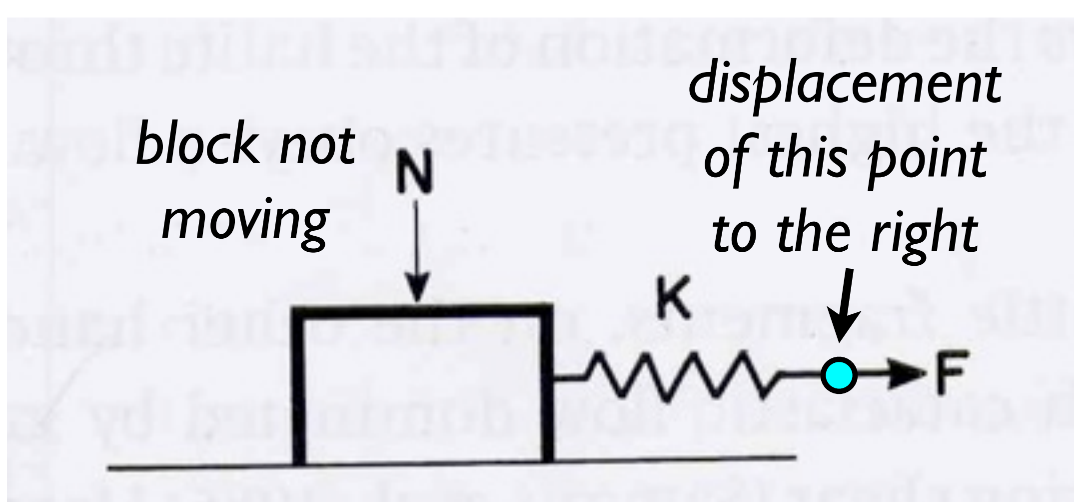


Fig. 2.16. Schematic diagram illustrating the origin of frictional instability: (a) a block-slider model; (b) a force–displacement diagram showing a hypothetical case in which the frictional resistance force falls with displacement at a rate faster than the system can respond.

Before the block starts to slide...

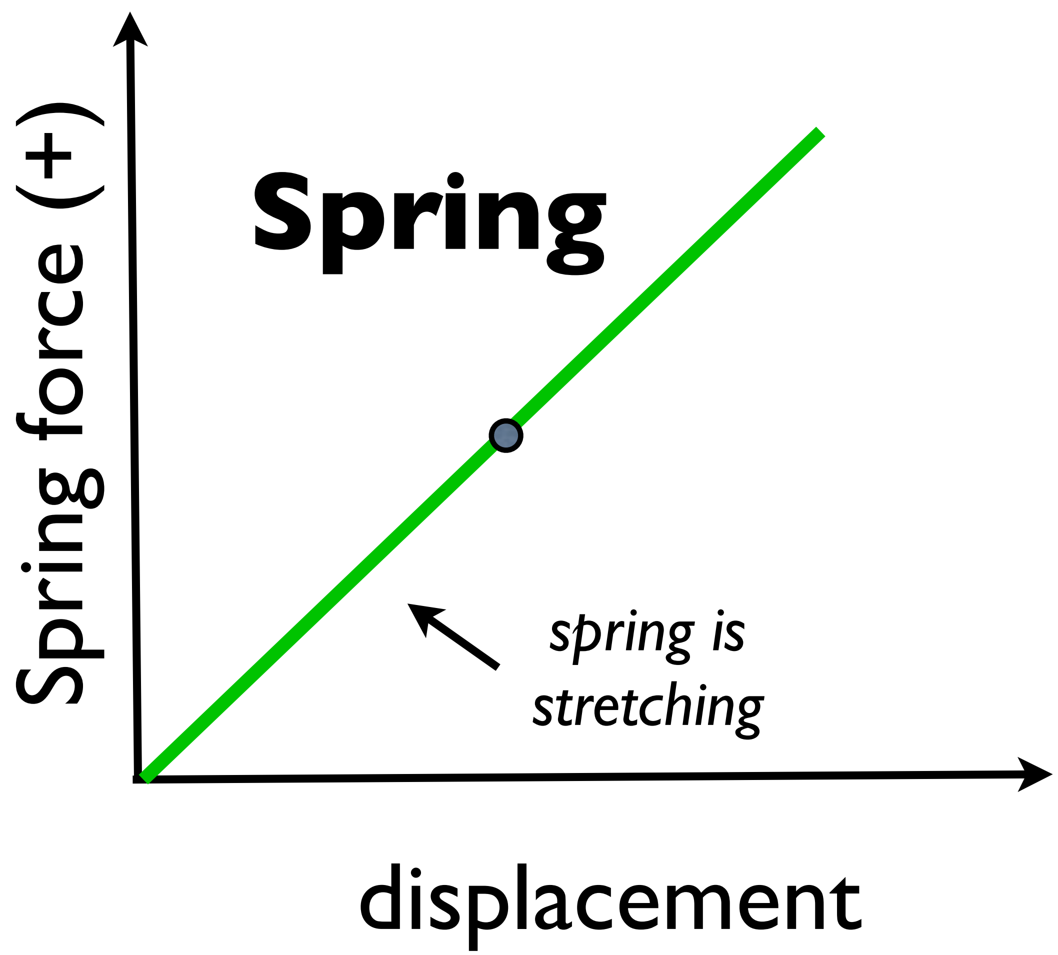


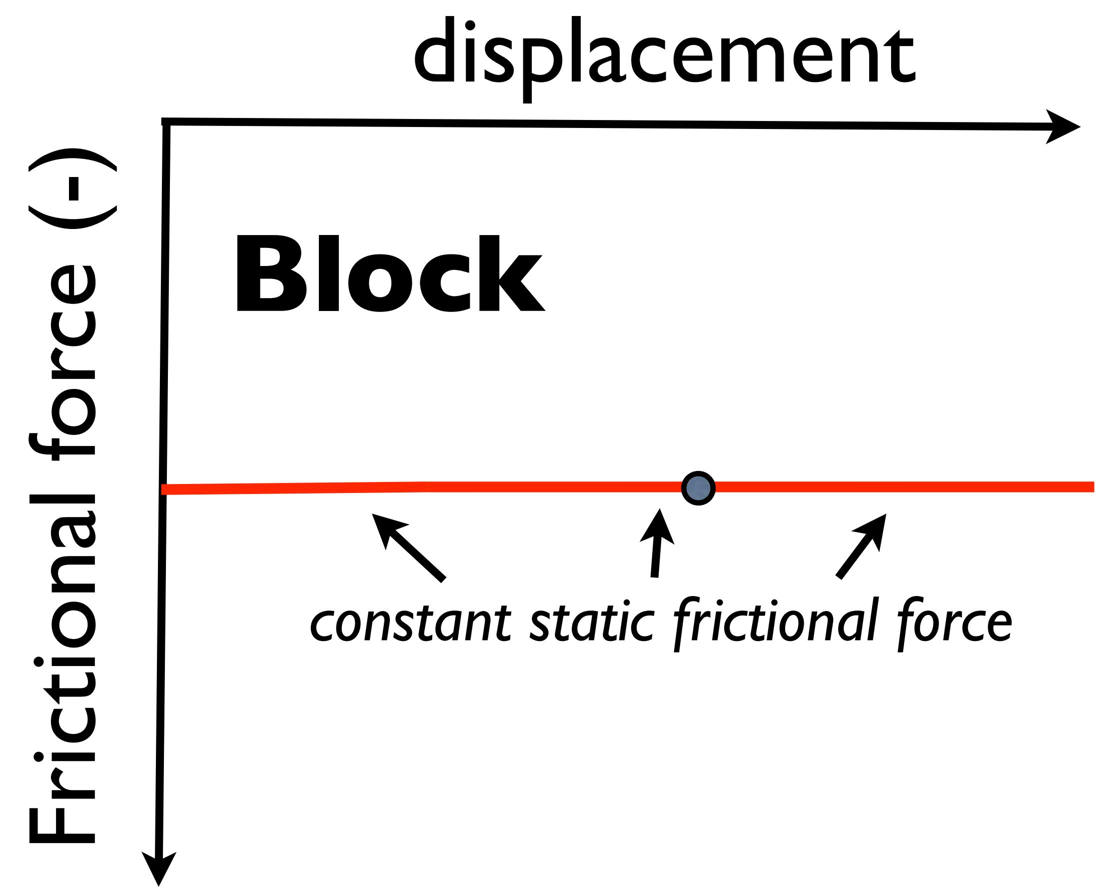


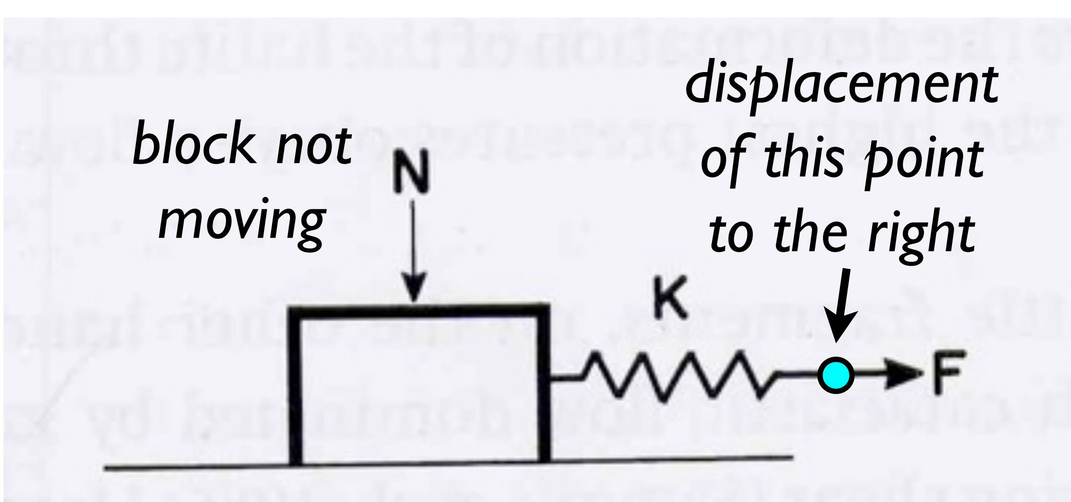


to the right =
+ x direction

Before the block starts to slide...

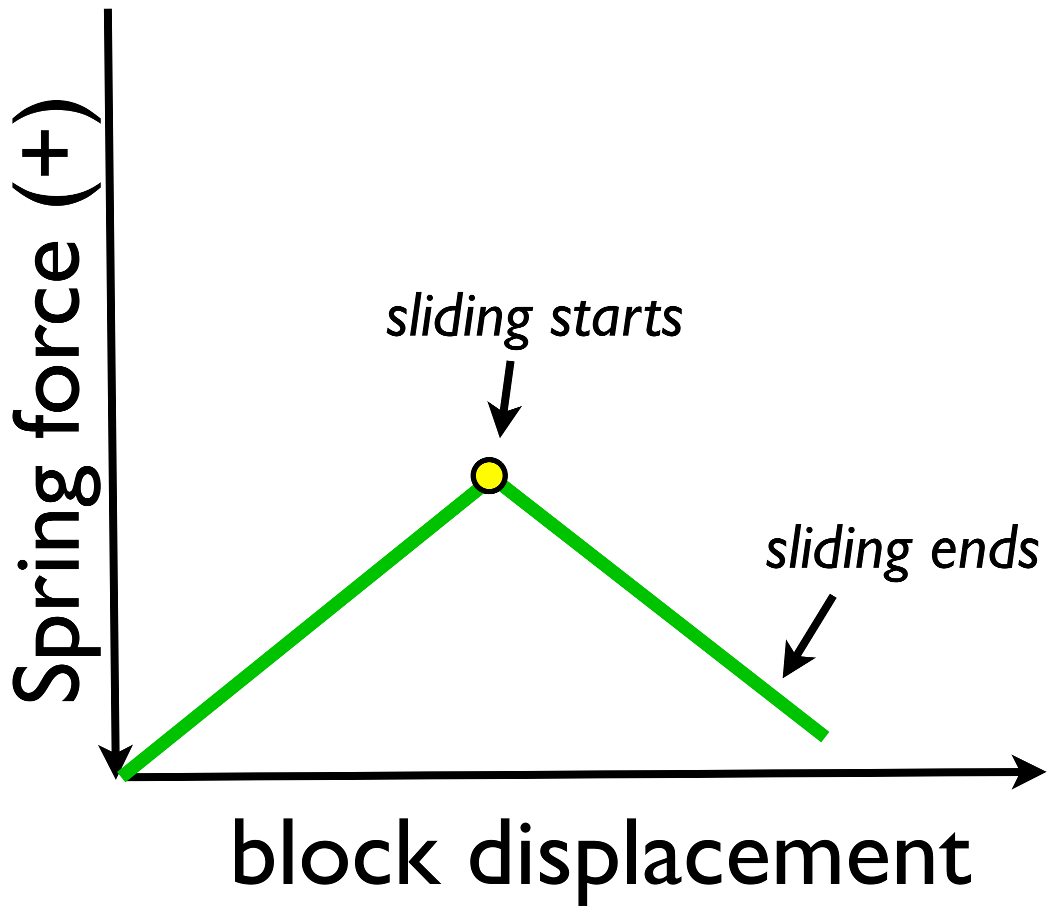


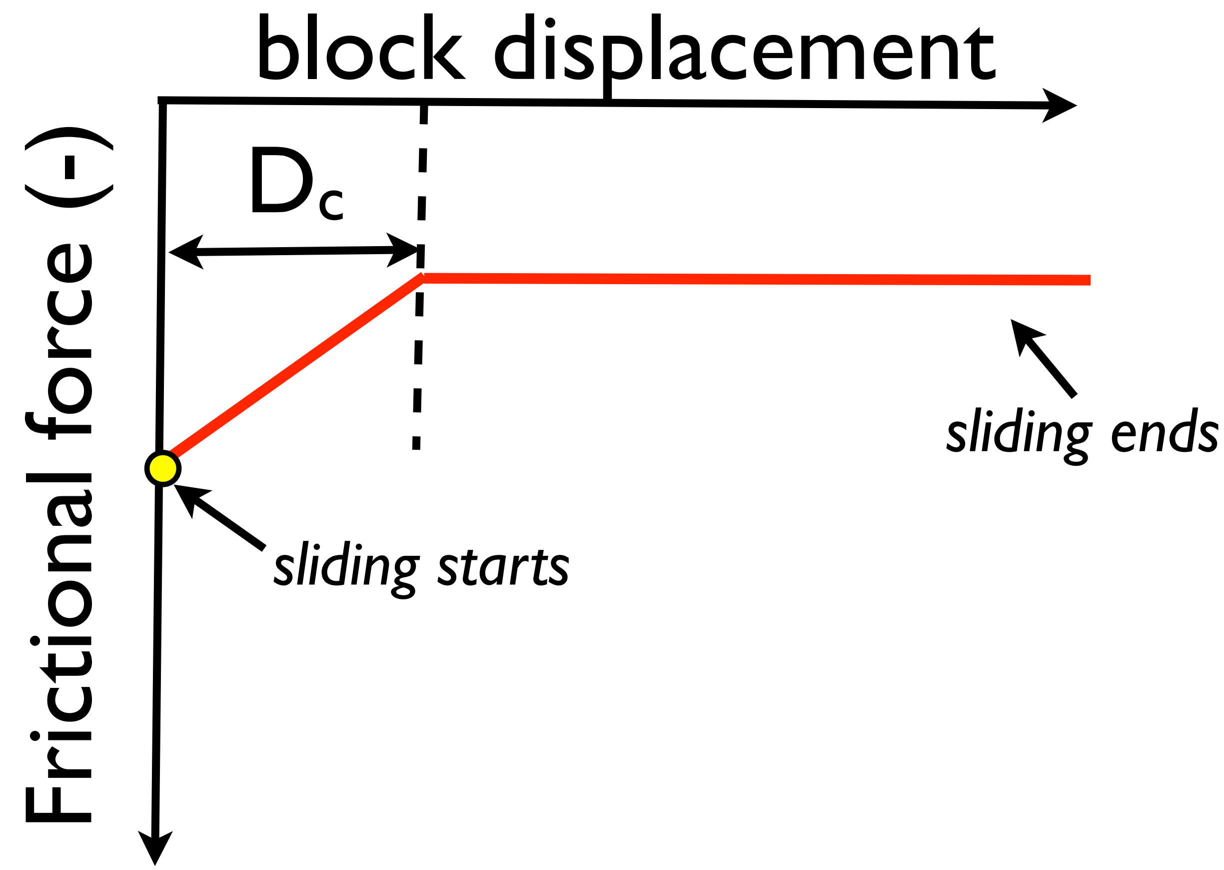


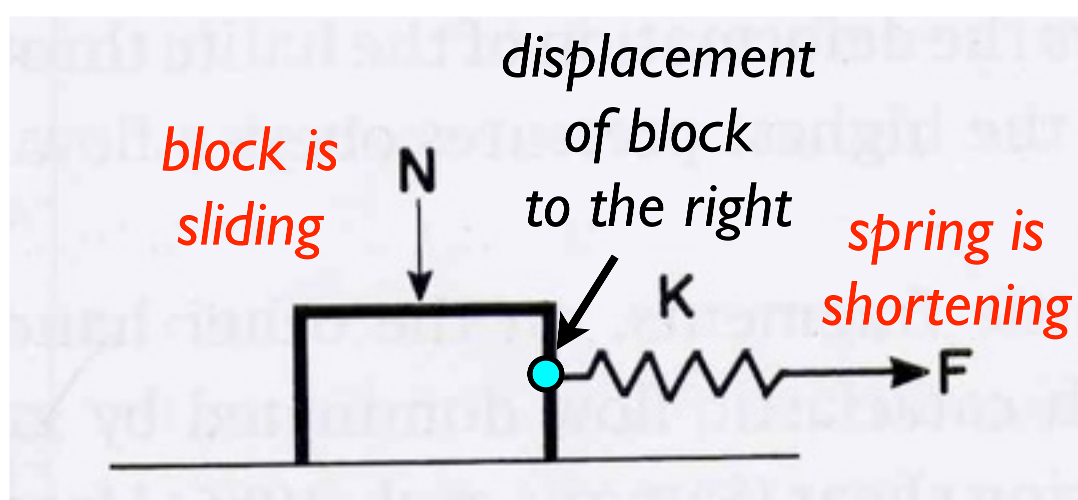


to the right =
+ x direction

Now block sliding begins... assume slip weakening friction

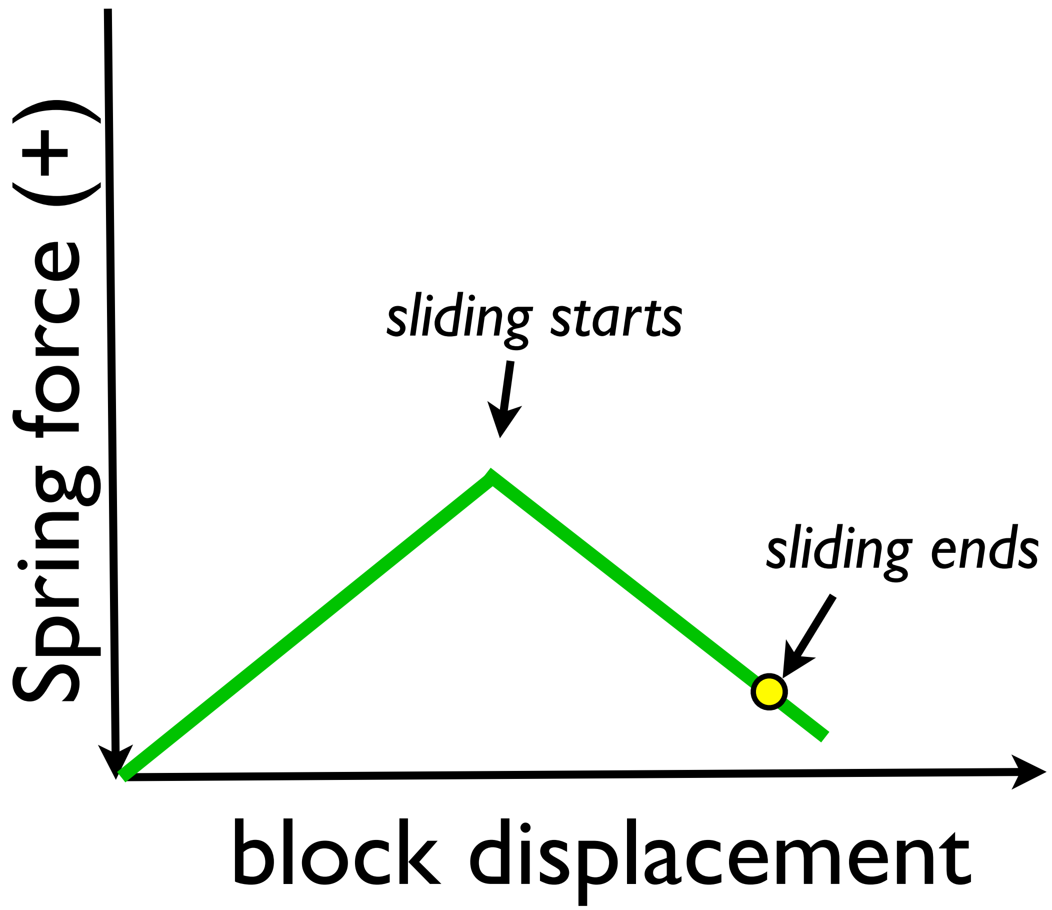


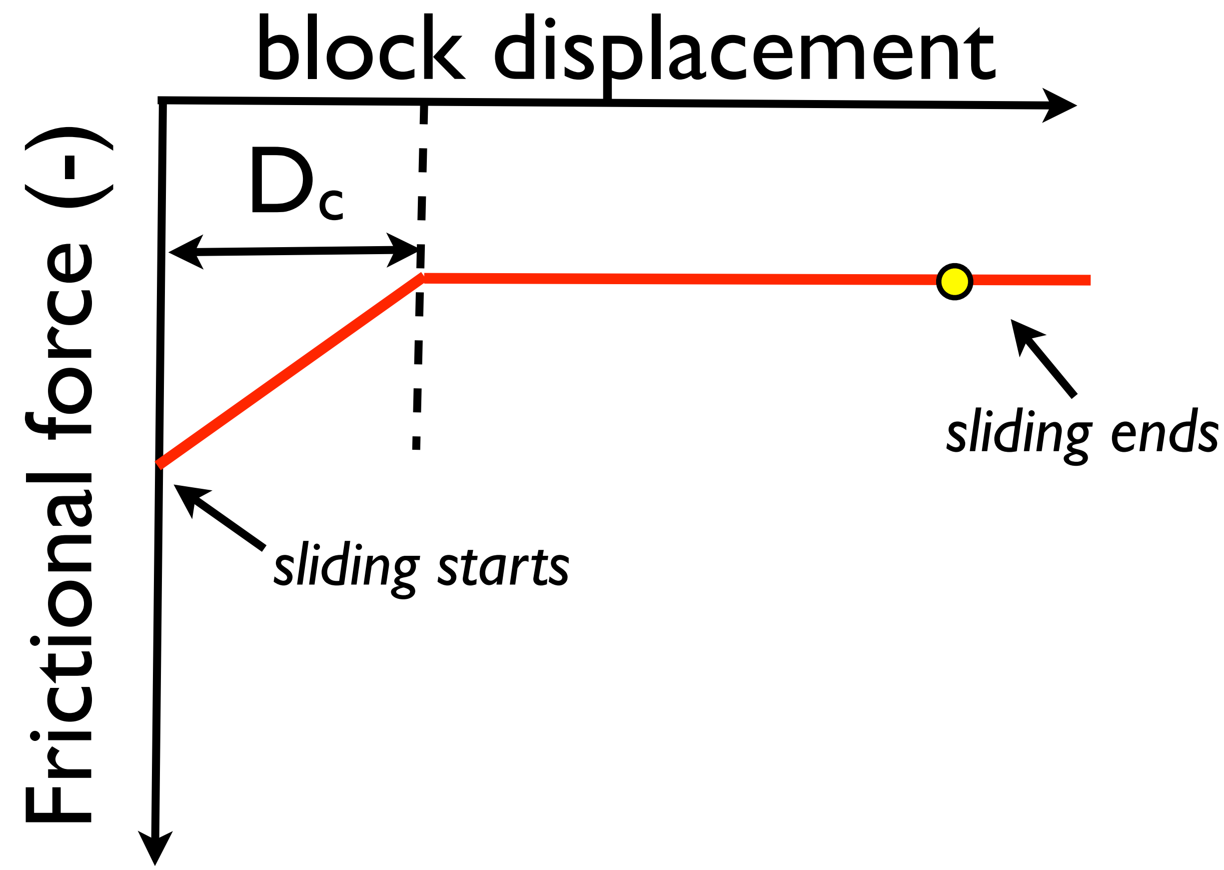


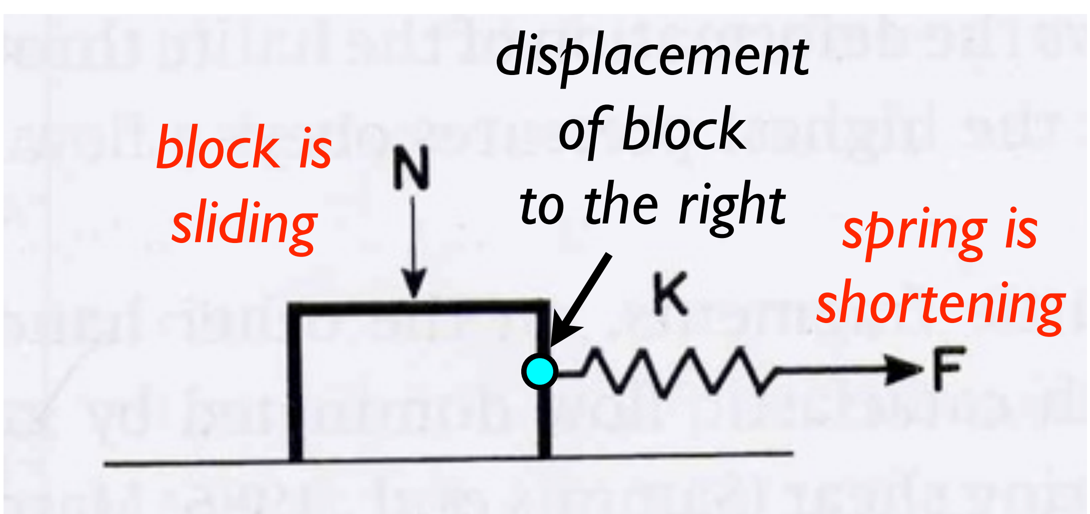


to the right =
+ x direction

Now block sliding begins... assume slip weakening friction

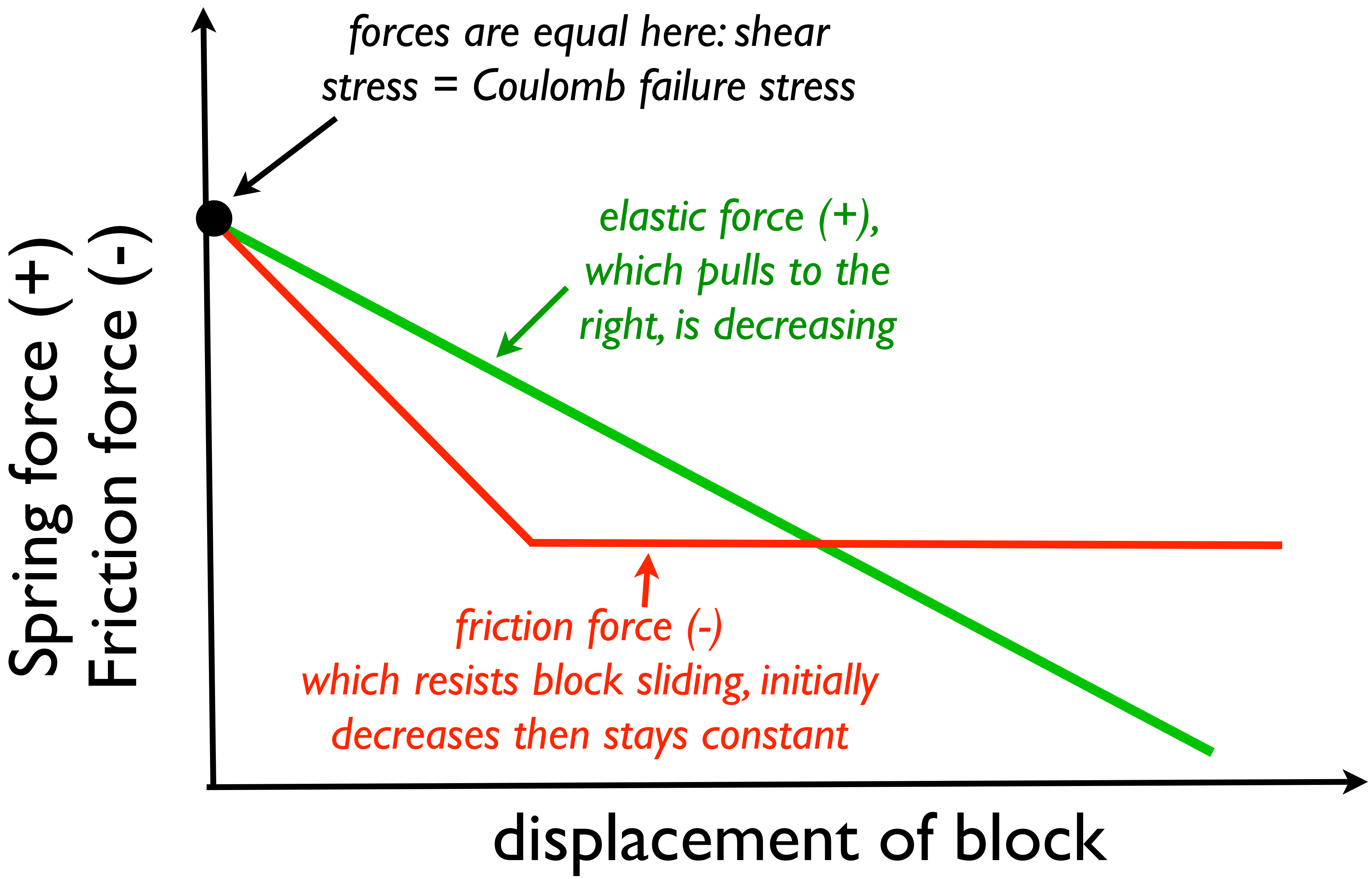


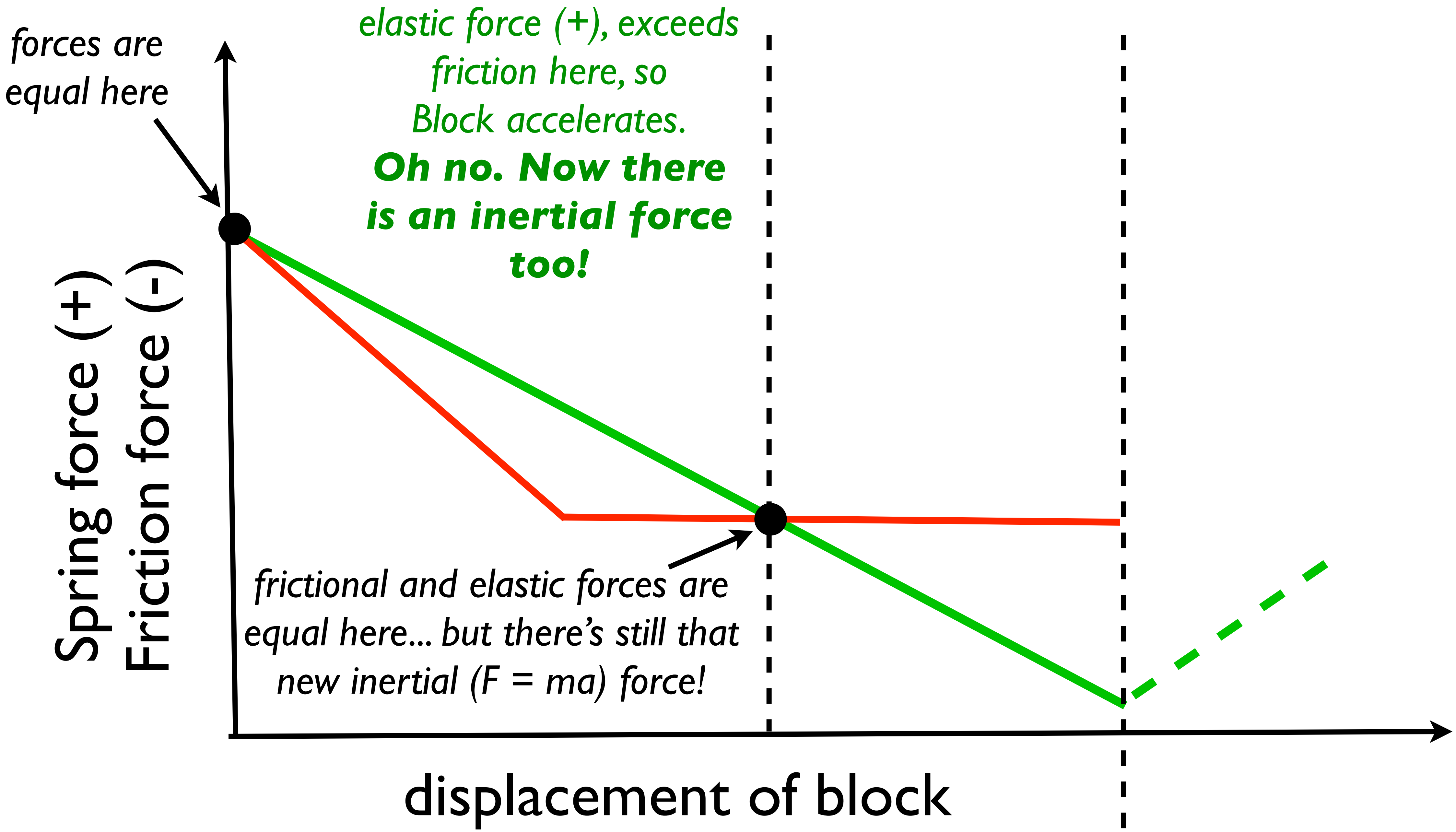


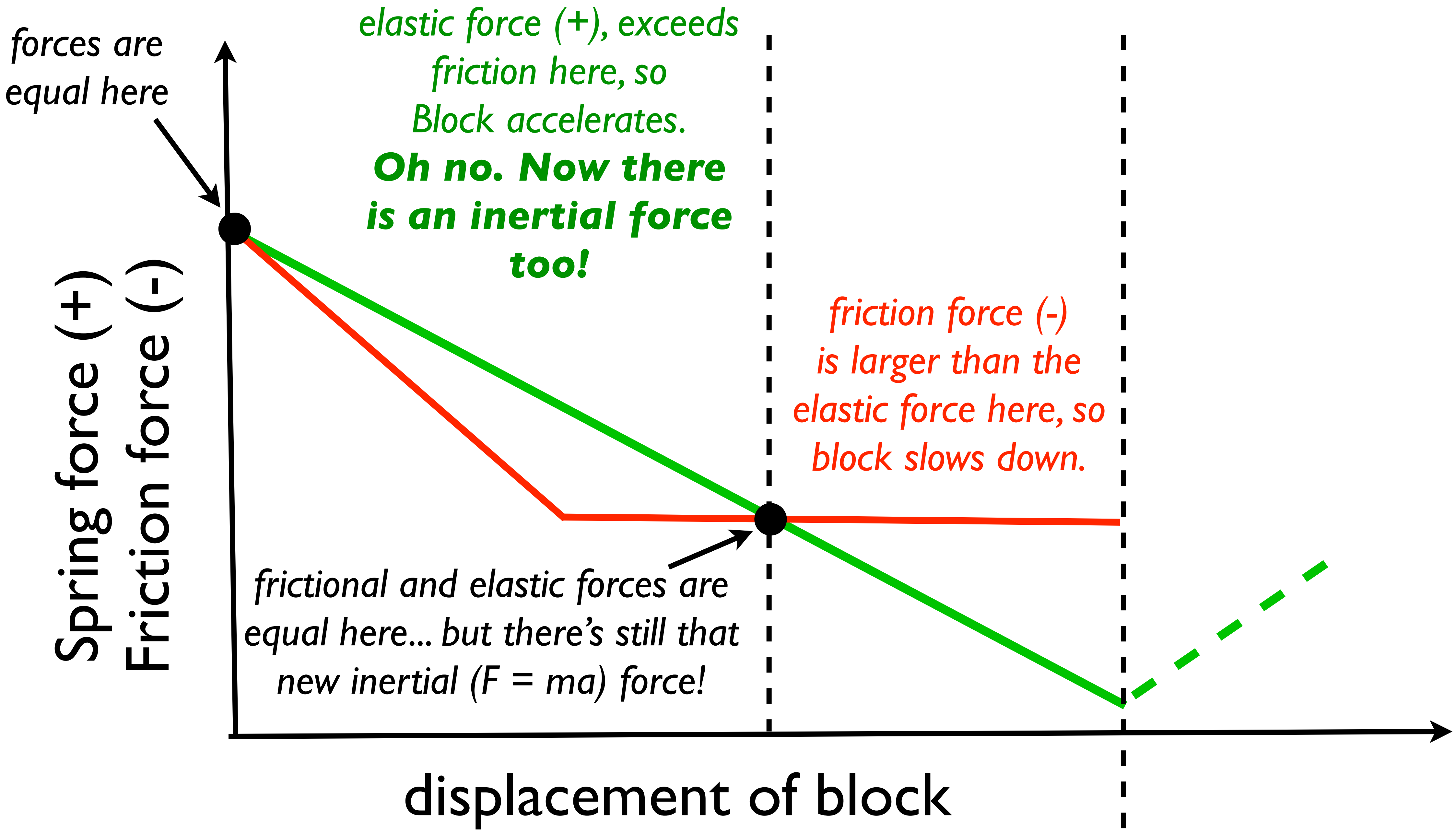


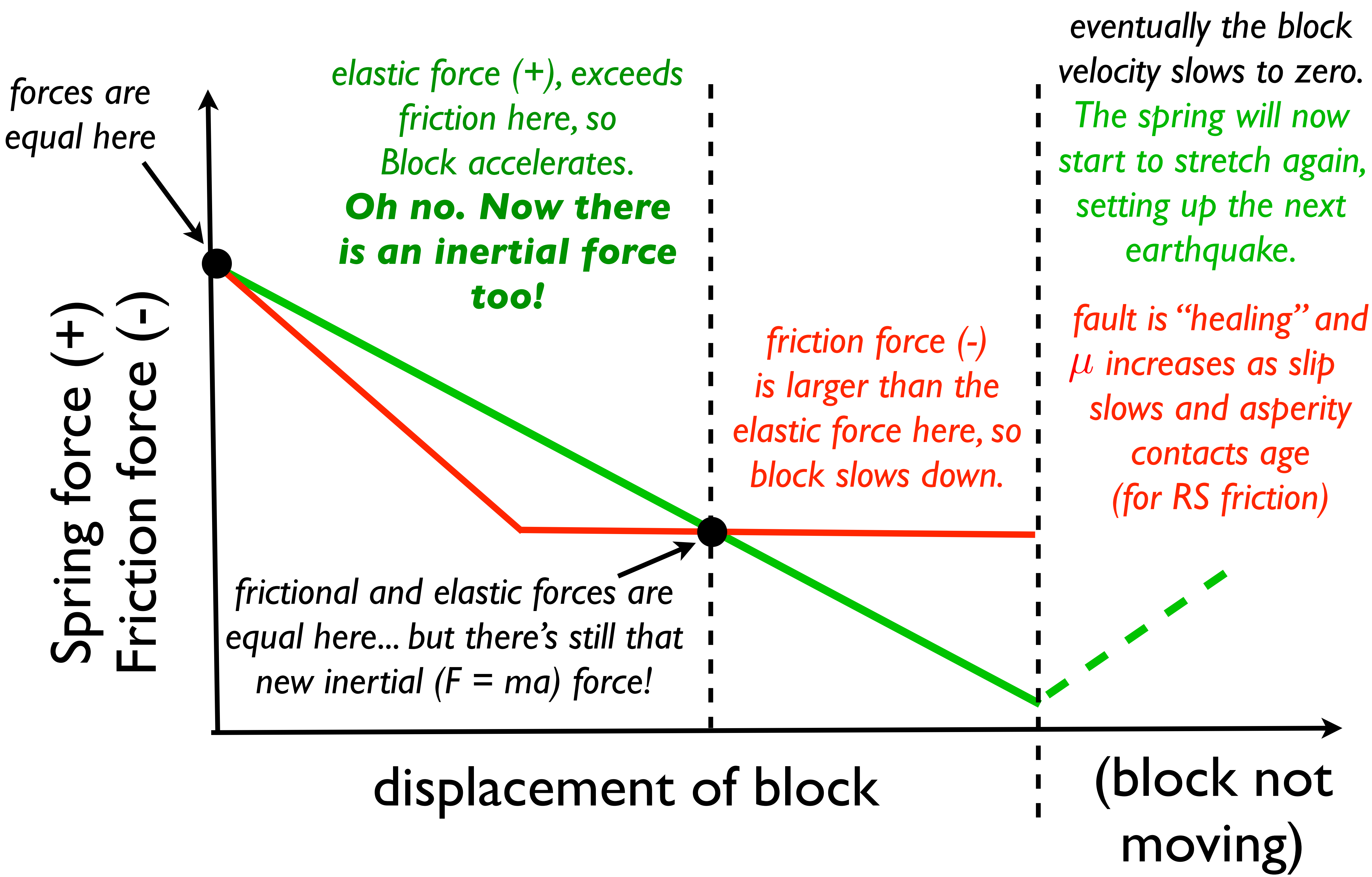
to the right =
+ x direction

Redraw this with absolute values of forces so the lines cross where |friction force| = |spring force|




forces are equal here
elastic force (+), exceeds friction here, so Block accelerates.
Oh no. Now there is an inertial force too!
Spring force (+)
Friction force (-)
frictional and elastic forces are equal here... but there's still that new inertial (F = ma) force!
displacement of block


forces are
equal here
elastic force (+), exceeds
friction here, so
Block accelerates.
Oh no. Now there
is an inertial force
too!
friction force (-)
is larger than the
elastic force here, so
block slows down.
frictional and elastic forces are
equal here... but there's still that
new inertial (F = ma) force!
Spring force (+)
Friction force (-)
displacement of block


forces are equal here
elastic force (+), exceeds friction here, so Block accelerates.
Oh no. Now there is an inertial force too!
eventually the block velocity slows to zero.
The spring will now start to stretch again, setting up the next earthquake.
fault is "healing" and μ increases as slip slows and asperity contacts age (for RS friction)
friction force (-) is larger than the elastic force here, so block slows down.
Spring force (+)
Friction force (-)
frictional and elastic forces are equal here... but there's still that new inertial (F = ma) force!
displacement of block
(block not moving)

What does this mean in the Earth?

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

D_c and (a-b) : from lab experiments

σ_n : from (approx.) $\rho g h$

k: spring: k related block slip to elastic force decrease of the spring.

Earth: k relates fault slip to elastic shear force decrease of the rock

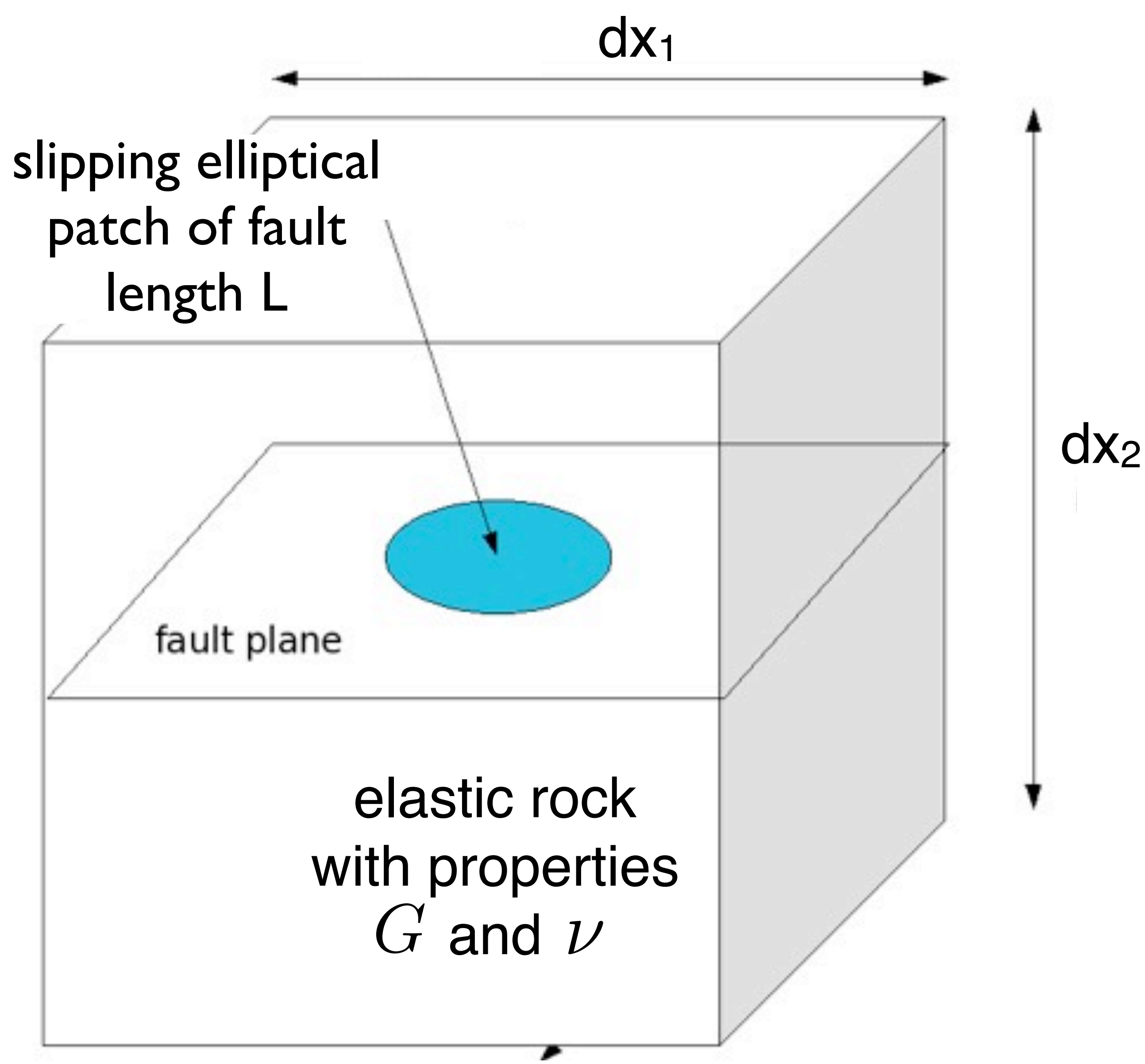
In the Earth, we use an equation for the stiffness k of a small, elliptical crack which comes from elasticity theory (and is proven by experiments)

k relates slip (offset) to the shear stress change

Equation for stiffness k for a small, elliptical crack is:

$$k = \frac{G}{(1-\nu)L}$$

G = shear modulus
ν = Poisson's ratio
L = length of slipping area



Earthquake machine:
k is the spring stiffness

Earth: k is the elastic force due to offset along crack (length L)

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

$$\frac{G}{(1-\nu)L} < \frac{\sigma_n(b-a)}{D_c}$$

k = crack stiffness
G = shear modulus
ν = Poisson's ratio
L = length of slipping area
$(b-a)$ = friction weakening parameter
σ_n = normal stress
D_c = friction weakening distance

$$L > \frac{D_c G}{(1-\nu)(b-a)\sigma_n}$$

This tells us that the slipping patch of fault must be bigger than a critical size to go unstable, *even* for a velocity weakening fault