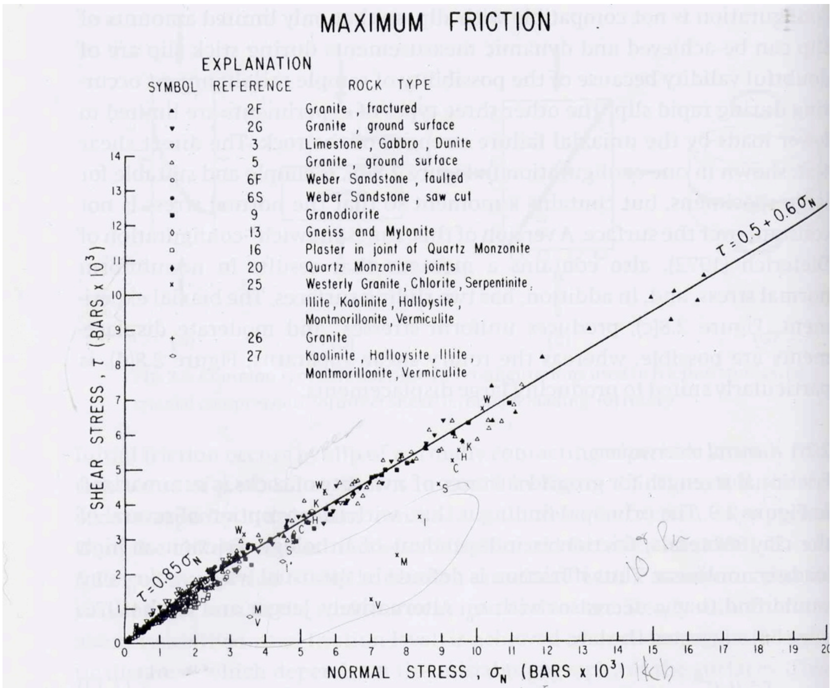


Fig. 2.9. Frictional strength for a wide variety of rocks plotted as a function of normal load. The lettered data points refer to clay minerals as indicated in the key. (From Byerlee, 1978.)

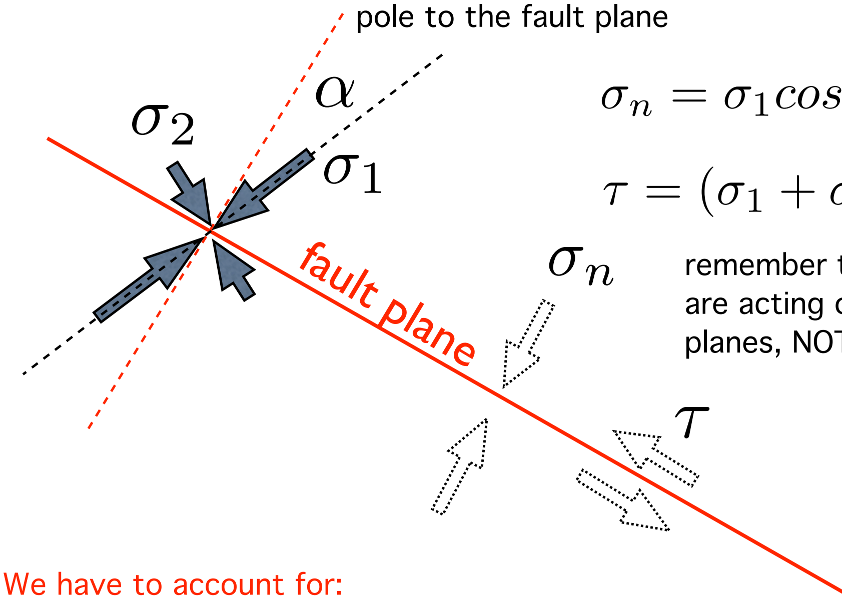
$$\tau = \mu_s \sigma_n$$

Byerlee's Law (1978)

rock type mostly unimportant

This works at T less than 350-400° C

α is the angle between the σ_1 direction and the pole to the fault plane



$$\sigma_n = \sigma_1 cos^2\alpha + \sigma_2 sin^2\alpha$$

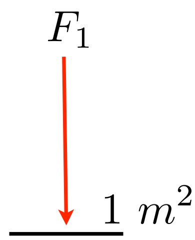
$$\tau = (\sigma_1 + \sigma_2) cos(\alpha) sin(\alpha)$$

remember that σ_1 and σ_2 are acting on the x_1 and x_2 planes, NOT on the fault plane.

We have to account for:

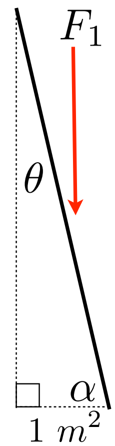
- component of the force vector acting on the fault plane.
- corrected area of the fault plane.

First: compute traction = force per unit area for a particular plane of your choice (traction is a vector)



Principal (normal) stress σ_1 is F_1 acting in the x_1 direction on the (perpendicular) plane.

$$\sigma_1 = \frac{F_1}{1\ m^2}$$



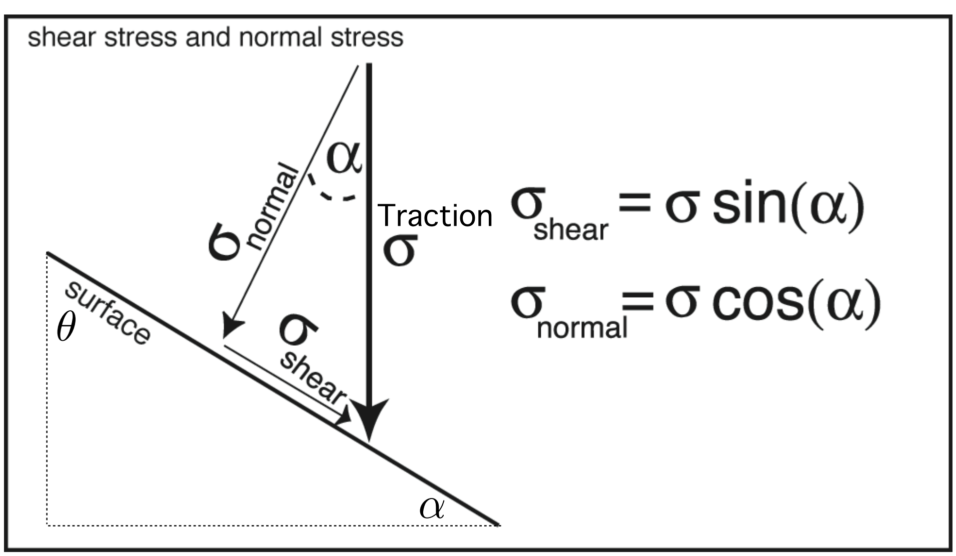
Same F_1 as before but now applied to a much bigger area

$$\sigma = \frac{F_1}{(1\ m^2/\ sin\ \theta)}$$

so for oblique planes, the tractions can be small (0 if the plane is parallel to the force vector)

$$\sigma = \sigma_1 sin\ \theta$$
$$\sigma = \sigma_1 cos\ \alpha$$

Next, we have to resolve this traction vector into plane-parallel (shear) and a plane-normal vectors.



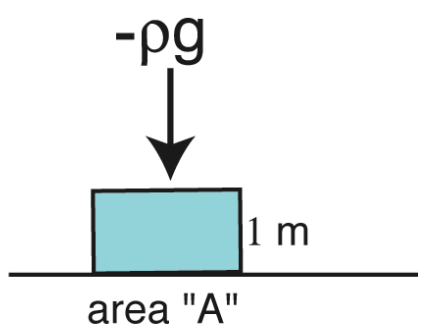
So if you are given principal stresses, these equations result:

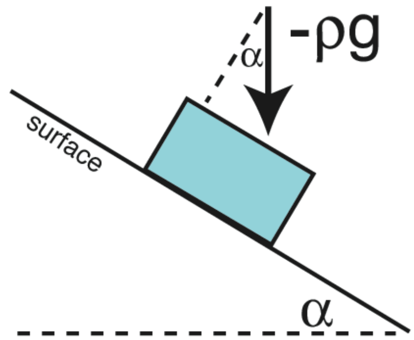
$$\sigma_n = \sigma_1 cos^2\alpha + \sigma_2 sin^2\alpha$$

$$\tau = (\sigma_1 + \sigma_2) cos(\alpha) sin(\alpha)$$

Friction example (using tractions)

friction





$F = -\rho * V * g$

$\sigma = F/A = -\rho * g * 1$

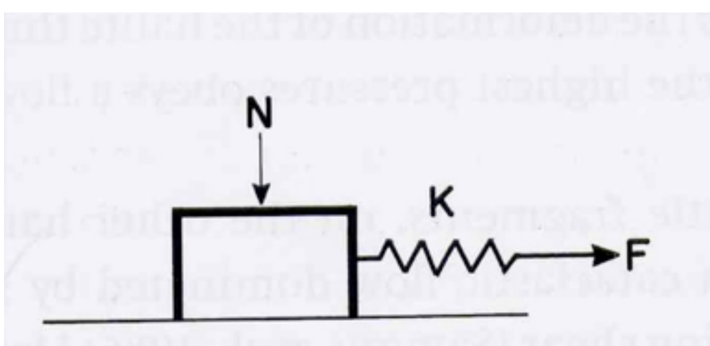
shear stress =

normal stress =

Sliding occurs if $\sigma_{shear} = \sigma_{normal} * \mu$

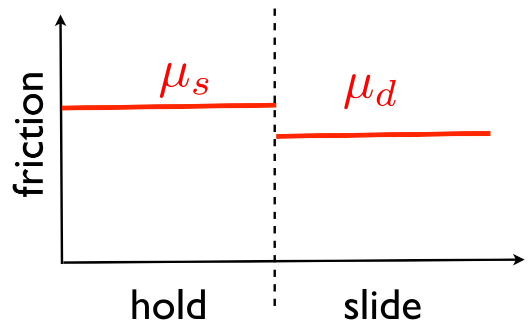
$\mu = \tan(\alpha)$

Block pulled along the floor

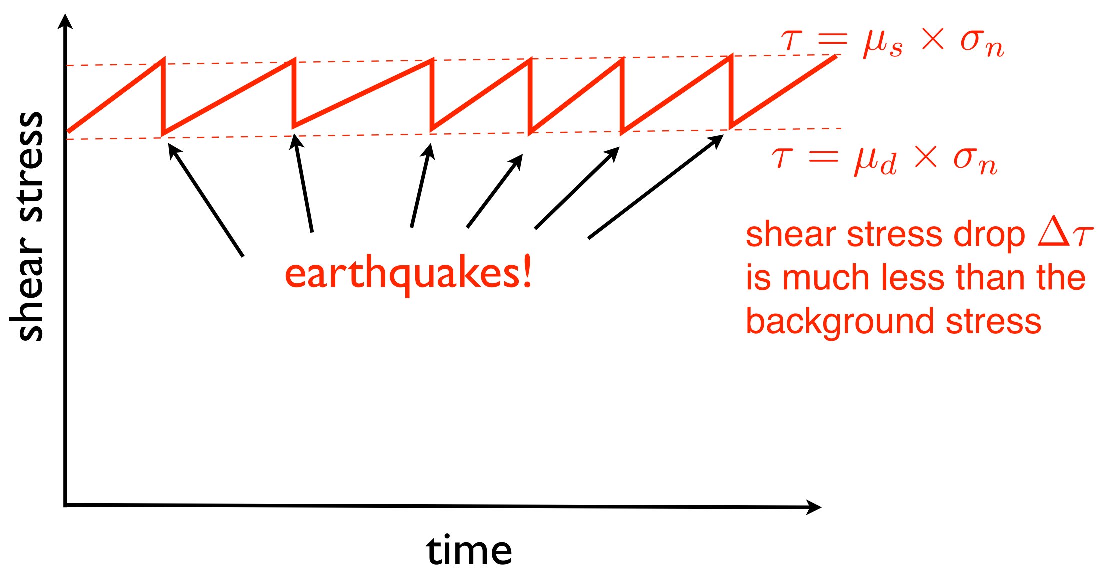


If A is the area of the bottom of this block

$$\sigma_n = N/A \qquad \sigma_{shear} = \tau = F/A$$



For many faults, earthquake shear stress drop is much smaller than "background" shear stress



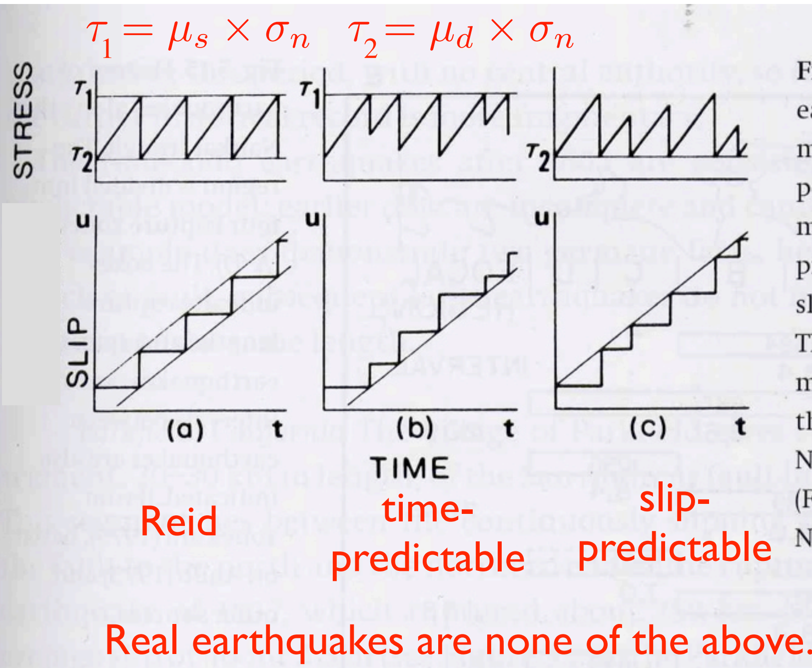


Fig. 5.13. Simple earthquake recurrence models: (a) Reid's perfectly periodic model; (b) time-predictable model; (c) slip-predictable model. The time-predictable model is motivated by the observation of the Nankaido earthquakes. (From Shimazaki and Nakata, 1980.)

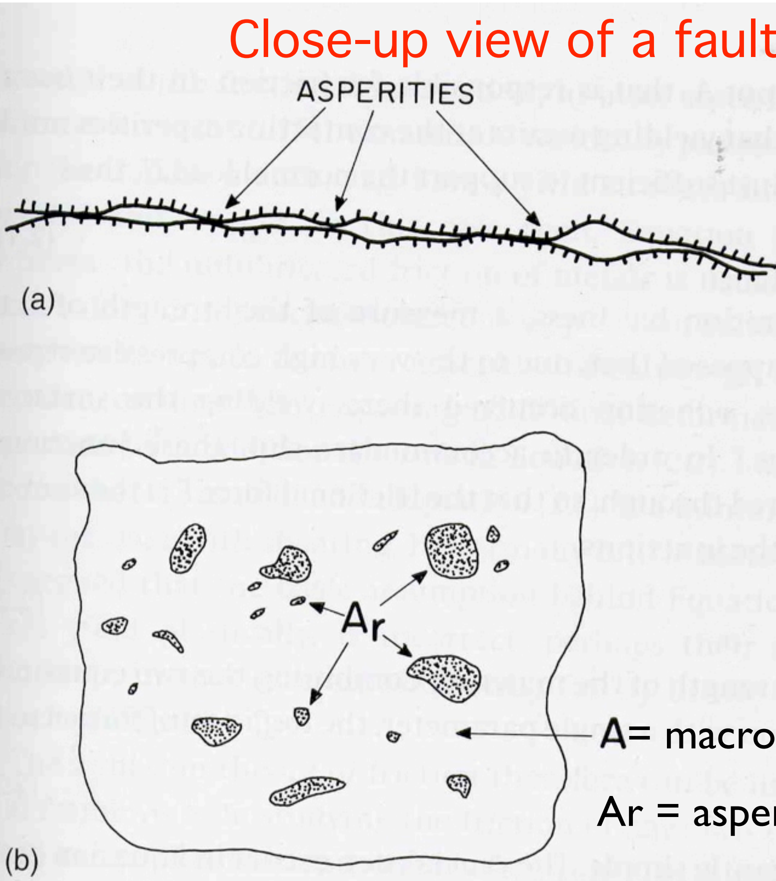
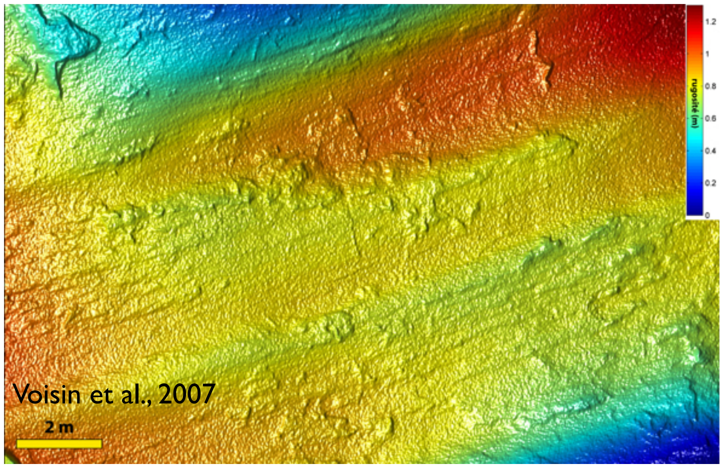


Fig. 2.1. Schematic diagram, in section and plan view, of contacting surface. The stippled regions in plan view represent the areas of asperity contact, which together comprise the real contact area A_r.

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



Asperities at a wide array of spatial scales

“smoother” profile in the slip direction

Frictional force is independent of the size of <u>macroscopic</u> areas in contact

Amonton’s First Law

Frictional force is proportional to normal force (“load”)

Amonton’s Second Law

Amonton (2) also works for stress (force/area)

Again, Amonton (1) is referring to the macroscopic area (not the area of the actual asperities)

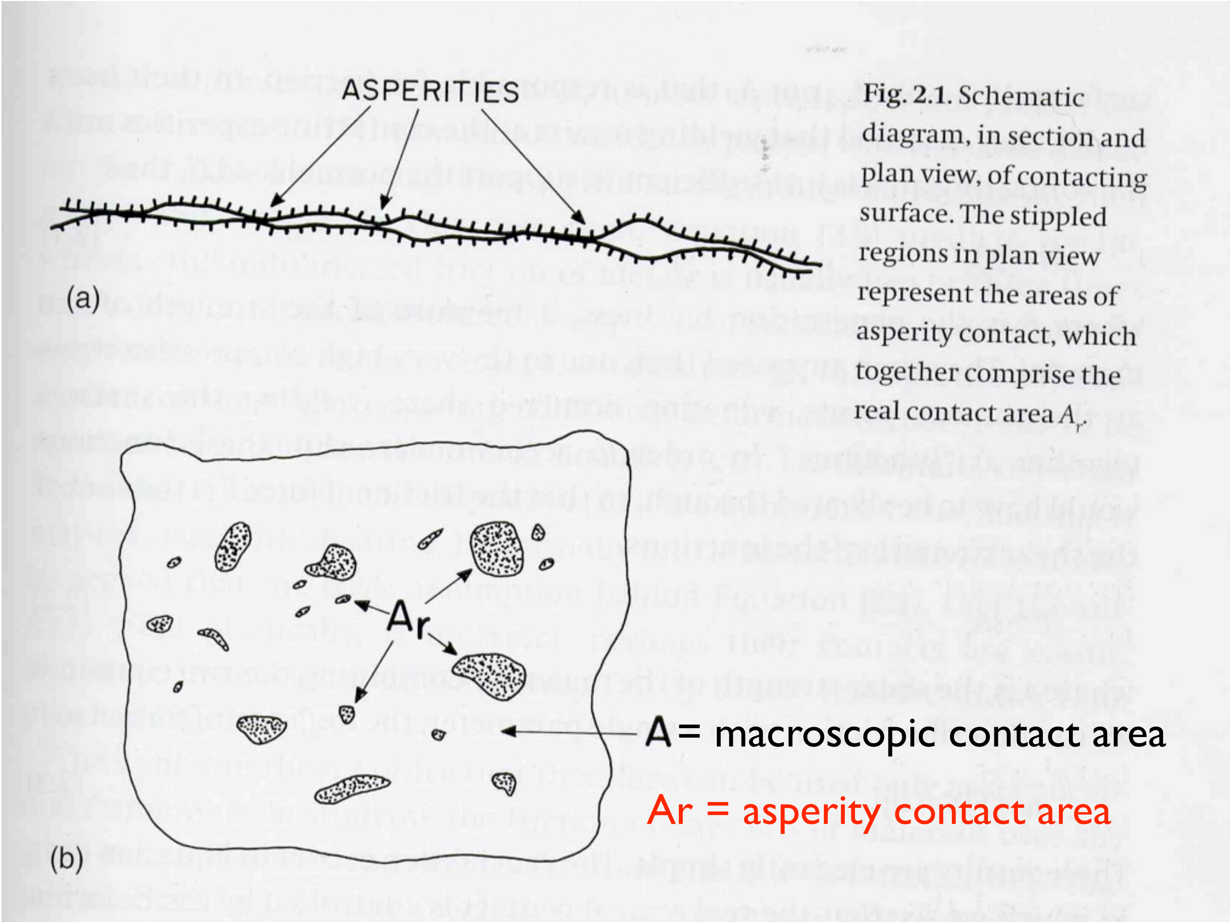
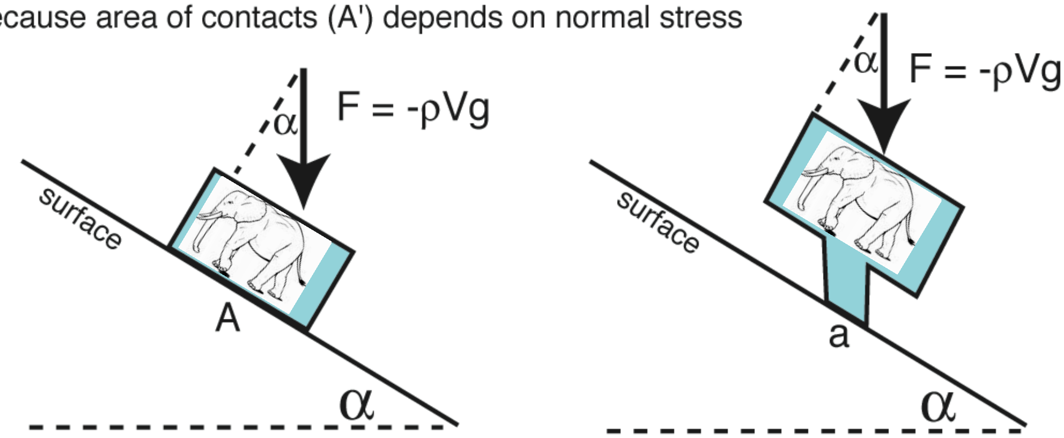


Fig. 2.1. Schematic diagram, in section and plan view, of contacting surface. The stippled regions in plan view represent the areas of asperity contact, which together comprise the real contact area A_r.

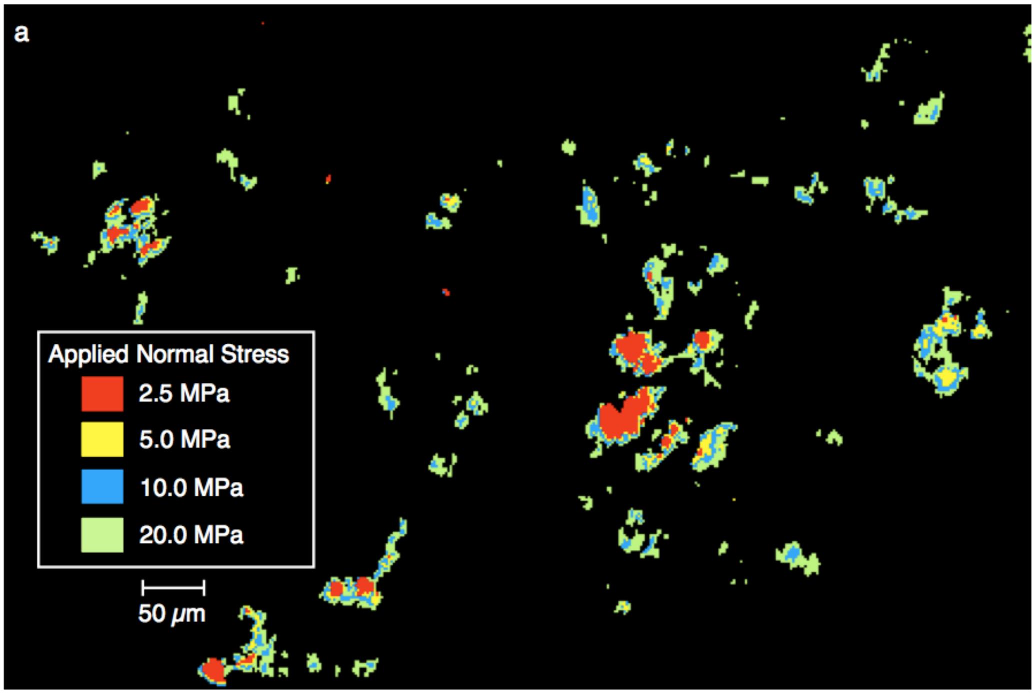
Amonton's First Law
friction force is insensitive to **macroscopic** area
because area of contacts (A') depends on normal stress



Same asperity 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

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

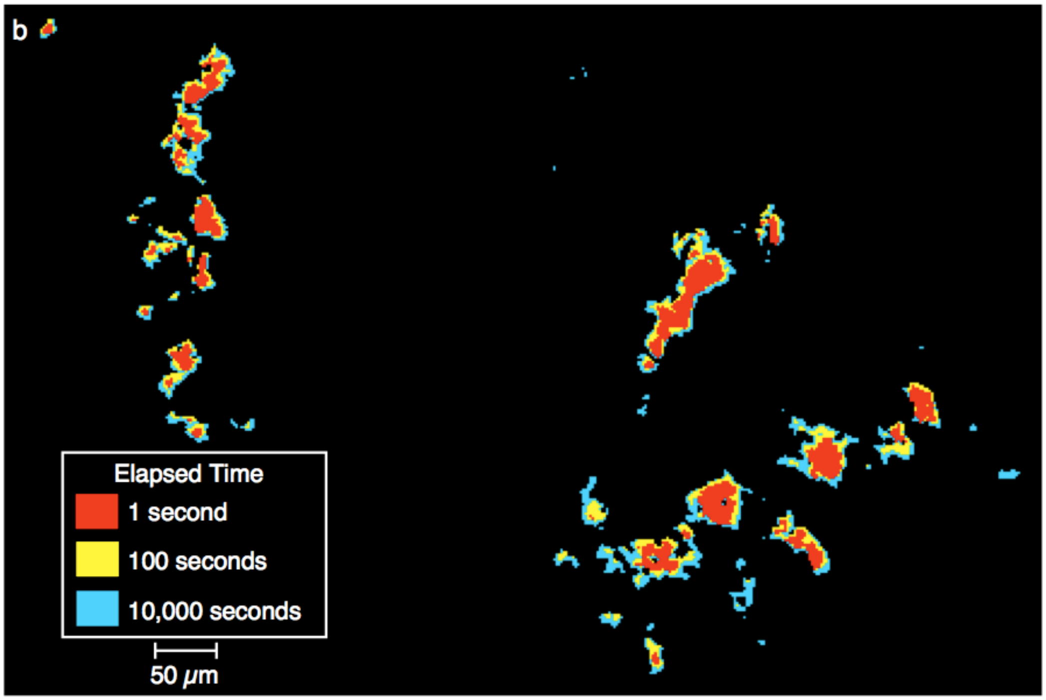
- Friction can increase with “hold” time. This happens through growth and increasing shear strength of contacts.

- If sliding speeds up, the average lifespan of asperities decreases

- This means that friction drops with sliding speed

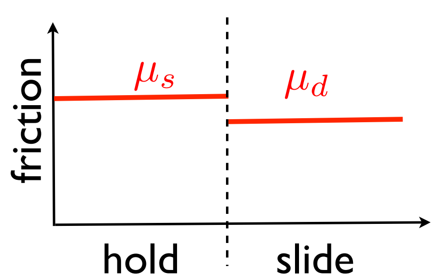
- θ is the “state variable” in some friction laws: it can be interpreted as the average age of the asperities

Dieterich and Kilgore, 1994

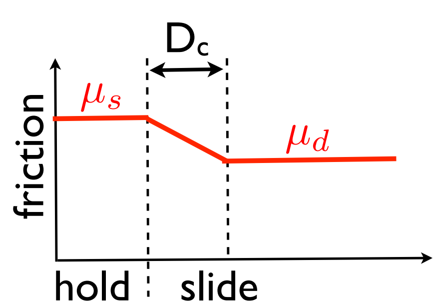


Asperity contact area also increases with hold time thanks to state variable (healing). This is increasing the frictional strength (mu times normal stress). Normal stress is constant in this experiment, so mu (that is, friction coefficient) is **increasing** with hold time.

Some ideas about static vs. dynamic friction



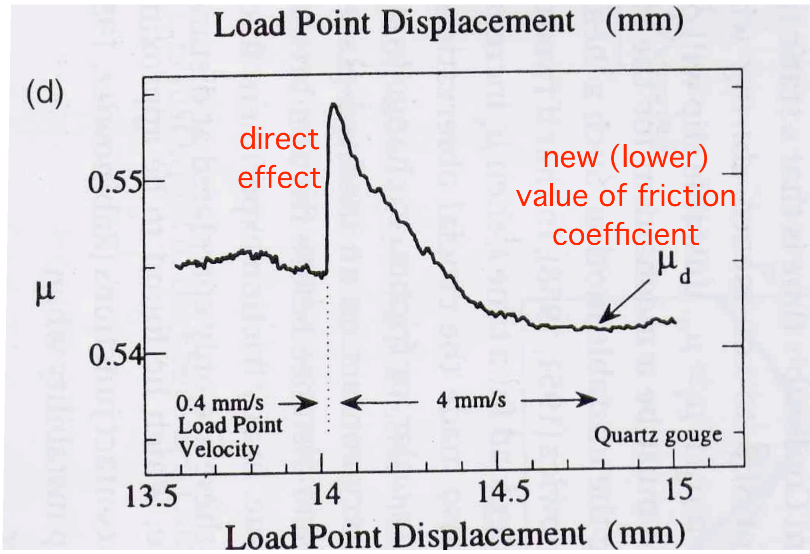
$$\tau = \mu_s \sigma_n$$



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

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

Rate- and state- dependent friction:
what the friction data look like

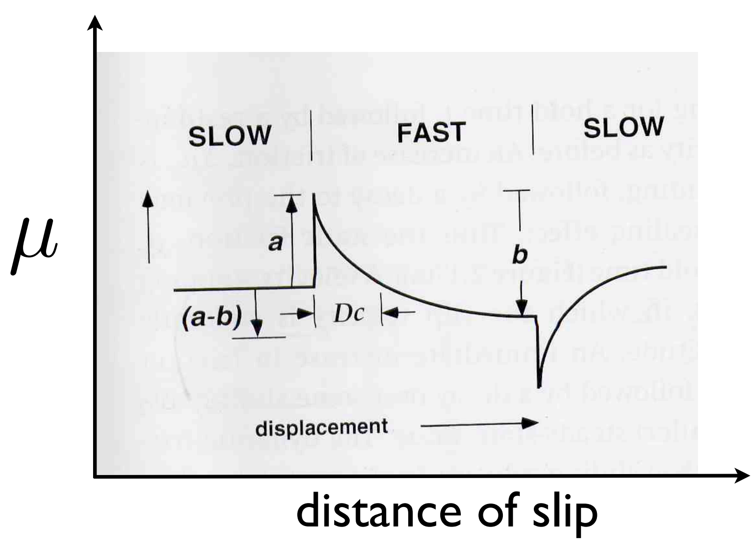


In this experiment they speed up sliding

initially, friction is higher ("direct effect")

then it evolves and settles at a lower value

Rate- and state- dependent friction

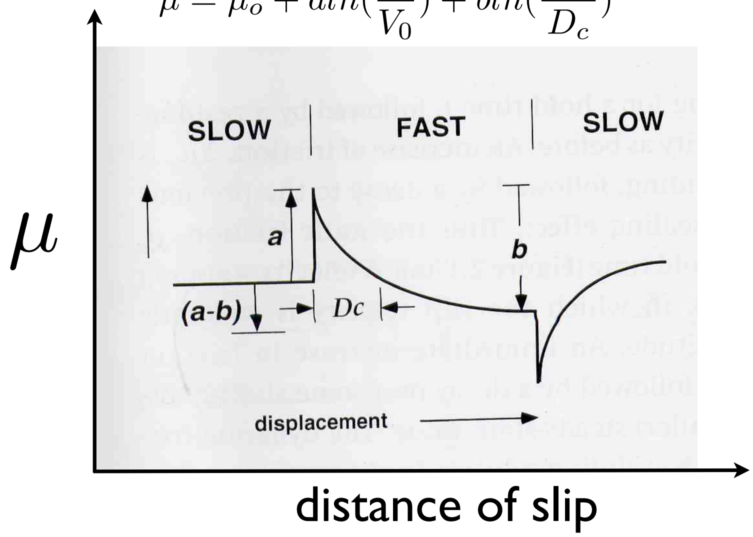


$$\mu = \mu_o + a ln(\frac{V}{V_0}) + b ln(\frac{V_o \theta}{D_c})$$

empirical equation

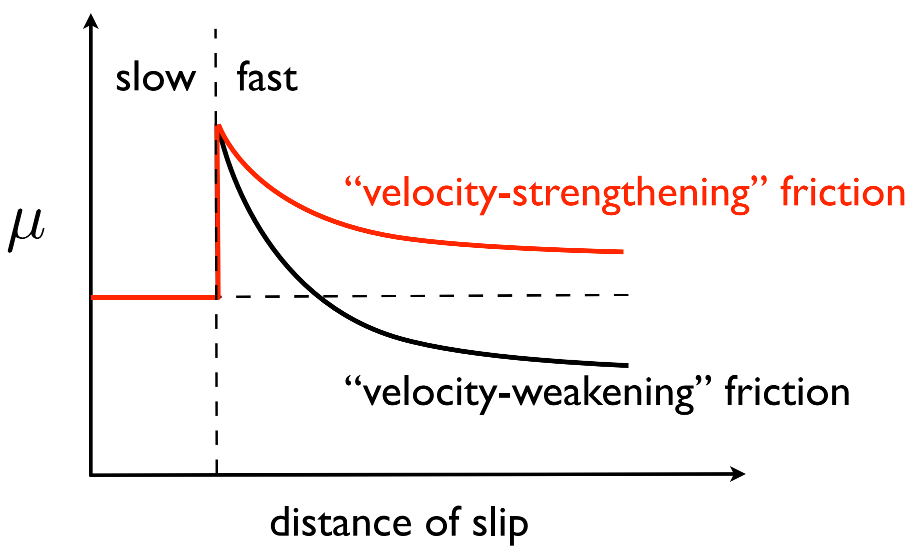
(Dieterich 1981; Ruina 1983)

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



If we assume that the value of the state variable (asperity contact age) is $\theta = \frac{D_c}{V}$
(after a steady state, new sliding velocity is reached)

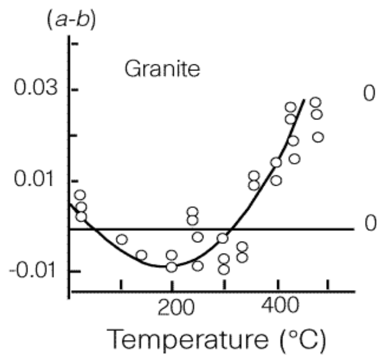
the "rate and state" friction equation is: $\mu = \mu_o + (a-b) ln(\frac{V}{V_o})$



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

if positive then _____
if negative then ______

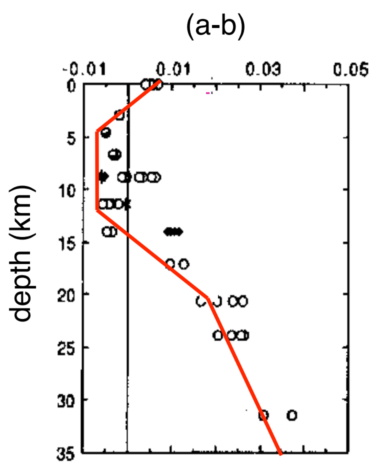
Effect of temperature on friction



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

Laboratory experiments show that stable frictional sliding is promoted at temperatures higher than about 300°C for most crustal rocks.

How (a-b) varies with depth



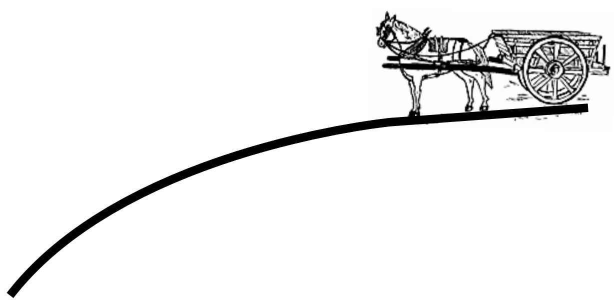
(Blanpied et al, 1991)

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.

velocity-strengthening friction:
faster sliding -->
stronger fault -->
slows sliding



velocity weakening friction:
faster sliding -->
weaker fault -->
even faster sliding