When you are standing on a flat surface, what is the normal stress you exert on the ground?

What is the shear stress?

How could you exert a non-zero shear stress on the ground?

Hydrostatic Pressure (fluids)

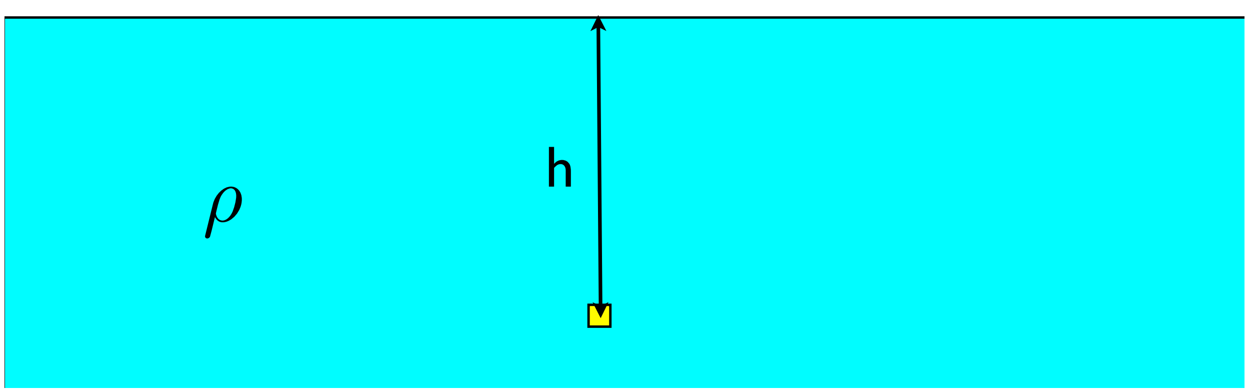
In a fluid normal stresses are -P ("hydrostatic pressure") shear stresses are 0

$$\begin{bmatrix} \sigma_1 & 0 \\ 0 & \sigma_2 \end{bmatrix} = \begin{bmatrix} \bar{\sigma} & 0 \\ 0 & \bar{\sigma} \end{bmatrix} = \begin{bmatrix} -P & 0 \\ 0 & -P \end{bmatrix}$$

$$\boxed{P = \rho g h}$$

Deep ocean floor = 4 km

(EQ works for water or ice sheets too with correct density)



At depth, below the Earth's upper crust normal stresses are *close* to -P ("lithostatic pressure"). Due to viscous flow of hot rock. Shear stresses are MUCH smaller.

$$\begin{bmatrix} \sigma_1 & 0 \\ 0 & \sigma_2 \end{bmatrix} \approx \begin{bmatrix} \bar{\sigma} & 0 \\ 0 & \bar{\sigma} \end{bmatrix} = \begin{bmatrix} -P & 0 \\ 0 & -P \end{bmatrix}$$

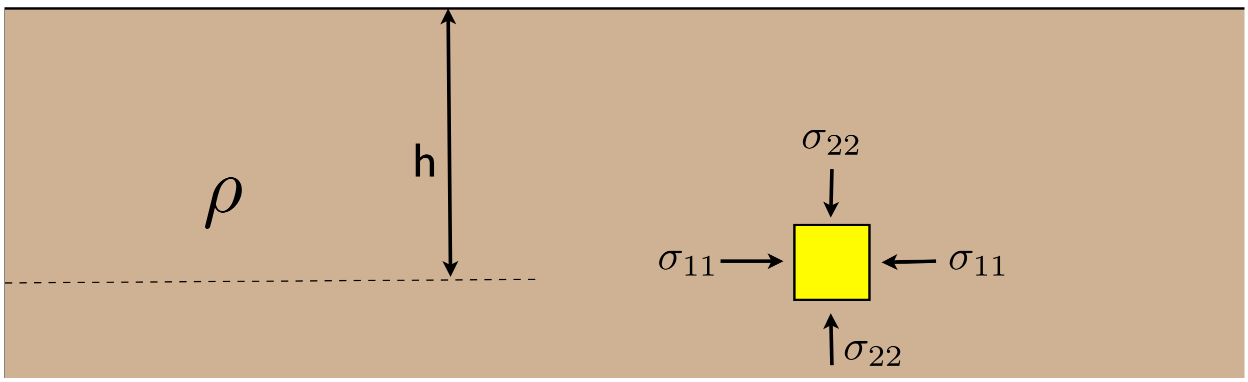
$\rho = 2500\ kg/m^3$

$g = 10\ m/s^2$

$h =\ depth\ (m)$

Moho (crust-mantle boundary) is 30 km down

Cascadia SZ (80 km below us)



In the brittle upper crust, the normal stresses differ from each other but the mean of the normal stresses ($\bar{\sigma}$) is essentially equal to -P.

At a typical hypocentre = 7 km

$\bar{\sigma}$ = ?

Deviatoric stress matrix is stress matrix minus mean normal stress (matrix)

$$\begin{bmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{21} & \sigma_{22} \end{bmatrix}_{DEV} = \begin{bmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{21} & \sigma_{22} \end{bmatrix} - \begin{bmatrix} \bar{\sigma} & 0 \\ 0 & \bar{\sigma} \end{bmatrix}$$

Only the deviatoric stresses contribute to shear stress (which drives faulting!)

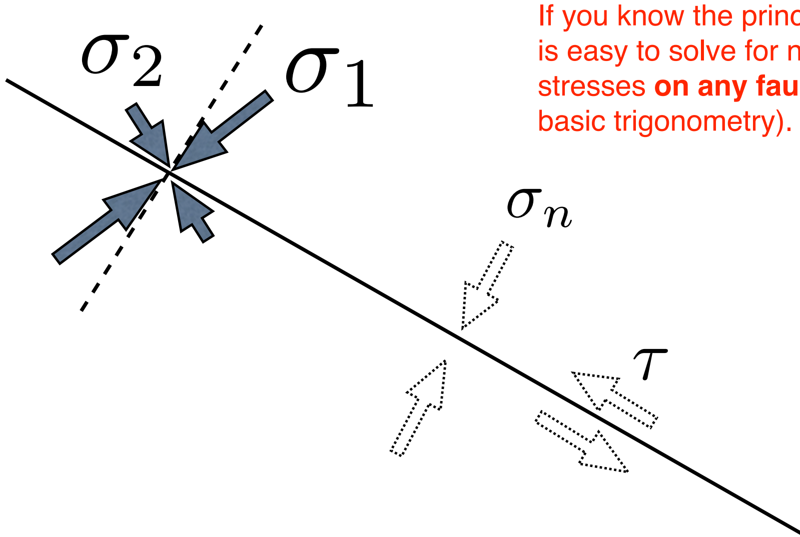
If you know the two principal stresses

$\sigma_1 - \sigma_2$ is called the "differential stress"

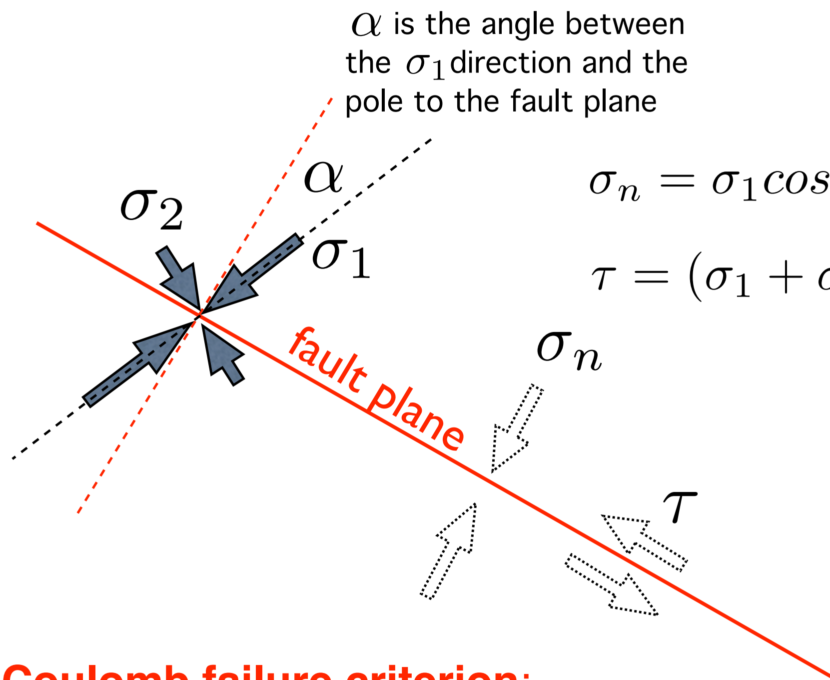
$(\sigma_1 - \sigma_2)/2$ is the largest possible value of τ

Shear stress (τ) leads to faulting

$$\sigma = \begin{pmatrix} \sigma_1 & 0 \\ 0 & \sigma_2 \end{pmatrix}$$



If you know the principal stresses it is easy to solve for normal and shear stresses **on any fault plane** (using basic trigonometry).



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

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

Coulomb failure criterion:
The fault can slip if:

$$\tau = \mu\sigma_n$$

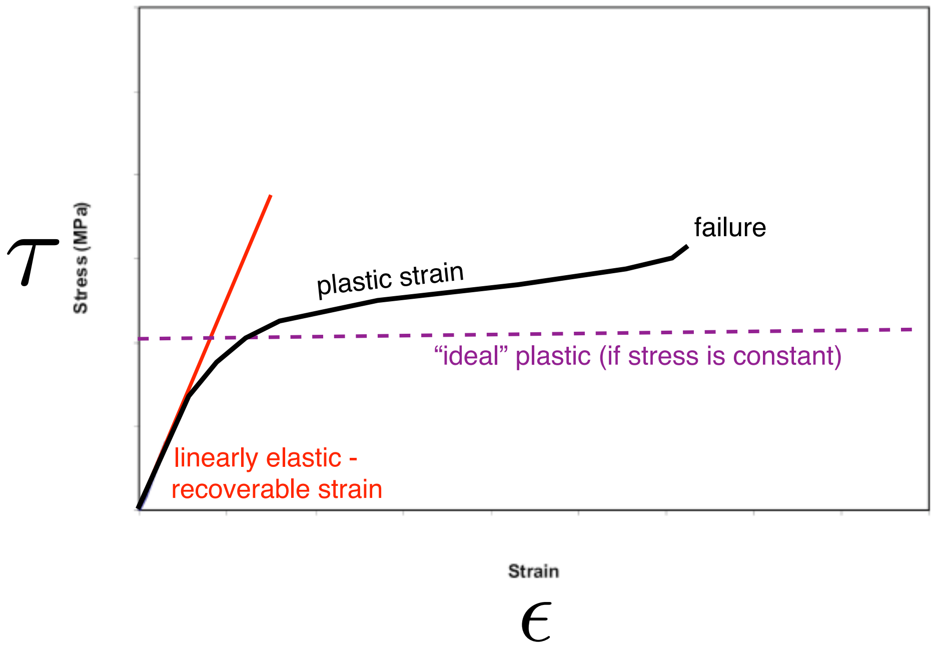
No shear stress acting on the fault? No earthquake.

A constitutive law or rheology relates stress to strain. For linear elasticity stress is proportional to strain. At higher differential stresses, plastic (permanent) strain or brittle failure (forming a fracture) can happen.

If a fracture is already present, then the Coulomb failure criterion tells us when the fault should slip.

(If there is measurable offset along a fracture, we call it a fault.)

Linear Elasticity: A constitutive law or rheology applicable for most Earth materials, <u>for small strain</u>. At bigger stresses, the rock undergoes permanent plastic strain and then brittle failure.



Rocks in the upper crust are brittle: this limits the maximum deviatoric stresses

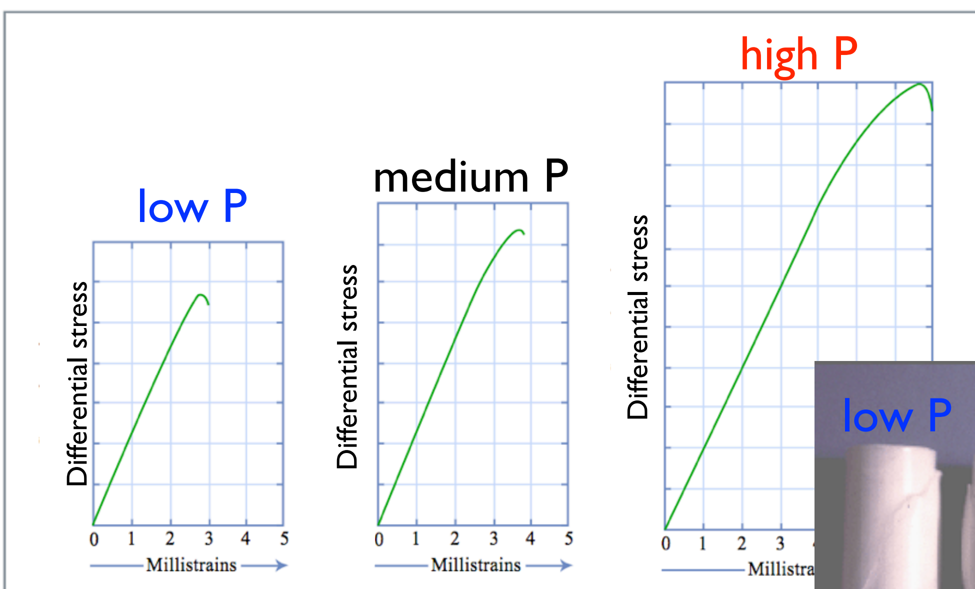
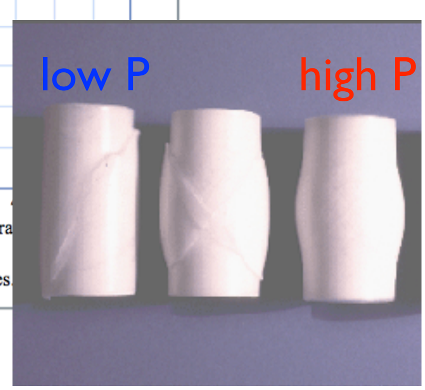


Figure 5.8. Stress-strain curves for Rand quartzite at various confining pressures

rocks are stronger in compression than in tension!

However, even at high pressures their strength has a limit:



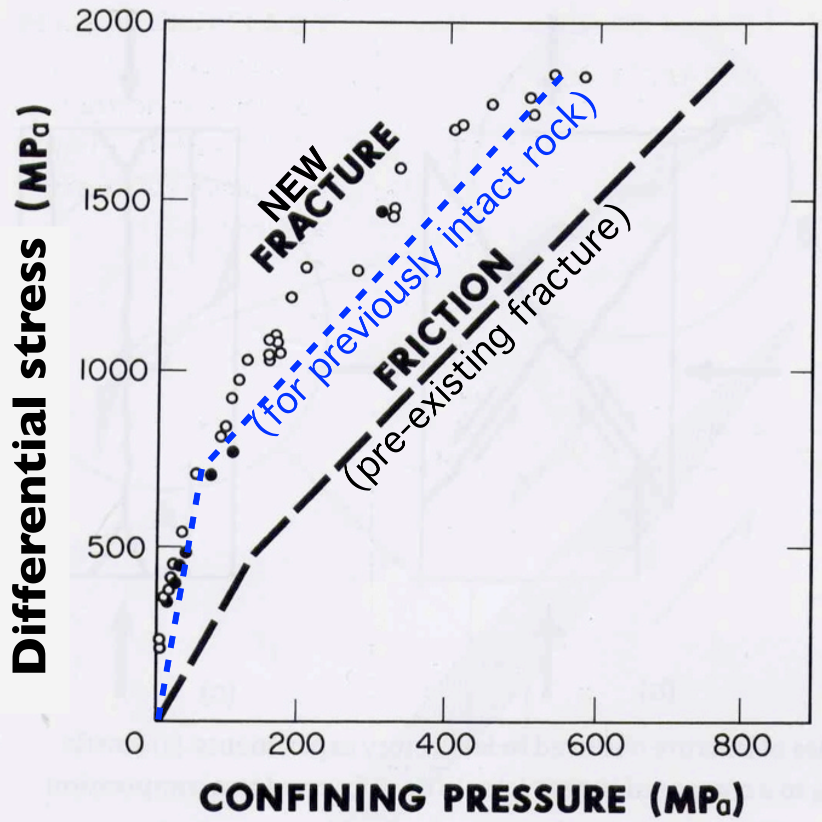


Fig. 1.13. The strength of Westerly granite as a function of confining pressure. Also shown, for reference, is the frictional strength for sliding on an optimally oriented plane. Data sources are: open circles, Brace *et al.* (1966) and Byerlee (1967a); closed circles, Hadley (1975); friction, Byerlee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

rocks are stronger at higher confining pressure

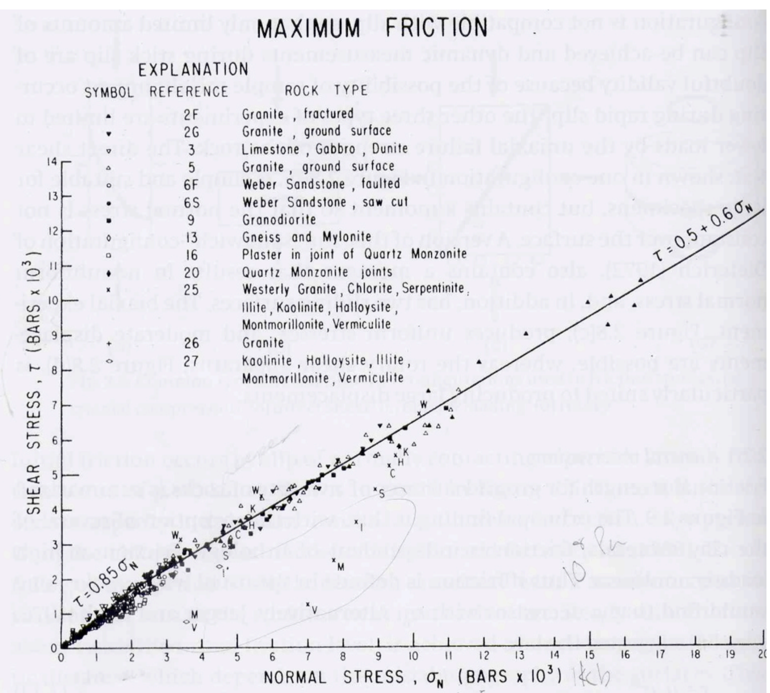


Fig. 2.9. Frictional strength for a wide variety of rocks plotted as a function of normal load. The lettered data points refer to clay minerals as indicated in the key. (From Byerlee, 1978.)

Note 1 kilobar is 10^8 Pa (or 100 MPa)

For a pre-existing fault, it may slip if:

$$\tau = \mu_s \sigma_n$$

"Byerlee's Law" (1978)

Does rock type matter?

This works at T less than 350-400° C: hot rocks creep

Coulomb failure criterion:
The fault can slip if:

$$\tau = \mu\sigma_n$$

Right before an earthquake,
At 7 km depth what is τ?

$\sigma_n = \rho g h$
$\mu = 0.7$
$\rho = 2500\ kg/m^3$

We can also estimate τ from shear strain accumulated between earthquakes if we know shear modulus G:

Parameters from the SAF

$t = 200\ yr$
$\dot{\epsilon}_{12} = 5 \times 10^{-7}\ /yr$
$\epsilon_{12} = \dot{\epsilon}_{12} \times t$

$G = 30\ GPa = 3 \times 10^{10}\ Pa$
$\tau_{12} = 2G\epsilon_{12}$

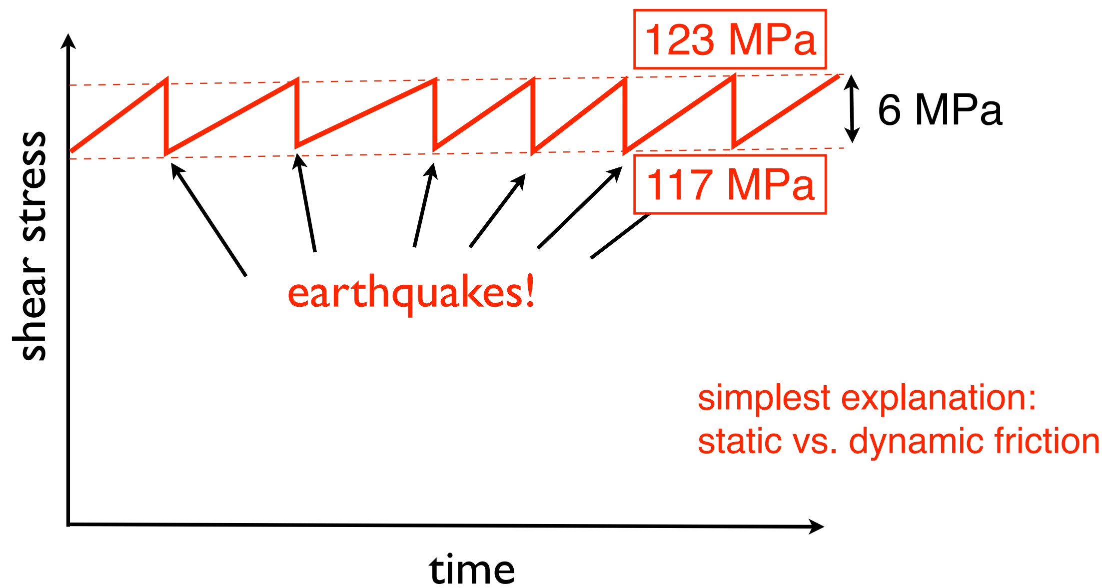
$\tau = 123\ MPa$ from $\tau = \mu\sigma_n$

$\tau = 6\ MPa$ from $\tau = 2G\epsilon_{12}$

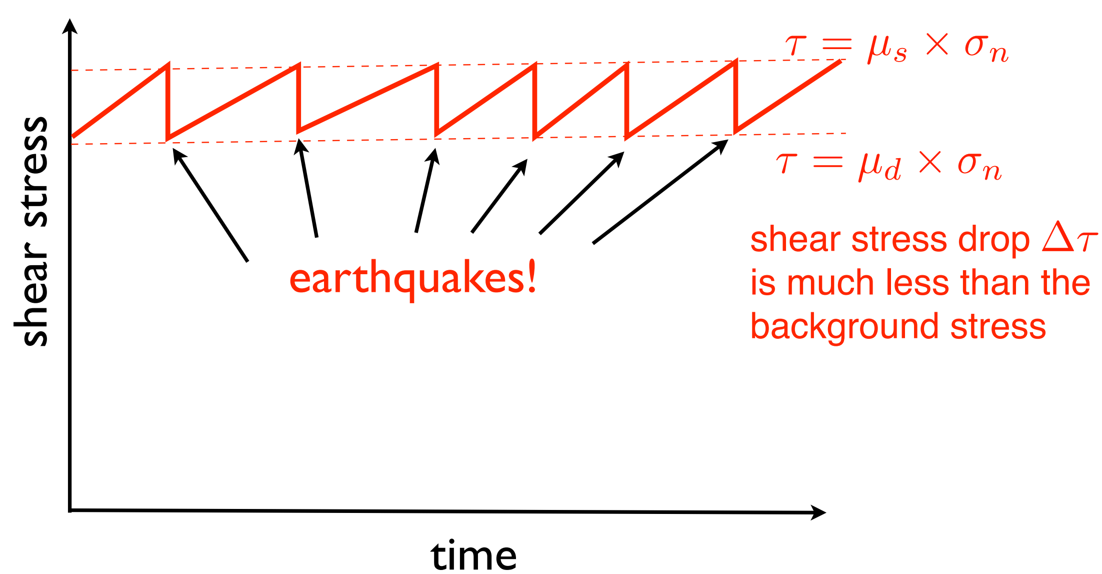
Which answer is right?

How could each answer be mistaken?

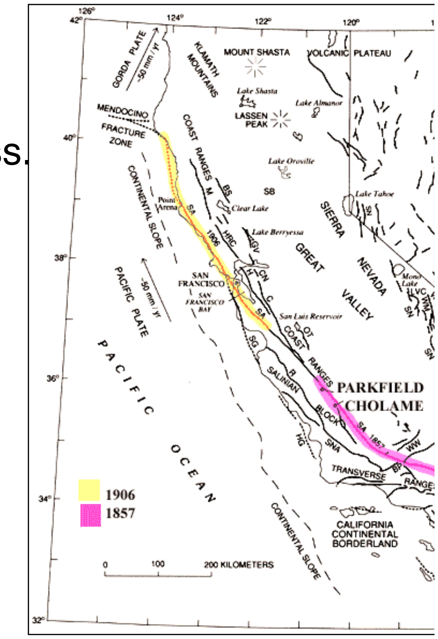
For many faults, earthquake shear stress drop is much smaller than “background” shear stress

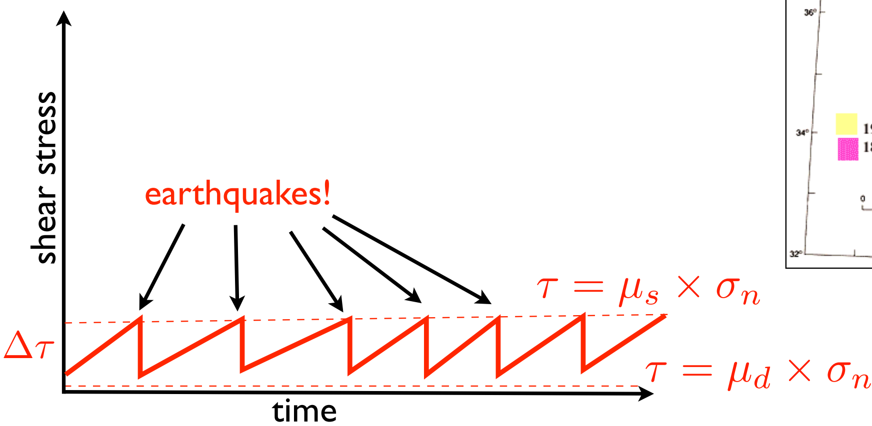


For many faults, earthquake shear stress drop is much smaller than “background” shear stress



Based on measurements of stresses in California crust, the shear stress acting on the SAF is very small. A large earthquake may release most of the accumulated stress. Cascadia SZ fault is the same way. This means tht the friction coefficient is ___.
This is probably not typical of most (smaller) faults.





The fault strength debate rages on...

Consensus seems to be that major faults are weak (low friction) and minor faults are strong.