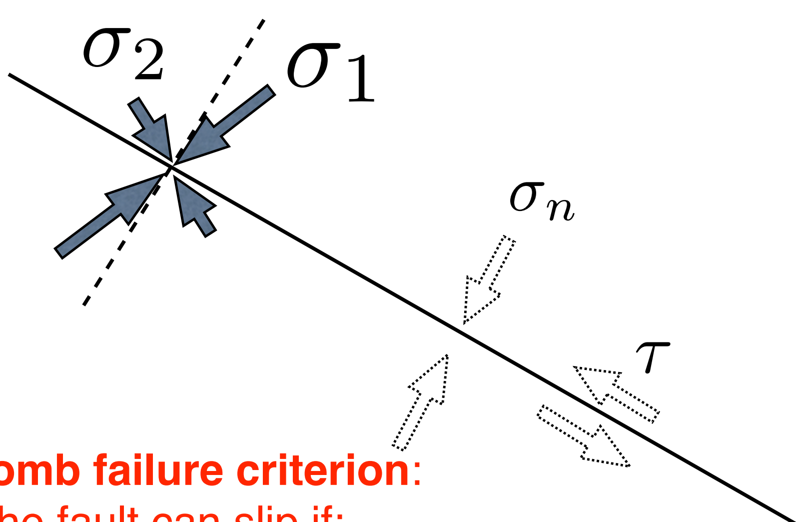
## Conditions for large versus small earthquakes

• Segmented (discontinuous) faults - rupture must jump from segment to segment, which takes energy **OR** long continuous fault

• Heterogeneous fault frictional strength and shear stress (so whole fault is NOT close to Coulomb failure threshold) **OR** whole fault close to Coulomb failure.

• Small stress drop and small "kick" to adjacent parts of the fault **OR** large stress drop and "kick" to adjacent parts of the fault.

## Importance of the normal stress (1) Coulomb failure criterion



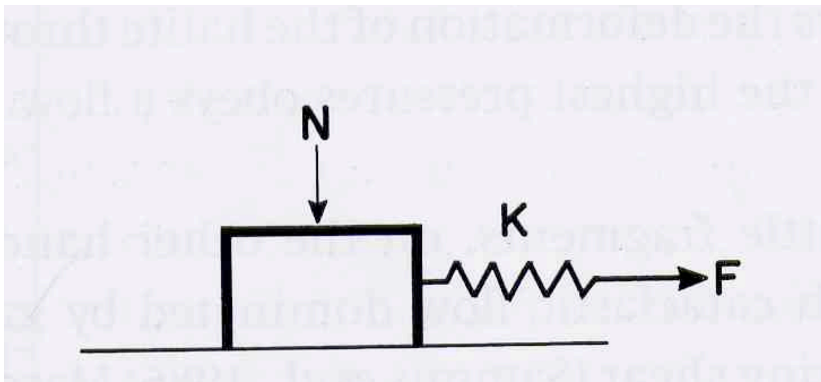

**Coulomb failure criterion**:

The fault can slip if:

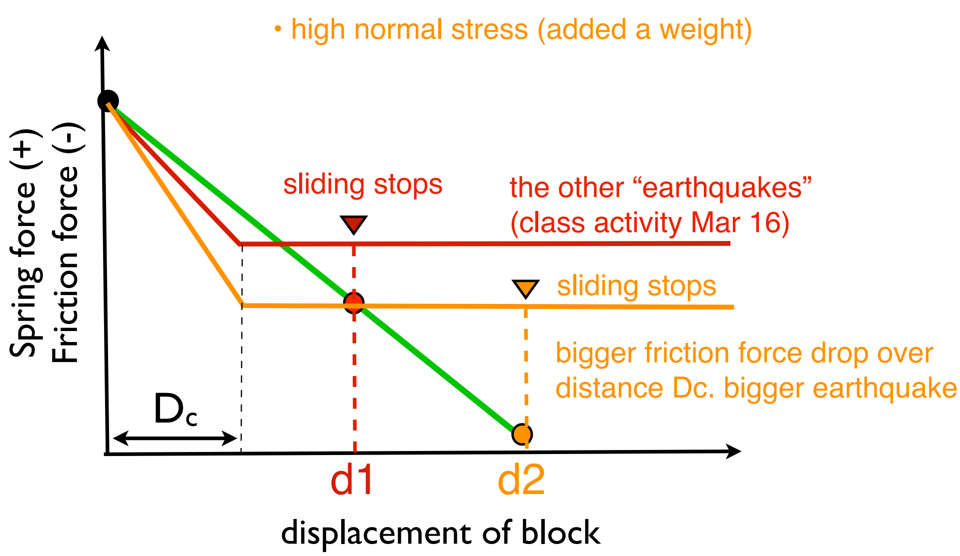
$$|\tau| = \mu|\sigma_n|$$

Importance of the normal stress
(1) Coulomb failure criterion

What happened when you extended the spring and then removed the brick?




Importance of the normal stress (2): drop in frictional resistance during sliding (velocity weakening friction) is $(a-b)\sigma_n$



Variations in frictional strength $\mu\sigma_n$
and in velocity weakening (a-b)$\sigma_n$
may be due to variations in $\sigma_n$ caused by pore fluid pressure.

## Consider the effect of water on the fault.

## Consider liquefaction of saturated sand

Grains are not touching. This is a fluid with grains floating in it.

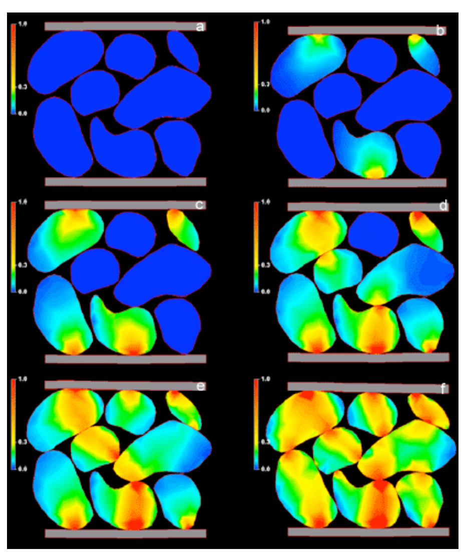
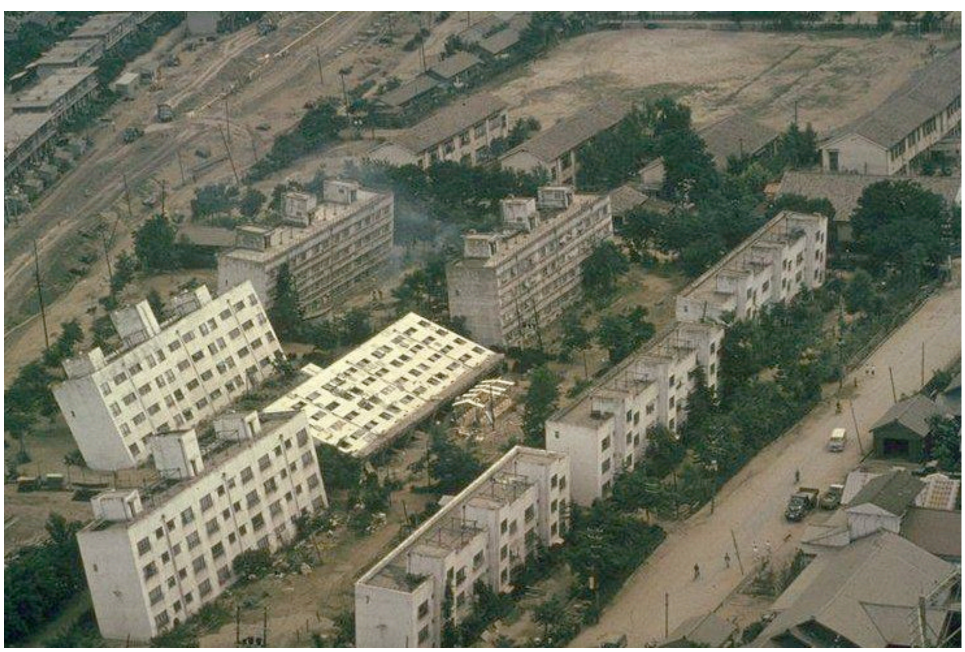


Image from Stanford University Rock Physics Lab

Grains are touching and are supporting the load (stressed parts of grains are red).

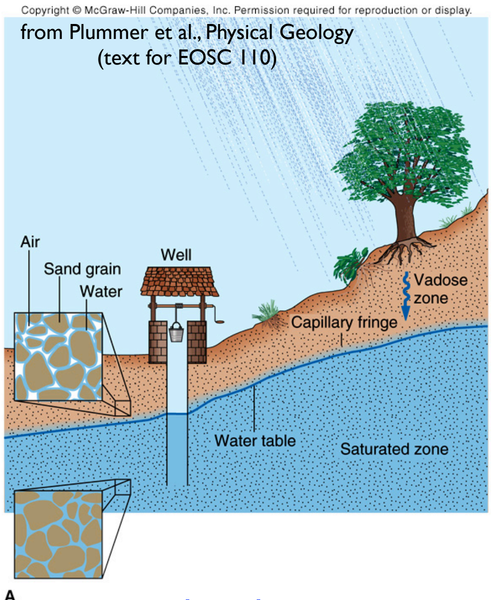
## 2010 Christchurch earthquake

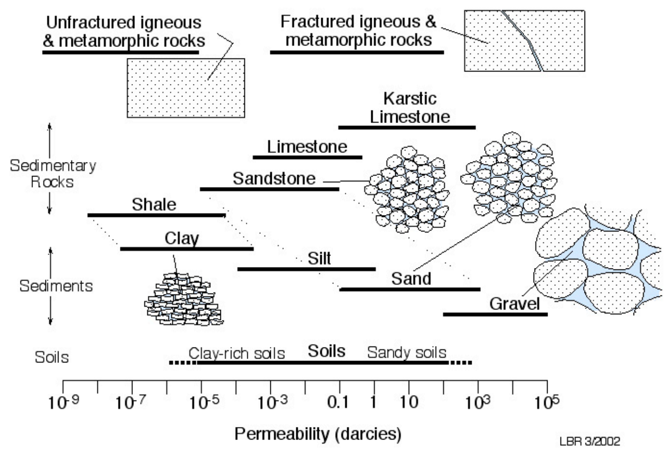
## 1964 Niigata earthquake



http://www.ce.washington.edu/~liquefaction/html/quakes/niigata/niigata.html

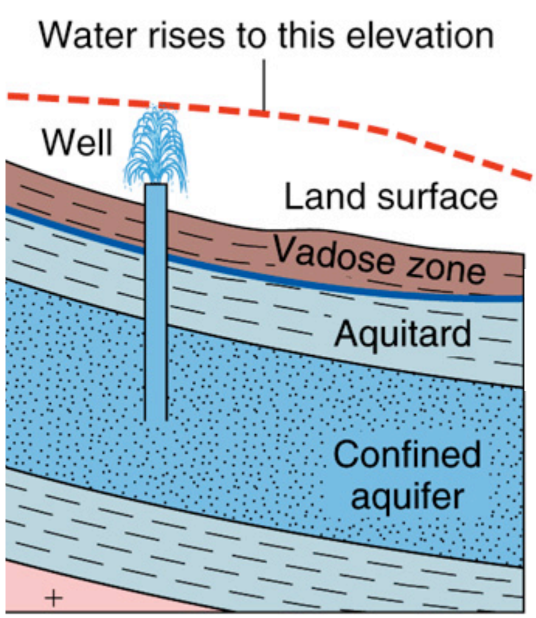
# Groundwater is present throughout the upper crust




After Freeze and Cherry, *Groundwater*, Table 2.2. "Soils" line is largely an LBR inference.

water level in porous, permeable rock = water level in well
water pressure at depth is same as for a column of water
("unconfined" shallow aquifer)



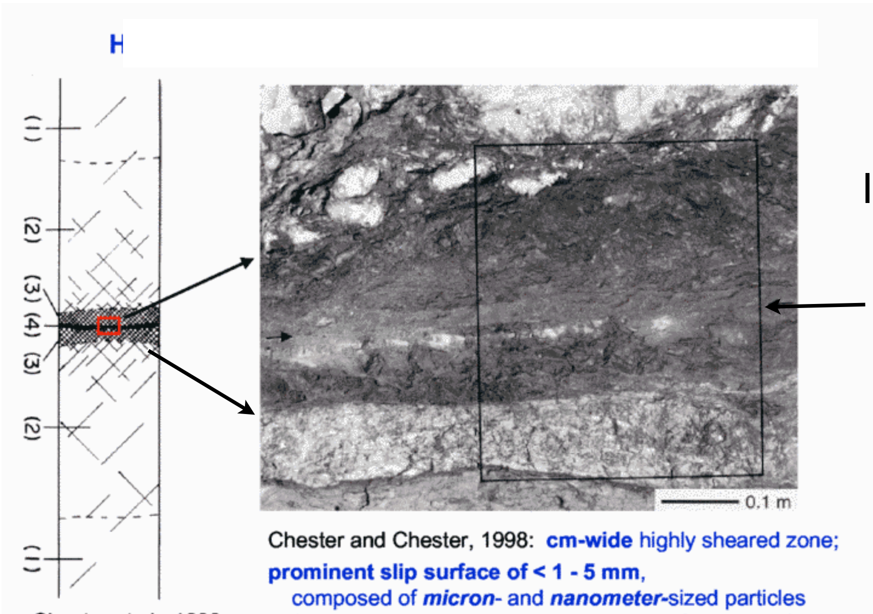

from Plummer et al., Physical Geology
(text for EOSC 110)

In some aquifers, and deeper in the crust, water in pores and cracks may become trapped.

Fluid cannot flow out faster than compaction is occurring, so water pressure goes up.

"pore fluid pressure" can approach the lithostatic pressure!

Water can become trapped inside low-permeability fault gouge, which may compact slightly over time



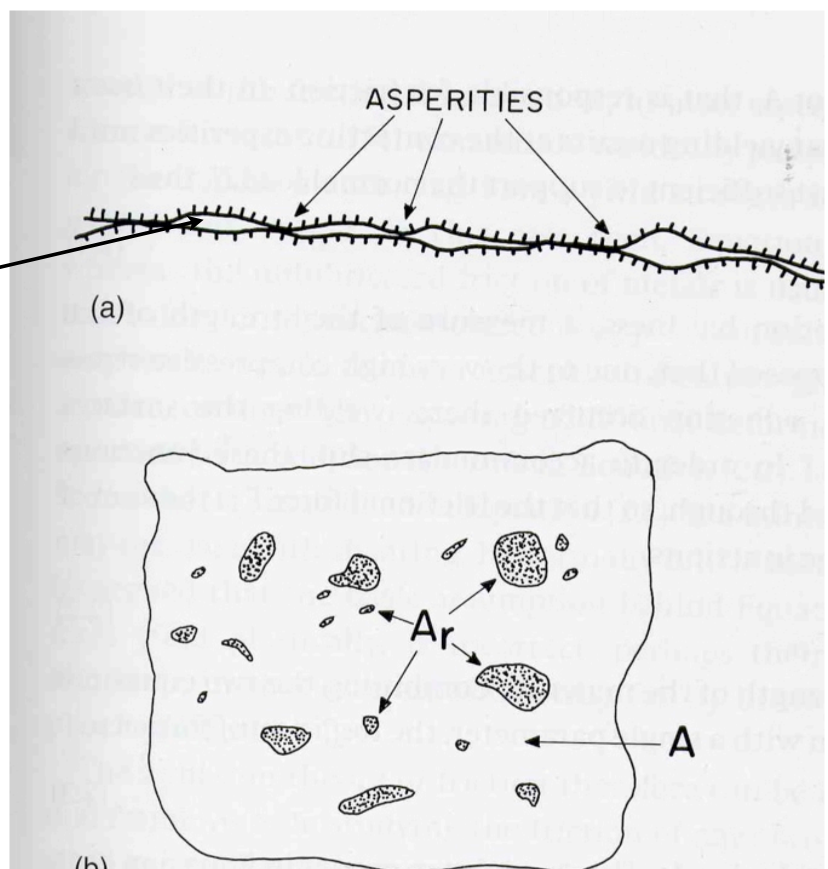

Chester et al., 1993

Chester and Chester, 1998: **cm-wide** highly sheared zone;
**prominent slip surface of < 1 - 5 mm**,
composed of ***micron***- and ***nanometer***-sized particles
(highly compressed granular material or fault gouge)

low permeability

pore pressure may increase dramatically!

just add water at high pressure. what will happen?




C. Scholz 2002

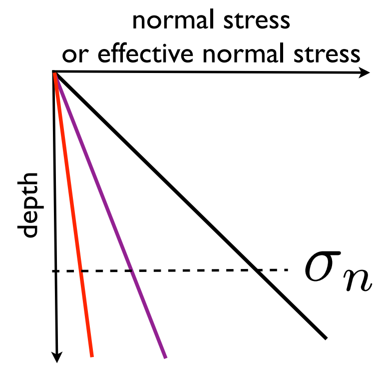
Pore pressure can dramatically reduce "effective normal stress"

$$|\sigma_e| = |\sigma_n| - P_p$$

At a depth of 10 km:

$\sigma_e$ if water is not overpressured?

$\sigma_e$ if pore pressure = 0.9 x lithostatic pressure?




**Coulomb failure criterion**:
The fault can slip if:

$$|\tau| = \mu|\sigma_n|$$

To take into account pore fluid pressure:

$$|\tau| = \mu|\sigma_e|$$

where

$$|\sigma_e| = |\sigma_n| - P_p$$

Coulomb criterion for fault slip

$$|\tau| = \mu|\sigma_e|$$

Now suppose the stresses change.

An earthquake is more likely if shear stress acting in the correct sense increases, and effective normal stress decreases.

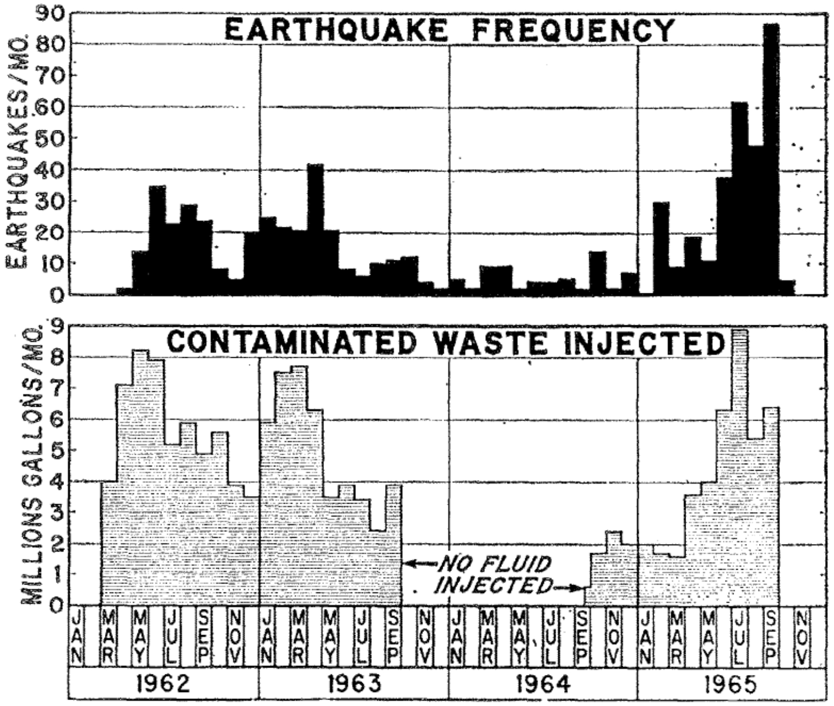
“Coulomb stress change”
(also known as “Coulomb Failure Function”) is

$$\Delta CFF = \Delta\tau + \mu\,\Delta\sigma_e$$

$\Delta CFF$ correlates with triggered earthquakes (and aftershocks)

Rocky Mt. Arsenal (US Army base) near Denver Colorado, early 1960’s: 3670 m deep well was drilled and used for disposal of wastewater...

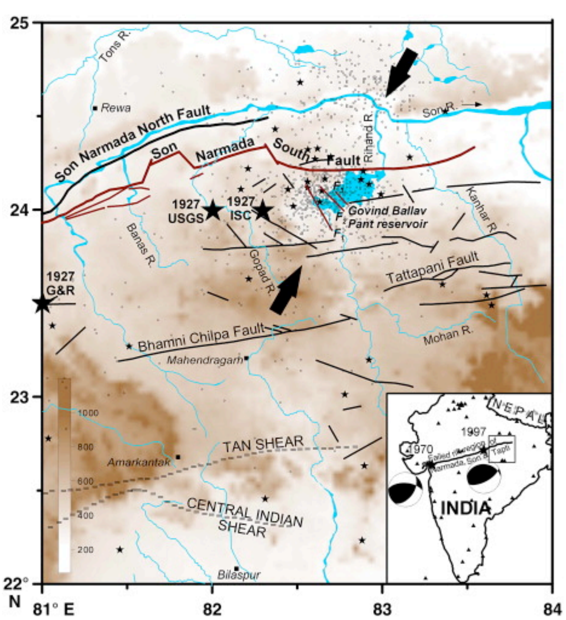
# Human-triggered earthquakes: wastewater injection wells



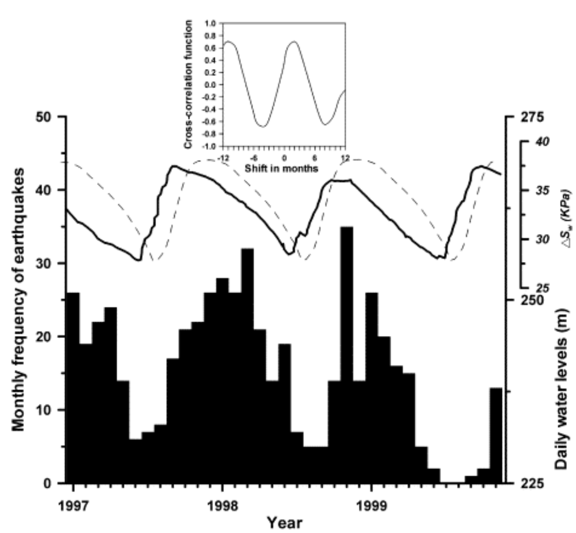

Still happens, recently in Arkansas and Switzerland.

$$\Delta CFF = \Delta\tau + \mu\ \Delta\sigma_e$$

# An example of seismicity changes due to changes in pore fluid pressure and/or surface loading by a reservoir in central India

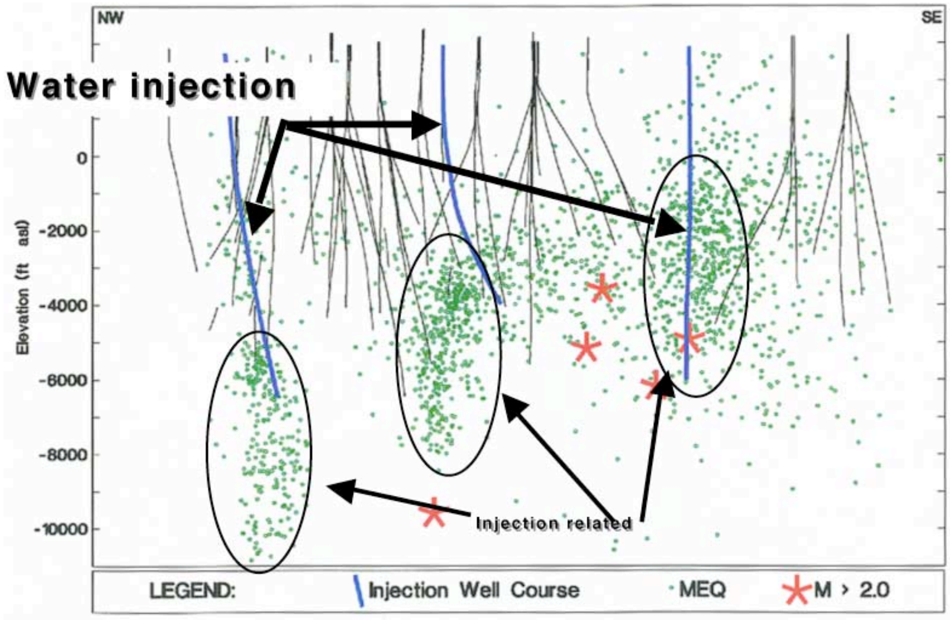



Gahalaut et al., 2007




$$\Delta CFF = \Delta\tau + \mu\ \Delta\sigma_e$$

# Hydrofracking actually depends on this



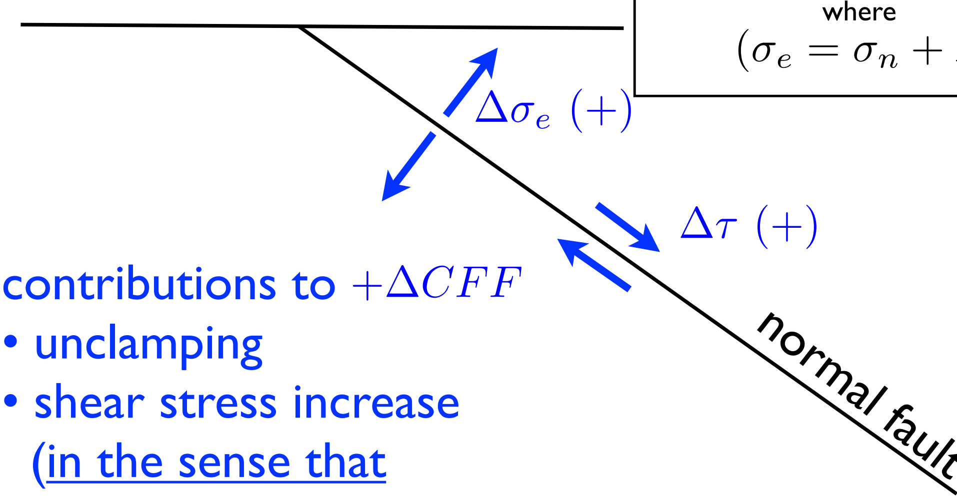

Lawrence Berkeley Lab

$$\boxed{P_p \qquad \begin{bmatrix} \Delta\sigma_{11} & \Delta\sigma_{12} \\ \Delta\sigma_{21} & \Delta\sigma_{22} \end{bmatrix}} \longrightarrow \boxed{\Delta\tau \qquad \Delta\sigma_e}$$

$$\Delta CFF = \Delta\tau + \mu_s \Delta\sigma_e$$

where

$$(\sigma_e = \sigma_n + P_p)$$



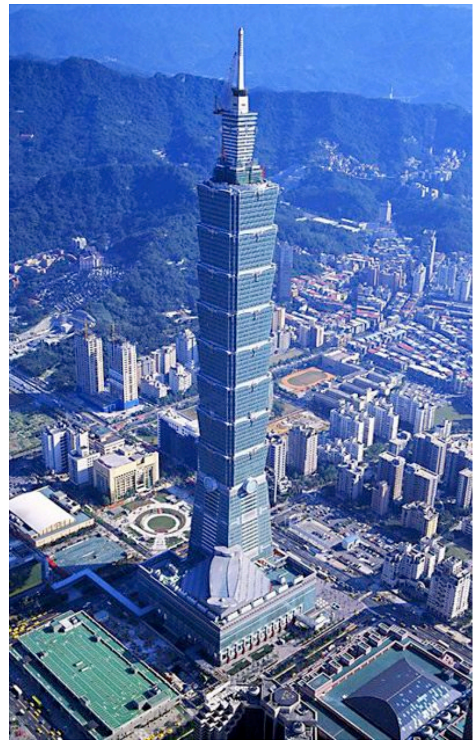

contributions to $+\Delta CFF$

- unclamping
- shear stress increase
  (in the sense that
  drives the fault slip)

GEOPHYSICAL RESEARCH LETTERS, VOL. 32, L22313, doi:10.1029/2005GL024223, 2005

**Seismicity increase after the construction of the world's tallest building: An active blind fault beneath the Taipei 101**

Cheng-Horng Lin
Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan



mass = 705,000 metric tons
= $7.05 \times 10^8$ kg

Force acting on ground = mass x gravitational acceleration = Q = $7.05 \times 10^9$ kg m/s$^2$

sfc area is 15000 sq m so stress at base is about 0.47 MPa (used by C. Lin...)

but triggered (??) quake was 3.8 km deep...

Coulomb stress changes from large earthquakes can be sufficient to trigger other earthquakes

This is the main reason for aftershocks

(Wednesday)