

Mechanismus hlubokých zemětřesení - přehled

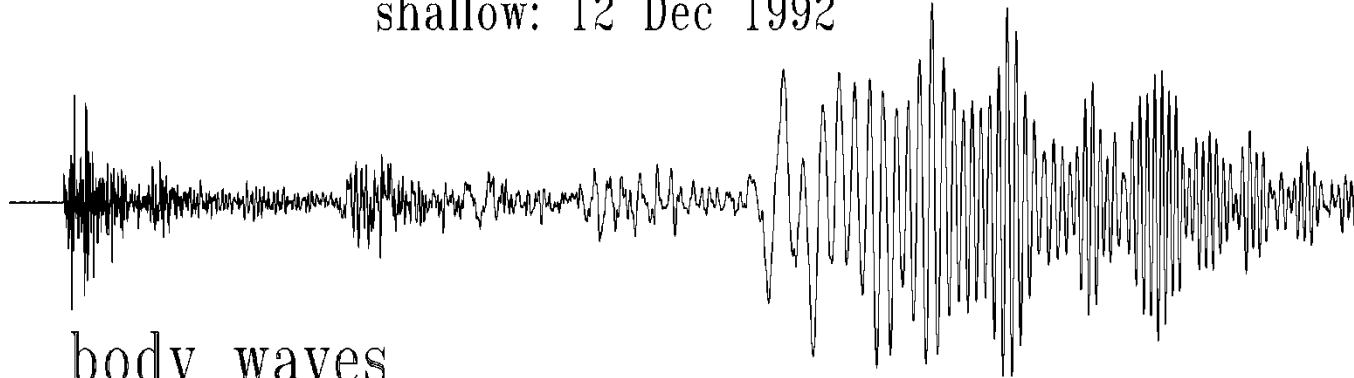
J. Zahradník

Katedra geofyziky MFF UK

**SHALLOW, INTERMEDIATE
AND DEEP
70, 300, 700 KM**

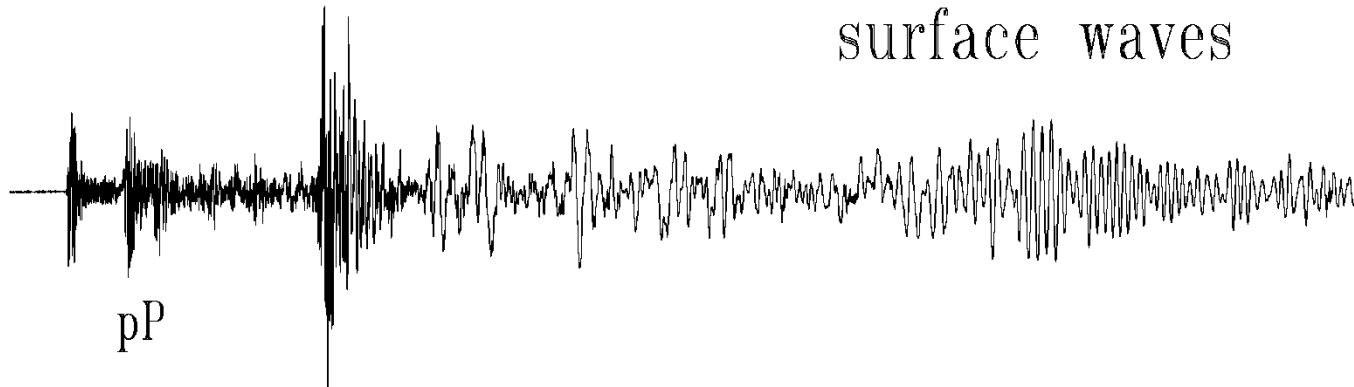
Discovery of deep events:
Kiyoo Wadati, 1928

shallow: 12 Dec 1992



body waves

surface waves



pP

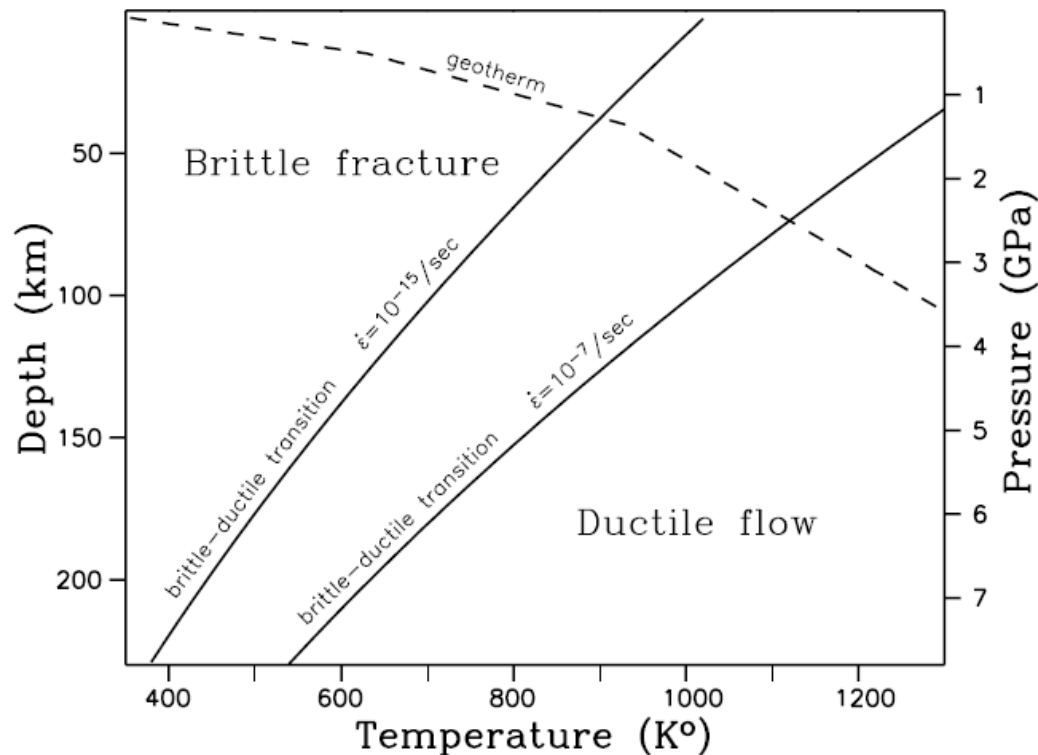
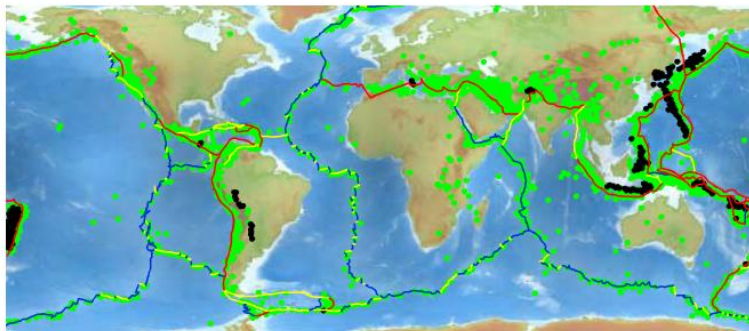


Fig. 1.12| Approximate relationship between pressure (depth), temperature, strain rate, and the mechanism of rock failure. At low temperatures, low pressures, and high strain rates rocks tend to fracture, whereas at high temperatures, high pressures, and low strain rates they fail by creep. The brittle-ductile transition depends on strain rate $\dot{\epsilon}$. For temperature/pressure conditions corresponding to mantle depths exceeding about 40–70 km, brittle fracture does not occur, suggesting that some other mechanism must be responsible for deep earthquakes. Relationships for brittle-ductile transitions determined by equating eq. 6 and eq. 9 from Houseman and England (1986); the plotted geotherm is from Stacey (1992).

ES1001 Earthquake Depths

The **focus** of an earthquake is the actual point underground where rocks break. The depth of the focus can be categorized as shallow (up to 70 km below the surface), intermediate (70 to 300 km), or deep (greater than 300 km).

Click the buttons below to see the global distribution of shallow, intermediate, and deep earthquakes.



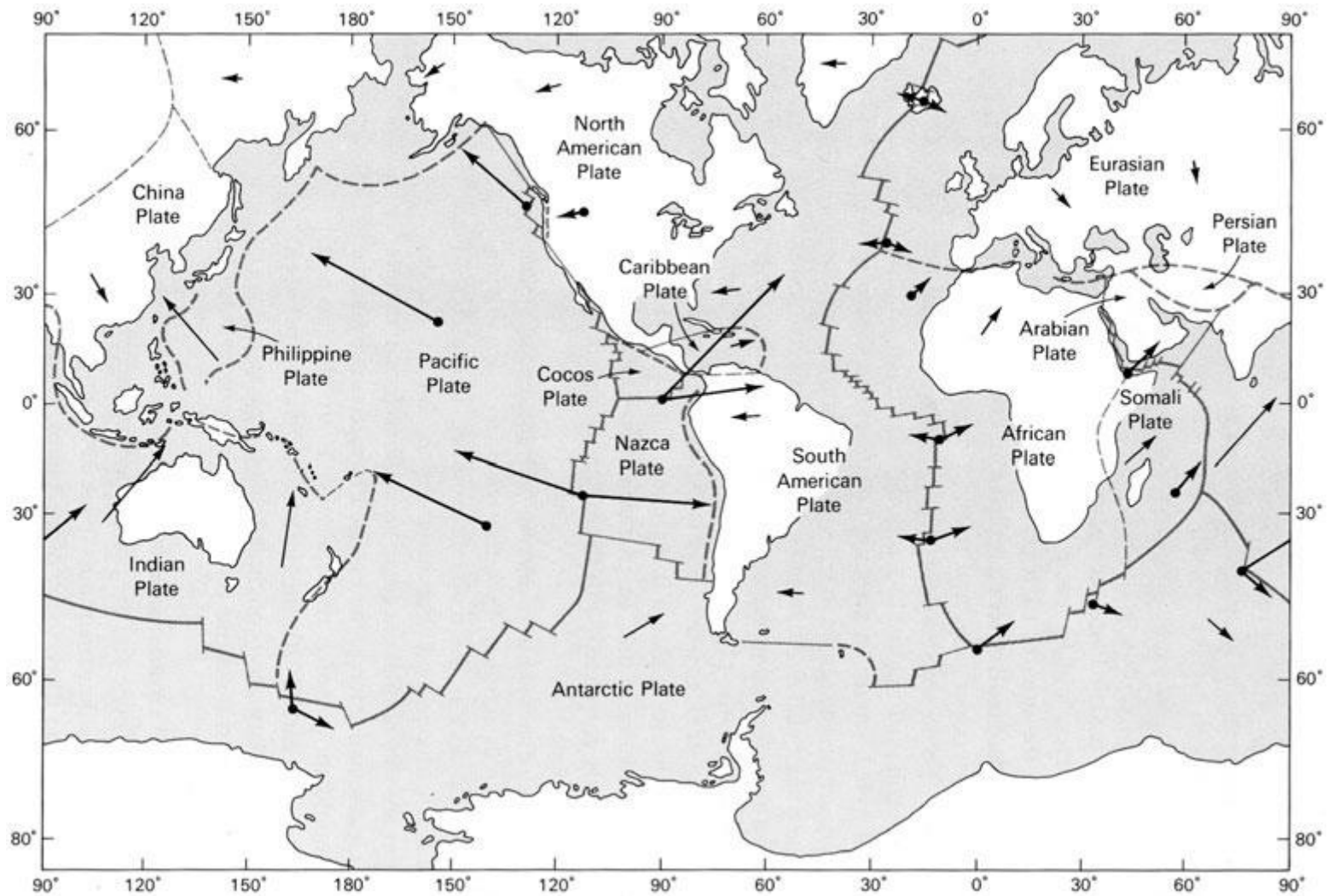
— Divergent Boundaries ● Shallow Focus ● Intermediate Focus ● Deep Focus
— Convergent Boundaries
— Transform Boundaries

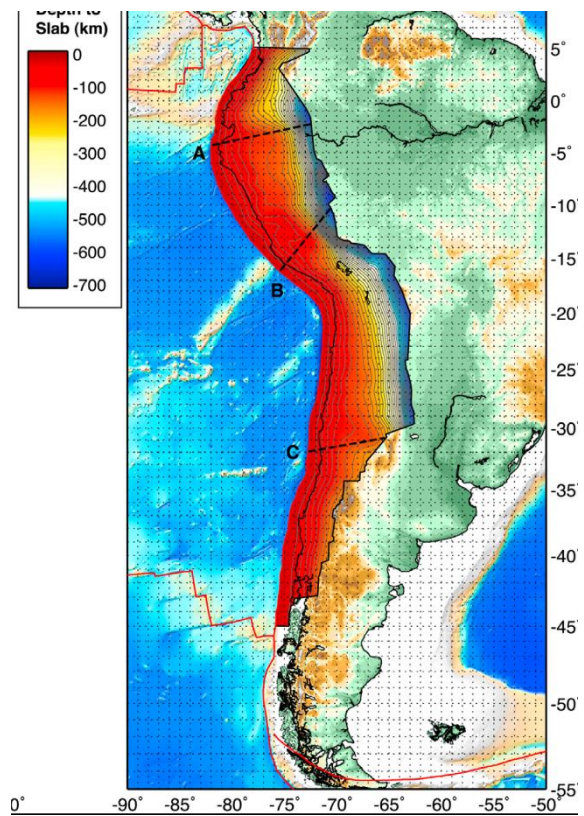
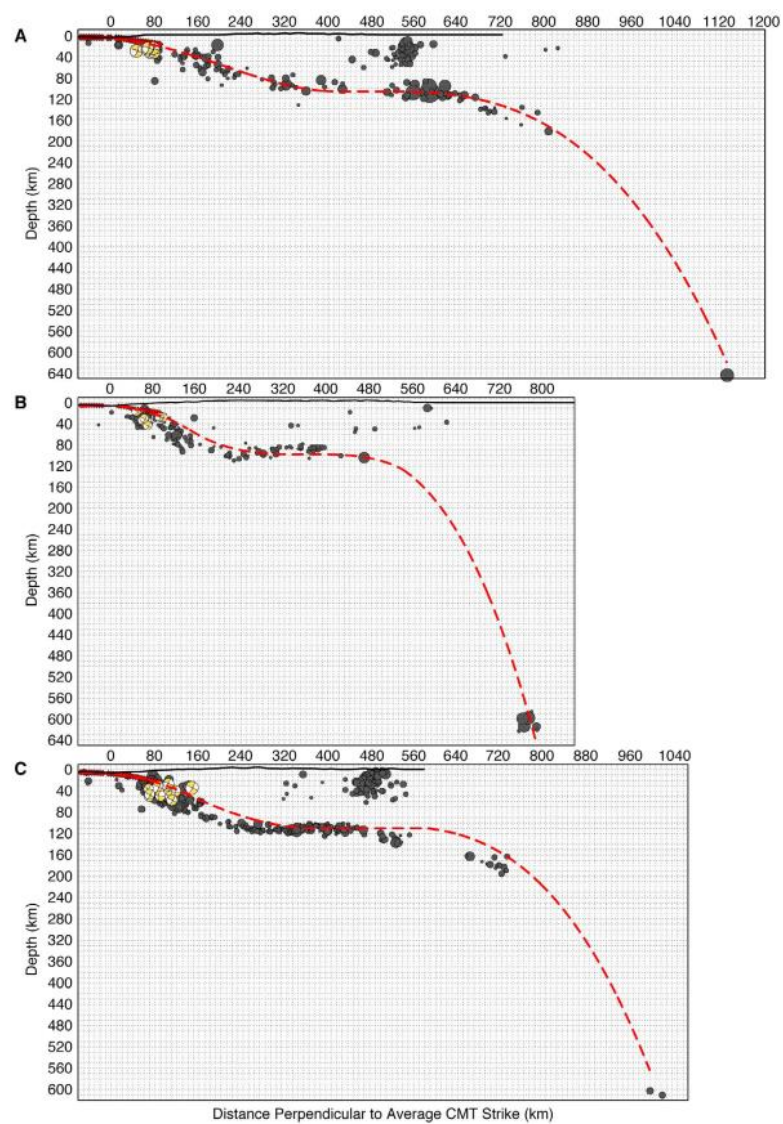
Jennifer Loomis, TERC

3. Which depth range has the most earthquakes? Which depth range has the fewest earthquakes?
4. At what type of plate boundary do you find most deep-focus earthquakes?
5. Explain why deep-focus earthquakes occur at this type of plate boundary but not at others.

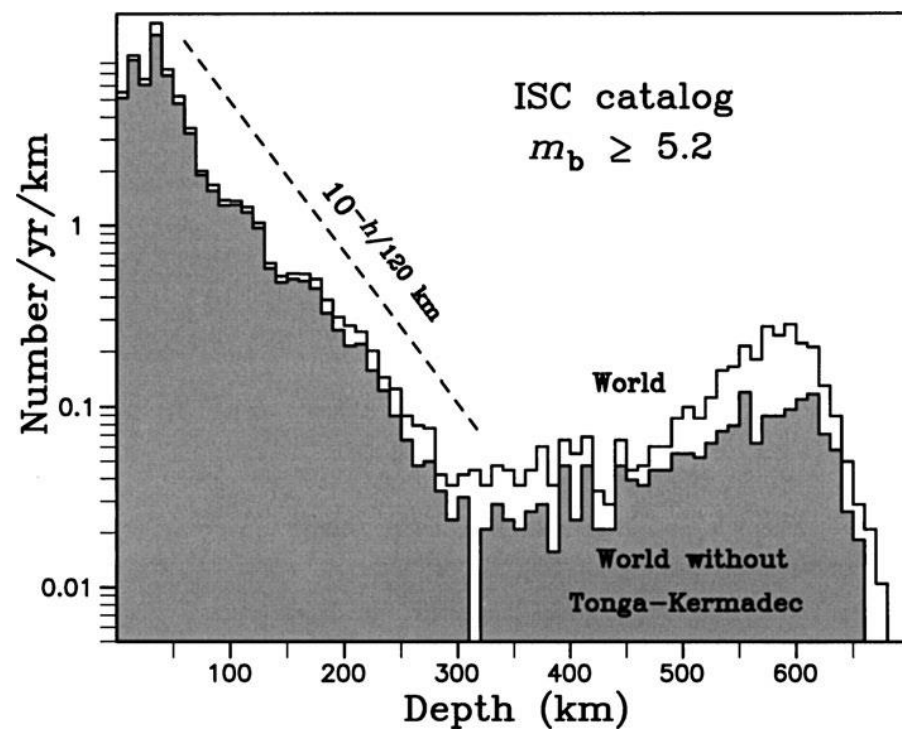
Step: 1 2 3 4 5 6 7

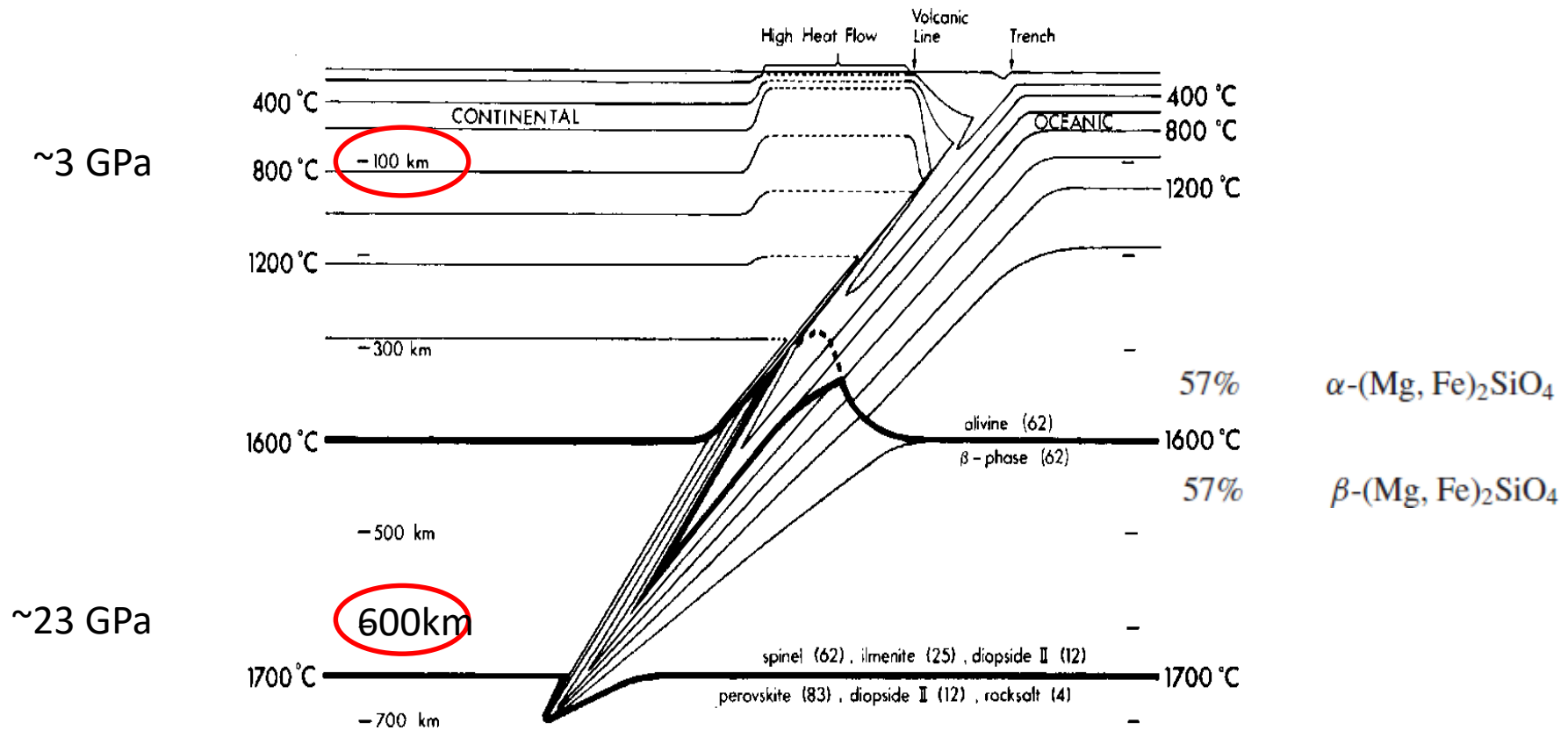
Back Next





hayes_etal_JGR2012.pdf

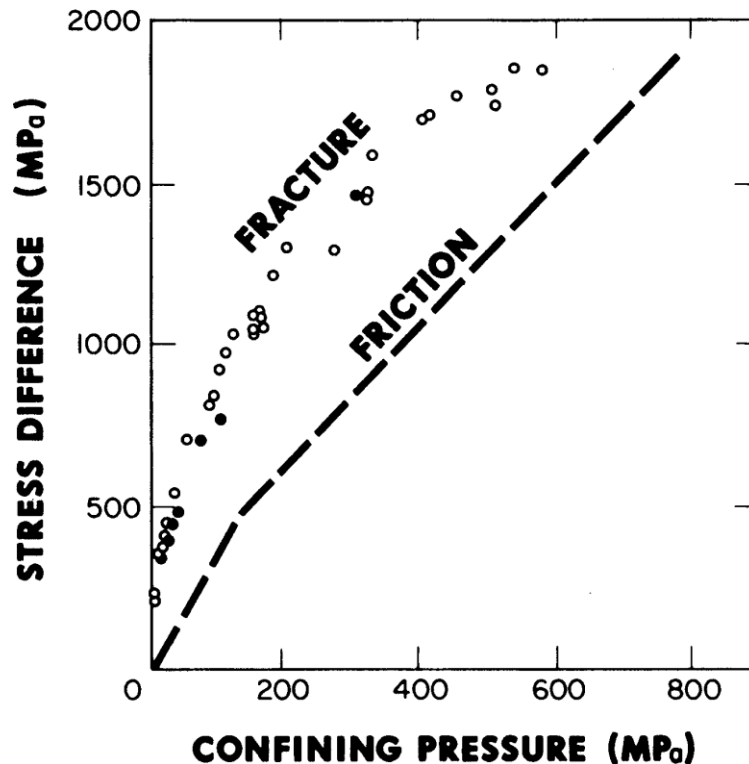




1 GPa = 10 000 bar (atm.)

Frohlich_2006_Deep_Earthquakes.pdf

stress tensor, some surface, traction
 τ shear stress, σ normal stress
 μ fracture/friction coefficient
 $\mu\sigma$ frictional shear stress



Fracture: Coulomb criterion

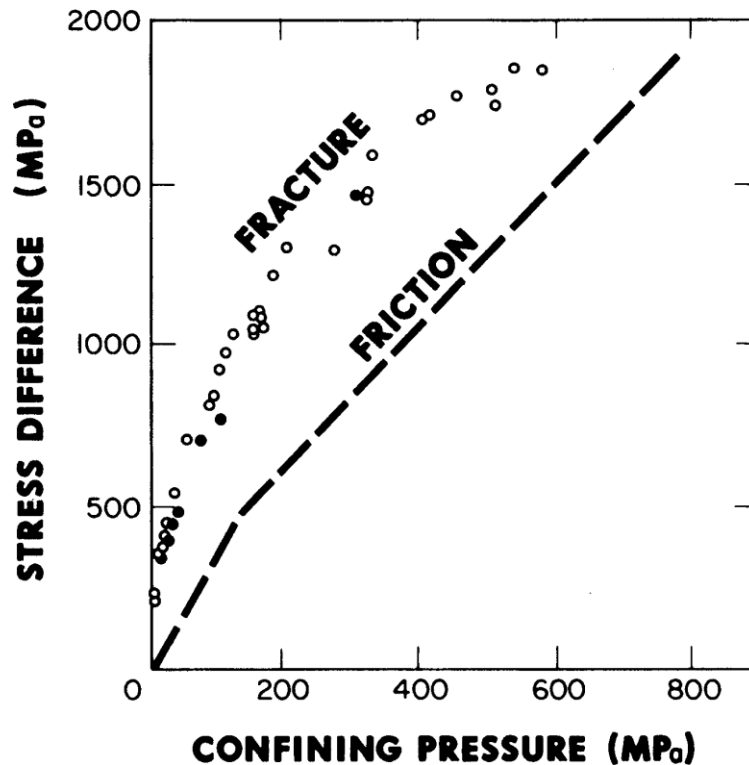
$$\tau > \tau_{\text{fracture limit}} = \tau_1 + \mu_1 \sigma_h$$

τ fract/frict limit = shear strength
stress difference

Friction: Byerlee's law

$$\tau > \tau_{\text{friction limit}} = \tau_2 + \mu_2 \sigma_h$$

stress tensor, some surface, traction
 τ shear stress, σ normal stress
 μ fracture/friction coefficient
 $\mu\sigma$ frictional shear stress



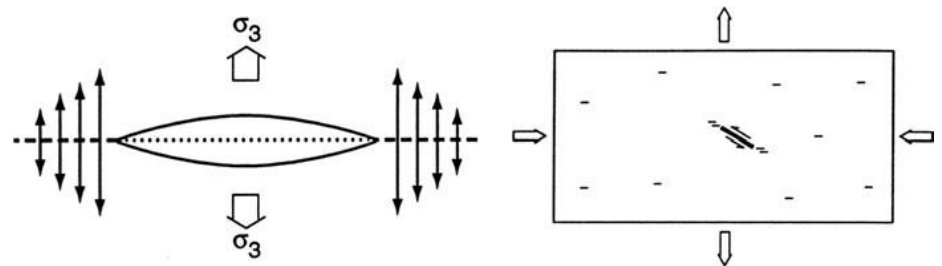
Fracture: Coulomb criterion

$$\tau > \tau_{\text{fracture limit}} = \tau_1 + \mu_1 \sigma_h$$

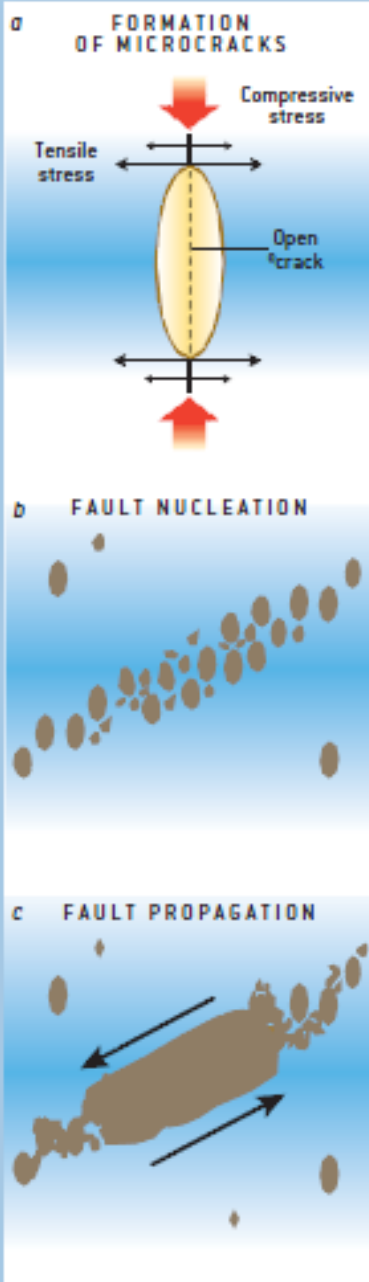
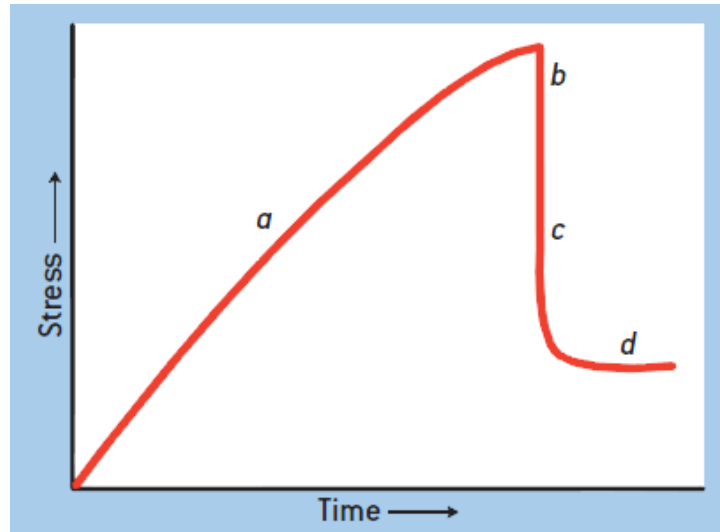
τ fract/frict limit = shear strength
 stress difference

Friction: Byerlee's law

$$\tau > \tau_{\text{friction limit}} = \tau_2 + \mu_2 \sigma_h$$



BRITTLE FAILURE



As brittle rocks experience mounting stress, microcracks open parallel to the direction from which they are compressed. (In rocks found more than 300 kilometers deep, pressure prohibits this dilation.... but...). At some critical point in time, these microfeatures link up and create a fault (*b*). Movements along the fault then relieve stress (*c*).

The deep earthquake paradox:

how could deep earthquakes occur
if the rocks at their source seem to be
either hot and too weak,
or colder but too strong
to fracture?

The deep earthquake paradox:

how could deep earthquakes occur
if the rocks at their source seem to be
either hot and too weak,
or colder but too strong
to fracture?

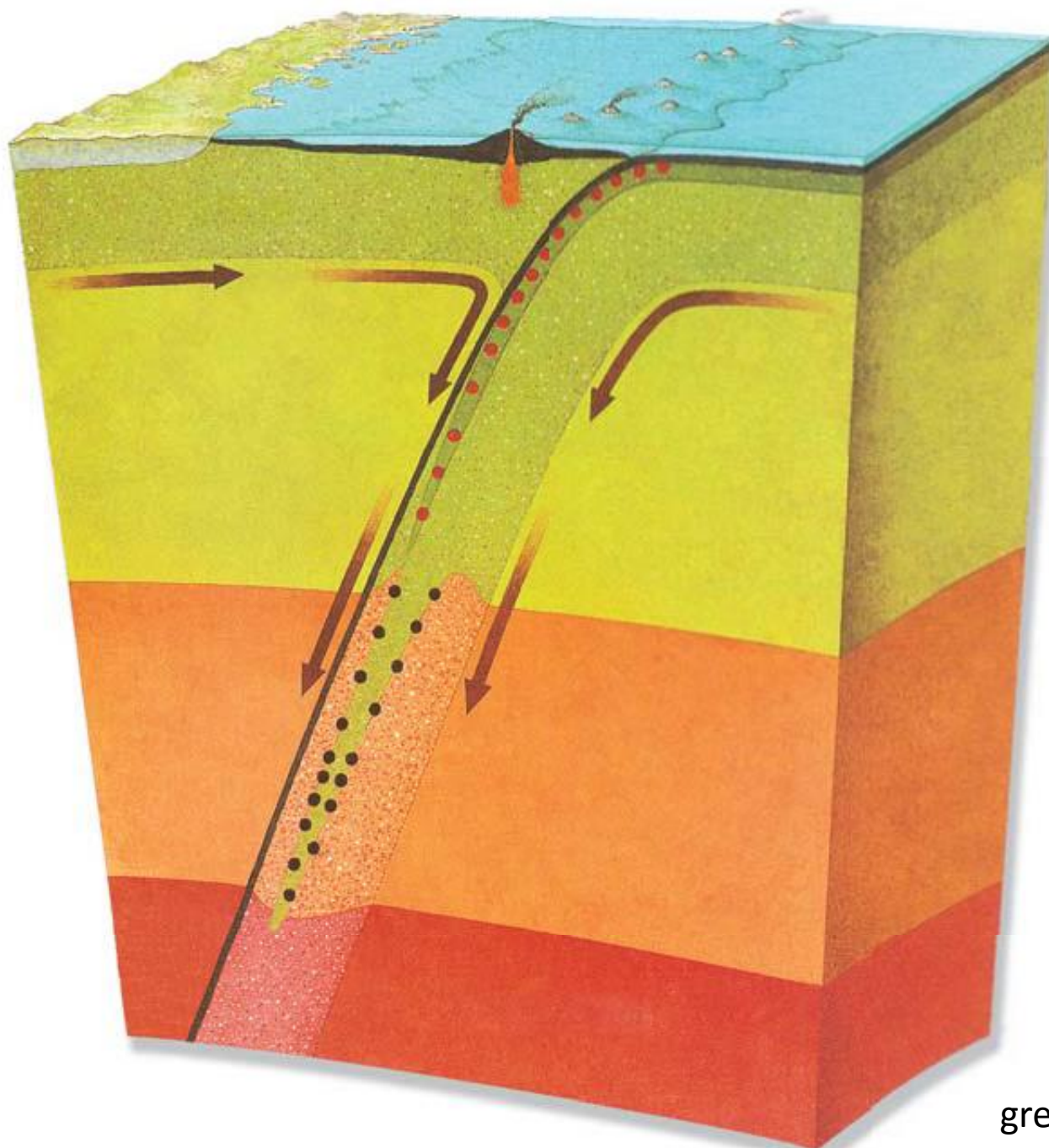
Friction: with liquid in pores
pressure p decreases the friction limit

Solution for intermediate earthquakes
Dehydration embrittlement

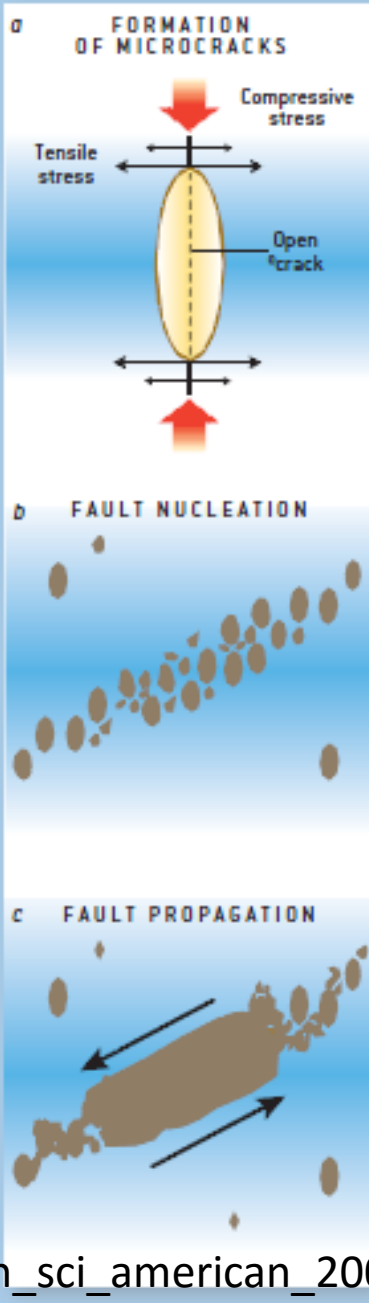
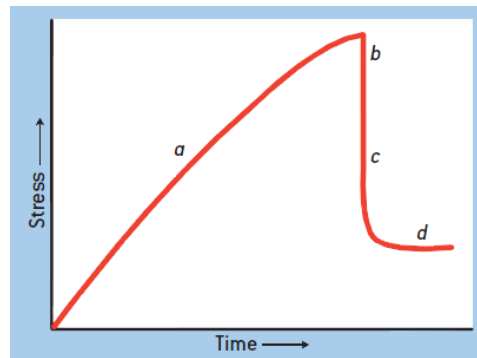
$$\tau > \tau_{\text{friction limit}} = \tau_2 + \mu_2 (\sigma_h - p)$$

Fluid-assisted faulting

Hydrated minerals release fluids when they reach appropriate temperature–
pressure conditions in the mantle, thus permitting brittle fracture to occur in the
mantle at greater depths than under dry conditions.



BRITTLE FAILURE



Common features of shallow and deep earthquakes:

Both processes involve the development of microscopic features that form a fault.

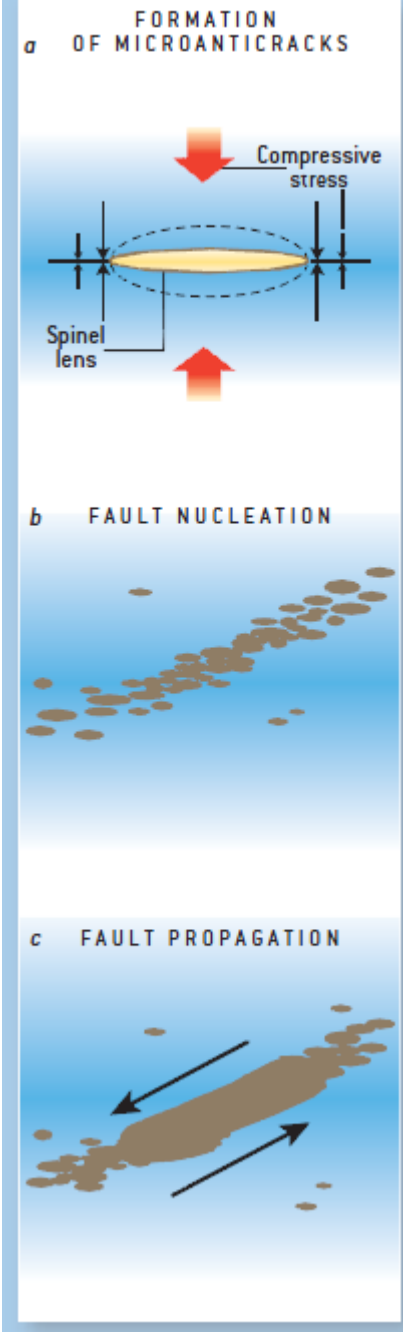
Shallow rocks - micro**cracks** open parallel to the direction from which they are compressed.

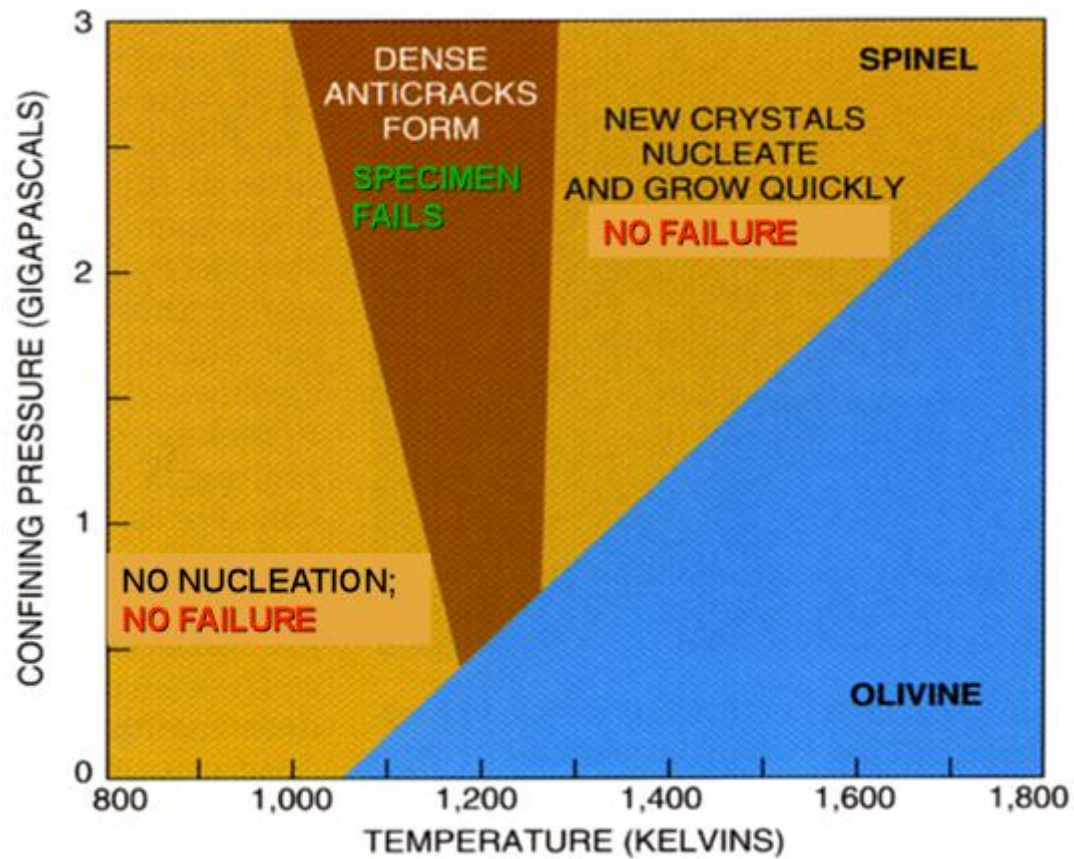
Deep rocks (> 300 km) pressure prohibits the dilation. Instead micro**anticracks** form, perpendicular to the direction from which these rocks are compressed.

Anticracks = lenses filled with fine-grained, dense material (spinel-phase olivine).

Transformation-induced faulting

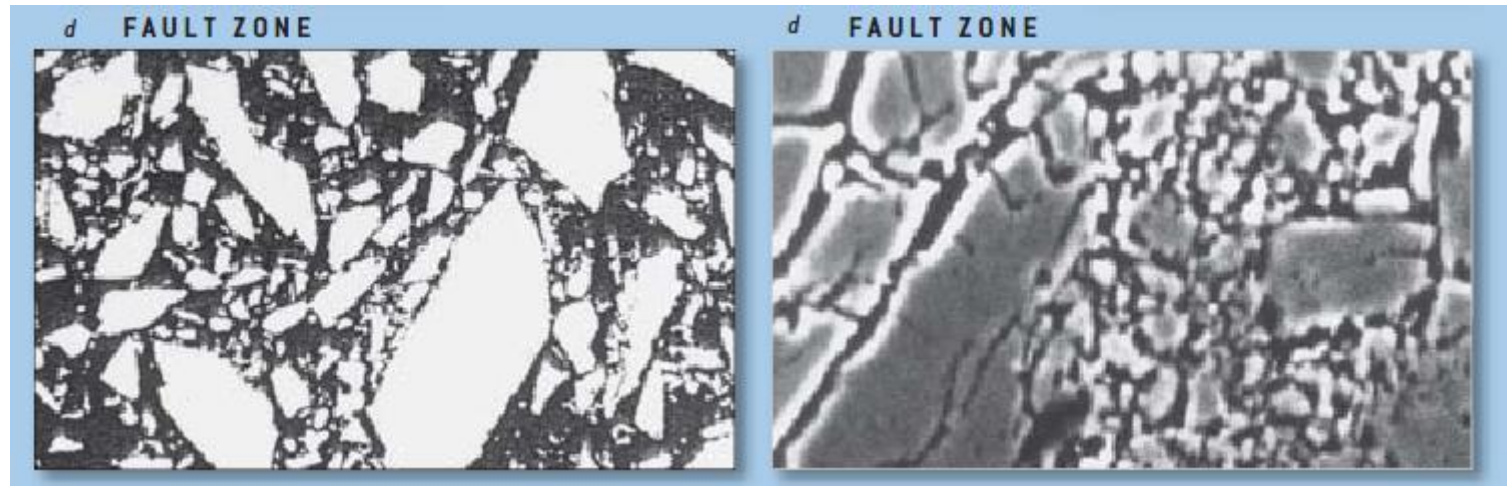
ANTICRACK FAILURE

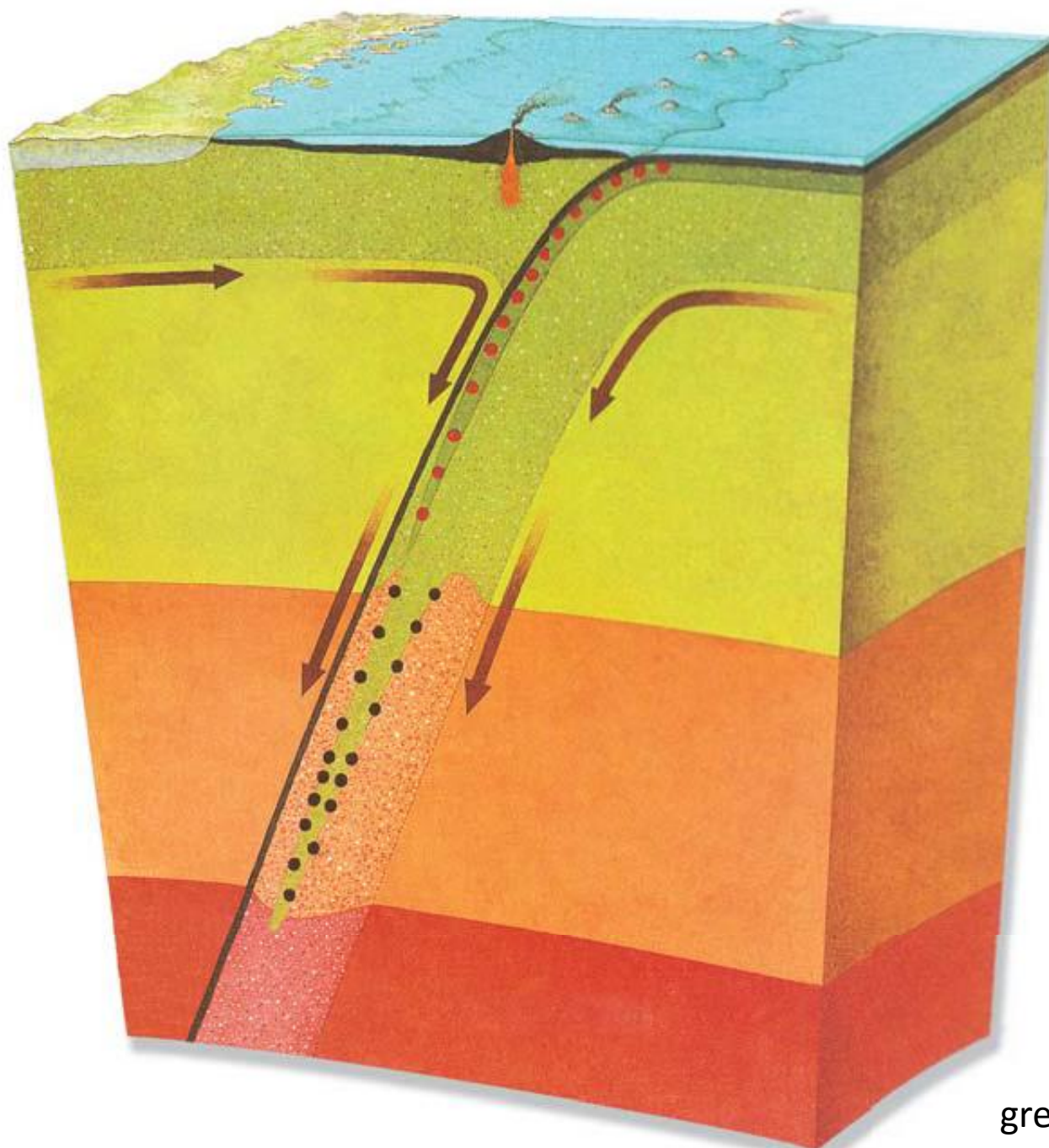


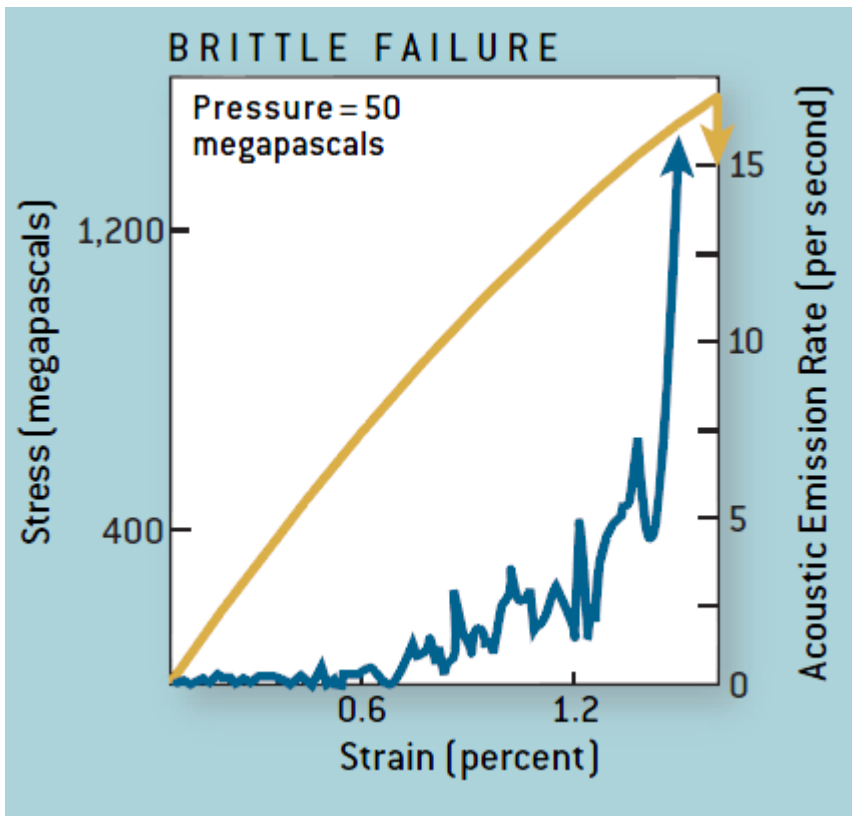
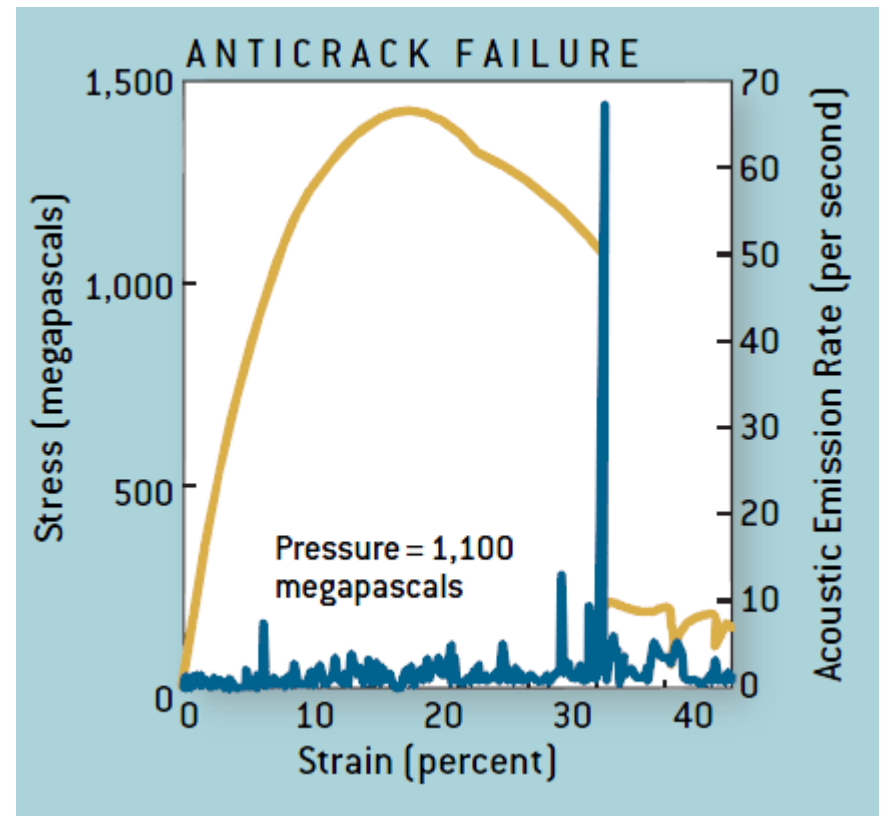


Brittle fault zones contain angular crystals showing a fractal size distribution.

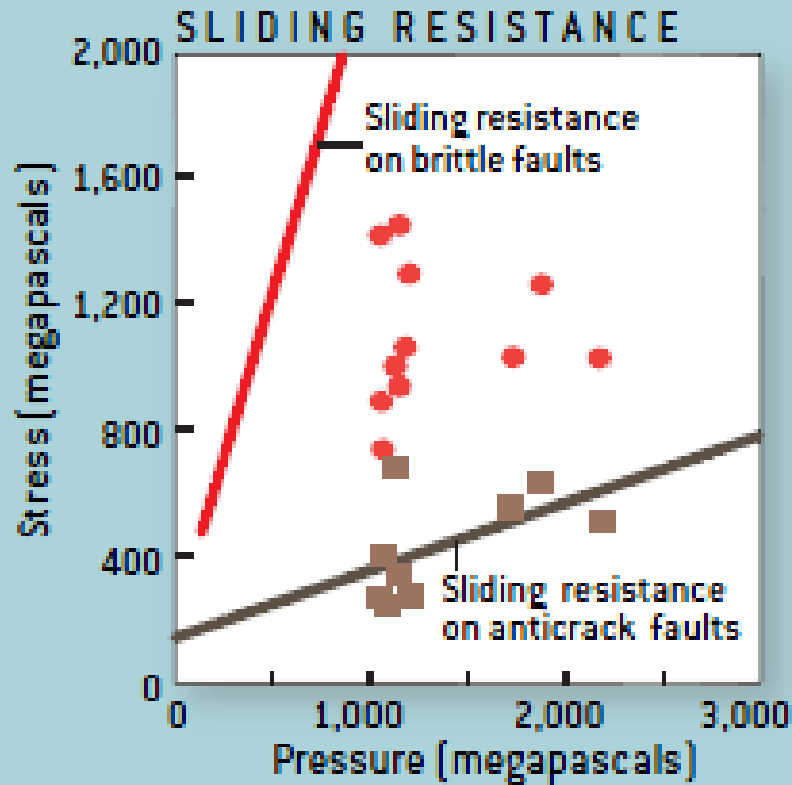
In anticrack fault zones, rounded olivine fragments are embedded in extremely fine grained spinel-phase olivine.







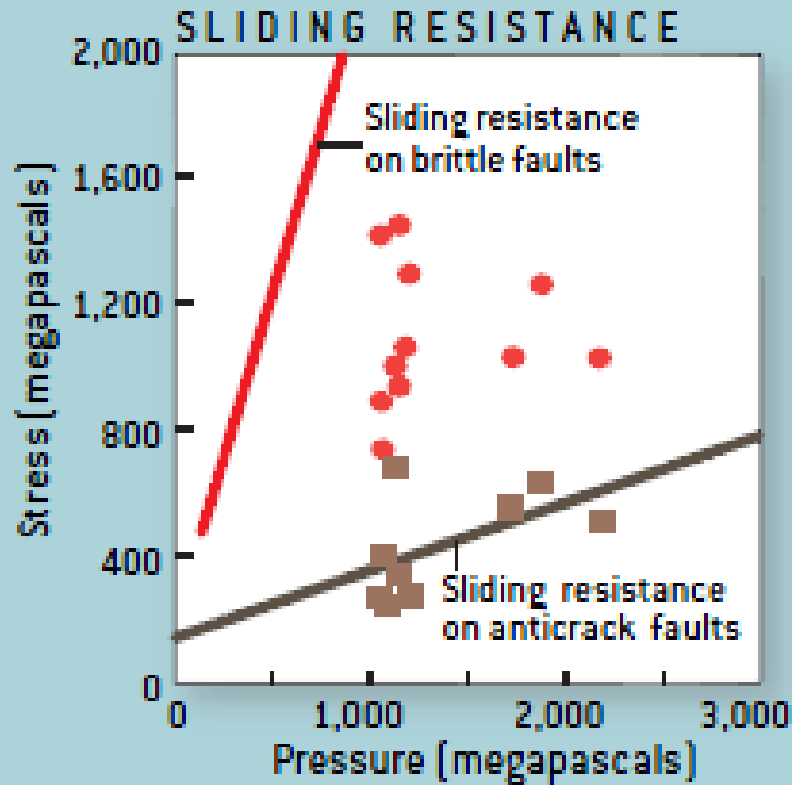
ACOUSTIC EMISSIONS (*blue*) occur when a fault suddenly slips, radiating energy that relieves stress (*yellow*). Brittle failure, the mechanism responsible for shallow earthquakes, emits noise before and during movement on a fault (*left*). In contrast, anticrack failure, the mechanism behind deep earthquakes, emits acoustic energy only when faulting takes place (*right*).



At higher pressures, brittle faulting can occur only under much greater stress (left *bottom*).

For this reason, brittle failure cannot explain deep-focus earthquakes.

HOWEVER: Pressure does not likewise inhibit anticrack failure.



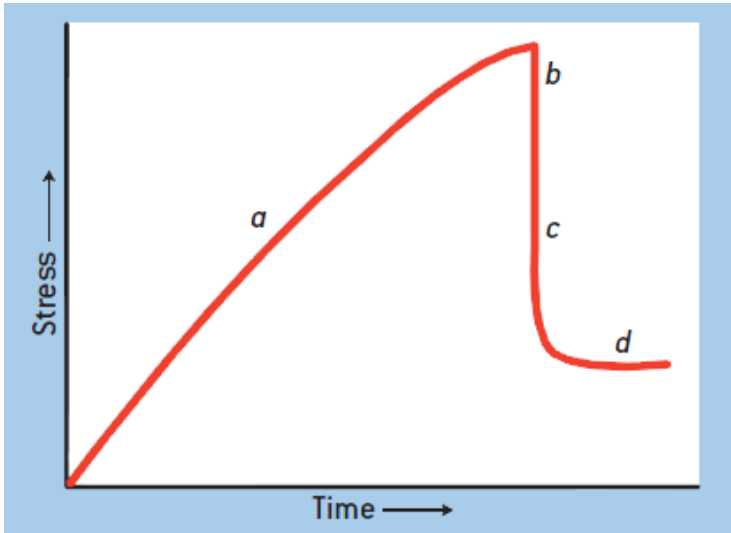
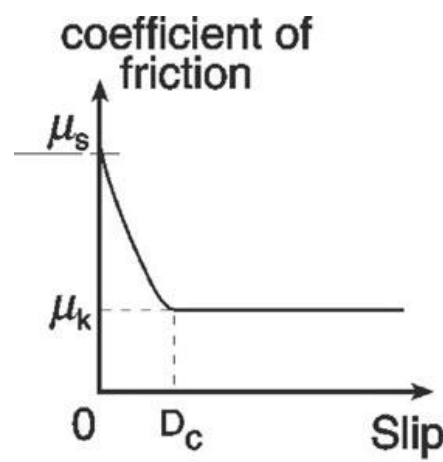
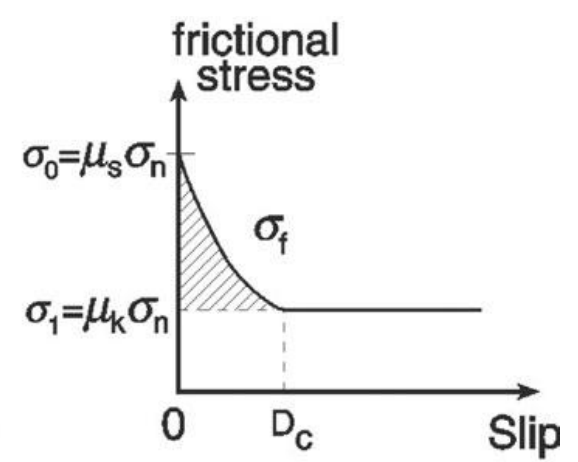
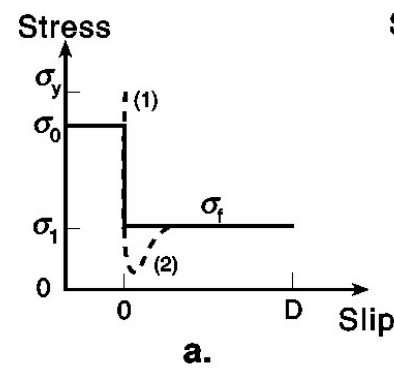
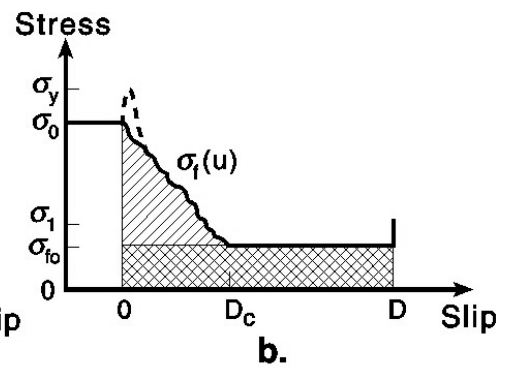
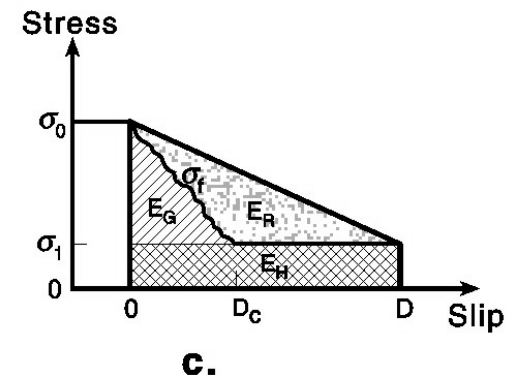
At higher pressures, brittle faulting can occur only under much greater stress (left *bottom*).

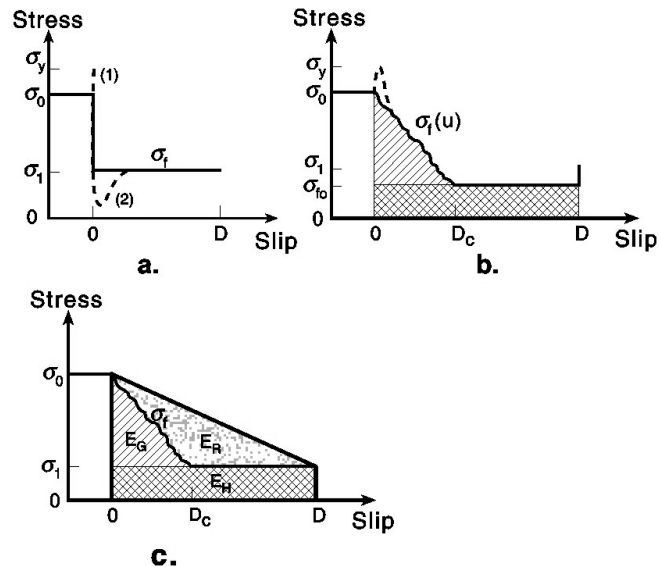
For this reason, brittle failure cannot explain deep-focus earthquakes.

HOWEVER: Pressure does not likewise inhibit anticrack failure.

superplasticity:







Kanamori & Brodsky, 2004
Fig. 18 (for unit area Σ)

E ... total potential energy
 E_r ... radiated seismic energy
 E_g ... fracture energy
 E_h ... heat, friction energy

$$E = (\sigma_0 + \sigma_1)/2 D \Sigma$$

$$E = (\sigma_0 - \sigma_1)/2 D \Sigma + \sigma_1 D \Sigma = (E_g + E_r) + E_h$$

$$E = (\Delta\sigma/2) D \Sigma + \sigma_1 D \Sigma$$

$\Delta\sigma$... (static) stress drop

$$(E_g + E_r) = (\Delta\sigma/2) D \Sigma = (\Delta\sigma/2) (M_0/\mu)$$

E_r = ... from integrated velocity

η ... seismic efficiency

$$E_r = \eta E = \eta (\Delta\sigma/2) D \Sigma + \eta \sigma_1 D \Sigma$$

$$E_r / D \Sigma = E_r \mu / M_0 = \eta (\Delta\sigma/2) + \eta \sigma_1$$

$$E_r \mu / M_0 = \text{def.} = \sigma_{\text{app}}$$

$$E_r \mu / M_0 = \text{def.} = \eta_{\text{eff}} (\Delta\sigma/2)$$

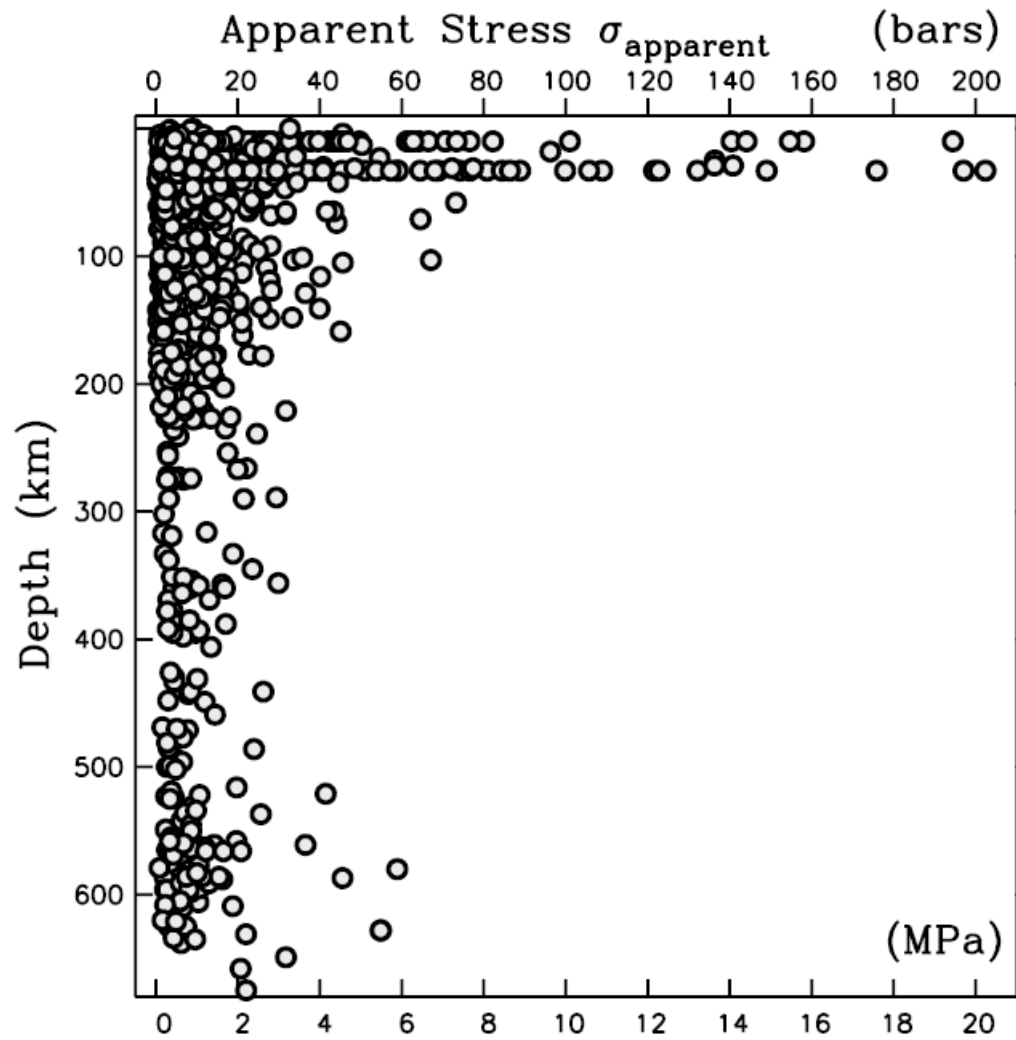
σ_{app} ... apparent stress

η_{eff} ... effective or radiation efficiency = $E_r / (E_g + E_r)$

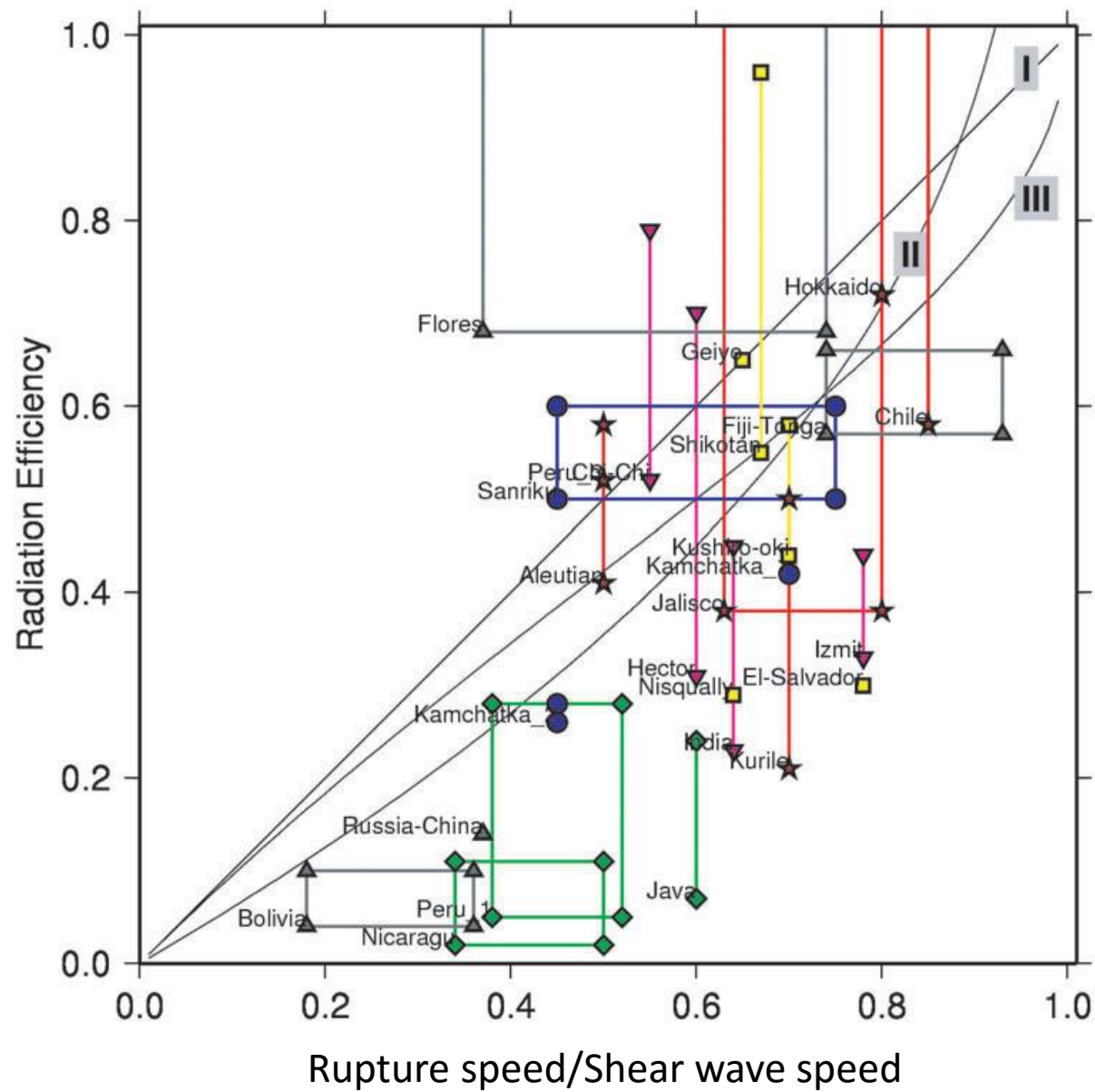
$$\eta_{\text{eff}} = 2\sigma_{\text{app}} / \Delta\sigma; \eta_{\text{eff}} > \eta$$

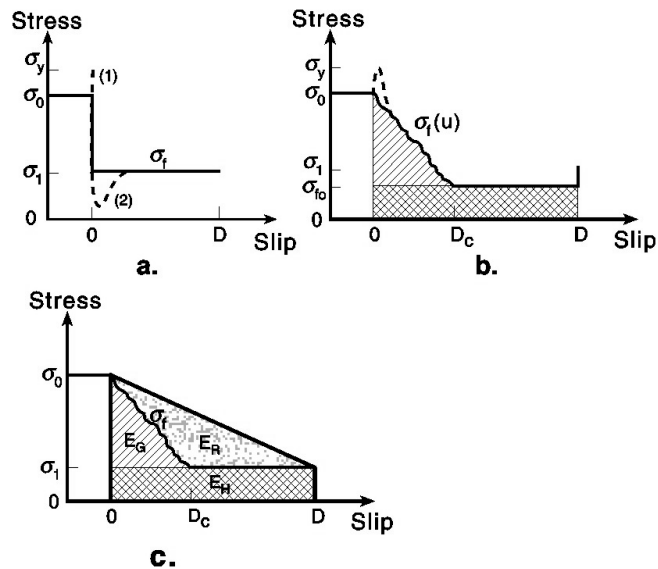
Frohlich, 2006:

app. stress is low, e.g. 1 MPa
 stress drop is high, e.g. 20 MPa
 rad. efficiency $\ll 1$, e.g. 0.1
 (see also Figs. 6.14 and 6.15)



Frohlich, 2006 Fig. 6.14





E ...total potential energy

E_r ... radiated seismic energy

E_g ... fracture energy

E_h ... heat, friction energy

$$(E_g + E_r) = (\Delta\sigma/2) D\Sigma = (\Delta\sigma/2) (M_0/\mu)$$

E_r = ... from integrated velocity

Kanamori & Brodsky, 2004

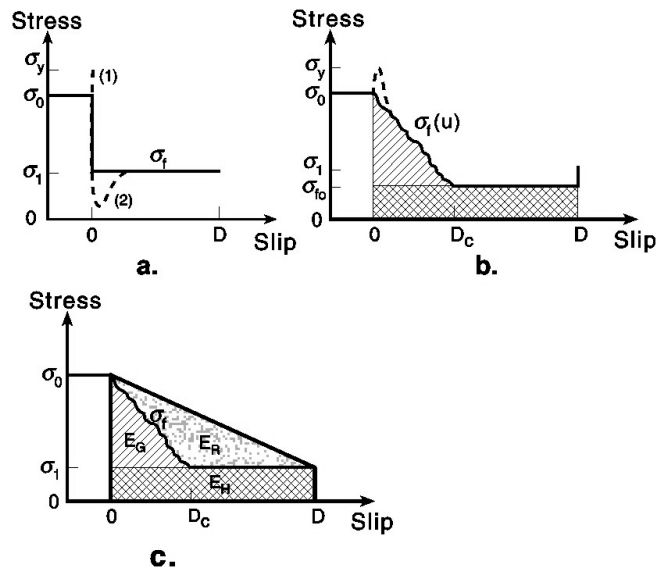
Fig. 18 (for unit area Σ)

η_{eff} ... effective or radiation efficiency = $E_r / (E_g + E_r)$

$\eta_{\text{eff}} = 2\sigma_{\text{app}} / \Delta\sigma$; $\eta_{\text{eff}} > \eta$

$E_g = (E_g + E_r) - E_r = (1/\eta_{\text{eff}} - 1)E_r$

E_g is lower bound of $E_g + E_h$ (total dissipation)



E ...total potential energy
 Er ... radiated seismic energy
 Eg ... fracture energy
 Eh... heat, friction energy

$(E_g + E_r) = (\Delta\sigma/2) D\Sigma = (\Delta\sigma/2) (M_0/\mu)$
 Er = ... from integrated velocity ...

Kanamori & Brodsky, 2004
 Fig. 18 (for unit area Σ)

η_{eff} ... effective or radiation efficiency = $E_r / (E_g + E_r)$
 $\eta_{\text{eff}} = 2\sigma_{\text{app}} / \Delta\sigma$; $\eta_{\text{eff}} > \eta$
 $E_g = (E_g + E_r) - E_r = (1/\eta_{\text{eff}} - 1)E_r$
 Eg is lower bound of $E_g + E_h$ (total dissipation)

e.g. **Bolivia 1994 earthquake, Mw 8.3; tot. diss. < 1.4e18 J**
 Comparable to the total thermal energy released during the volcanic eruption of Mount St. Helens in 1980.



