ESS 411/511 Geophysical Continuum Mechanics Class #17

Highlights from Class #16 – Madie Mamer
Today's highlights on Monday – Abigail Thienes

Our text doesn't cover our next topics very thoroughly, so we will use a few other sources, which are posted on the class web site under READING & NOTES. https://courses.washington.edu/ess511/NOTES/notes.shtml

- Stein and Wysession 5.7.2
- Stein and Wysession 5.7.3/4
- Raymond notes on failure

Also see slides about upcoming topics

- Failure and Mohr's circles – slides

Your short CR/NC Pre-class prep writing assignment (1 point) in Canvas

- It will be due in Canvas at the start of class.
- I will send another message when it is posted in Canvas.

ESS 411/511 Geophysical Continuum Mechanics

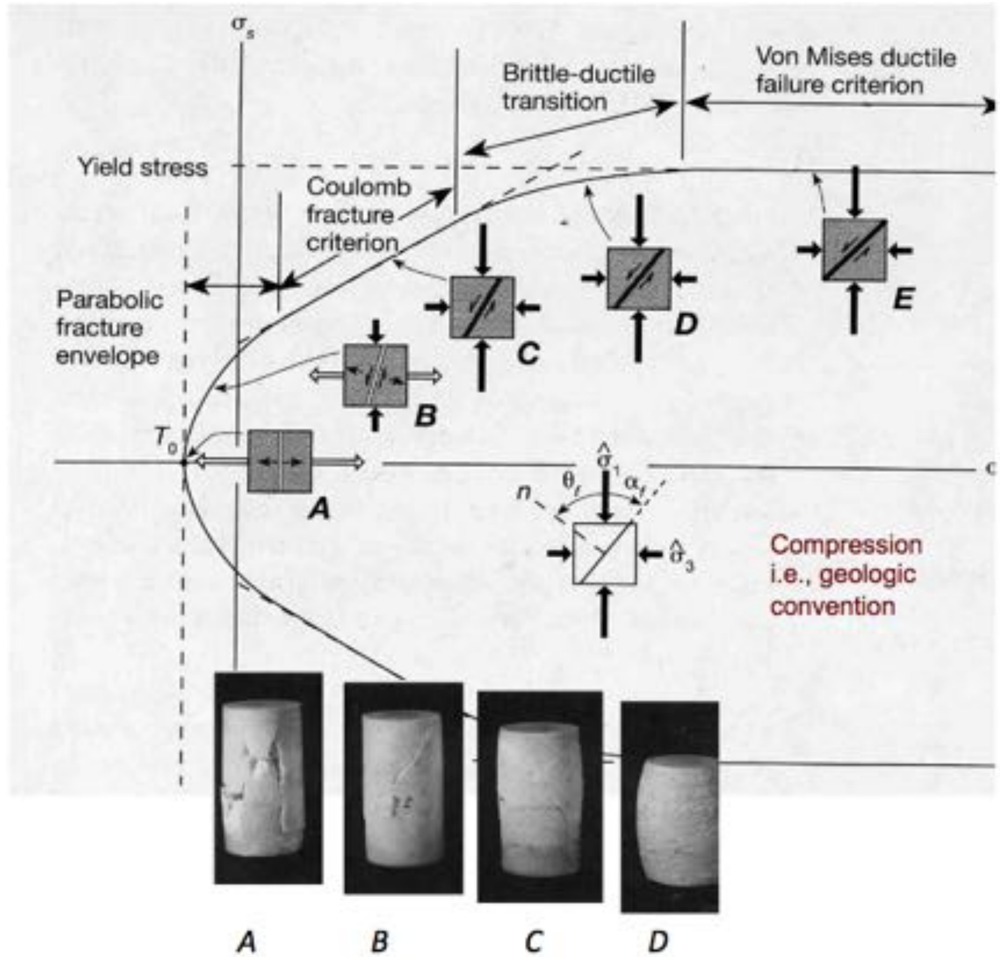
Broad Outline for the Quarter

- Continuum mechanics in 1-D
- 1-D models with springs, dashpots, sliding blocks
- Attenuation
- Mathematical tools – vectors, tensors, coordinate changes
- Stress – principal values, Mohr's circles for 3-D stress
- Coulomb failure, pore pressure, crustal strength
- Measuring stress in the Earth
- Strain – Finite strain; infinitesimal strains
- Moments – lithosphere bending; Earthquake moment magnitude
- Conservation laws
- Constitutive relations for elastic and viscous materials
- Elastic waves; kinematic waves

ESS 511 60-second Project updates

- Andrew
- Barrett
- Maleen
- Zoe
- Madeleine

Class-prep questions for today (break-out rooms)



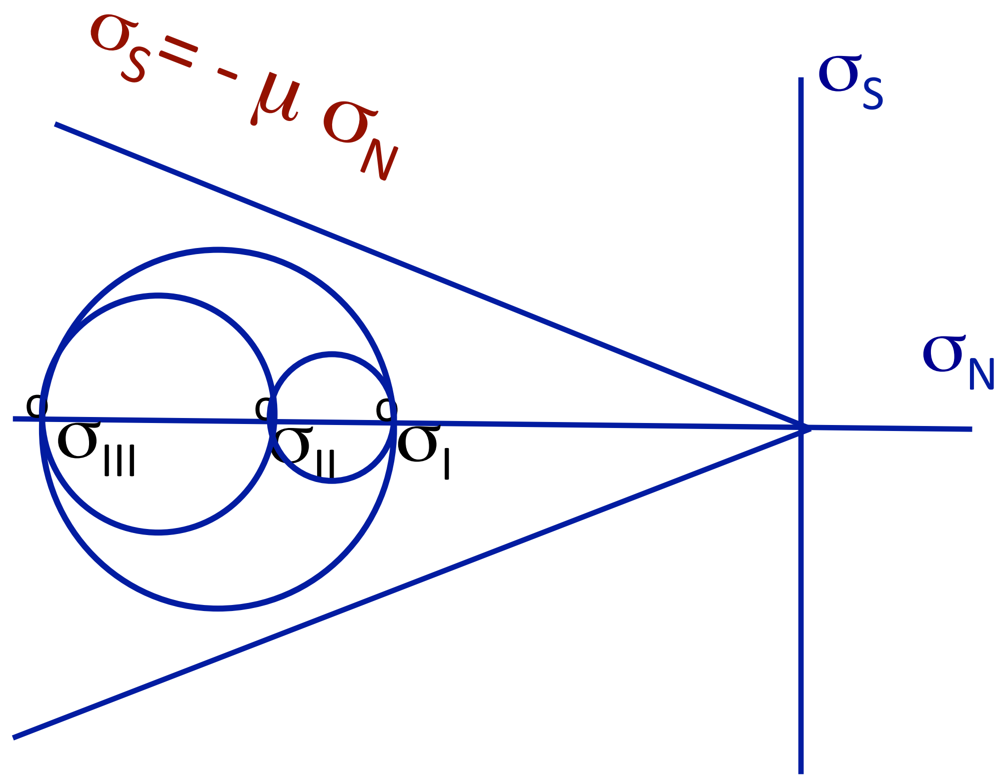
Style of Failure under Various Normal Stresses σ_N

The figure shows the failure envelope and failure modes in stress space, based on experiments on rocks subjected to a range of normal stresses σ_N. Note that these authors used the convention that compression is positive (yuck …)

- Describe in words what is happening in this generalization of the failure envelopes that we have discussed in class.
- In a sentence or two for each, describe characteristics of the failure mode in each of the 5 stress regimes *A, B, C, D*, and *E*. The regime names, the angles of the failure planes, and the visual states of the samples after the experiments ended may be helpful.

Differential stress

$\sigma_I - \sigma_{III}$



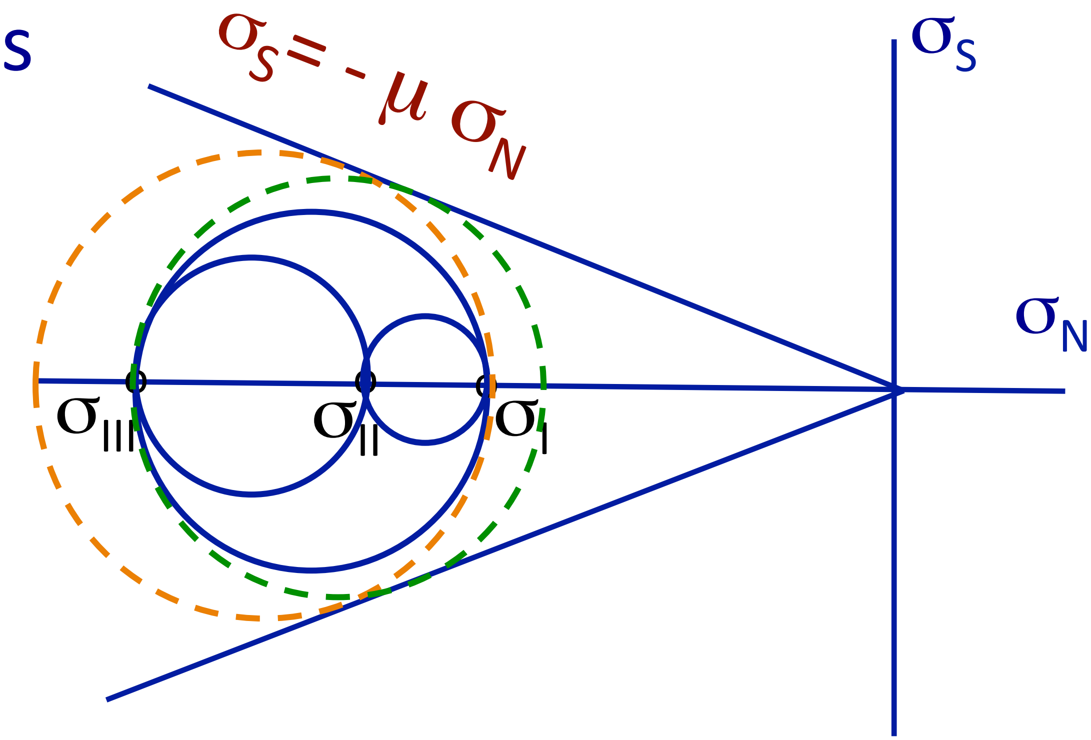
But, if $\sigma_{III} = \sigma_I$, all 3 principal stresses are equal

- What do the 3 Mohr's circle look like?
- Describe this state of stress inside the body.
- Is frictional failure possible, if differential stress is zero?

Differential stress

$\sigma_I - \sigma_{III}$

So differential stress is essential in order to have failure



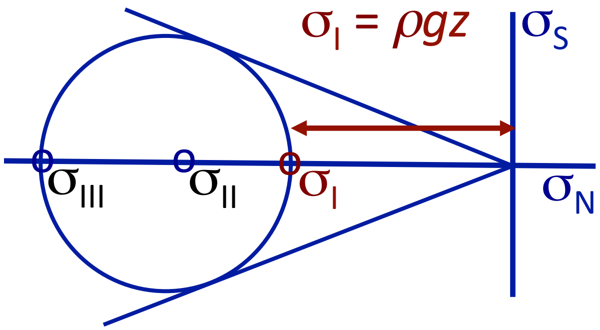
How could we change the stress state in order to cause failure?

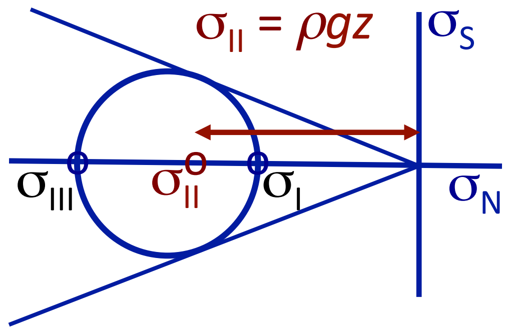
- Hold σ_I make σ_{III} more negative (squeeze harder in x_3)
- Hold σ_{III}, make σ_I less negative (don't squeeze as hard in x_1)

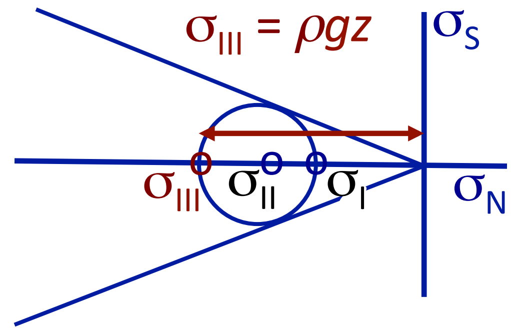
Types of faults

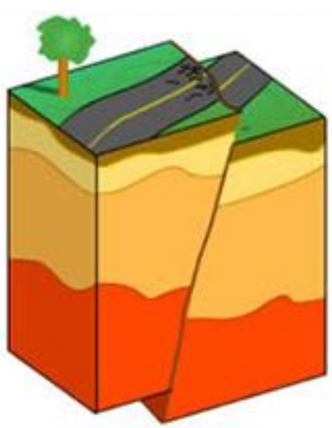
The Earth's surface is traction-free, so one of the principal directions is generally vertical

- What are the orientations of the principal axes of stress $\hat{e}_1^*$, $\hat{e}_2^*$, $\hat{e}_3^*$ in each case?

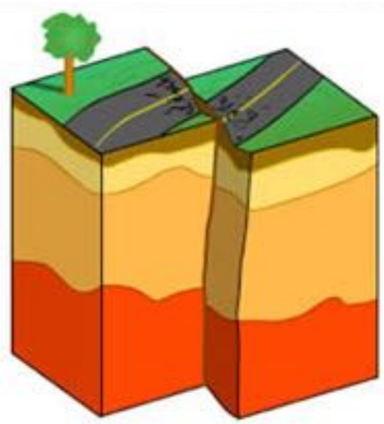




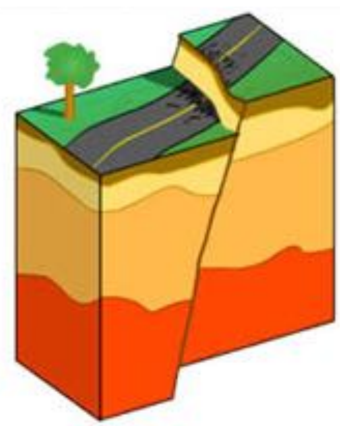




Reverse fault

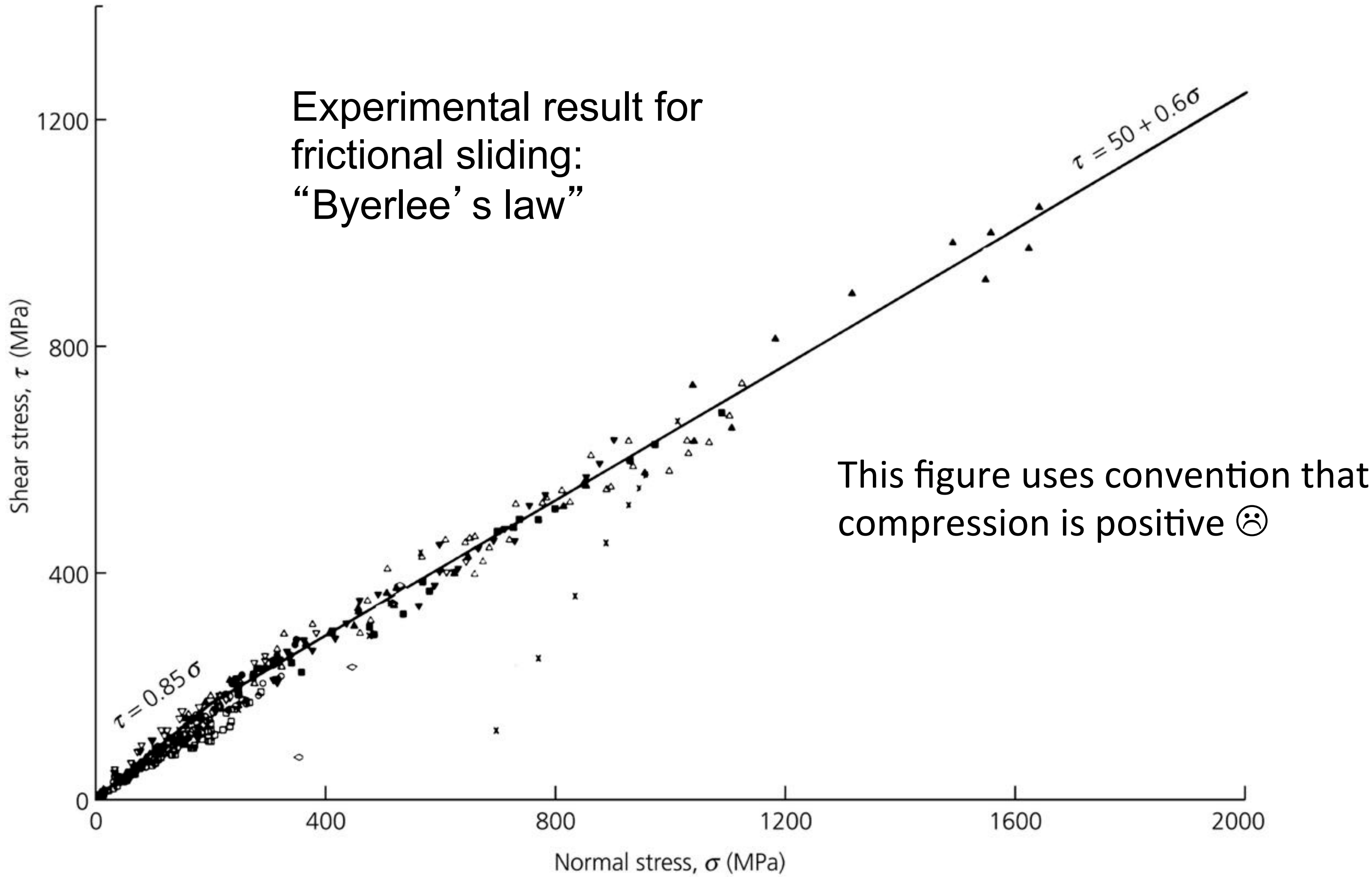


Strike-slip fault



Normal fault

Figure 5.7-10: Relation between shear stress and normal stress for frictional sliding.

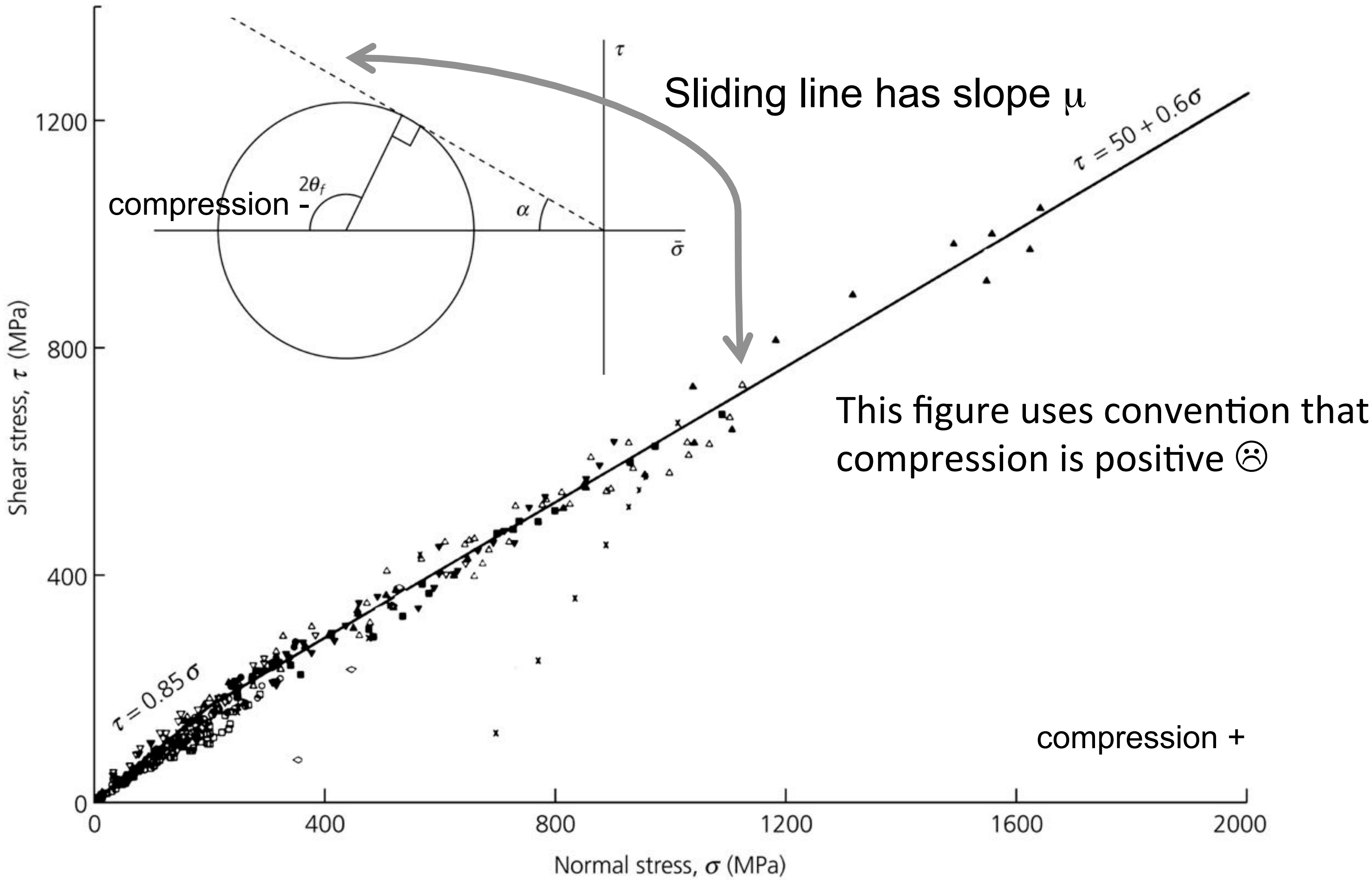


Lab experiments show a linear relation between the maximum shear stress that rocks can support at any given normal stress. This is called Byerlee's Law.

$$\tau \approx -.85\bar{\sigma} \qquad \bar{\sigma} < 200 \text{ MPa}$$

$$\tau \approx 50 - .6\bar{\sigma} \qquad \bar{\sigma} > 200 \text{ MPa.}$$

Figure 5.7-10: Relation between shear stress and normal stress for frictional sliding.



Byerlee's law

$$\tau \approx -.85\bar{\sigma} \qquad \bar{\sigma} < 200 \text{ MPa}$$

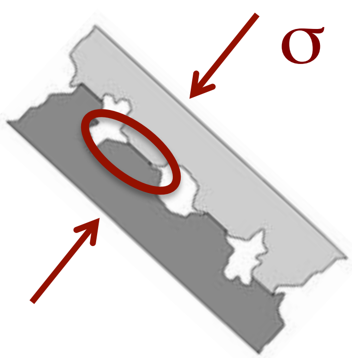
$$\tau \approx 50 - .6\bar{\sigma} \qquad \bar{\sigma} > 200 \text{ MPa.}$$

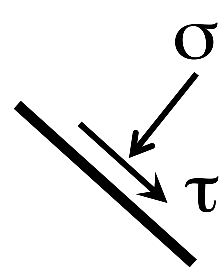
Two regions

Coulomb stress and rock fracture

- Notion of friction:
  - More shear stress τ is needed to overcome increase in normal stress σ and cause a fault to slip – Byerlee's law is an example
- Coulomb stress
  - $\sigma_S = \tau - \mu (\sigma_N - p)$
  - where μ is intrinsic coefficient of friction, p is pore pressure (***not*** the mean stress $p=-\sigma_{ii}/3$, need to be careful of context)

- Basis is that real area of contact (much smaller than apparent area) is controlled by normal stress
  - deformation of asperities in response to normal stress increases contact area
  - harder to over-ride asperities at higher normal stress





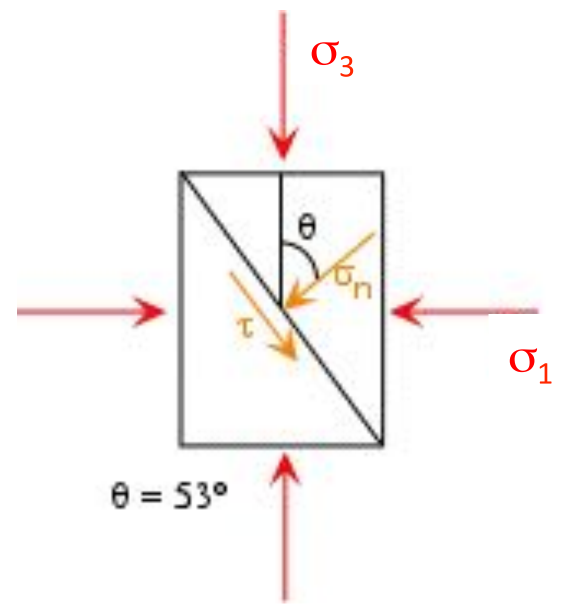
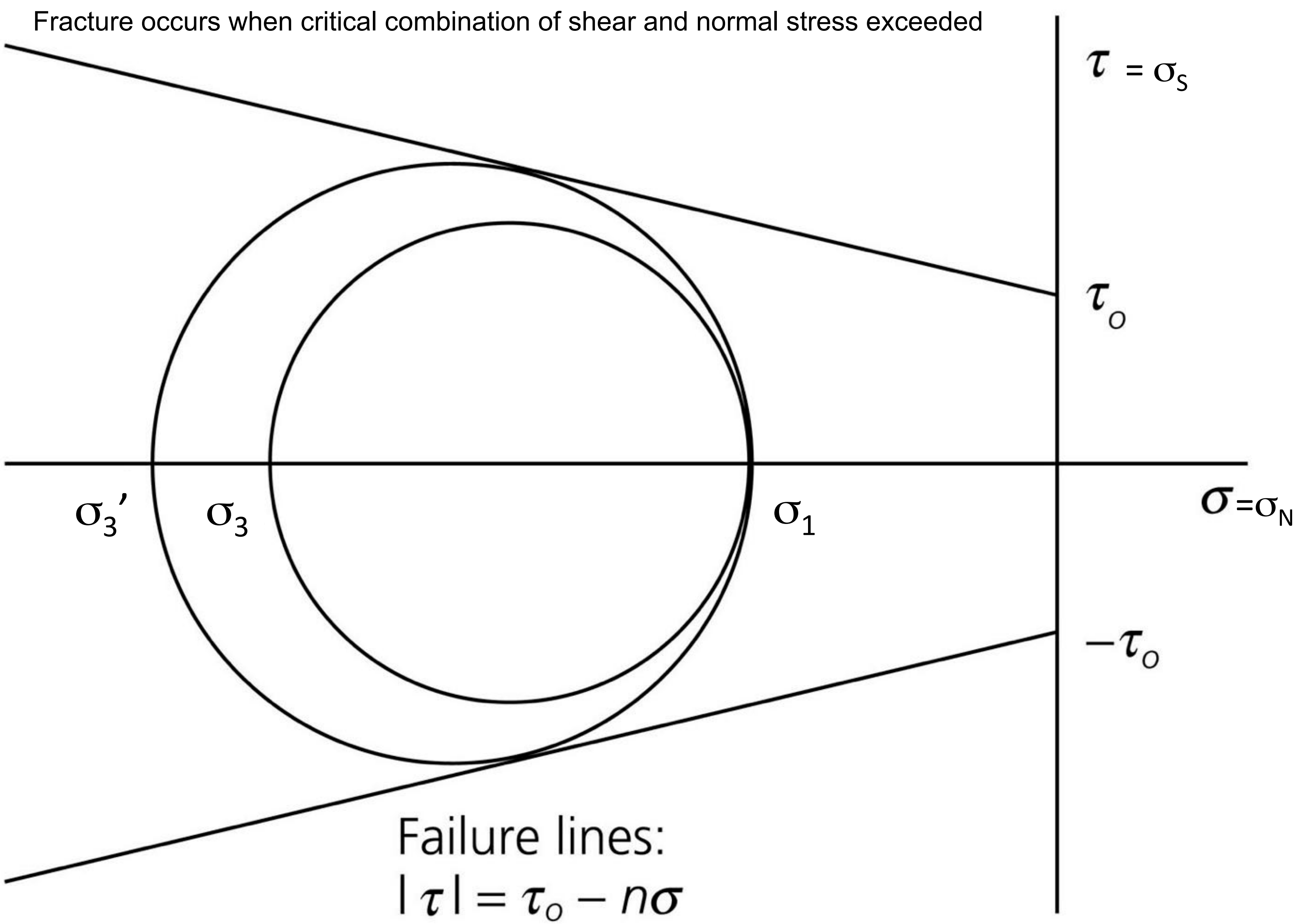
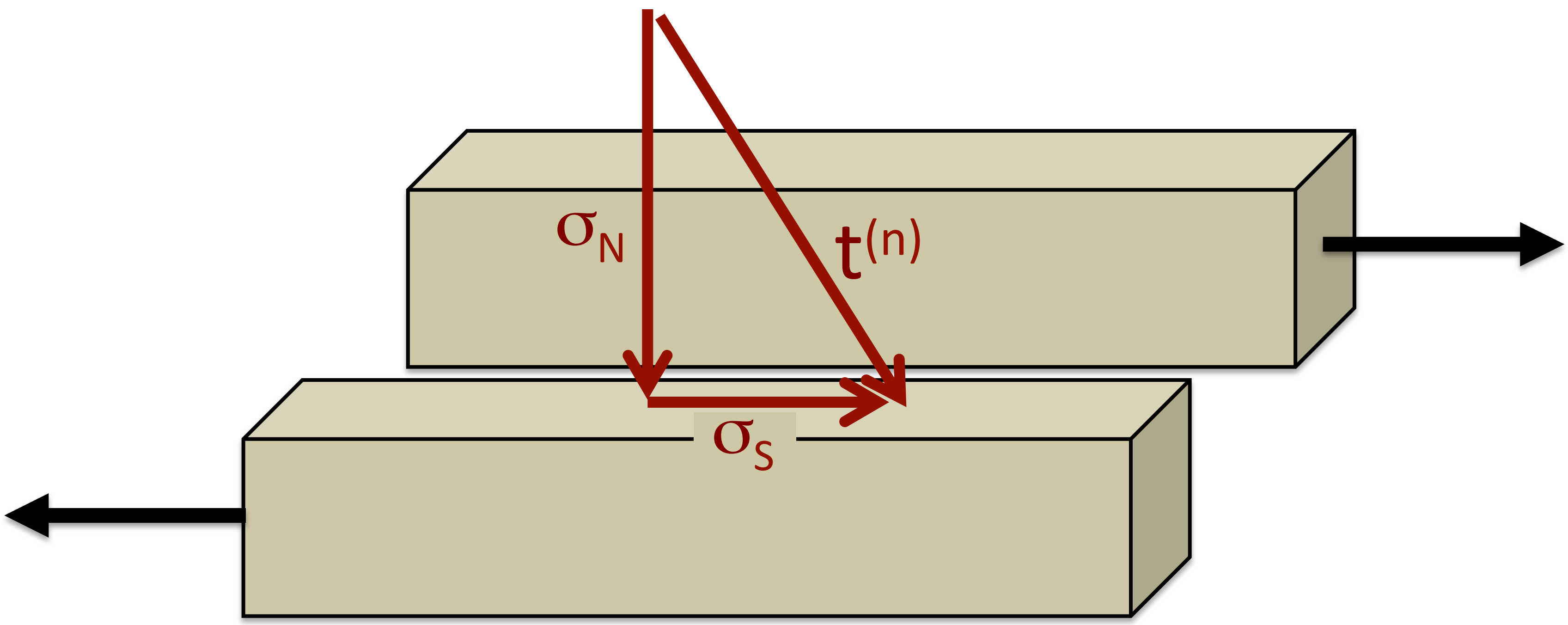


Figure 5.7-6: Definition of the Coulomb-Mohr failure criterion.



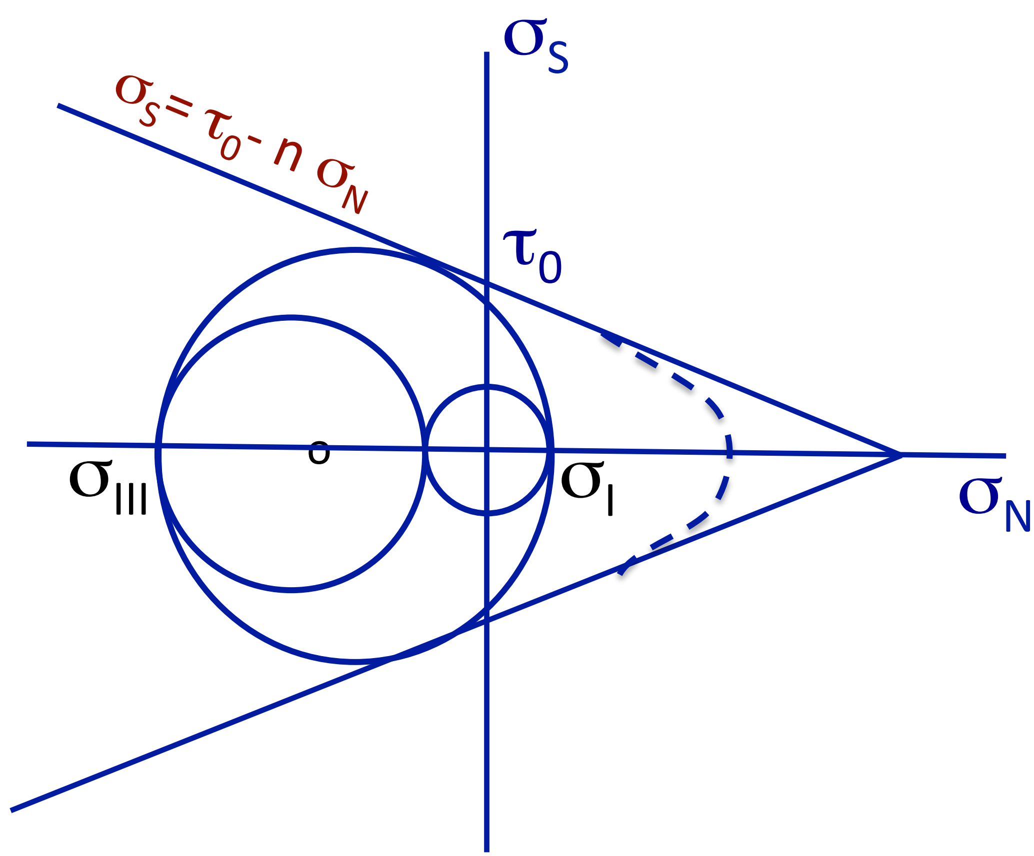
Mohr-Coulomb Fracture



$\sigma_S = \tau_0 - n\,\sigma_N$ n is ***coefficient of internal friction*** for fracture on a new fault surface

τ_0 is cohesion of the material in absence of any confining stress σ_N

Mohr-Coulomb Fracture

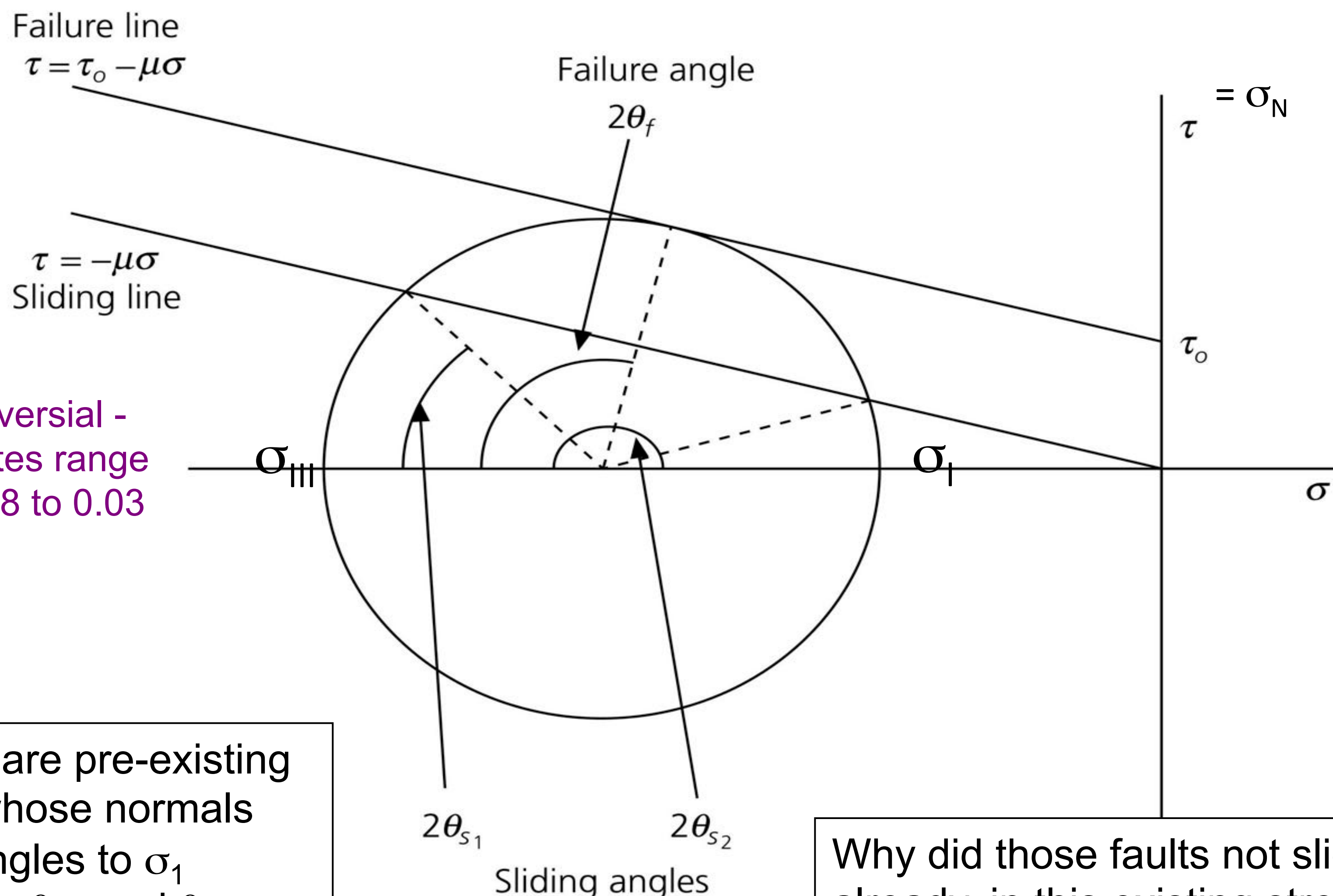


Now we are actually breaking rock …

$\sigma_S = \tau_0 - n\,\sigma_N$ n is ***coefficient of internal friction*** for fracture on a new fault surface

τ_0 is cohesion of the material in absence of any confining stress σ_N

Figure 5.7-9: Mohr's circle for sliding on preexisting faults.

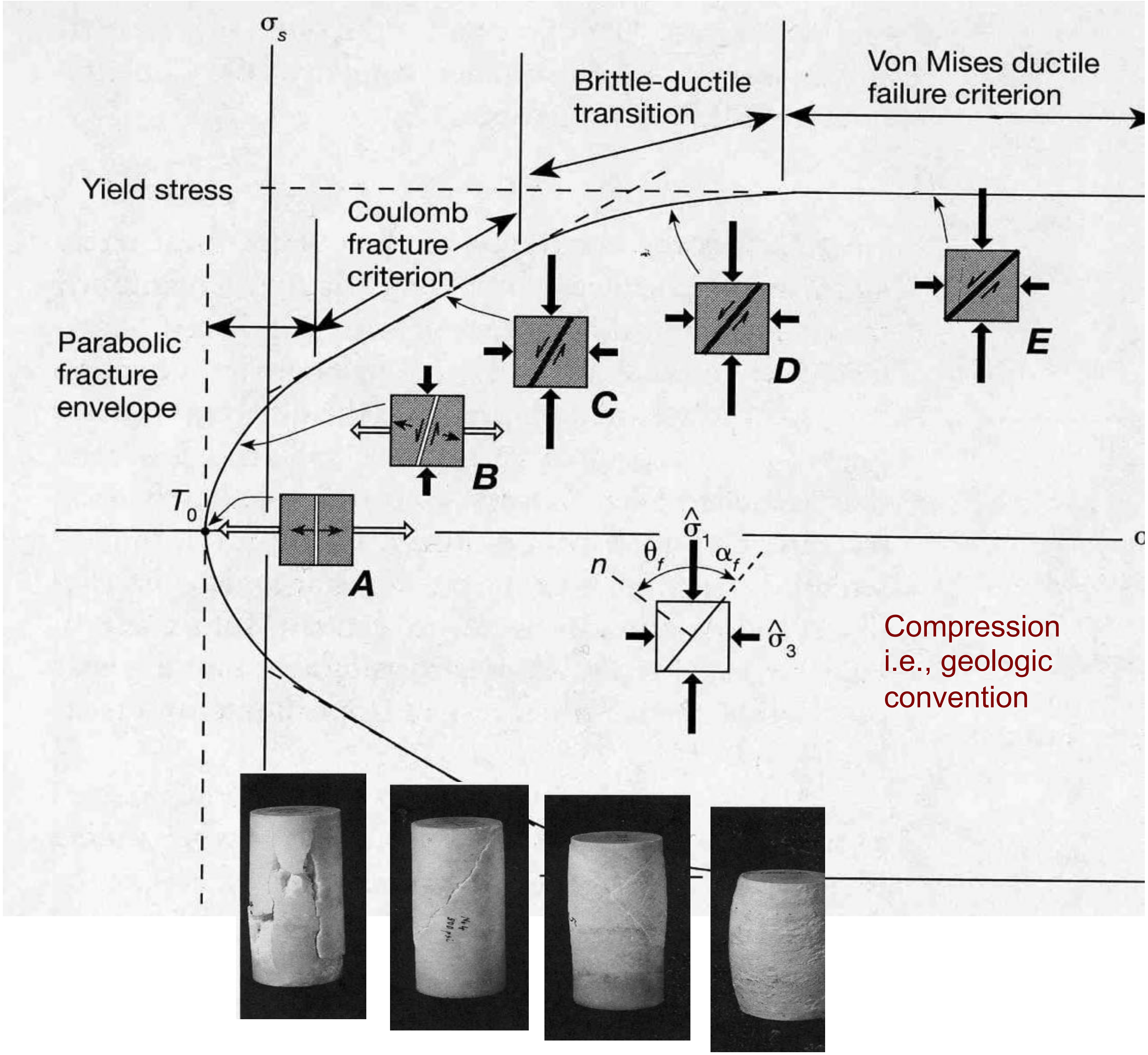


Controversial - estimates range from 0.8 to 0.03

If there are pre-existing faults whose normals have angles to σ_1 between θ_{S1} and θ_{S2} those faults will slide before new fracture can occur.

Why did those faults not slide already, in this existing stress field?

- A recent earthquake could have just raised the differential stress (σ_I-σ_{III})



σ_s
Von Mises ductile failure criterion
Brittle-ductile transition
Yield stress
Coulomb fracture criterion
Parabolic fracture envelope
T_0
A
B
C
D
E
$\hat{\sigma}_1$
$\hat{\sigma}_3$
θ_f
α_f
n
Compression i.e., geologic convention

A *B* *C* *D*

Depths and Overburden stress

$P = \rho g z$

$\rho = 2700 \text{ kg m}^{-3}$
$g \sim 10 \text{ m s}^{-2}$
$z = 10 \text{ km}$

Estimate overburden load at 10 km depth

Pore pressure p

Fluids in rock pores and cracks is a lubricant

Failure when pore fluid is present with pore pressure p

$$\sigma_S = -\mu(\sigma_N + p)$$

remember that p is positive, but compressive stress is negative

- Pore pressure reduces the clamping effect of σ_N
- Pressure jacks apart the locking asperities on faults
- Can lead to failure

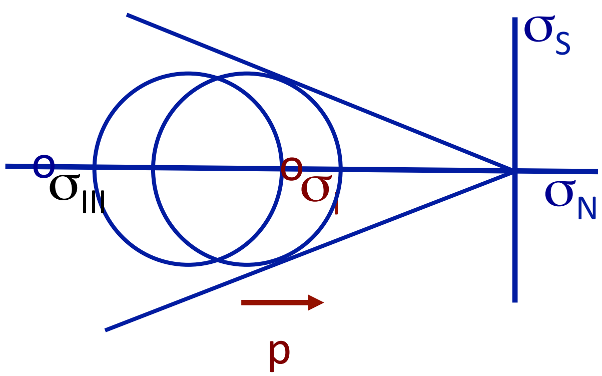
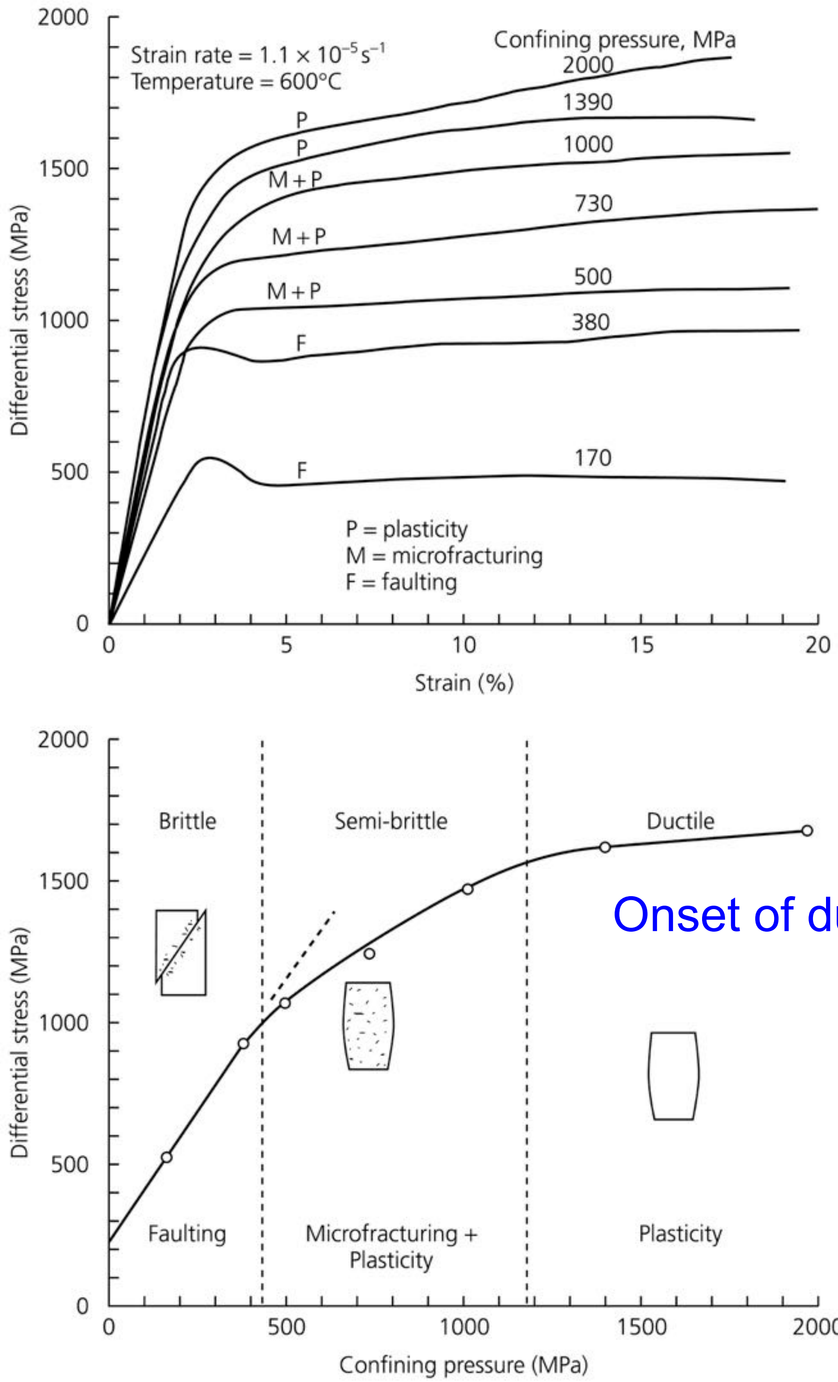
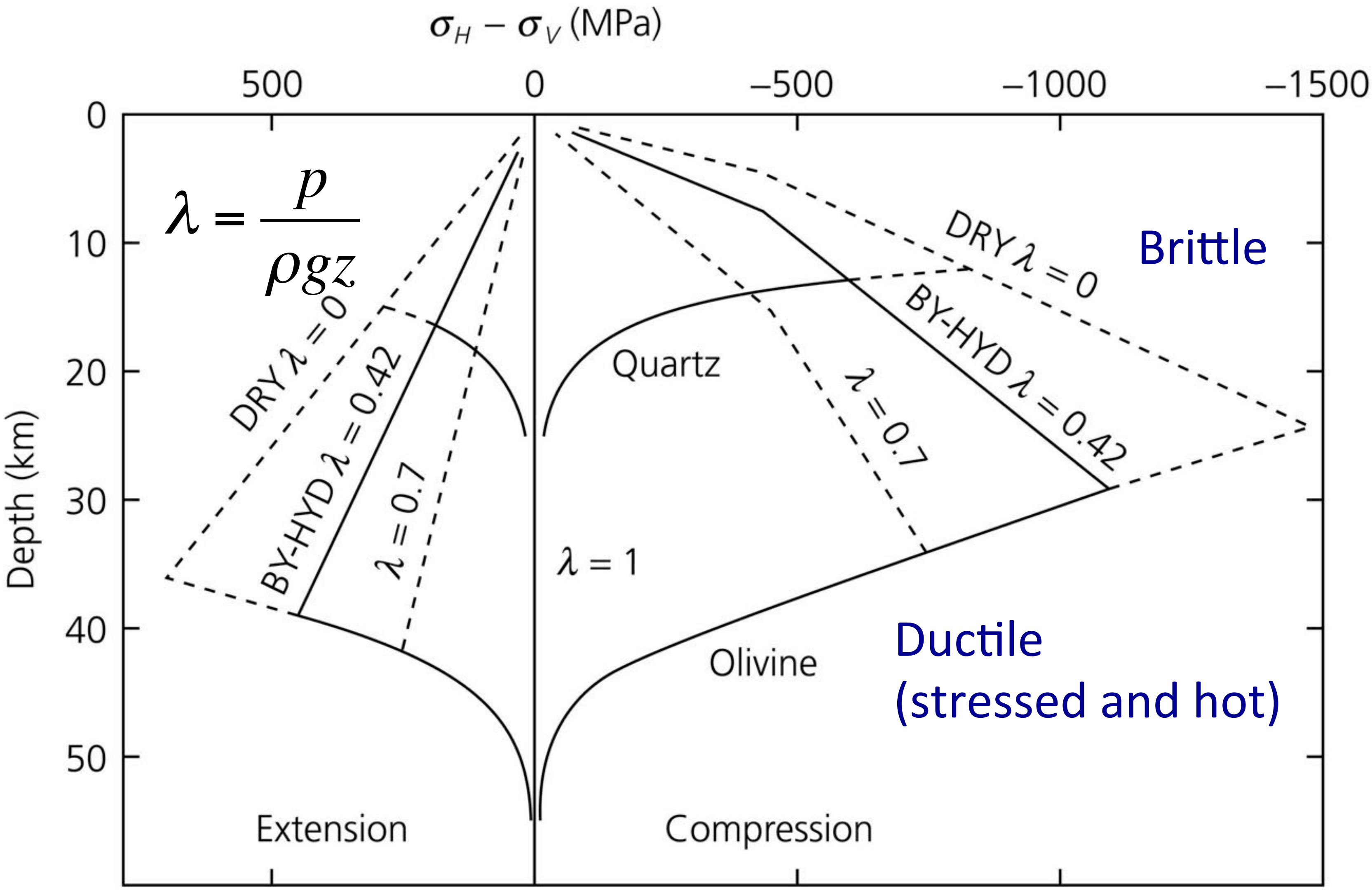


Figure 5.7-3: Rheology of rocks subjected to large compressive stresses.

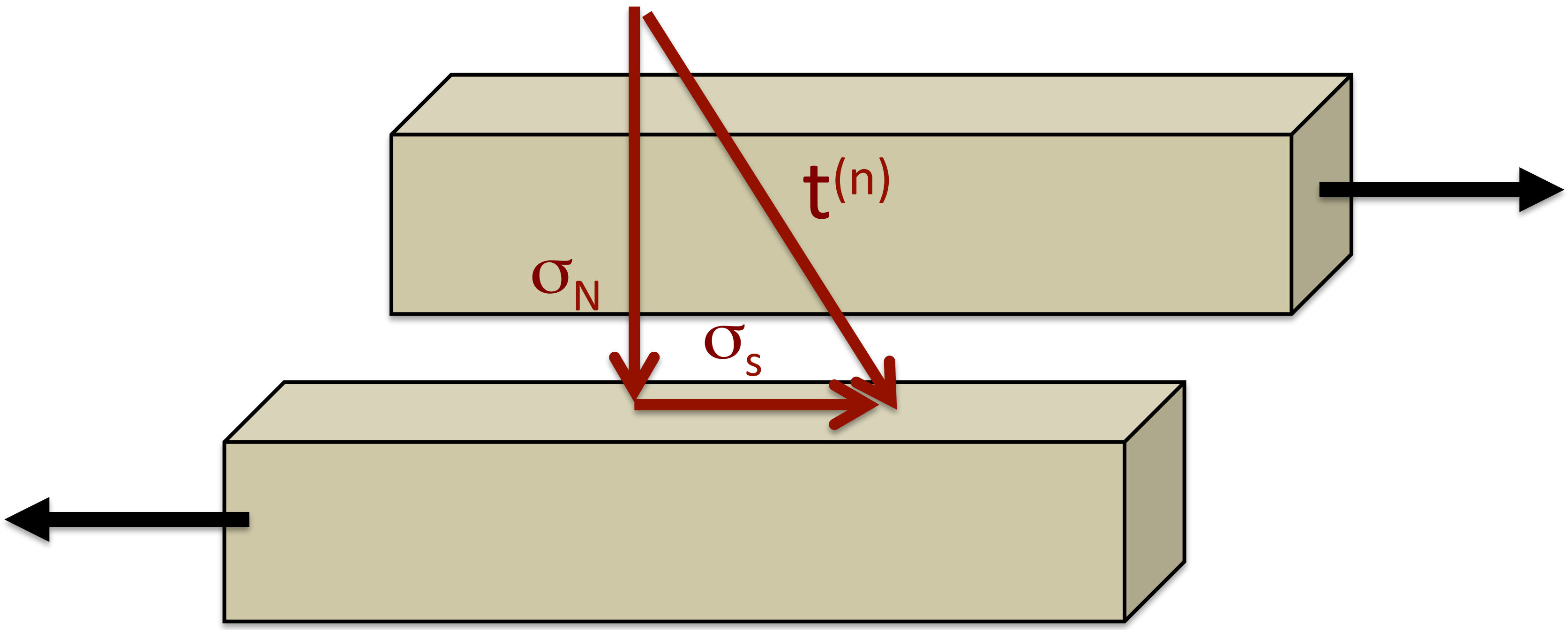


Onset of ductility

Strength of the Lithosphere

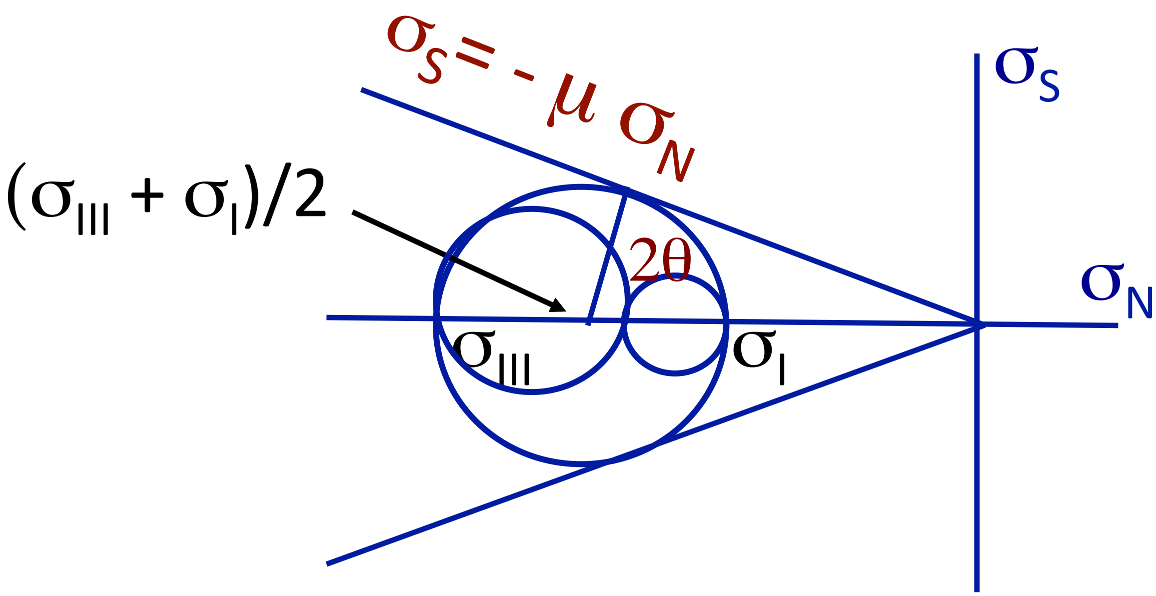


Sliding friction



$\sigma_S = -\,\mu\,\sigma_N$ μ is ***coefficient of friction*** for sliding on a pre-existing break

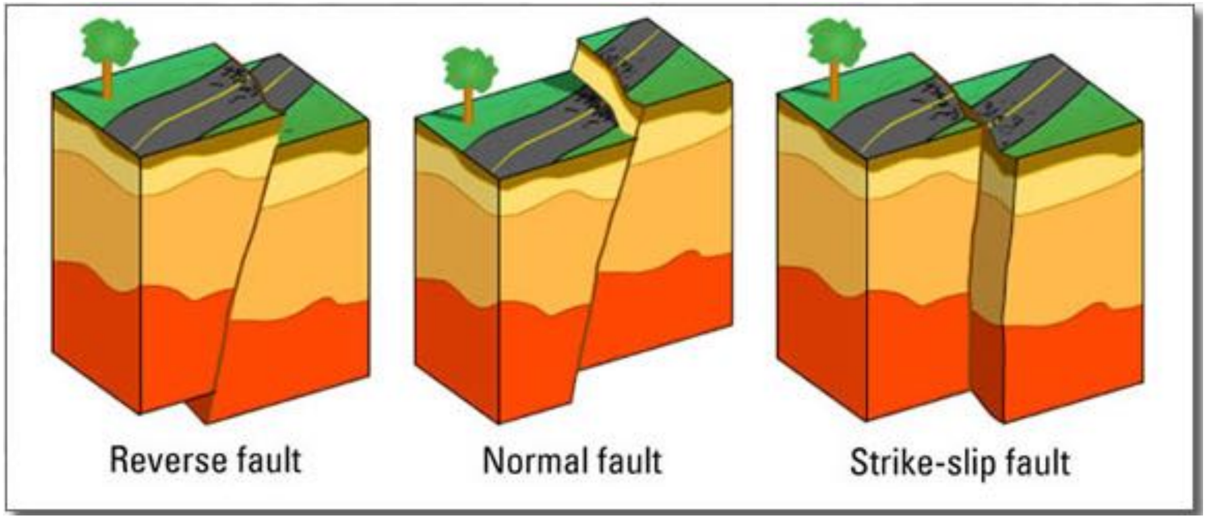
Frictional sliding



$\sigma_S = -\mu\,\sigma_N$ μ is ***coefficient of friction*** for sliding on a pre-existing break

Types of faults

The Earth's surface is traction-free, so one of the principal directions is generally vertical



What are the orientations of the principal axes of stress $\hat{e}_1^*, \hat{e}_2^*, \hat{e}_3^*$ in each case?