The Abdus Salam
International Centre
for Theoretical Physics

ICTP Diploma Programme

Earth System Physics

Seismology

Seismic sources - 1
Faulting

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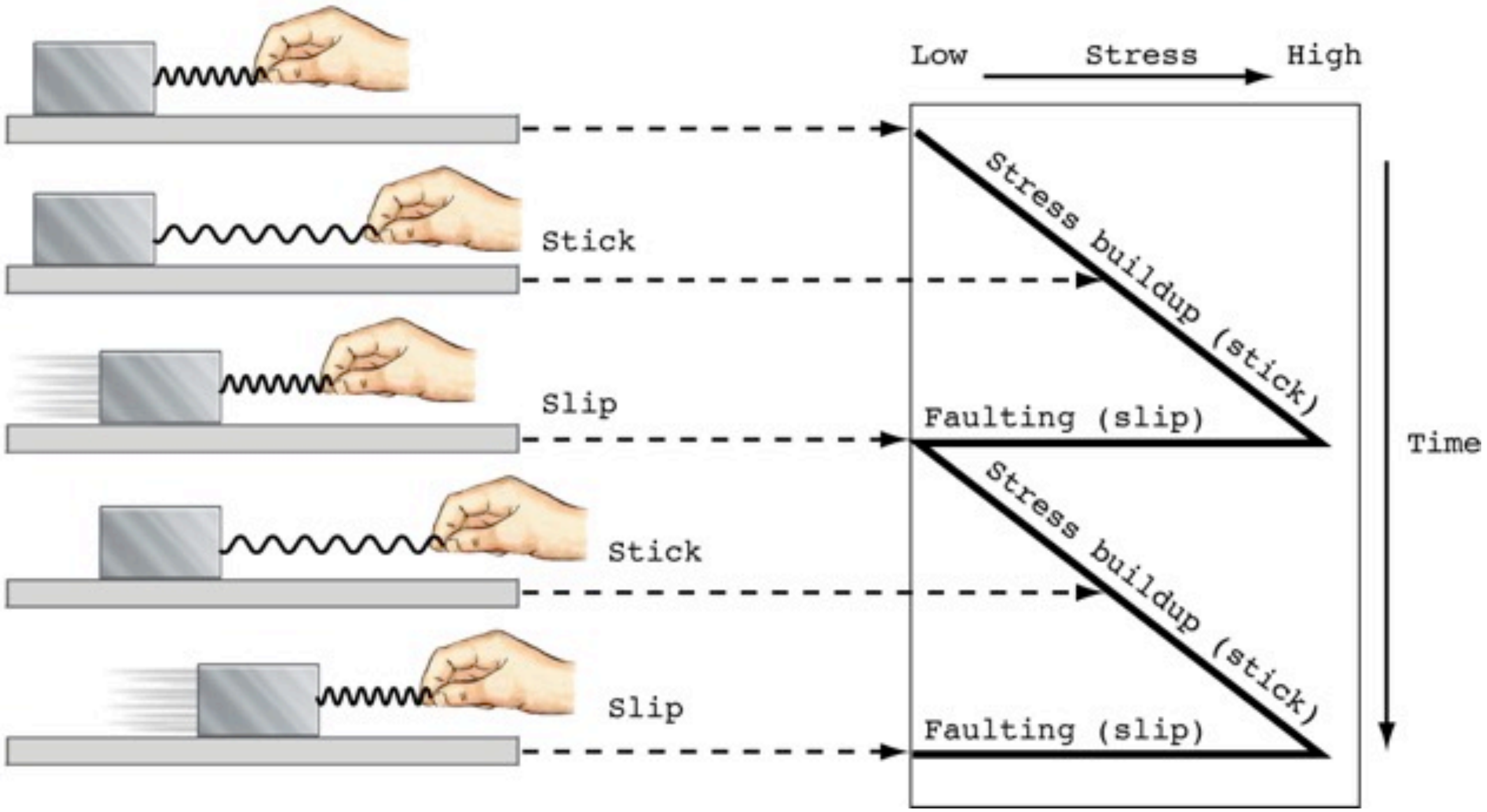
Seismic sources - 1

Basic Dynamics

- stress cycle (stick-slip)
- friction
- Mohr-Coulomb criterion
- stress and faulting
- fault geometry
- fault angles (strike, dip and rake)
- rupture process

Stick-slip

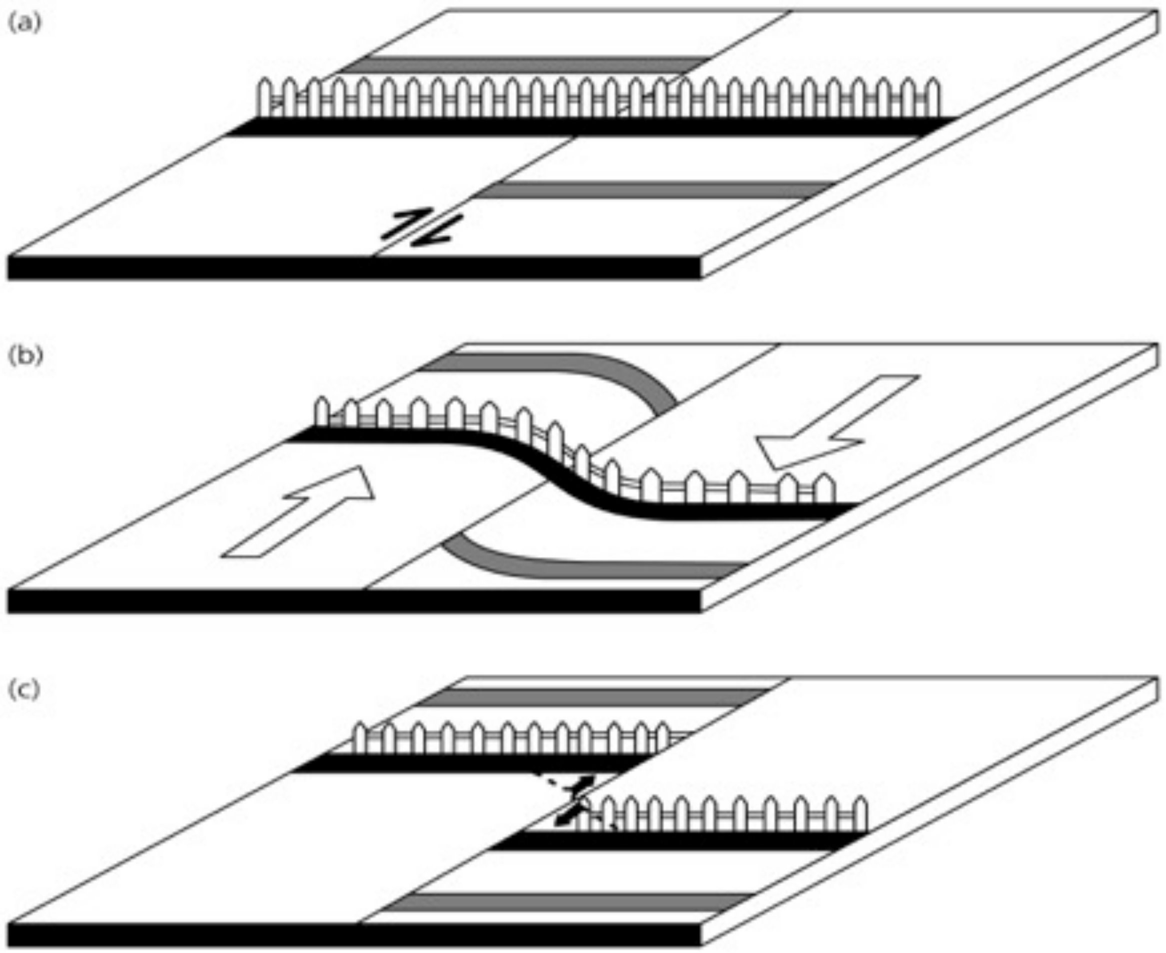


Earth, S. Marshak, W.W. Norton

Elastic strain accumulates during the interseismic period and is released during an earthquake. The elastic strain causes the earthquake –in the sense that the elastic energy stored around the fault drives earthquake rupture.
There are three basic stages in Reid's hypothesis.

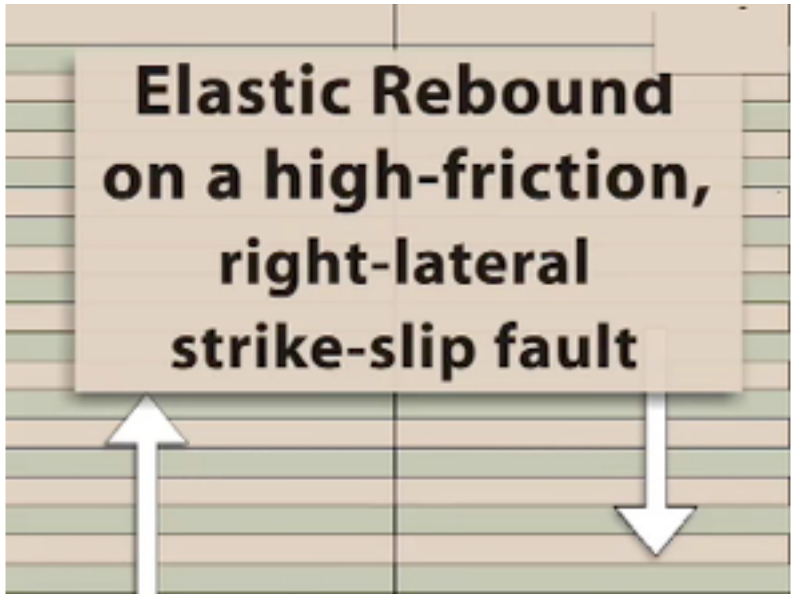
1) Stress accumulation (e.g., due to plate tectonic motion)
2) Stress reaches or exceeds the (frictional) failure strength
3) Failure, seismic energy release (elastic waves), and fault rupture propagation

Elastic rebound (Reid)



From an examination of the displacement of the ground surface which accompanied the 1906 San Francisco earthquake, Henry Fielding Reid, Professor of Geology at Johns Hopkins University, concluded that the earthquake must have involved an "elastic rebound" of previously stored elastic stress.

Reid, H.F., "The mechanics of the earthquake", v. 2 of "The California earthquake of April 18, 1906". Report of the State Earthquake Investigation Commission, Carnegie Institution of Washington Publication 87, 1910.



Elastic Rebound on a high-friction, right-lateral strike-slip fault

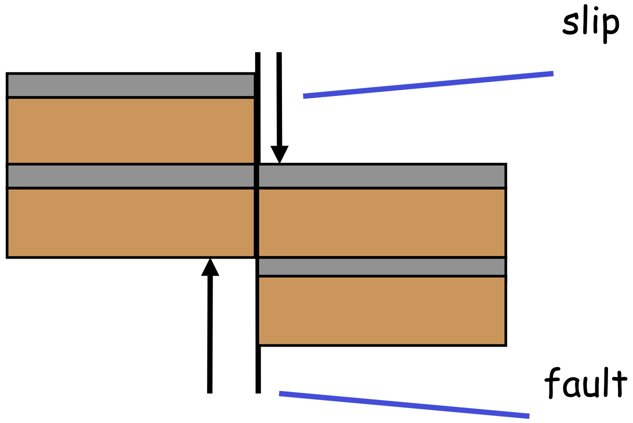
http://www.iris.edu/hq/programs/education_and_outreach/aotm/4

Figure 4.1-4: Displacement of crops rows during the 1979 Imperial fault earthquake.

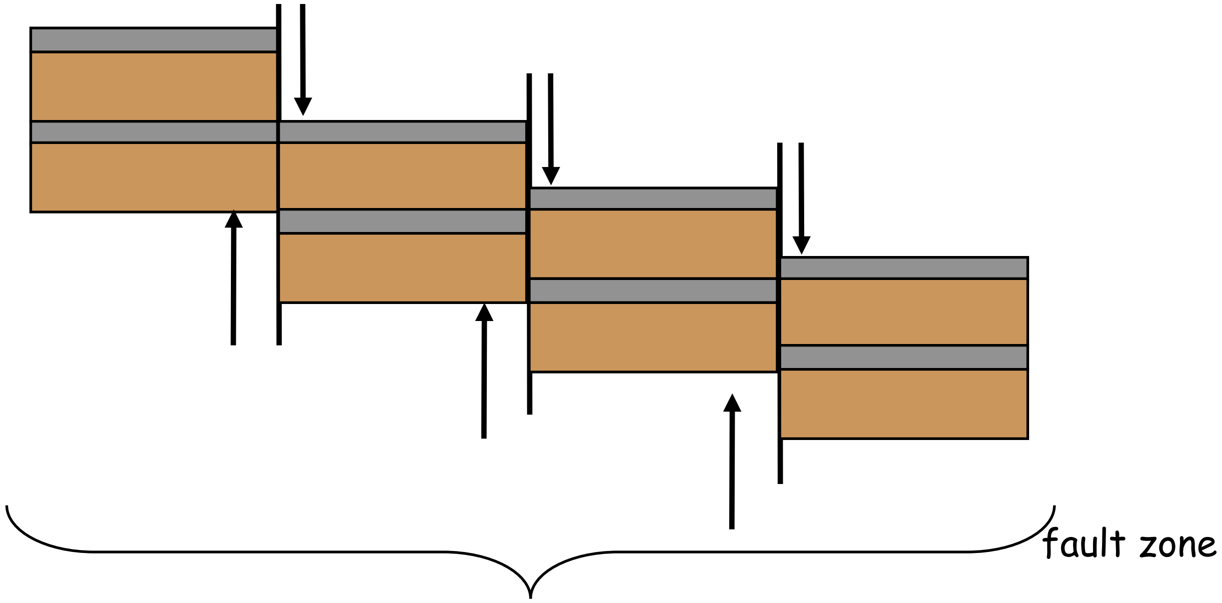
Faults

fault: • surface across which measurable **slip** occurs;

- slip is **parallel** to the fault surface (**shear displacement**);
- slip develops primarily by **brittle** processes- distinguishes faults from shear zones



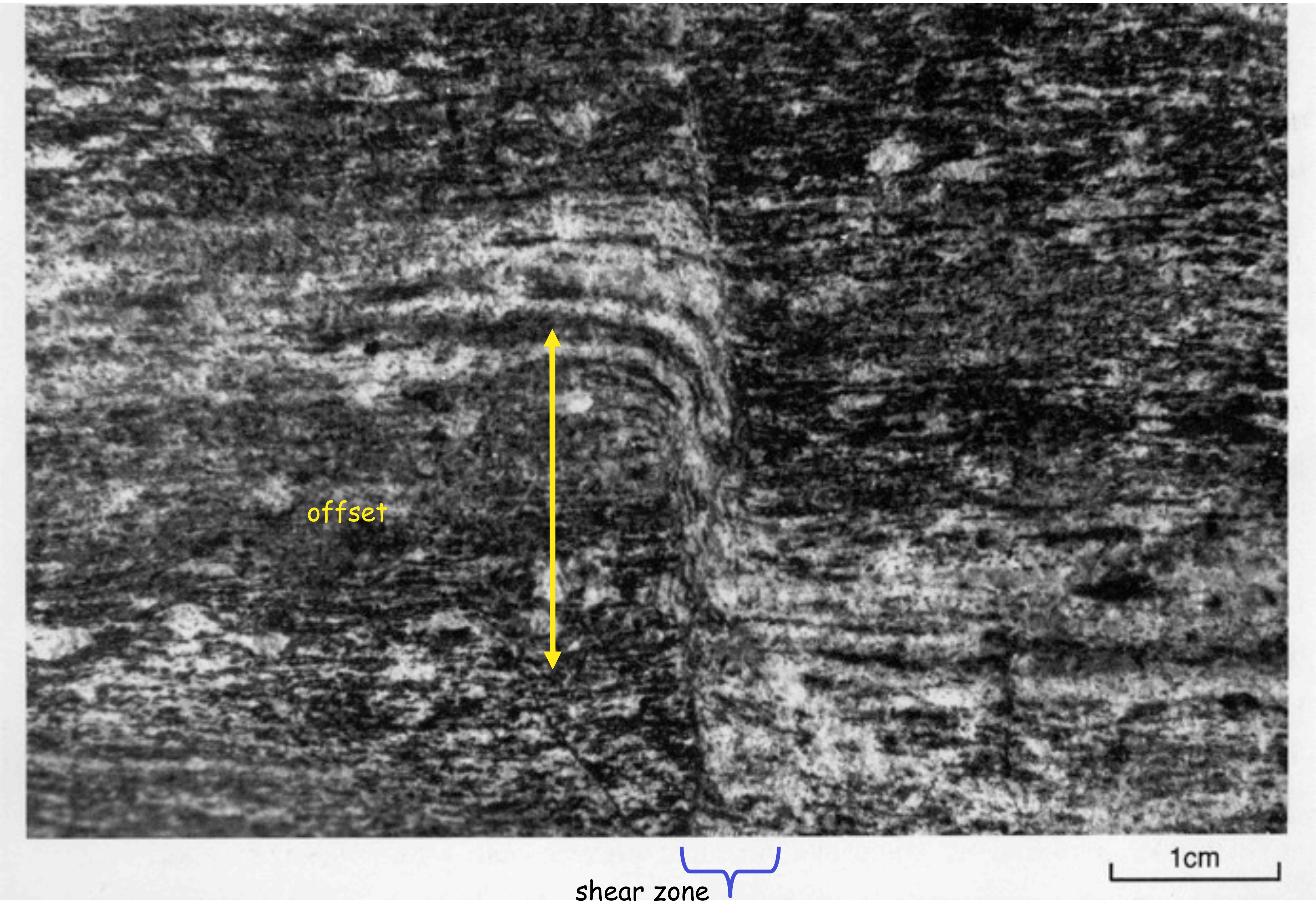
fault zones: brittle structures where loss of cohesion and slip occur on several faults within a band of definable width



Shear zones

shear zones: **ductile** structures

- rock does not lose mesoscopic cohesion
- form at deep crustal levels;
- deformation is distributed across band of definable width;



How does brittle deformation take place?

solid composed of atoms or ions bonded to one another through chemical bonds which can be visualized as tiny springs

- each chemical bond has an equilibrium length
- any two chemical bonds connected to same atom have an equilibrium angle between them

during elastic strain.....bonds holding atoms together in solid, stretch, shorten, and/or bend, but they do not break...

once stress is removed, the bonds return to equilibrium...

elastic strain is recoverable

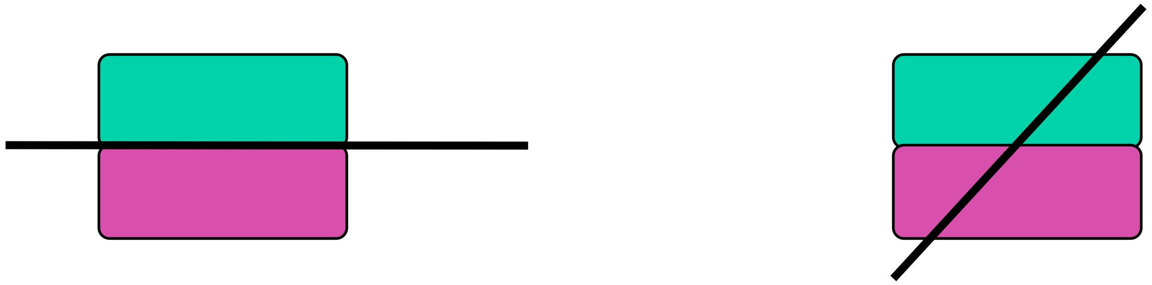
rock cannot develop large elastic strains (only a few percent)

...must deform in a ductile way (does not break)

...must deform in a brittle way (does break)

during brittle deformation… stresses become large enough to bend, then break atomic bonds…. new fracture forms or old surface slips

fractures can be between grains or across grains



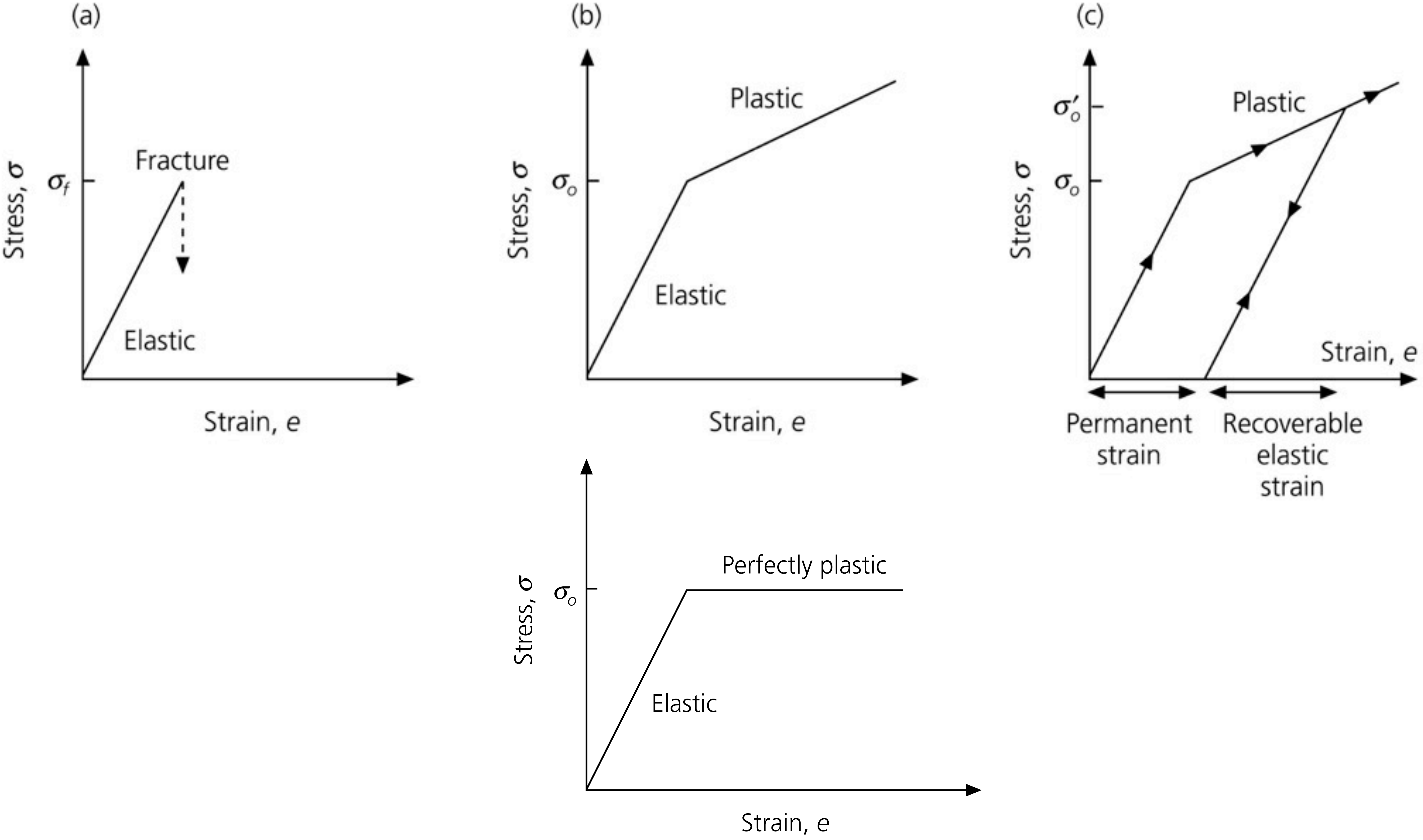
what exactly happens when something breaks?

…discussing solids…. (liquids and gases don't break)

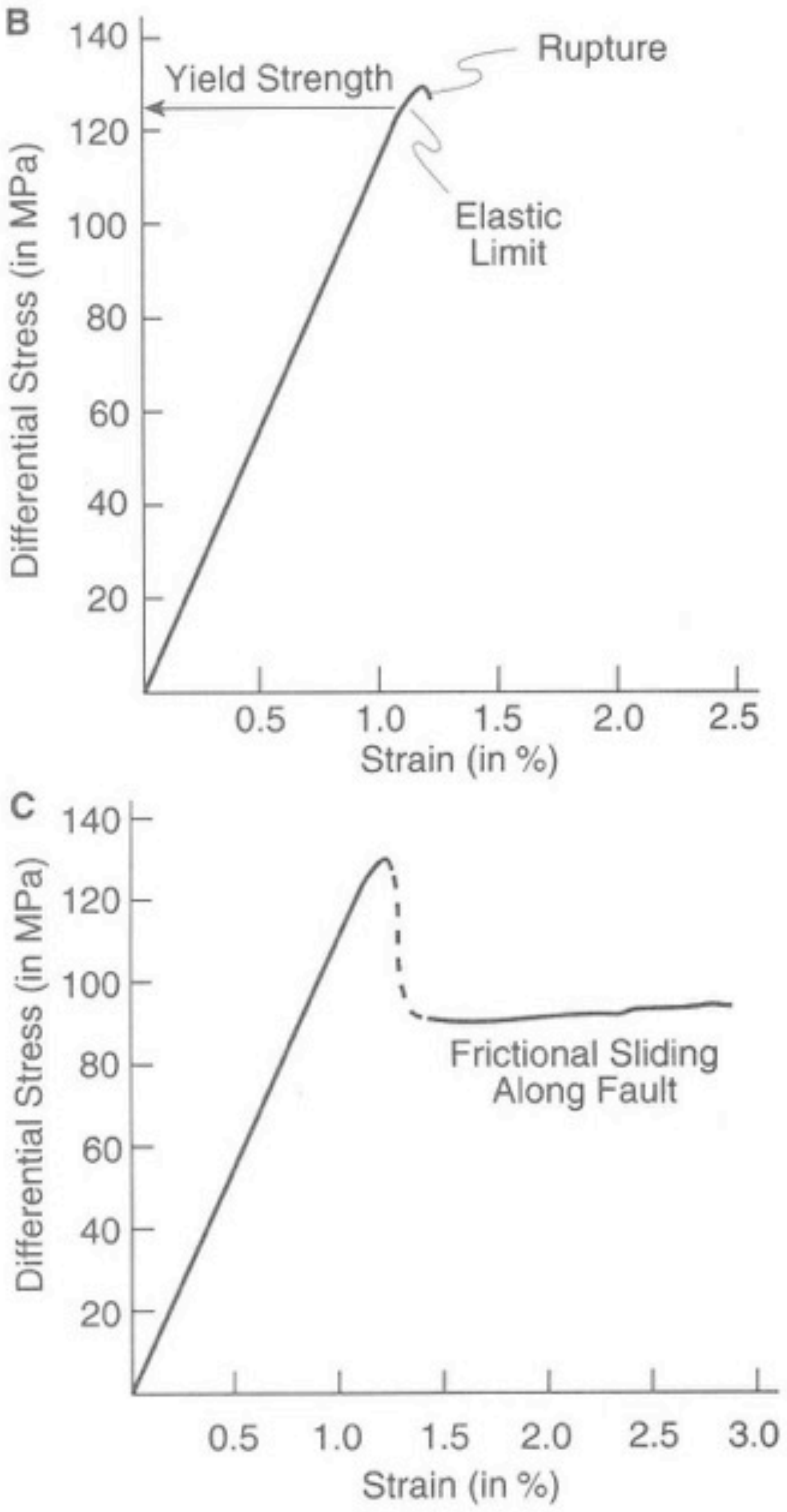
…breaks bonds at atomic scale…

Different rheology

Figure 5.7-1: Elastic and plastic rheologies.

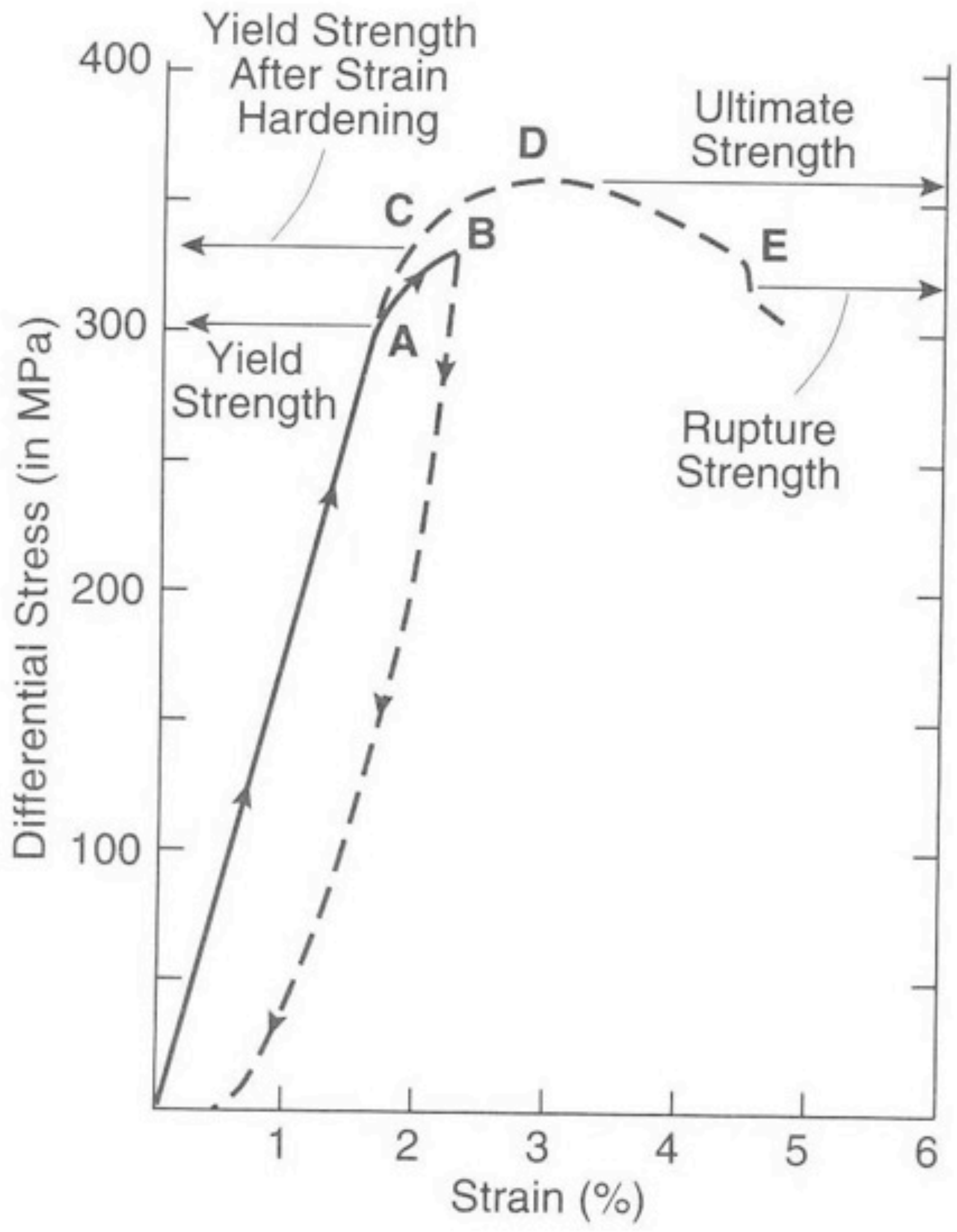


Rheology



Elastic limit: no longer a linear relationship between stress and strain- rock behaves in a different manner

Yield strength: The differential stress at which the rock is no longer behaving in an elastic fashion



Plastic behavior produces an irreversible change in shape as a result of rearranging chemical bonds in the crystal lattice- without failure!

Ductile rocks are rocks that undergo a lot of plastic deformation

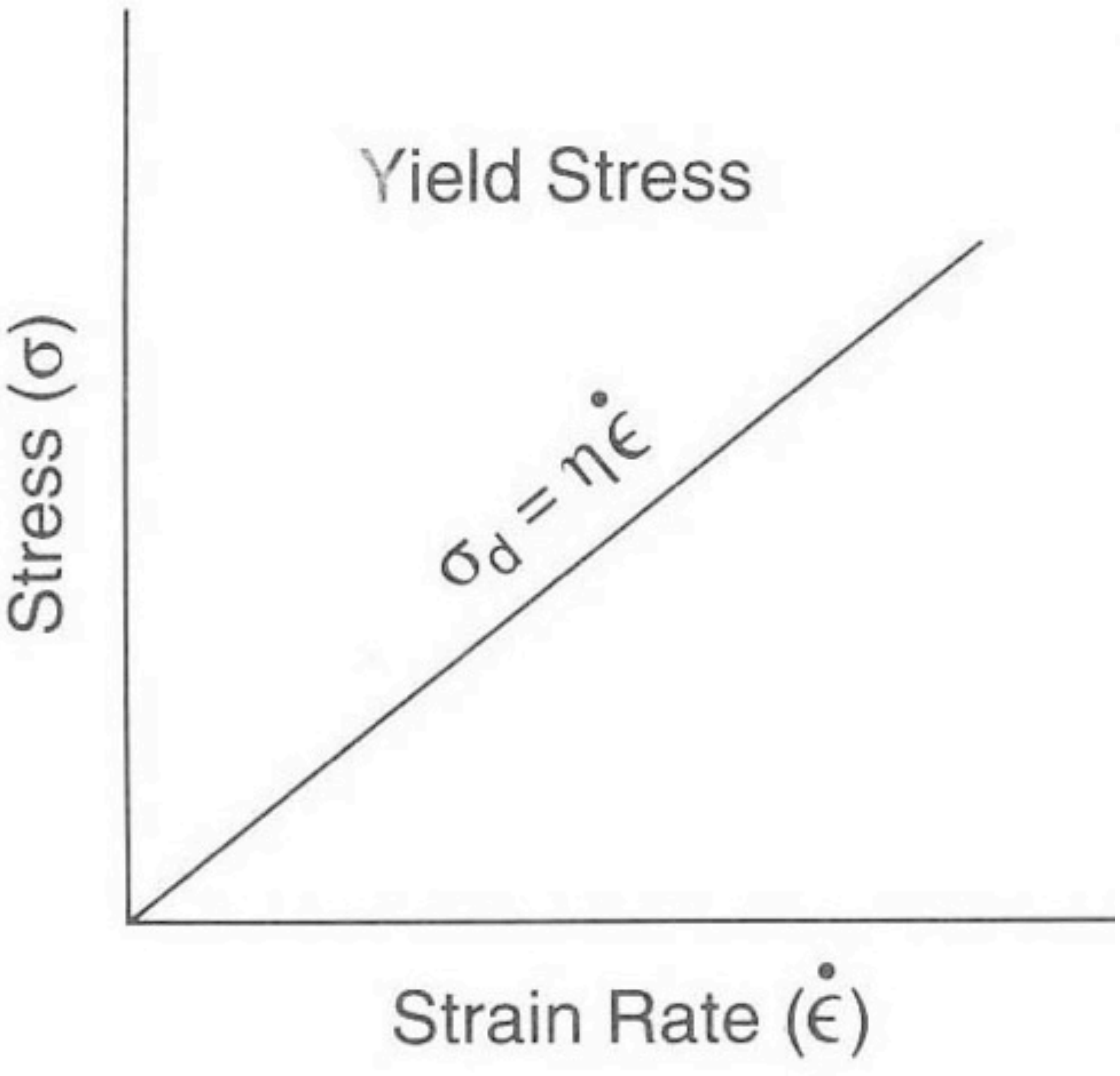
Viscous (fluid) behavior

Newtonian fluids

For an ideal Newtonian fluid:

differential stress = viscosity X strain rate

viscosity: measure of resistance to flow



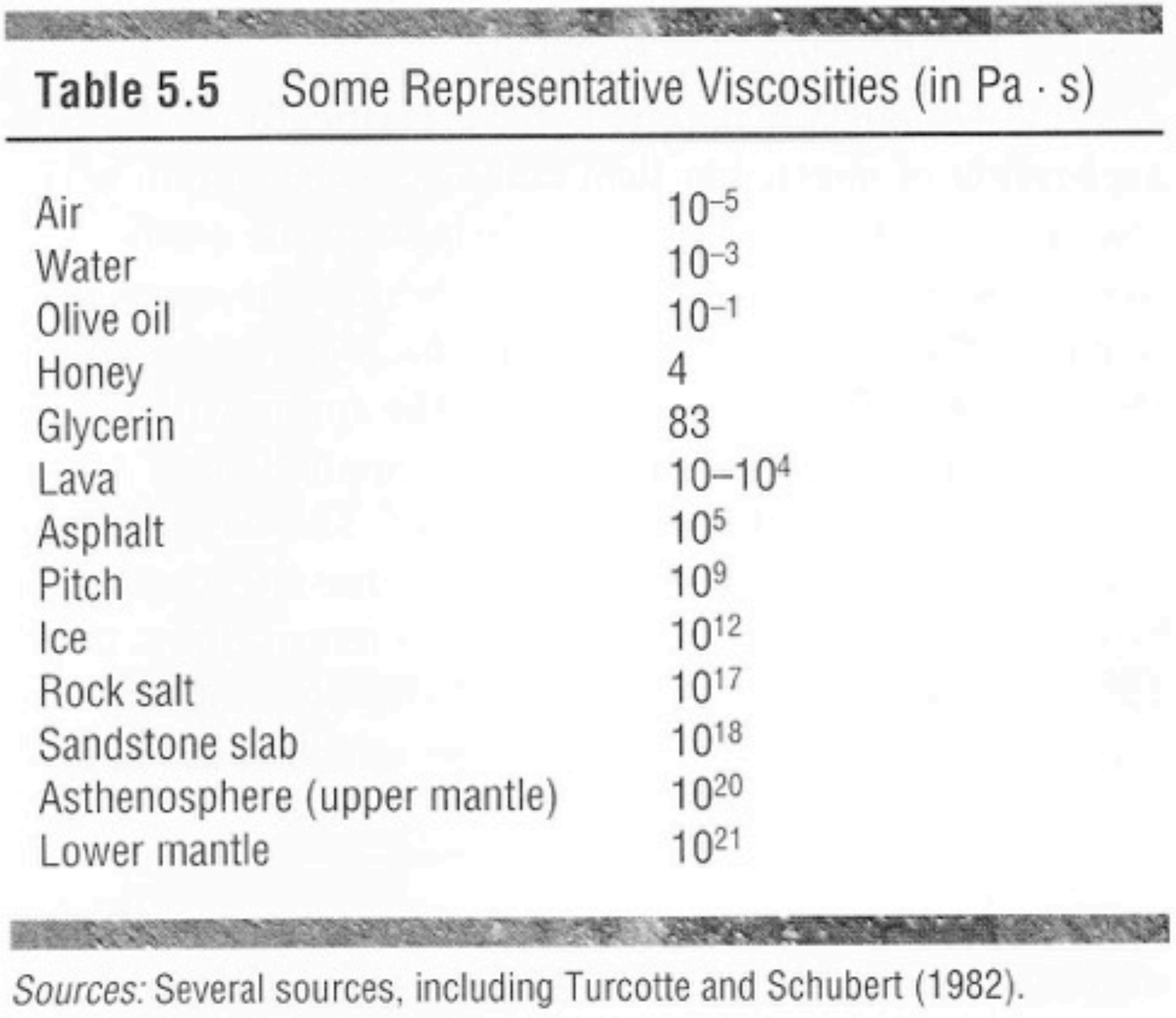
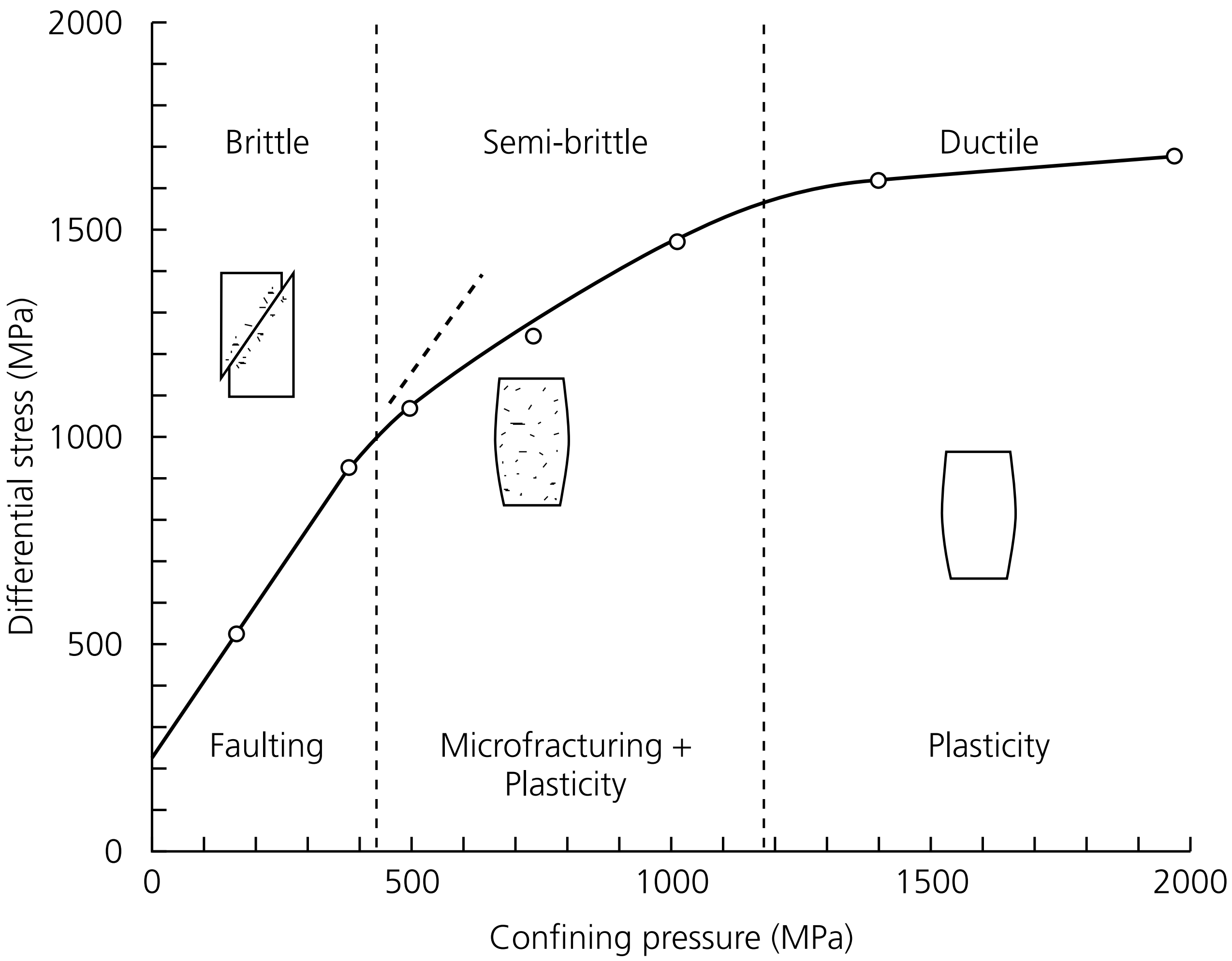


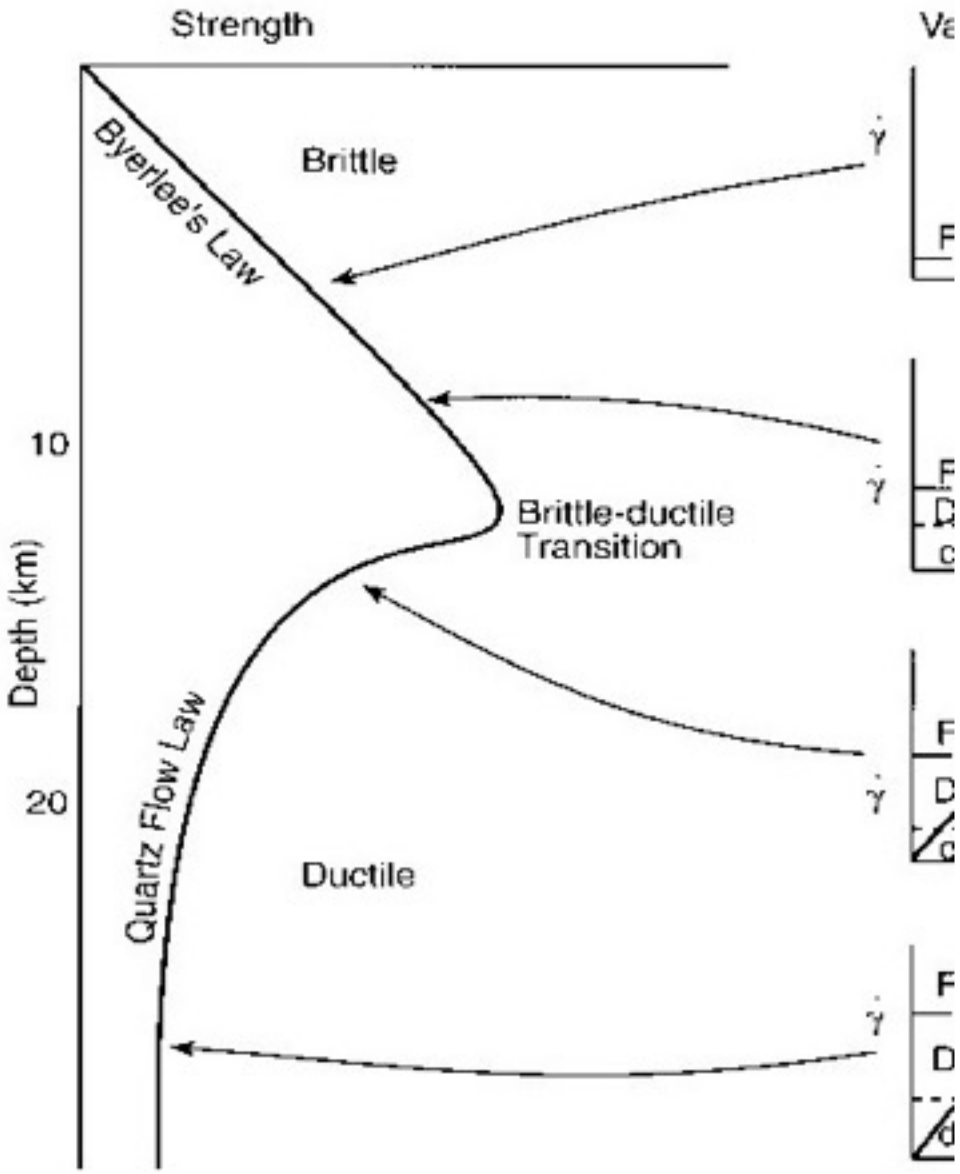
Table 5.5 Some Representative Viscosities (in Pa · s)

Air	10^{-5}
Water	10^{-3}
Olive oil	10^{-1}
Honey	4
Glycerin	83
Lava	10–10^{4}
Asphalt	10^{5}
Pitch	10^{9}
Ice	10^{12}
Rock salt	10^{17}
Sandstone slab	10^{18}
Asthenosphere (upper mantle)	10^{20}
Lower mantle	10^{21}

Sources: Several sources, including Turcotte and Schubert (1982).

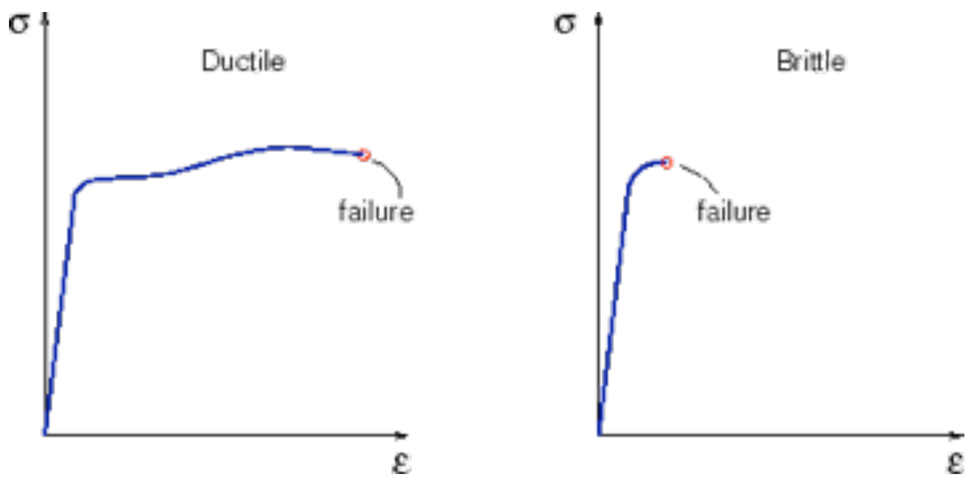
The brittle-ductile transition

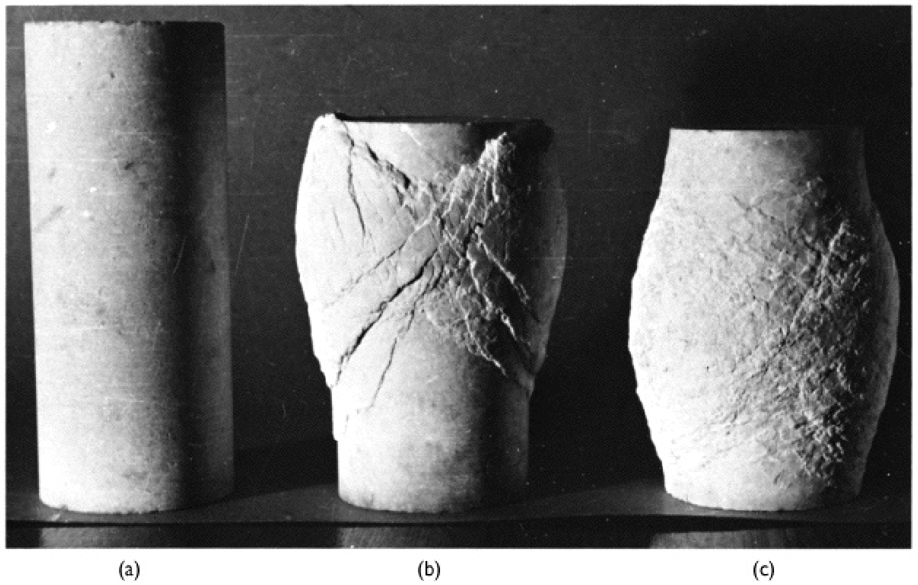


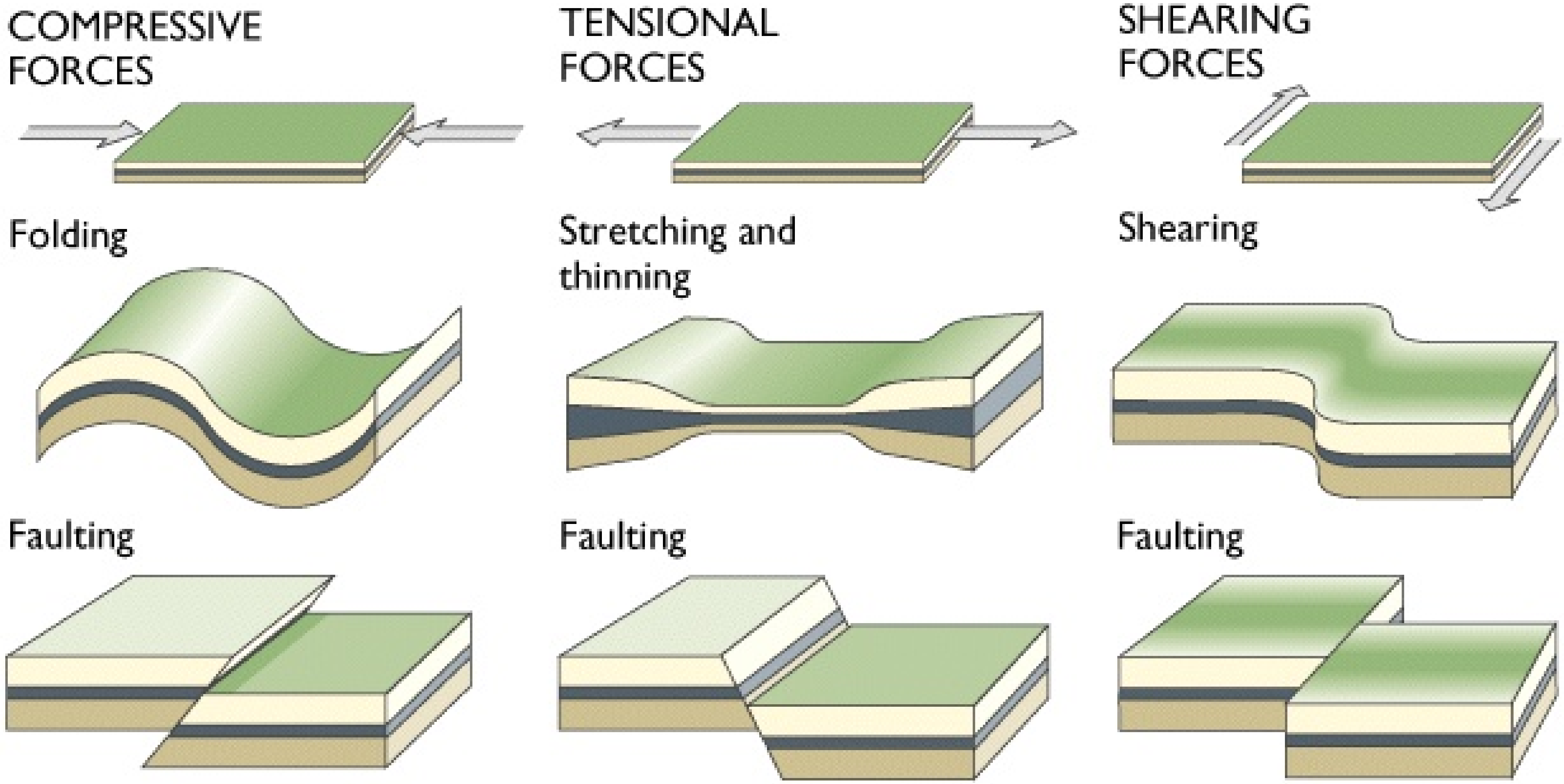


- Earthquakes no deeper than transition
- Lower crust can flow!!!
- Lower crust decoupled from upper crust

Brittle & Ductile





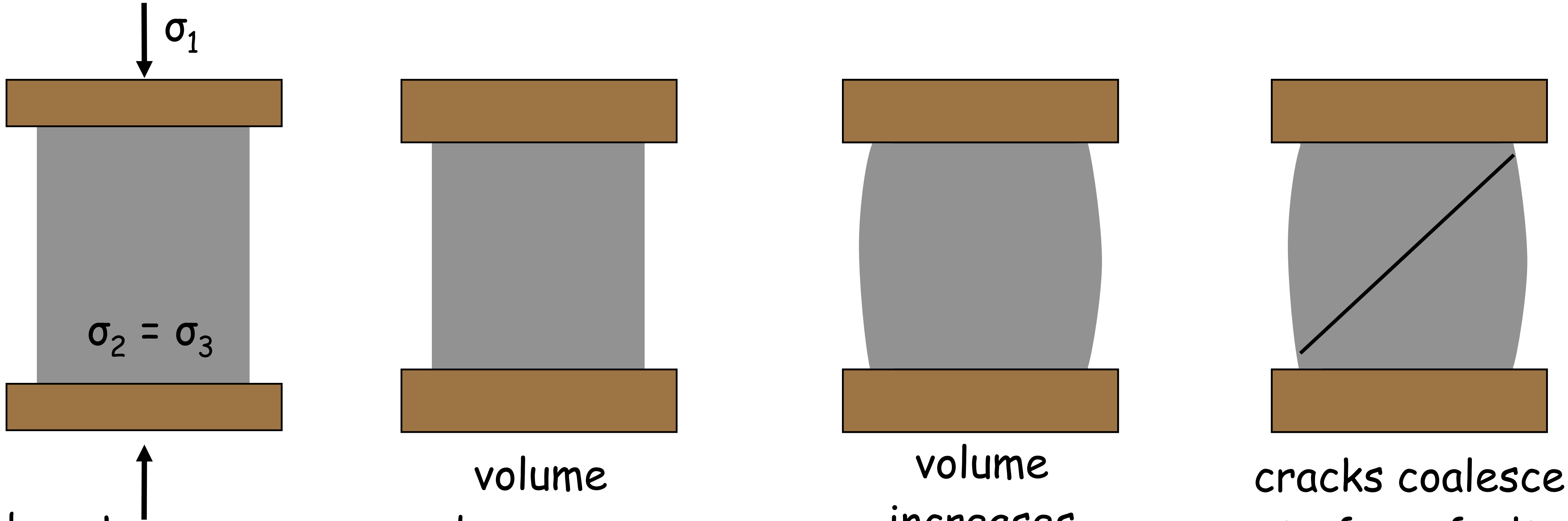


Shear rupture (fracture)

surface across which rock loses continuity when shear stresses parallel to surface are sufficiently large

in rock cylinder experiments, shear fractures form at acute angle to far-field σ_1 $(\sigma_1 > \sigma_2 = \sigma_3)$

normal stress component across surface generates frictional resistance; if shear stress component exceeds resistance → evolve into fault



laboratory triaxial-loading

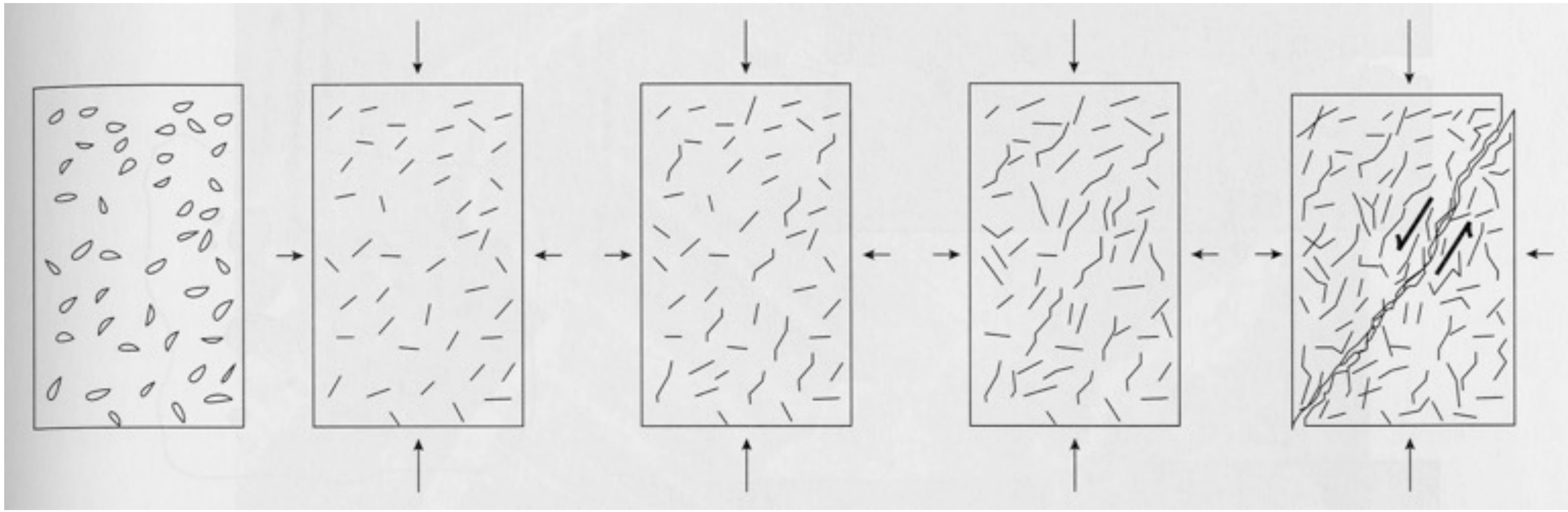
volume decreases

volume increases (dilatancy-cracking)

cracks coalesce to form fault (failure)

Shear fracture

what happened in the rock cylinder during experiment?



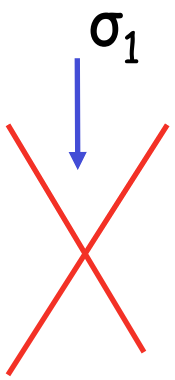
cracks form

cracks coalesce

from: van der Pluijm and Marshak, 1997

failure strength for shear fracture: not a definition of stress state when single crack propagates, but when many cracks coalesce to form throughgoing rupture

two shear ruptures can form (conjugates):
each at 30° to axial stress; angle between two is 60°
acute bisectrix of fractures parallels far-field σ_1



in reality, only one orientation will continue as it offsets other

Fault mechanics basic rules

The first roots of fault mechanics can be traced to

1) **Coulomb failure criterion** (1773). The shear strength of of a rock is equal to initial strength plus a constant times the normal stress on the plane of failure:

$$\left|\tau\right|_{failure} = c + \mu_i \sigma_n$$

where μ_i is called **coefficient of internal friction**.

2) **Amontons**' (second) law for frictional sliding on an existing crack:

$$\tau = \mu_s \sigma$$

where μ_s is called **coefficient of friction**, that has a larger value before sliding takes places (static friction), and a smaller value when sliding takes place (kinetic friction); the values are related to roughness of the fault surface (**asperities**).

3) **Byerlee**'s law (1978), for normal stresses > 200 Mpa
(valid for depths greater than 6 km):

$$\left|\tau\right| = 50 + 0.6\sigma_n$$

Stress

If the coordinate axes $(\hat{\mathbf{e}}_1, \hat{\mathbf{e}}_2)$ are oriented in the principal stress directions, the stress tensor is diagonal,

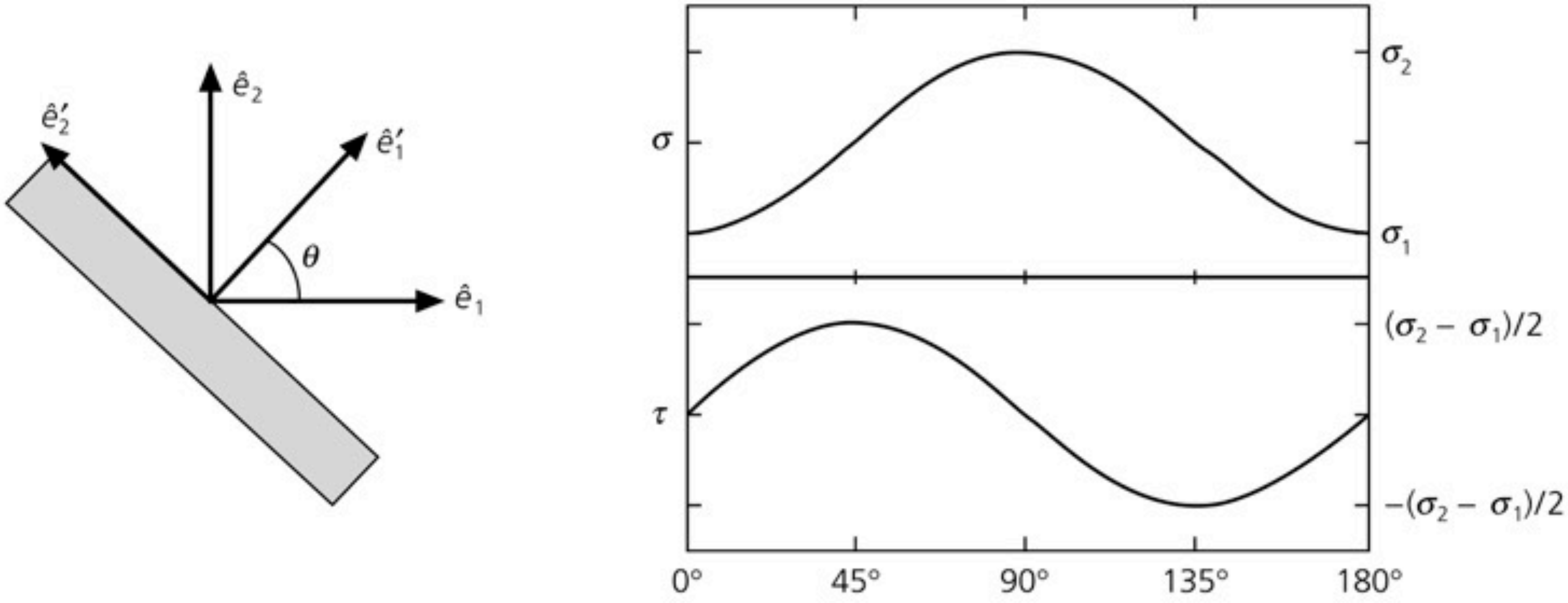
$$\sigma_{ij} = \begin{pmatrix} \sigma_1 & 0 \\ 0 & \sigma_2 \end{pmatrix}$$

Now rotate the coordinate system by an angle θ: $A = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$

$$\sigma'_{ij} = A\sigma A^T = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}\begin{pmatrix} \sigma_1 & 0 \\ 0 & \sigma_2 \end{pmatrix}\begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} = \begin{pmatrix} \sigma_1\cos^2\theta + \sigma_2\sin^2\theta & (\sigma_2 - \sigma_1)\sin\theta\cos\theta \\ (\sigma_2 - \sigma_1)\sin\theta\cos\theta & \sigma_1\sin^2\theta + \sigma_2\cos^2\theta \end{pmatrix}$$

Stress - 2

Figure 5.7-4: Normal and shear stresses as a function of geometry.



Normal stress:

$$\sigma = \sigma'_{11} = \sigma_1 \cos^2\theta + \sigma_2 \sin^2\theta = \frac{(\sigma_1 + \sigma_2)}{2} + \frac{(\sigma_1 - \sigma_2)}{2}\cos 2\theta$$

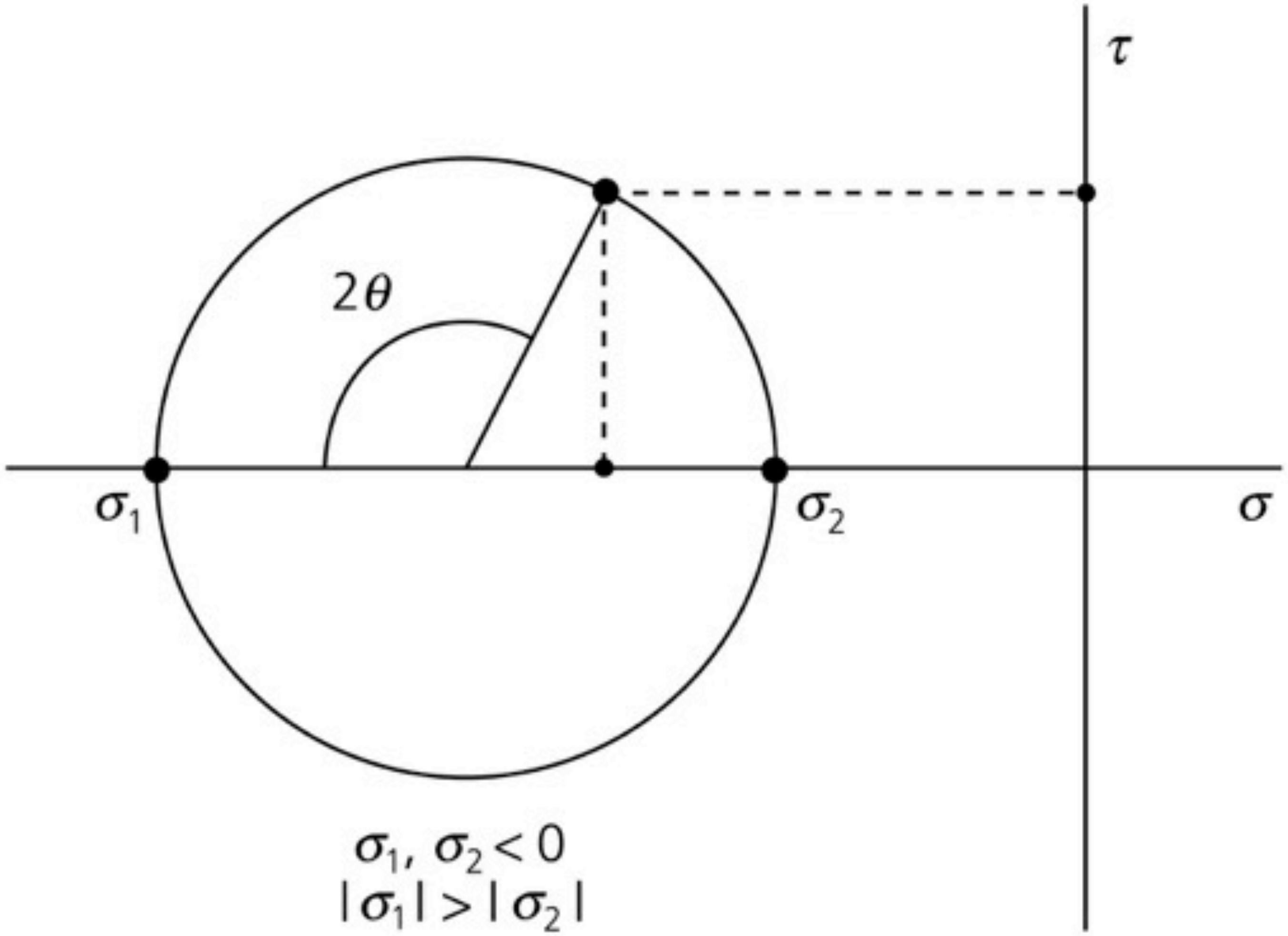
Shear stress:

$$\tau = \sigma'_{12} = (\sigma_2 - \sigma_1)\sin\theta\cos\theta = \frac{(\sigma_2 - \sigma_1)}{2}\sin 2\theta.$$

Mohr's circle shows the values of σ and τ as functions of θ (the angle between the normal to a plane and the principal stress direction, σ_1.

Mohr's circle

Figure 5.7-5: Definition of Mohr's circle.



Normal stress:

$$\sigma = \sigma'_{11} = \sigma_1 \cos^2\theta + \sigma_2 \sin^2\theta = \frac{(\sigma_1 + \sigma_2)}{2} + \frac{(\sigma_1 -}{2}$$

Shear stress:

$$\tau = \sigma'_{12} = (\sigma_2 - \sigma_1)\sin\theta\cos\theta = \frac{(\sigma_2 - \sigma_1)}{2}\sin 2\theta.$$

Mohr's circle shows the values of σ and τ as functions of θ (the angle between the normal to a plane and the principal stress direction, σ_1.

http://www.science-animations.com/support-files/mohrcircle.swf

Type of experiments...

axial compression:

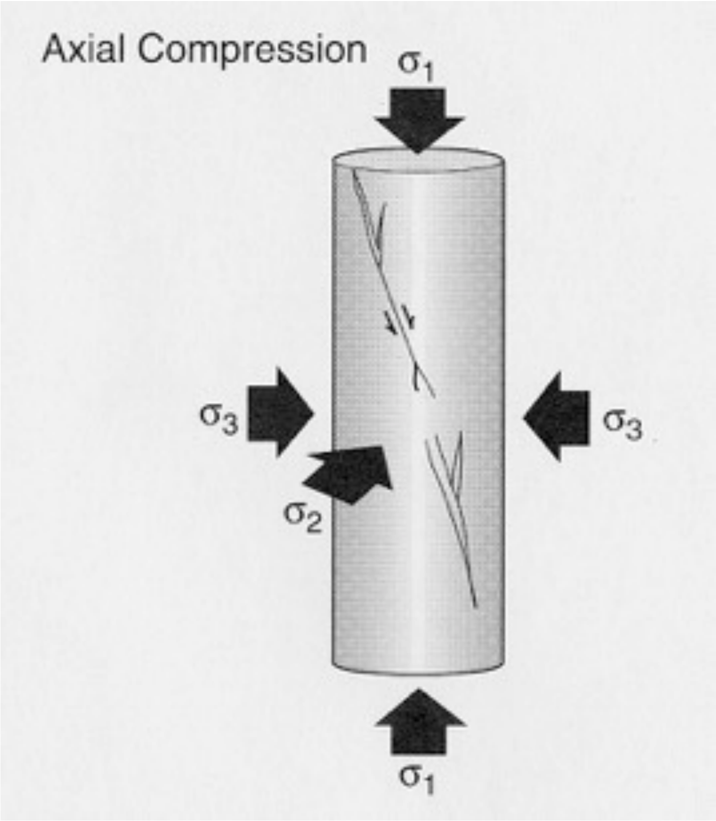
vertical axial compressive stress > confining pressure

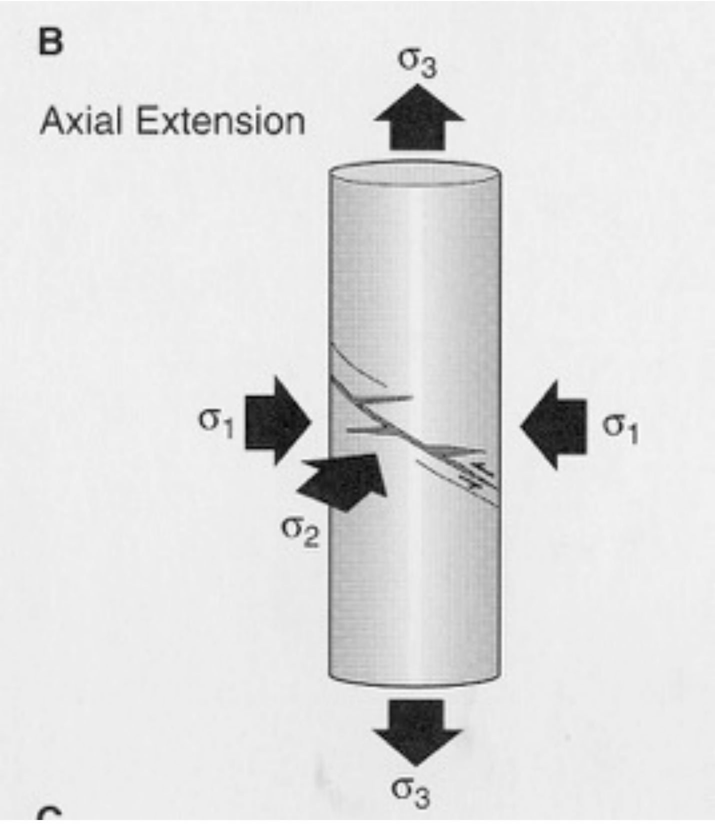
axial extension:

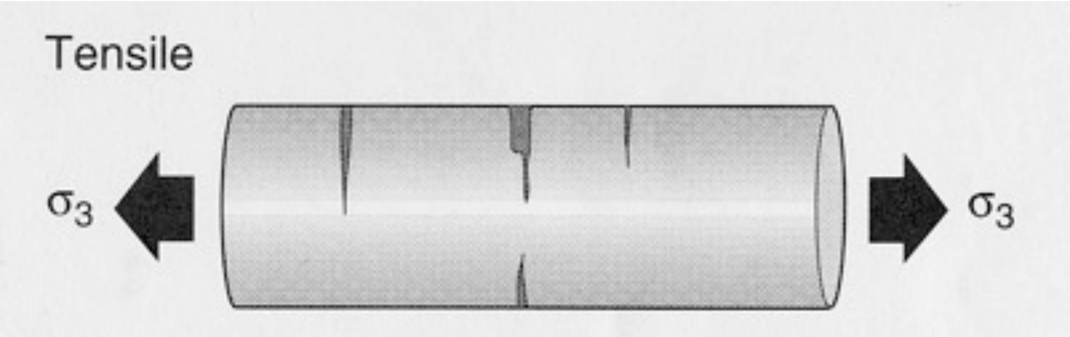
confining pressure > vertical axial compressive stress

tensile strength:

rocks pulled apart







from: Davis and Reynolds, 1996

called triaxial deformation experiments… this is misleading…

most do not permit three principal stresses to vary independently

Common experiments

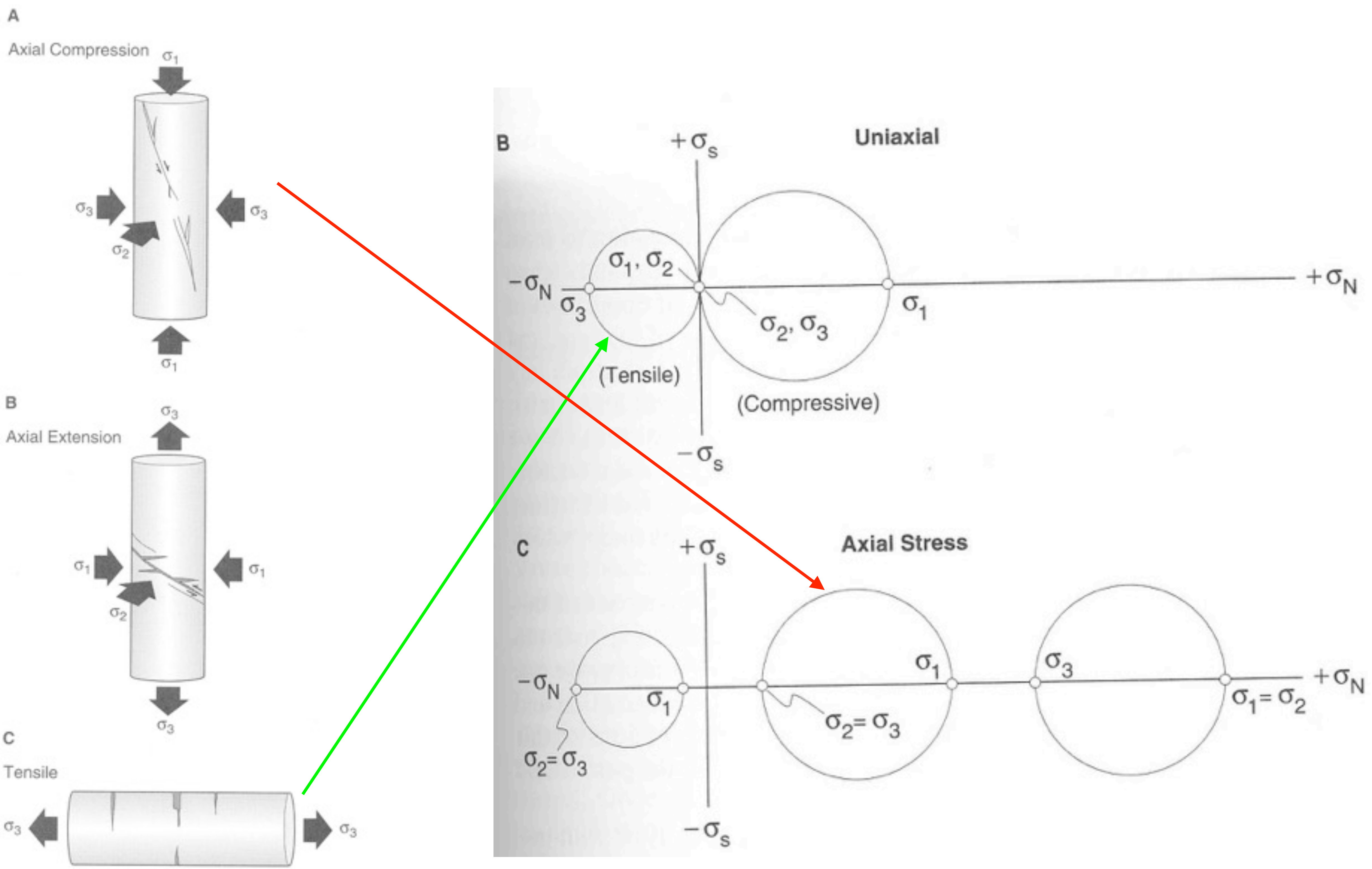
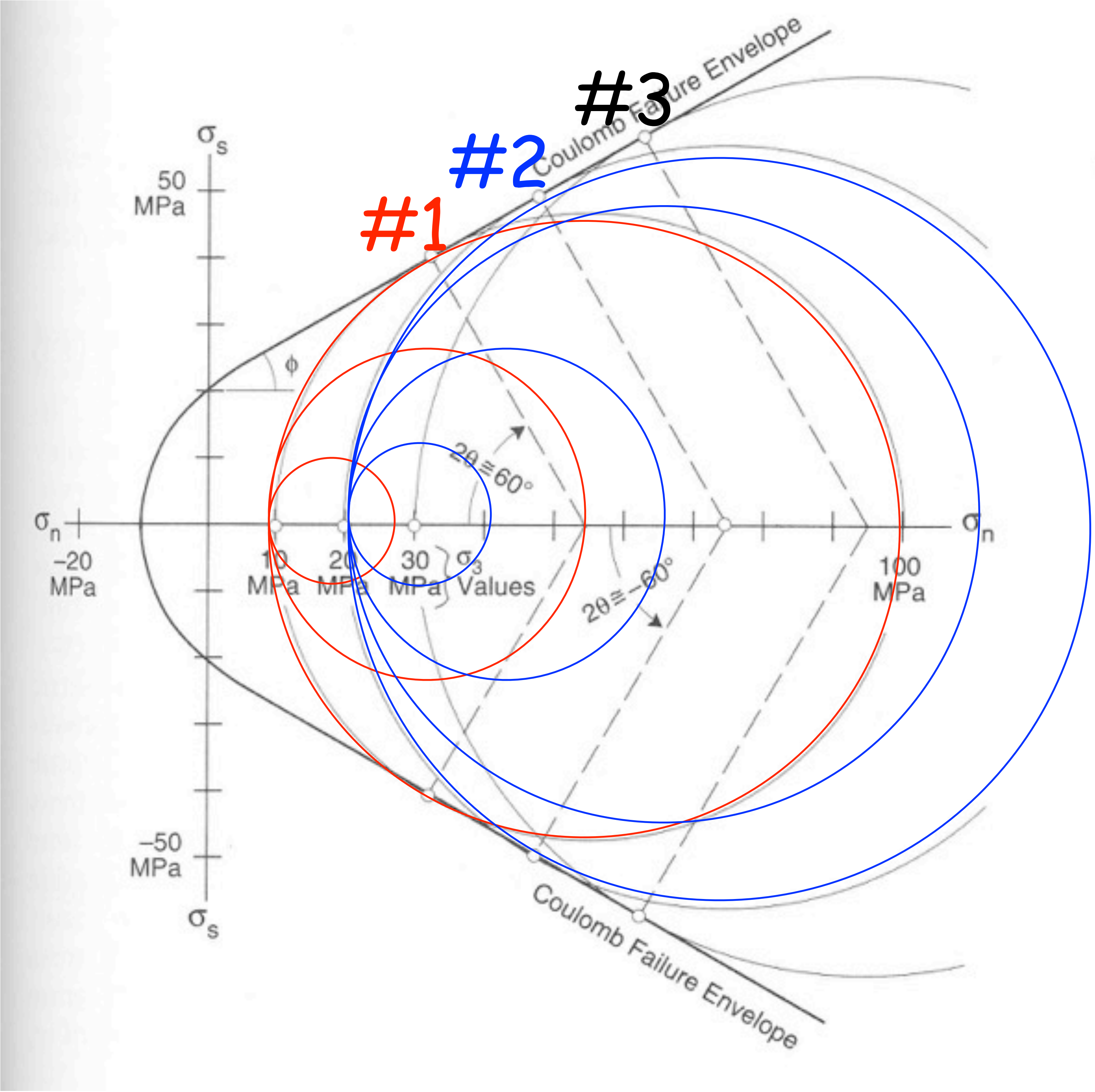
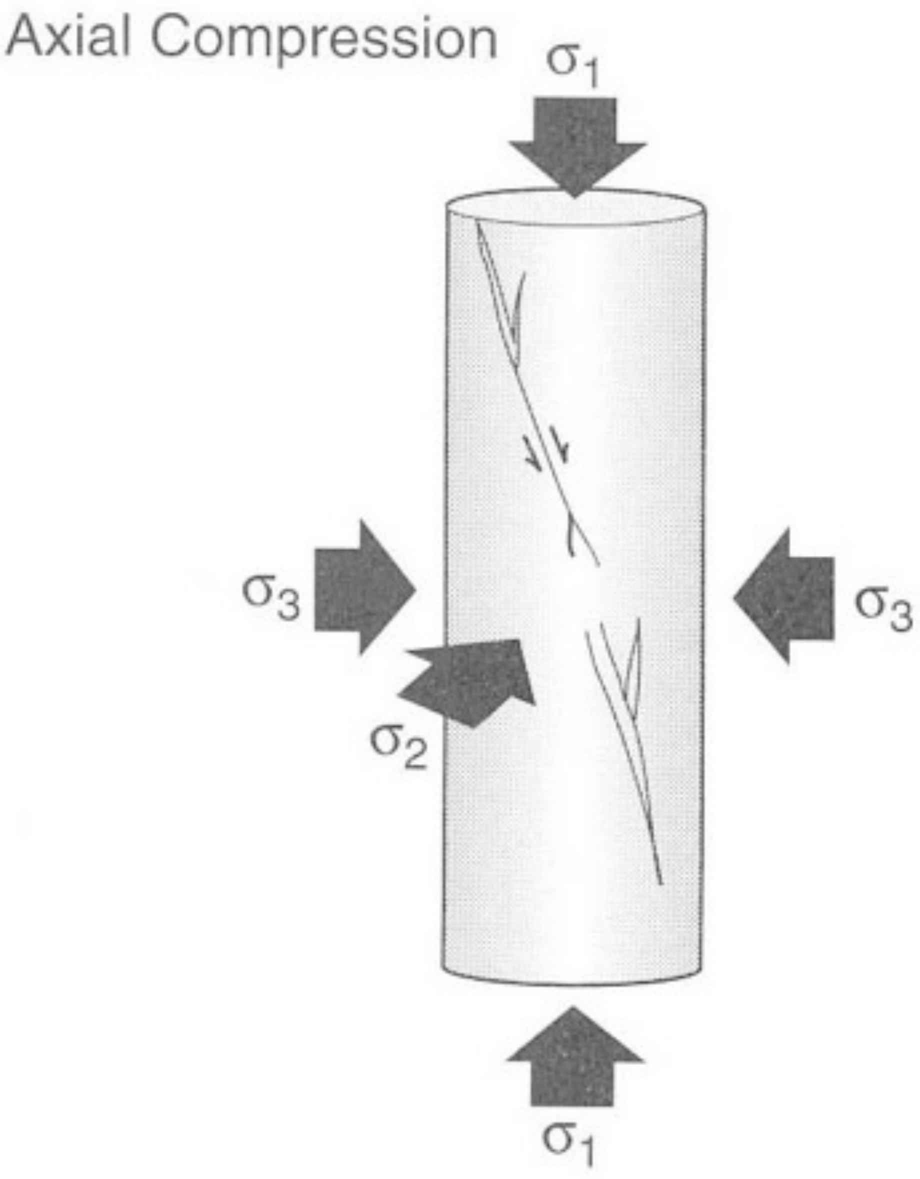


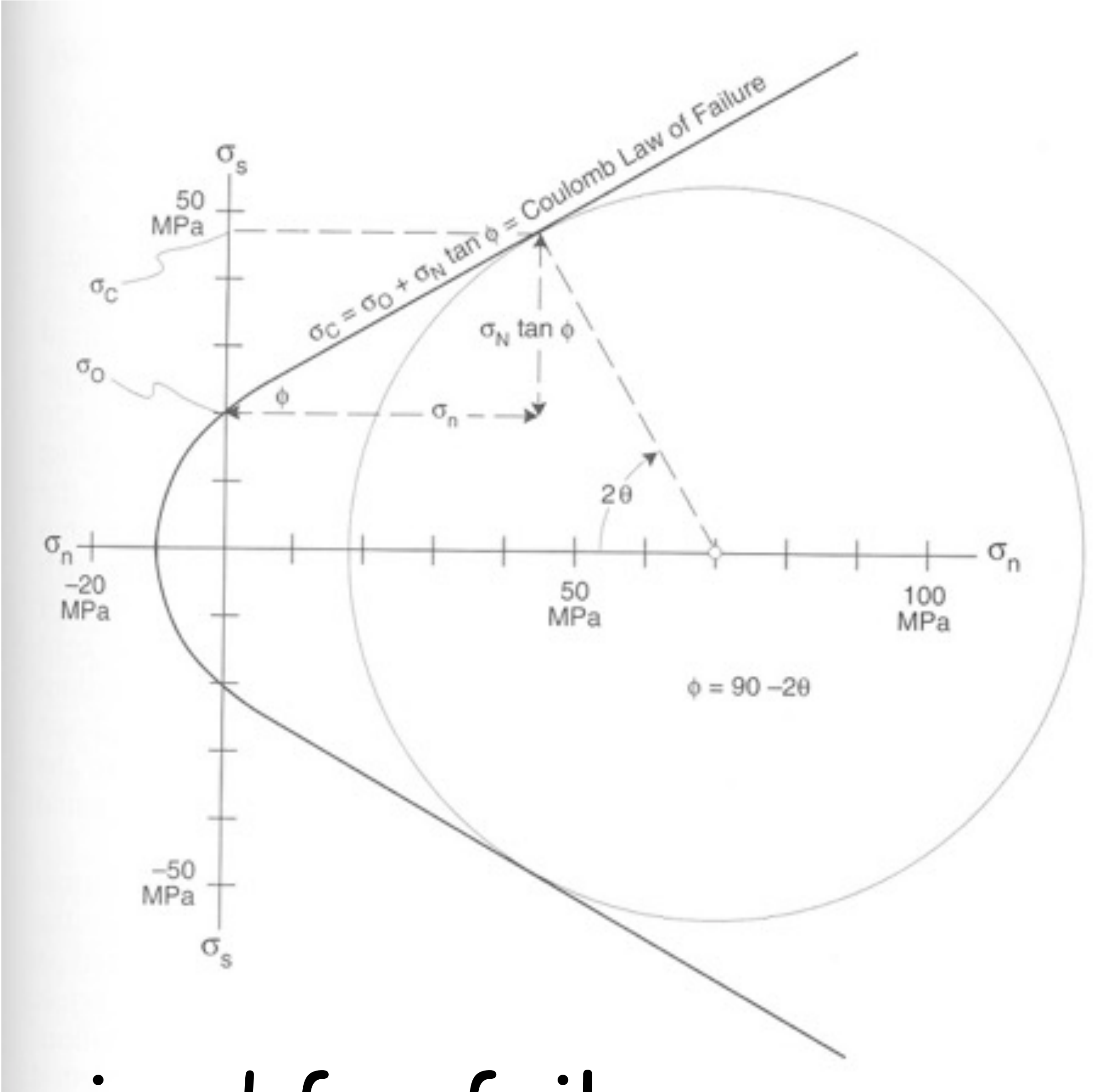
Figure 3.28 Types of deformation experiments: (*A*) Axial compression; (*B*) axial extension; (*C*) tensile.

Compressive tests





Coulomb's law of failure



$$\sigma_c = \sigma_0 + \tan\varphi(\sigma_n)$$

σ_c = critical shear stress required for failure

σ_0 = cohesive strength

$\tan\phi$ = coefficient of internal friction ($\phi=90-2\theta$)

σ_n = normal stress

Failure envelope for different rocks

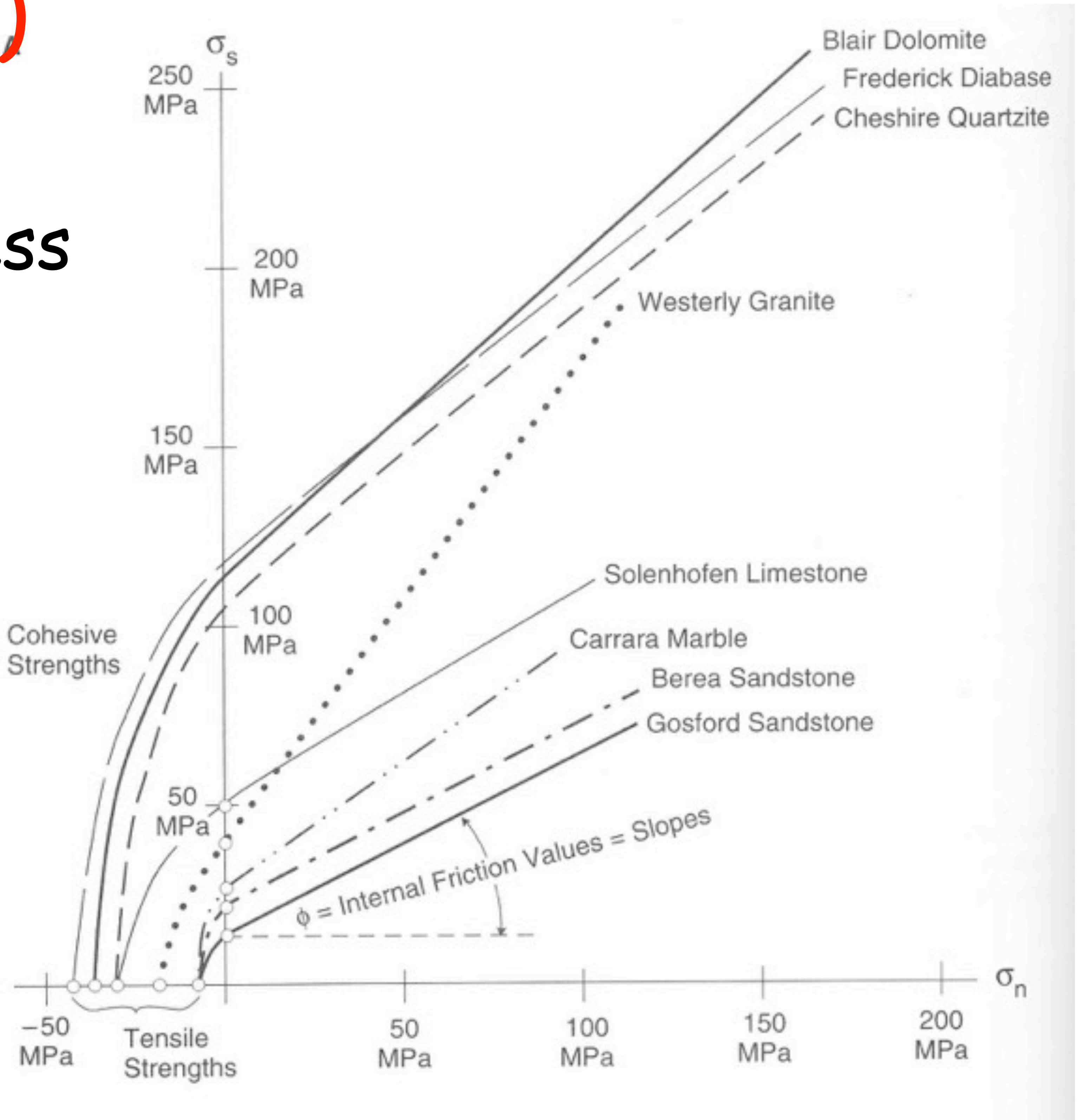
$$\sigma_c = \sigma_0 + \tan\phi(\sigma_n)$$

σ_c = critical shear stress required for failure

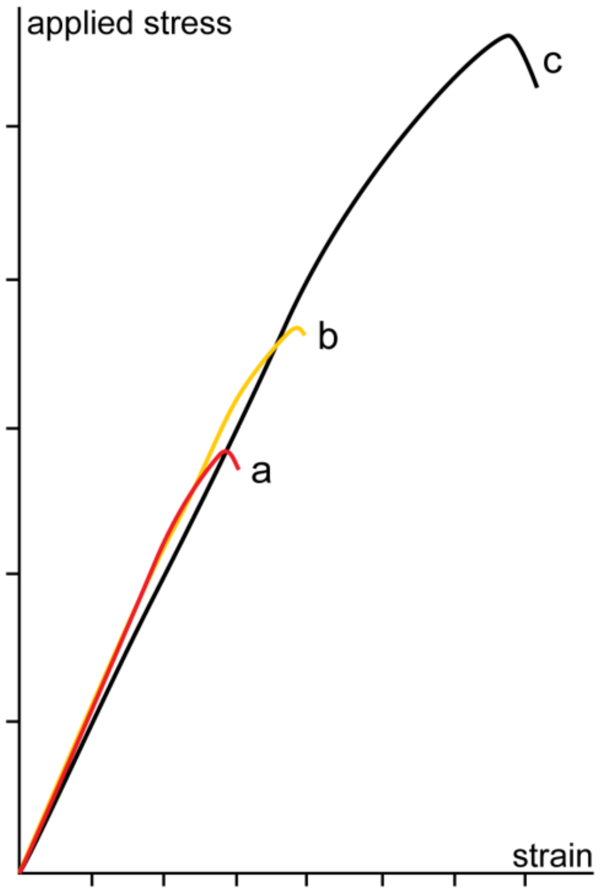
σ_0 = cohesive strength

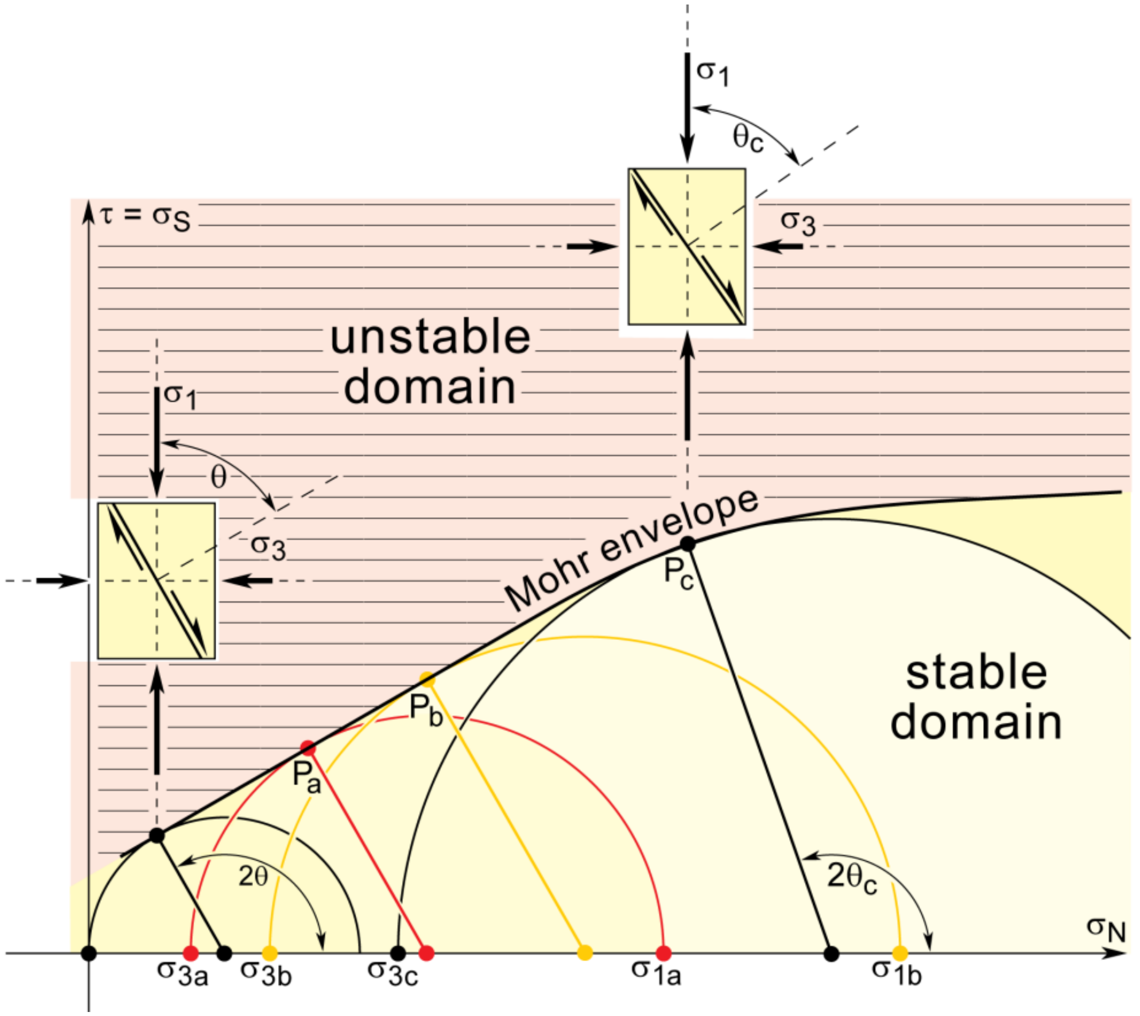
$\tan\phi$ = coefficient of internal friction

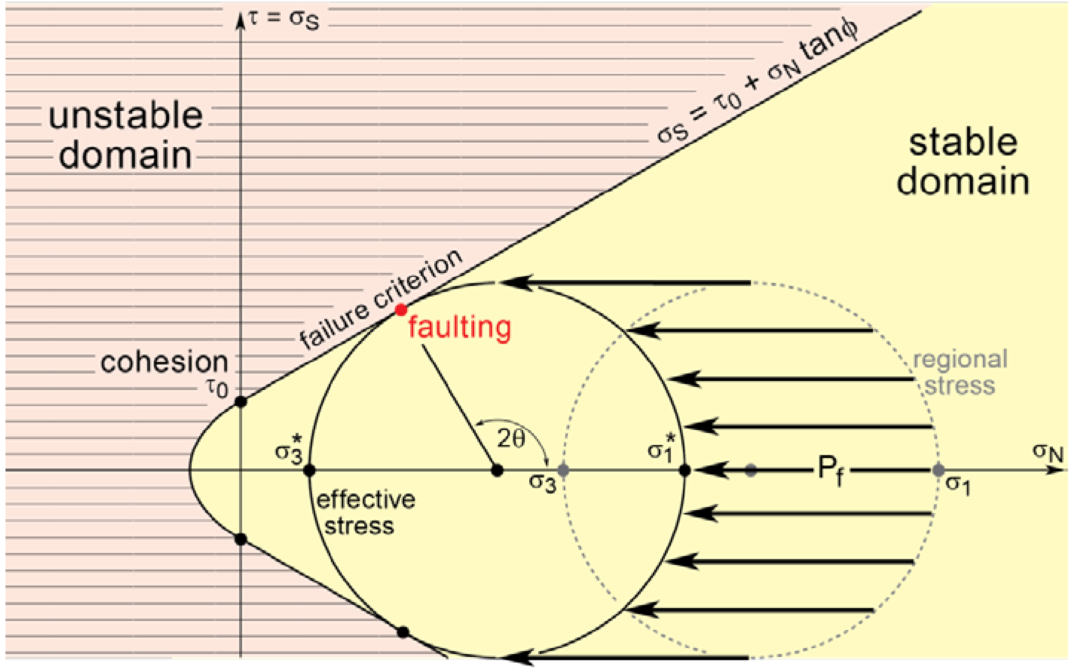
σ_n = normal stress



Mohr-Coulomb criterion



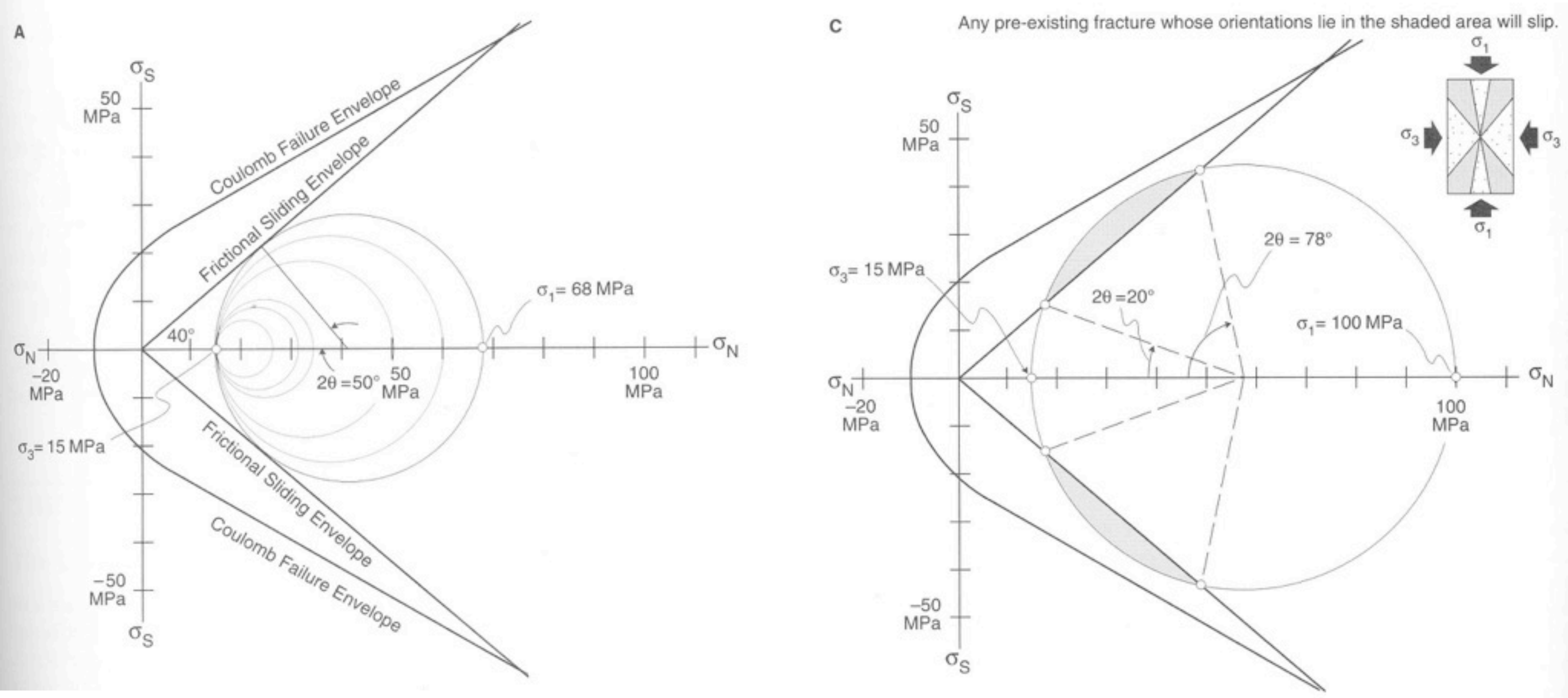




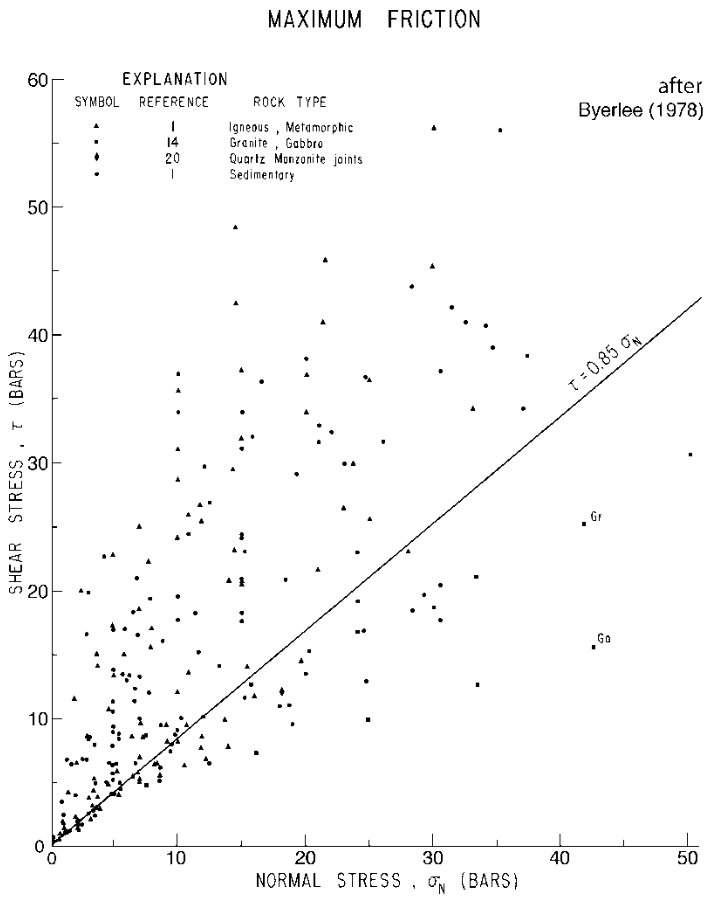
Effect of a pore pressure P_f represented in a Mohr diagram

Preexisting fractures

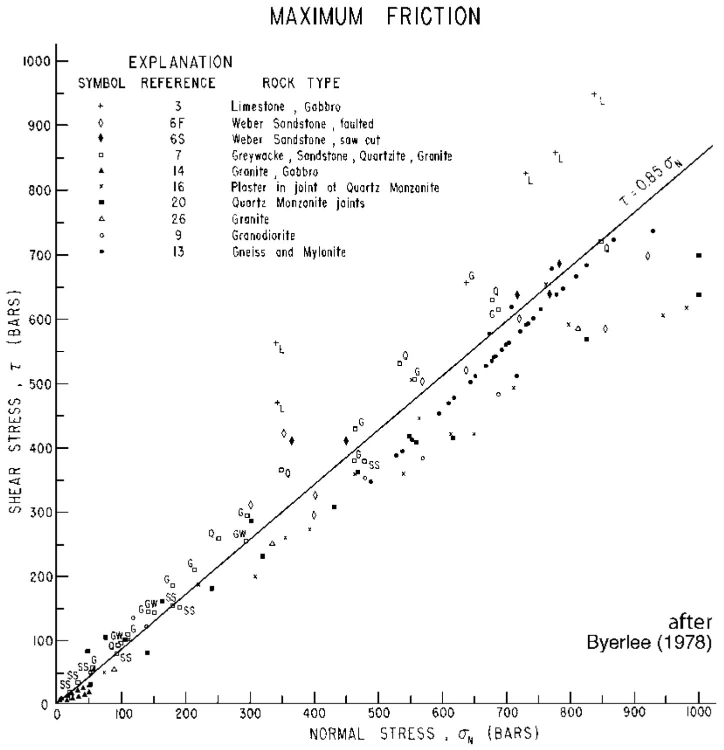
Preexisting fractures of suitable orientation may fail before a new fracture is formed



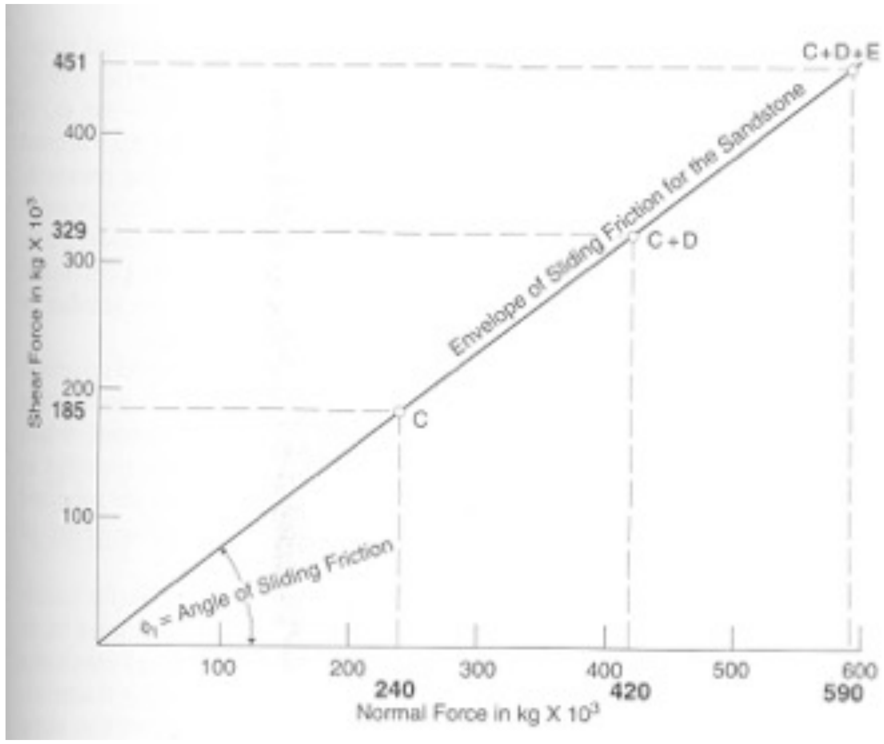
Byerlee’s law

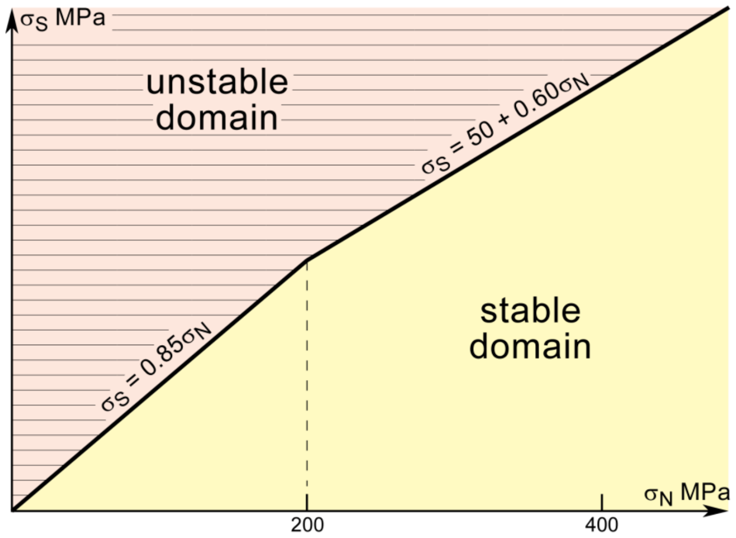


Shear stress plotted as a function of normal stress at the maximum friction for a variety of rock types at normal stresses up to 50 bars.



Shear stress plotted as a function of normal stress at the maximum friction for a variety of rock types at normal stresses up to 1000 bars.



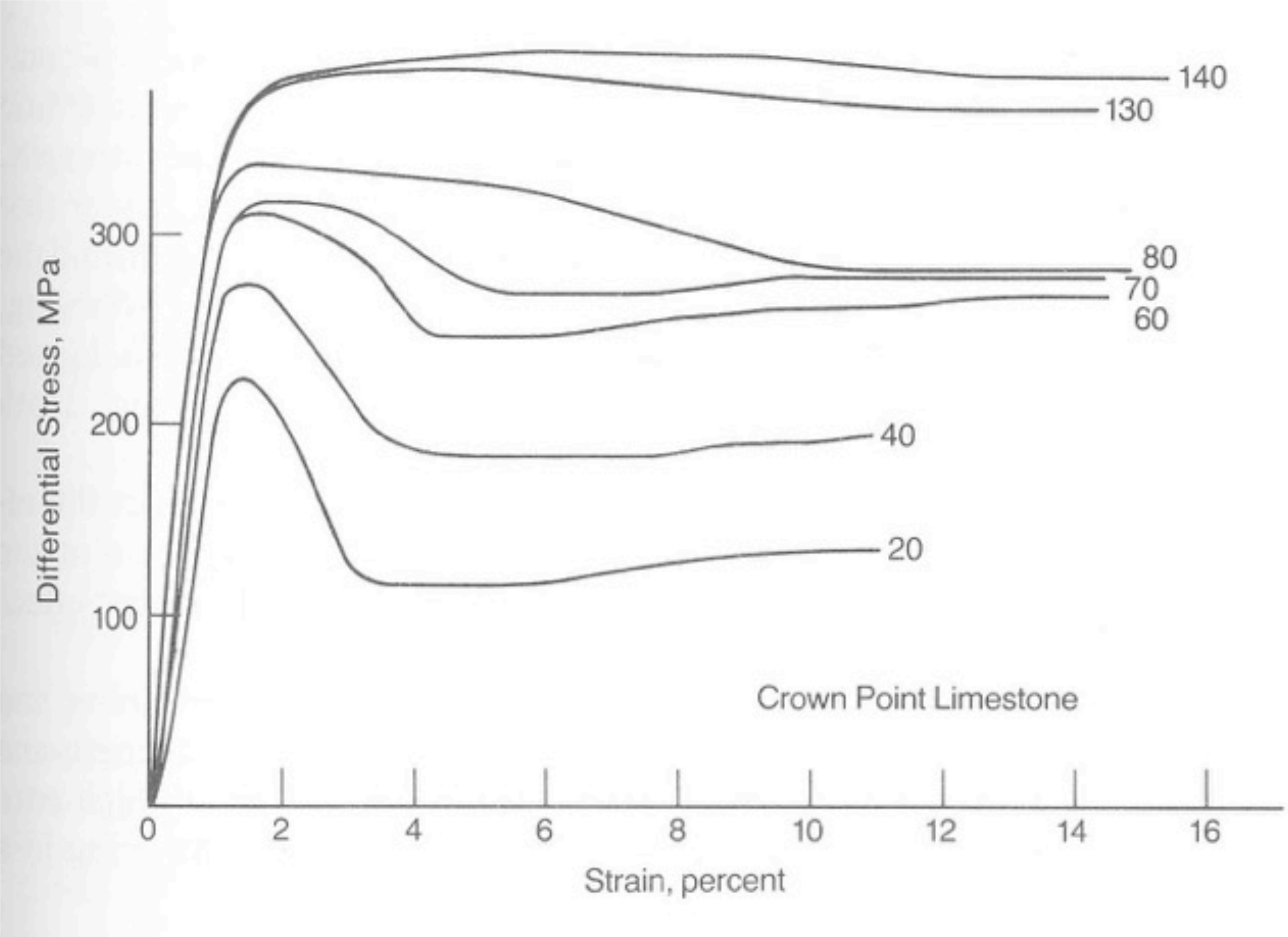


Byerlee’s law for pre-existing fault surfaces

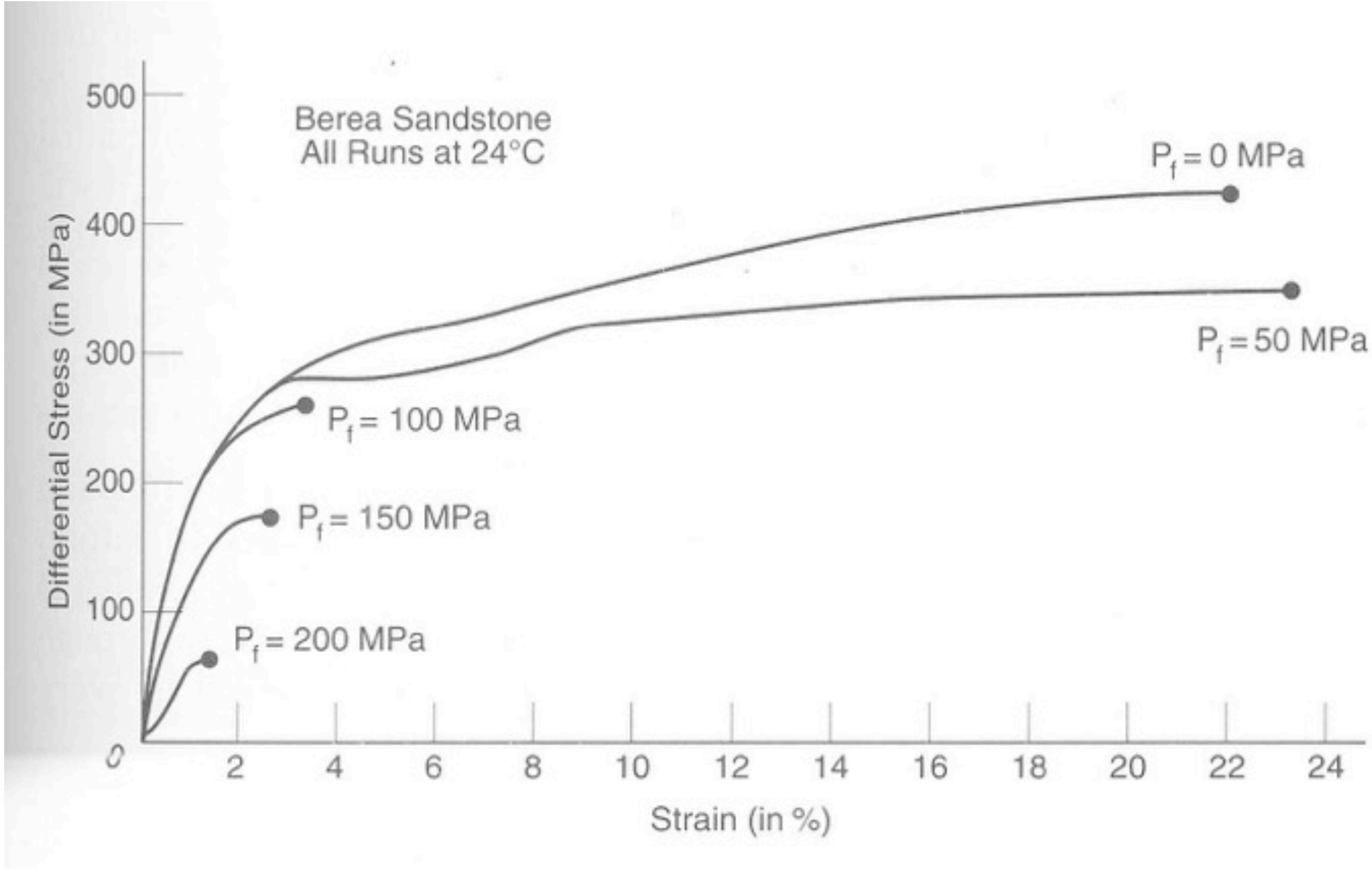
For confining pressures corresponding to shallow crustal depths (up to 200MPa≈8km), equation becomes: σ_S=0.85 σ_N

For confining pressures between 200 and 2000 MPa, the frictional strength of pre-cut rocks is better described by including a "cohesion-like" parameter: σ_S =50MPa+0.6 σ_N

Strength increases with confining pressure



Strength decreases with increasing fluid pressure



Strength decreases with temperature

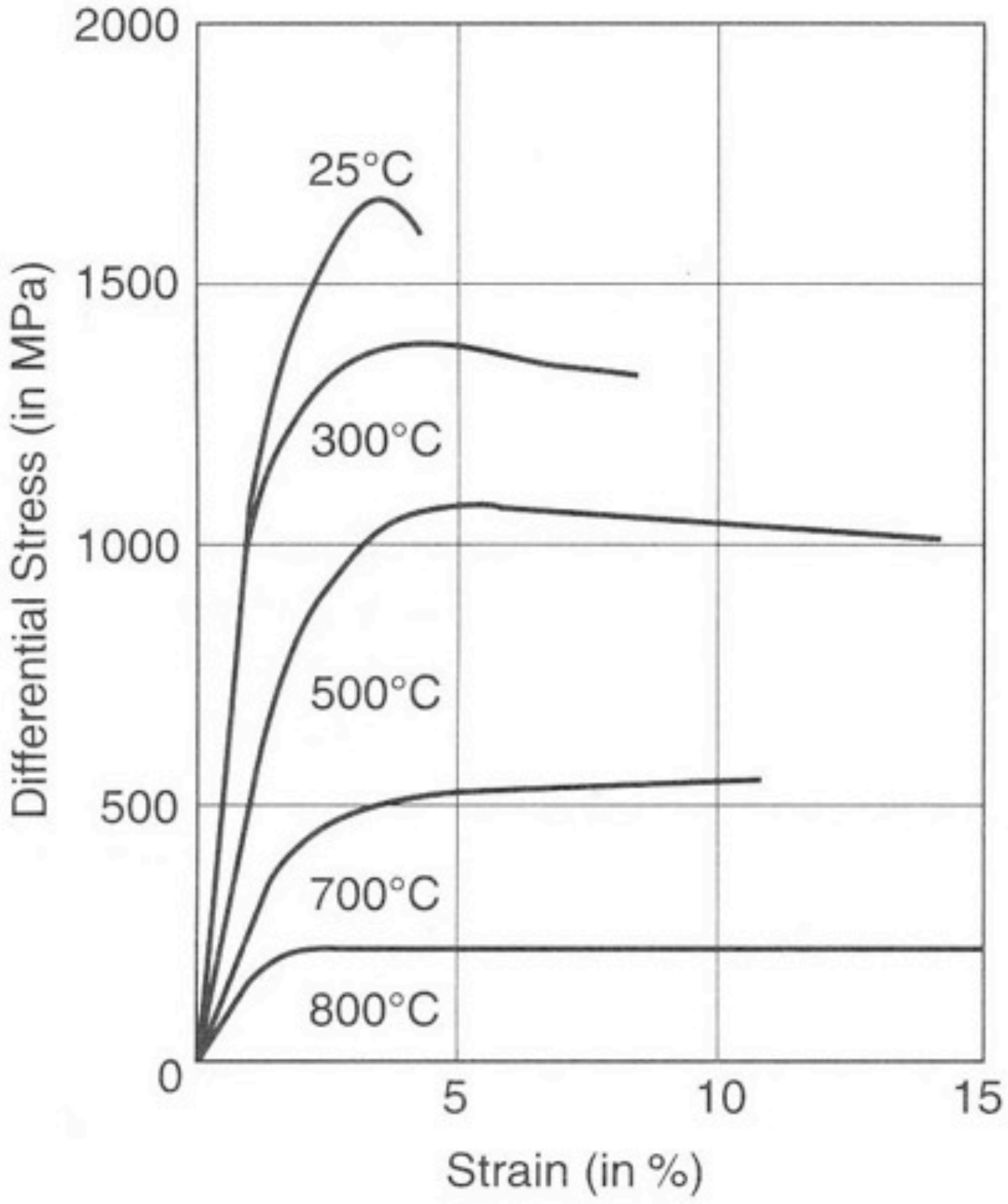


Figure 3.40 Stress–strain diagram for basalt deformed at 5-kbar confining pressure under a variety of temperature conditions. [From Griggs, Turner, and Heard (1960), Geological Society of America.]

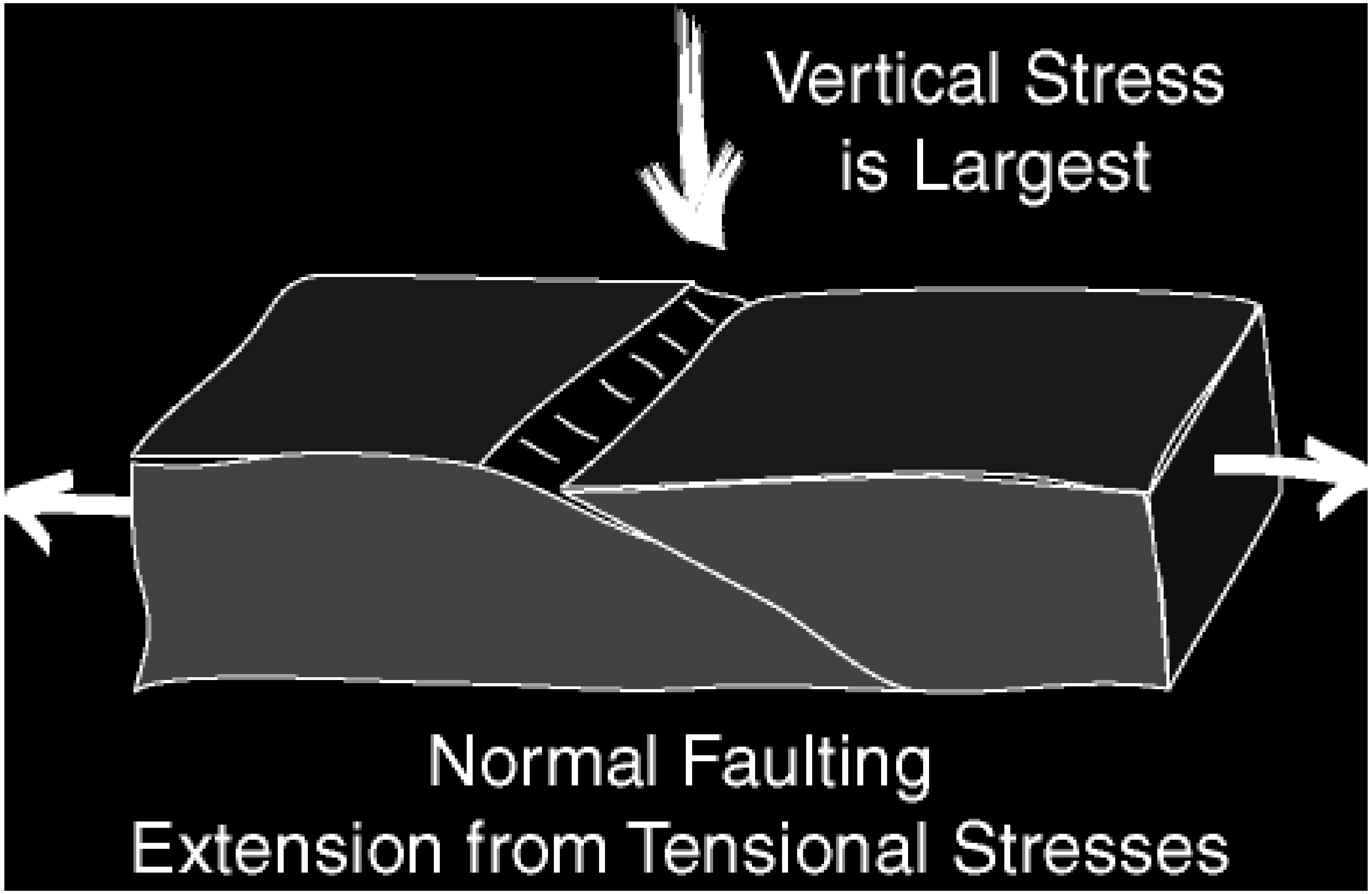
Anderson's Theory of Faulting

The Earth's surface is a free surface (contact between rock and atmosphere), and cannot be subject to shear stress.

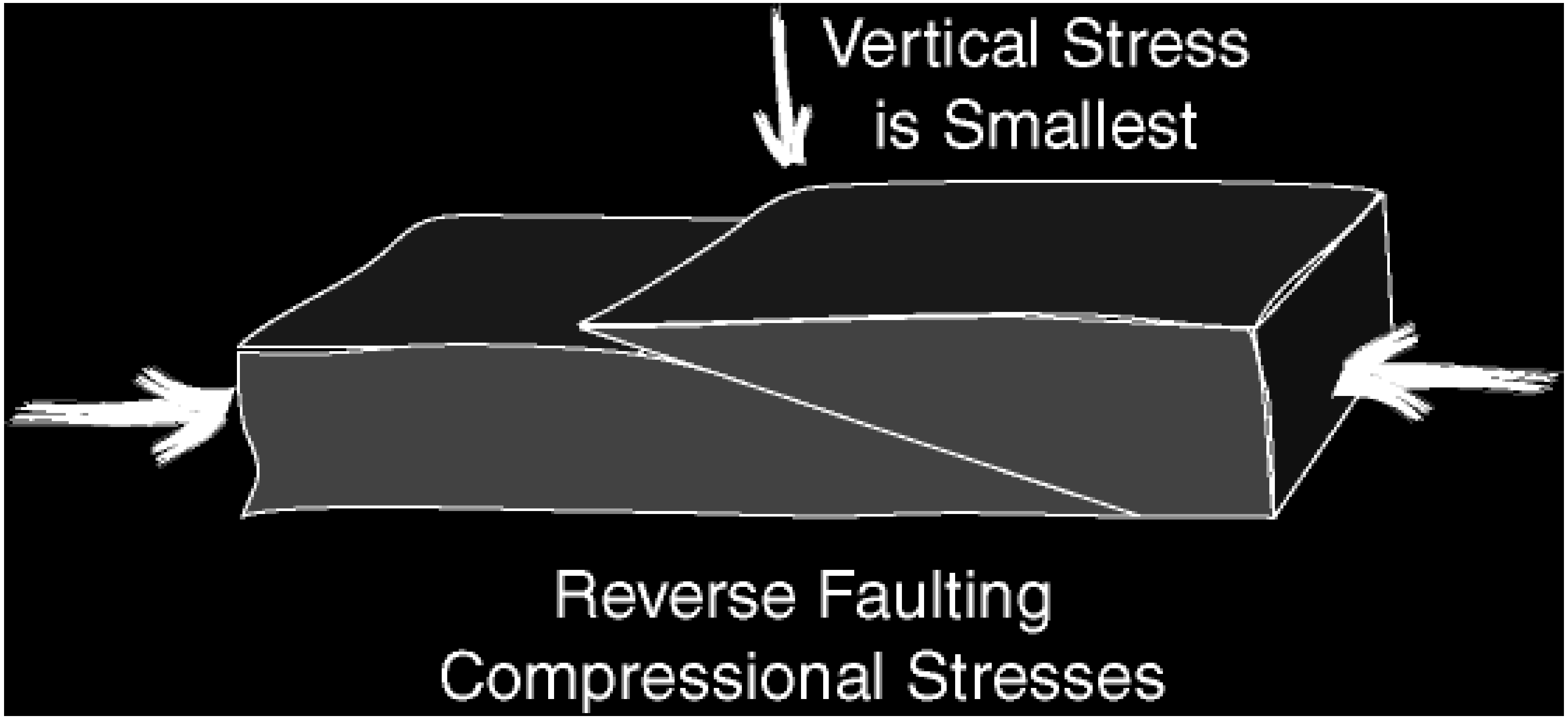
As the principal stress directions are directions of zero shear stress, they must be parallel (2 of them) and perpendicular (1 of them) to the Earth's surface.

Combined with an angle of failure of 30 degrees from σ_1, this gives:

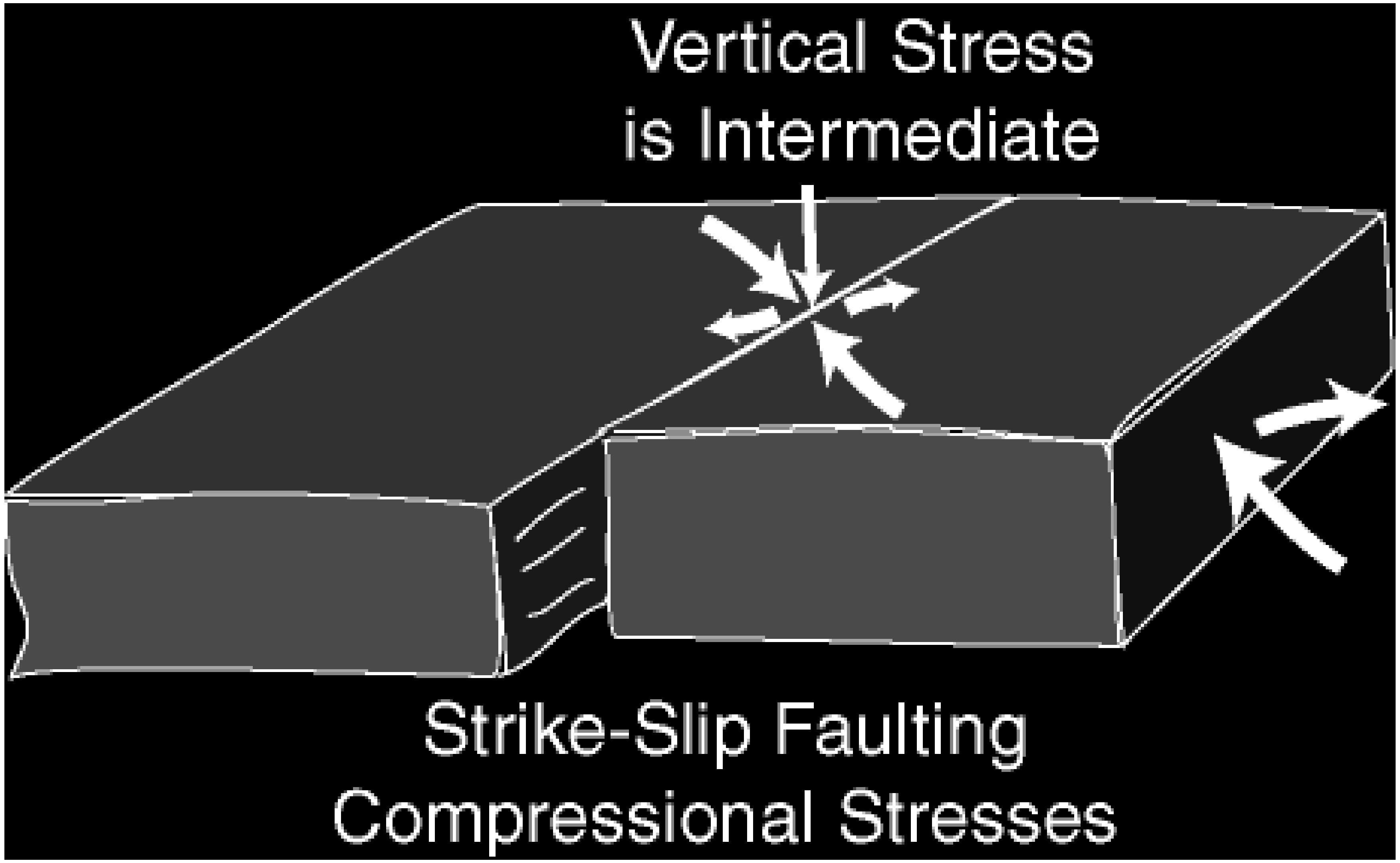
Normal Faulting Stresses



Reverse Faulting Stresses



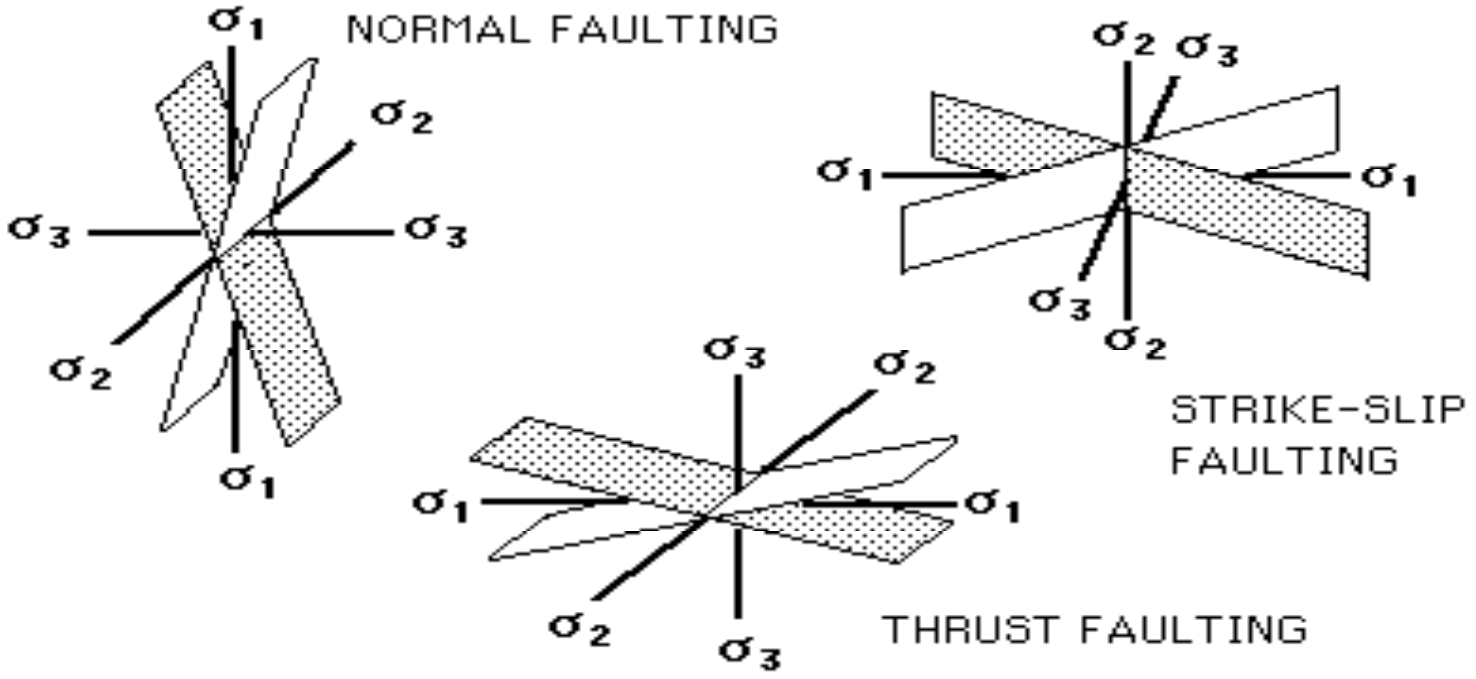
Strike-Slip Faulting Stresses



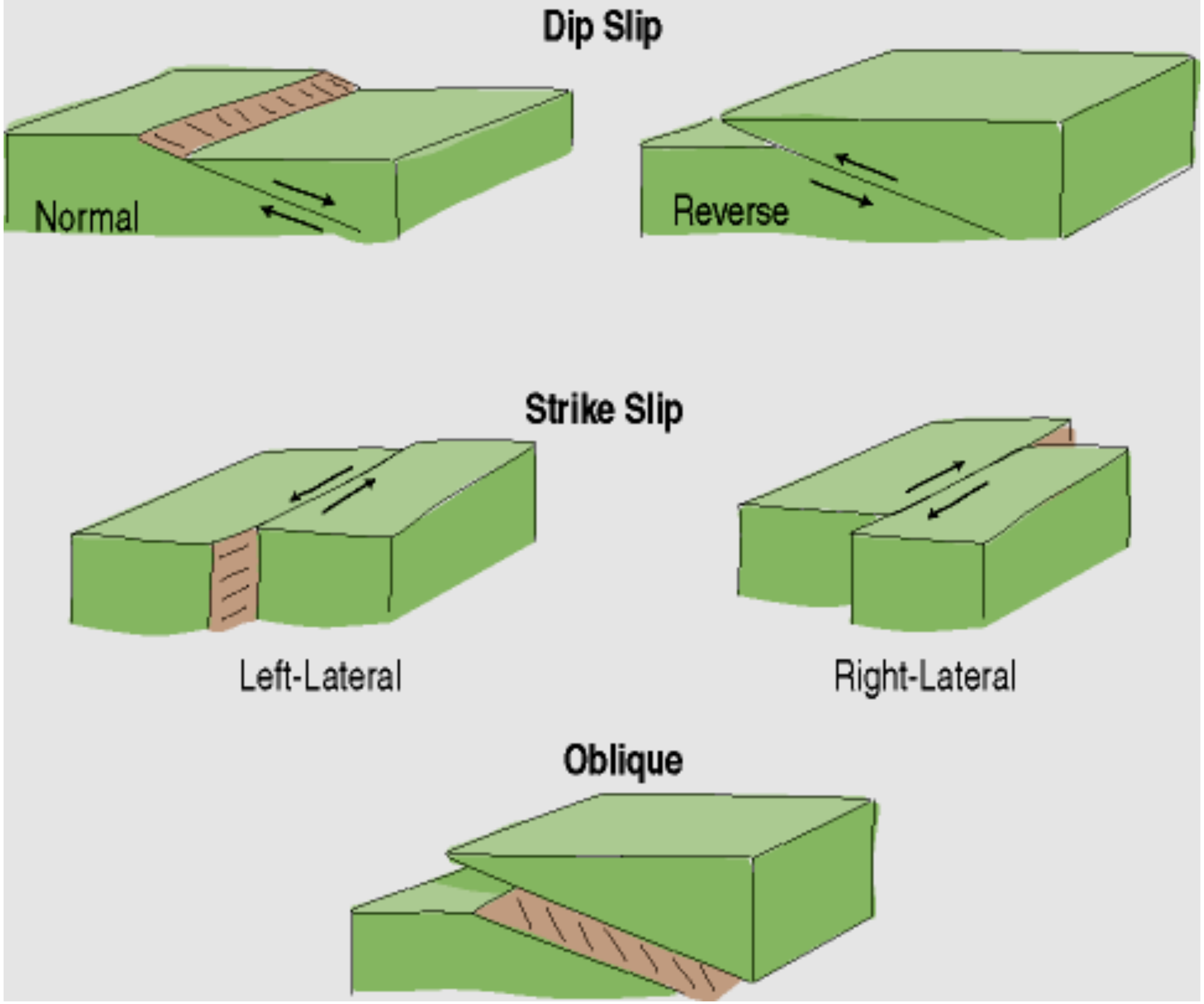
Friction

A number of factors can control friction: temperature, slip rate and slip history. Many materials become weaker with repeated slip (slip weakening).
They may exhibit an inverse dependence of friction on slip velocity (velocity weakening).
Stick slip behaviour is observed only at temperatures below 300°C.

Anderson's theory of faulting: he recognized that principal stress orientations could vary among geological provinces within the upper crust of the earth. He deduced the connection between three common fault types: normal, strike-slip, and thrust and the three principal stress systems arising as a consequence of the assumption that one principal stress must be normal to the eart h's surface.



Faulting Summary



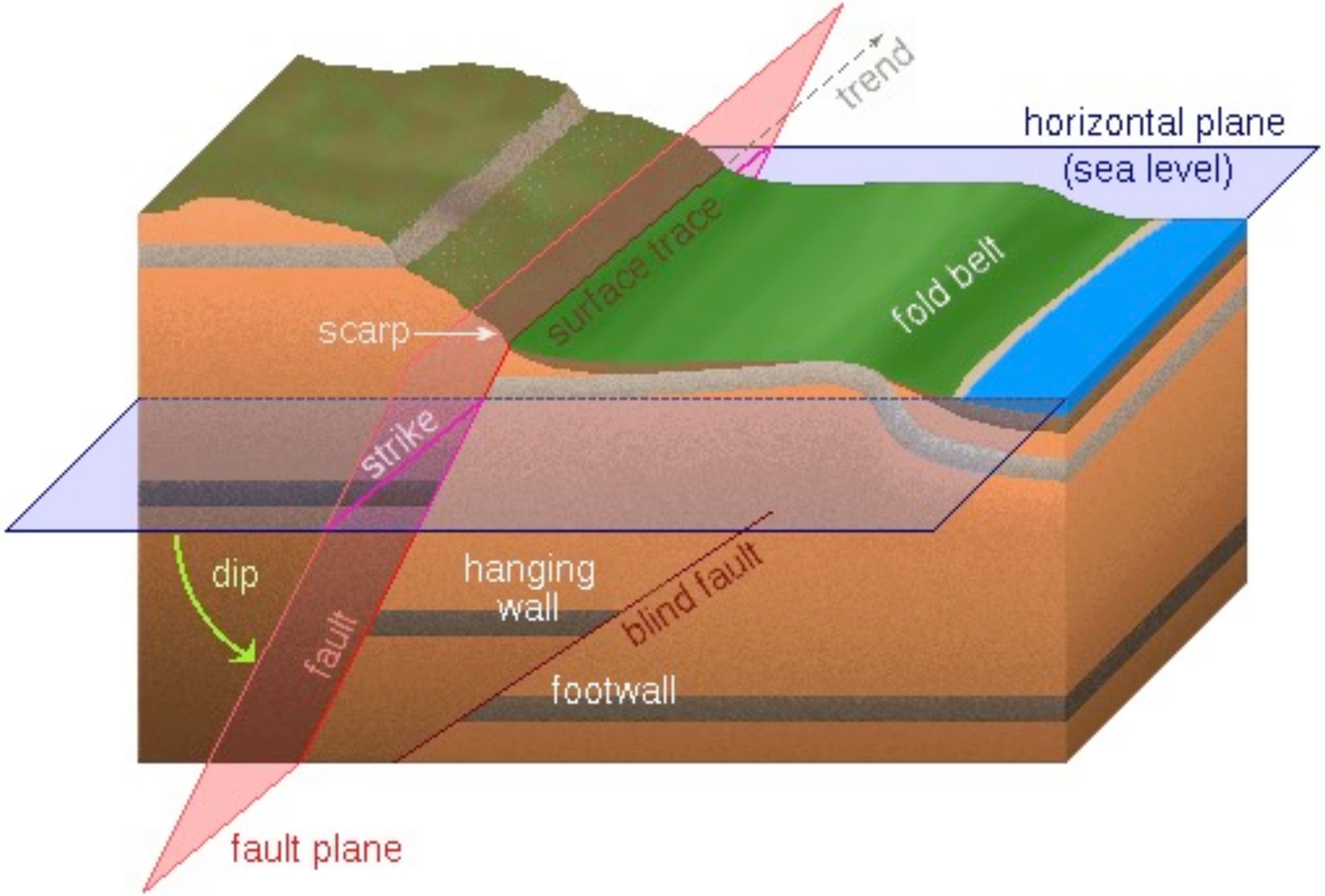
Faults which move along the direction of the dip and are described as either **normal** or **reverse**, depending on their motion.

The hanging wall slips horizontally (no motion in the direction of fault dip). There are 2 cases depending on how the rocks on the other side of the fault move – **right lateral** and **left lateral**.

A combination of dip-slip and strike-slip motion.

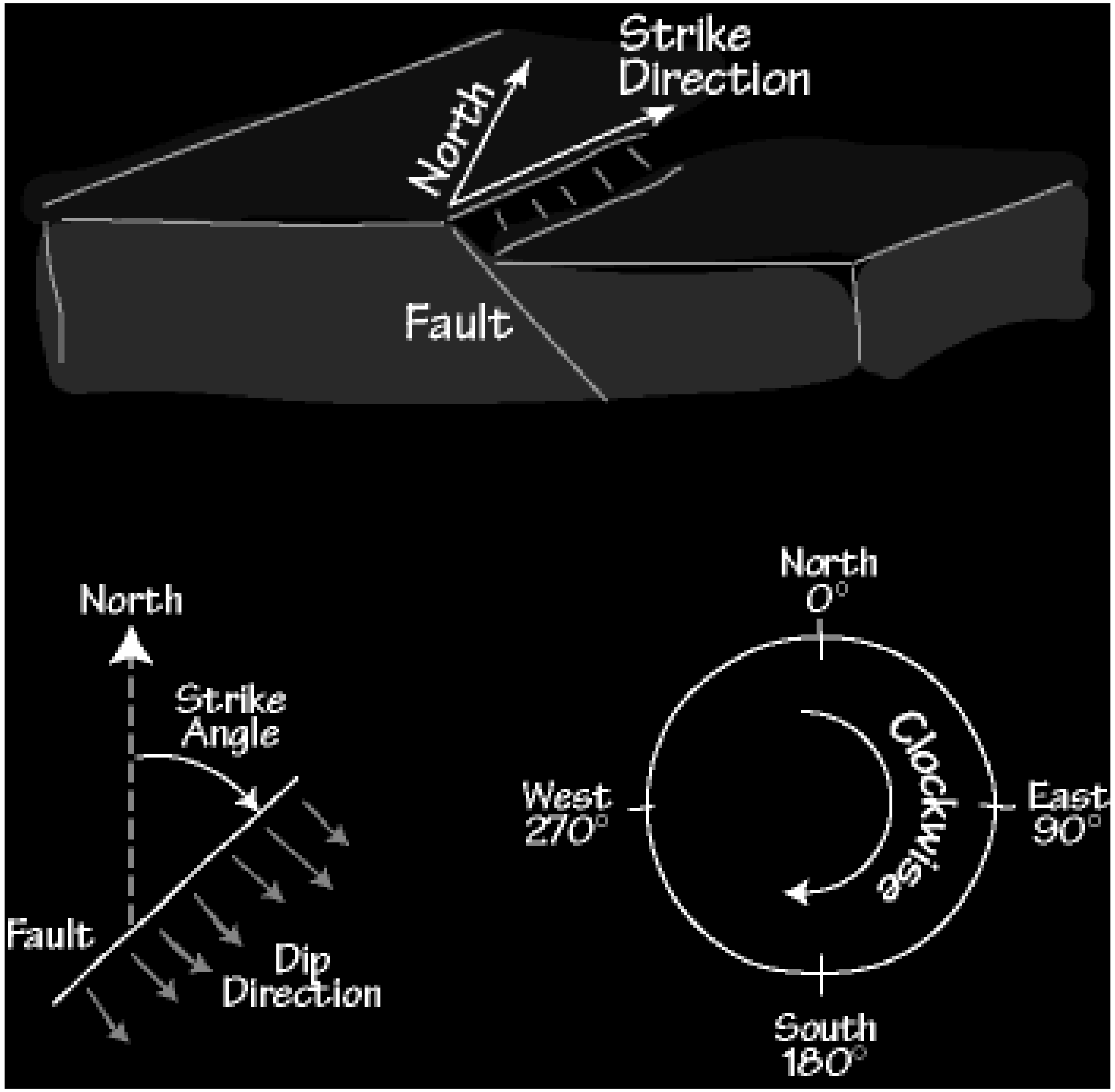
Earthquakes and Faults

- ☑ Earthquakes occur on faults, but not all of the fault ruptures during each earthquake.



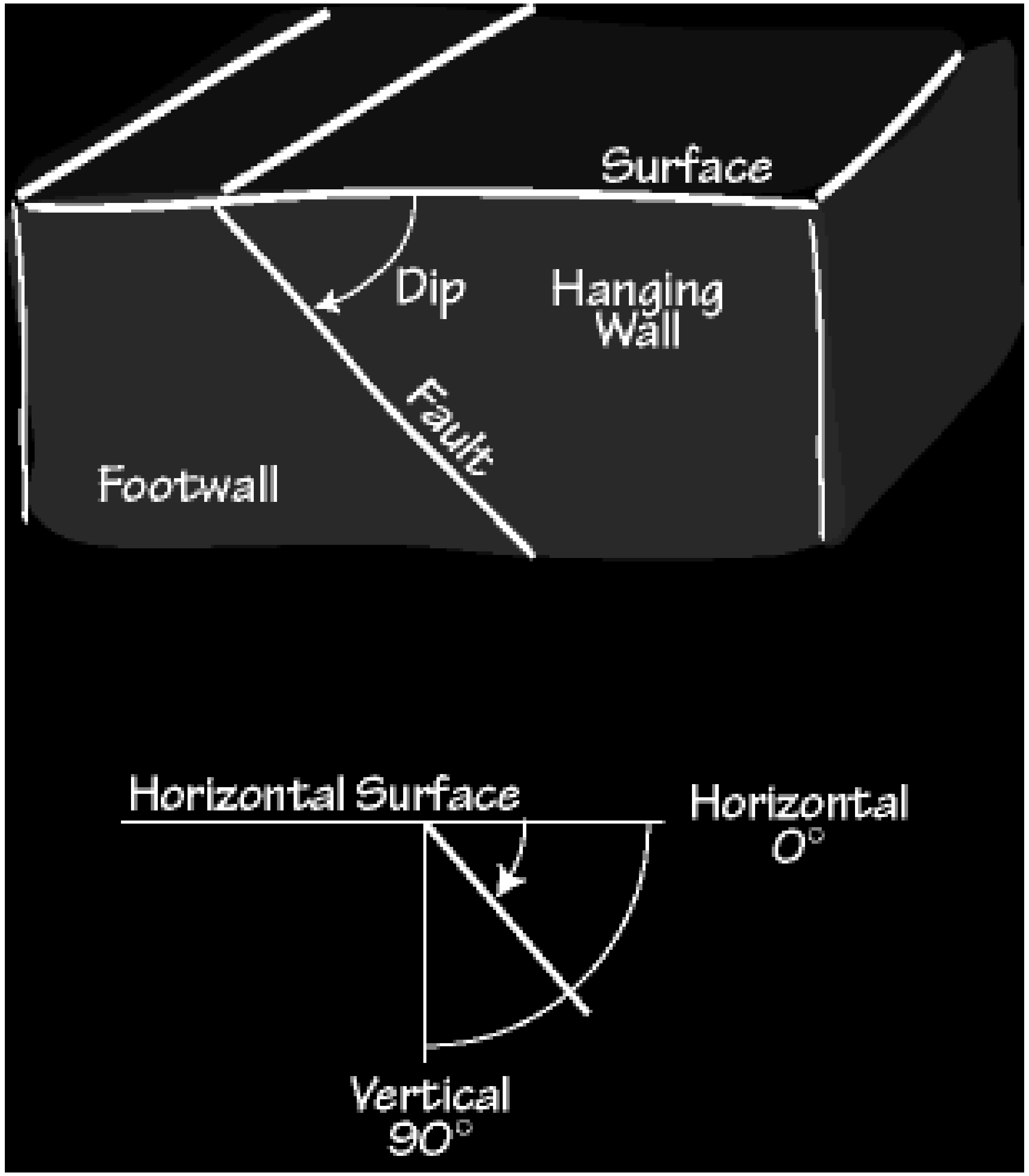
Fault Geometry Terminology: STRIKE

Strike is an angle use to describe the orientation of the fault surface with respect to North.



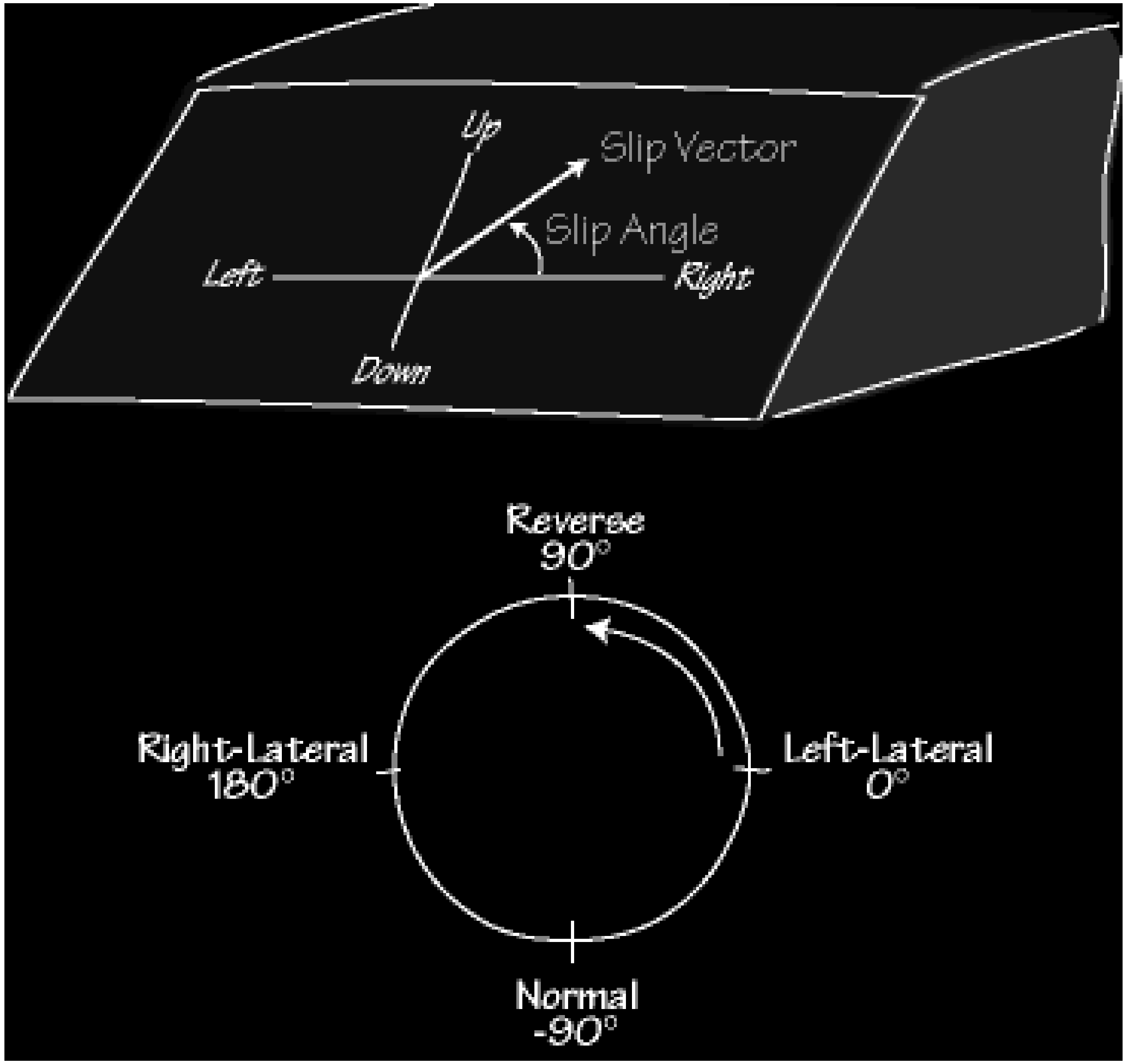
Fault Geometry Terminology: DIP

The orientation of the fault surface with respect to Earth's surface is defined by the fault **dip**.



Fault Geometry Terminology: SLIP

Slip (or rake) is the angle used to describe the orientation of the movement of the hanging wall relative to the foot wall.

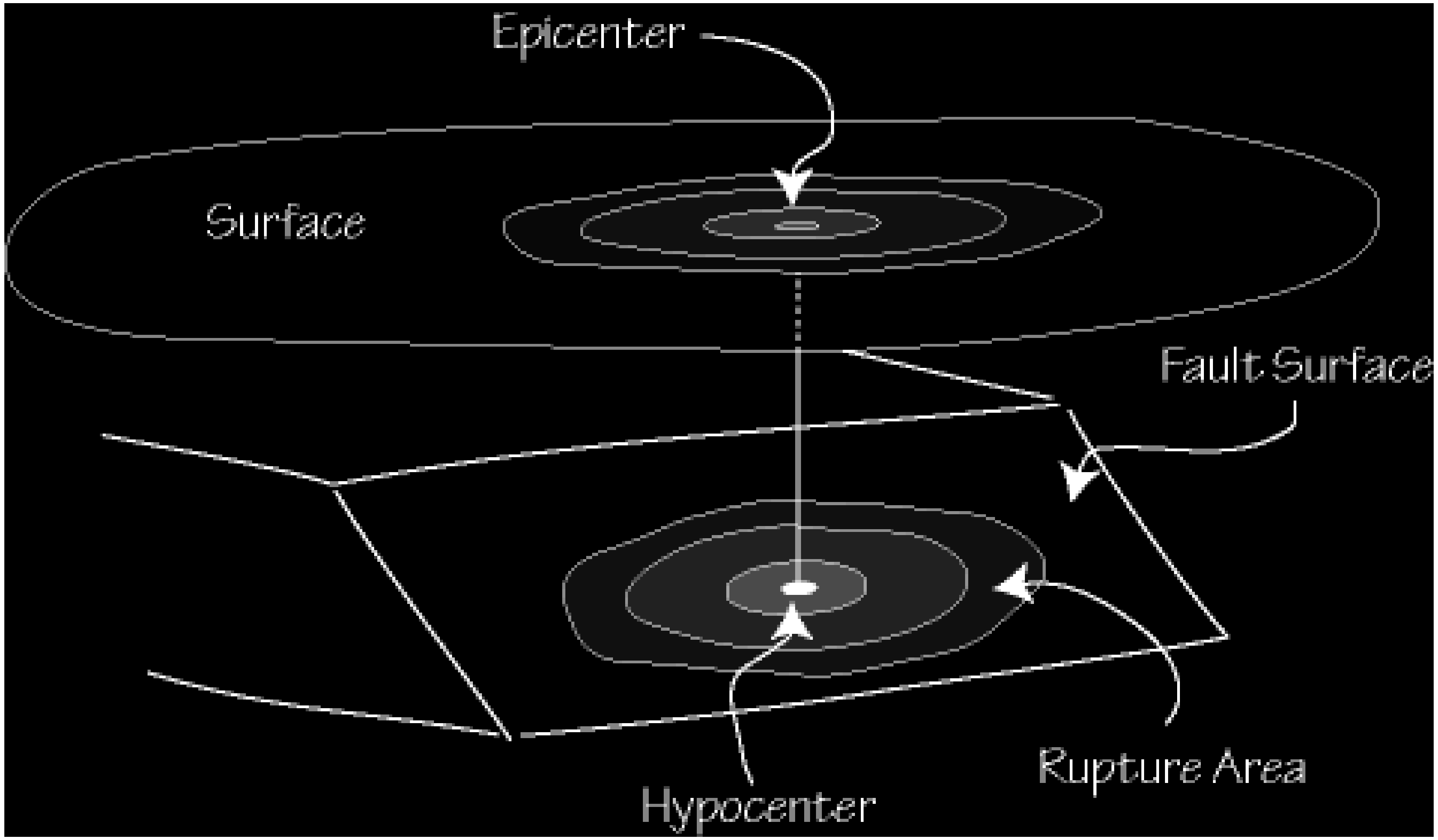


Earthquakes and Faults

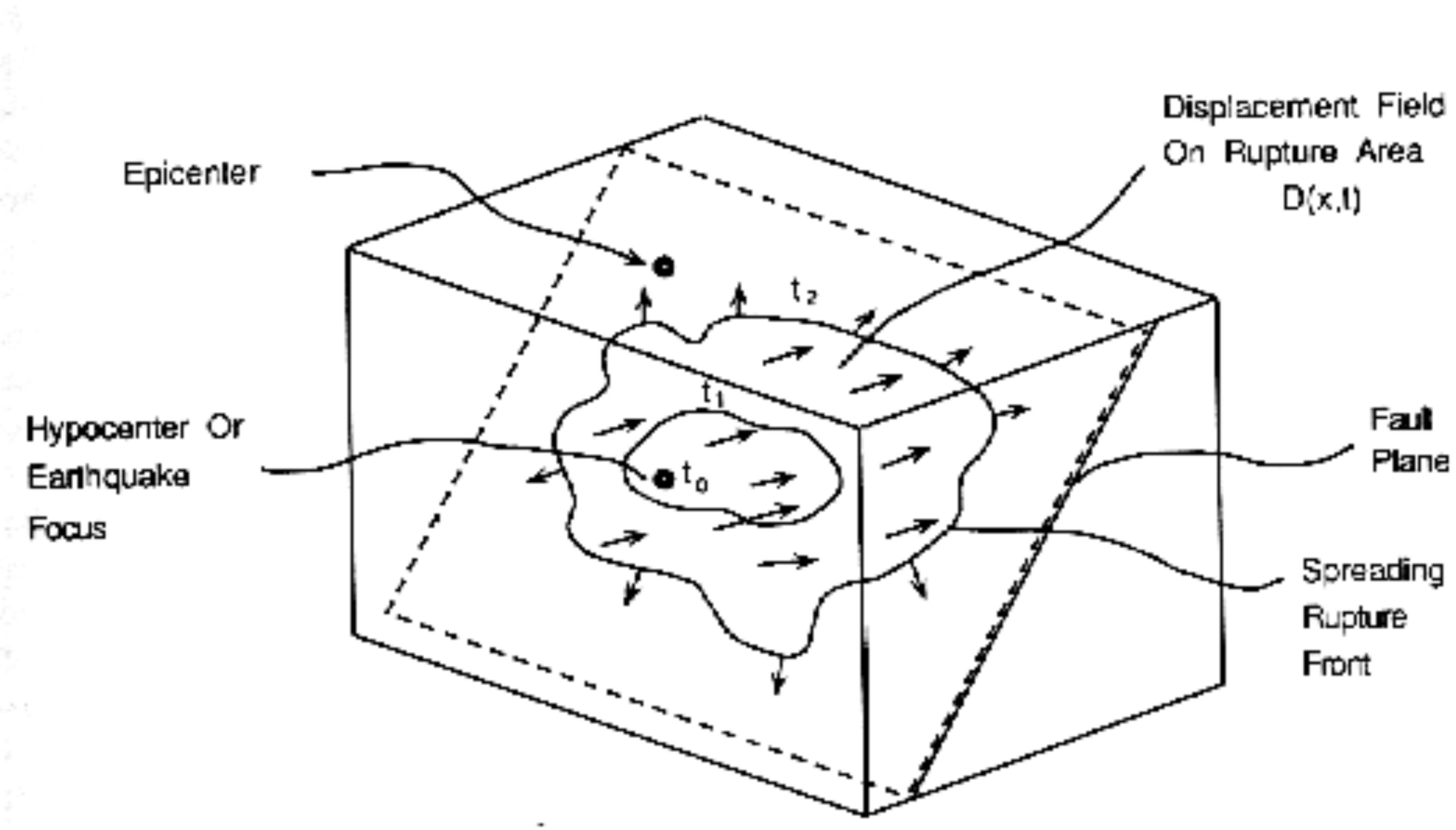
☑ Earthquakes occur on faults, but not all of the fault ruptures during each earthquake.

☑ The hypocenter (or focus) is the place where the rupture begins, the epicenter is the place directly above the hypocenter.

Hypocenter and Epicenter



Rupture process



Schematic diagram of rupture on a fault plane. Slipping points radiate outgoing P- and S waves. In general, rupture wavefront is not regular and slip vector, as well as slipping time, is different for the points on the fault.

Fault slip involves 3 main stages:

1) initiation of fault sliding
2) rupture front expansion
3) termination of rupture process.