SEISMOLOGY

Master Degree Programme in Physics - UNITS
Physics of the Earth and of the Environment

SEISMIC SOURCES 1: FAULTING

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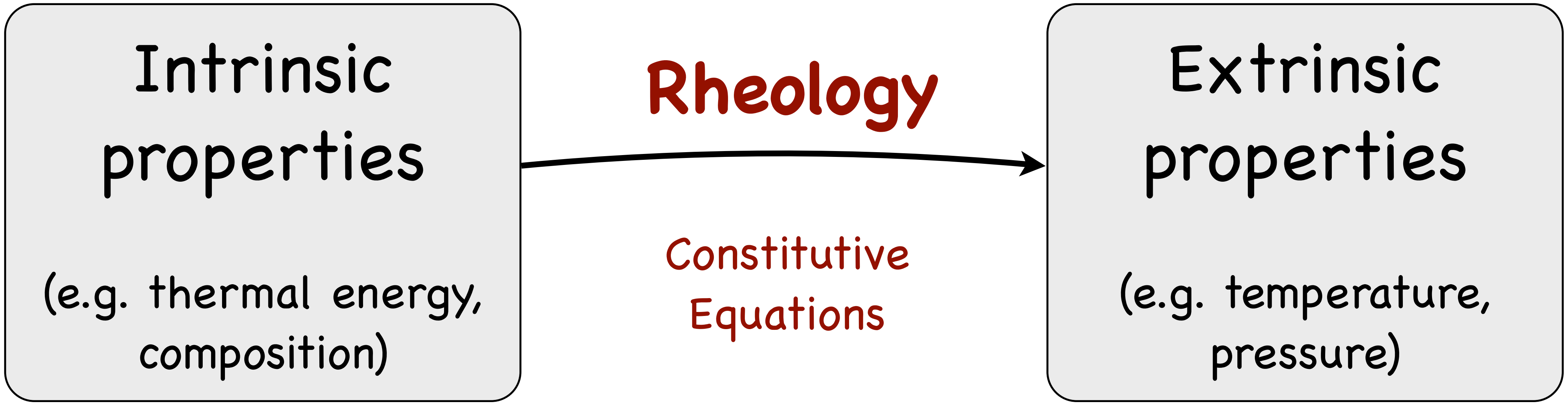
Seismic sources - 1

Basic Dynamics

- **brittle deformation**
  - stress states
- **rupture process**
  - fault geometry
- **stresses and faulting**
  - stress cycle (stick-slip)

Constitutive equations



Intrinsic properties

(e.g. thermal energy, composition)

Rheology

Constitutive Equations

Extrinsic properties

(e.g. temperature, pressure)

A single equation describing material responses over the wide range of physical conditions would include too many parameters to be practicable.

It is more suitable to consider few ideal classes of response (rheologies such as elastic, viscous, plastic, etc.) which some materials display to various degrees of approximation under various physical conditions.

Mechanical Properties

Homogeneity
Isotropy

Material

Parameters

Elasticity
Viscosity
Plasticity

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)

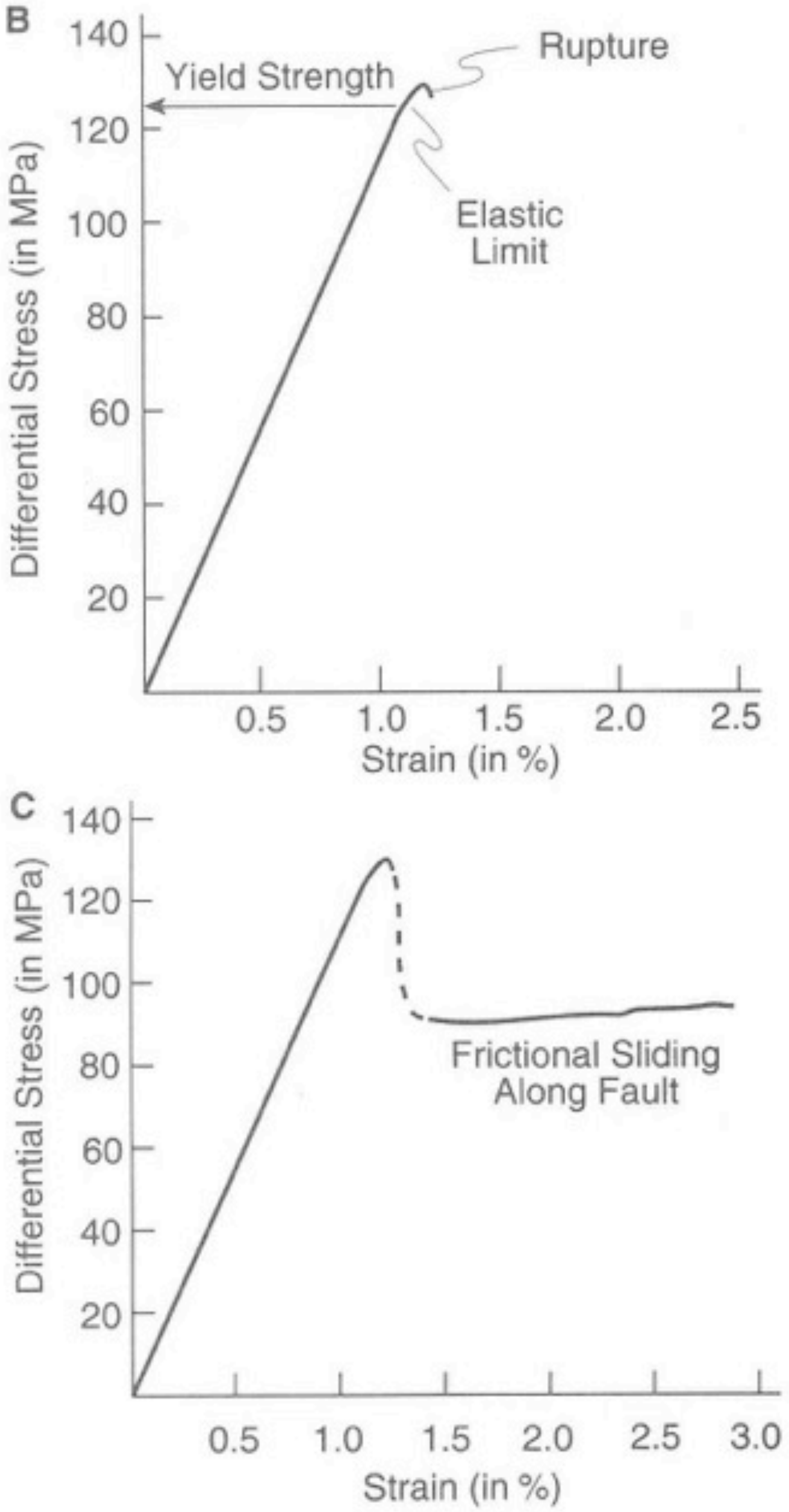
...must deform in a ductile way (does not break)

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

Brittle behaviour

- The maximum stress a rock can withstand before beginning to deform permanently (inelastic behavior) is its **yield** point or elastic limit.
- At this stress level, and low confining pressure and low temperature, most rocks and minerals **break** into fragments.
  - Localized deformation at the yield stress is permanent; therefore, the brittle behavior yields a plastic deformation. With this definition, brittle behavior refers to a state of stress at which rupture, i.e. loss of cohesion occurs.
- The brittle mode of deformation includes both **fracturing** and **sliding**, hence governs the development of **faults**.
  - Faults are inclined to the axis of loading and show a localized offset parallel to their surface.

Rheology

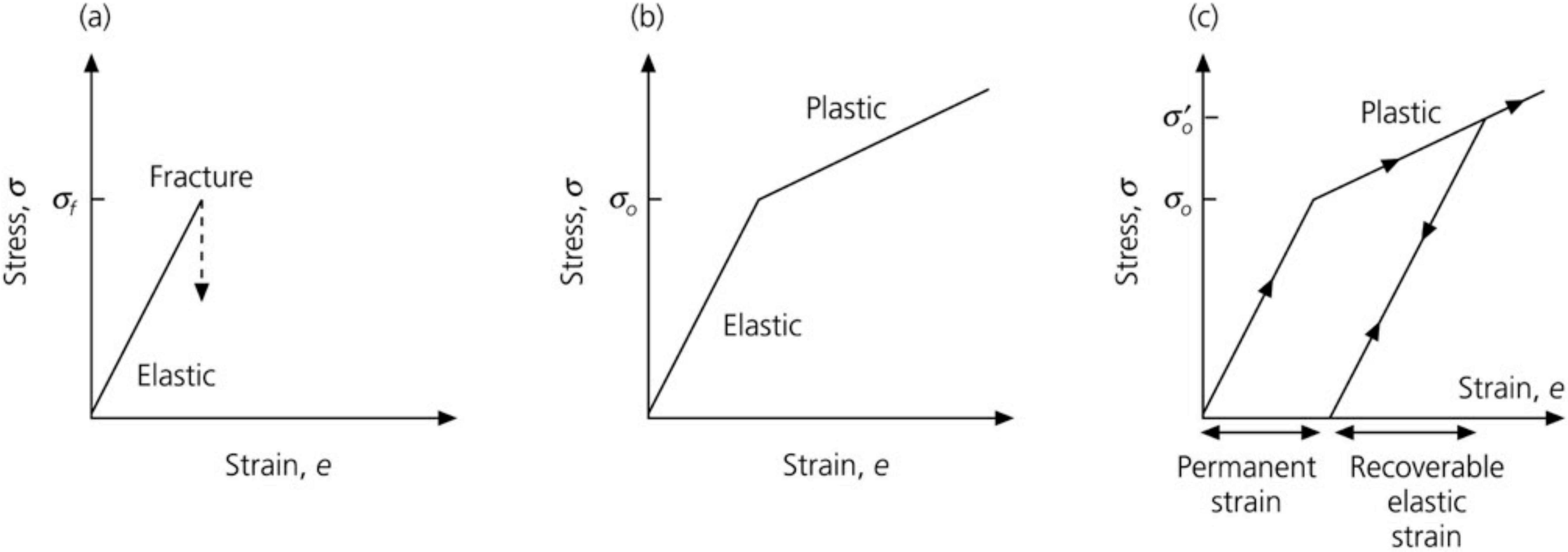


Elastic limit: no longer a linear relationship between stress and strain- rock behaves in a different manner

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

Different Rheologies

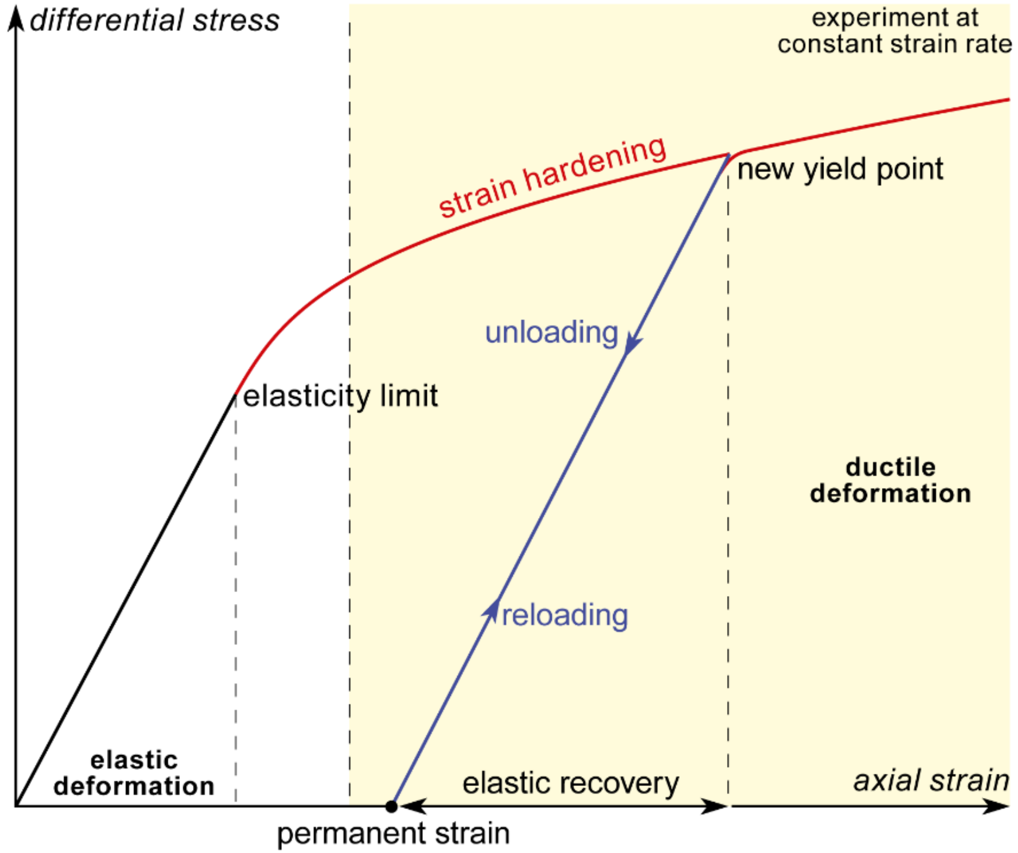
Figure 5.7-1: Elastic and plastic rheologies.



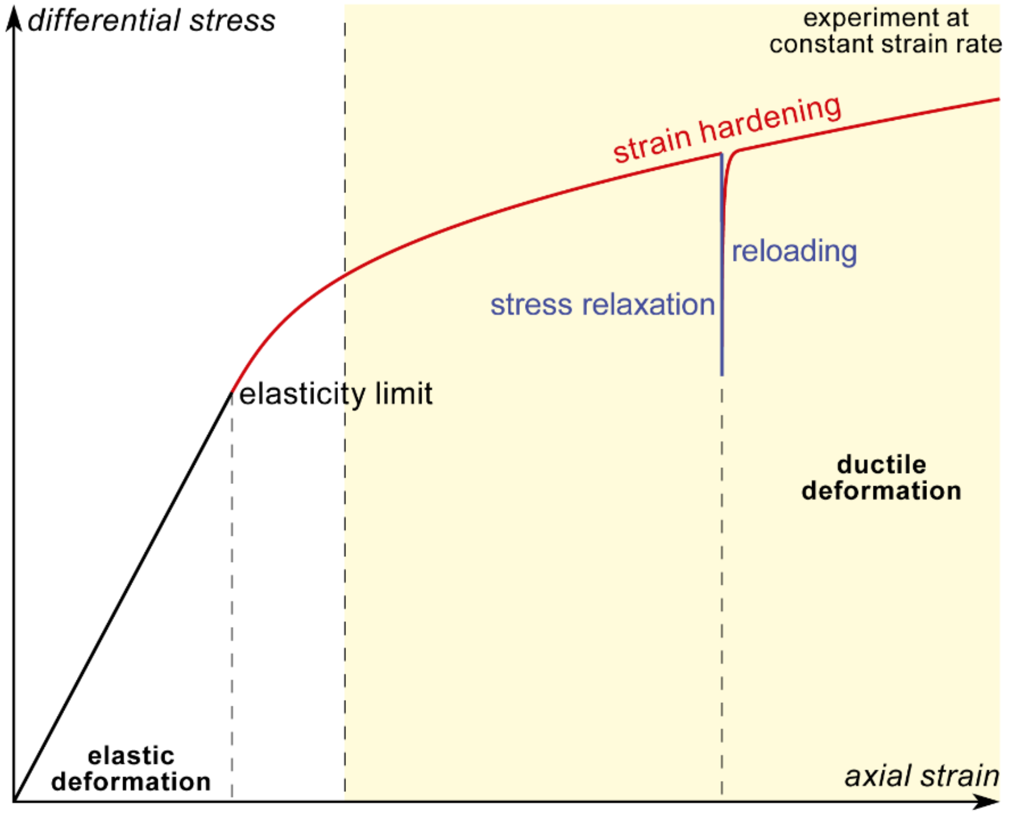
The mechanical properties of rocks deforming in the brittle regime are nearly insensitive to temperature, but very sensitive to strain-rate and **confining pressure**. Indeed, **friction** critically depends on the pressure acting across planes.

The fracture strength of rocks at the Earth's surface is the lowest and is controlled by the failure criteria only, but it increases with depth due to increasing lithostatic pressure.

Strain Hardening



Idealised stress-strain curve of a loading-unloading test



Idealised stress-strain curve of a specimen hold at constant strain

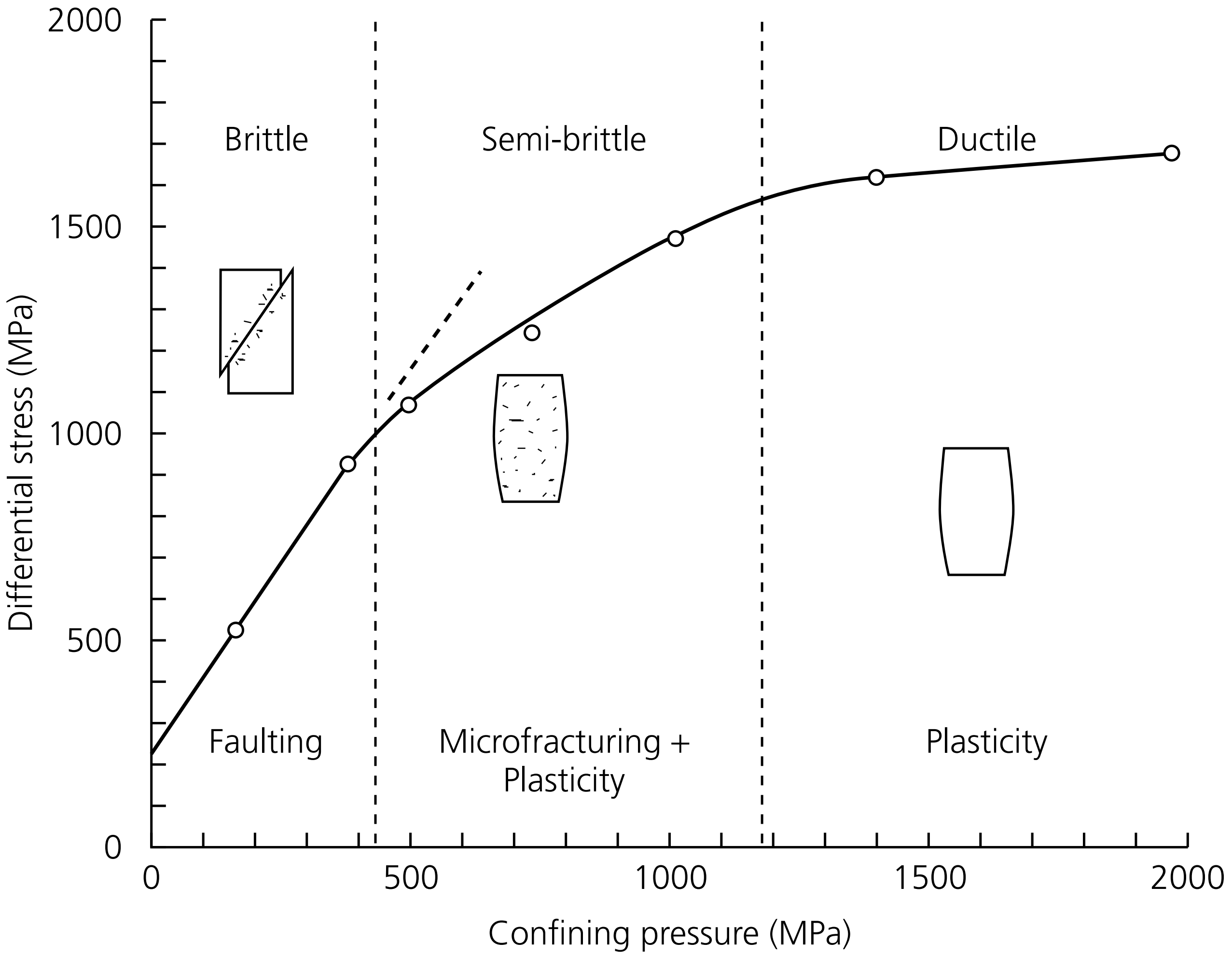
- Continuing an experiment at low temperatures, the slope of the stress-strain graph of many materials diminishes but remains positive beyond the yield point. An ever increasing (but slower than in the elastic domain) stress is required for deformation to increase from the yield point onward. The material exhibits essentially ductile behavior while undergoing irrecoverable deformation. This effect is **strain hardening**.
- Strain hardening reflects **intracrystalline deformation**. Deformation displaces atoms of the crystal lattice with the introduction of dislocations, which in turn create local elastic strain. The movement of these dislocations (dislocation glide) results in permanent deformation. The dislocation density increases, hence the elastic energy in the crystal lattice increases during hardening, which explains why the material becomes stronger. Inversely, strain hardening can be suppressed by prolonged but moderate heating (recovery) or by intense heating that induces total recrystallization of the material (annealing).

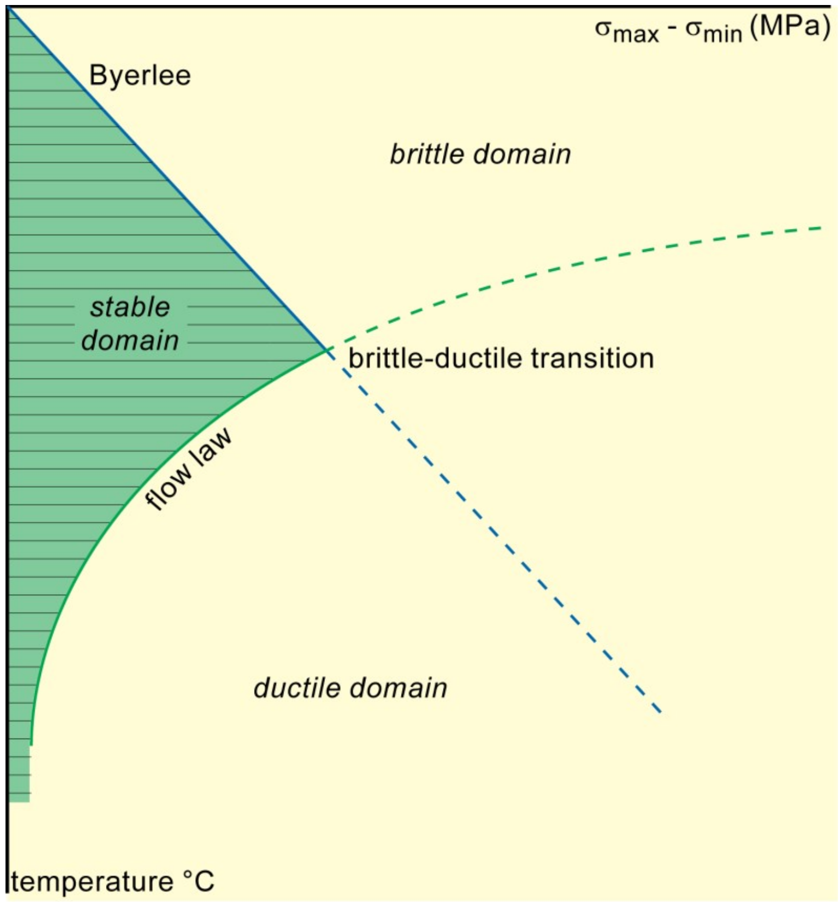
Ductile behaviour

- The term **ductility** is used in geology to indicate the capacity (% of strain) of rock to undergo permanent deformation without the development of macroscopic fractures. The term does not refer to the microscopic deformation mechanisms:
  - **Ductile flow** commonly involves deformation of individual grains by several solid-state deformation mechanisms such as crystallographic slip, twinning, or other processes in which atomic diffusion plays a part.
  - **Diffusion flow** refers to the transport of material from one site to another. The three diffusion processes are: volume diffusion, grain-boundary diffusion, and pressure solution. A set of conditions (relative heat, pressure, time, fluids, etc.) must be met before the rock deforms.
  - **Granular flow** applies to the pervasive microcracking permitting movement of microfragments and grains, which is often compared to the flow of dry sand. Grain boundary sliding plays a major role. The mechanism under high confining pressure is sometimes called superplastic flow to account for friction on the moving particle (grain) boundaries.

- The ductile behavior is dominantly **temperature-dependent** and prevails in the deeper crustal and lithospheric levels or regions with a high thermal gradient. The stress magnitude, strain-rate and the mineral composition of the rock medium are other important controlling parameters.

Brittle-ductile transition





Elementary construction of a rheological profile

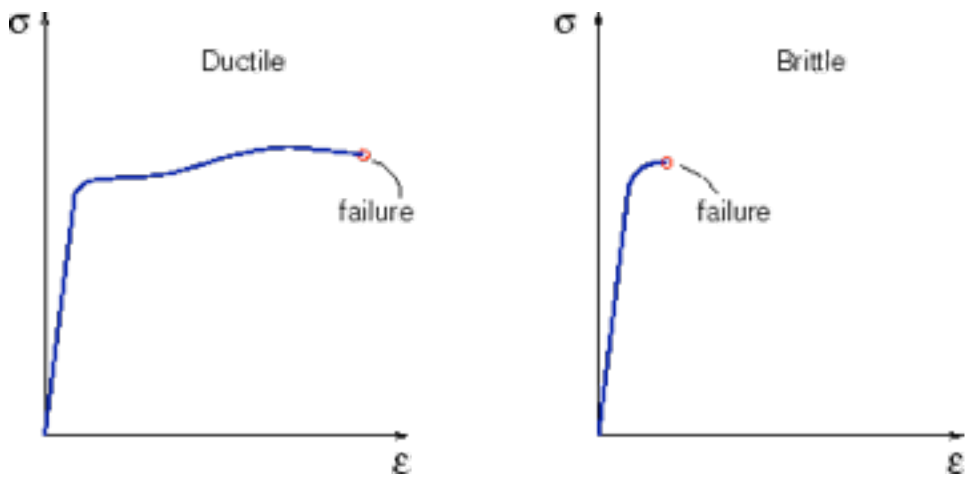
The effect of increased confining pressure is to inhibit fracturing and cracking: as the confining pressure is increased the behavior of rocks passes through a transition from brittle to ductile behavior for each particular type of rock.

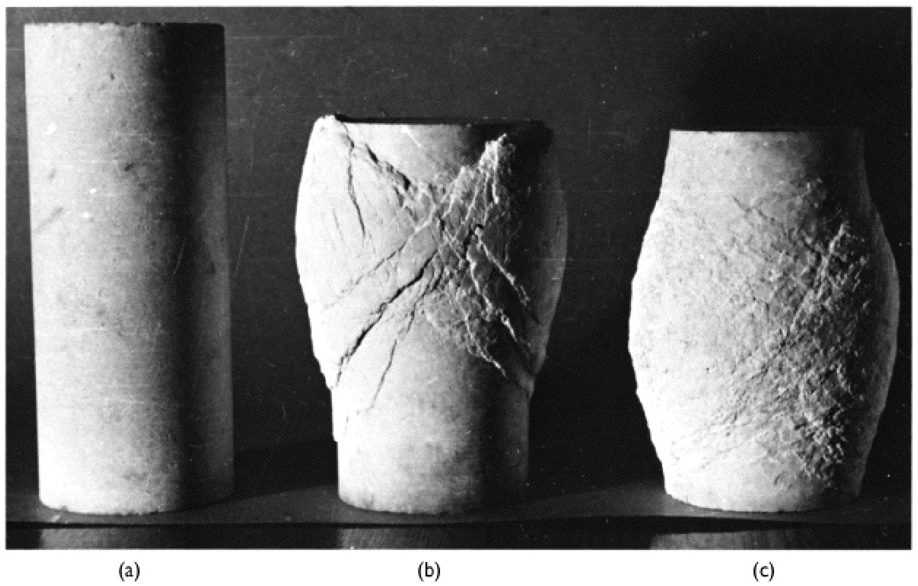
This brittle-ductile transition is generally placed at the lower limit of most crustal seismicity. This transition is not sharp, nor is it a consistent depth or temperature. It is a function of hydrostatic pressure, temperature, and strain-rate as well. In general, the lower the temperature and hydrostatic pressure, and the higher the strain-rate, the more likely is a rock to behave in a brittle manner.

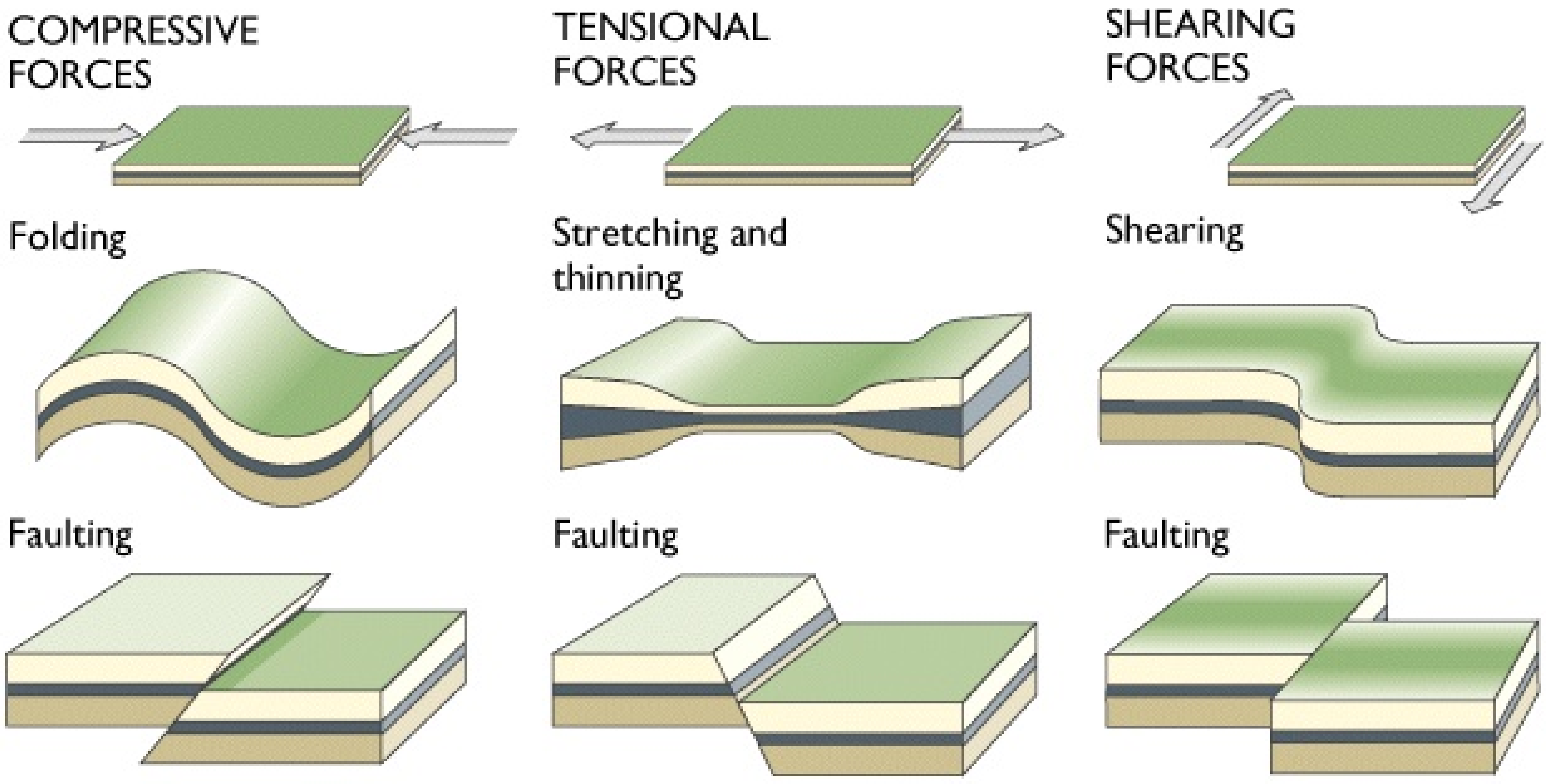
In reality, there is a broad transition between brittle and ductile behaviors, where “semi-brittle” or “semi-ductile” deformation involves a mixture of frictional sliding and ductile flow on the microscale.

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

Brittle & Ductile



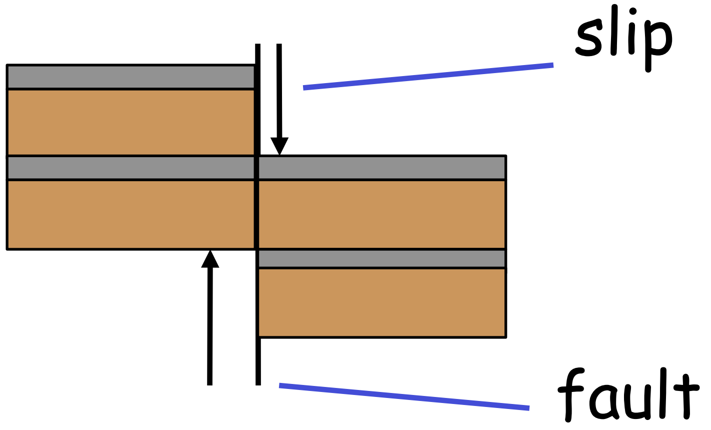




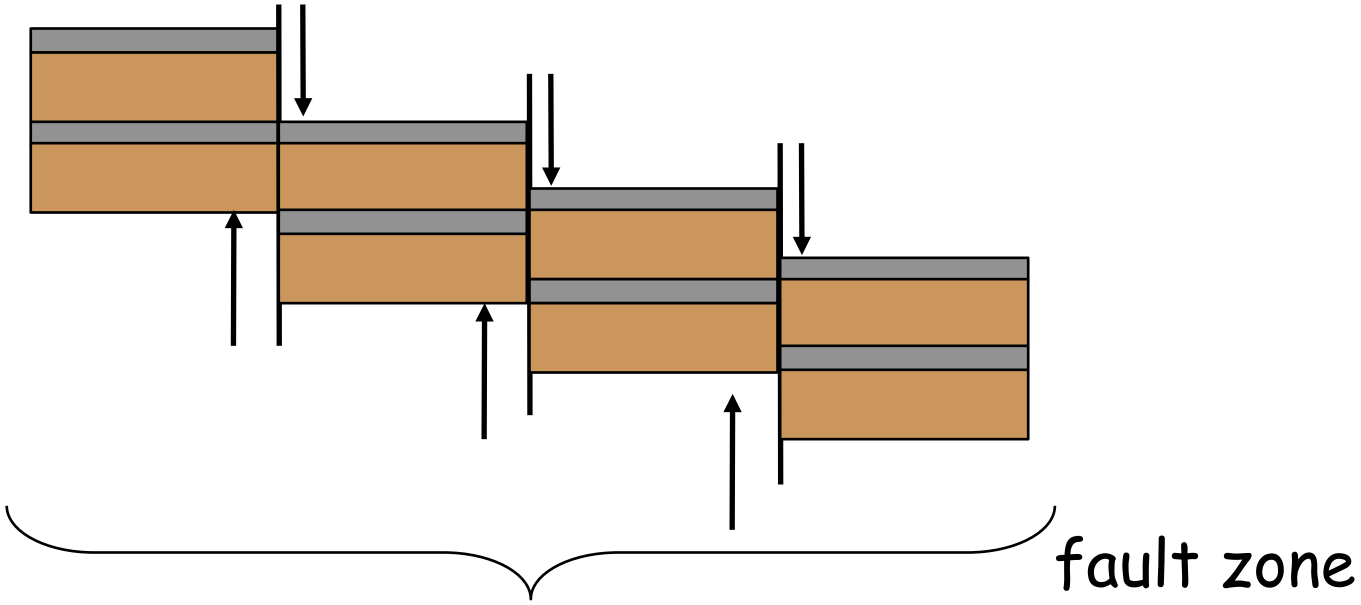
Faults

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

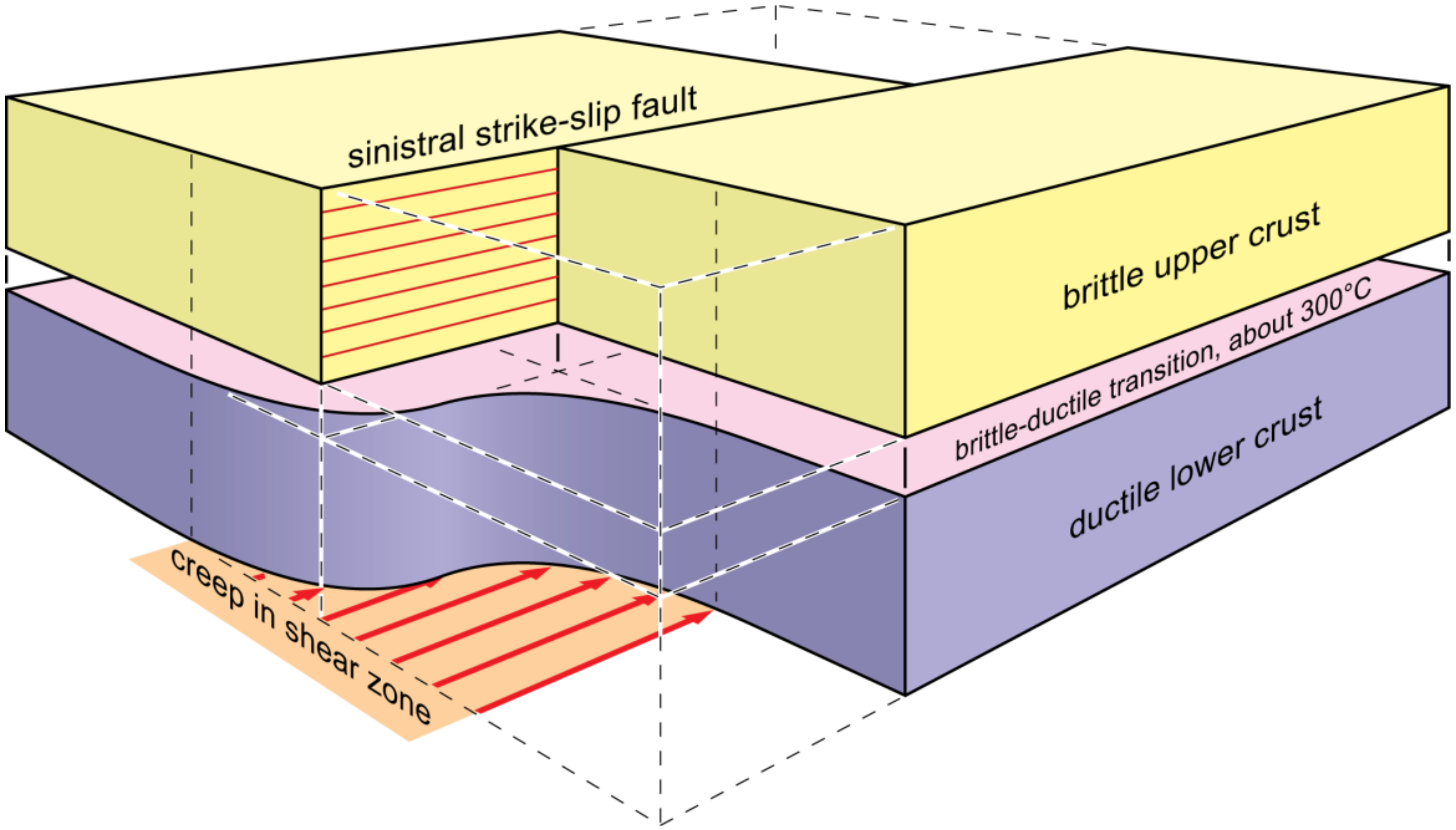


Fault zones: brittle structures where loss of cohesion and slip occur on several faults within a band of definable width



Creep

Fault creep is very slow slip, at typical average rates of a few cm/yr, without perceptible earthquake. This steady, aseismic displacement probably takes place under near-constant shear stress within ductile shear zones and faults lubricated by clay minerals.



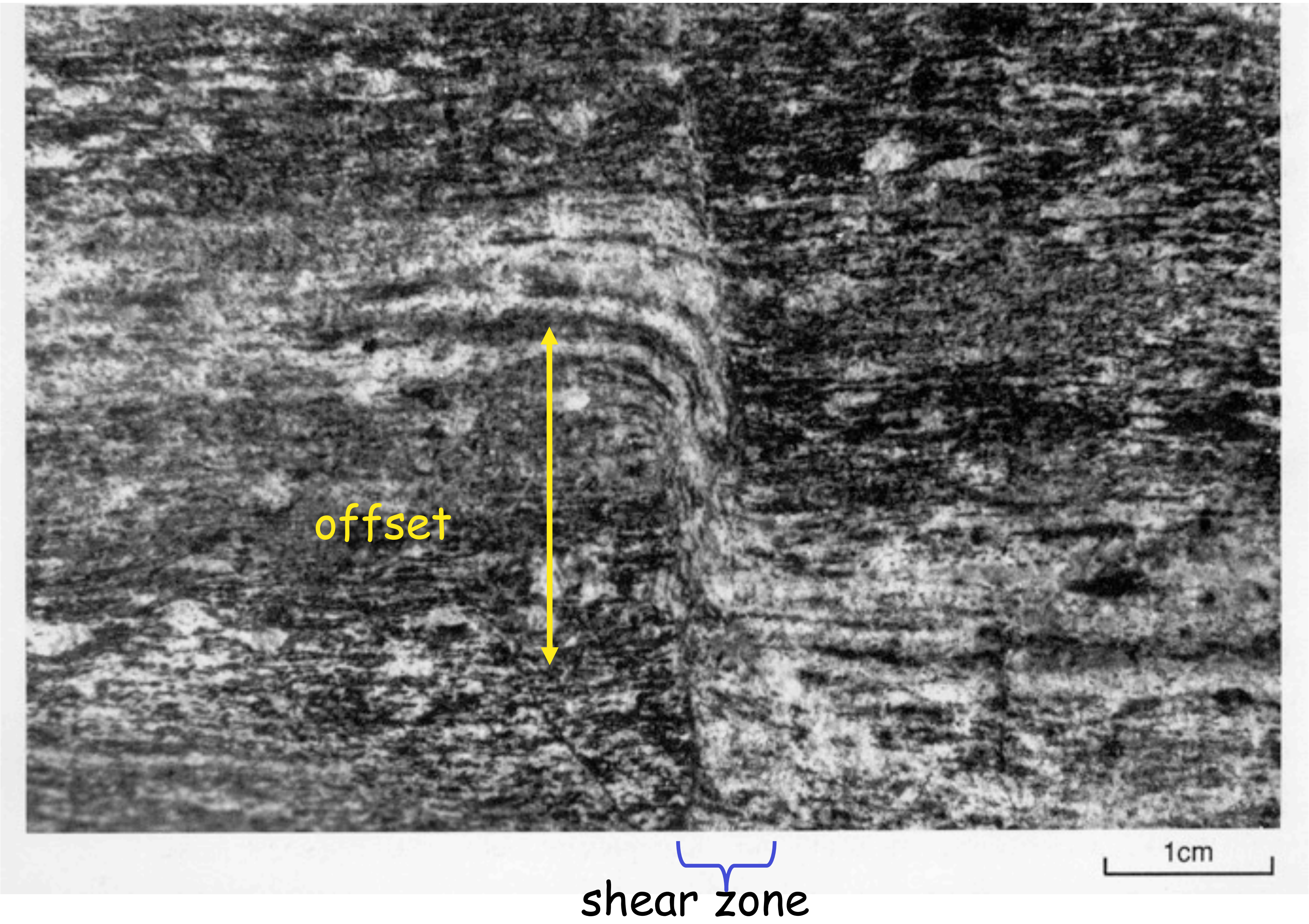
The observation that slip on natural faults can occur with or without generating detectable seismic waves is paralleled by the laboratory observation that frictional sliding between rock surfaces can occur with or without detectable and sharp stress drops. **Stable sliding** occurs at a constant velocity without jerks and stress drops. **Unstable sliding**, also called **stick-slip**, repetitively occurs with prominent jumps corresponding to episodic stress drops.

http://www.files.ethz.ch/structuralgeology/JPB/index.html

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;



Type of experiments...

axial compression:

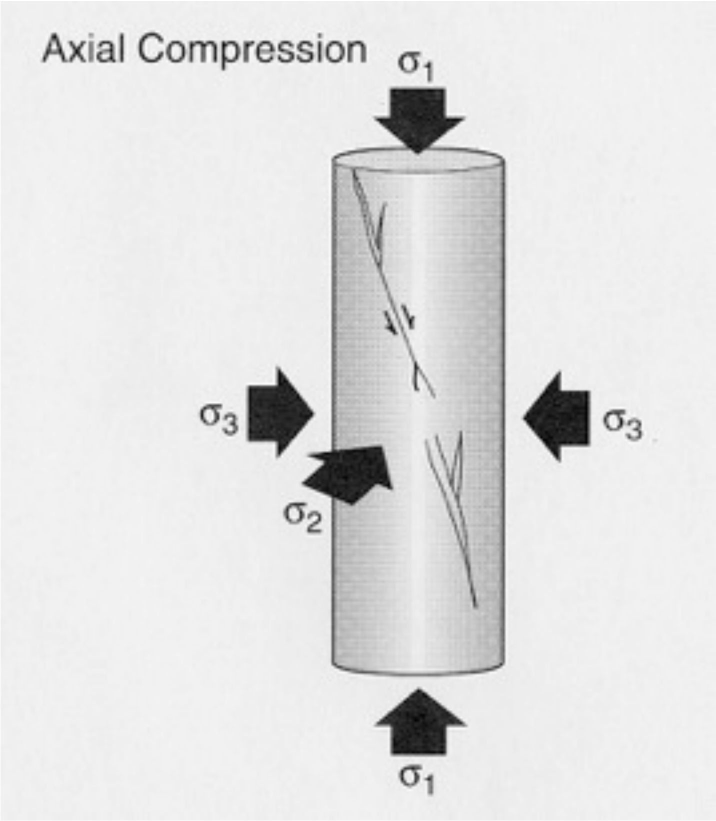
vertical axial compressive stress > confining pressure

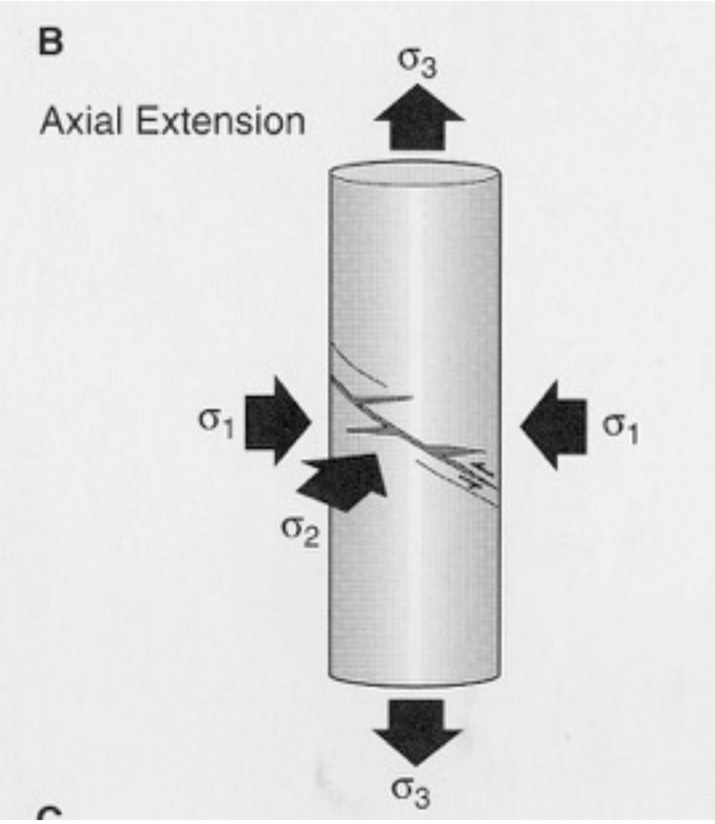
axial extension:

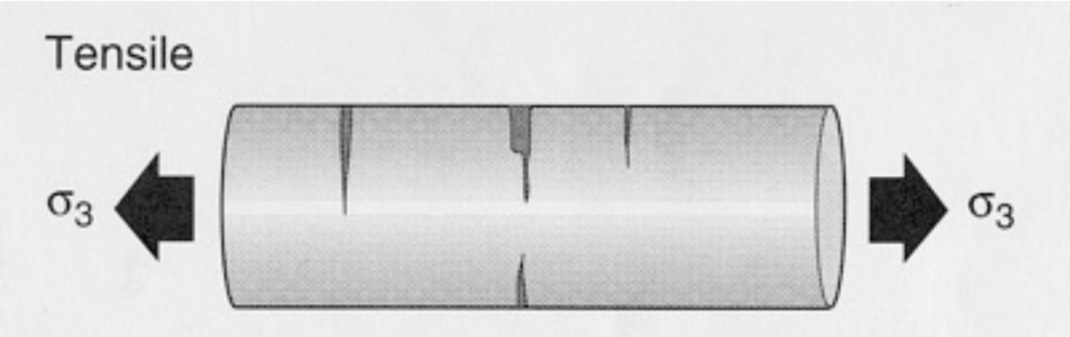
confining pressure > vertical axial compressive stress

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

Brittle deformation processes

1) **tensile cracking**:
opening and propagation of cracks into unfractured material

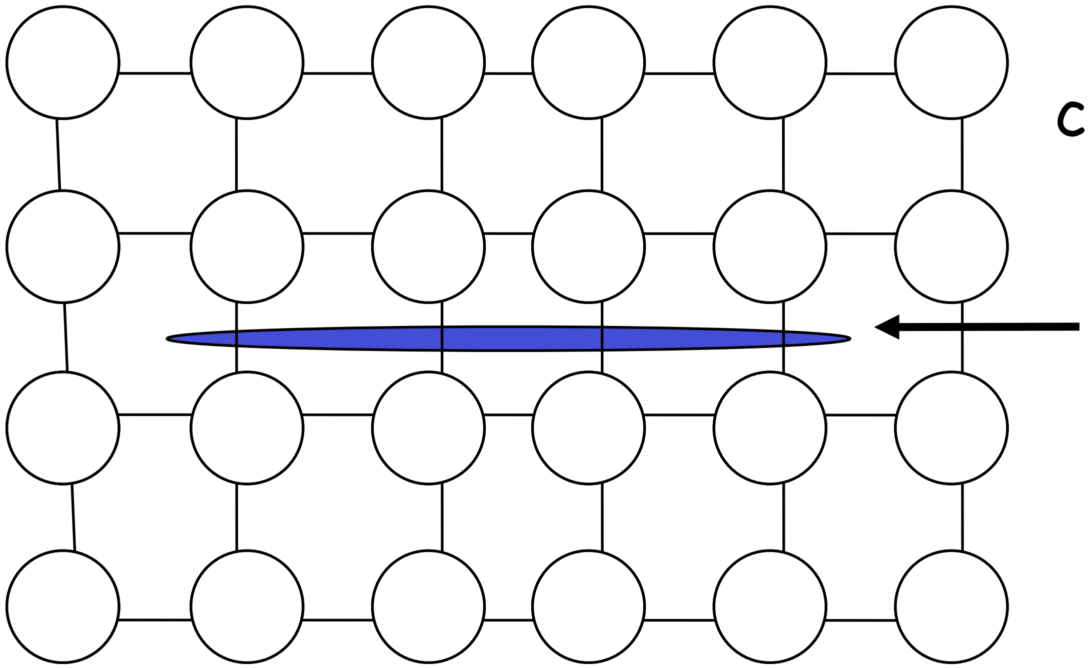
2) **shear rupture**:
initiation of macroscopic shear fracture

3) **frictional sliding**:
sliding on preexisting fracture

4) **cataclastic flow**:
macroscopic ductile flow from grain-scale fracturing and frictional sliding

1) Tensile cracking

cracks on atomic scale:



crystal lattice (atoms and bonds)

crack

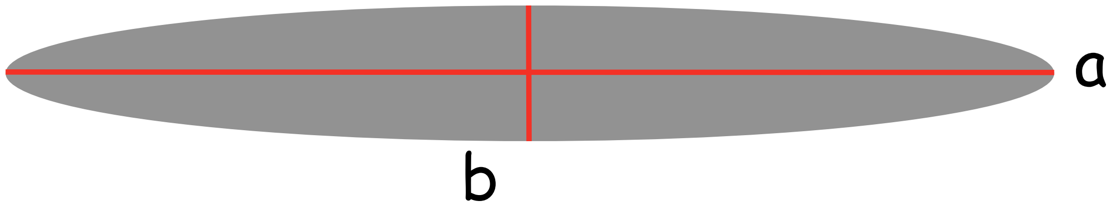
one model is for crack surface to break at once…
tensile stress necessary is equal to strength of each chemical bond
multiplied by number of bonds

this theoretical strength is ~500 to 5000 MPa
….very large number!…
measurement of rock strength in Earth's crust suggests
tensile cracking occurs at about 10 MPa or less

this is known as the strength paradox

engineers realized far-field stress
(stress applied at a distance from area of interest)
is concentrated at sides of flaws (holes) in an
elastic (recoverable) medium

concentration along an ellipse-shaped flaw is
(2a + 1)/b with a as long axis and b as short axis of ellipse

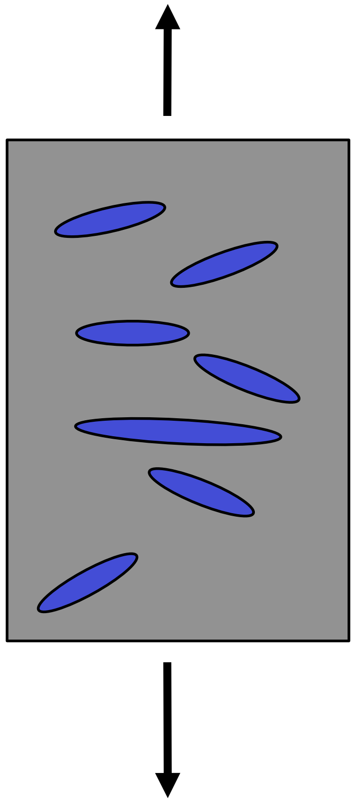


stress concentration at ends of elliptical hole depend on axial ratio:
axial ratio of 8:1--concentration factor of 17
axial ratio of 32:1--concentration factor of 65

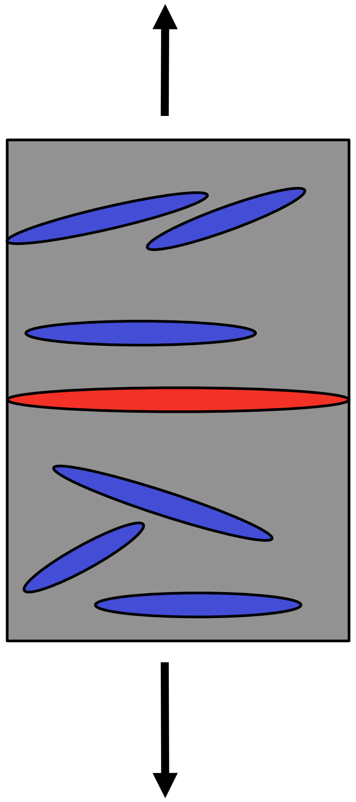
Griffith Crack Theory

Griffith crack theory and linear elastic fracture mechanics
imply cracks do not form instantaneously….
begin at small flaw and grow outward
not all bonds break at once → theoretical strength is not reality

what happens during tensile cracking?
…look at laboratory experiments
rock cylinders stretched along axis



opening of
microcracks



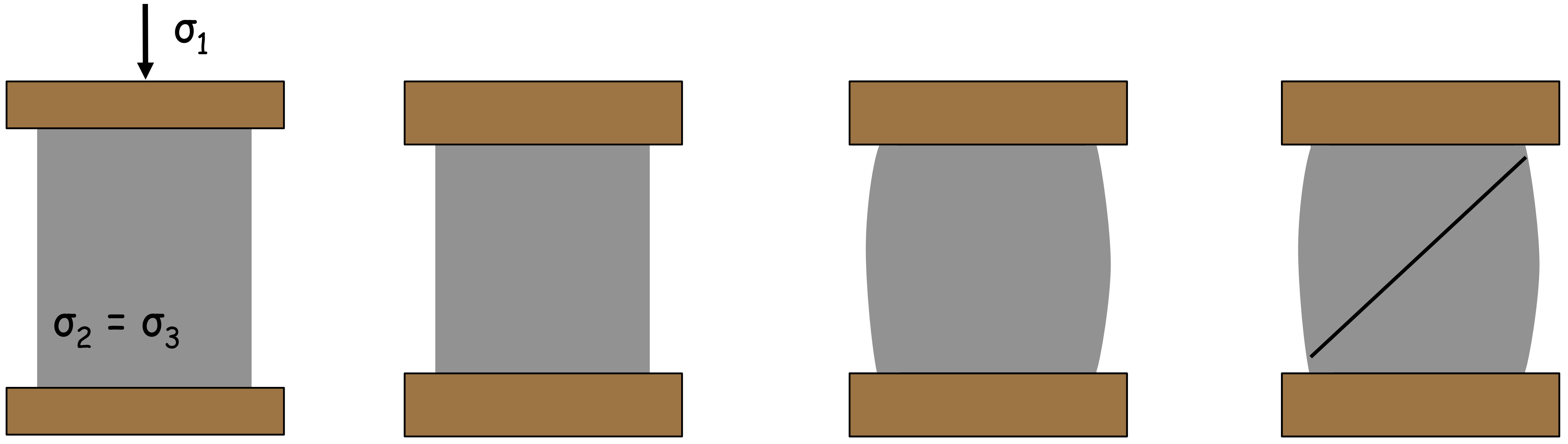
largest crack forms
throughgoing crack
(when crack reaches
edges of sample, the
sample separates into
two pieces)

2) 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



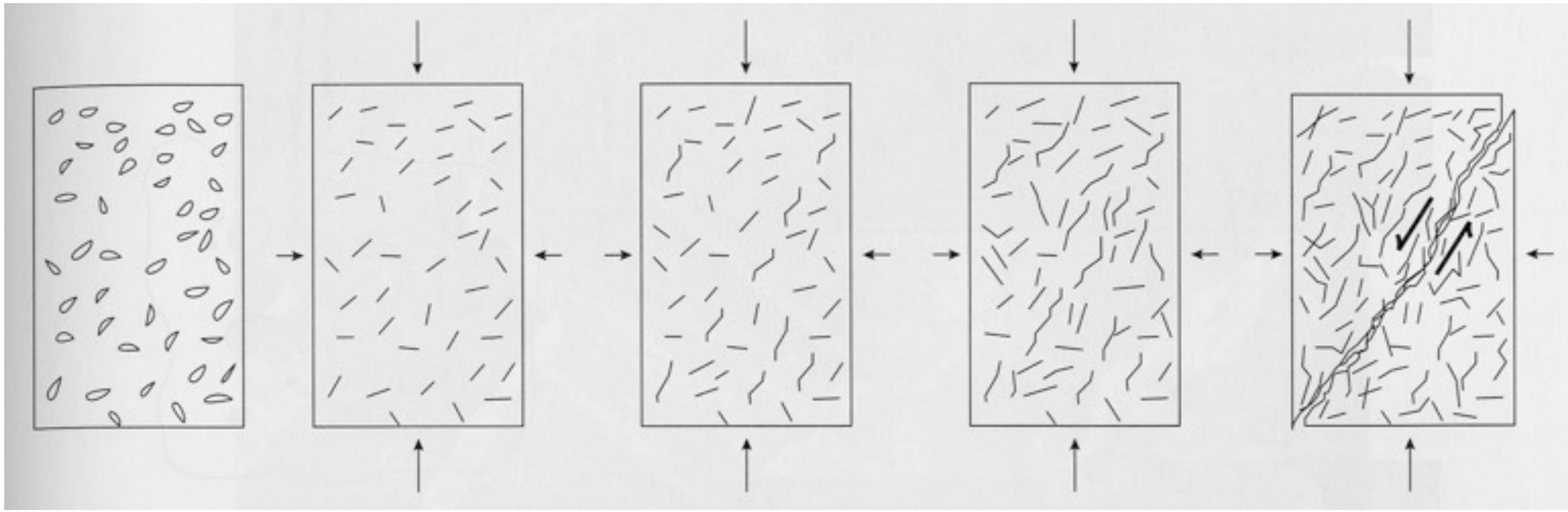
laboratory triaxial-loading

volume decreases

volume increases (dilatancy-cracking)

cracks coalesce to form fault (failure)

what happened in the rock cylinder during experiment?



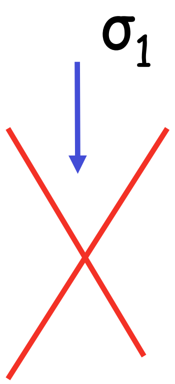
cracks form

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

Stress recap

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

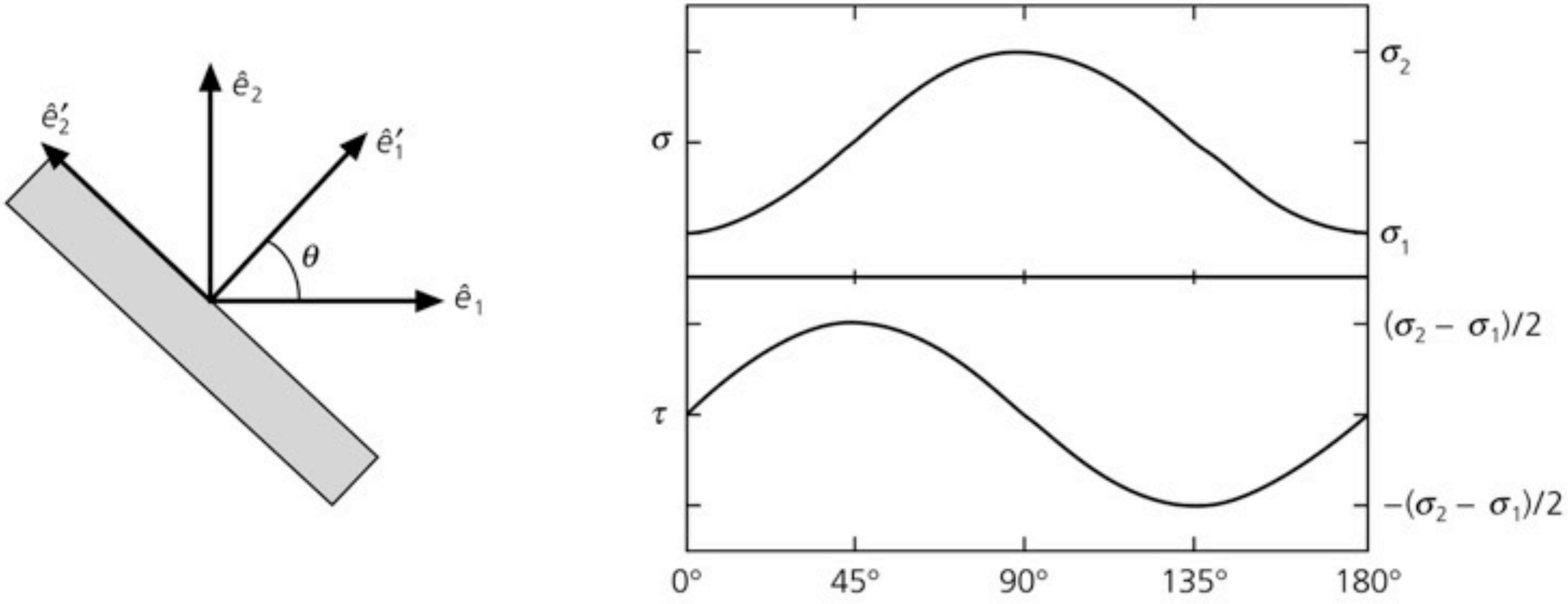
$$\sigma_{ij} = \begin{pmatrix} \sigma_1 & 0 \\ 0 & \sigma_2 \end{pmatrix}$$

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 recap - 2

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



Normal stress:

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

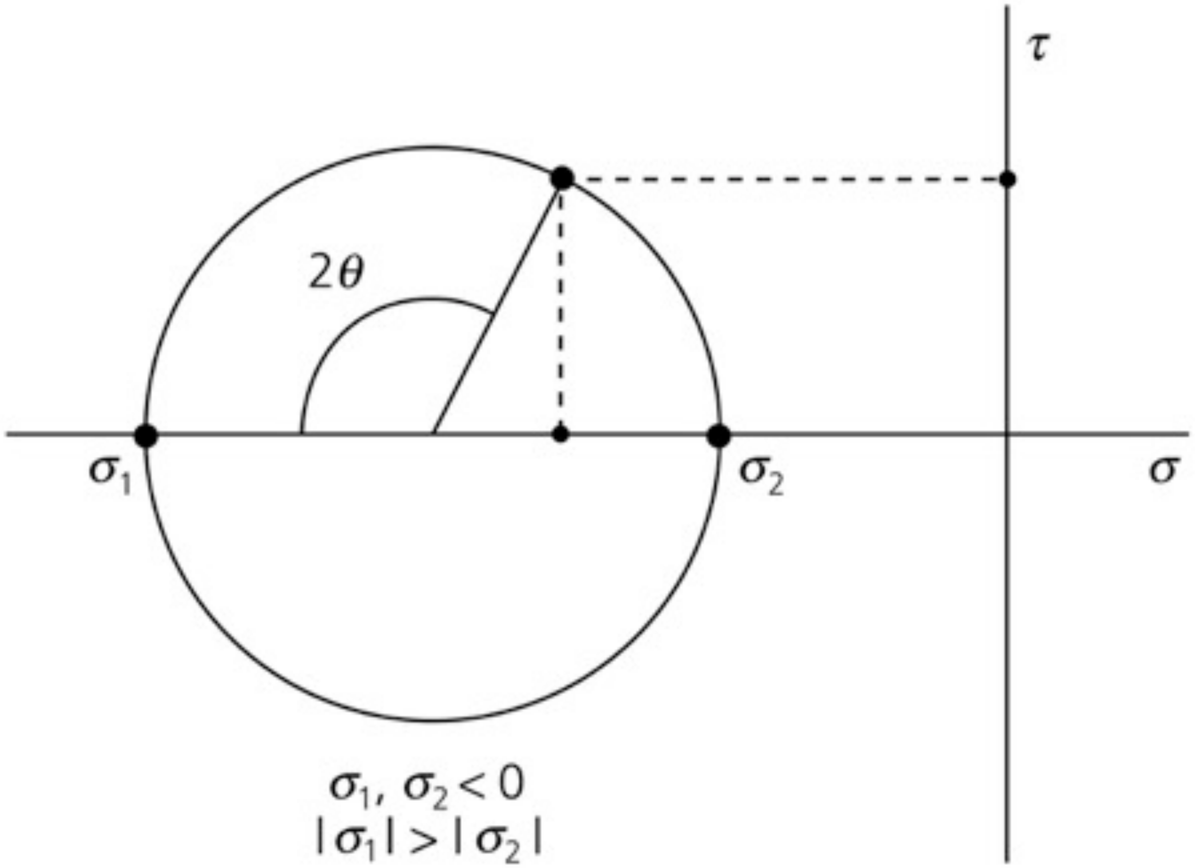
Shear stress:

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

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:

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

Shear stress:

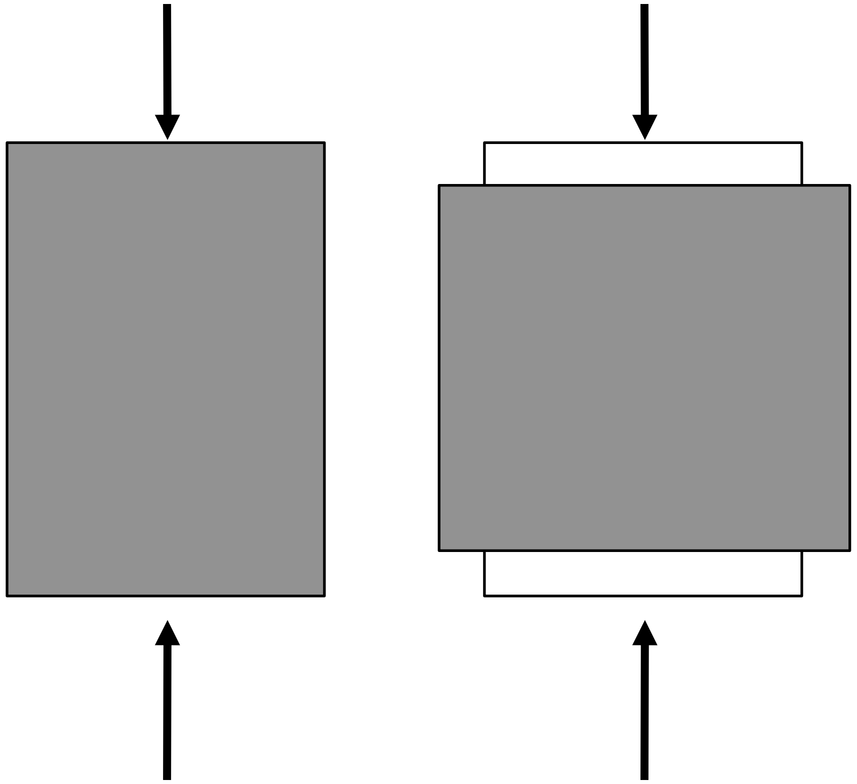
$$\tau = \sigma'_{12} = (\sigma_2 - \sigma_1)\sin\theta\cos\theta = \frac{(\sigma_2 - \sigma_1)}{2}\sin 2\theta.$$

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.

2) Shear fracture - reprise

let us return to rock cylinder laboratory experiments…

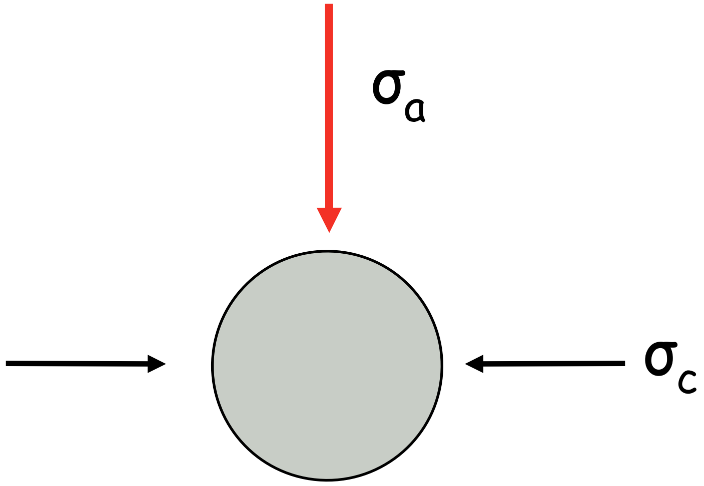
- piece of rock cut into cylinder with length 2-4 times diameter;
- sample placed between two steel pistons which are forced together;
- applied stress changes length, diameter, volume of sample, which are measured by strain gauges attached to sample



at first, when stress is removed, sample returns to original shape: recoverable

characteristic of elastic deformation (rubber band) but, if enough stress is applied, sample fractures (breaks)

…conduct triaxial loading experiments to determine applied stress at which sample breaks



σ_a= axial stress, σ_1

σ_c= confining stress, σ_3

first experiment… set confining pressure low and increase axial load (stress) until sample breaks

second experiment… set confining pressure higher and increase axial load (stress) until new sample breaks

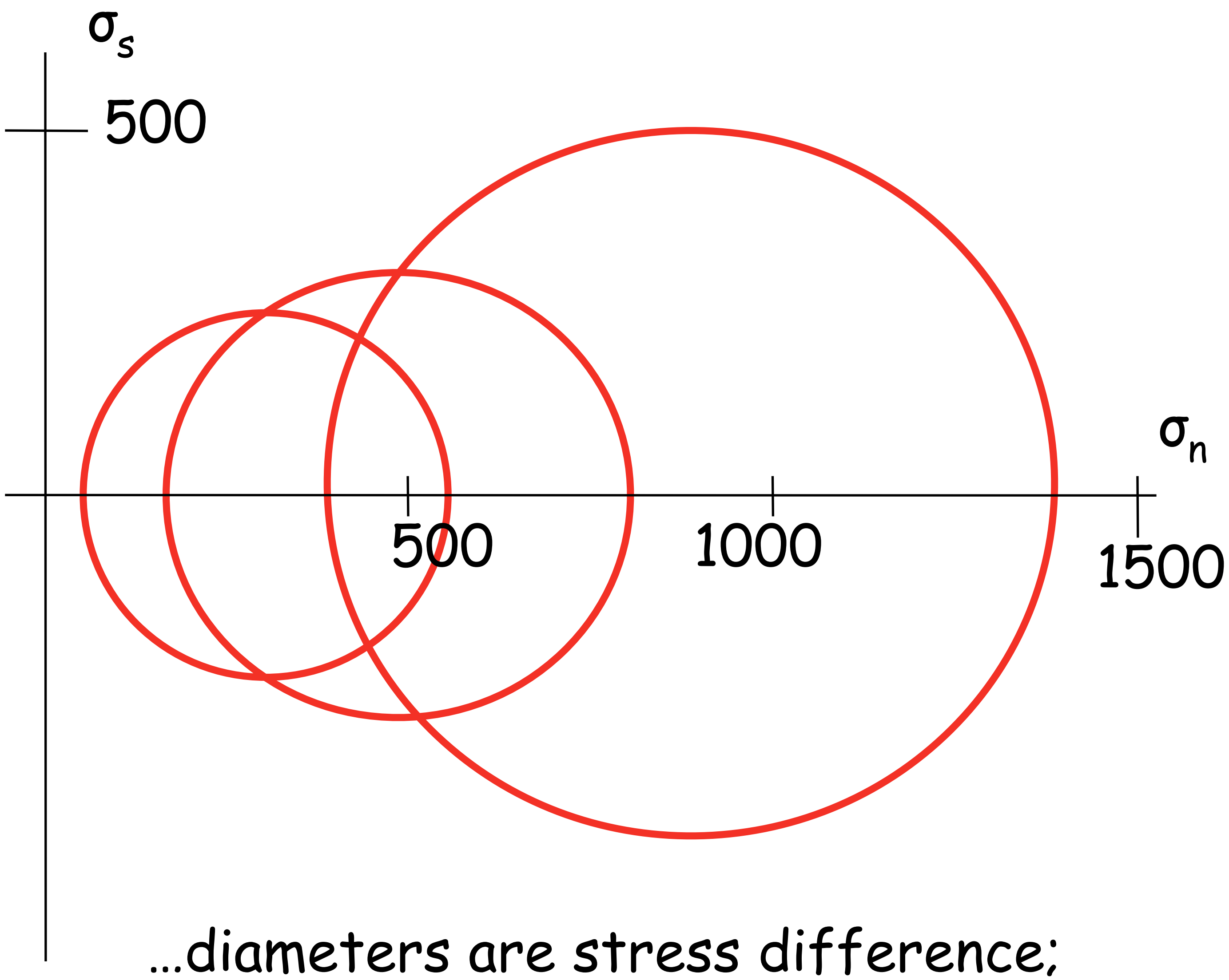
keep repeating experiments…

you will generate a series of pairs of confining stresses and associated axial stresses at which samples break...

σ_c	σ_a	$\sigma_a - \sigma_c$
40	540	500 MPa
150	800	650 MPa
400	1400	1000 MPa

we use these as σ_1 and σ_3 and plot Mohr circles...

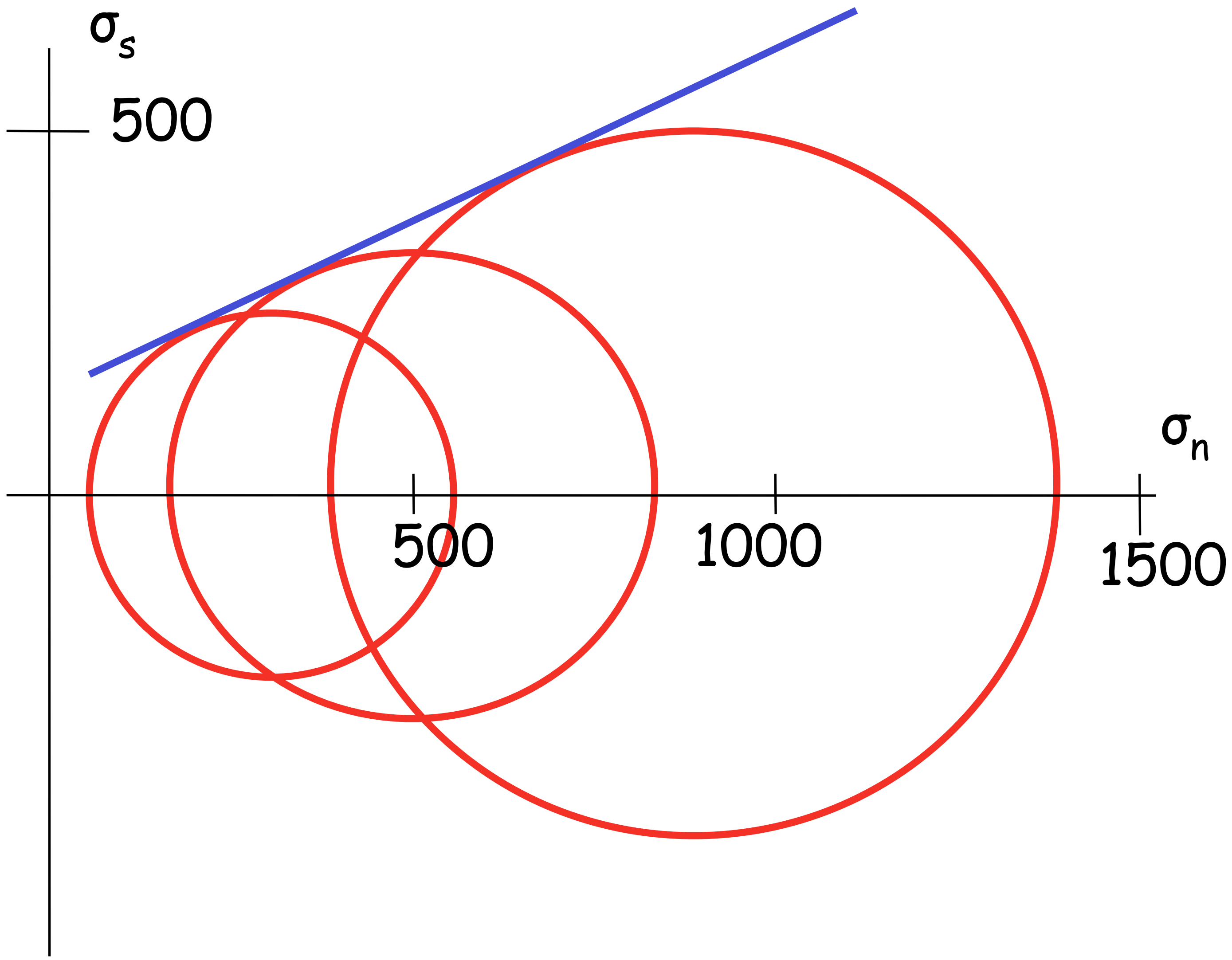
get a sequence of circles offset from one another



...diameters are stress difference;

...centers are stress sum/2

Failure envelope



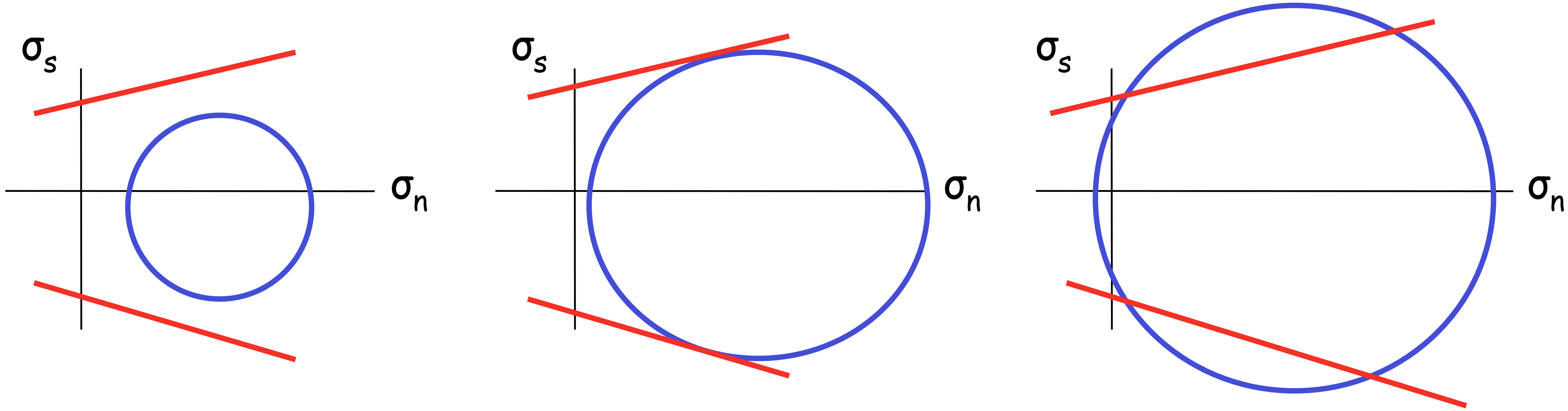
Mohr circles that define stress states where samples fracture (critical stress states) together define the failure envelope for a particular rock

failure envelope is tangent to circles of all critical stress states
and is a straight line…

can also draw failure envelope in negative quadrant for σ_s
(mirror image about σ_n axis)

plot of either Coulomb or Mohr-Coulomb criterion defines failure envelope on Mohr diagram

failure envelope separates fields of "stable" and "unstable" stress



no failure
(stable)

failure at two points
(brittle failure)

impossible
(unstable)

Mohr circle
inside envelope

Mohr circle
tangent to envelope

Mohr circle
outside envelope

Coulomb criterion

what does this straight line mean?

…corresponds to **Coulomb fracture criterion**

Charles Coulomb in 18th century proposed that formation of shear stress parallel to failure relates to normal stress by…

$$\sigma_s = C + \tan\varphi\,(\sigma_n) \quad \text{(empirical)}$$

σ_s = shear stress parallel to fracture at failure

C = cohesion of rock (constant)

σ_n = normal stress across shear zone at instant of failure

$\tan\varphi = \mu$ = coefficient of internal friction (constant of proportionality)

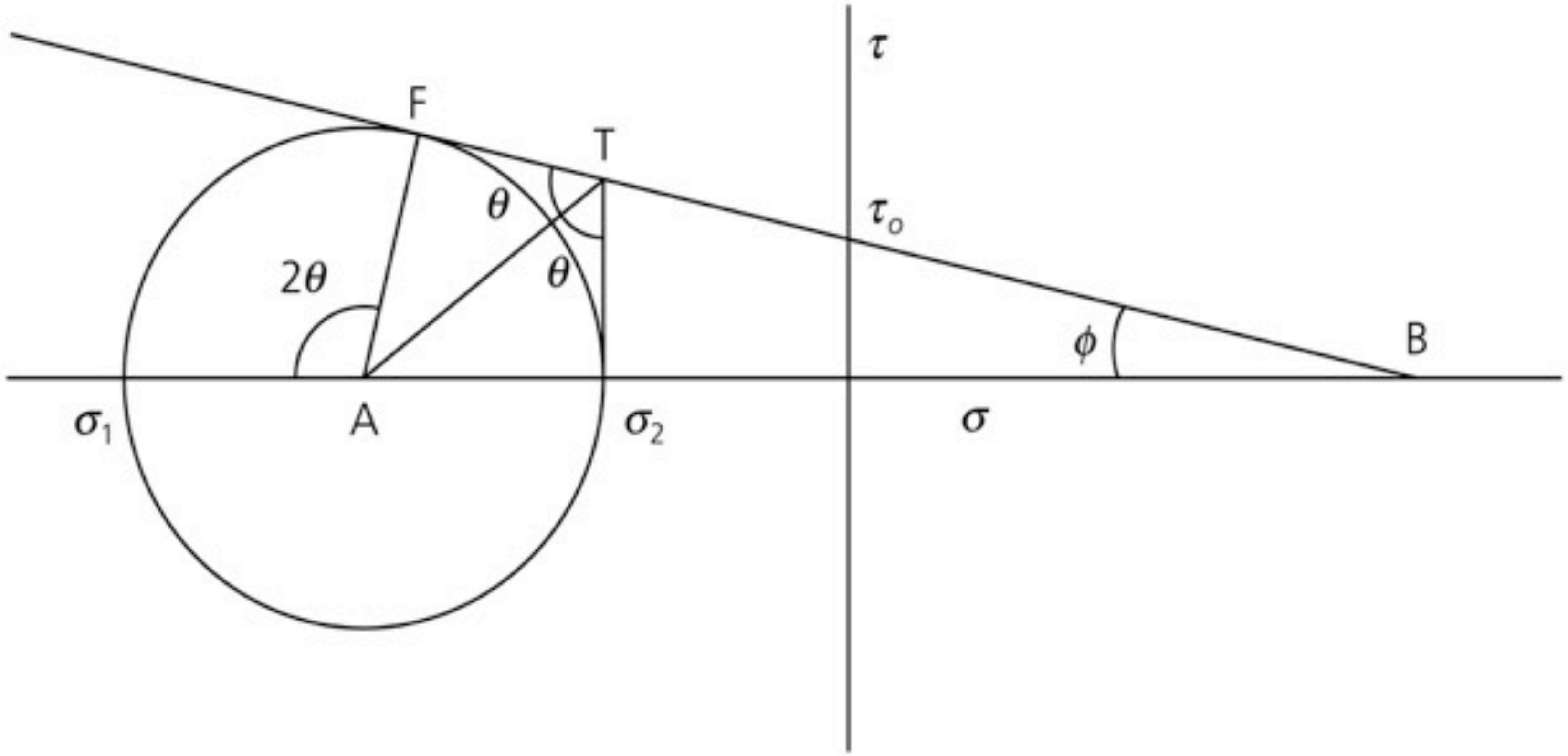
this has form of $y = mx + b$ (equation of a line)

$y = \sigma_s$ $x = \sigma_n$ b = intercept on σ_s axis m = slope = $\tan\varphi = \mu$

so Coulomb criterion plots as straight line on σ_n , σ_s plot

Coulomb criterion

Figure 5.7-7: Relation between cohesive stress, internal friction, and geometry of failure.



Laboratory experiments on rocks under compression show that fracture occurs when a critical combination of the absolute value of shear stress and the normal stress is exceeded.

Coulomb-Mohr failure criterion: $|\tau| = \tau_o - n\sigma$

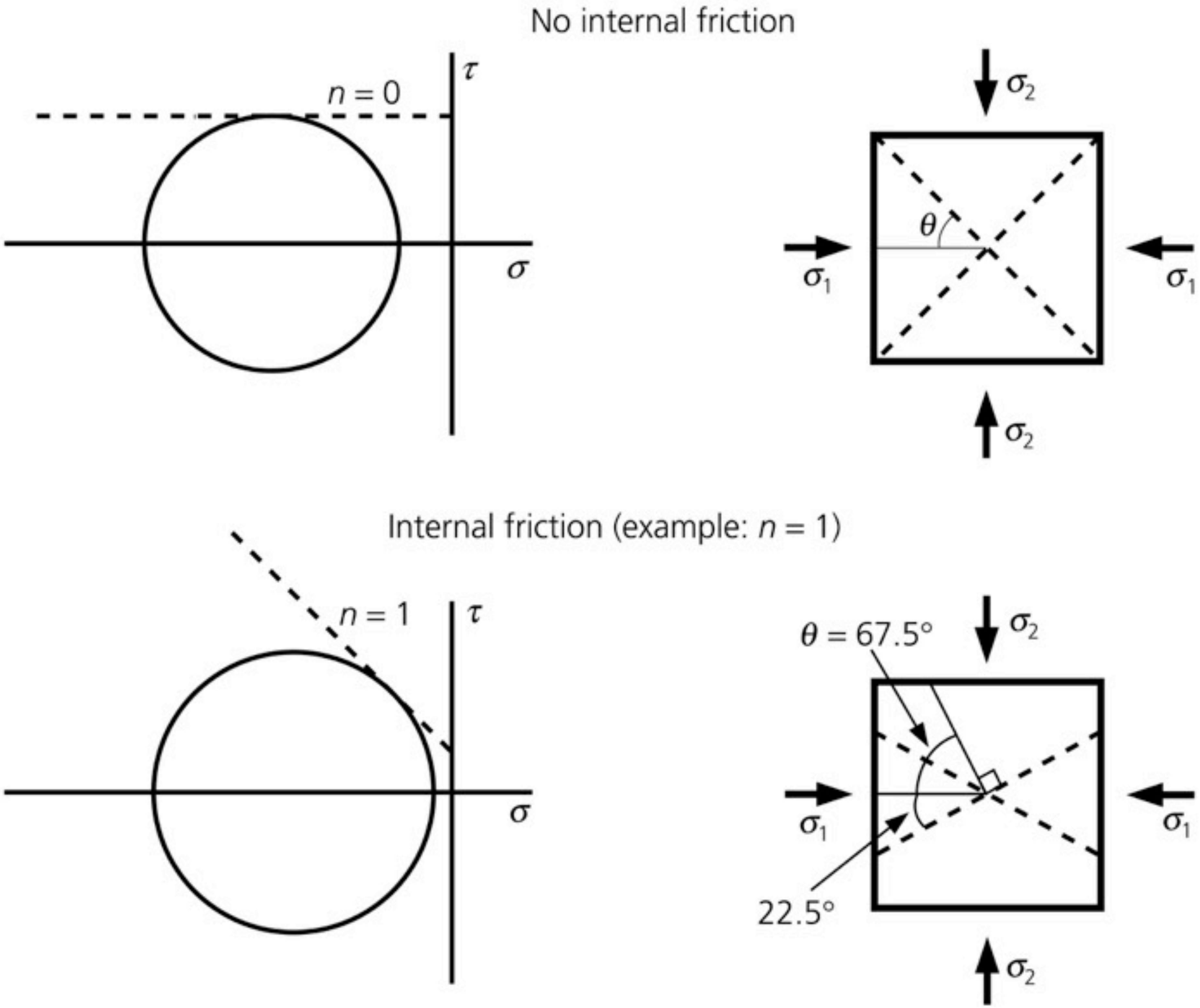
τ_o = cohesive strength; n = coefficient of internal friction

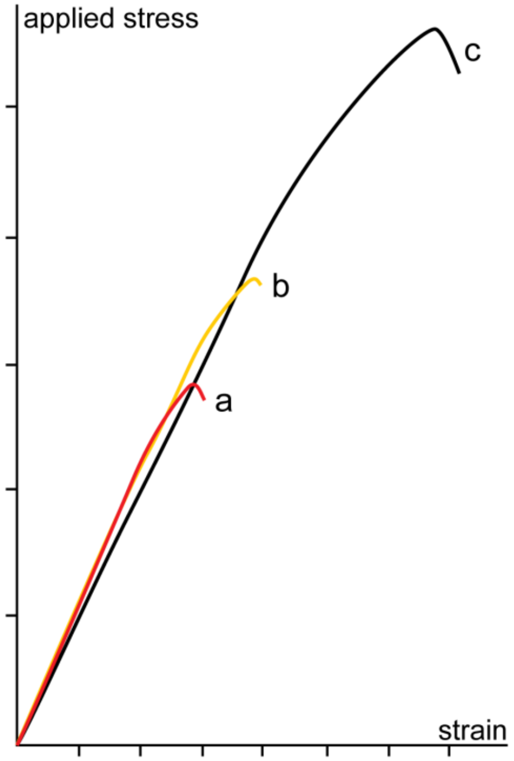
$|\tau| = \tau_o - \sigma \tan\phi$ where $n = \tan\phi$ and ϕ

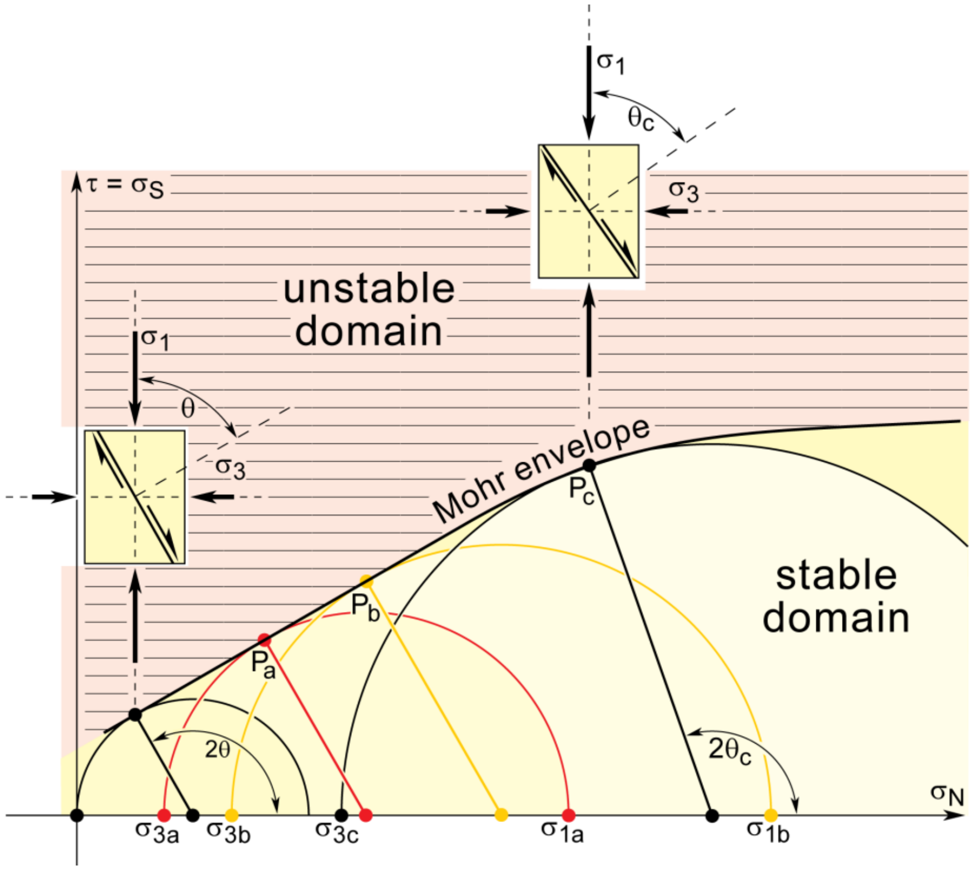
$\phi = 2\theta - 90^\circ$ so $\theta = \phi/2 + 45^\circ$

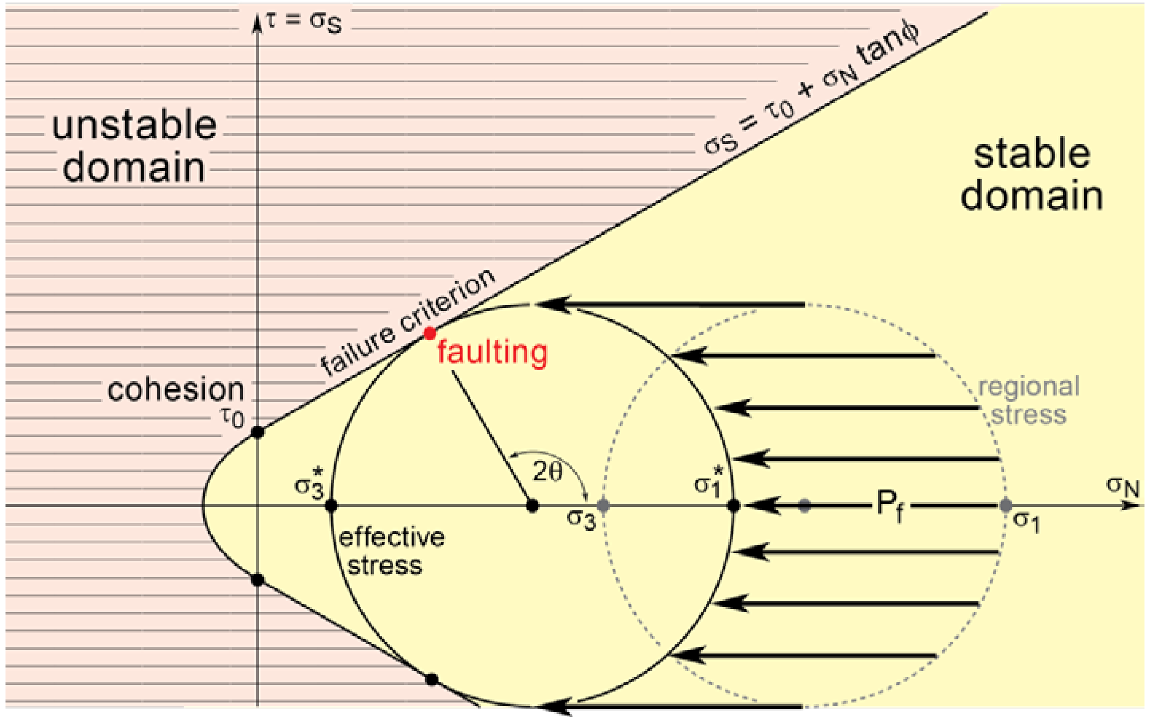
Internal friction

Figure 5.7-8: Failure with and without internal friction.

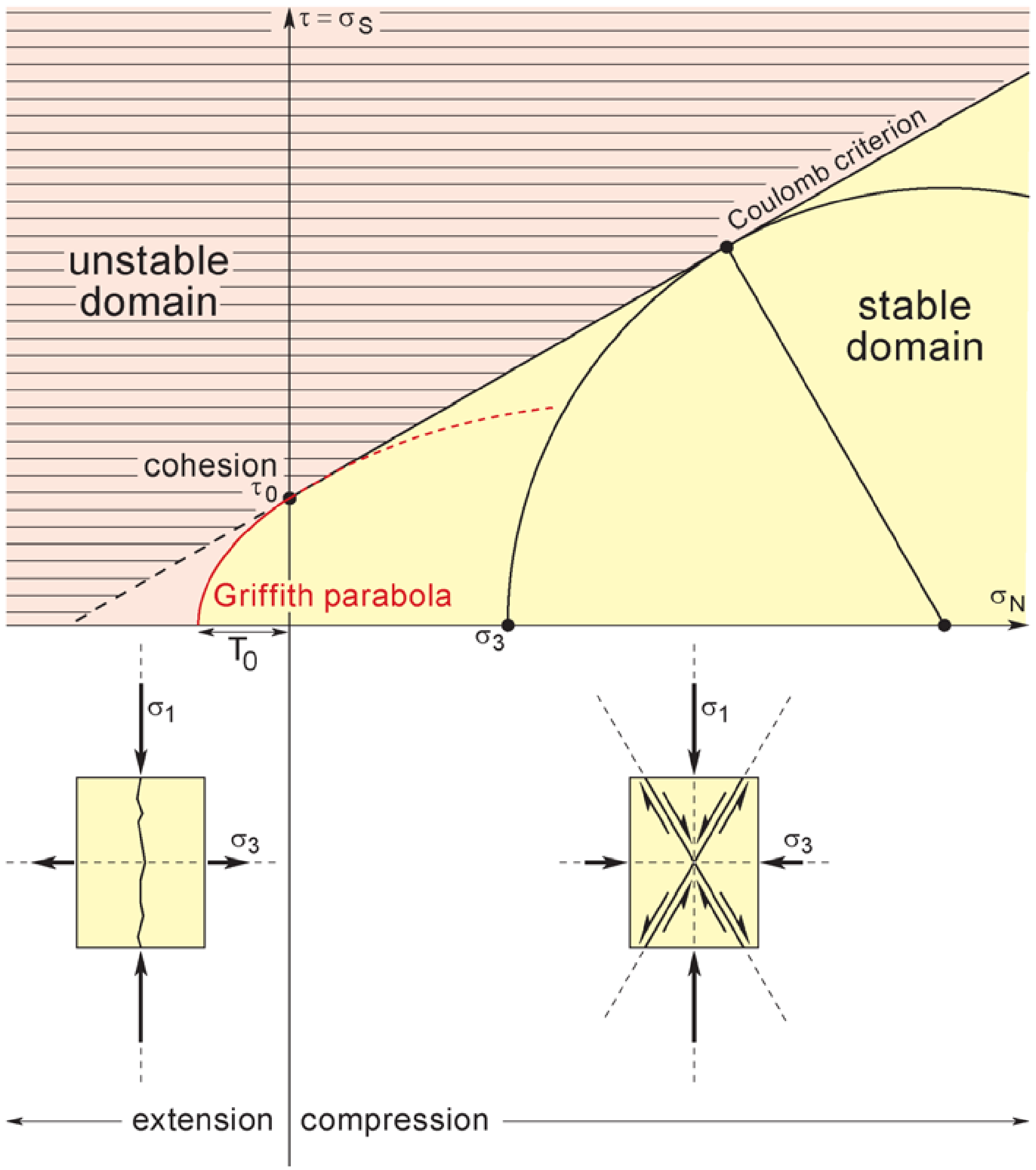








Effect of a pore pressure P_f represented in a Mohr diagram



Representation of the Griffith failure criterion

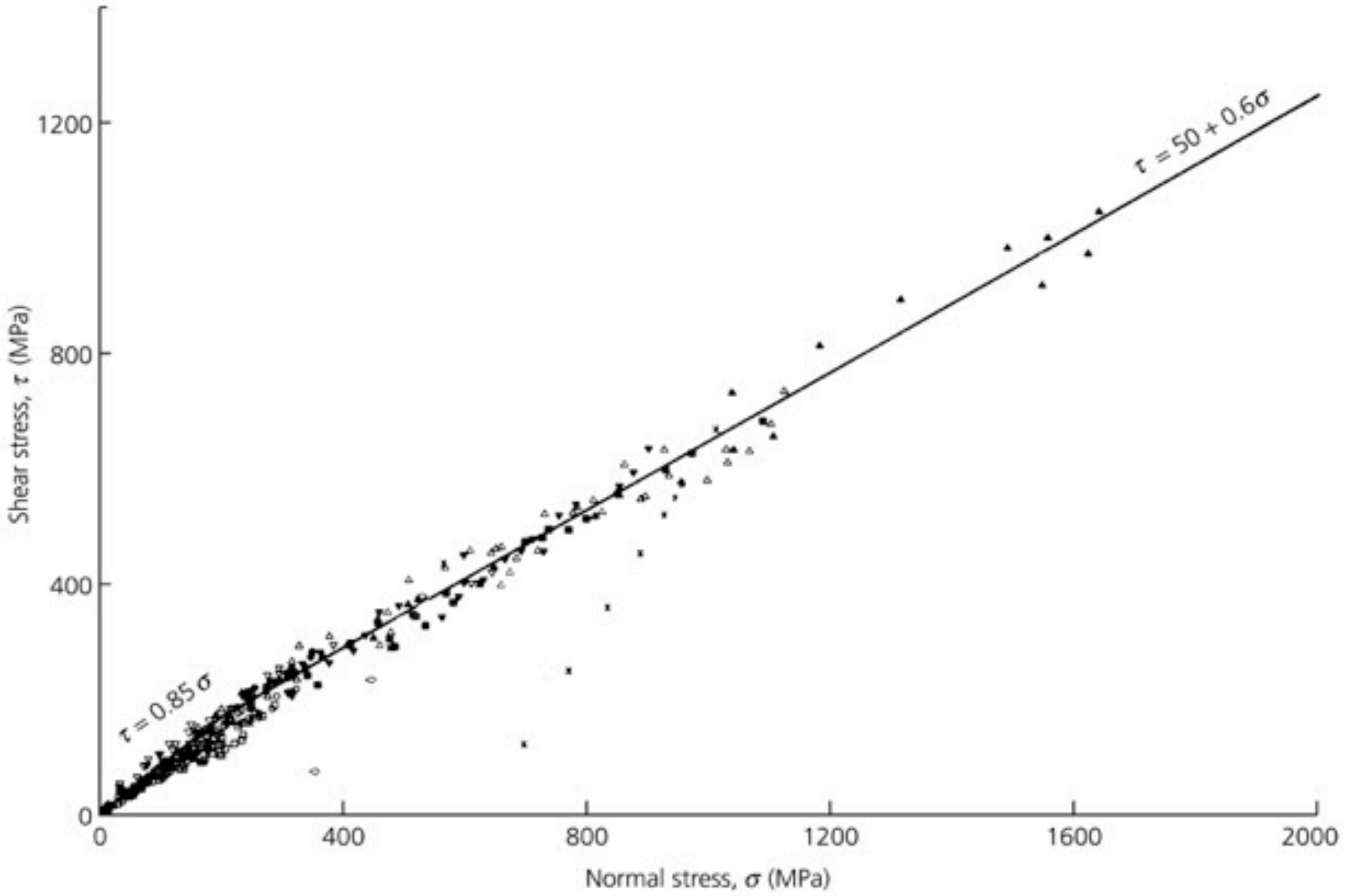
$$\sigma_S^2 = 4T_0\,(T_0 + \sigma_N)$$

with respect to the Coulomb criterion in the two-dimensional Mohr diagram

3) Frictional sliding

The coefficient of internal friction μ on existing fractures in consolidated rocks determines which shear stress is required to cause further movement on the fault planes. Friction requires certain critical shear stress to be reached before sliding initiates on preexisting fracture.

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



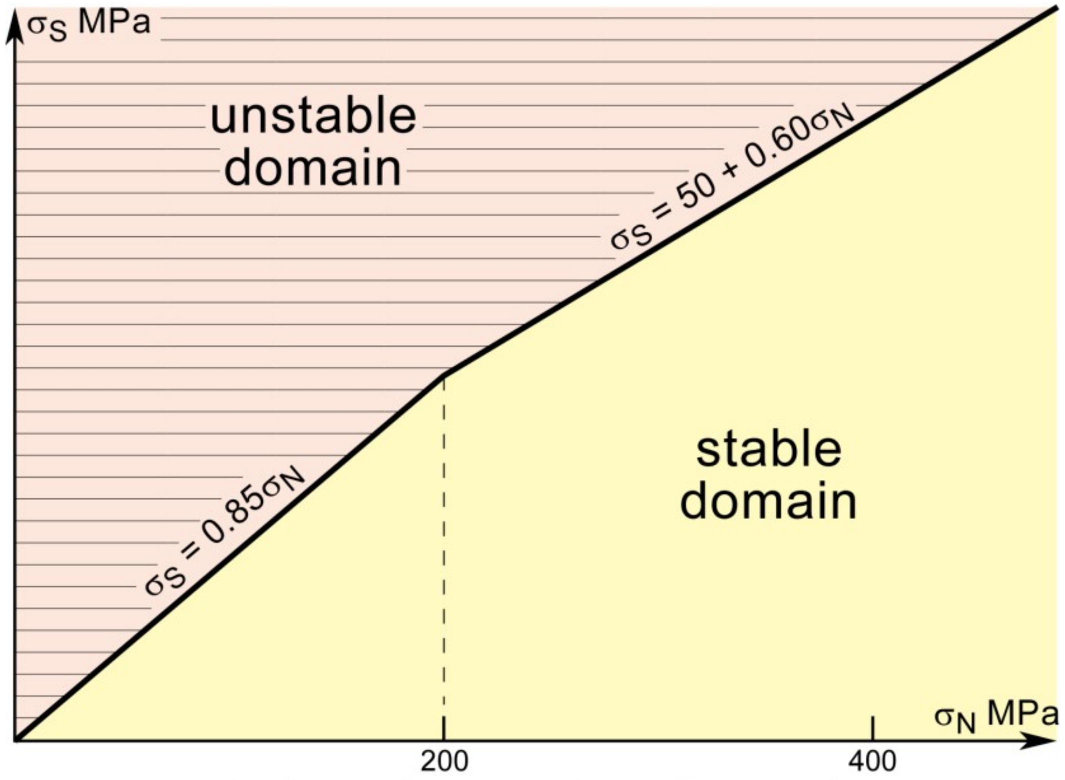
Lab experiments provide a linear relationship between the maximum shear and normal stress that rocks can withstand, called Byerlee's Law:

$$\tau \approx -.85\bar{\sigma} \qquad \bar{\sigma} < 200 \text{ MPa}$$
$$\tau \approx 50 - .6\bar{\sigma} \qquad \bar{\sigma} > 200 \text{ MPa.}$$

Failure criterion for frictional sliding

Byerlee's law

- The large scatter of data point under very low normal stress reflects surface roughness, the area of contact of the asperities, less influent under higher confining pressure because the latter prevents dilatancy of the shear fracture. Instead, shearing and smearing of asperities tends to stabilize frictional properties
- For confining pressures between 200 and 2000 MPa, the frictional strength of pre-cut rocks is better described by including a "cohesion-like" parameter.
- The Byerlee's law refers to equations (9) and (10), together. They are empirical and indicate that the shear stress required to activate frictional slip along a pre-existing fracture surface is largely insensitive to the composition of the rock. These laws seem to be valid for normal stresses up to 1500 MPa and temperatures < 400°C, which allows defining a lower boundary to stresses acting in the brittle lithosphere.

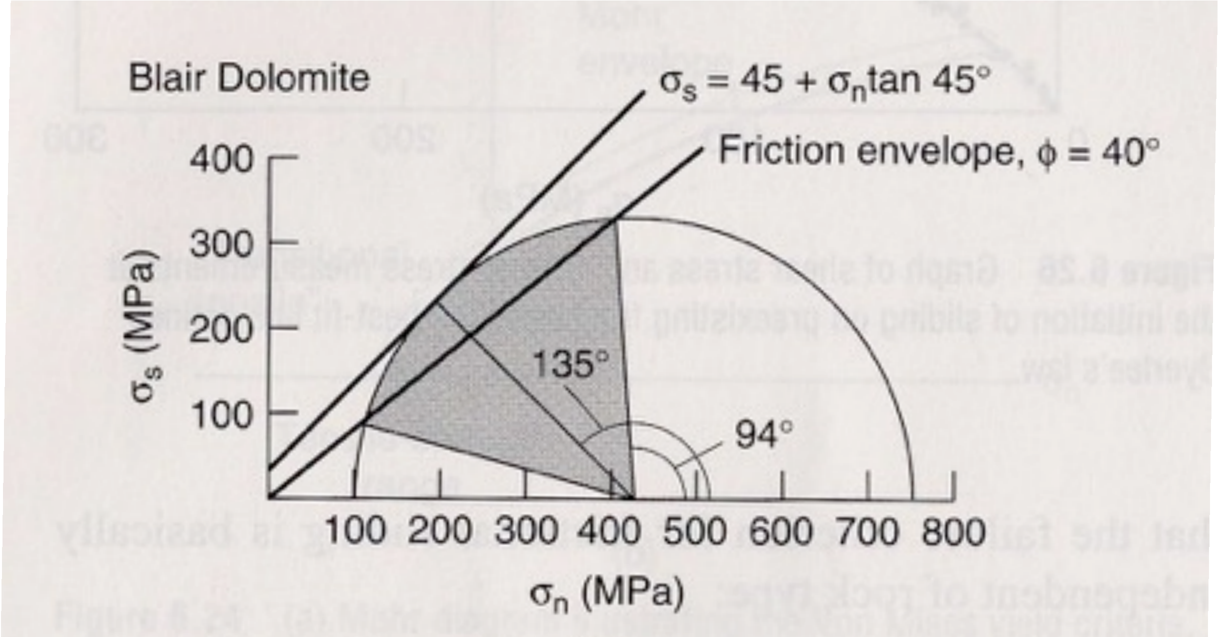


Byerlee's law for pre-existing fault surfaces the important question:

will new fractures form or will existing fractures slide?

examine failure envelopes to decide

figure below shows both Byerlee's law for frictional sliding and
Coulomb shear fracture envelope for Blair Dolomite



from: van der Pluijm and Marshak, 1997

slope and intercept of two envelopes are different…
for specific orientations of preexisting fractures,
Mohr circle touches frictional envelope first

→ **preexisting fractures will slide before new fracture forms**

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.

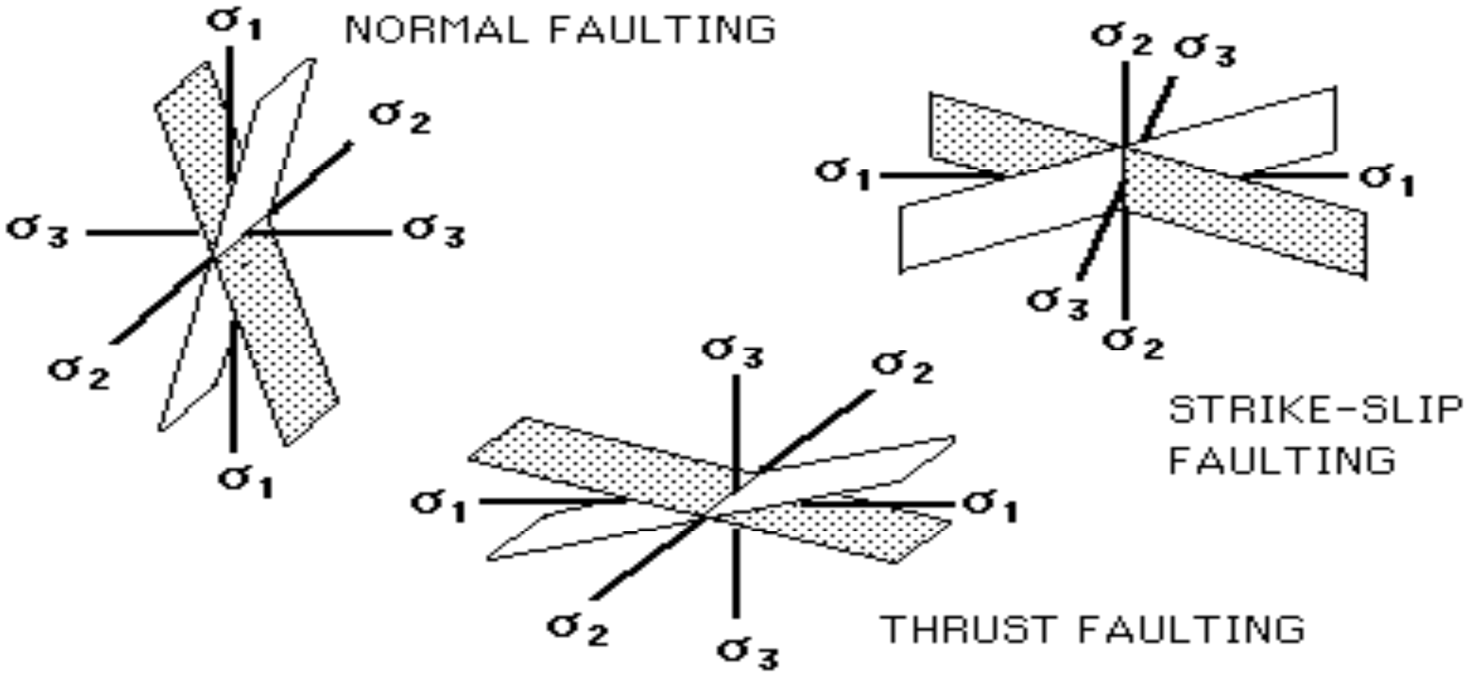
As the principal stress directions are directions of zero shear stress, they must be parallel (2 of them) and perpendicular (1 of them) to the Earth's surface.

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

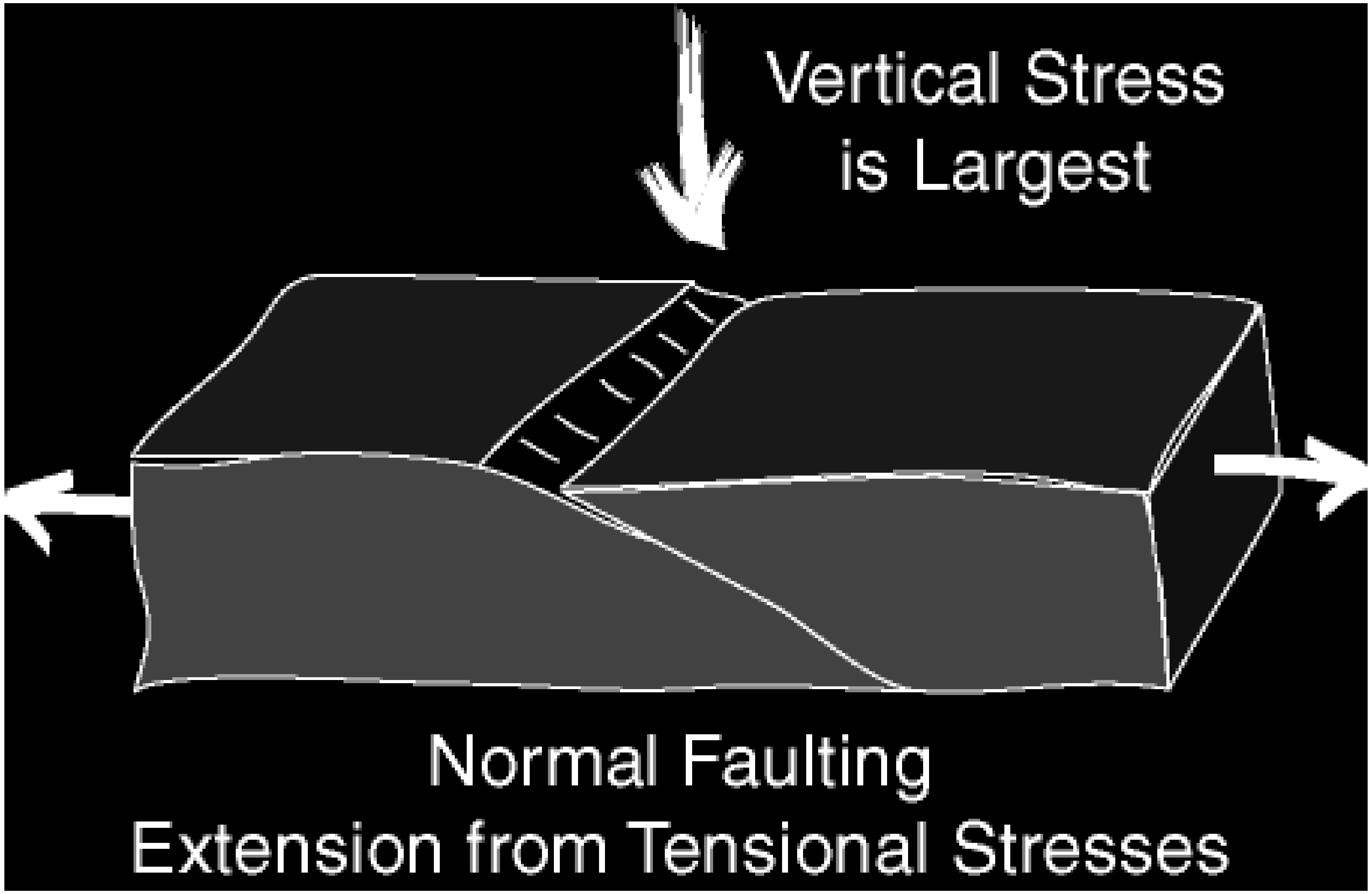
Friction and Faulting

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.

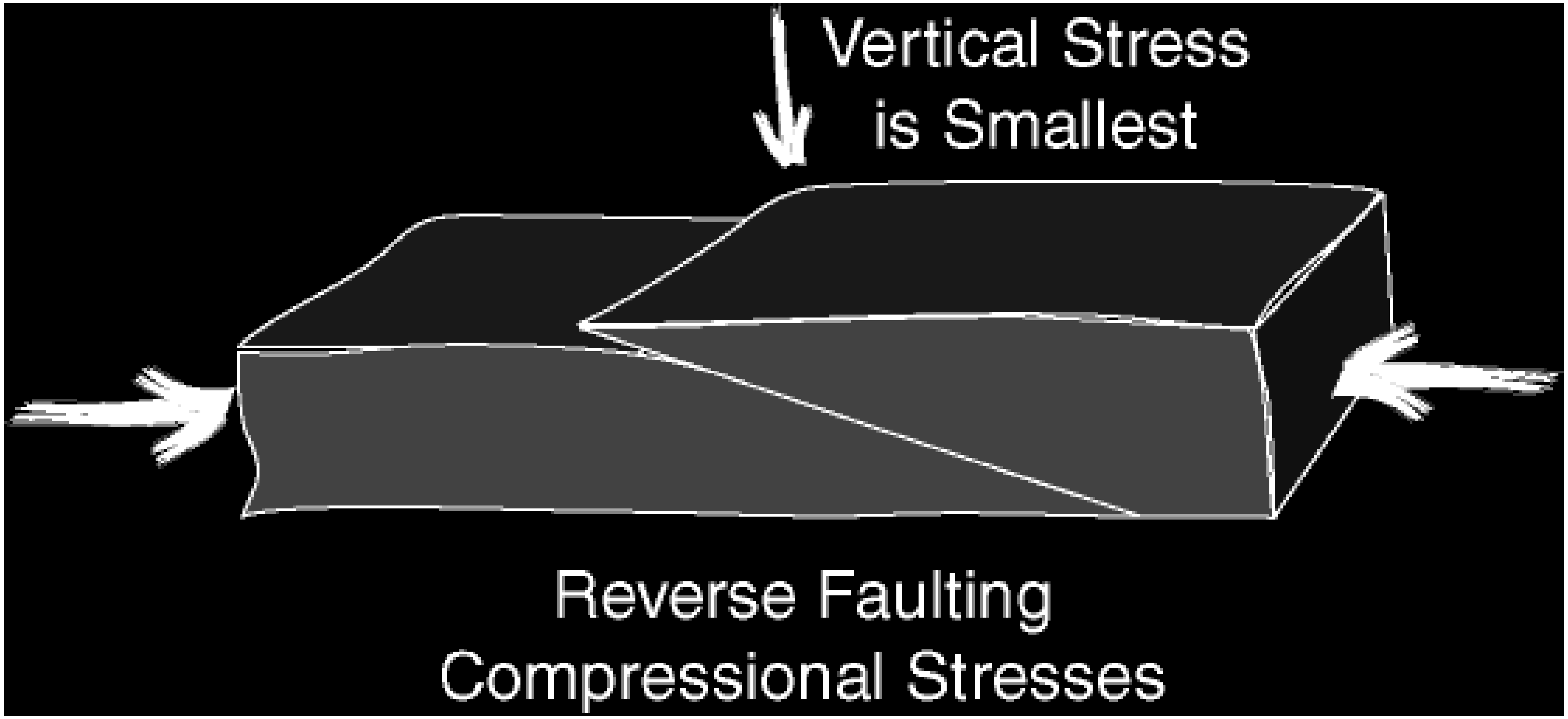
Anderson's theory of faulting: he recognized that principal stress orientations could vary among geological provinces within the upper crust of the earth. He deduced the connection between three common fault types: normal, strike-slip, and thrust and the three principal stress systems arising as a consequence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



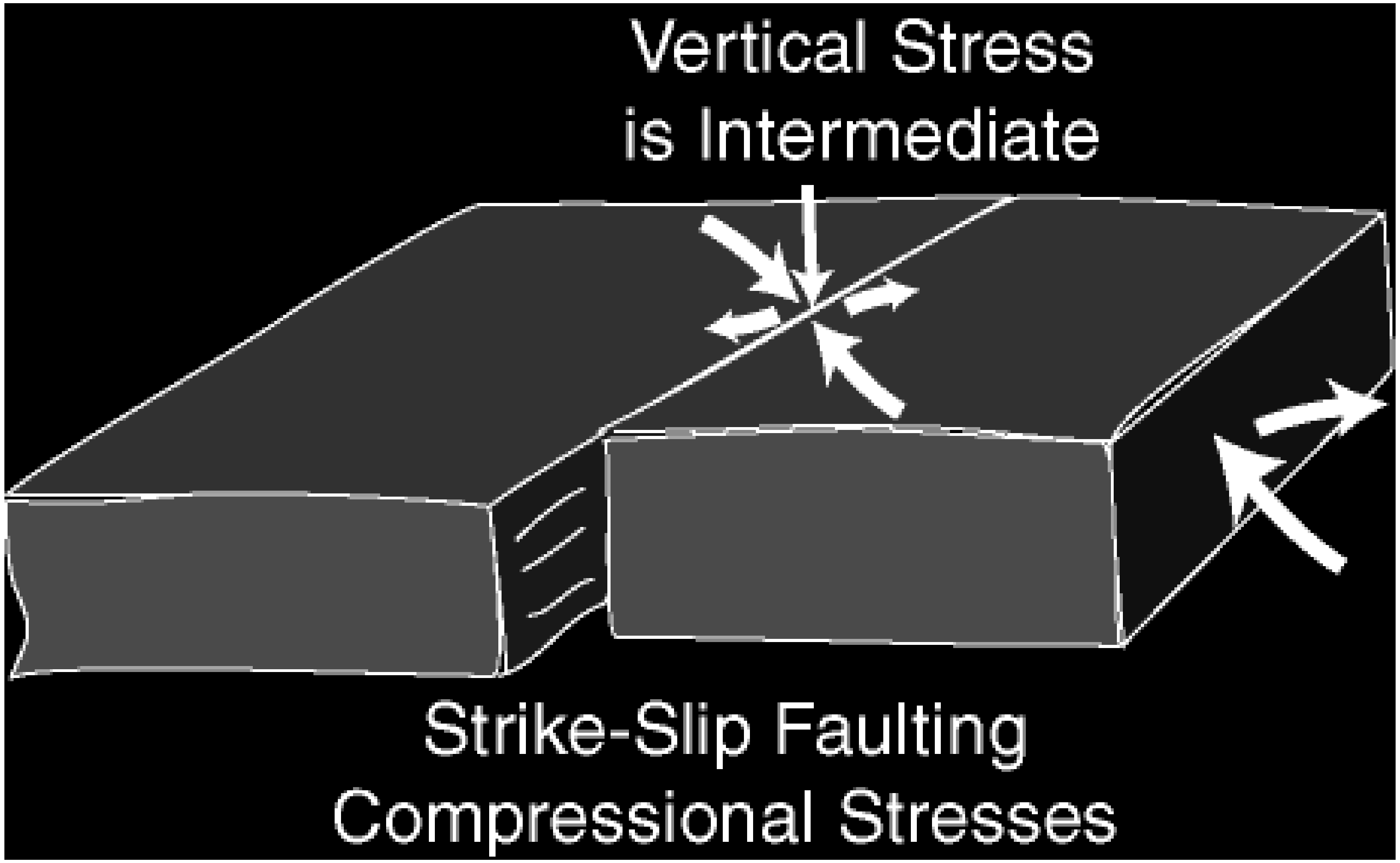
Normal Faulting Stresses



Reverse Faulting Stresses

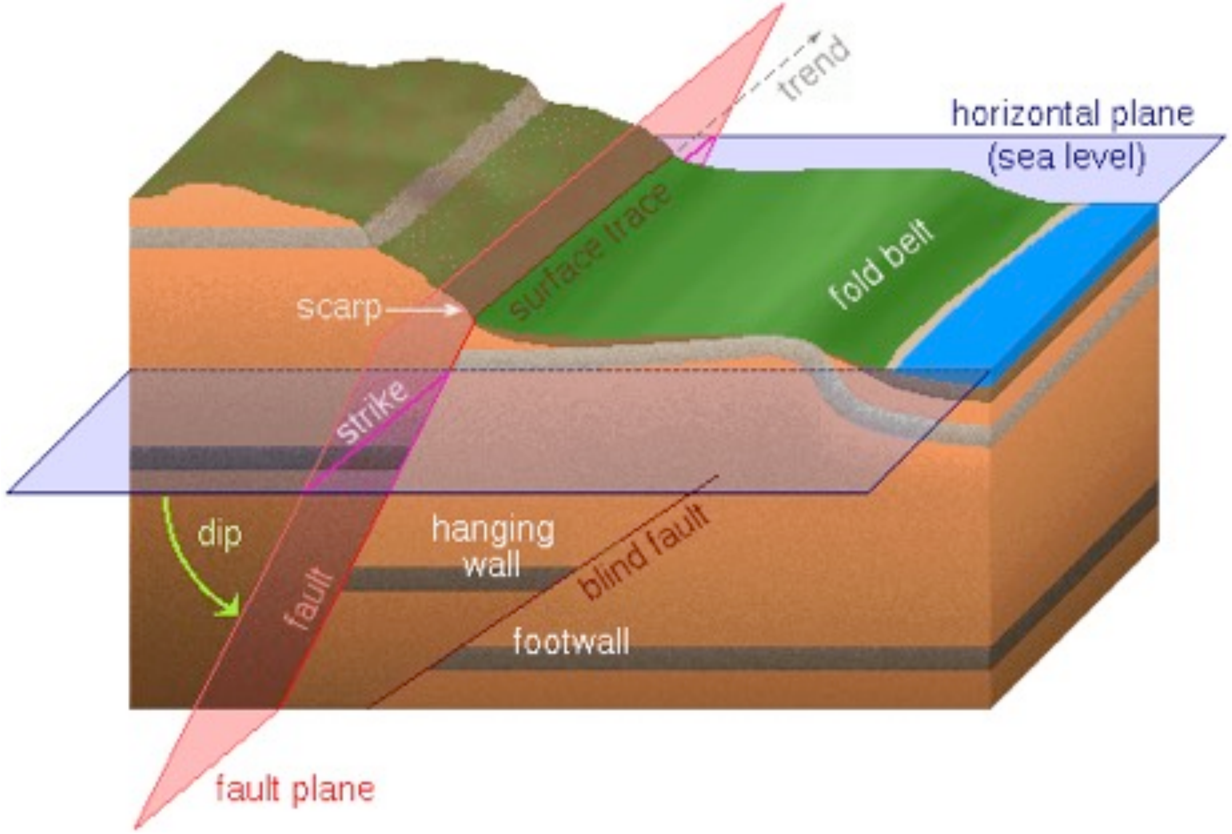


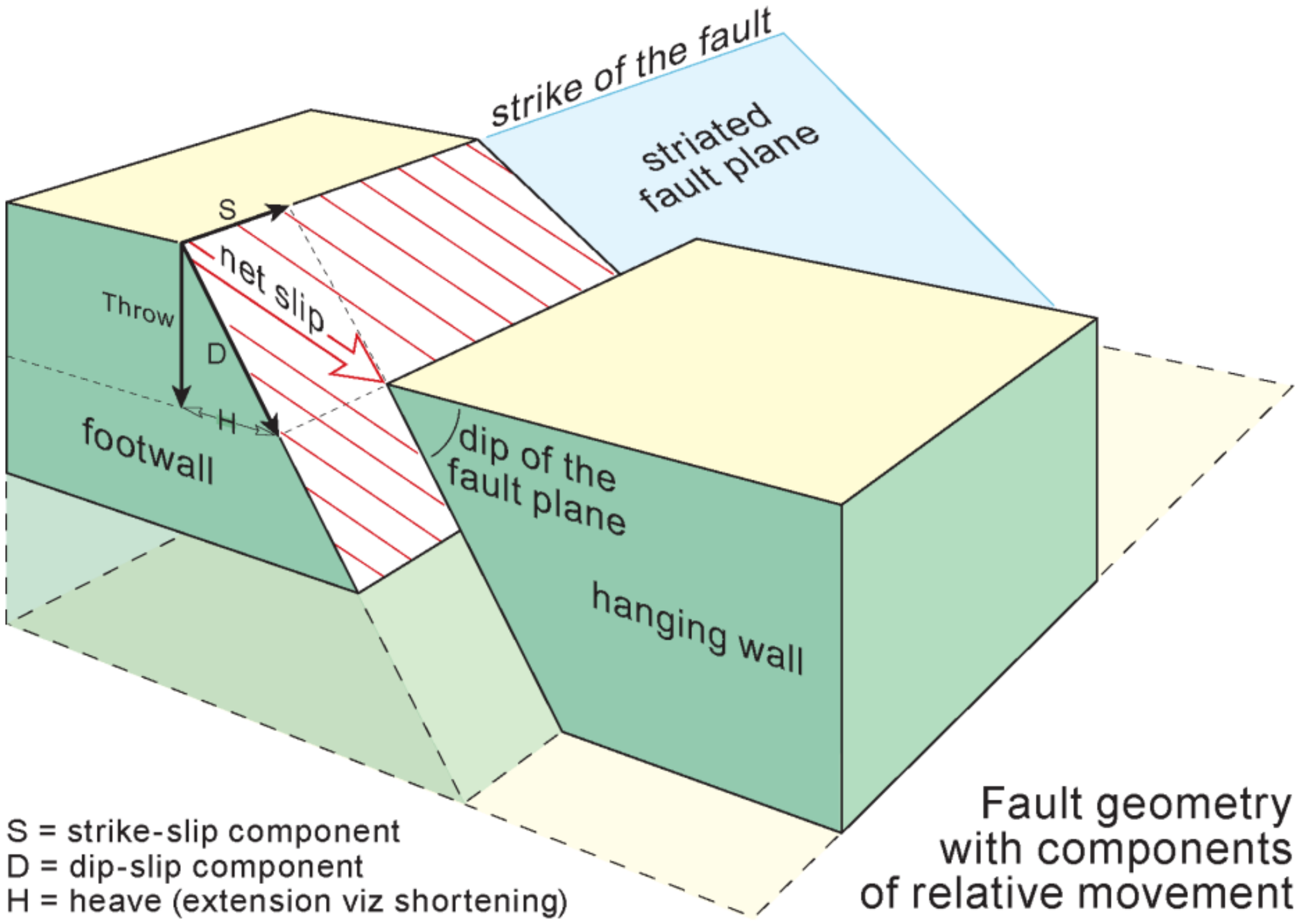
Strike-Slip Faulting Stresses



Earthquakes and Faults

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





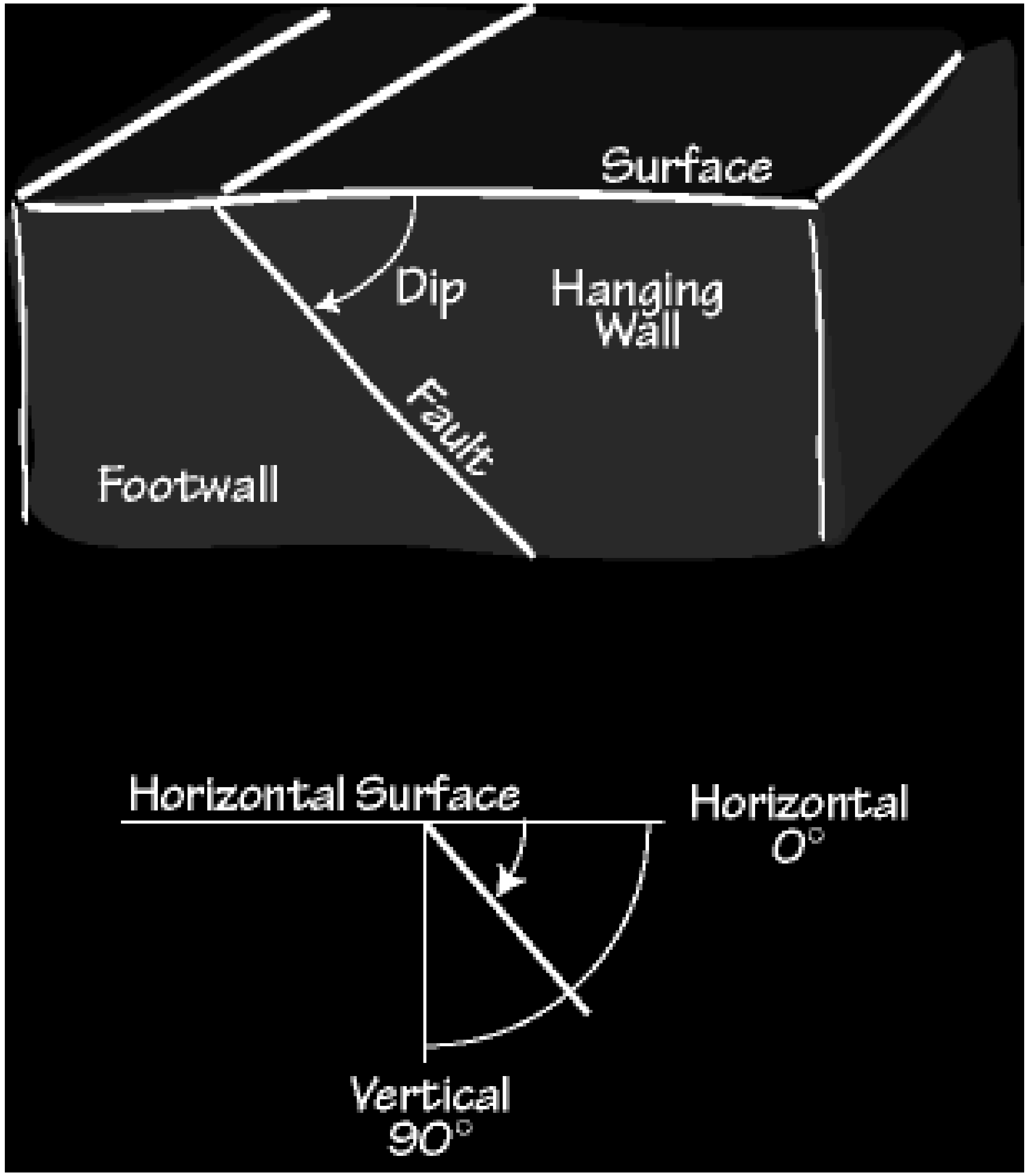
S = strike-slip component
D = dip-slip component
H = heave (extension viz shortening)

Fault geometry with components of relative movement

http://www.files.ethz.ch/structuralgeology/JPB/files/English/3faults.pdf

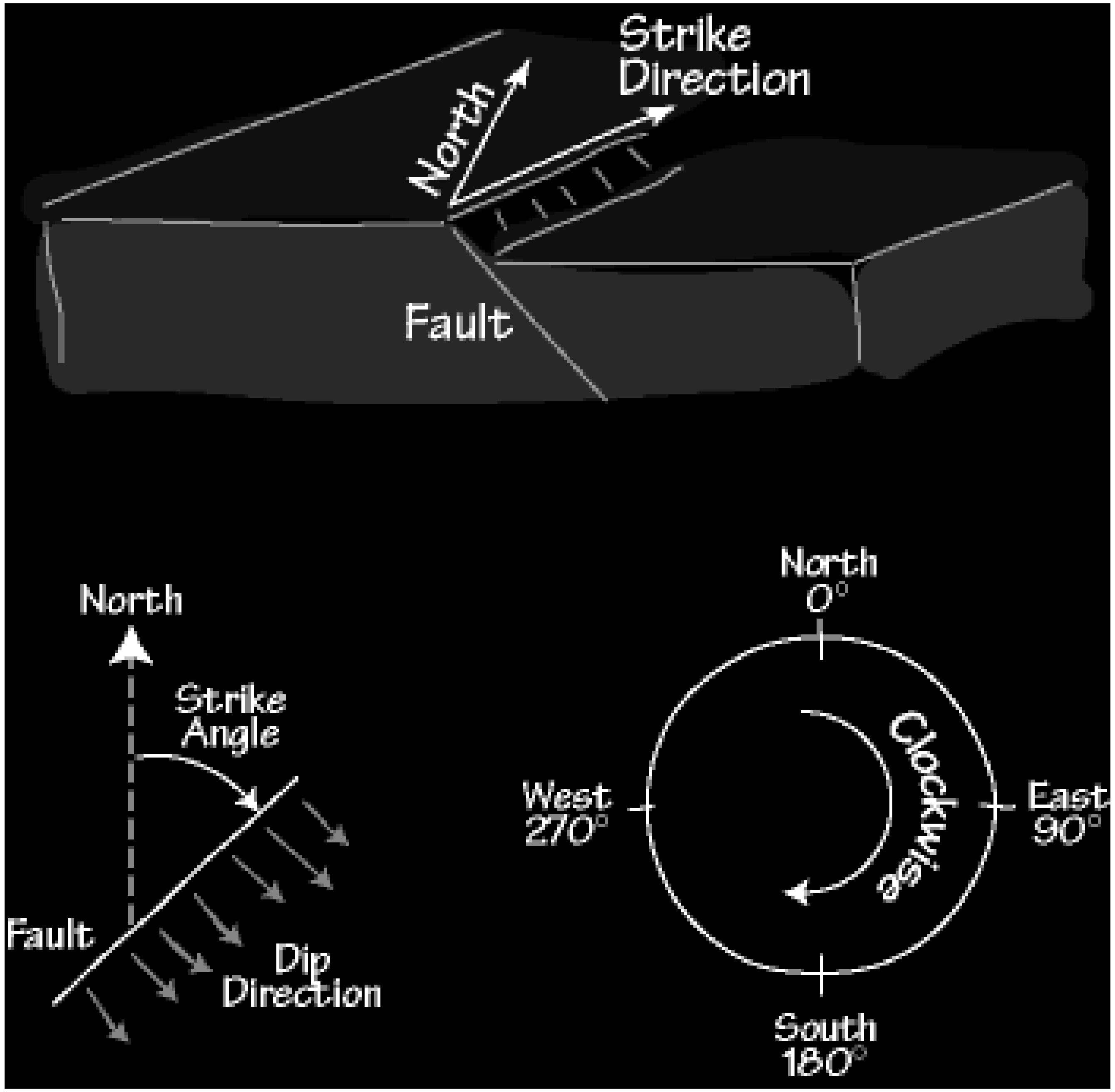
Fault Geometry Terminology: DIP

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



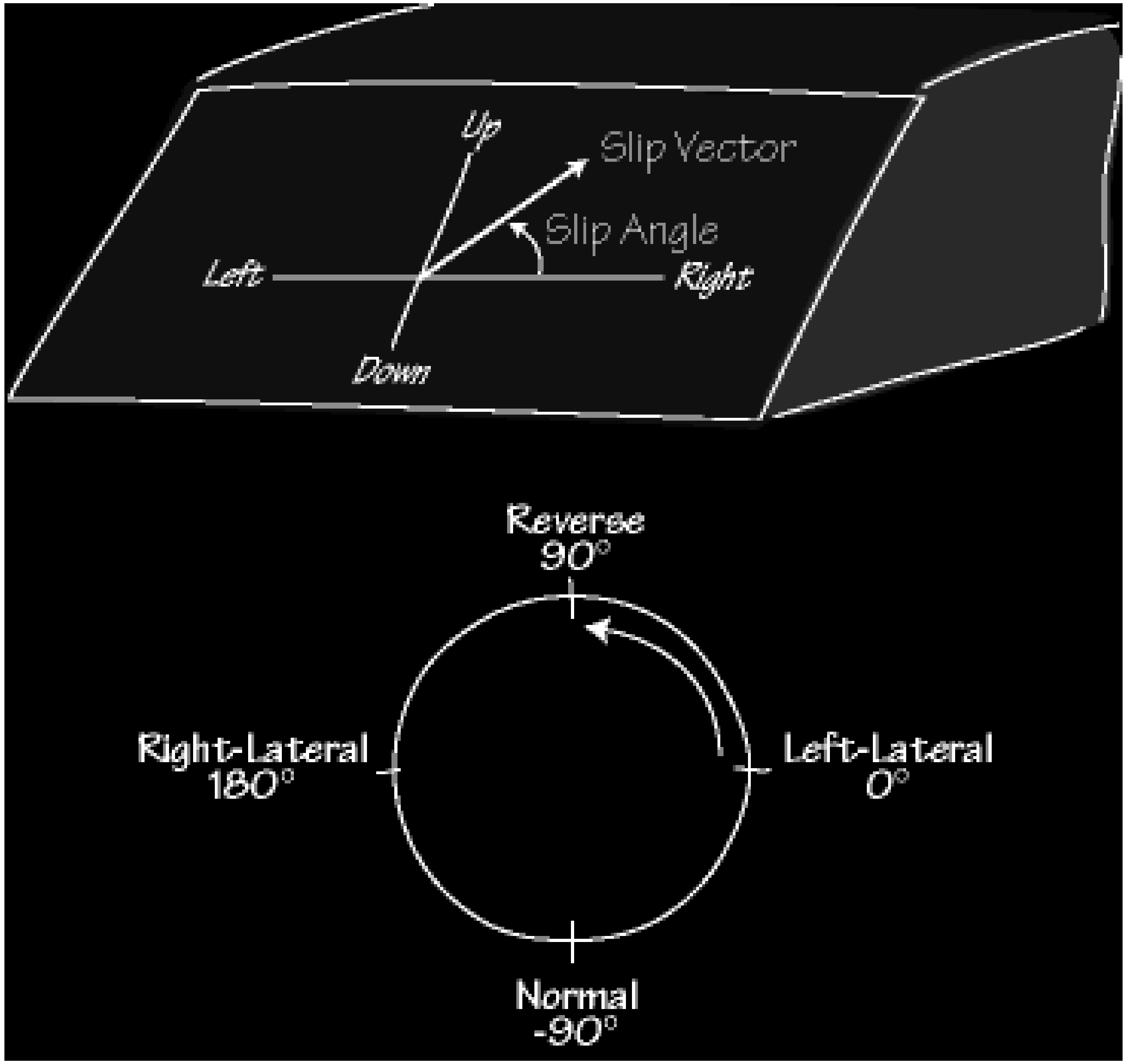
Fault Geometry Terminology: STRIKE

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



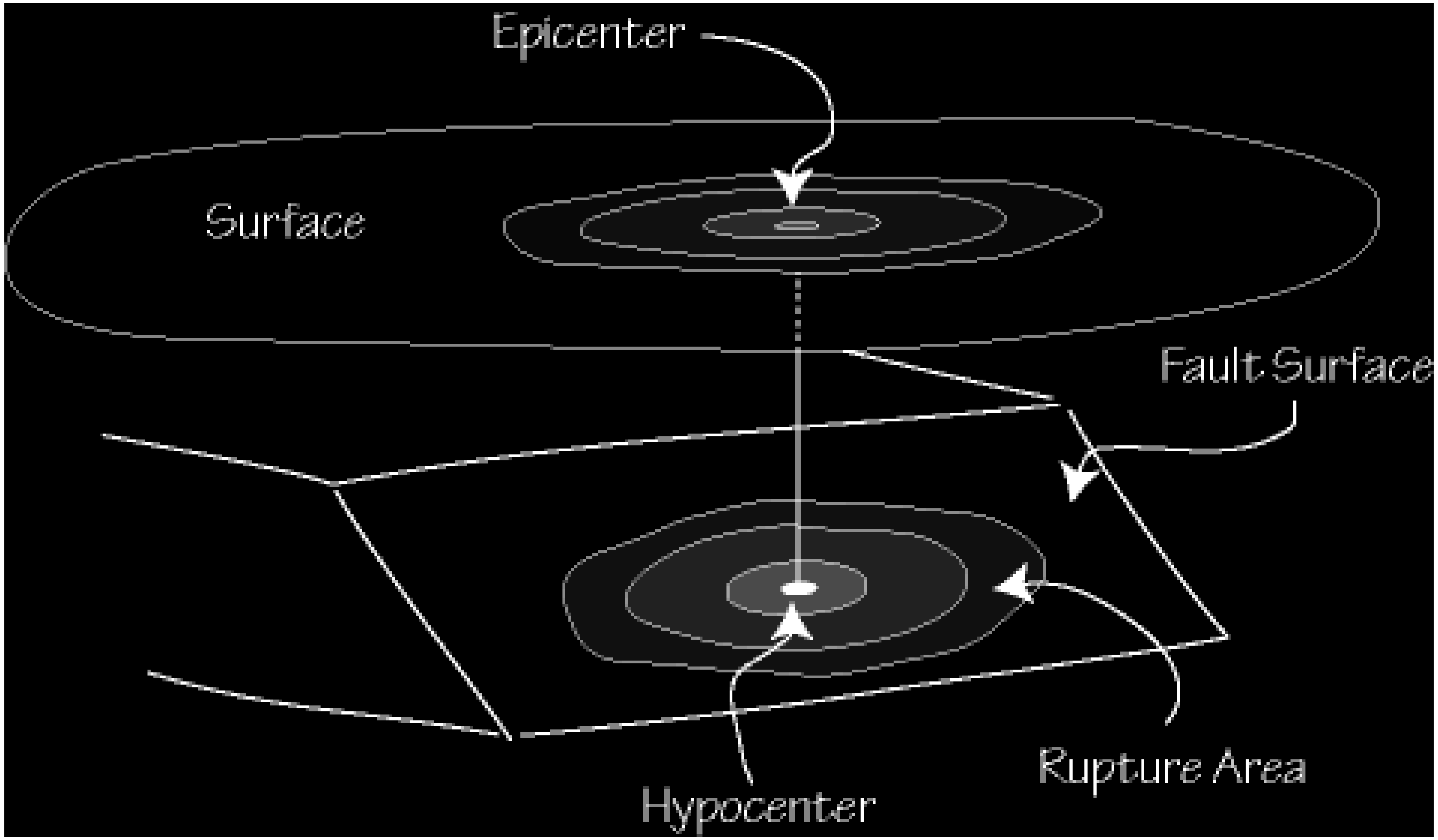
Fault Geometry Terminology: SLIP

Slip angle is used to describe the orientation of the movement of the hanging wall relative to the foot wall.

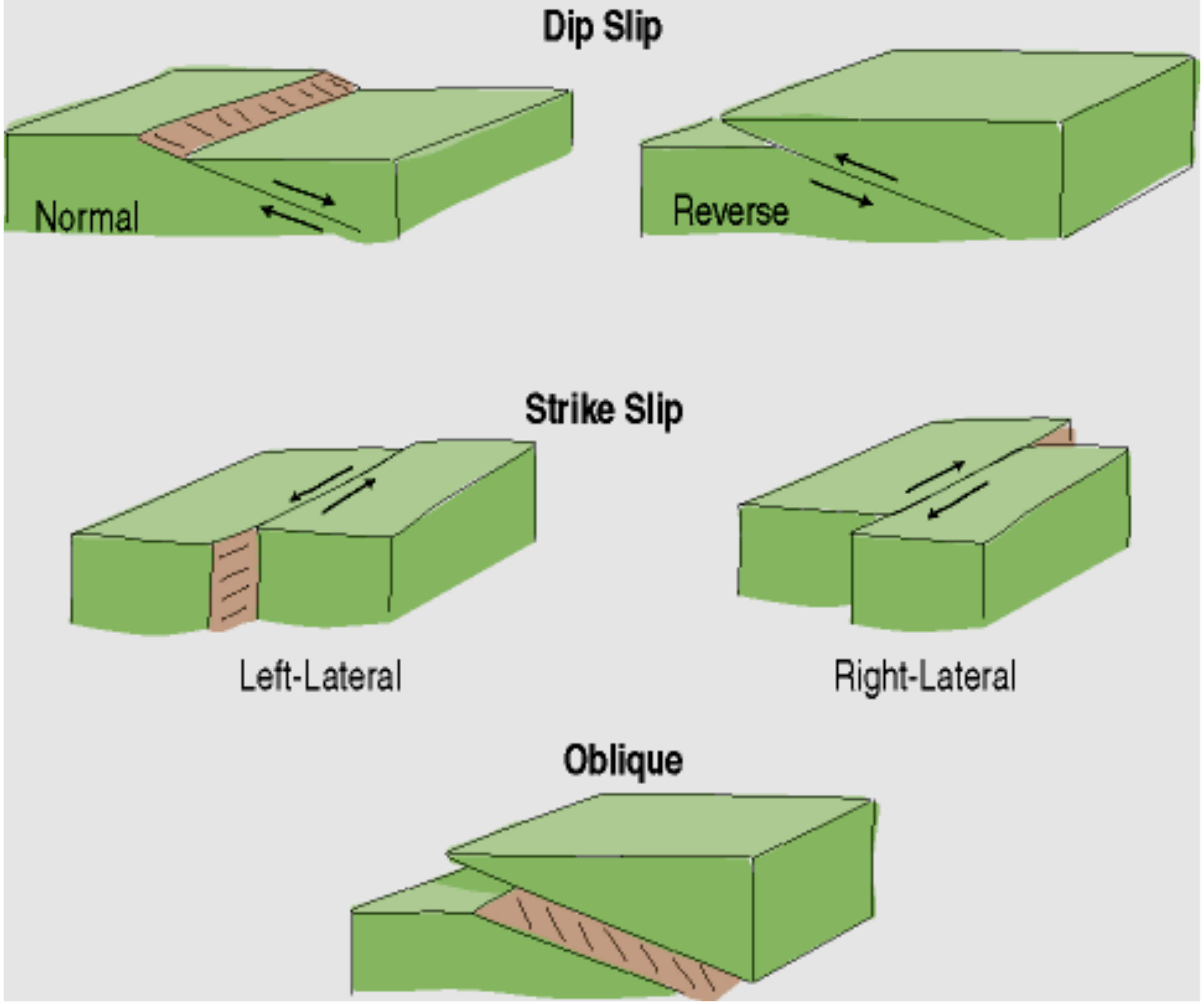


Hypocenter and Epicenter

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



Faulting Summary



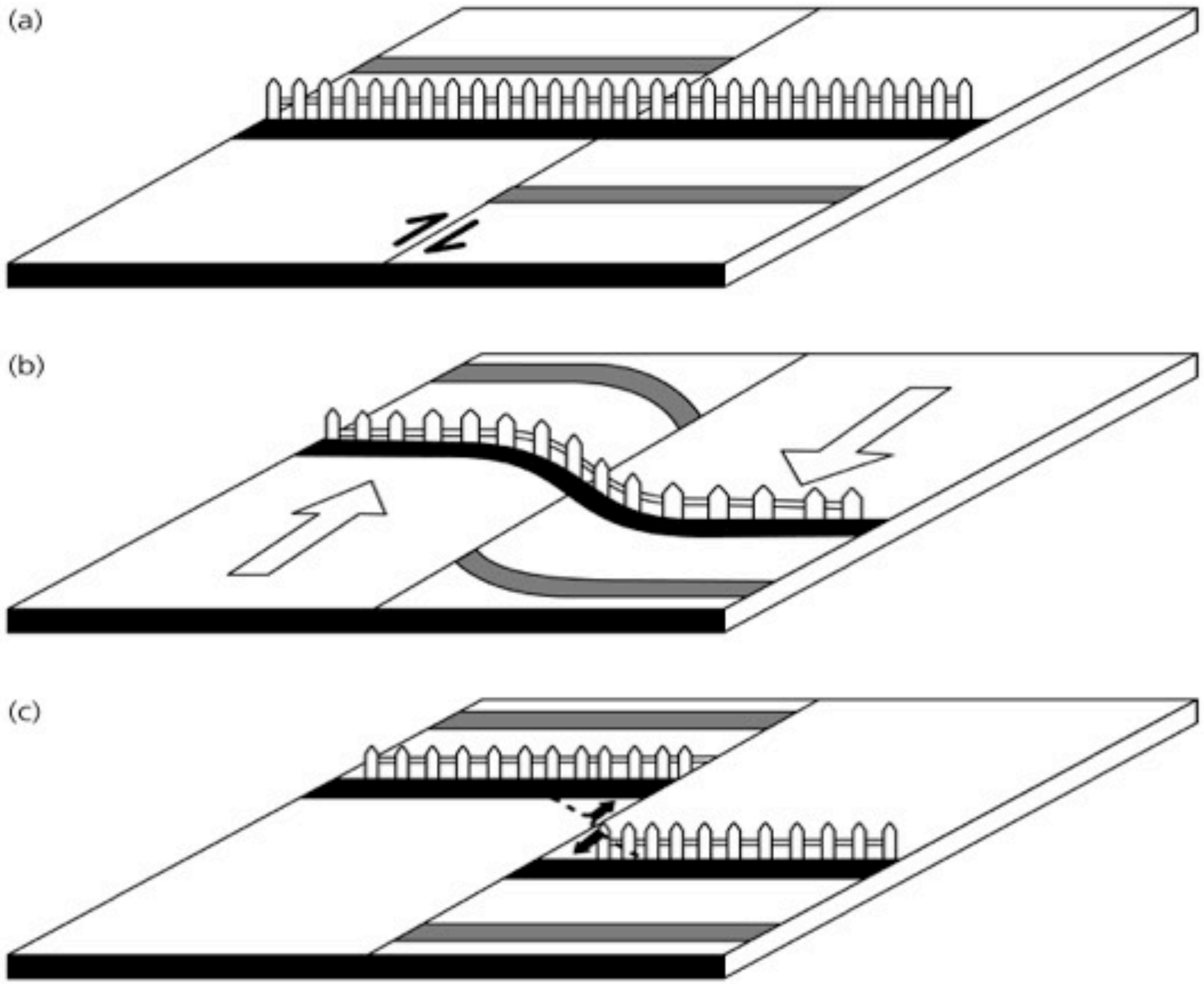
Faults which move along the direction of the dip and are described as either **normal** or **reverse**, depending on their motion.

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**.

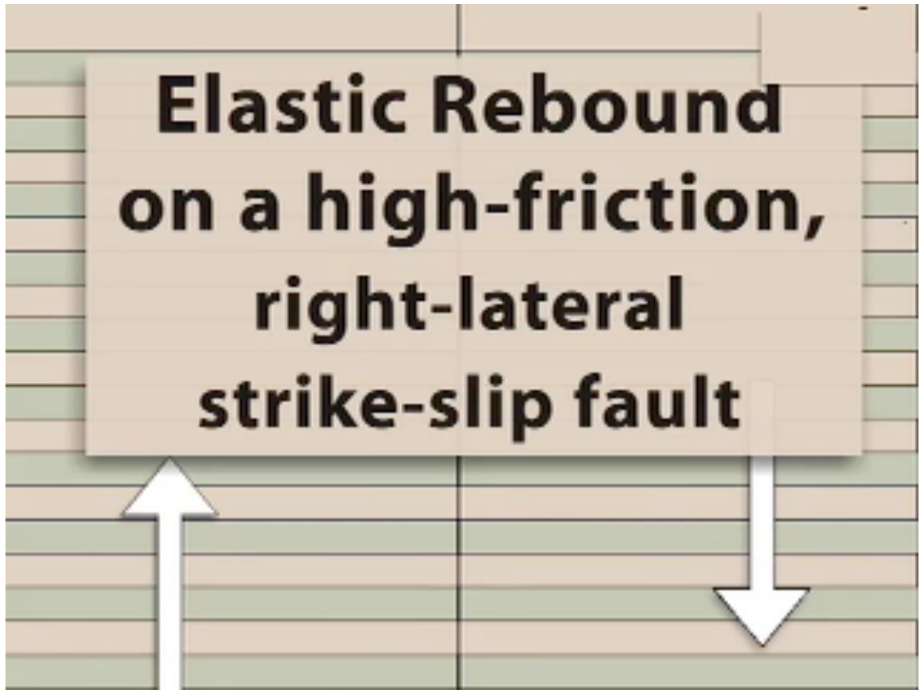
A combination of dip-slip and strike-slip motion.

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.



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.

Earthquake rupture

Can be described by: a) formation and b) propagation of a crack.

The crack tip acts as a stress concentrator and if the stress exceeds some critical value then sudden slip occurs, and it drops to the dynamic frictional value; when the slip has stopped the stress reaches a final level

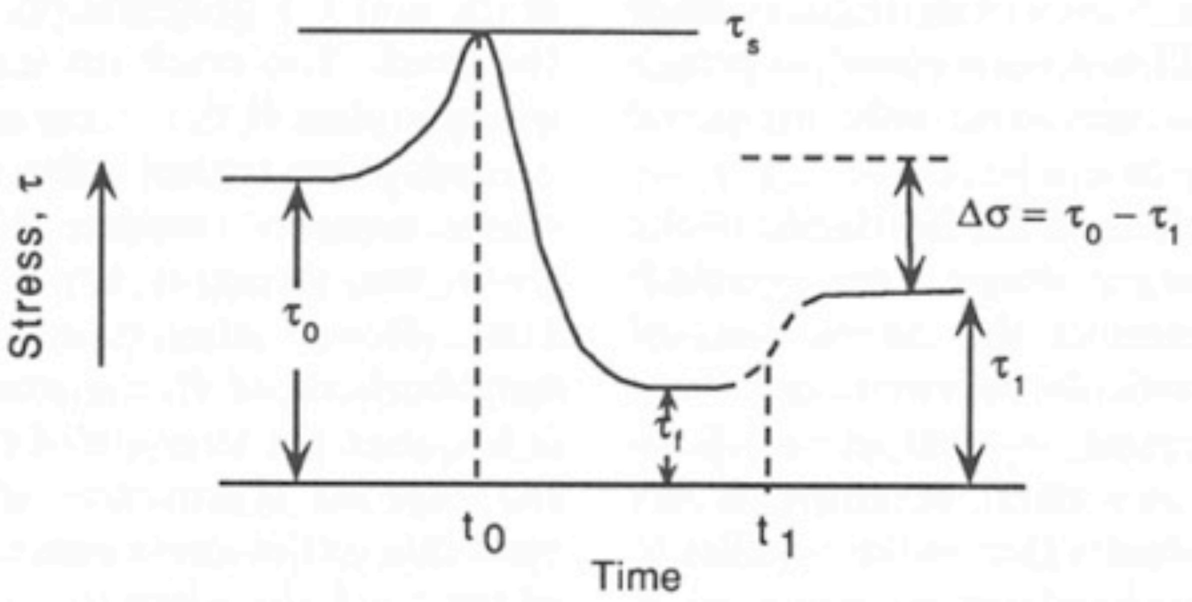
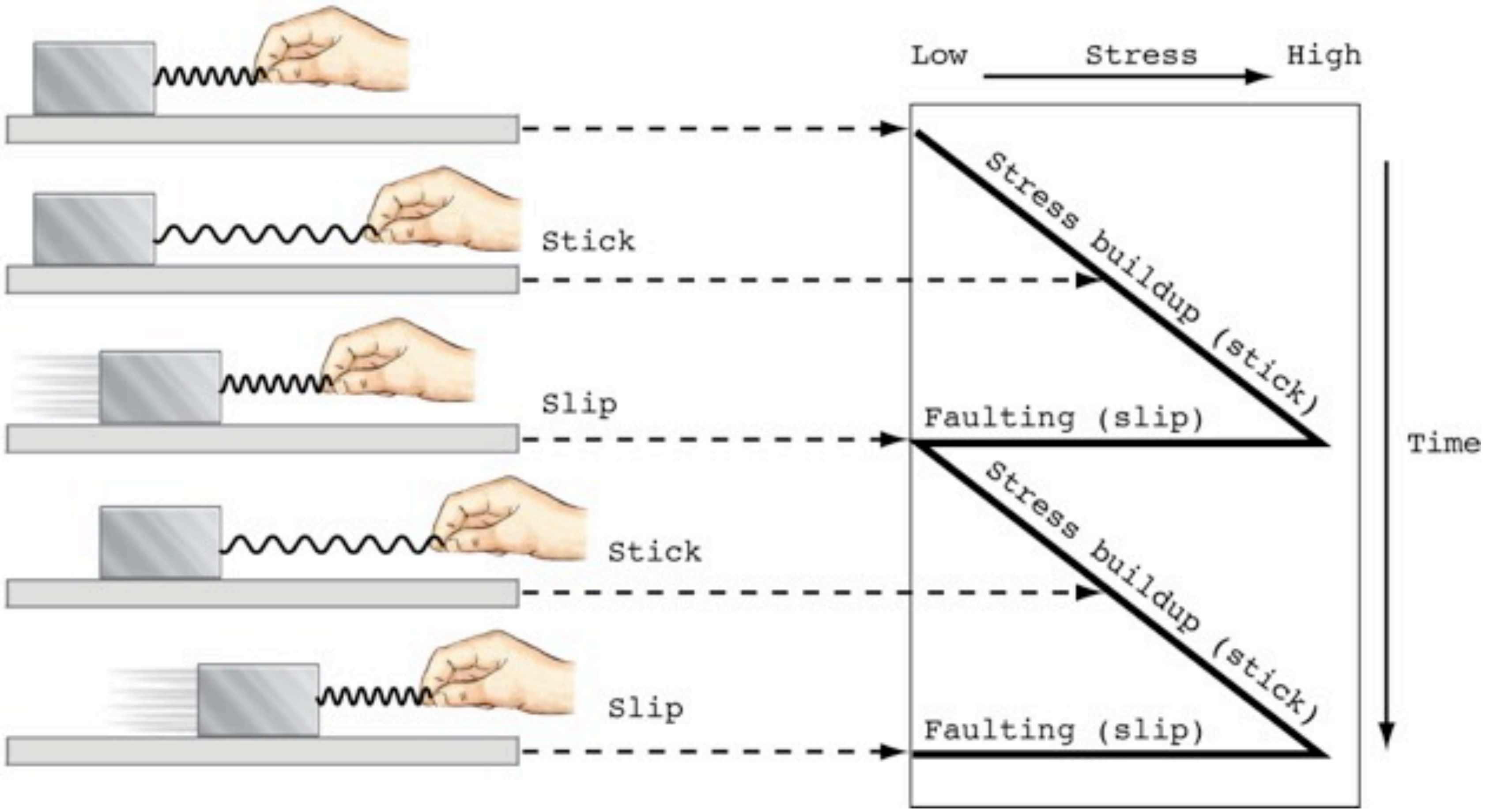


FIGURE 9.2 Stress at a point on a fault surface. As the rupture front approaches the point, stress increases to a value of τ_s, after which failure occurs at the point. The point slips to a displacement D, and stress is reduced to some value τ_f. The difference between the initial stress and the final stress, $\Delta\sigma$, is defined as the stress drop. (After Yamashita, 1976.)

Stick-slip

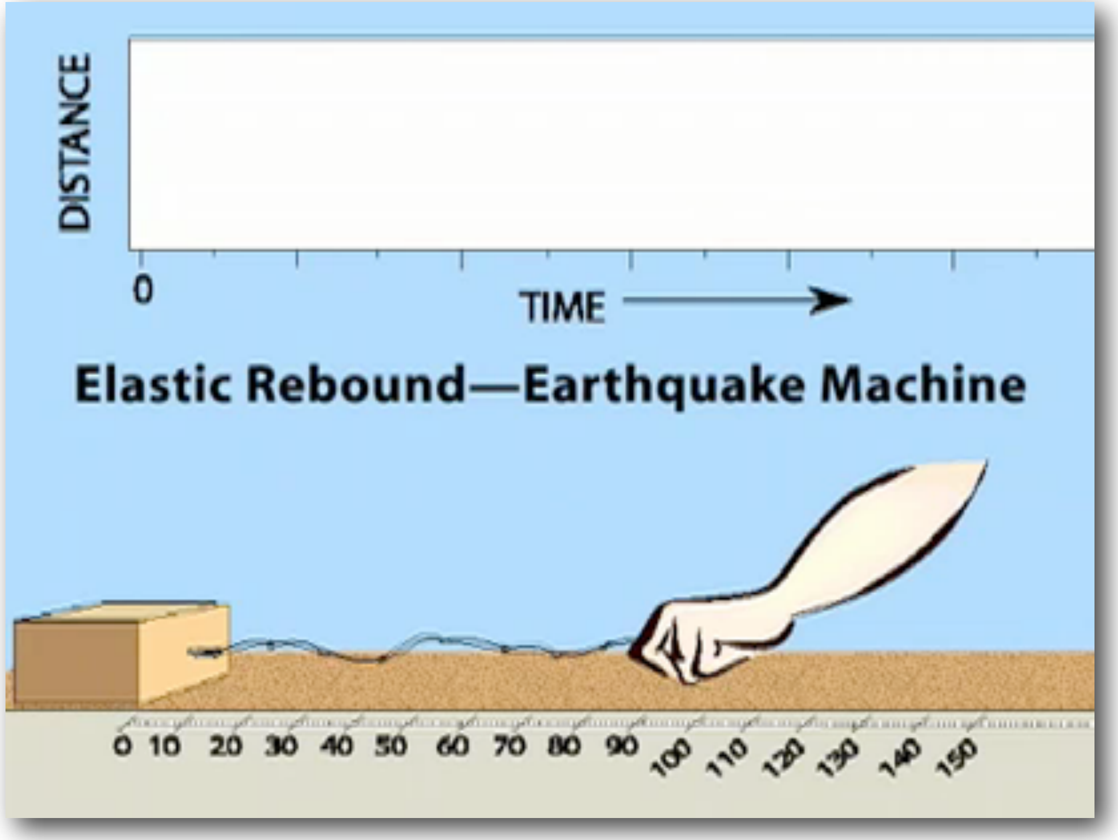


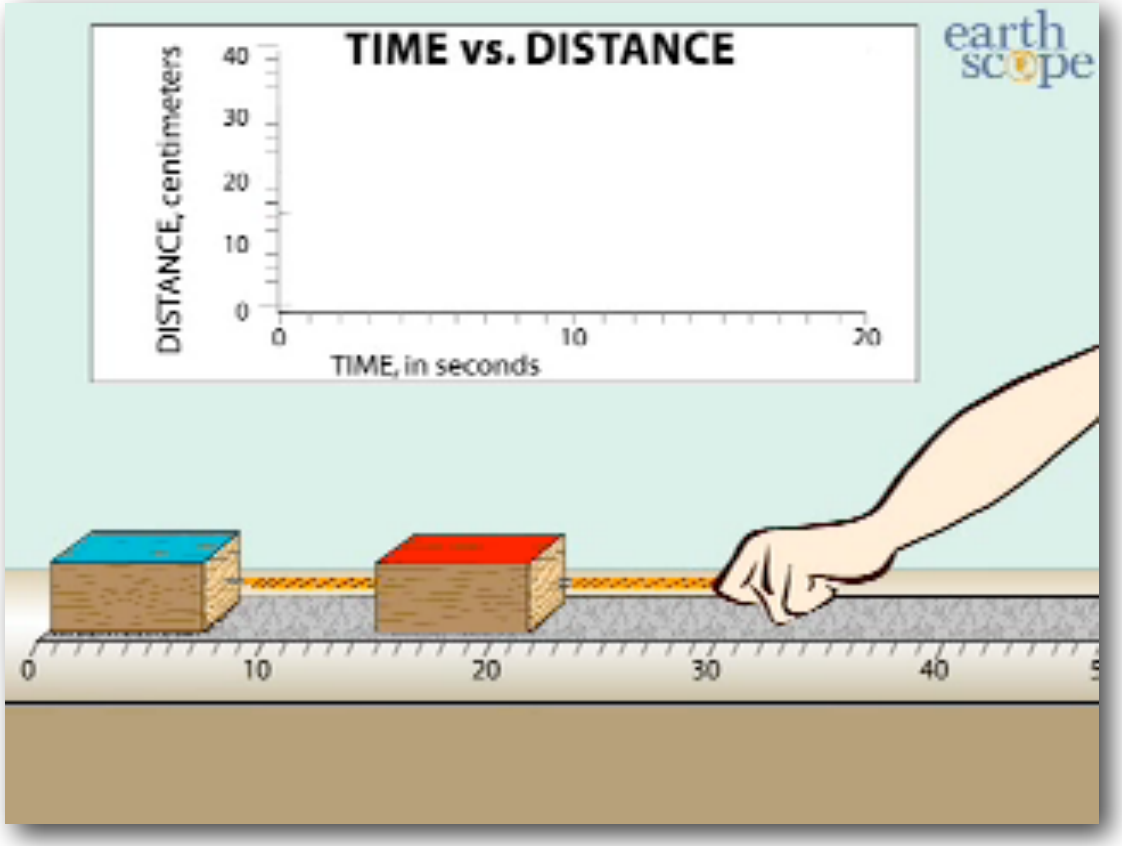
Earth, S. Marshak, W.W. Norton

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

Stick-slip





http://www.iris.edu/hq/programs/education_and_outreach/aotm/1

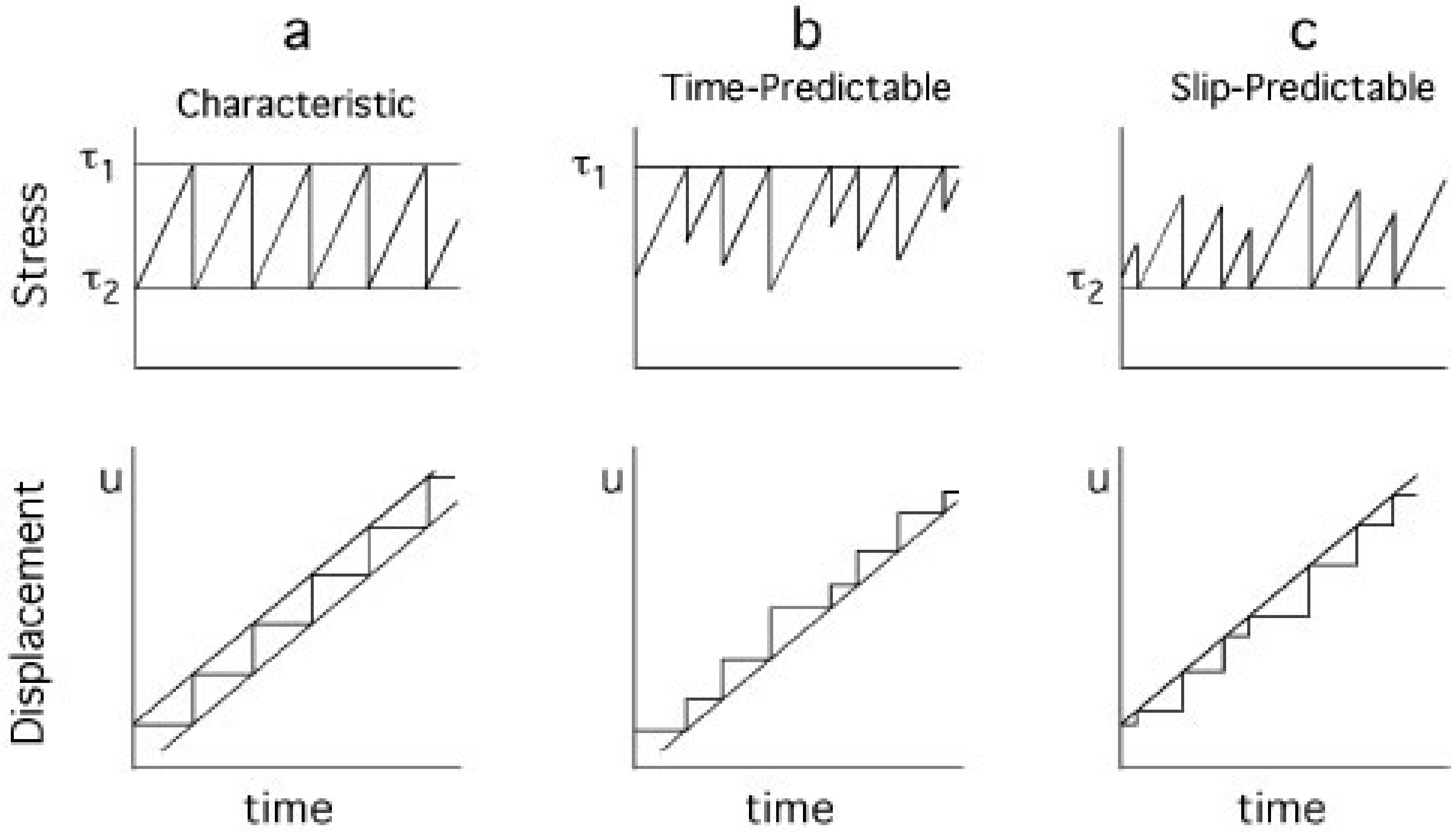
Stress cycle: prediction models

τ_1 is the shear stress at initiation of slip and reflects fault strength. τ_2 is the shear stress at which slip ceases and reflects fault friction.

(a) **Characteristic model** of stick-slip faulting. Each earthquake is identical in stress history, recurrence interval and slip.

(b) **Time-predictable model**. If slip is proportional to stress drop, and plate motions are steady, we can predict the time of the next earthquake based on the amount of slip during the previous earthquake.

(c) **Slip-predictable model**. Knowing the time of the last earthquake and assuming steady plate motion, we can predict the size of an earthquake expected at a particular time.



Stress cycle

The stress drop causes a time interval during which the stress builds up again to critical value. This type of frictional behaviour is known as **stick-slip**, or unstable sliding (as opposed to continue slip on smooth surfaces: stable sliding).

Earthquakes are generally thought to be **recurring slip episodes on preexisting faults**: the importance is no more on the strength of the rock but on the stress-stability cycle.