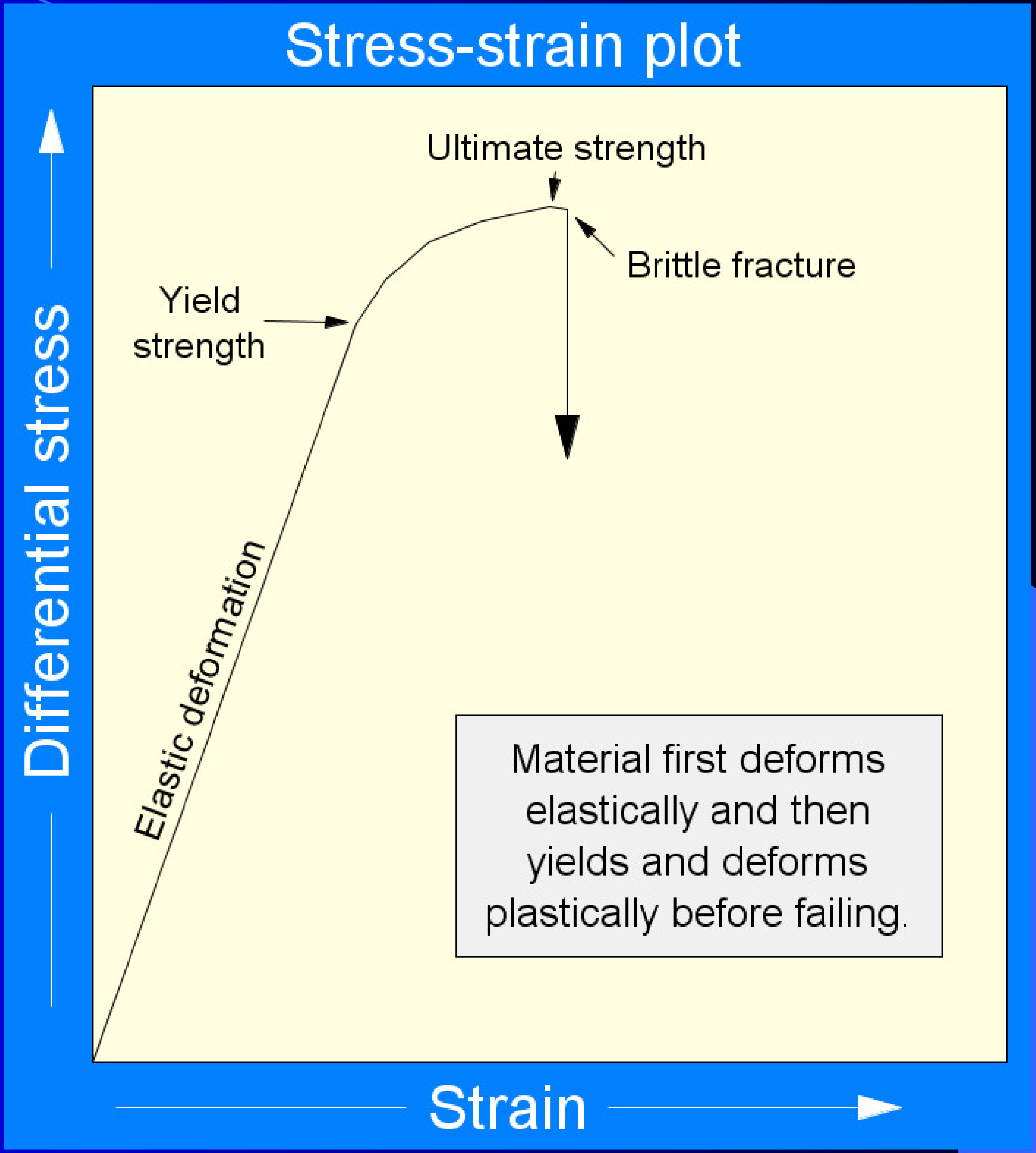
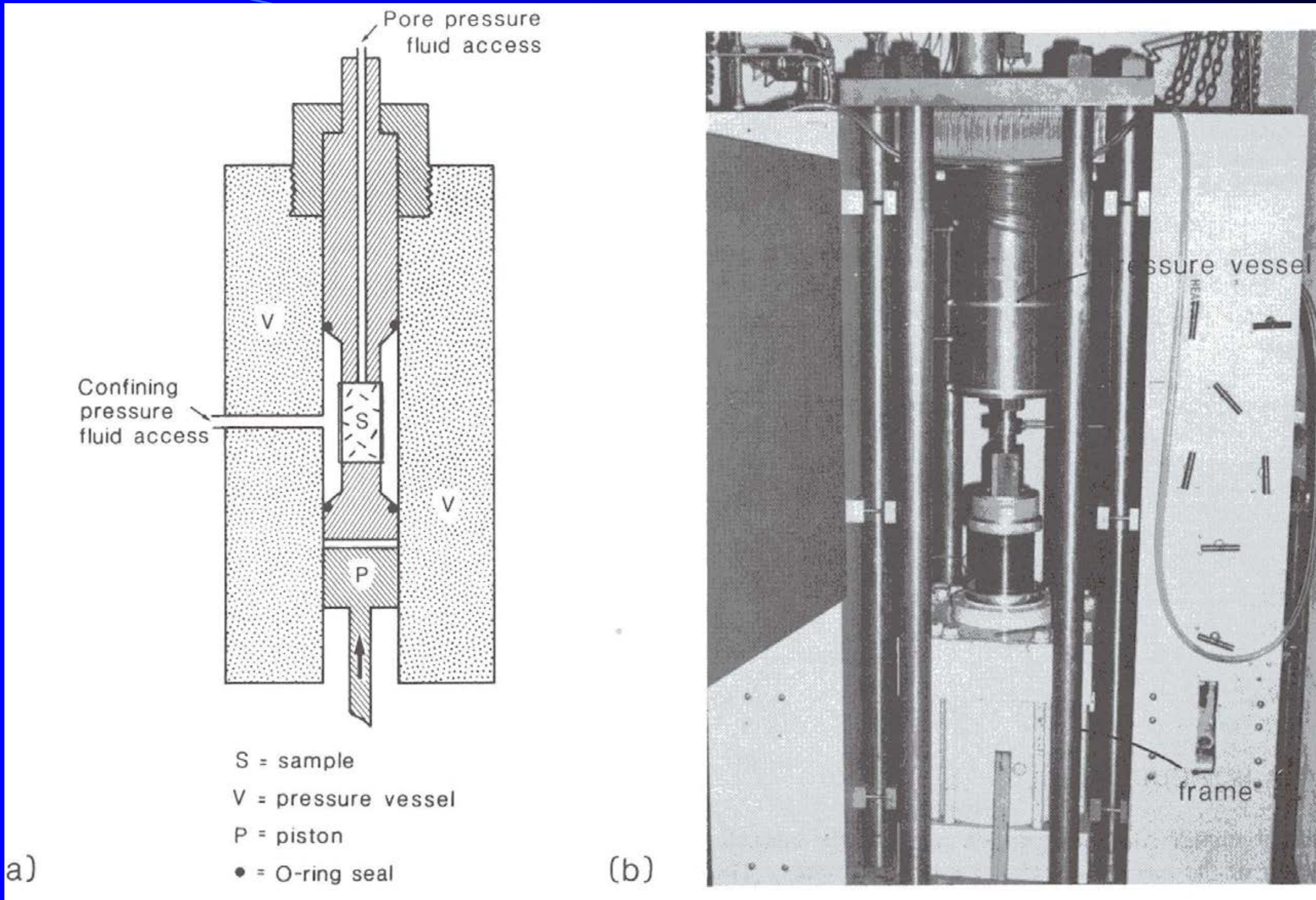
89.325 – Geology for Engineers
Rock Mechanics and Deformation of Earth Materials

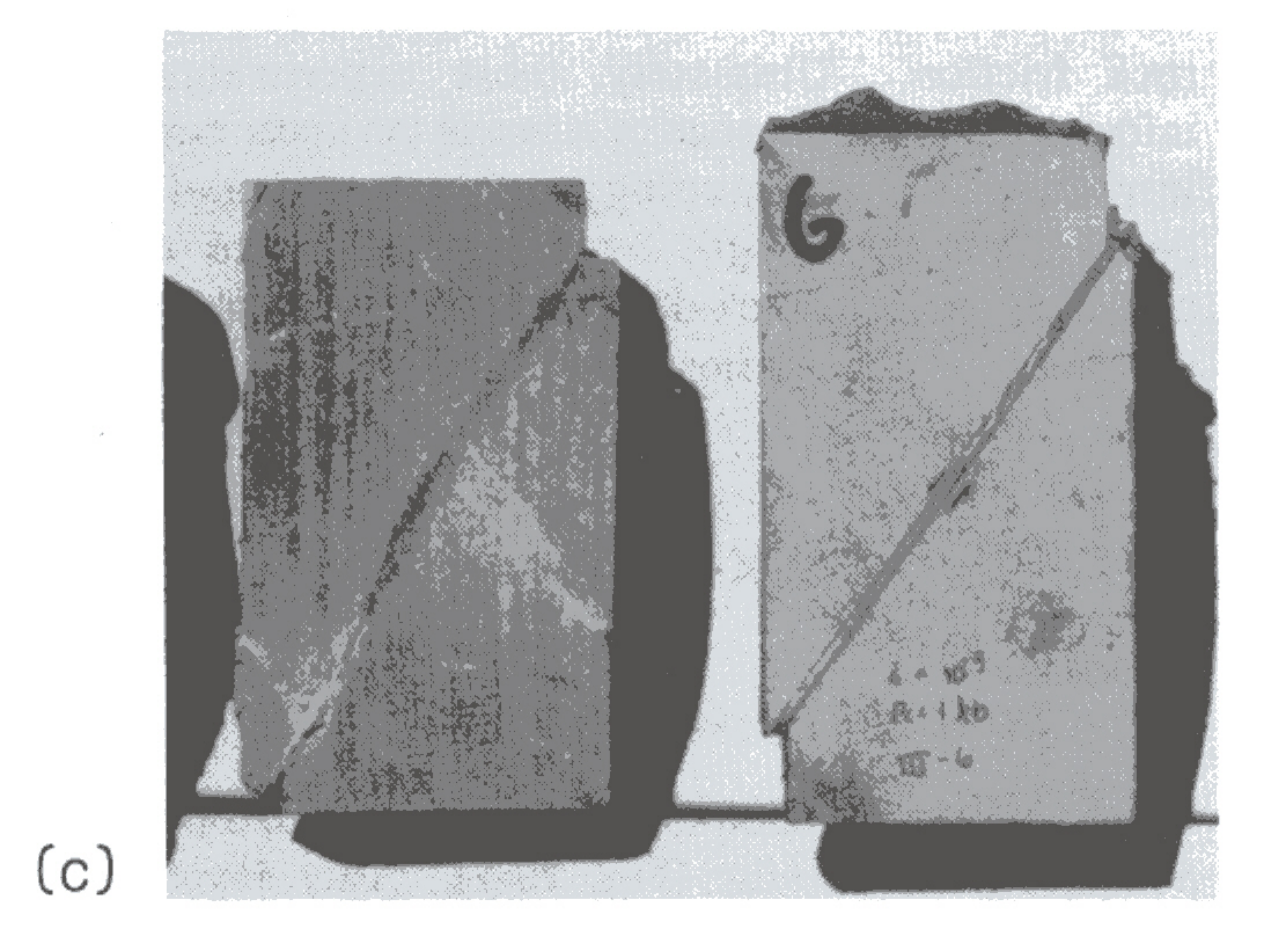
Faults and Fractures

Why do rocks break? Rock mechanics experiments – a first order understanding.



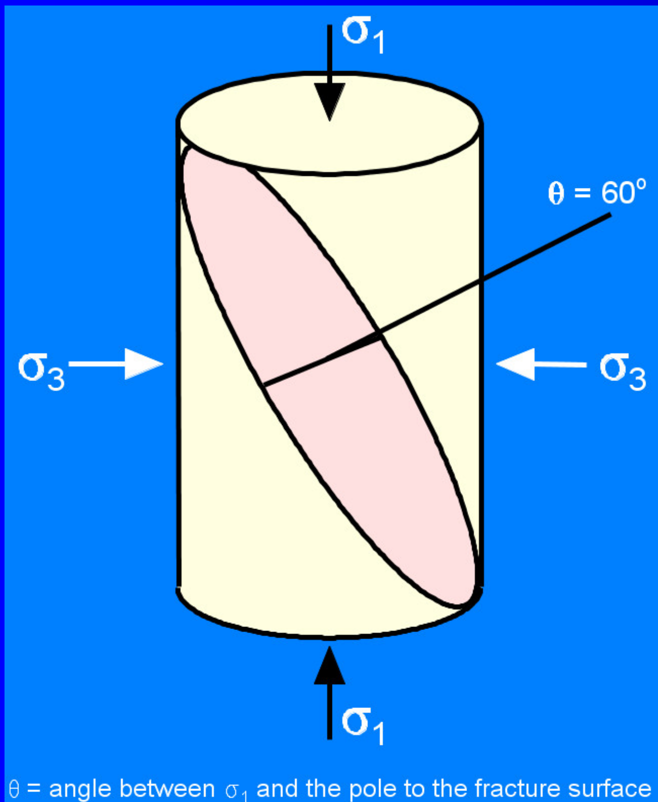


Triaxial load machine. a) cross-sectional sketch showing the pressure vessel, sample, and piston; b) photograph of machine. An example of confined testing.



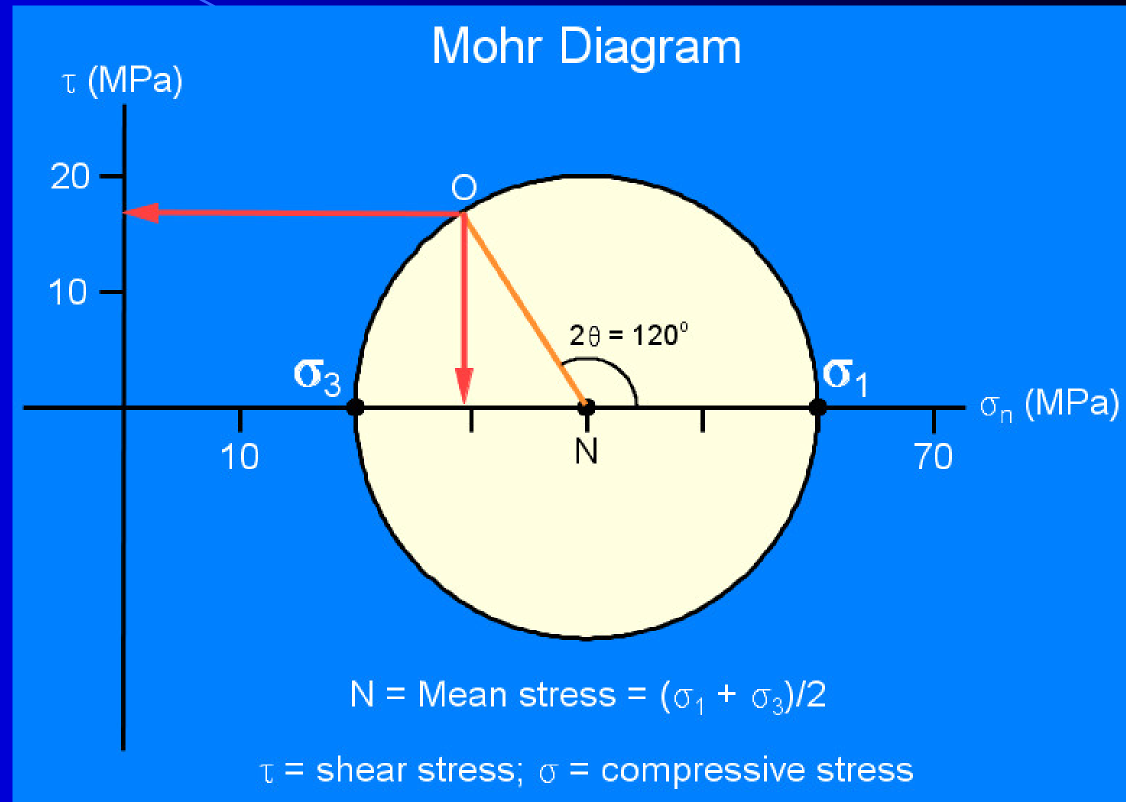
Two deformed samples. L) induced fracture; R) saw-cut for friction experiments. There is a 5 mm-thick layer of gouge along the cut. Samples are 3.5" long and 2" in diameter.

Graphical representation of data from rock mechanics experiments – principal stress directions and the Mohr Diagram



Principal stress directions. Orthogonal coordinate system.

$F_1 \$F_2 \$ F_3$



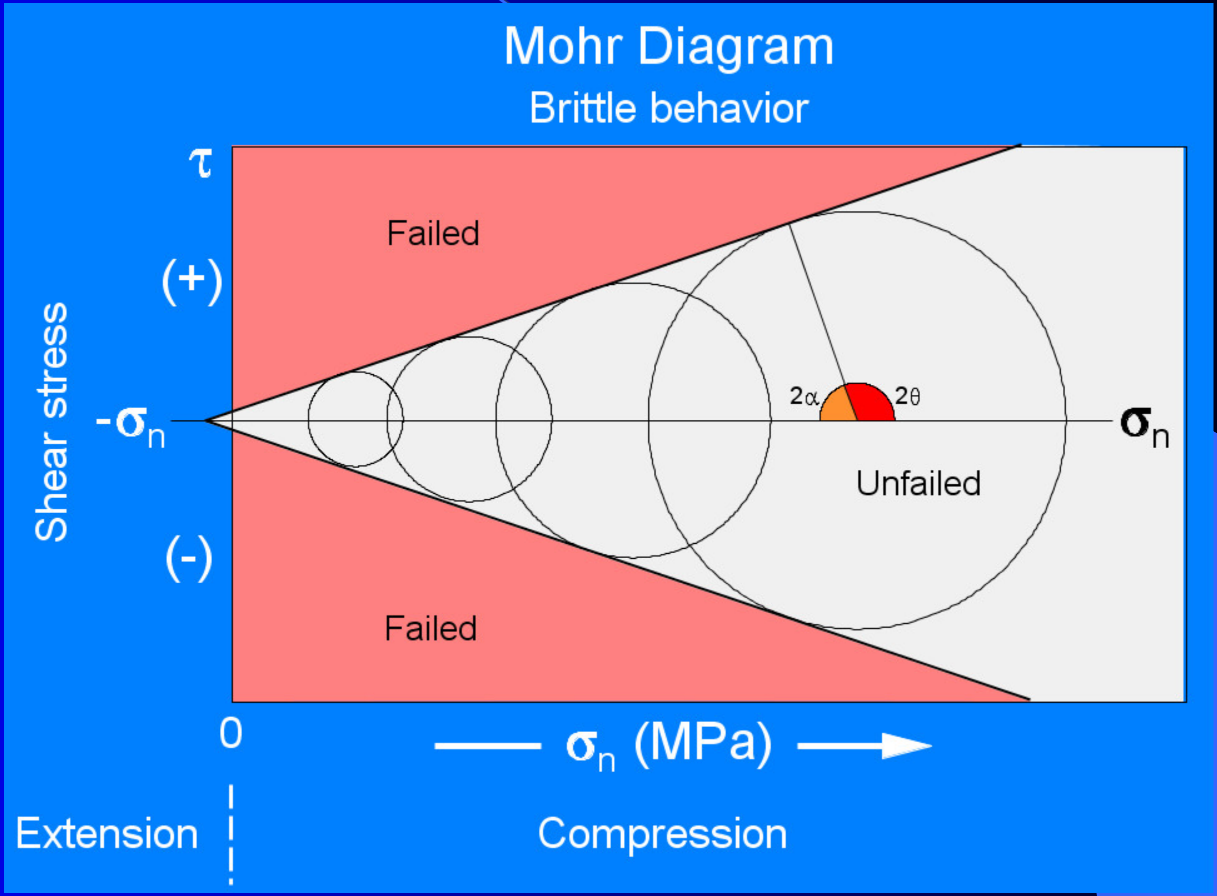
The Mohr Diagram is a graphical representation of the compressive and shear stress on a plane. In this example, 2 = 60º, the angle between the principal stress direction and the pole to the plane.

Results of a triaxial load machine experiment. In this case the material exhibited brittle behavior. Coulomb-Mohr envelope is bounded by straight lines.

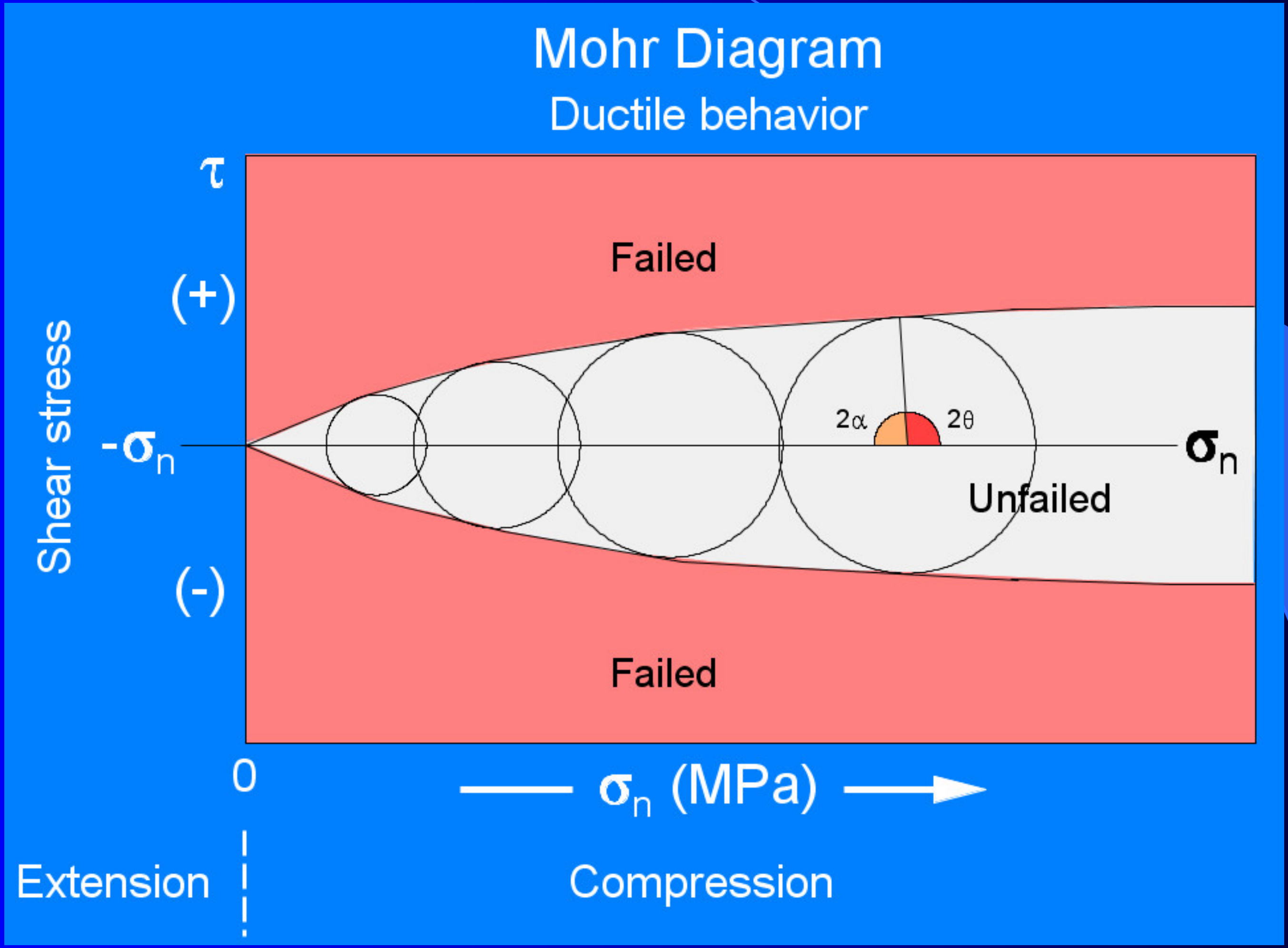
Experimental Data

F_1 and F_3 at failure

Test Run	F_3 MPa	F_1 MPa
1	75	175
2	160	325
3	270	545
4	420	840



Results of a triaxial load machine experiment. In this case the material exhibited ductile behavior. Coulomb-Mohr envelope is bounded by curved lines.



What happens if fractures are present in the rock?

Equations for friction sliding:

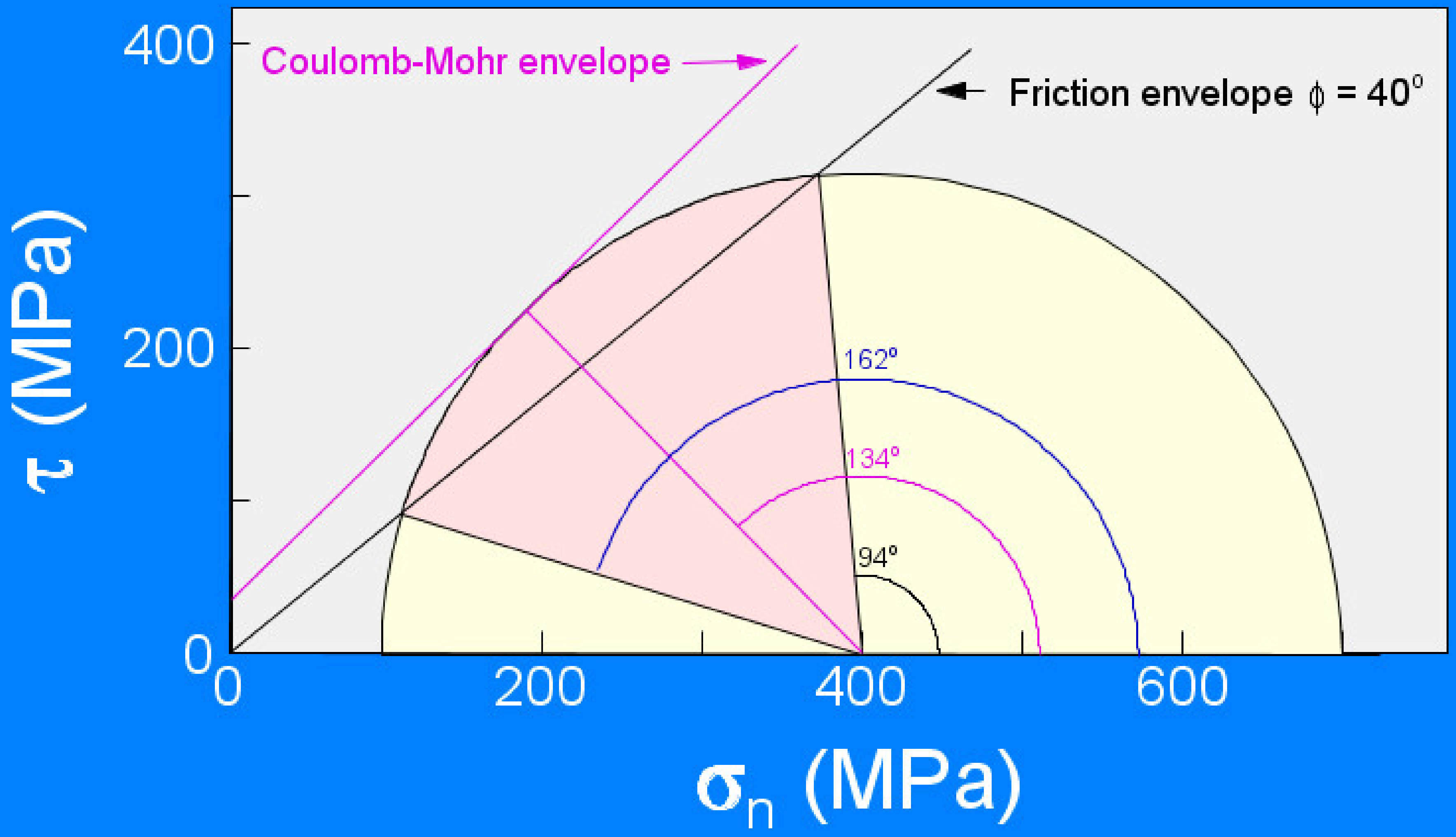
1) Mean Stress < 200 MPa (Depth < 7.5 km)

$$J = 0.85(F_n)$$

2) Mean stress > 200 MPa (Depth > 7.5 km)

$$J = 50 + 0.6(F_n)$$

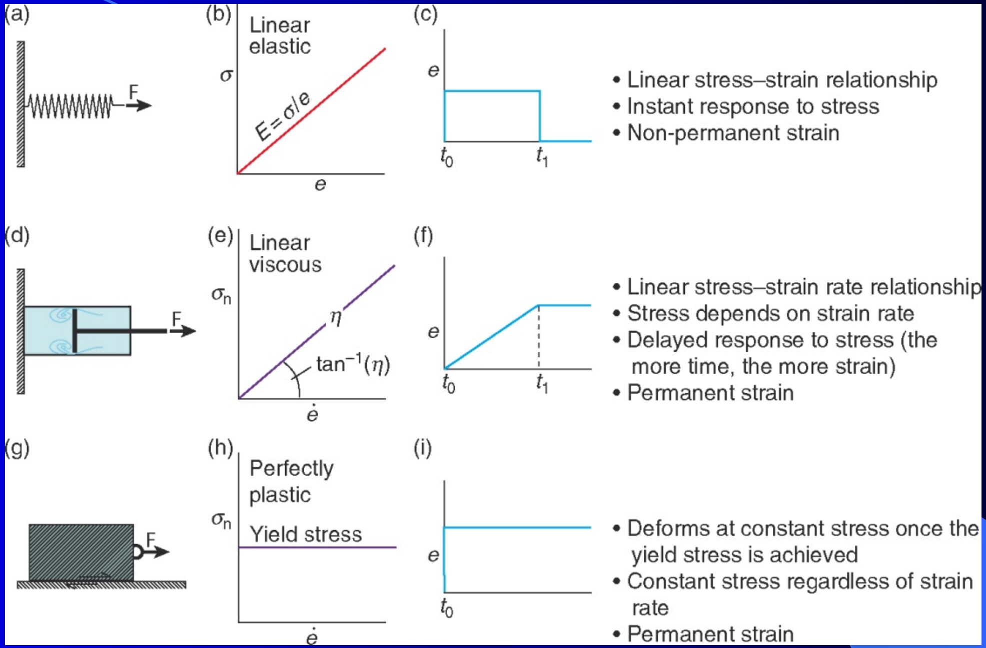
These are empirical equations based on rock mechanics experiments.

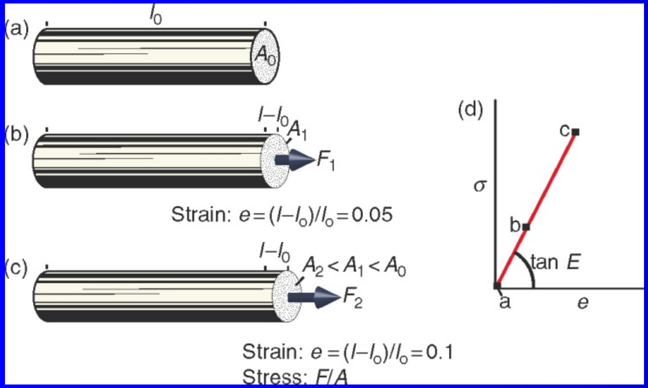


Movement will occur along existing fault planes dipping between 47º and 81º (friction envelope). If fault planes with these orientations are not present in the rock, fracture will occur at 67º when the stress (as represented by the Mohr circle) reaches the Coulomb-Mohr envelope.

Behavior of Materials

- Elastic
- Viscous
- Plastic





Hooke's Law: $\sigma = Ee$

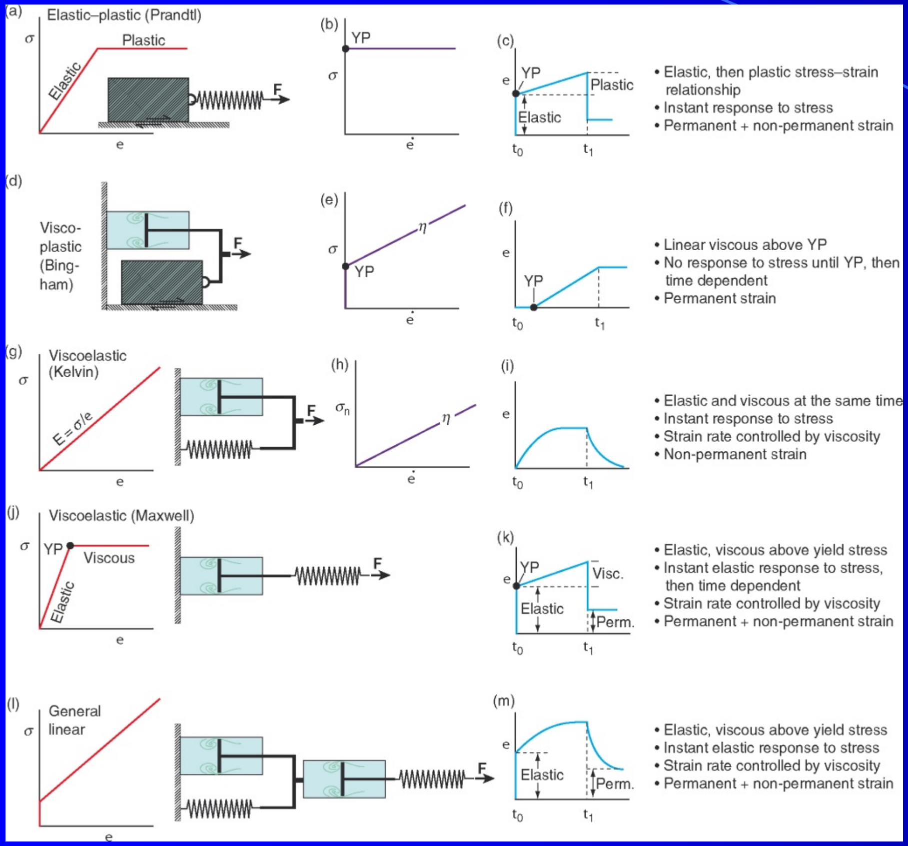
σ = stress

E = Young's modulus

e = extension (one-dimensional strain)

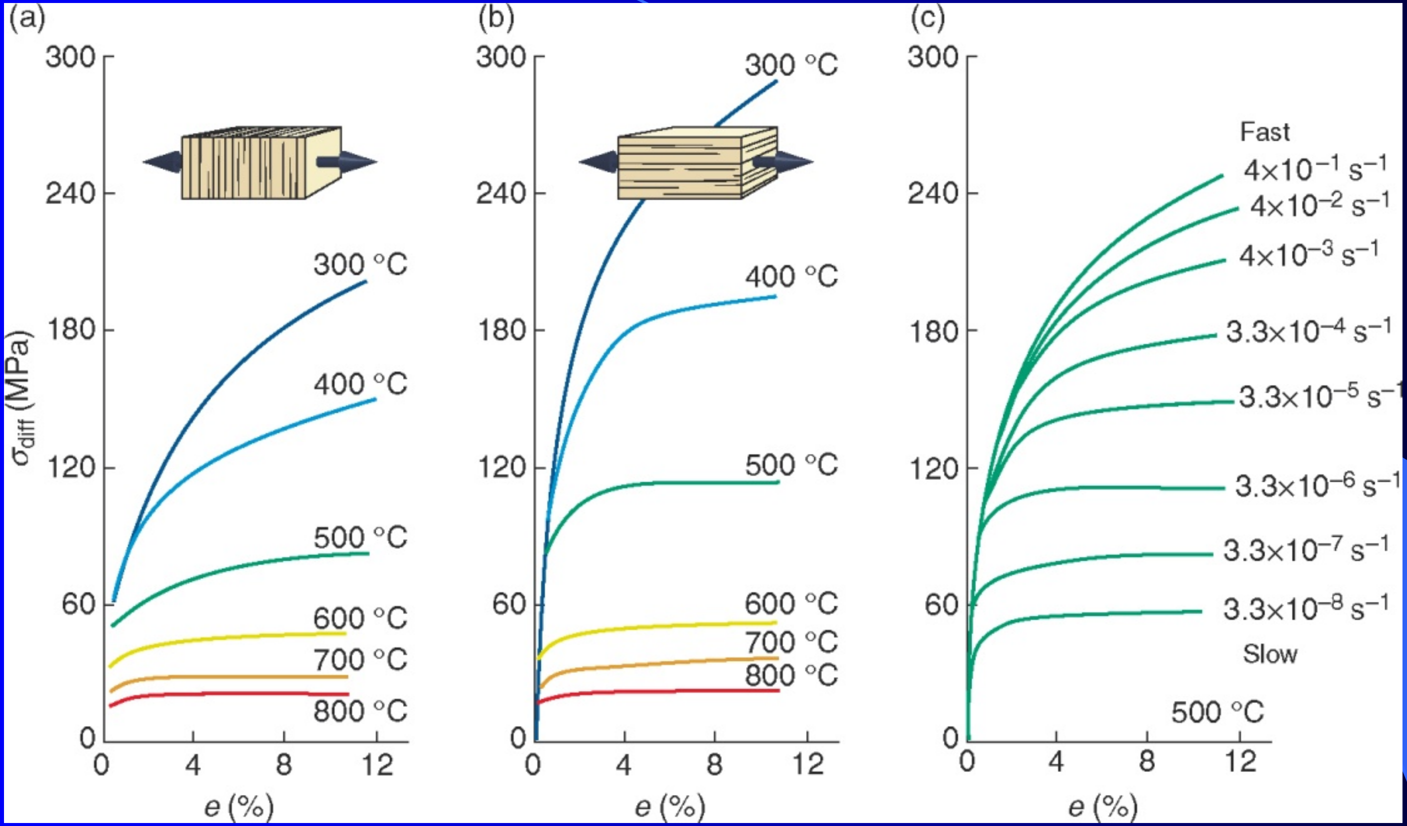
$E = \sigma/e$ = stress/strain

Combined Models



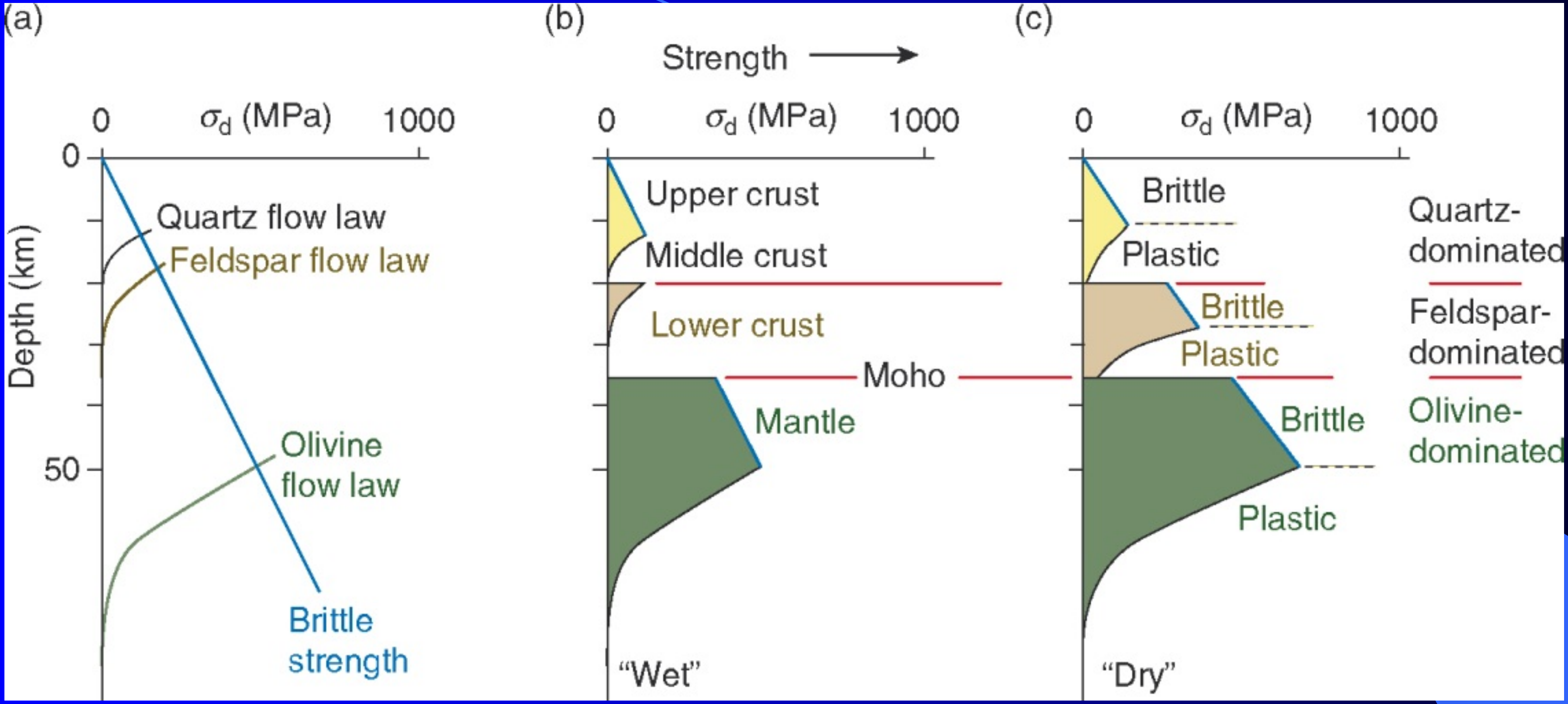
- Elastic-plastic can be applied to the large-scale deformation of the crust and mantle.
- Viscoplastic can be used to describe lava flows.
- Viscoelastic models are used in large-scale modeling of the crust where the elastic deformation describes the short-term response to stress and the viscous part describes the long term response.
- General linear behavior describes the response of natural rocks to stress.

Behavior of materials as a function of temperature, orientation of fabric, and strain rate.



Increasing the temperature, increasing the amount of fluid, lowering the strain rate and, in plastically deforming rocks, reducing the grain size all tend to cause strain weakening.

Brittle-Plastic (Ductile) Transitions in the Crust

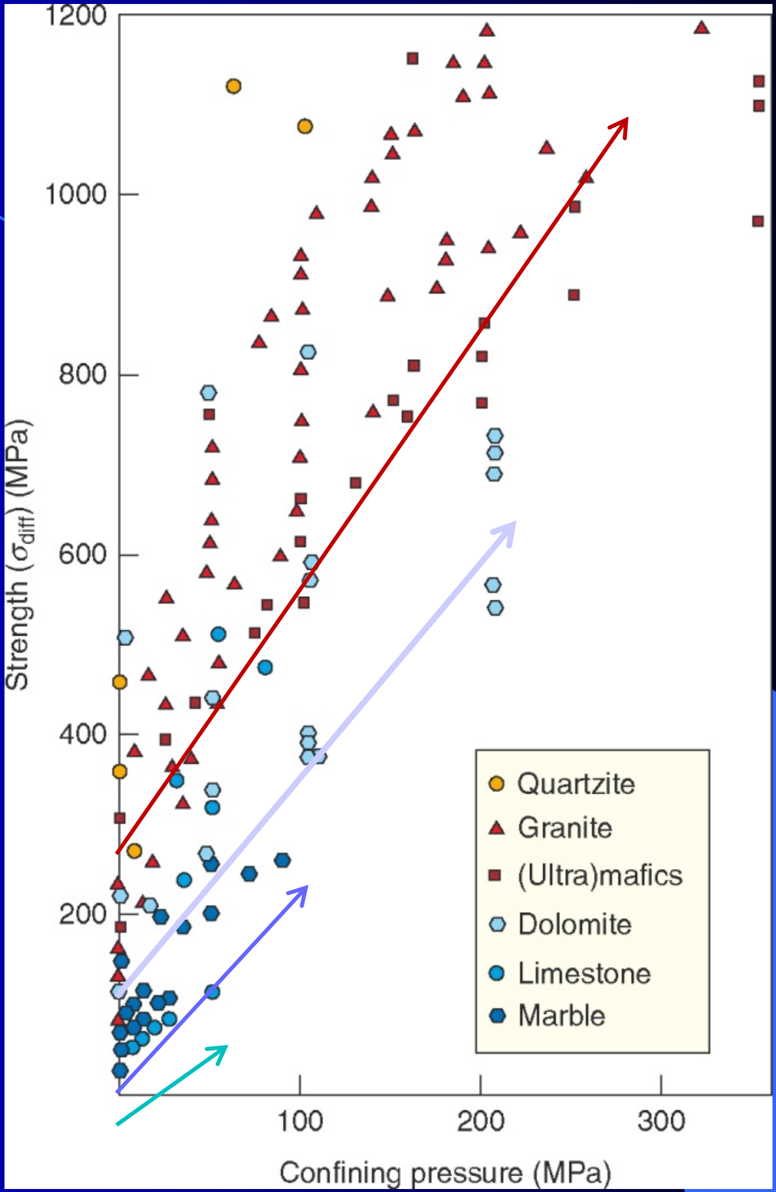


Rheological stratification of the continental crust based on a combination of the brittle friction and plastic flow laws derived experimentally for quartz, feldspar, and olivine. Transition occurs where the brittle and plastic flow laws intersect. Varying rock types with varying mineralogy control these transitions. Dry rocks (c) are considerably stronger than wet rocks (b) and can sustain higher differential stress.

Differential stress at any given point in the Earth is limited by the strength of the rock itself. Any attempt to increase the differential stress above the ultimate rock strength will lead to deformation.

The strength of various rock types increases with confining pressure (burial depth). The absolute strength depends on lithology (mineralogy).

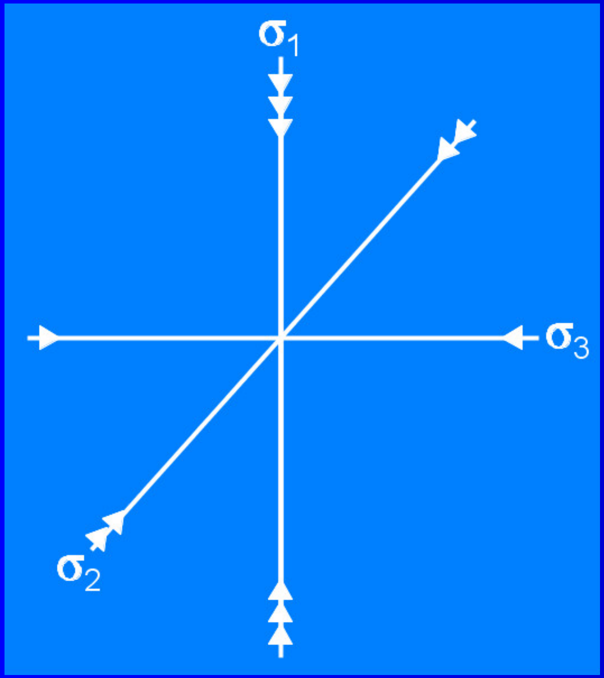
When the differential stress exceeds the strength of the rock, the rock will deform.



Types of Faults

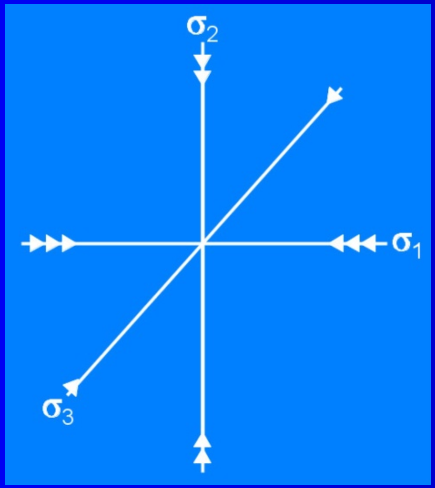
Normal fault. Left side moved down relative to right side.

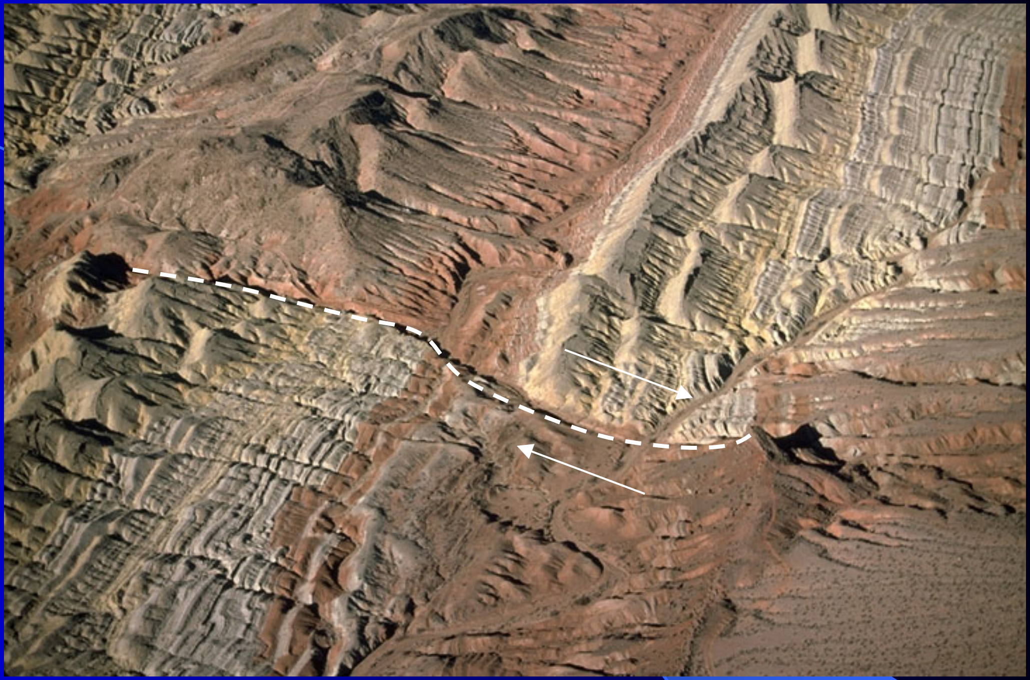
Principal stress orientations



Right lateral **strike-slip fault**.

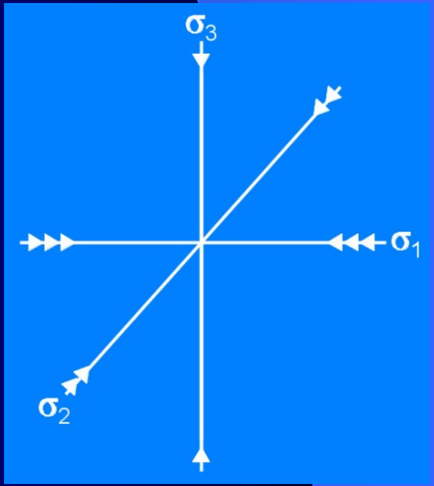
Principle stress orientations





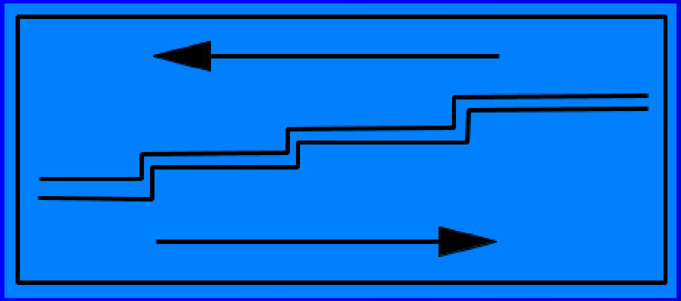
Thrust fault. Block on left thrust up and over the block on the right.

Principal stress orientations



Slickenslides show sense and direction of movement on a fault plane.

Direction of movement



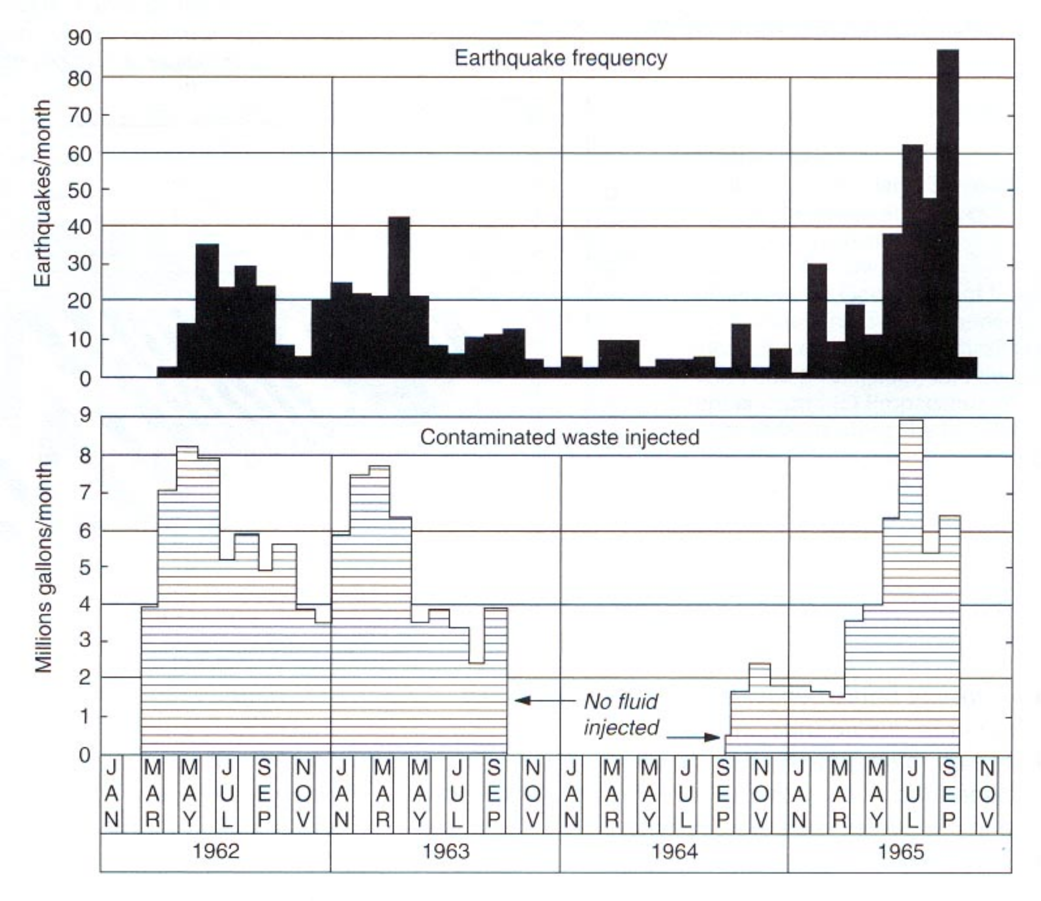
Fluids and earthquakes

If water, or another fluid, occurs in a fault zone

$$\tau = \mu(\sigma_n - P_w) = \mu S$$

where P_w = fluid pressure and $(\sigma_n - P_w)$ = effective normal stress S.

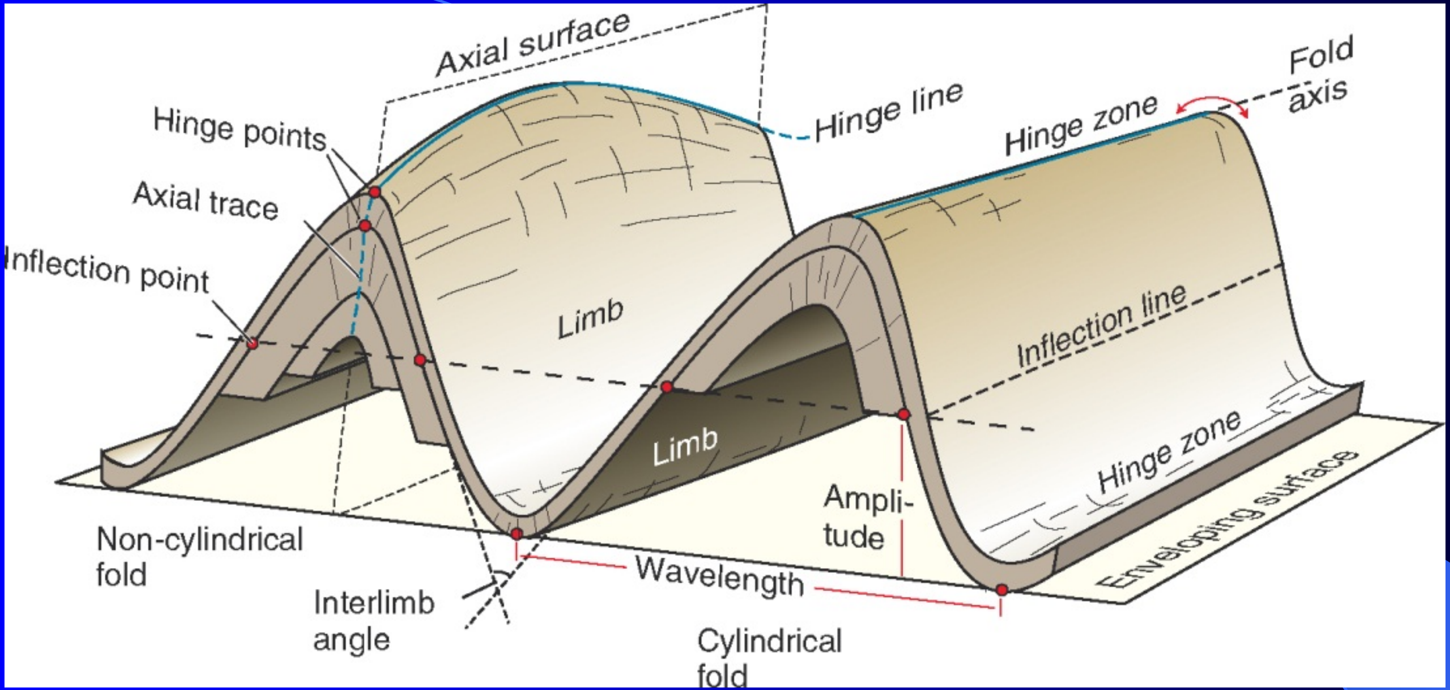
The famous beer can experiment – an interesting way to spend an evening doing science.



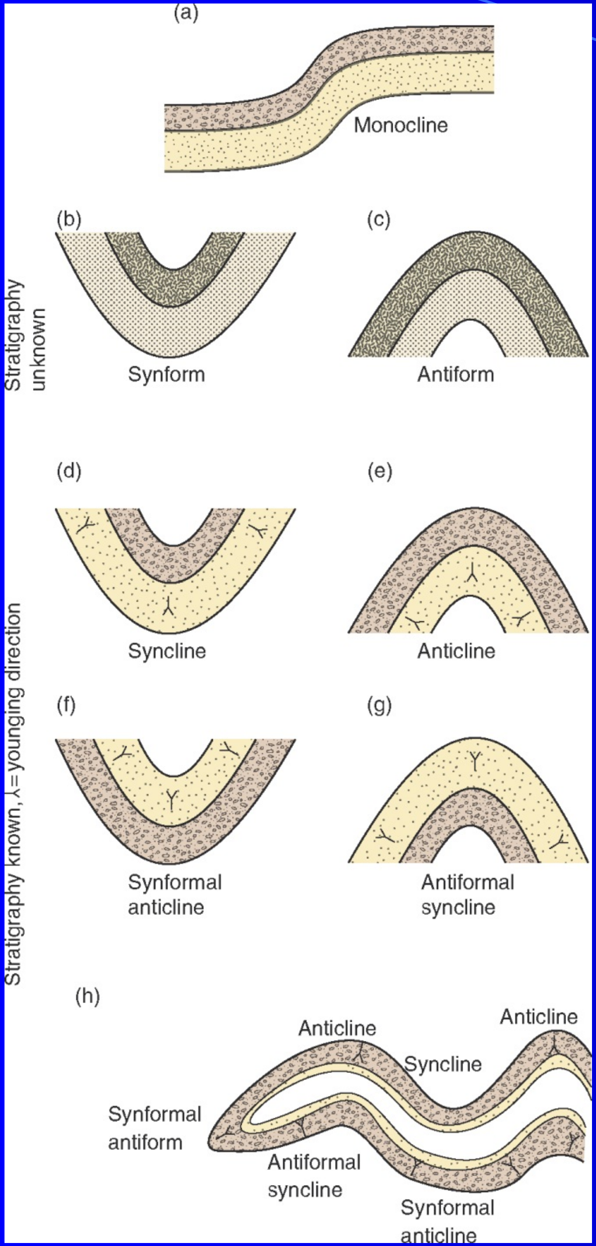
Rocky Mount Arsenal deep waste-disposal well and Denver earthquakes.

Folds and Folding

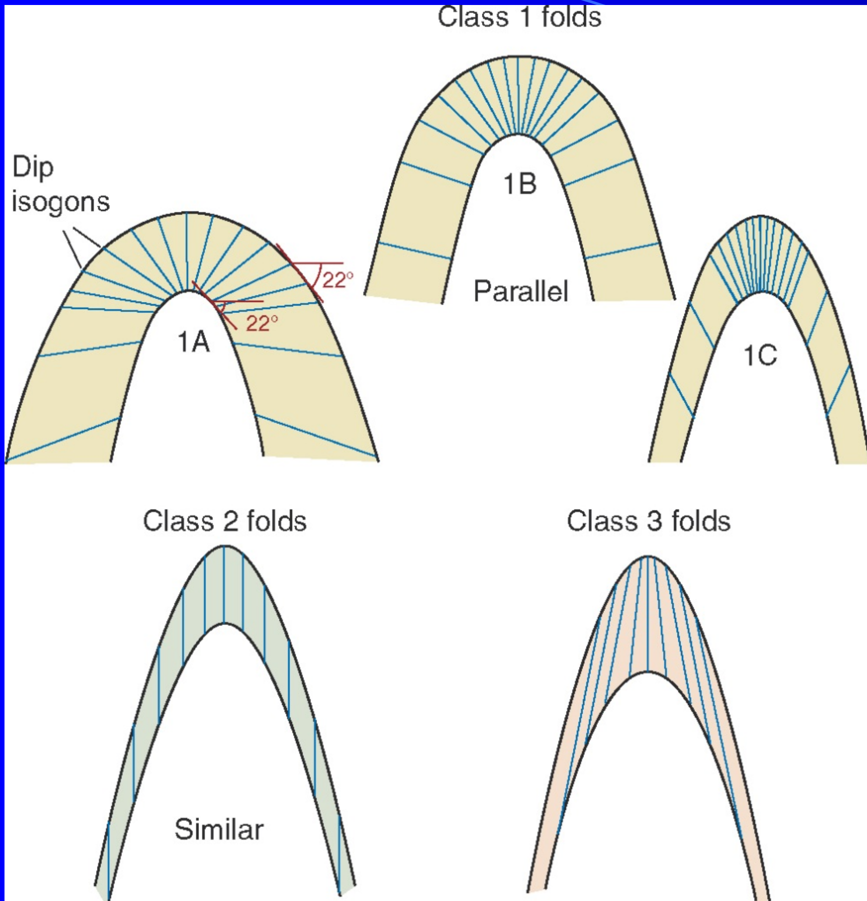
Folding – Geometric Description:

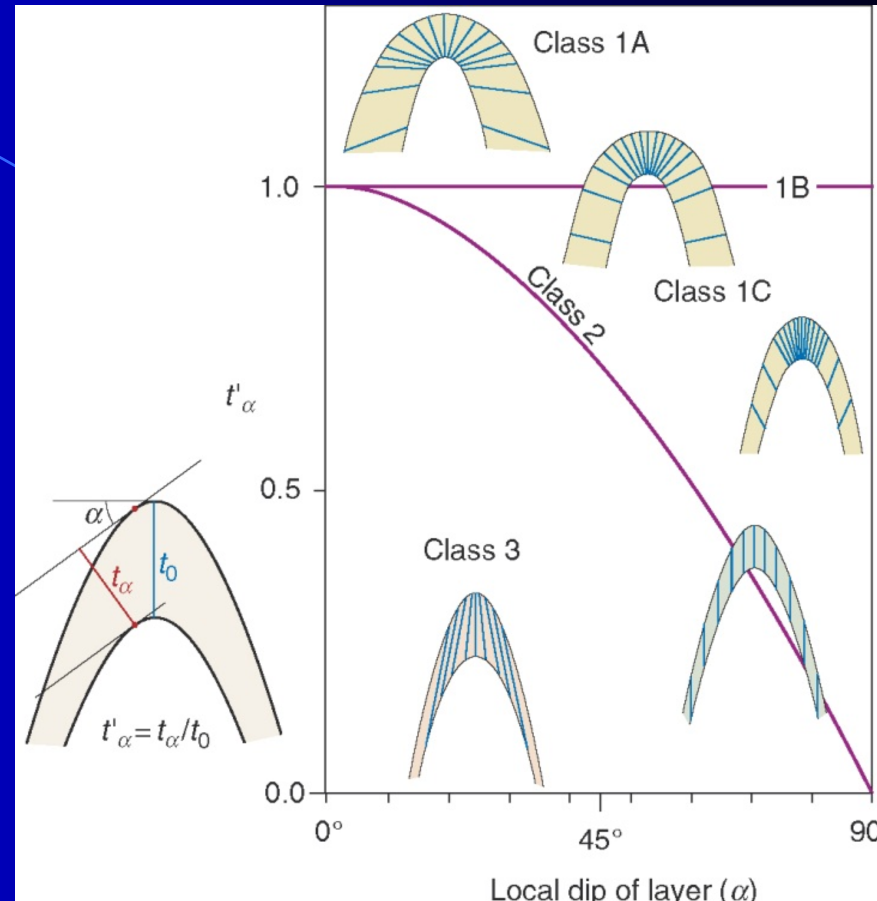


- The hinge connects the two limbs of a fold.
- The hinge point is the point of maximum curvature and is located in the center of the hinge zone.
- The hinge line is the three-dimensional equivalent of the hinge point.
- If the hinge line appears as a straight line it is called a fold axis.
- The axial surface (or axial plane when approximately planar) connects the hinge line of two or more folded surfaces.
- The axial trace represents the intersection between the axial plane and the surface of observation.
- The inflection point (inflection line) is where there is a change in curvature of a fold limb.
- The interlimb angle is the angle enclosed by the two limbs of a fold.
- The enveloping surface is the surface tangent to individual hinges along a folded layer.



- Monocline – a sub-cylindrical fold with only one inclined limb
- Synform – structure where limbs point up
- Antiform – structure where limbs point down
- Syncline – younger rocks in the center
- Anticline – older rocks in the center
- Synformal anticline – inverted anticline
- Antiformal syncline – inverted syncline
- Upright fold – vertical axial plane and horizontal hinge line.
- Recumbent fold – horizontal axial plane and hinge line.



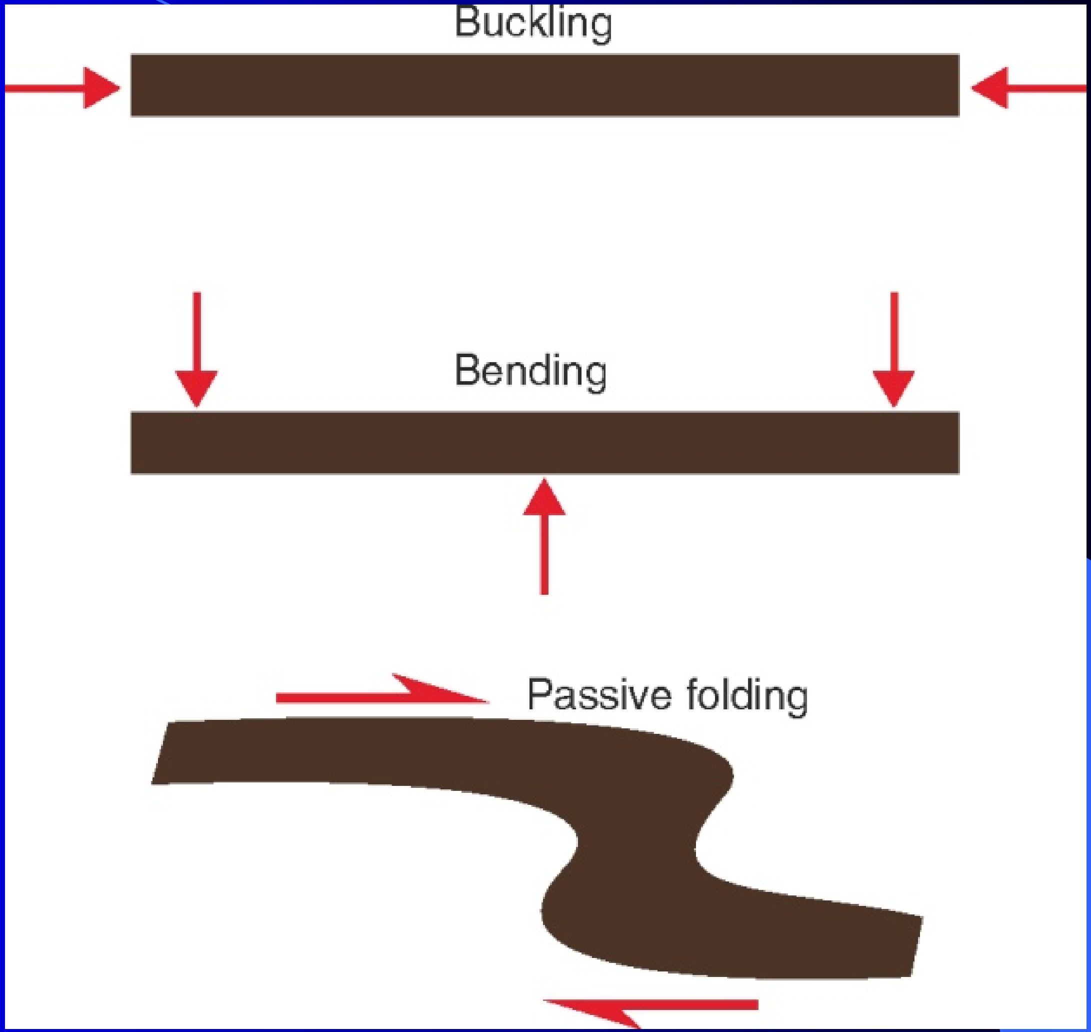


Ramsay's (1967) classification of folds (l). Dip isogons are lines connecting points of identical dip for vertically oriented folds. Mathematical representation (r) of the Ramsay classification. The plot shows the relationship between the dip of a particular layer and the thickness of that layer at different locations on the limb of the fold relative to the thickness of the layer in the fold axis.

Folding Mechanisms

Types of folding:

- Buckling – active folding. There is a viscosity contrast between the folding layer and its host rock. Forces are applied parallel to the layer
- Bending – forces are applied across the layer.
- Passive folding – layers are simply passive markers with no rheological influence



Active folding (buckling) – Class 1B folds

Buckling occurs when a competent layer in a less competent layer is shortened parallel to the length of the layer. There must be irregularities on which folds can nucleate .

Top figure:

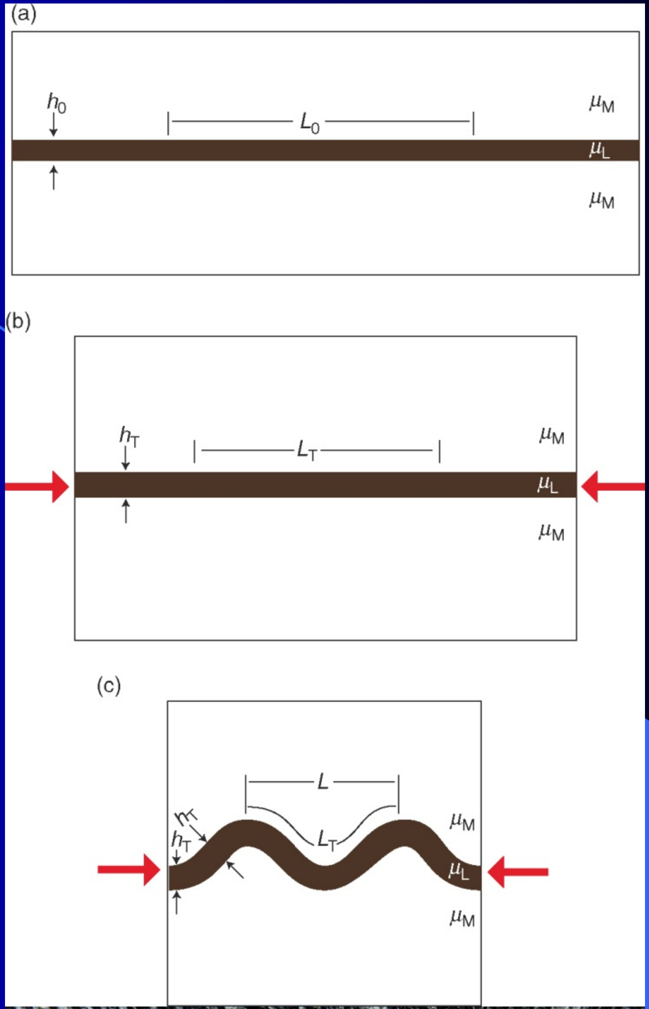
L_o = length of the original layer
h_o = thickness of the original layer

L_T = length of layer after initial shortening
h_T = thickness of original layer after initial shortening

μ_L = viscosity of layer
μ_M = viscosity of matrix

L = wavelength of fold

Bottom figure: Two folded layers of different thicknesses. The upper and thinner one shows a smaller dominant wavelength than the lower one.



Bending

Bending occurs when forces act across a layer at high angle.

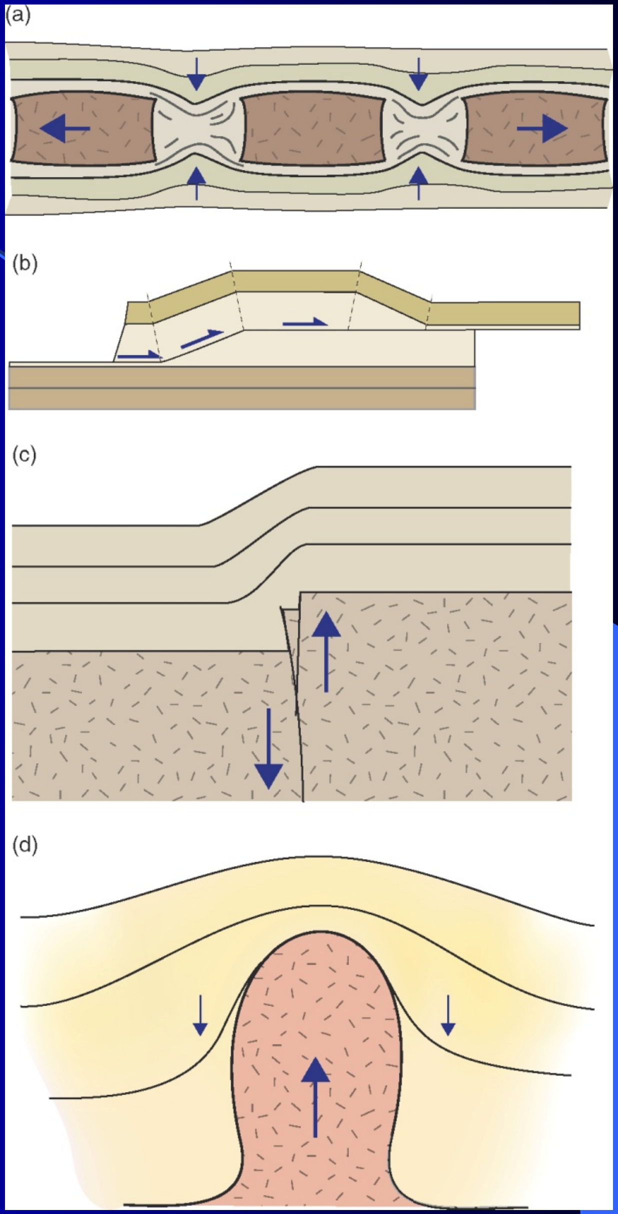
Examples of bending:

a) Between boudins

b) Above thrust ramps

c) Above reactivated faults

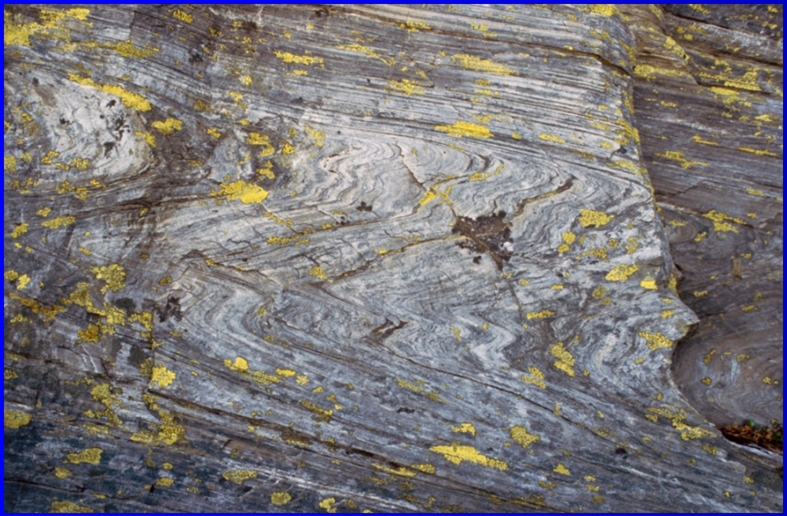
d) Above shallow intrusions or salt diapirs

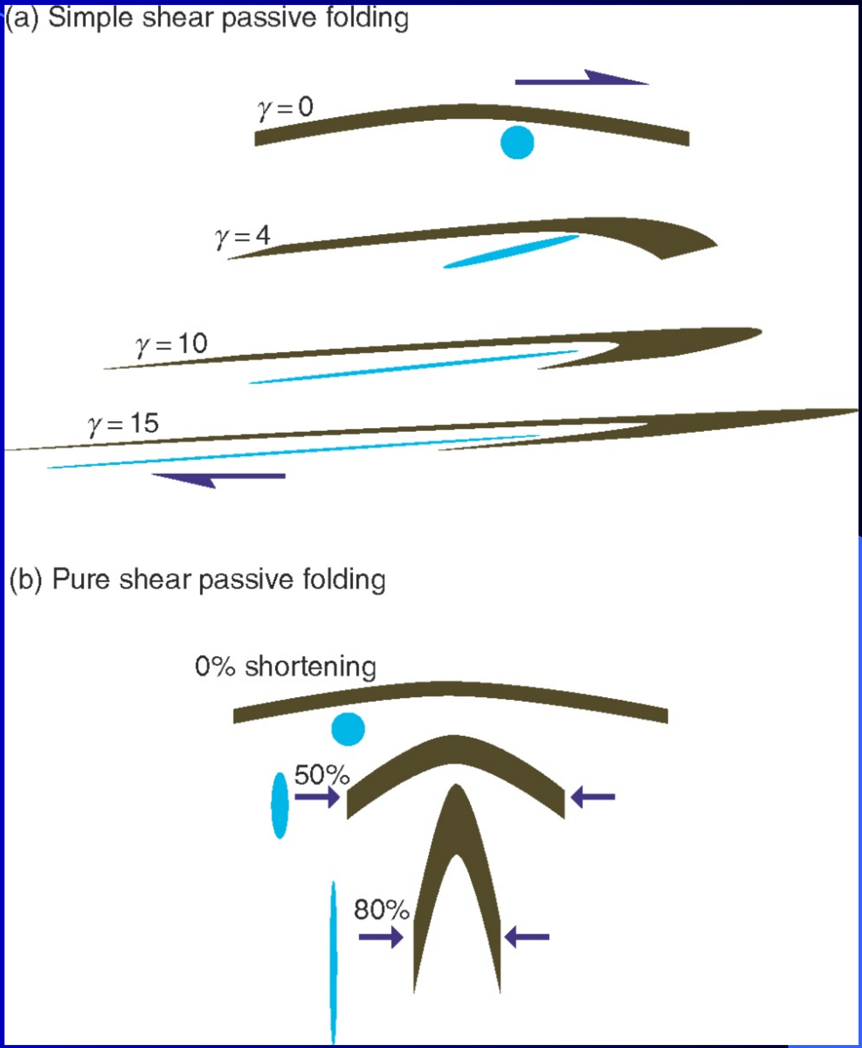


Passive (class 2 folds) folding

Passive folding produces harmonic folds where the layering plays no mechanical role and therefore has no influence on the shape of the fold.

Passive folds can form in response to any kind of ductile strain – simple shear, subsimple shear, transpression, and pure (coaxial) shear.



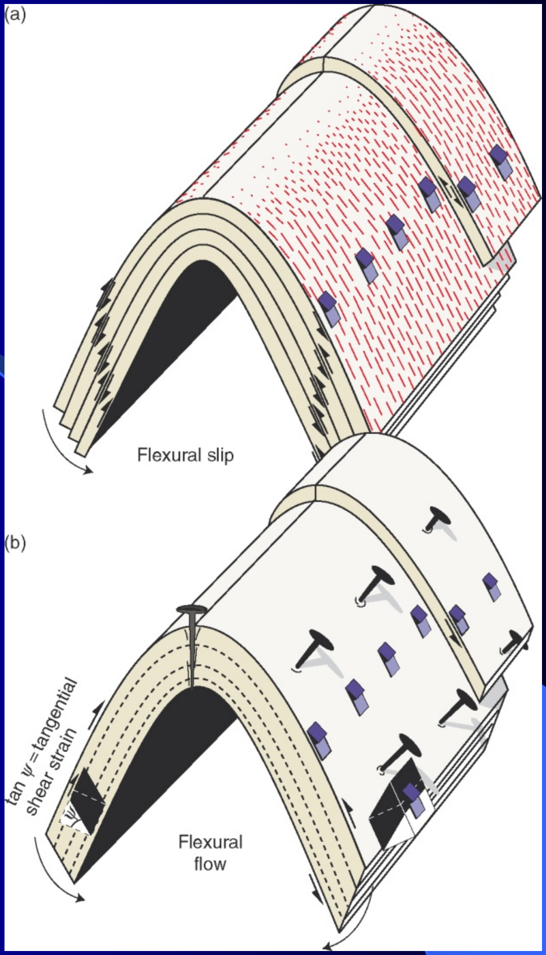


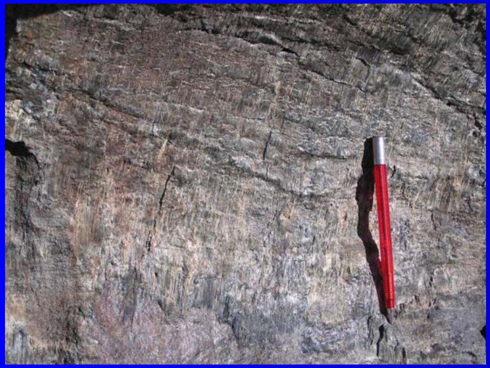
Flexural slip, flexural flow, orthogonal flexure (Class 1B)

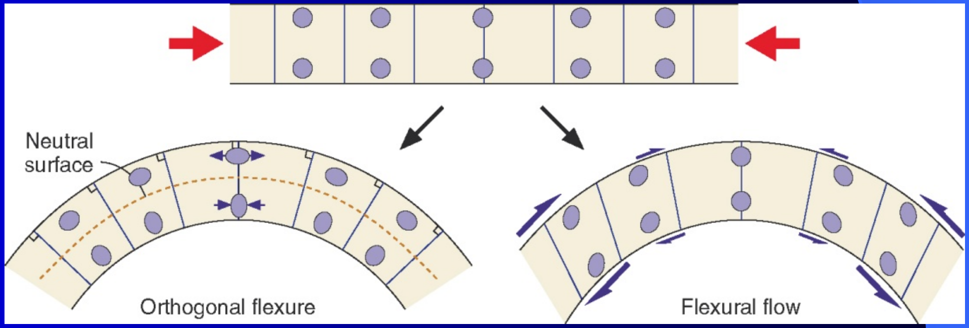
Flexural slip – deforming medium is layered or has a strong mechanical anisotropy (peanut butter and jelly sandwich). Slickenlines on folded weak layers and constant bed thickness are indicative of flexural slip.

Flexural flow – strain becomes more evenly distributed in the limbs. More common in the plastic regime. Shear increases down the limbs because there is a change in orientation (paperback book). Pure flexural folds have no neutral surface and strain increases away from the hinge zone.

Orthogonal flexure – all lines originally orthogonal to the layering remain so throughout the deformation history. Orthogonal flexure produces parallel folds with a neutral surface.





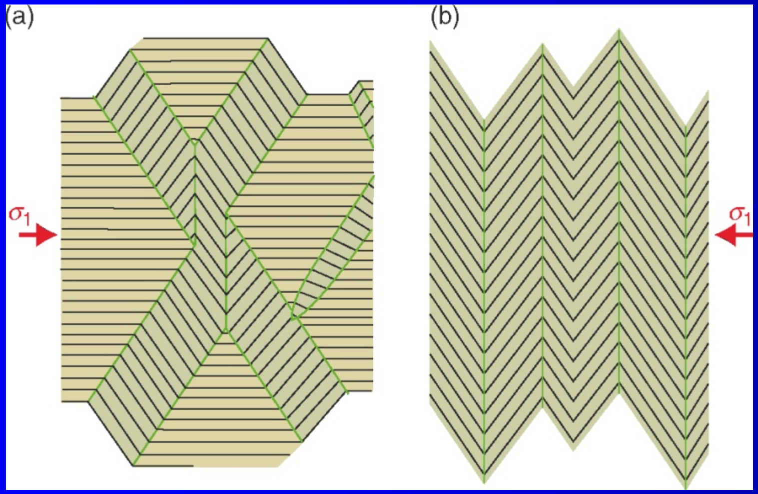


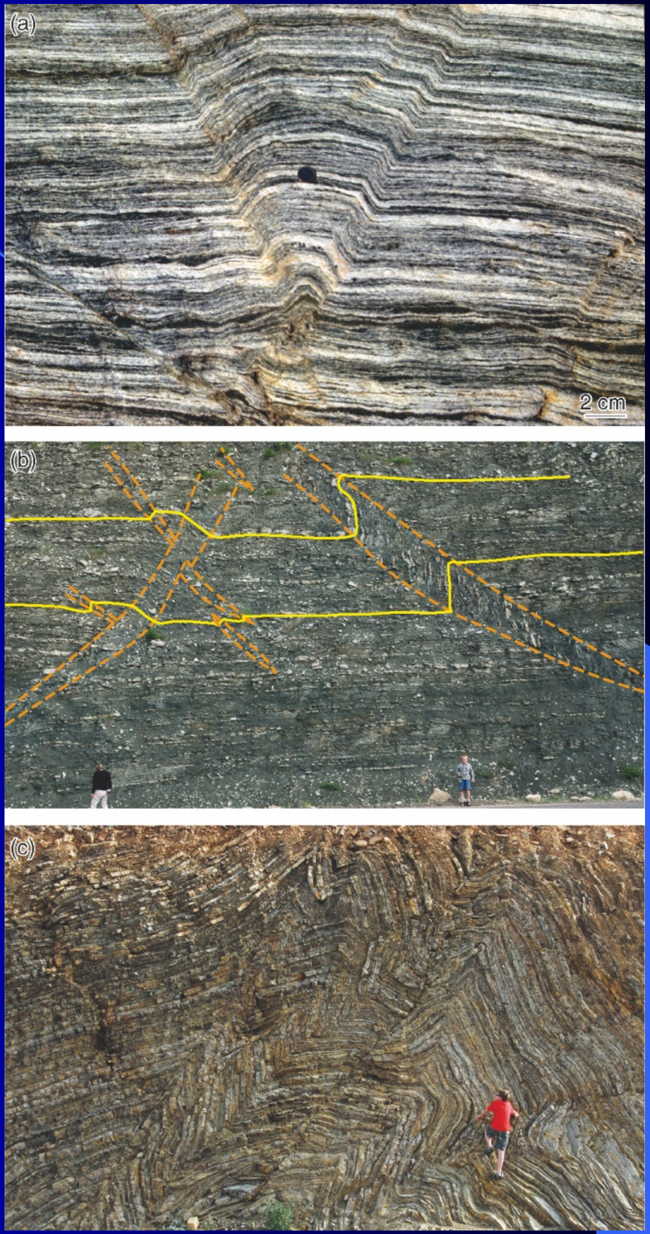
Kink bands (Class 2)

Kink bands – centimeter to decimeter wide zones or bands with sharp boundaries across which the foliation is abruptly rotated.

Figure (right): (a) conjugate kink bands in mylonitized anorthosite gabbro; (b) kink folds related to Laramide thrusting in north Wyoming; (c) kink like folds in oceanic sediments.

Figure (below): (a) the orientation of σ_1 can be determined from the orientation of conjugate sets of kink bands; (b) continued kink band growth can produce chevron folds.





Chevron folds (Class 2)

Chevron folds most likely form by flexural slip of multilayered rocks during layer-parallel shortening. Typically competent layers are separated by thin incompetent layers. The space problem in the hinge zone is resolved by ductile flow of the incompetent (dark) layers or collapse of competent layers in the hinge zone. Strained parts of competent layers are marked in red, showing that layer thickness is maintained on the limbs.