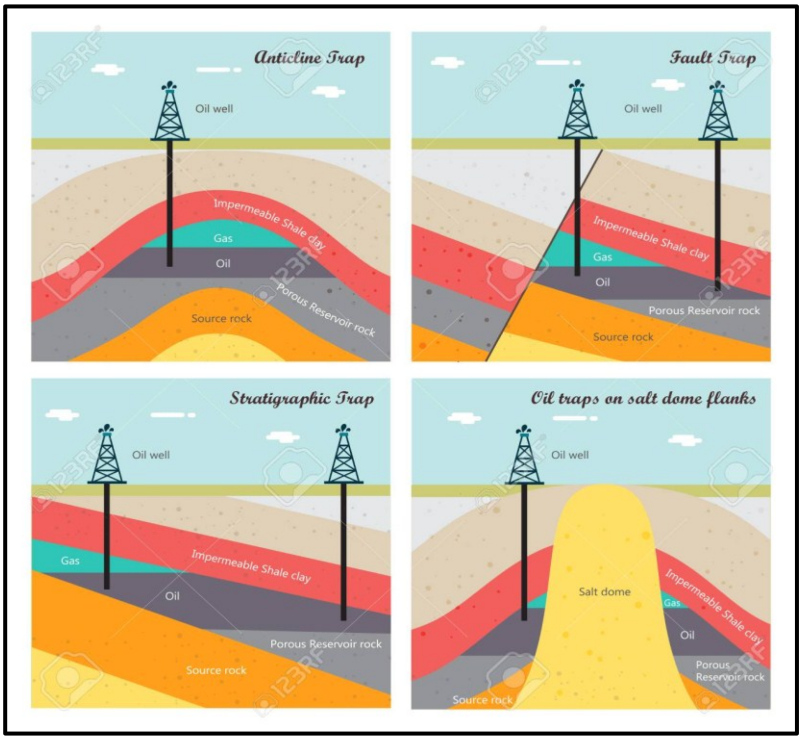
Structural Geology

Dr. Janan M. Barno - 2018

Is the study of the three-dimensional distribution of rock units with respect to their deformational histories? The primary goal of structural geology is to use measurements of present-day rock geometries to uncover information about the history of deformation (strain) in the rocks, and ultimately, to understand the stress field that resulted in the observed strain and geometries. This understanding of the dynamics of the stress field can be linked to important events in the geologic past; a common goal is to understand the structural evolution of a particular area with respect to regionally widespread patterns of rock deformation (e.g., mountain building, rifting) due to plate tectonics.

Use and Importance:

*The study of geologic structures has been of prime importance in **economic geology**, both **petroleum** geology and **mining** geology. **Folded** and **faulted** rock strata commonly form traps that accumulate and concentrate fluids such as petroleum and natural gas. Similarly, faulted and structurally complex areas are notable as permeable zones for hydrothermal fluids, resulting in concentrated areas of base and precious metal **ore** deposits. Veins of minerals containing various metals commonly occupy faults and fractures in structurally*



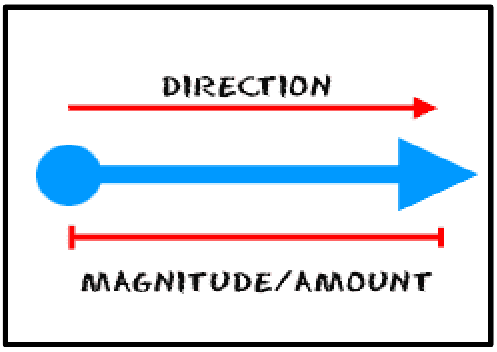
complex areas. These structurally fractured and faulted zones often occur in association with intrusive igneous rocks. They often also occur around geologic reef complexes and collapse features such as ancient sinkholes. Deposits of gold, silver, copper, lead, zinc, and other metals, are commonly located in structurally complex areas.

Structural geology is a critical part of engineering geology, which is concerned with the physical and mechanical properties of natural rocks. Structural fabrics and defects such as faults, folds, foliations and joints are internal weaknesses of rocks which may affect the stability of human engineered structures such as dams, road cuts, open pit mines and underground mines or road tunnels.

Force (F): *is a vector quantity that changes or tends to produce a change in the motion of a body. Force is defined by its* ***magnitude*** *and* ***direction****.*

Hence it may be expressed by an arrow, the length of which is proportional to the magnitude of the force, and the direction of which indicates the direction in which the force is acting.

Vector *is a numerical* ***value*** *in a specific* ***direction****, and is used in both math and physics. The force vector describes a specific amount of force and its direction. You need both value and direction to have a vector.*



Units of Measurements:

A force is a ***push****,* ***pull****, or* ***dragging*** *on an object that changes its velocity or direction. Most often, force is designated as a newton* ***(N)*** *in the metric or* ***SI*** *system of measurement.*

A ***newton*** *is the force required to give a mass of 1 kilogram* ***(1 kg)*** *an acceleration of 1 meter per second per second* ***(1*** m/s^2***)****. It is abbreviated as* ***N****.*

In the ***C.G.S****. system the principal units are length (****centimeters****), mass (****grams****). Time (****seconds****), and force (****dynes****). You might use the dyne, if working with small objects.*

The net force applied to the object equals the mass of the object multiplied by the amount of its acceleration

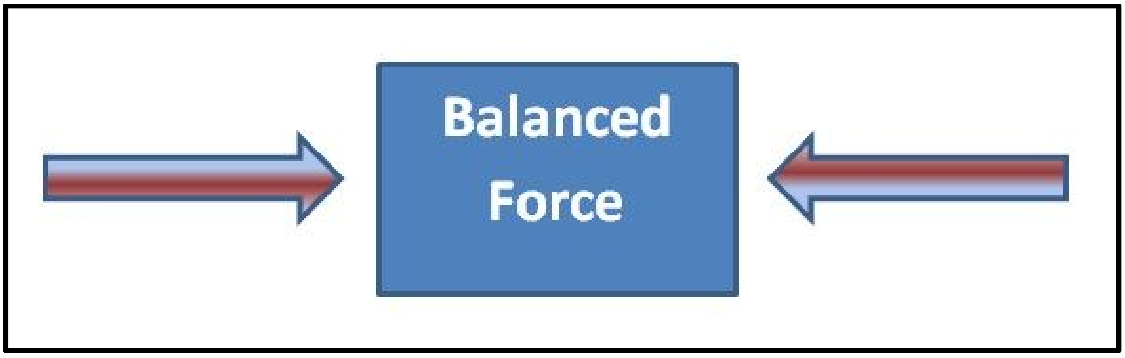
$$F = ma$$

Where ***F*** *is force,* ***m*** *is mass, and* ***a*** *is acceleration.*

Balanced forces

Force that do not cause a change in motion of a body. Are two forces acting in opposite directions on an object, and equal in size.

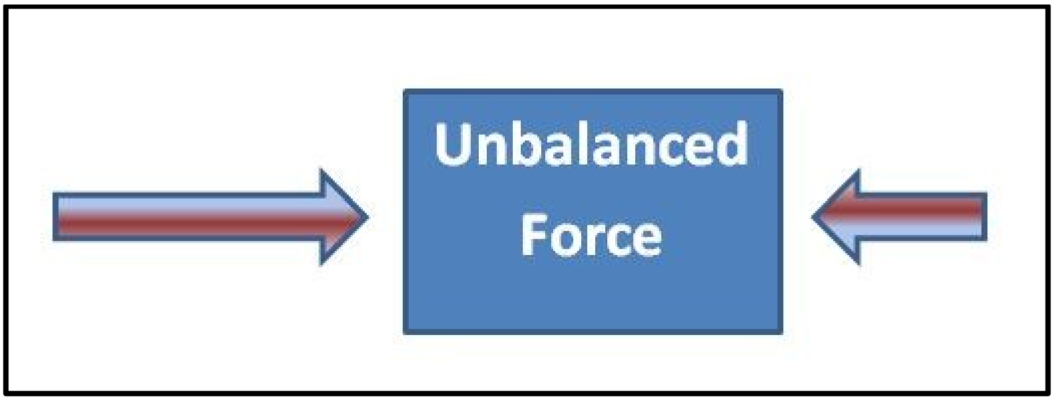
When balanced forces act on an object at rest, the object will not move. If you push against a wall, the wall pushes back with an equal but opposite force. Neither you nor the wall will move.



Unbalanced forces

Forces that cause a change in the motion of a body.

When two forces acting on an object are not equal in size, we say that they are unbalanced forces. If the forces on an object are unbalanced this is what happens: an object that is not moving starts to move. An object that is moving changes speed or direction.



Composition and resolution of forces:

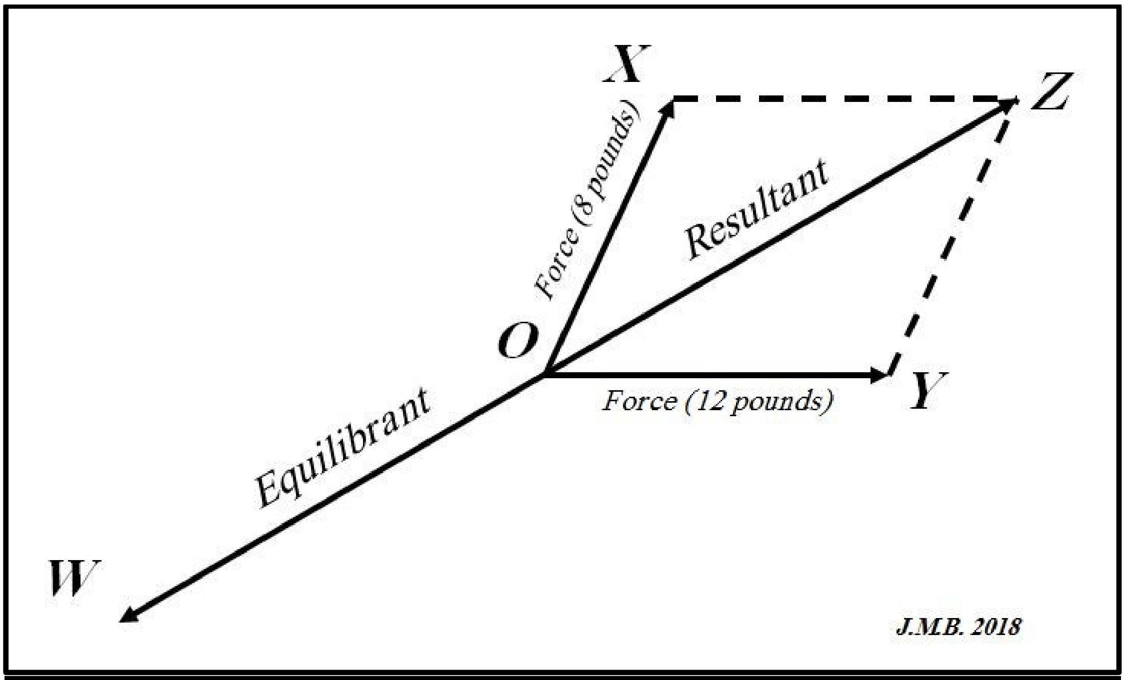
Force may be represented by a vector, that is, a line oriented in the direction in which the force is operating and proportional in length to the intensity of the force. Two or more forces may act in different directions at a point, as in the figure below. Where OX (8 pounds) and OY (12 pounds) act at O. the same result would be produced by the force OZ acting in the direction indicated; OZ is the resultant of OX and OY.

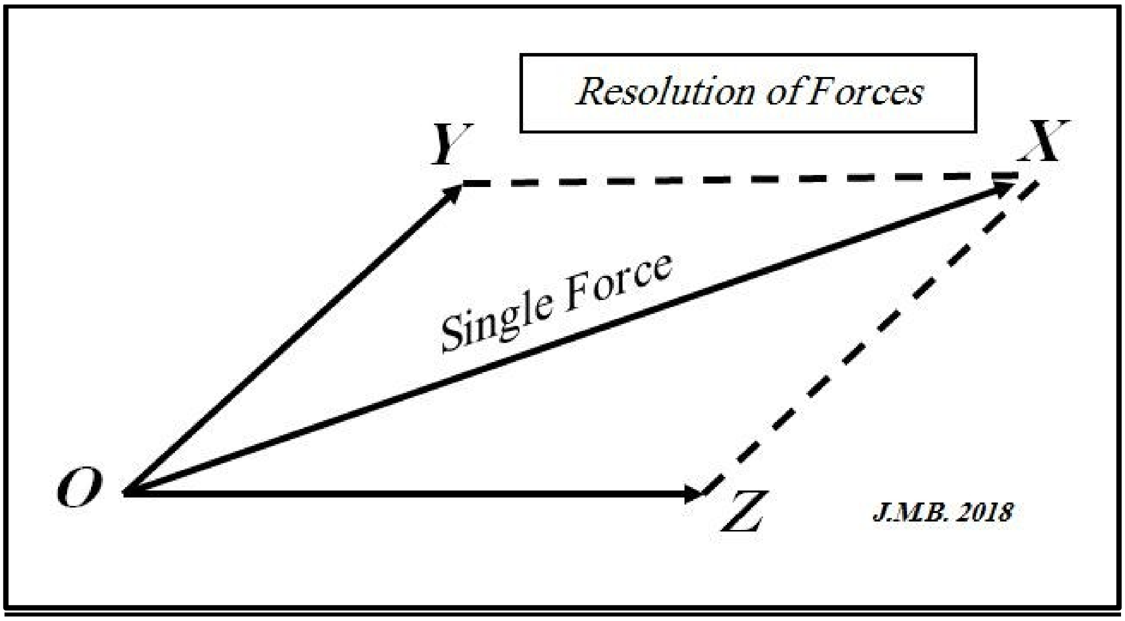
A ***resultant*** *is a single force that produces the same result as two or more forces, and it may be represented by the diagonal of a parallelogram constructed on two arrows that represent the two forces.*

The ***equilibrant*** *is the force necessary to balance two or more forces. In the figure OW is the force necessary to balance OX and OY; it's equal to the resultant of the two forces, but act in the opposite direction.*

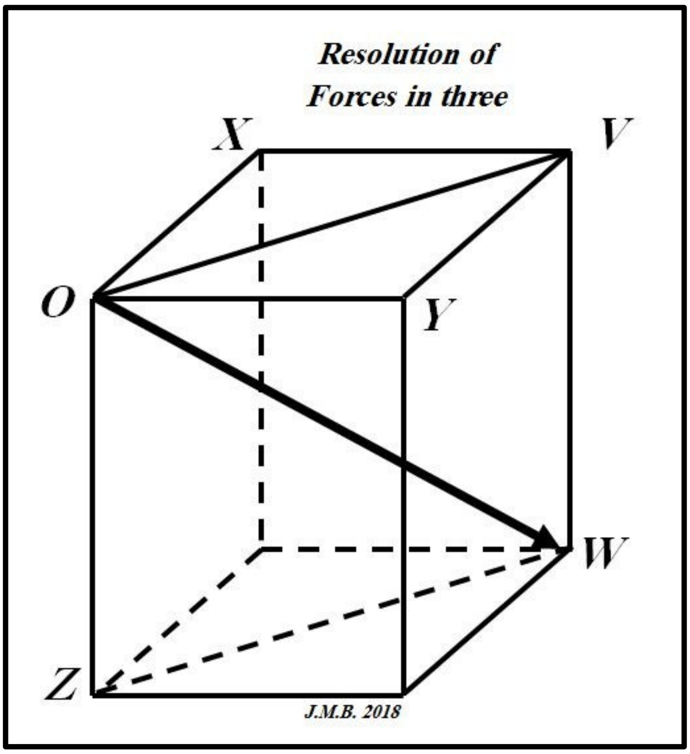
Composition of forces *is a process of finding a resultant of forces that can produce the same effect of several forces on a body.*

Resolution of forces *is the process of finding the components of a single force so that these component forces can produce the same result (effect) on a body as the single force.*





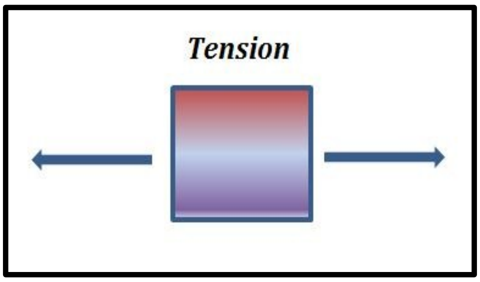
The preceding discussion of the composition and resolution of forces has been confined to two dimensions, but geology is concerned with three dimensions. In the figure below an inclined force OW lies in the vertical plane OZVW. This force may be resolved in to two components, one of which, OZ is vertical; the other, OV, lies in the horizontal plane OXVY. The OV may in turn be resolved into OX and OY, which lie in the horizontal plane and at right angles to each other.



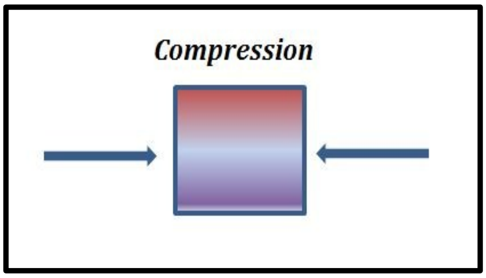
Differential Forces:

In many instances the forces acting on a body are not equal on all sides. A body is said to be under:

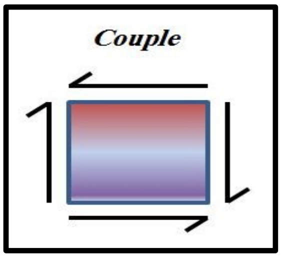
1- ***Tension*** *(tensile forces) when its subjected to external forces that tend to pull it apart, it may be represented by two arrows that are on the same straight line and are directed away from each other.*



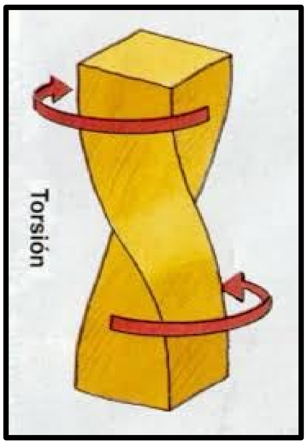
2- ***Compression*** *(compressive forces) when it's subjected to external forces that tend to compress it (squeeze). Compression may be represented by two arrows that are on the same straight line and are directed toward each other.*



3- ***A couple*** *(shear) consists of two equal forces that act in opposite directions in the same plane, but not along the same line. It can be represented by the upper and lower arrows, which are not on the same straight line and which are directed away from each other. To prevent rotation and preserve equilibrium a second couple is necessary as shown by the vertical arrows.*

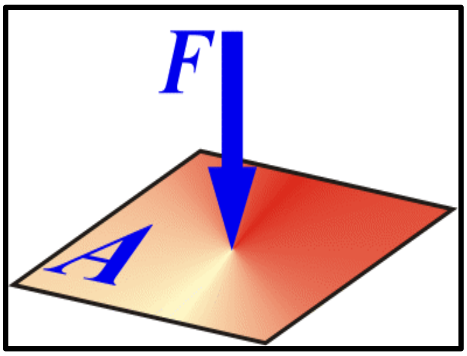


4- ***Torsion*** *results from twisting. If the two ends of a rod are turned in opposite directions, the rod is subjected to torsion.*



Stress

Stress, is the force applied to an object.



In geology, represented by the symbol **σ** *(sigma), is defined as the force per unit area [A], or $\sigma = F/A$. You can, therefore, consider stress as the intensity of force, or a measure of how concentrated a force is. A given force acting on a small area will have a greater intensity than that same force acting on a larger area (a flat-Tensile headed hammer).*

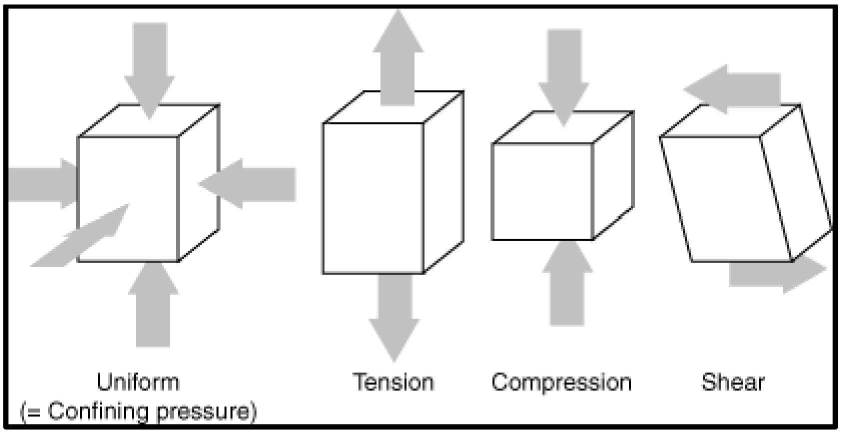
Four types of stresses act on materials:

1- ***Compressive stress****: is directed pressure that tends to compress a body. Squeezes rocks together, causing rocks to fold or fracture (break).*

2- ***Tensile stress****: is directed pressure that tends to pull the body a part. Rocks under tension lengthen or break apart.*

3- ***Shearing stress****: when forces are parallel but moving in opposite directions, the stress is called shear stress, act as a couple on both sides of a surface.*

4- ***Confining stress****: A deeply buried rock is pushed down by the weight of all the material above it. Since the rock cannot move, it cannot deform. This is called confining stress.*



The Components of Stress

The orientation and magnitude of the stress state of a body is defined in terms of its components projected in a reference frame, which contains three mutually perpendicular coordinate axes, ***X****,* ***Y****, and* ***Z****.*

We resolve the stress acting on each face of a cube into three components. For a face normal to the ***x-axis*** *the components are* ***σxx****, which is the component normal to that face, and* ***σxy*** *and* ***σxz****, which are the two components parallel to that face.*

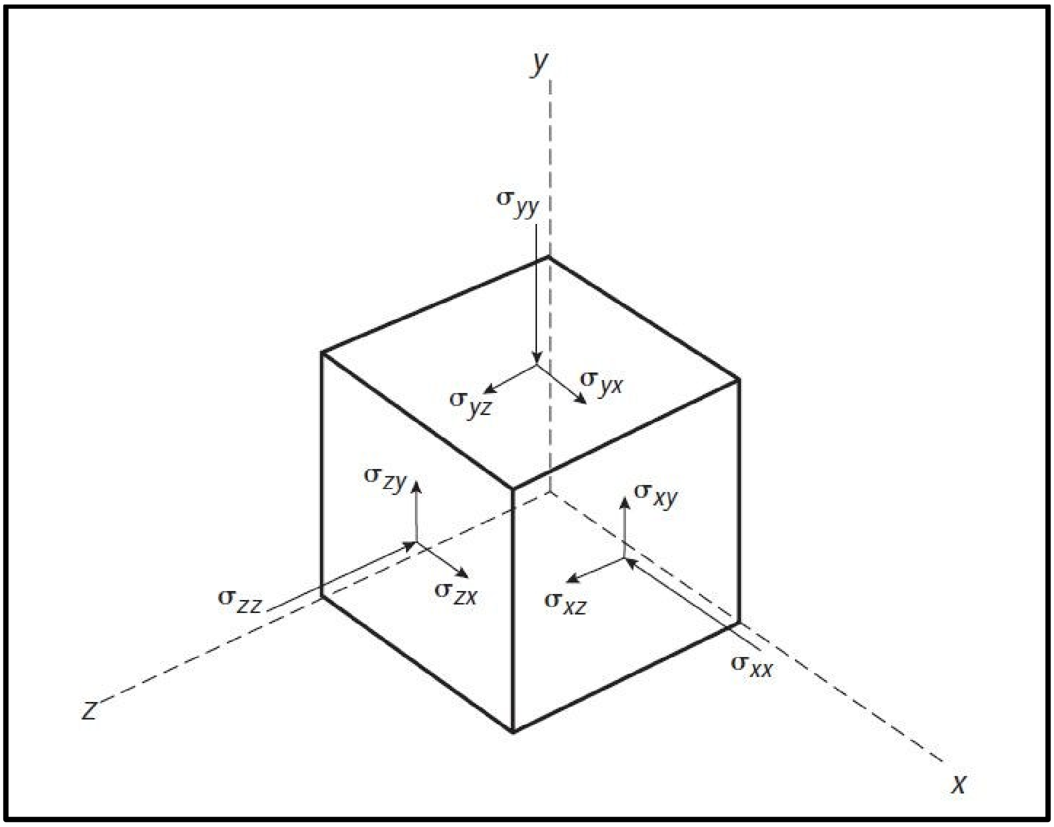
These last two stresses are ***shear*** *stress components, acting along one of the other coordinate axes* ***y*** *and* ***z****, respectively. Applying this same procedure for the faces normal to* ***y*** *and* ***z****, we obtain a total of nine stress components.*

In the direction of ***X: Y: Z****:*

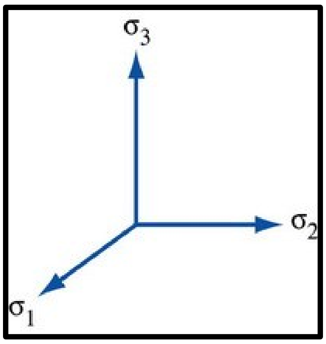
stress on the face normal to ***x: σxx σxy σxz***

stress on the face normal to ***y: σyx σyy σyz***

stress on the face normal to ***z: σzx σzy σzz***



The principal stress in native:



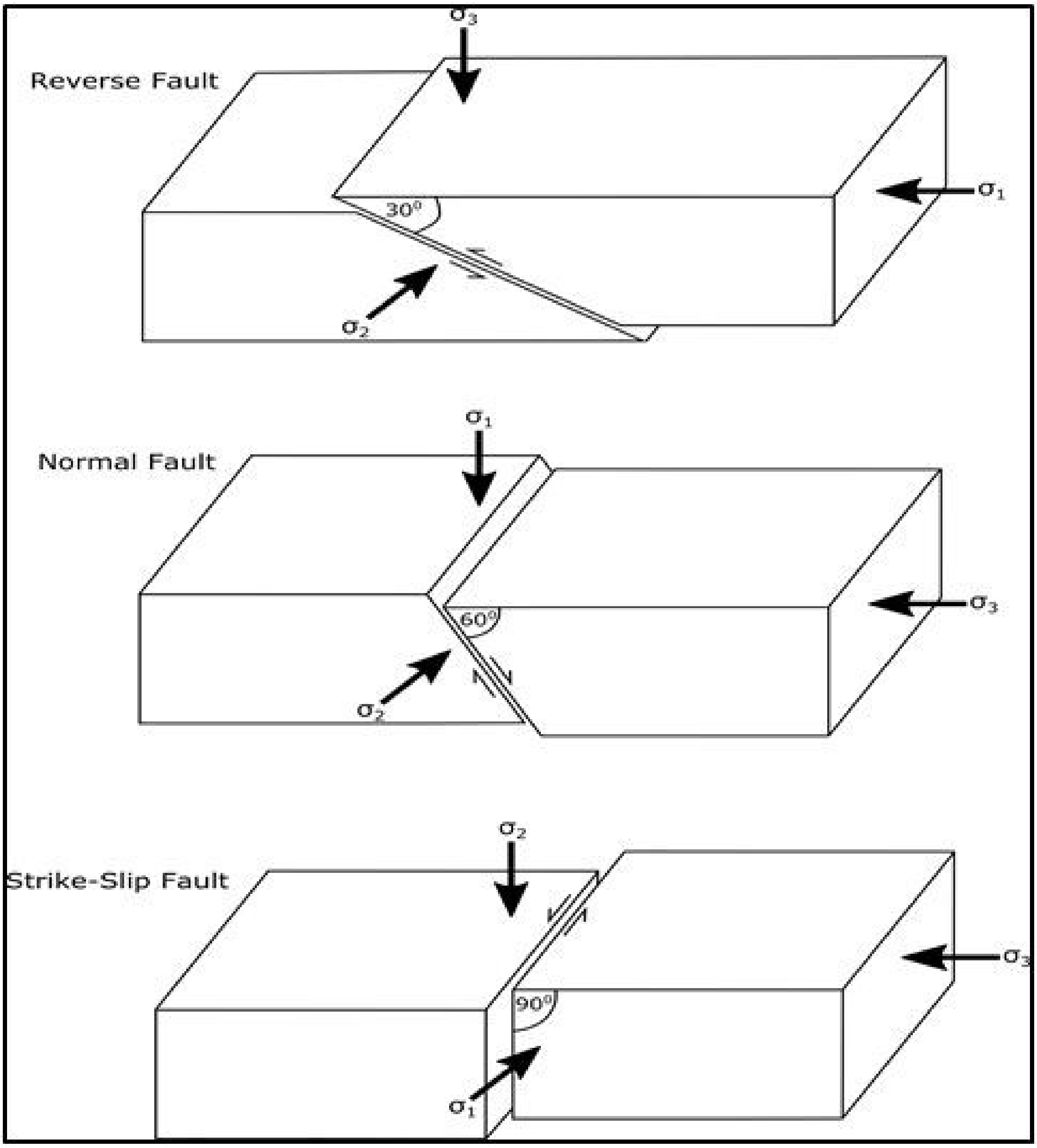
The stress acting at any point may be referred to three mutually perpendicular axes known as the principal stress axes:

σ 1 *= maximum principal stress axis*

σ 2*= intermediate stress axis*

σ 3*= minimum principal stress axis*

These three orthogonal stress axes directed perpendicular to principal planes can be compressive, tensile or various contributions are possible.



Stress States

If the three principal stresses are equal in magnitude, we call the stress ***isotropic****. This stress state is represented by a* ***sphere*** *rather than an ellipsoid, because all three radiuses are equal. If the principal stresses are unequal in magnitude, the stress is called* ***anisotropic****. The maximum principal stress is given the symbol* $\sigma 1$*, the intermediate and minimum principal stresses acting along the other two axes are given the symbols* $\sigma 2$ *and* $\sigma 3$*, respectively. Thus, by (geologic) convention:*

$$\sigma 1 \geq \sigma 2 \geq \sigma 3$$

Mean Stress and Deviatoric Stress

The ***mean stress*** *is defined as* $(\sigma 1 + \sigma 2 + \sigma 3)/3$*, using the symbol* σm*. The difference between mean stress and total stress is the* ***deviatoric stress*** (σdev)*, so*

$$\sigma = \sigma mean + \sigma dev$$

Deviatoric Stress *a stress component in a system which consists of unequal principal-stresses.*

The mean stress is often called the hydrostatic component of stress or the ***hydrostatic pressure****, because a fluid is stressed* ***equally*** *in all directions. Because the magnitude of the hydrostatic stress is equal in all directions it is an* ***isotropic*** *stress component. When we consider rocks at depth in the Earth we generally refer to* ***Lithostatic pressure*** *The Lithostatic stress component is best explained by a simple but powerful calculation.*

Consider a rock at a depth of 3 km in the middle of a continent. The Lithostatic pressure at this point is a function of the weight of the overlying rock column because other (tectonic) stresses are unimportant. The local pressure is a function of rock ***density****,* ***depth****, and* ***gravity****:*

$$Pl = \rho \; . \; g \; . \; h$$

If ρ (density) equals a representative crustal value of 2700 kg/m3, g (gravity) is 9.8 m/s2, and h (depth) is 3000 m, we get:

Pl = 2700* 9.8* 3000 = 79.4 * 10^6 Pa ≈ 80 MPa (or 800 bars)

In other words, for every kilometer in the Earth's crust the lithostatic pressure increases by approximately 27 MPa. With depth the density of rocks increases.

The Stress differences

Is the algebraic difference between the greatest and least principal stress

$$(\sigma 1 - \sigma 3) = \int d$$

Example 1:

Maximum principal stress **σ1 = + 1000 kg/cm²** (*compressive*)

Minimum principal stress **σ3 = + 500 kg/cm²** (*compressive*)

The stress difference **σ1 – σ3 = 1000 – 500 = 500 kg/cm²**

Example 2:

Maximum principal stress **σ1 = + 1 kg/cm²** (*compressive*)

Minimum principal stress **σ3 = - 1000 kg/cm²** (*tensile*)

The stress difference **σ1 – σ3 = 1 – (- 1000) = 1 + 1000 = 1001 kg/cm²**

Deformation and Strain

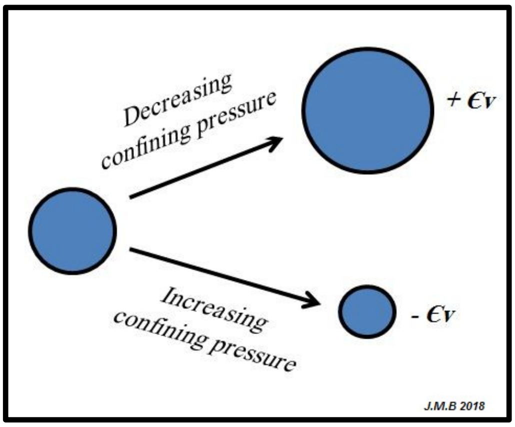
Deformation and strain are closely related terms that are sometimes used as synonyms, but they are not the same.

Deformation *describes the collective displacements of points in a body; in other words, it describes the complete transformation from the initial to the final geometry of a body.*

Strain *can be defined as the change in shape and size of a body resulting from the action of an applied stress field.*

It can be either:

1- ***Dilation****: which is a change in volume (ϵ_v)*



$$\epsilon_v = \Delta v / V_o$$

Δv: *Change in volume.*

V_o: *original volume.*

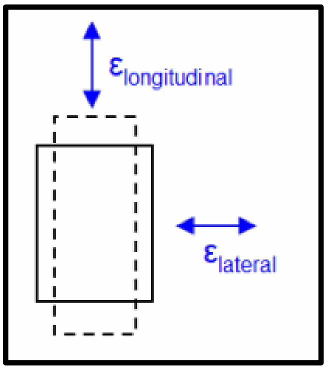
Normally occurs due to confining pressure.

- *With increasing confining pressure the volume of the body decrease and the dilation is* ***negative****.*
- *With decreasing confining pressure the volume of the body increase and the dilation is* ***positive****.*

2- ***Distortion****: which is a change in shape, usually due to stress (directed pressure).*

It can be either:

1- ***Longitudinal strain****:* $\epsilon_L = \Delta L / L_o$

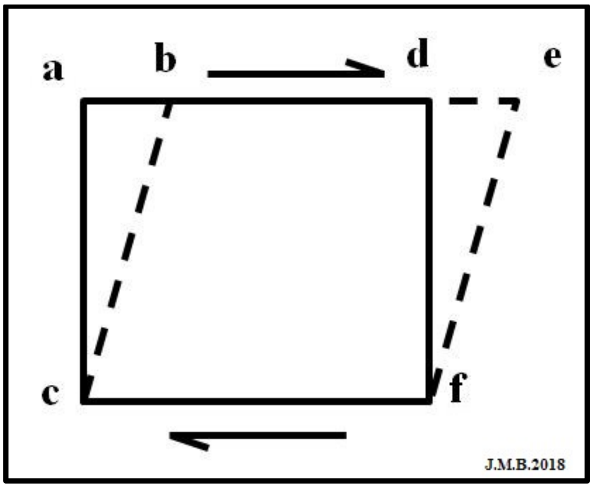


ΔL: *Change in length.*

L_o: *original length.*

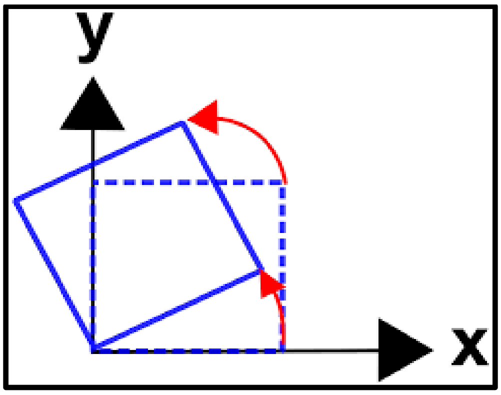
2- Shear strain: $\gamma = ab / ac$

*Square shape is deformed into parallelogram **bcfe** by couple forces.*

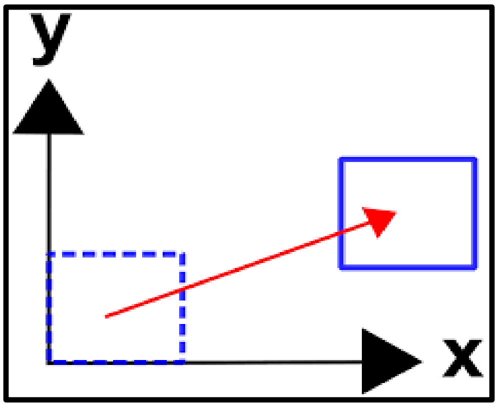


3- Rotation or displacement:

Rotation is the action of rotating about an axis or center.



*A **displacement** is a vector whose length is the shortest distance from the initial to the final position of a point*



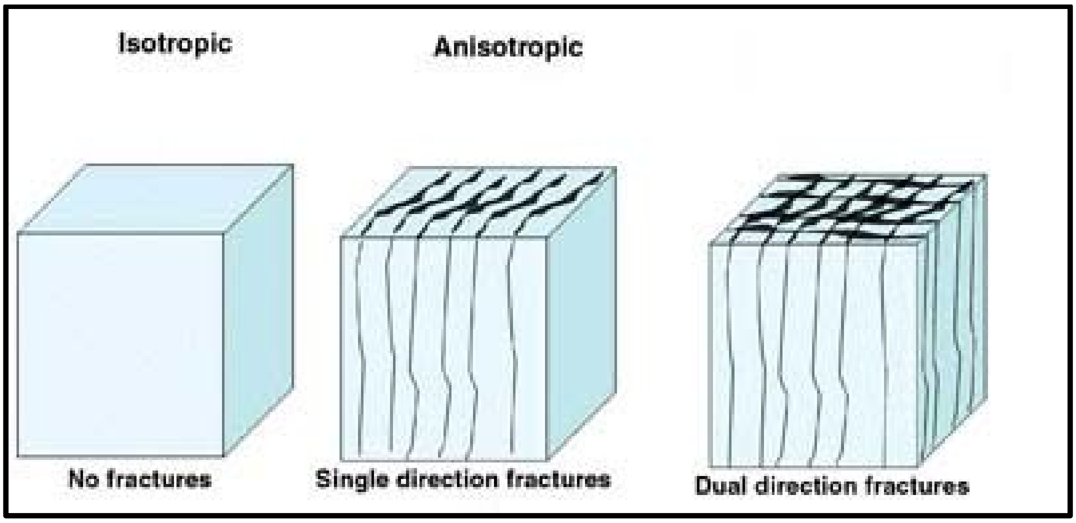
Isotropic materials

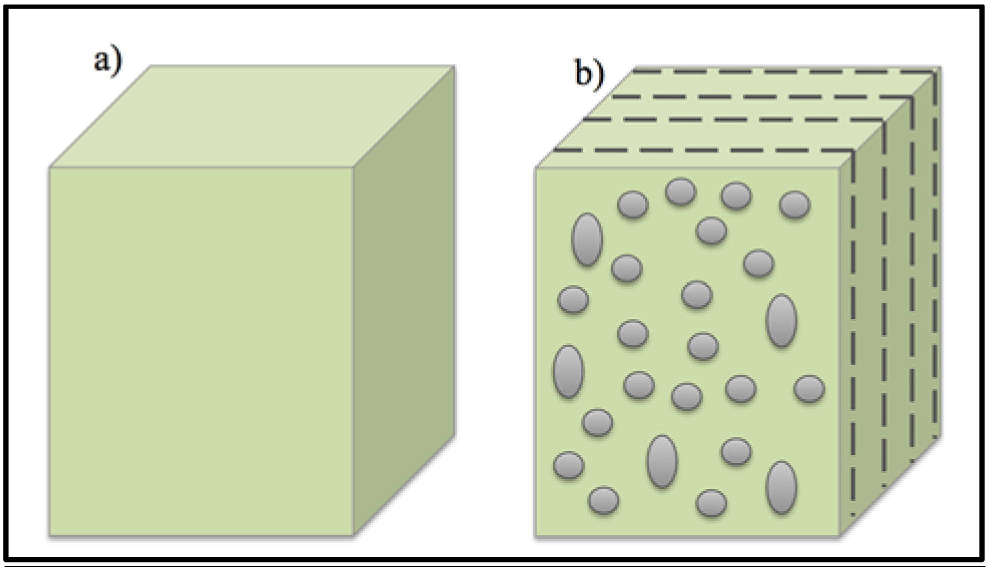
*Are materials whose mechanical properties are uniform in all directions and it will change in **volume**, but not in **shape**?*

An isotropic materials

Are materials whose mechanical properties are varying in all directions?

Examples *of anisotropic rocks: rocks having bedding plane, banding or foliation, joints, veins and faults. Their strength depends upon the orientation of the applied force with respect to the planner structures.*

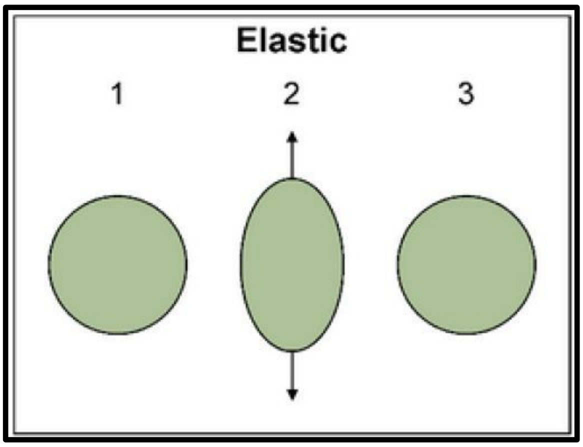




Three stages of deformation

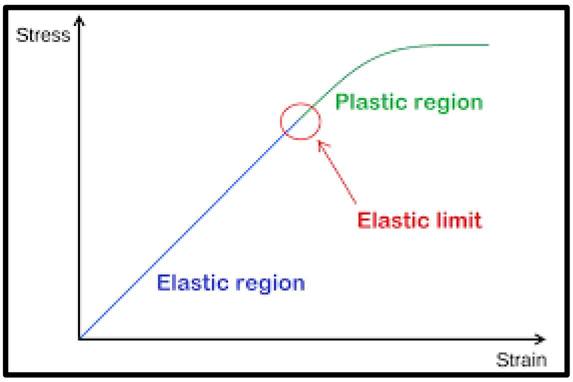
Where a body is subjected to stress for a short period of time (minutes or hours), it passes through three stages of deformation:

1- ***Elastic deformation stage****: in which the strain is proportional to stress according to Hooks law, (a law stating that the strain in a solid is proportional to the applied stress within the elastic limit of that solid), but if the stress is removed, the body returns to its original shape and size.*

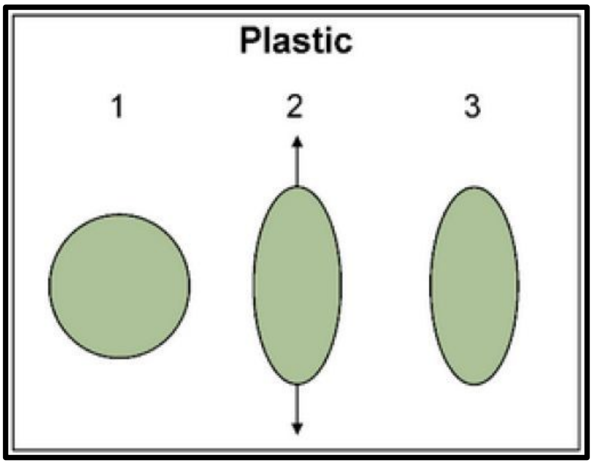


Elastic Limit: *is the maximum stress level at which the body behaves elastically.*

The study of earthquakes, elastic properties are very important. As you know, seismic waves from an earthquake pass through the Earth to seismic monitoring stations around the world. As they travel, these seismic waves briefly deform the rocks, but after they have passed, the rocks return to their undeformed state.



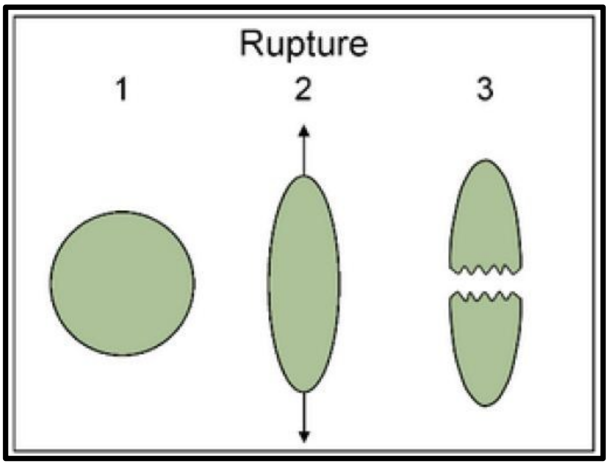
2- ***Plastic deformation stage****: if the elastic limit is exceeded, the body pass into a second stage of deformation called plastic deformation (permanent), and the body does not return to its original shape or volume, or it returns only partially.*



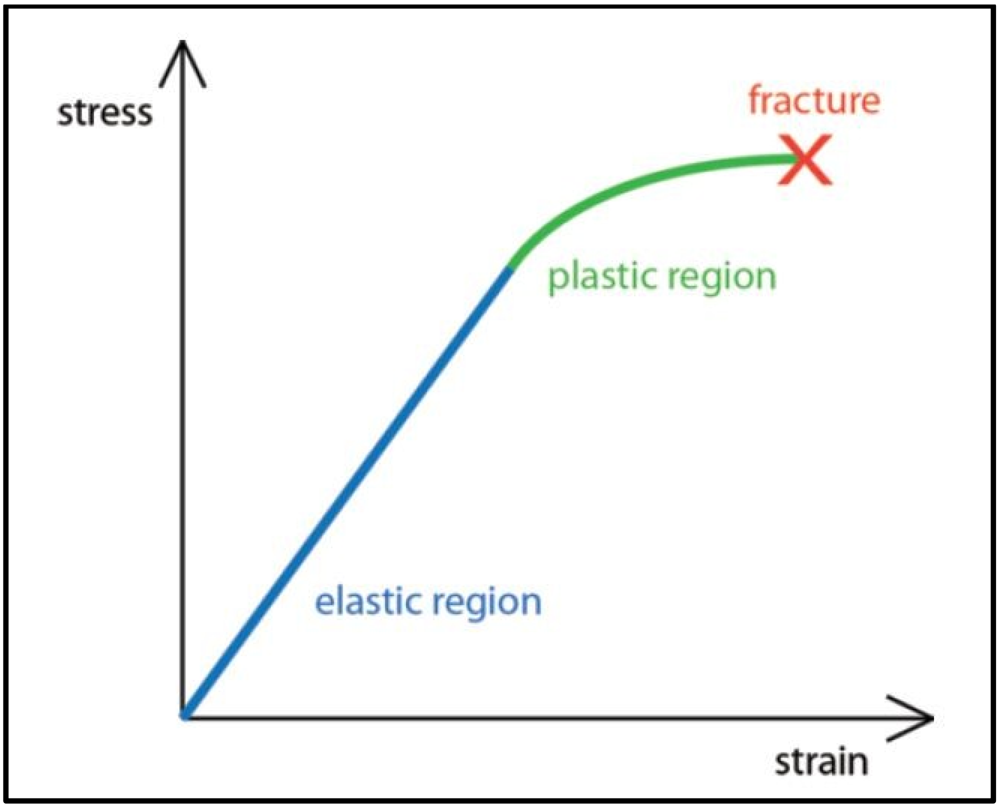
Example: *steel rod begins to get thinner on "neck" in the middle and the constriction remains even if the stress is removed.*

Plastic limit: *is the maximum stress level at which the body behaves plastically.*

3- Rupture (Fracture) deformation stage: *if the stress increased and passes or exceeds the plastic limit, the body fails by rupture; it can be broken along a fracture.*



With increasing stress, the rock undergoes: (1) elastic deformation, (2) plastic deformation, and (3) fracture.



Brittle and Ductile Deformation

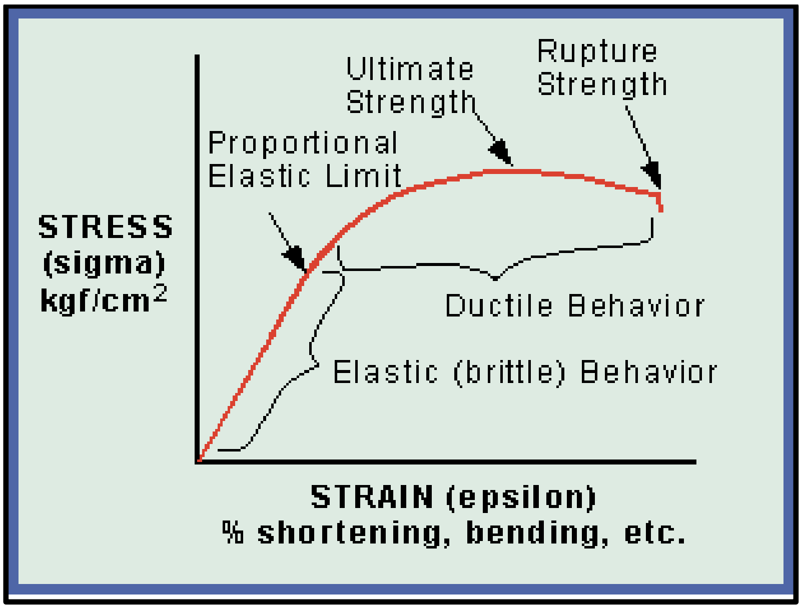
Rocks can experience squeezing (compression), stretching (tension), or pushing in different directions (shear stress) in response to stress. This response depends on the type of stress, the rate at which it is applied, the environmental conditions of the rocks (such as temperature and pressure), and their composition.

*Generally, **rocks** respond to stress in one of two ways: they break, or they bend.*

*When a rock breaks, it is called **brittle** deformation. Any material that breaks into pieces exhibits **brittle** behavior.*

*When rocks bend or flow, like clay, it is called **ductile** deformation.*

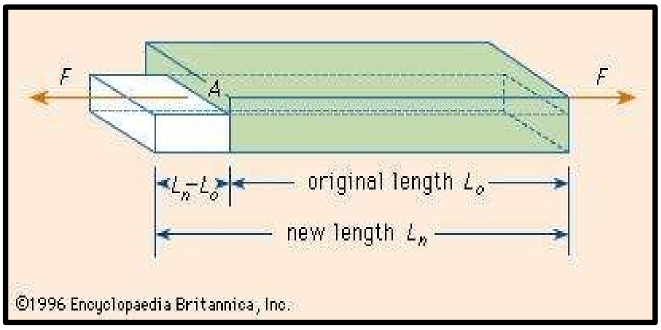
- ***Brittle substances**: are materials that rupture before any plastic deformation takes place, if the elastic limit is exceeded; the rock rupture.*
- ***Ductile substances**: are materials that undergo a large plastic deformation before rupture after elastic limit has been exceeded.*



YOUNG'S MODULUS (Modulus of Elasticity) E

Studying of the mechanical properties of materials is important because it helps us understand how materials behave, and allows us to develop new products and improve existing ones. The Young's modulus of a material is a useful property to know in order to predict the behavior of the material when subjected to a force. This is important for almost everything around us, from buildings, to bridges to vehicles and more.

***Young's modulus**, numerical constant, named for the 18th-century English physician and physicist Thomas Young, that describes the elastic properties of a solid undergoing tension or compression in only one direction, as in the case of a metal rod that after being stretched or compressed lengthwise returns to its original length. Young's modulus is a measure of the ability of a material to withstand changes in length when under lengthwise tension or compression. Sometimes referred to as the modulus of elasticity, **Young's modulus is equal to the longitudinal stress divided by the strain**. Stress and strain may be described as follows in the case of a metal bar under tension.*



If a metal bar of cross-sectional area A *is pulled by a force* F *at each end, the bar stretches from its original length* L0 *to a new length* Ln. *(Simultaneously the cross section decreases.) The stress is the quotient of the tensile force divided by the cross-sectional area, or* F/A. *The strain or relative deformation is the change in length,* Ln − L0*, divided by the original length, or (*Ln − L0*)/*L0*. (Strain is dimensionless.) Thus Young's modulus may be expressed mathematically as*

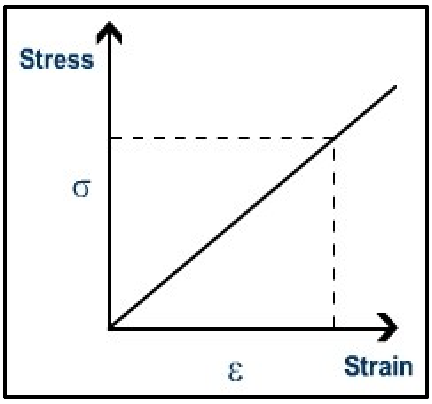
Young's modulus = stress/strain = (FL_0)/A ($Ln - L_0$).

$$E \equiv \frac{\sigma(\varepsilon)}{\varepsilon} = \frac{F/A}{\Delta L/L_0} = \frac{FL_0}{A\Delta L}$$

This is a specific form of Hooke's law of elasticity. The units of Young's modulus in the English system are pounds per square inch (psi), and in the metric system newton's per square meter (N/m^2). The value of Young's modulus for aluminum is about 1.0 × 10^7 psi, or 7.0 × 10^{10} N/m^2. The value for steel is about three times greater, which means that it takes three times as much force to stretch a steel bar the same amount as a similarly shaped aluminum bar.

*Young's modulus is **meaningful only in the range in which the stress is proportional to the strain**, and the material returns to its original dimensions when the external force is removed. As stresses increase, Young's modulus may no longer remain constant but decrease, or the material may either flow, undergoing permanent deformation, or finally break.*

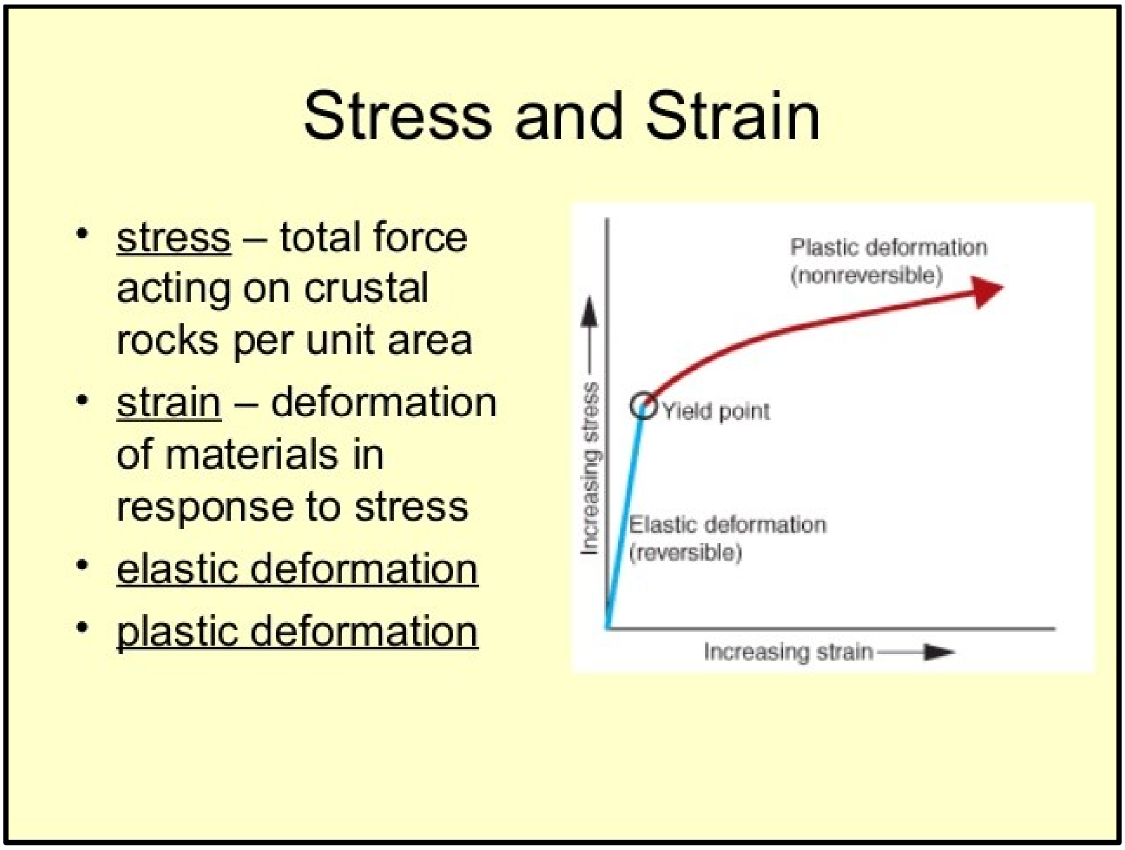
When a metal bar under tension is elongated, its width is slightly diminished. This lateral shrinkage constitutes a transverse strain that is equal to the change in the width divided by the original width.



*The ratio of the transverse strain to the longitudinal strain is called **Poisson's ratio**. The average value of Poisson's ratio for steels is 0.28, and for aluminum alloys, 0.33. The volume of materials that have Poisson's ratios less than 0.50 increases under longitudinal tension and decrease under longitudinal compression.*

Yield Point

The yield point *is the point on a stress–strain curve that indicates the limit of elastic behavior and the beginning of plastic behavior. Yielding means the start of breaking of fibers.*



Yield strength or yield stress *is the material property defined as the stress at which a material begins to deform plastically whereas yield point is the point where nonlinear (elastic + plastic) deformation begins. Prior to the yield point the material will deform elastically and will return to its original shape when the applied stress is removed. Once the yield point is passed, some fraction of the deformation will be permanent and non-reversible.*