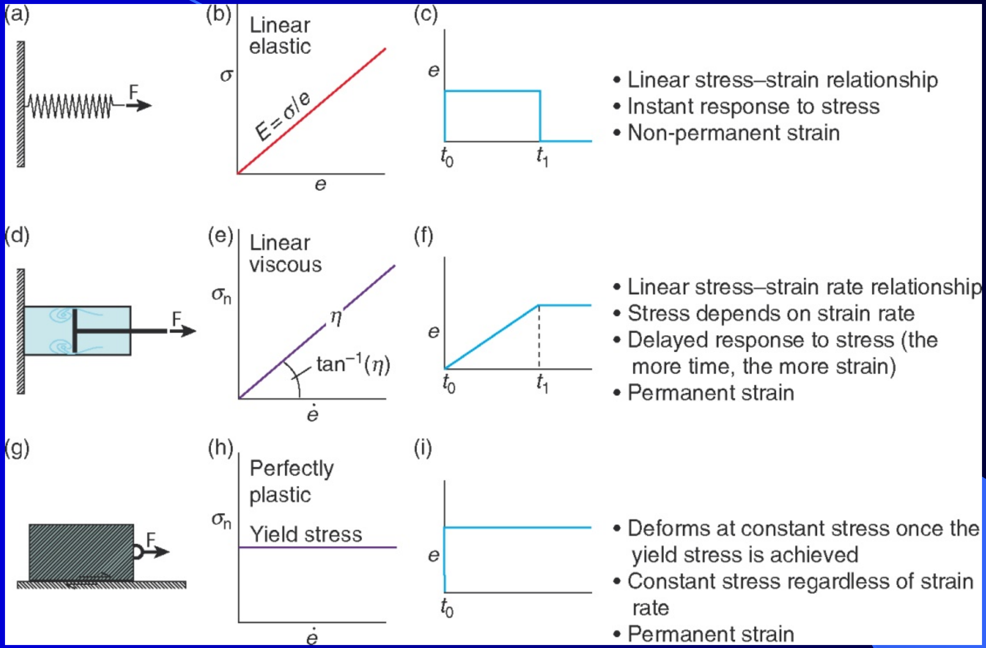
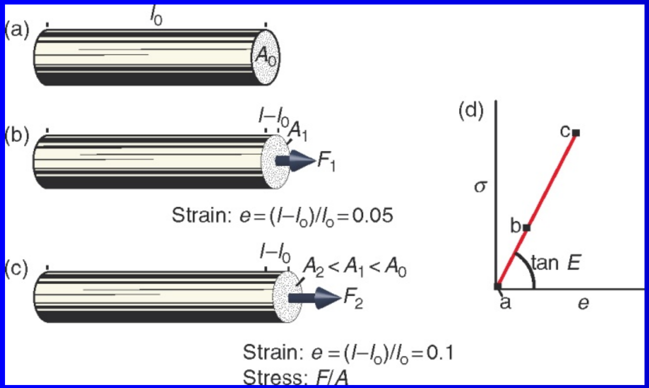
Behavior of Materials

- Elastic
- Viscous
- Plastic





Hooke's Law: $\sigma = Ee$

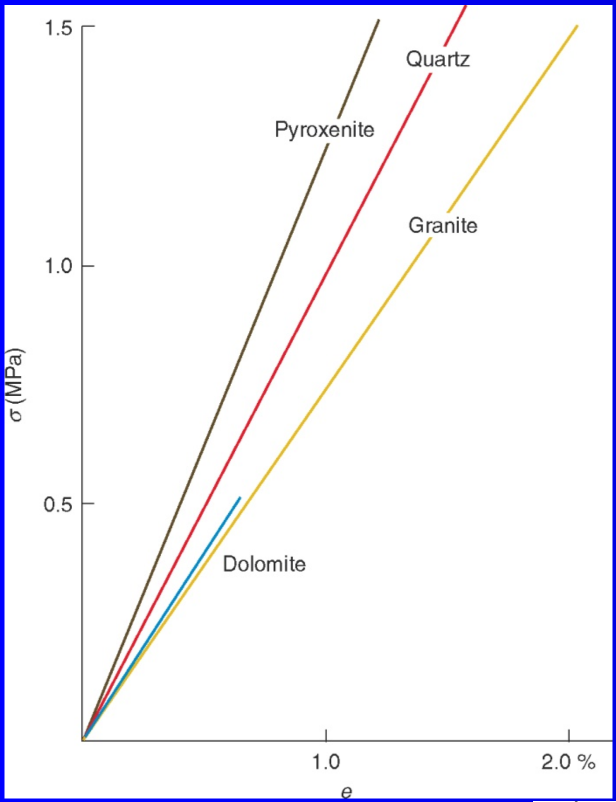
σ = stress

E = Young's modulus

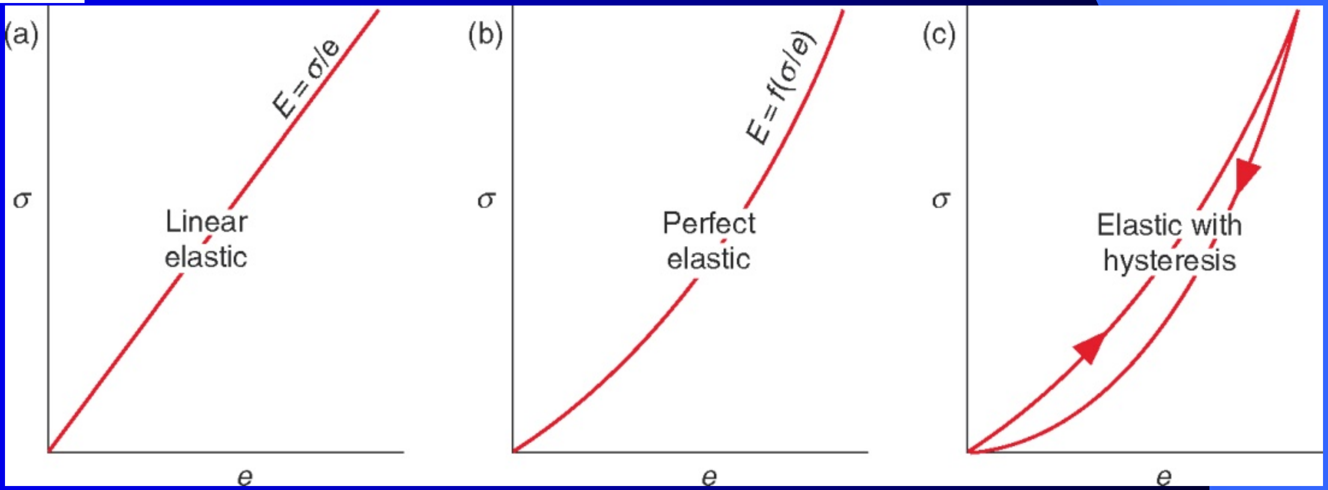
e = extension (one-dimensional strain)

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

Types of Elasticity

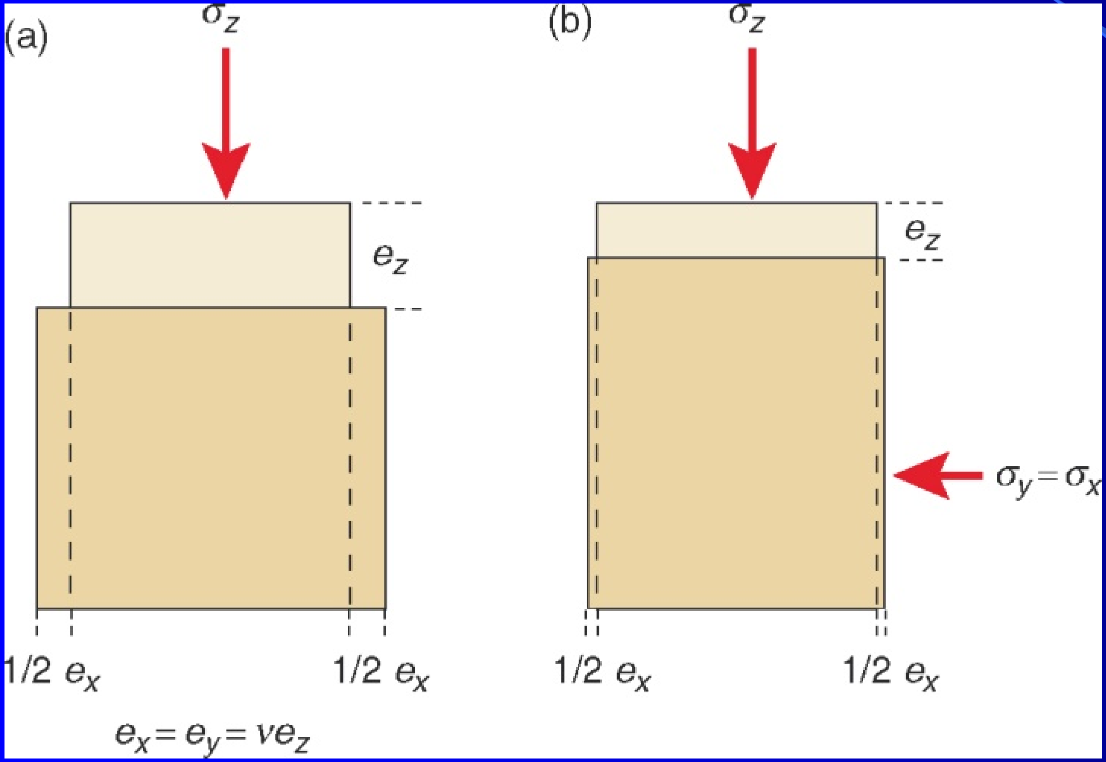


- Linear elastic (constant relationship between stress and strain). Young's modulus is constant. Some minerals and rocks show this behavior
- Perfect elastic (stress-strain curve during loading and unloading is the same). Young's modulus is not constant.
- Elastic with hysteresis (loading and unloading show different stress-stain curves).



Poisson's ratio

Poisson's ratio = ratio between the extensions normal and parallel to the principal stress vector.



$\nu = -e_x/e_z$

The minus sign is often omitted when referring to the Poisson's ratio for rocks.

For a perfectly incompressible material Poisson's ratio = 0.5

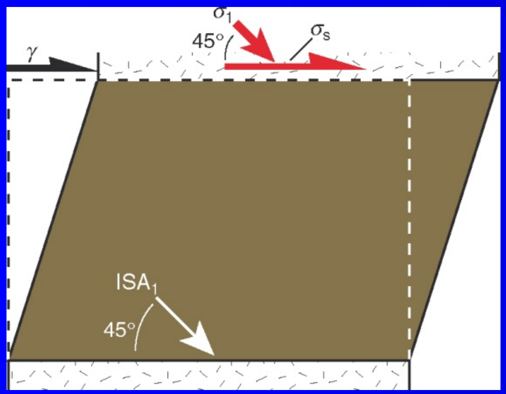
If the material is compressible, Poisson's ratio <0.5

If pressure causes deformation:

Bulk modulus $= K = \frac{\Delta p}{\Delta V / \Delta V_o}$

Poisson's ratio can be determined from seismic wave velocities

Viscous materials (fluids)



Newtonian fluid – shear stress and shear strain **rate** are related.

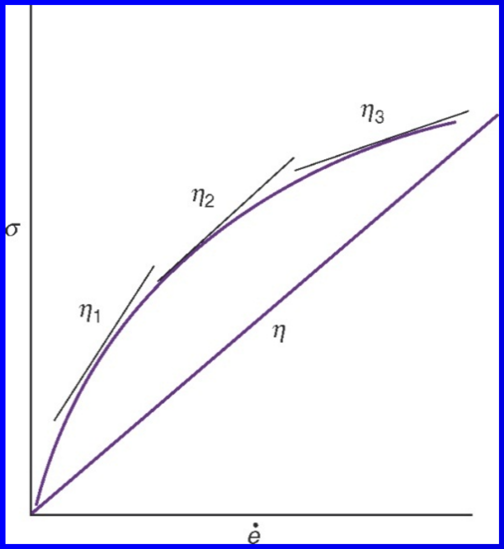
$\sigma_s = \eta\dot{\gamma}$

Where σ_s = shear stress, η = viscosity, and $\dot{\gamma}$ = strain rate

Alternative formulation

$\sigma_n = \eta\dot{e}$

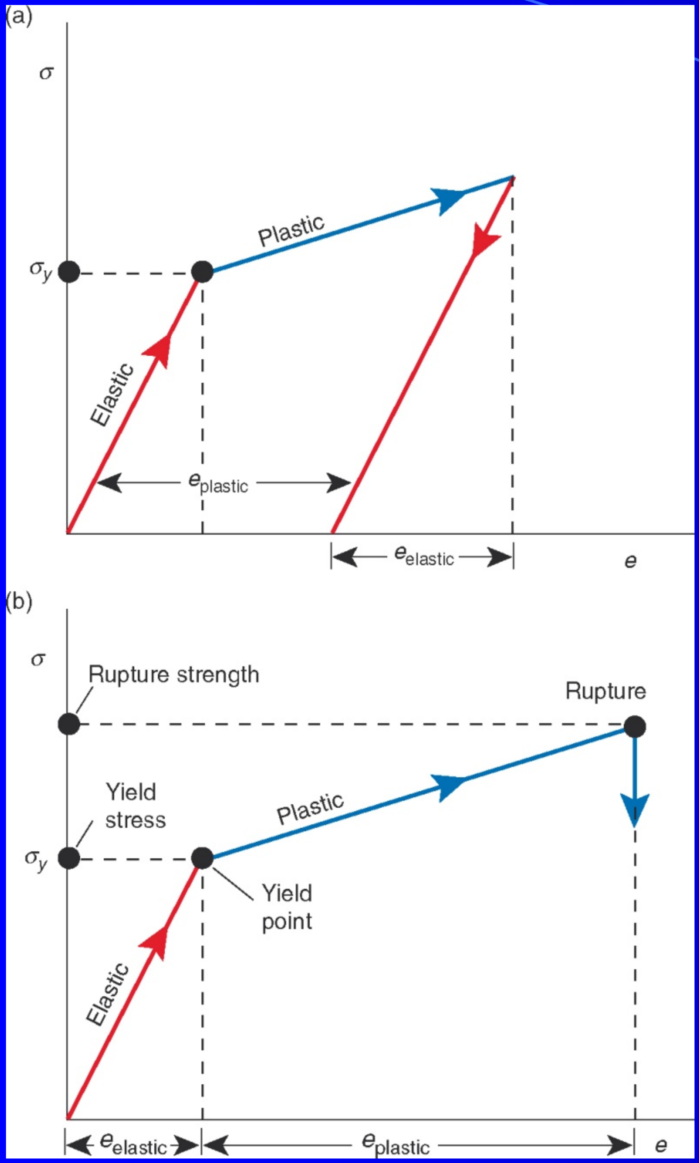
Where σ_n = normal stress and $\dot{e}$ = elongation rate (p. 104)



Viscous deformation is irreversible and creates permanent strain.

Linear and non-linear viscous behavior (Fig to left)

Competency is resistance of layers or objects to flow.



Plastic strain is the permanent change in shape or size of a body without fracture, accumulated over time by a sustained stress beyond the elastic limit (yield point) of the material.

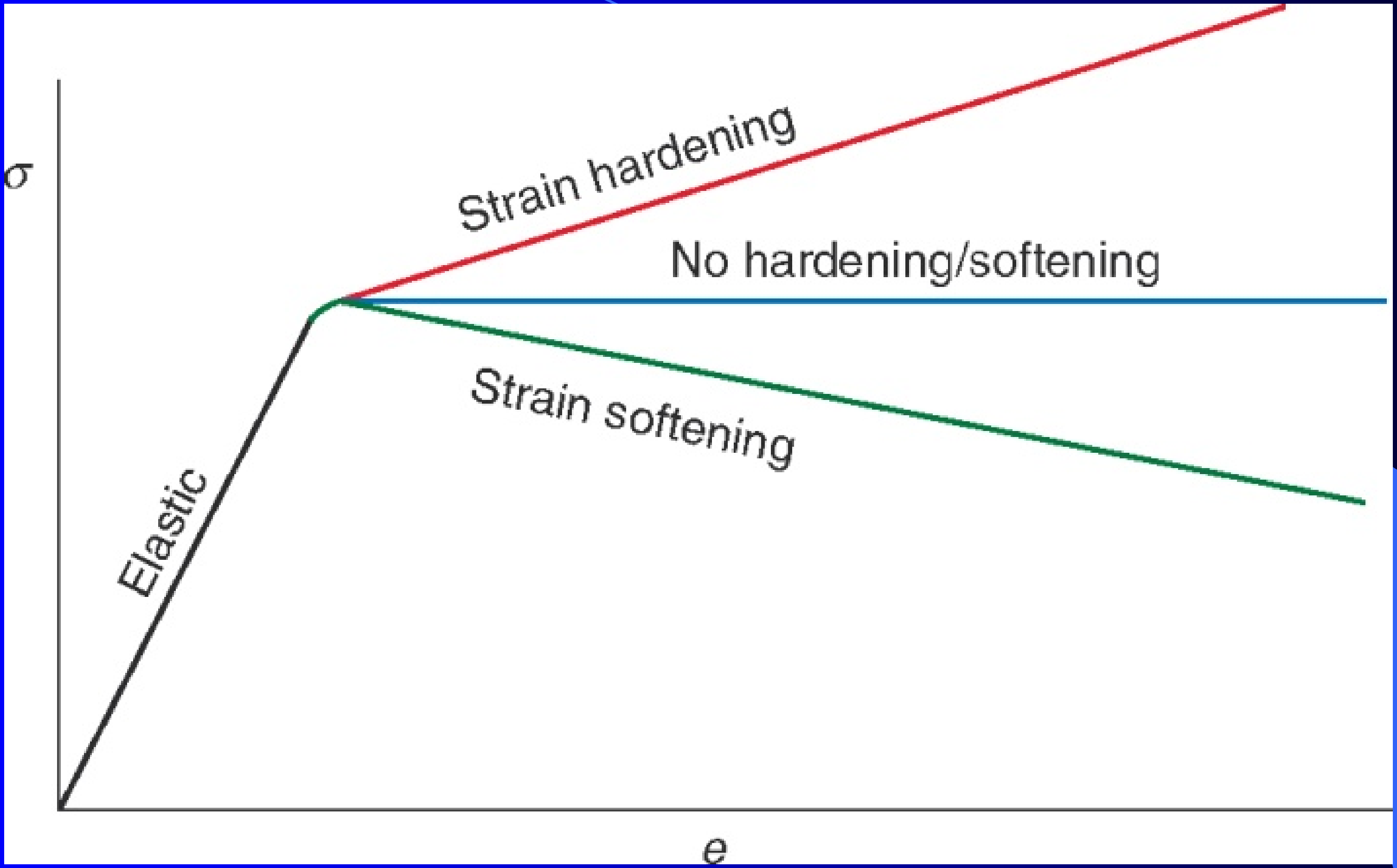
For a perfect plastic material the stress cannot rise above the yield stress and strain can continue to accumulate without any change is stress.

There are different equations for different plastic flow mechanisms. A general example is a power-law equation of the form

$$e = A\sigma^n \exp(-Q/RT)$$

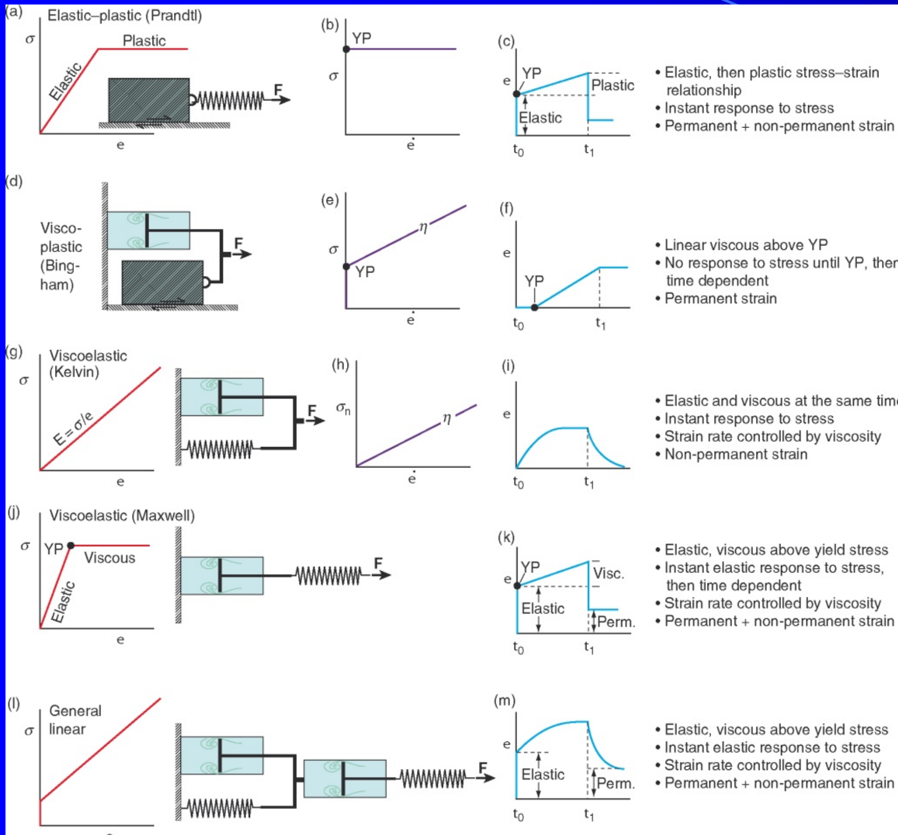
where e = strain rate, A = a constant, σ = stress, n is an exponent fit to the experimental data, Q = activation energy, T = absolute temperature, and R = the ideal gas constant. When n =1 the material behaves as a perfectly viscous fluid.

Strain hardening and strain softening versus perfect plastic behavior



The blue curve represents creep which occurs when the material continues to deform without any increase in the applied force or stress.

Combined Models



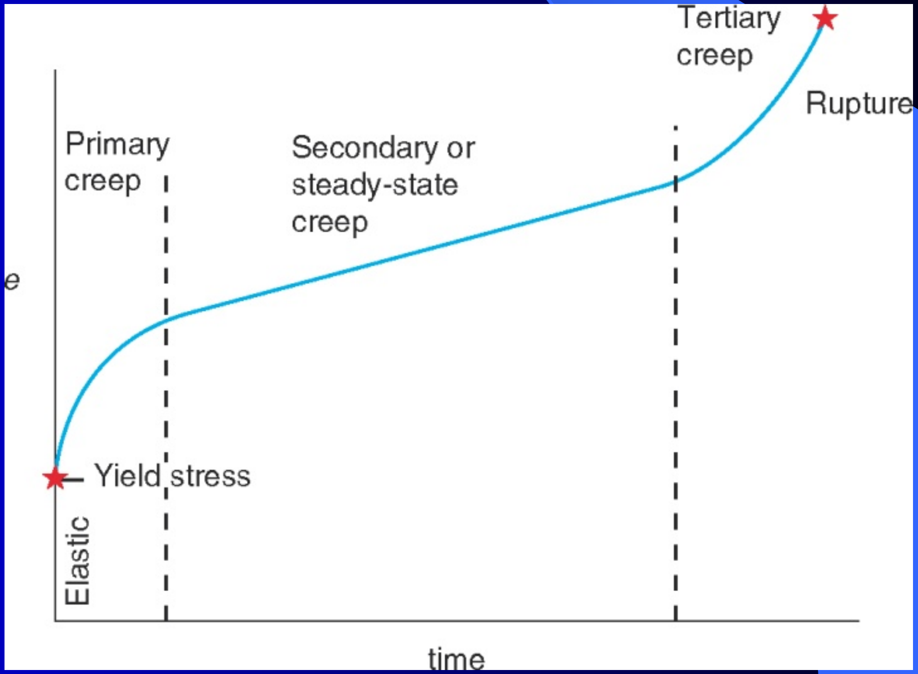
- Elastic-plastic can be applied to the large-scale deformation of the crust and mantle.
- Viscoplastic can be used to describe lava flows.
- Viscoelastic models are used in large-scale modeling of the crust where the elastic deformation describes the short-term response to stress and the viscous part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

For the Kelvin model: $\sigma = Ee + \eta\dot{e}$

For the Maxwell model: $\dot{e} = \frac{\sigma}{E} + \sigma/\eta$

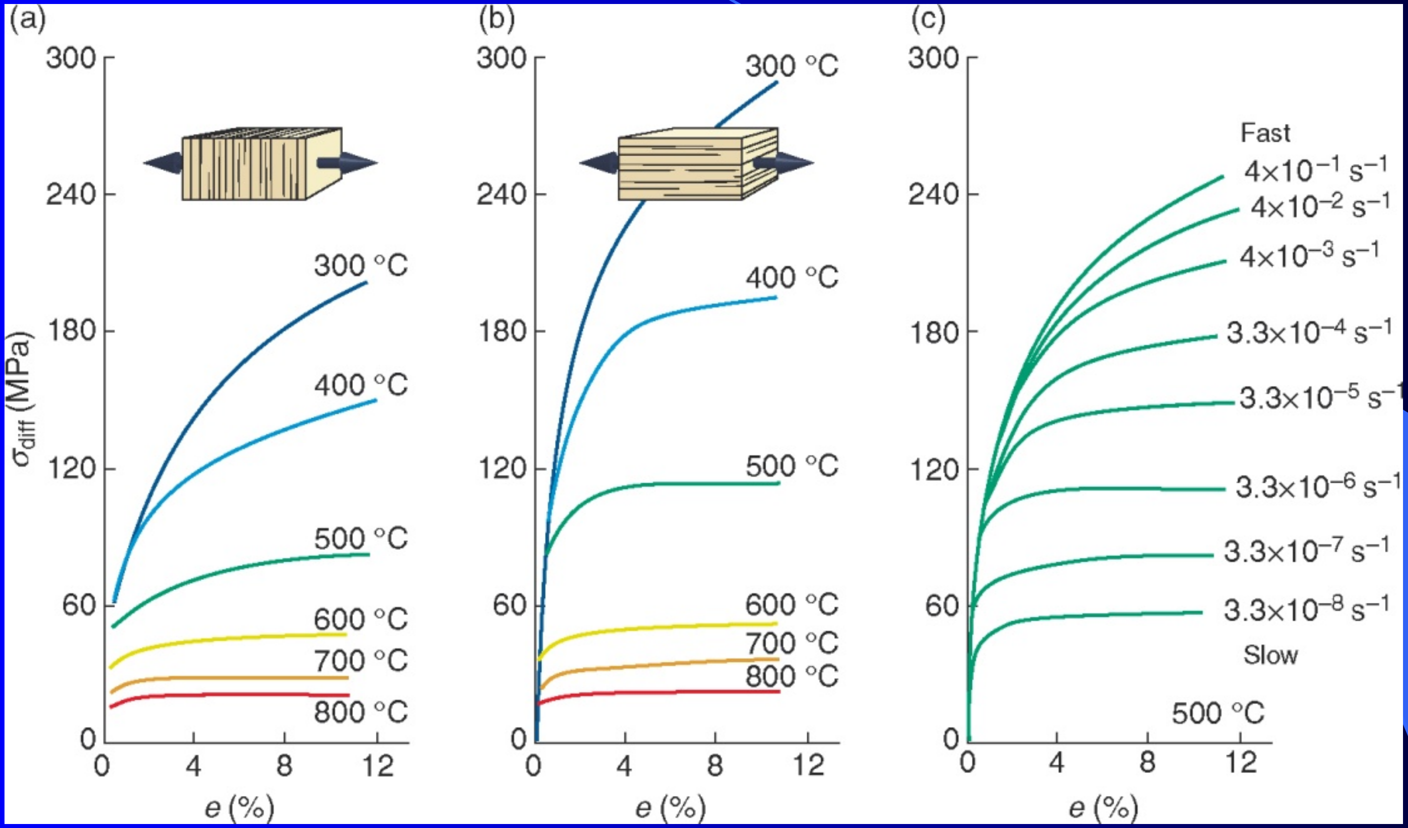
Constant stress (creep) experiments

- Stress field is constant. The result is low-strain-rate deformation
- Creep – “plastic deformation of a material that is subjected to a persistent and constant stress when that material is at a high homologous temperature.”
- Homologous temperature: $T_H = T/T_m$ where T is the temperature of the material and T_m is the melting temperature. Temperatures are in K. Substances compared at the same homologous temperature tend to have similar behavior.



- Creep begins at $T_H = 0.5$ and becomes more active as T_H approaches 1.
- Primary creep occurs at a decreasing strain rate.
- Secondary creep is a region of relatively constant strain rate
- Tertiary creep rapid increase in strain rate leading to rupture.

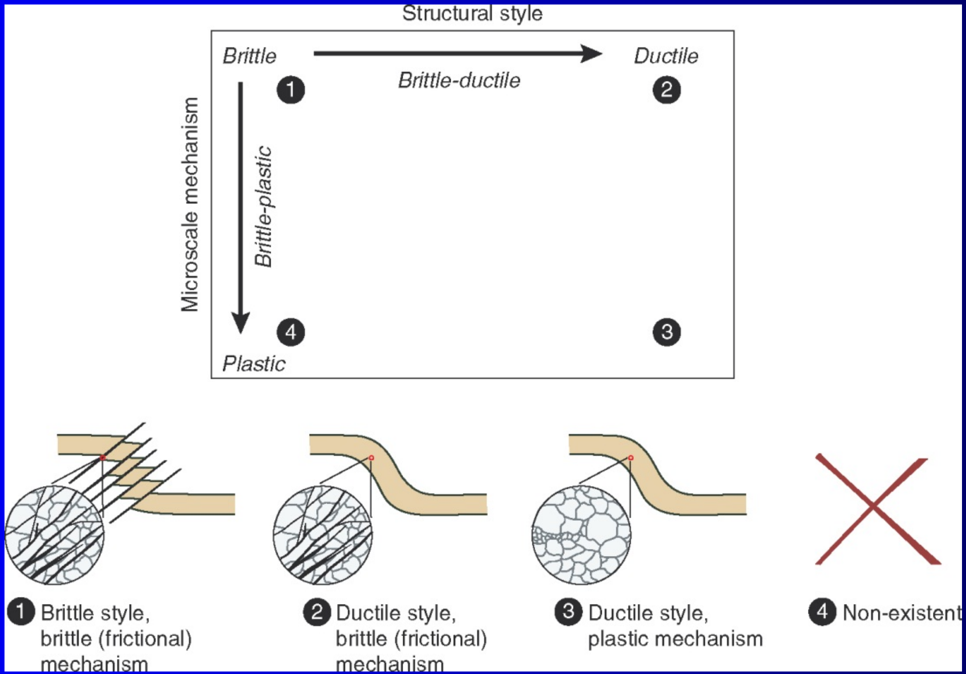
Behavior of materials as a function of temperature, orientation of fabric, and strain rate.



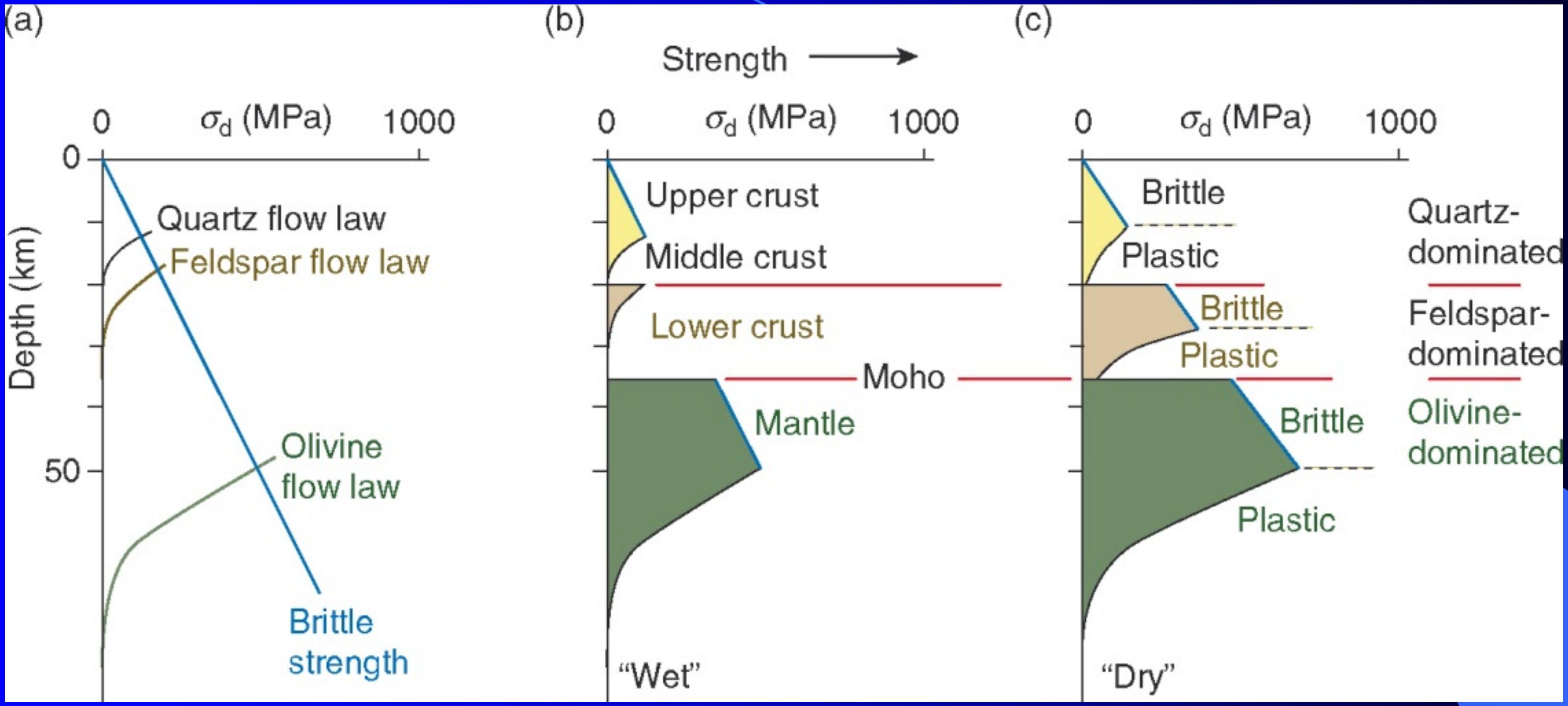
Increasing the temperature, increasing the amount of fluid, lowering the strain rate and, in plastically deforming rocks, reducing the grain size all tend to cause strain weakening.

Plastic, Ductile, and Brittle Deformation

- Brittle material deforms by fracture when subjected to stress beyond the yield point
- Ductile material accumulates permanent strain without macroscopically visible fracturing until ultimate strength is exceeded
- Brittle deformation involves frictional deformation at the microscope. Grains slide past each other
- Plastic deformation occurs at the atomic scale without the breaking of atomic bonds due to creep processes



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.