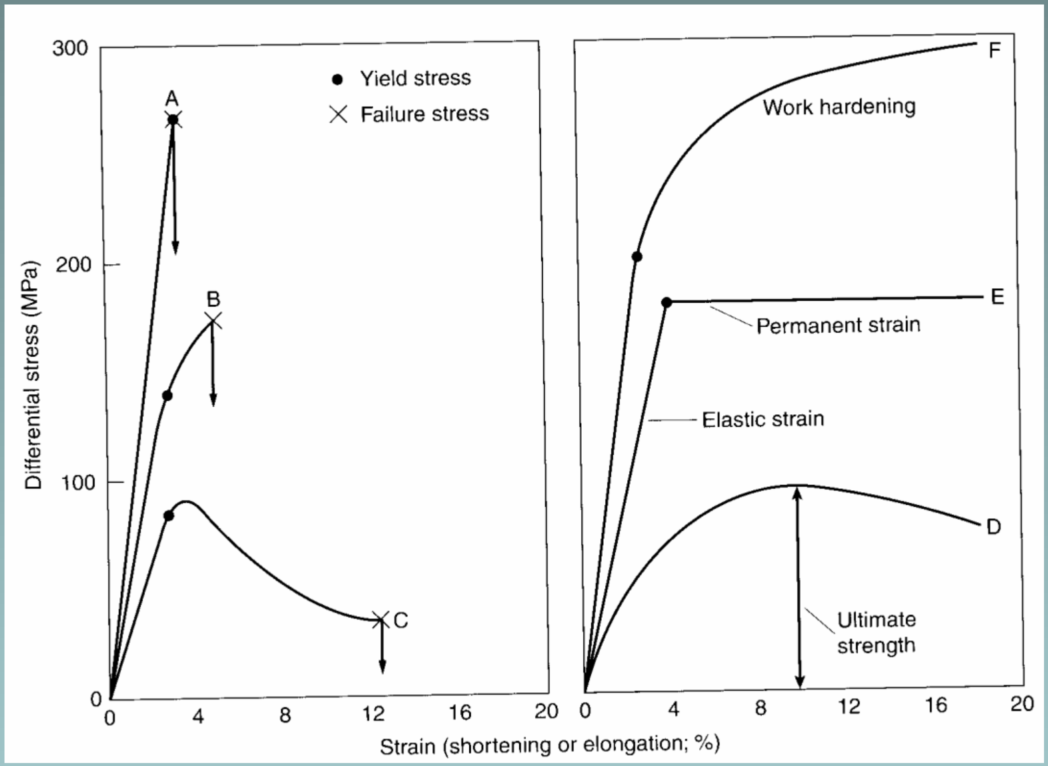
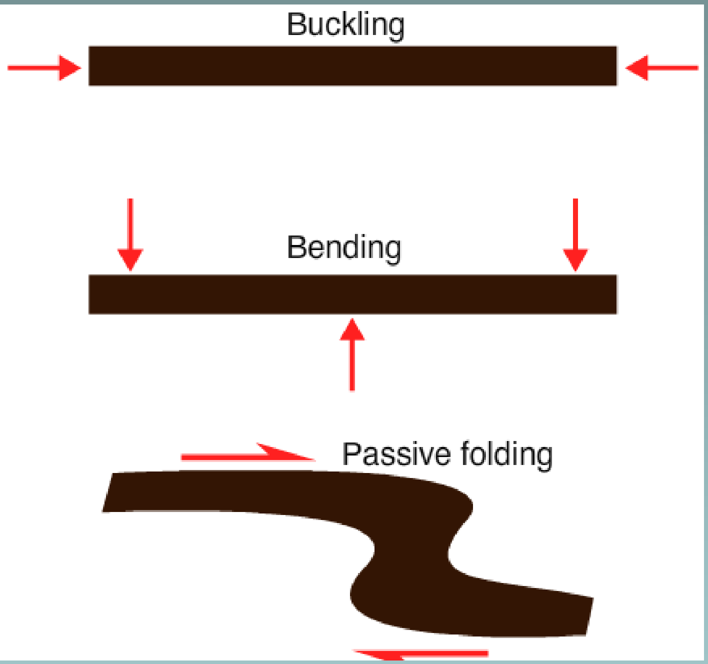
• **Failure:** Rock is unable to support stress increase without permanent deformation

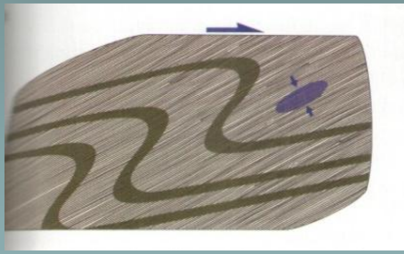


Lecture 4: Failure in rocks

(Reference: Fossen, Chapter 6)

Stress & Strain Not correlatable





- Heterogeneous rocks
- Non-linear behavior between stress & strain
- Deflection of Stress field

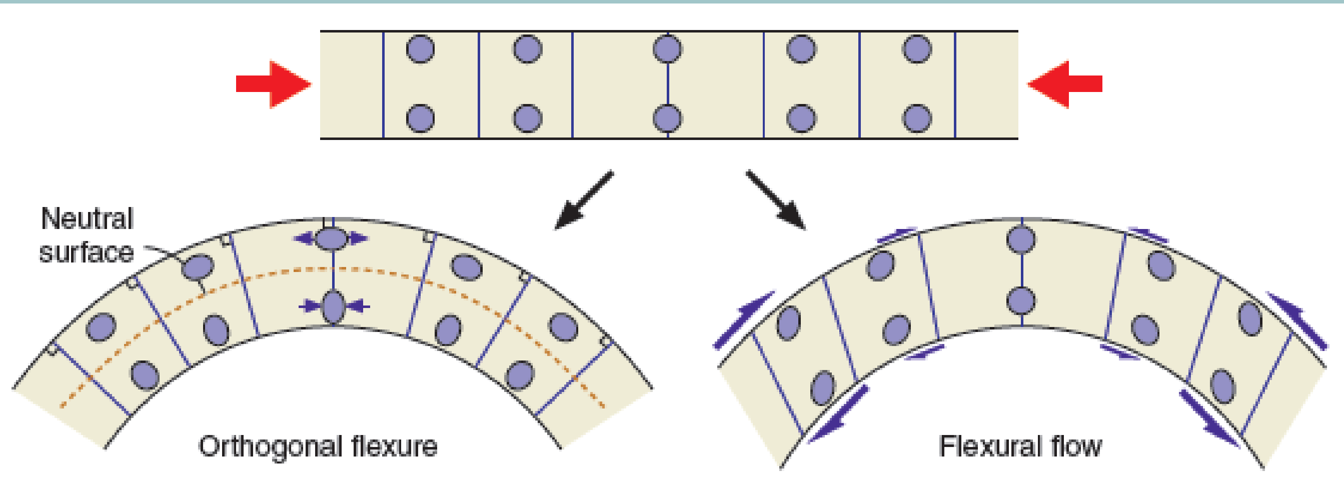


Figure 11.28 Layer-parallel shortening resulting in orthogonal flexure and flexural flow. Note what happens to the originally orthogonal lines. Strain ellipses are indicated.

Deflection of Stress field

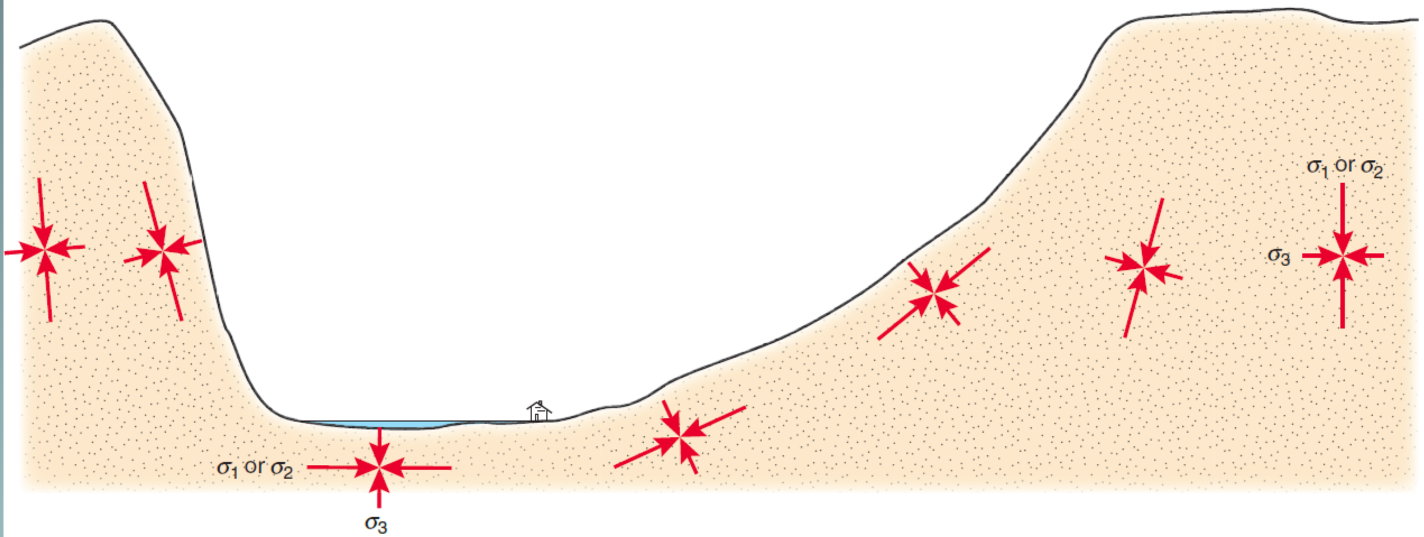


Figure 5.3 State of stress around a valley or fjord. One of the principal stresses will always be perpendicular to the free surface of the Earth, because the shear stress is zero along any free surface. Thus, a non-planar surface causes the orientation of the stresses to rotate as shown on the figure. Note that these deviations occur near the surface only, but must be considered when stress is measured at or near the surface or other free surfaces (tunnel walls, etc.).

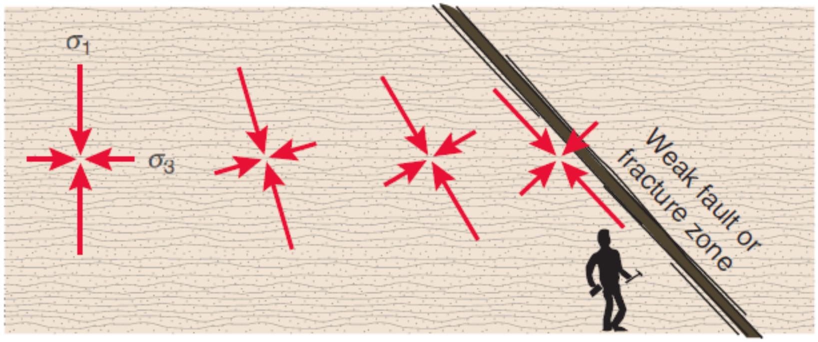


Figure 5.4 Deflection of the stress field near a fault or fracture zone. The structure is weaker than the surrounding rock and can support lower shear stresses than its surroundings. The situation is similar to that where an open surface exists, e.g. the free surface of the Earth (see Figure 5.3).

Dangers of correlating Strain with Stress

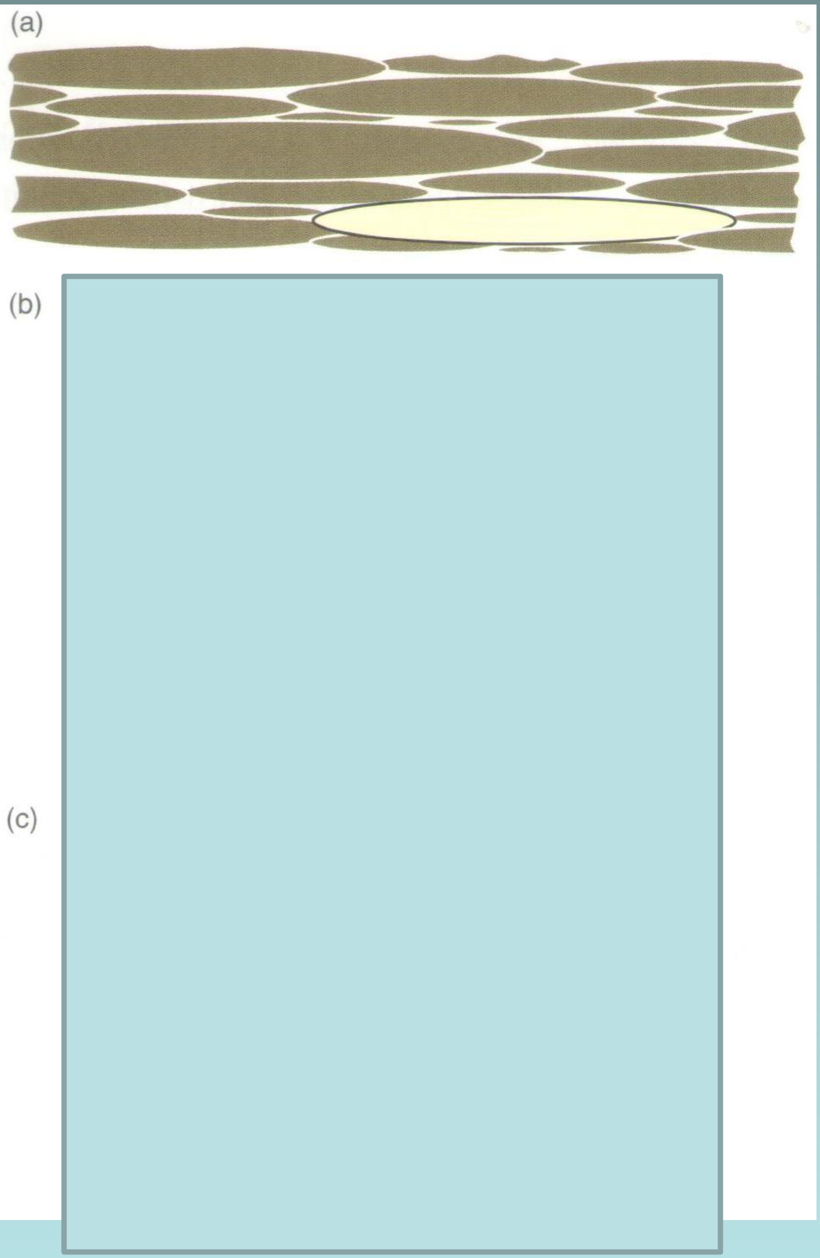


Figure 2.37 Deformed markers (a) such as strained pebbles or ooids give no information about the type of deformation. It could represent simple shear (b), pure shear (c) or any other type of deformation. Knowledge of the orientation of shear zone boundaries or lithologic layering could however give us the necessary information. The yellow ellipses in the three illustrations are identical.

Material properties of deformed rocks

Experimental Rock Deformation

Rheology: **Response of rocks to stress (Typically, study of flow of rocks)**

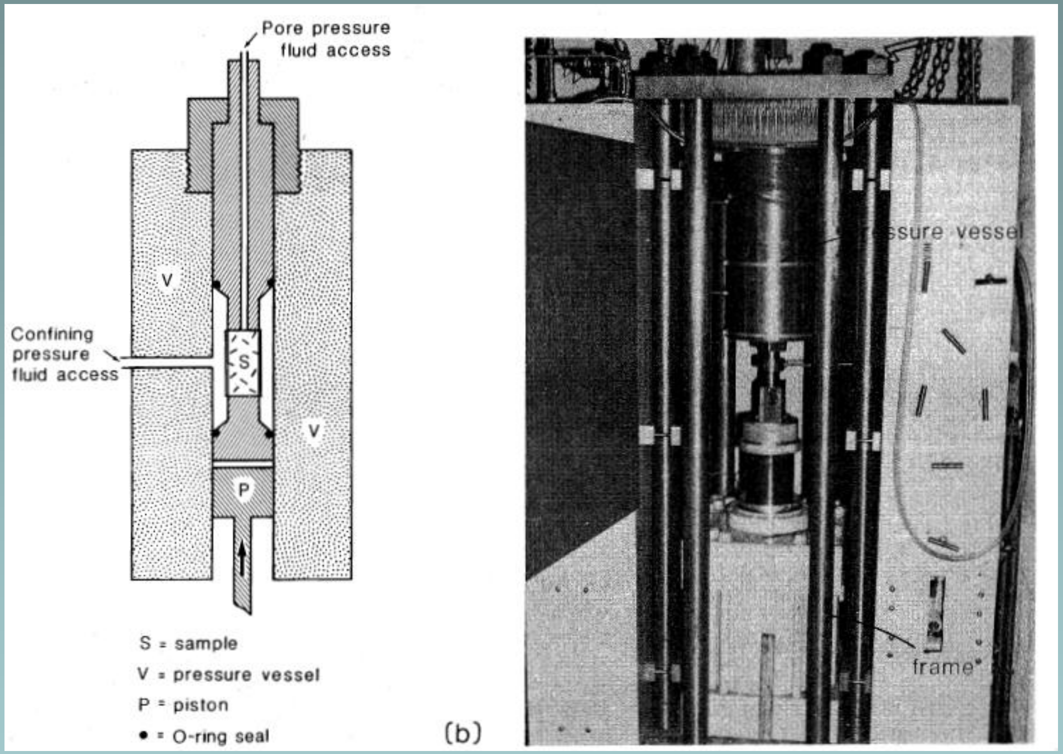
Strength: **Maximum stress sustained by a rock before it fails (σ_1- σ_3)**

Response of Rocks to Deformation Depend on:

- **Temperature**
- **Confining Pressure**
- **Pore pressure**
- **Strain rate**
- **Composition**
- **Grain Size**
- **Chemical environment**

Triaxial Load Machine

Grigg's Apparatus



Sample cylinder = Length:Diameter = 2:1
Sample diameter: 5 mm (small); 2.5 cm (medium); 30 cm (large).

Constituitive equations: Linear and nonlinear relationships among σ, e, ė

Strain rate (ė): Time taken to accumulate a certain amount of strain (e/t)
Geologic ė = 10^{-12} to 10^{-14} s^{-1}

• **Failure:** **Rock is unable to support stress increase without permanent deformation**

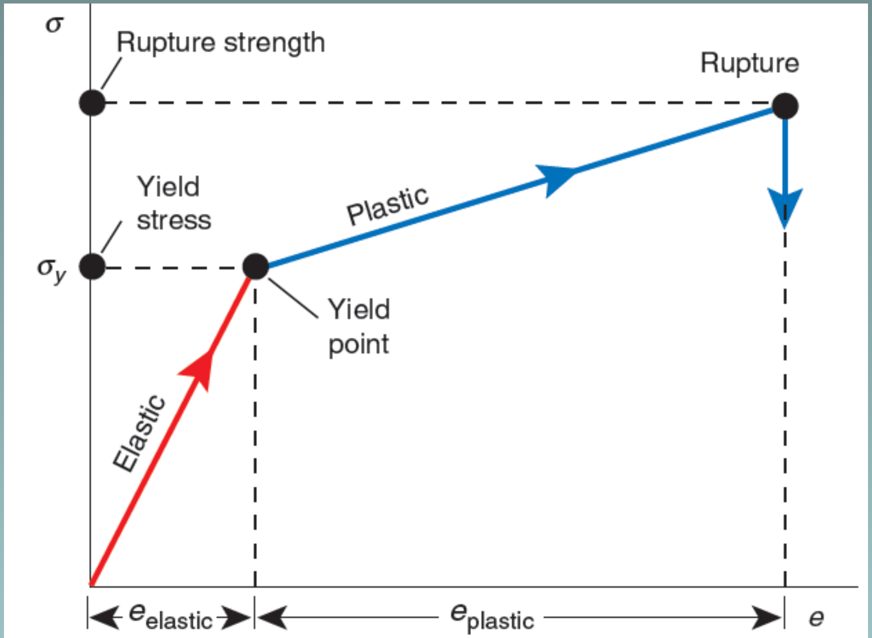
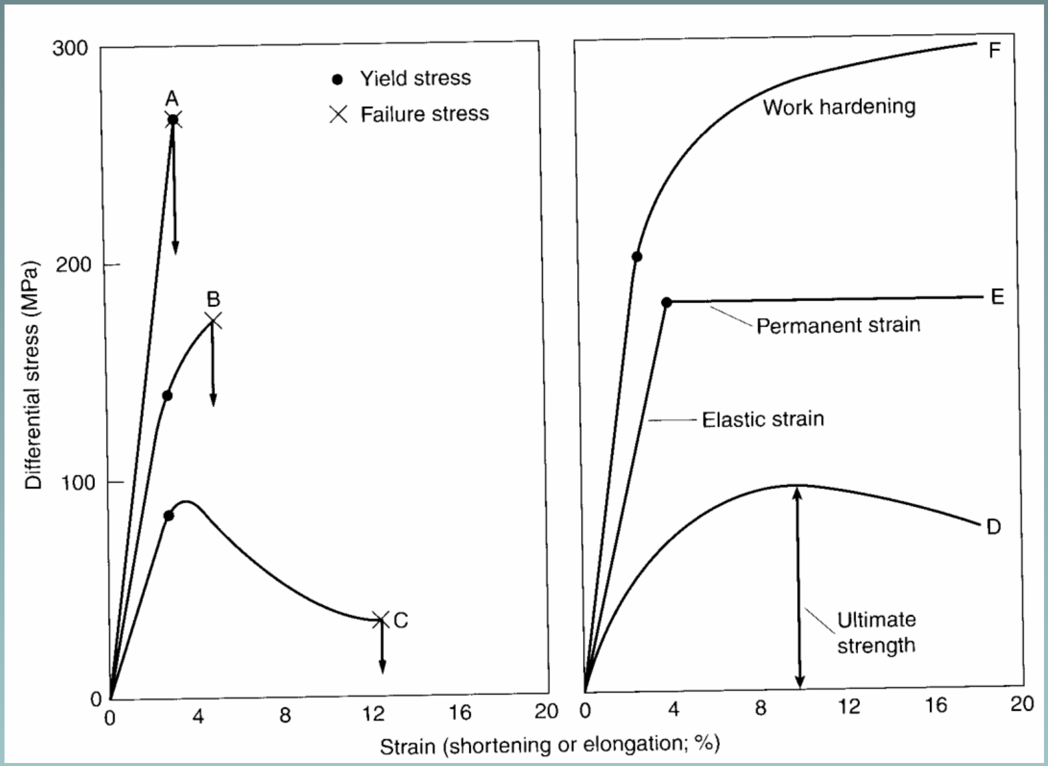


Figure 6.9 Stress–strain curve for elastic–plastic deformation. (a) Elastic strain is replaced by plastic strain as the yield stress (σ_y) is reached. When stress is removed the elastic strain is released, and the plastic or permanent strain remains. (b) In this case the stress is increased to the point where brittle rupture occurs.

Recoverable vs Nonrecoverable/permanent strain

Yield stress: **The value of stress that marks the onset of permanent strain.**

• **Failure:** **Rock is unable to support stress increase without permanent deformation**



Non-linear behavior between stress and strain

Brittle Failure – Rock breaks to form continuous fractures resulting in the loss of cohesion.

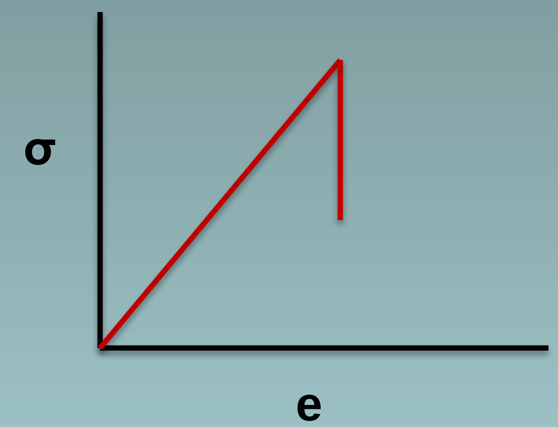
Ductile Failure – Rock deforms permanently without losing cohesion.

Brittle Failure – 1. Development of new fracture in an intact rock

2. Slip on a pre-existing fracture in a previously fractured rock

Brittle Deformation (Macroscopic behavior)

- Through going fault
- Stress drop
- Acoustic emission
- Dilatancy



- Increase in strength with increasing confining P

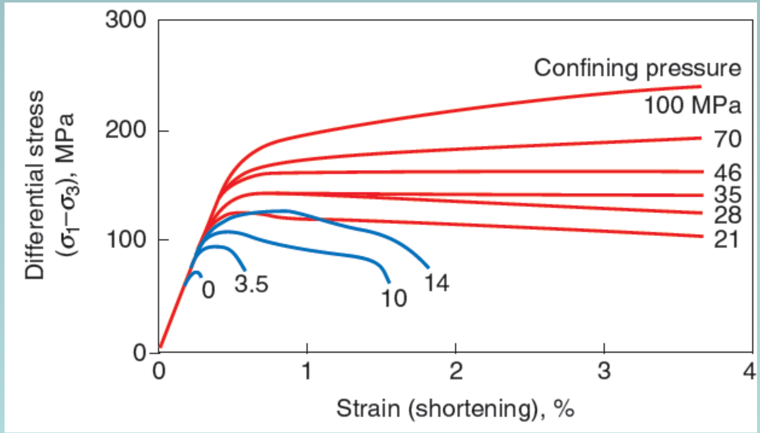
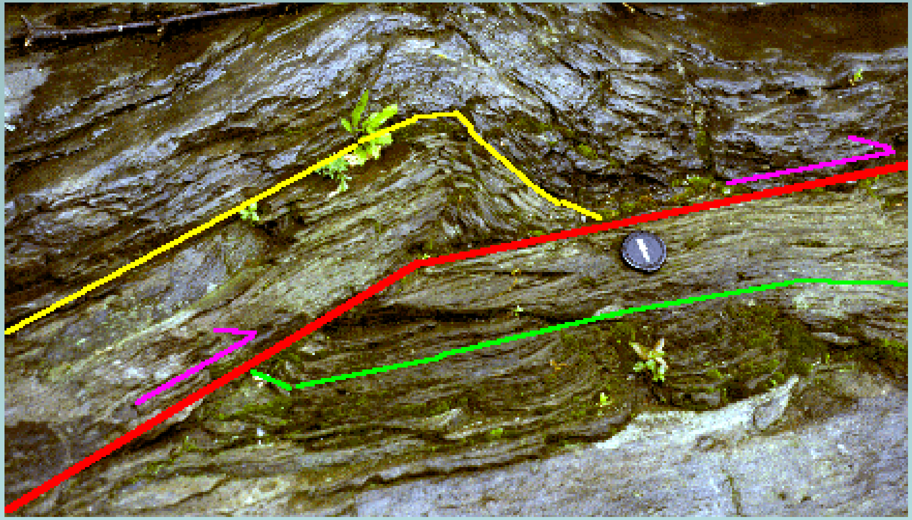


Figure 7.8 Stress–strain curves for triaxial compression of marble for a range of confining pressures. Increasing the confining pressure increases the differential stress that the rock can sustain before failure (blue curves). Above a critical confining pressure the rock retains its strength as it deforms plastically (red curves). From Paterson (1958).

Ductile Deformation: Continuous deformation, and so none of the above!

But…



Flowing rocks with fractures

Missing something!

Problems of using "Brittle & Ductile" (scale-dependent)

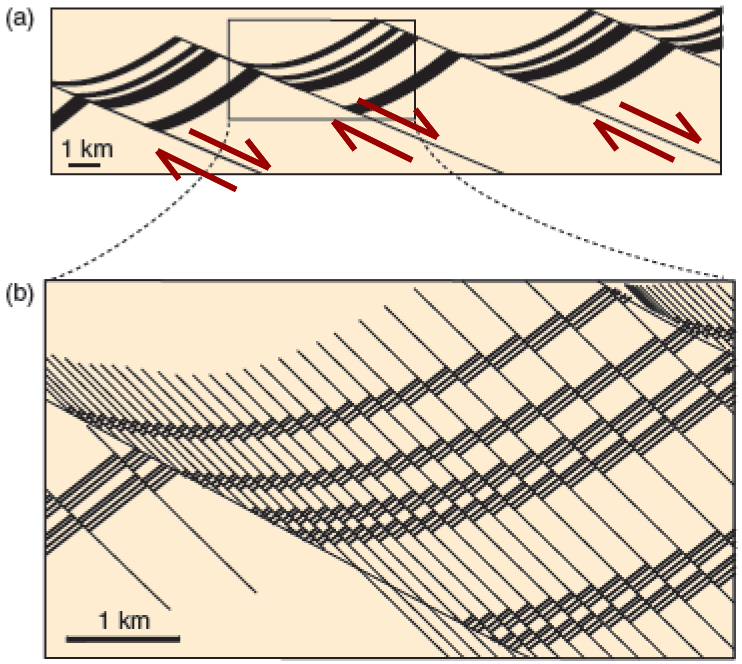


Figure 6.16 The scale-dependent nature of the ductile deformation style illustrated by a regional profile (top), where layers look continuous (ductile deformation style), and close-up (bottom), where it becomes apparent that the deformation is by multiple small faults. This example is directly relevant to seismic versus subseismic deformation.

Problems of using "Brittle & Ductile"

Importance of multi-scale analysis in rock deformation studies

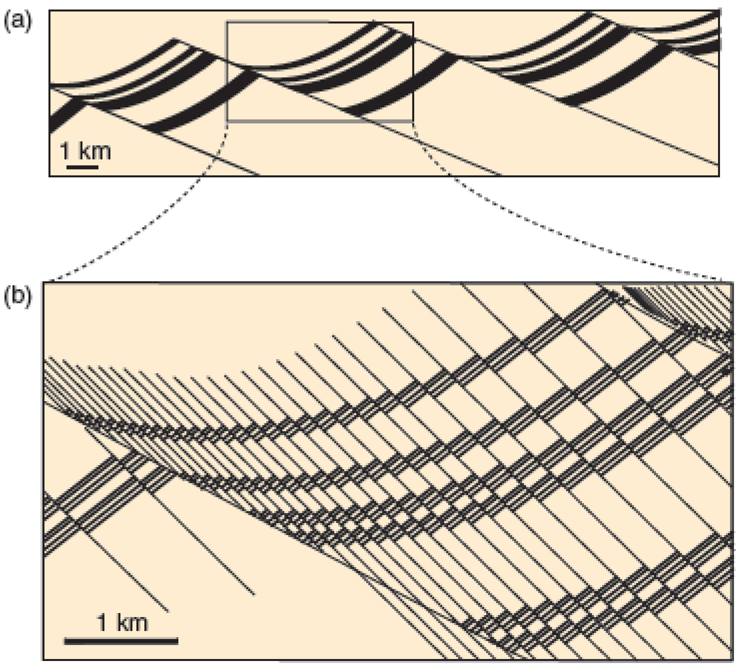


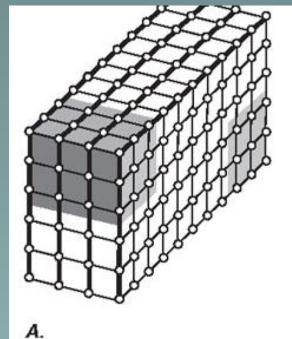
Figure 6.16 The scale-dependent nature of the ductile deformation style illustrated by a regional profile (top), where layers look continuous (ductile deformation style), and close-up (bottom), where it becomes apparent that the deformation is by multiple small faults. This example is directly relevant to seismic versus subseismic deformation.

So what do we do? (Microstructures)

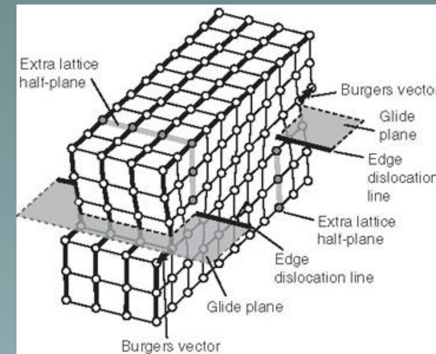
Deformation mechanism at microscopic scale (example, frictional, dislocation-creep diffusion creep)

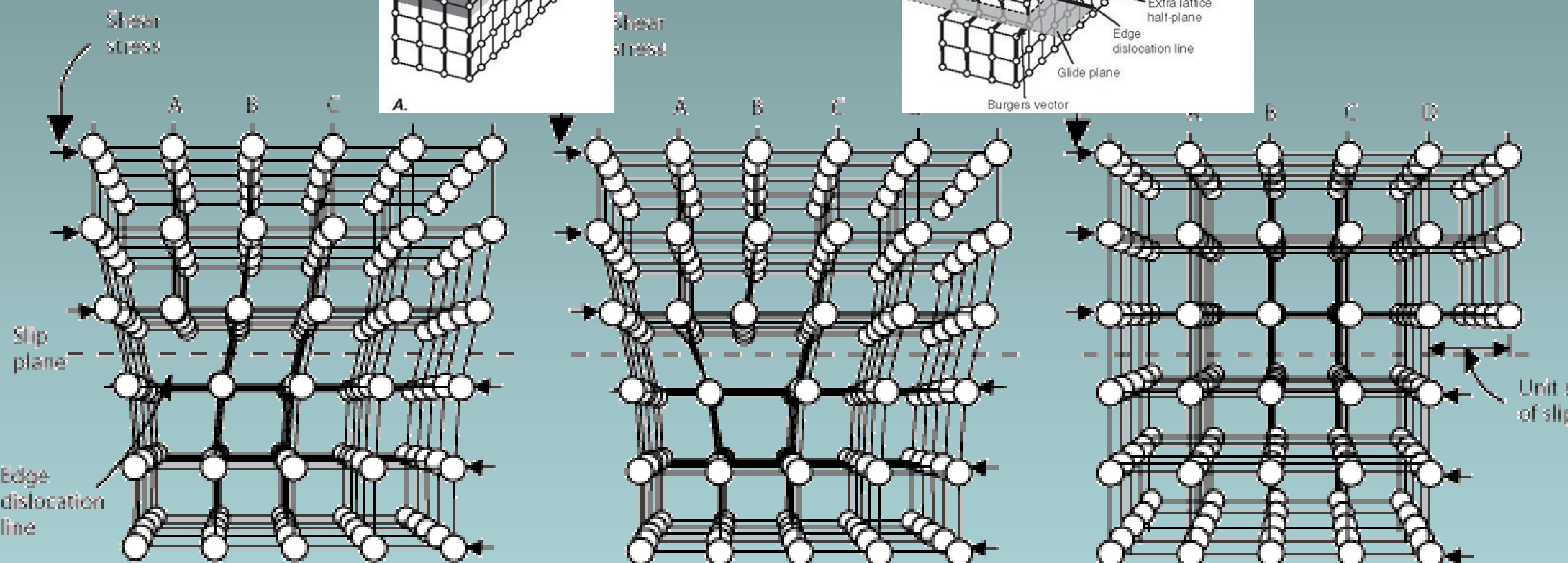
Linear Defects

Dislocation (edge):



→

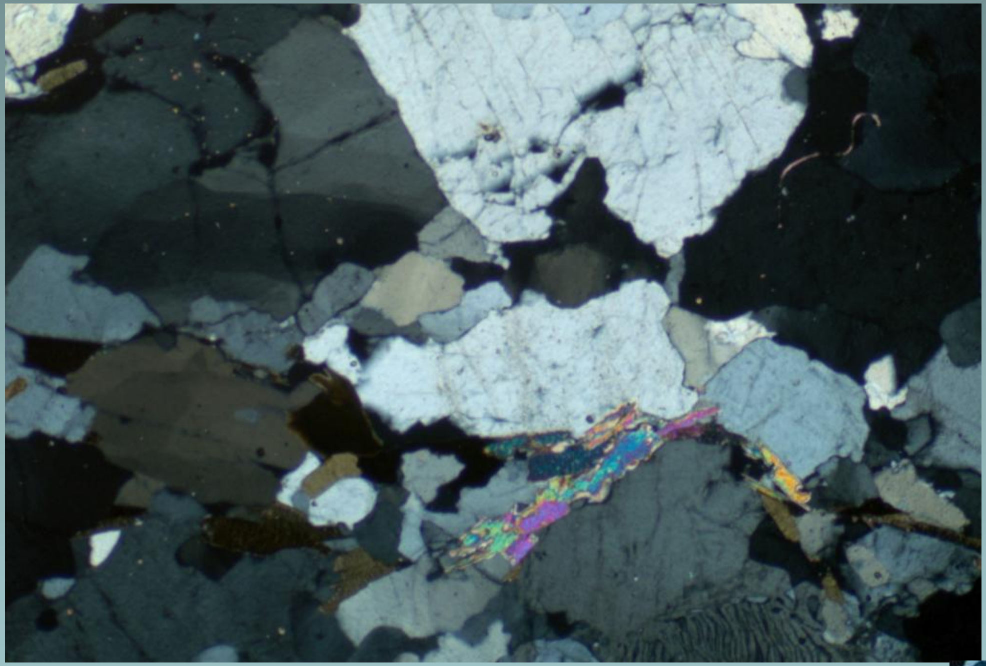


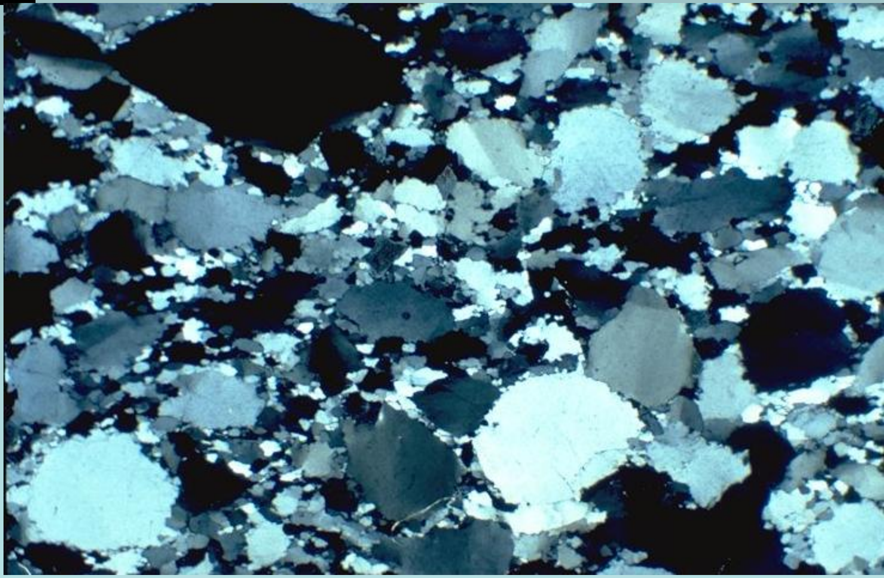


Shear the shaded volume by 1 lattice spacing perpendicular to its internal edge → extra half plane of atoms → edge of the half plane is edge dislocation line

- **Shearing requires breaking the bonds in lattice planes that cross the glide plane & reconnecting the half planes above and below the glide plane, that are one lattice spaci away from original connection.**
- **Slipped & unslipped material are both undeformed.**

Dislocation creep

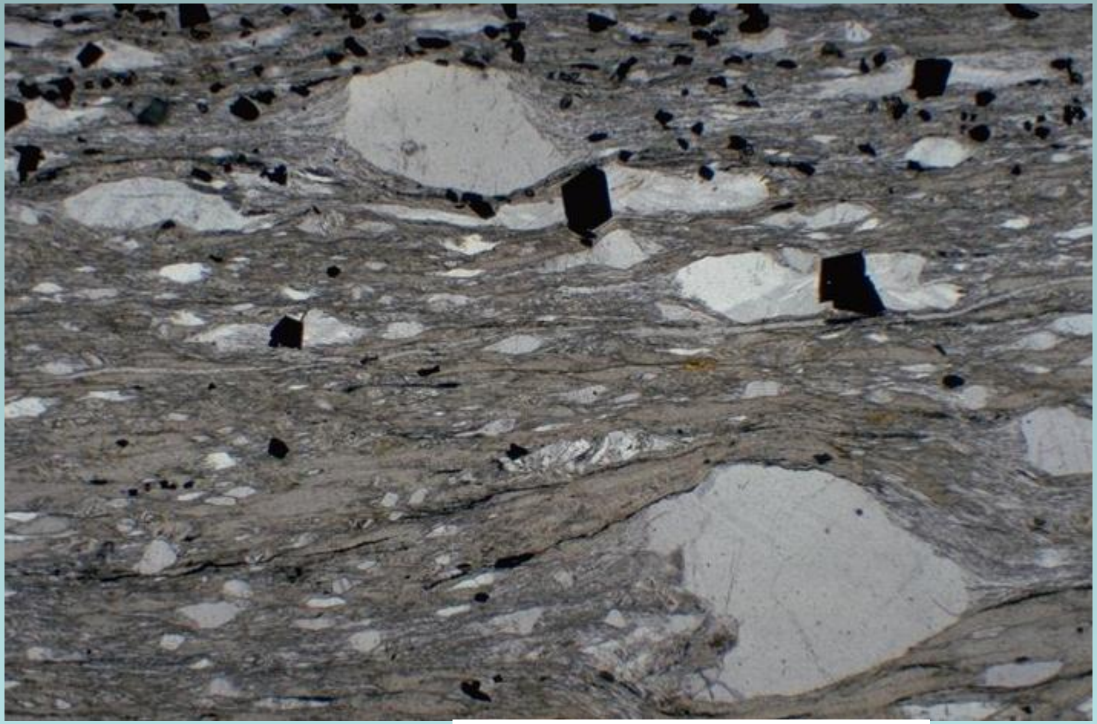




Effects of Point defects -- Diffusion

Diffusion: **Slow migration of one material through another that results from random thermal motions of atoms, and that is driven by a gradient in chemical activity (concentration gradient) or by a non-zero differential stress.**

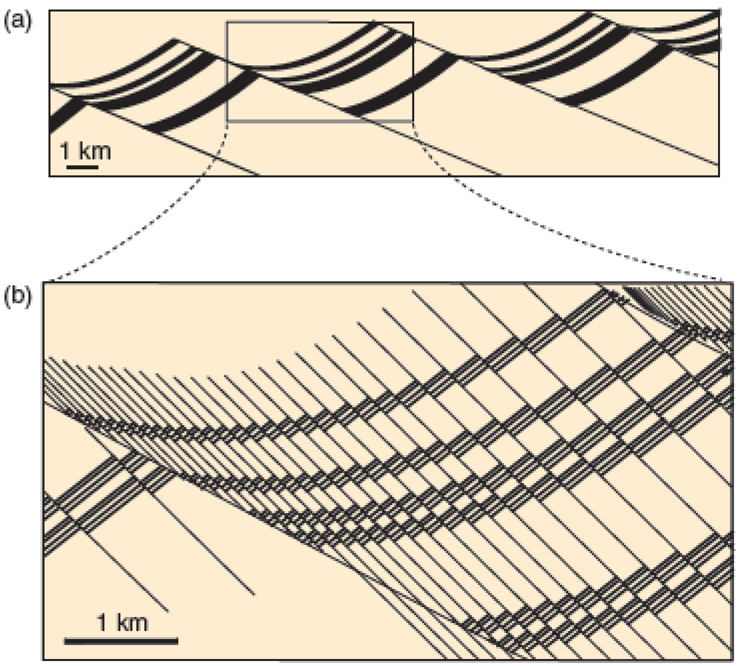
Diffusion creep **in rocks may result from diffusion of point defects through a Crystal lattice , diffusion of atoms/ions along grain boundaries, diffusion of dissolved components in a fluid along grain boundaries.**



Cross nicols view

Problems of using "Brittle & Ductile"

Importance of multi-scale analysis in rock deformation studies



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So what do we do? (Microstructures)

Deformation mechanism at microscopic scale (example, frictional, dislocation-creep diffusion creep)

Frictional Deformation &

Plastic deformation is generally defined as the permanent change in shape or size of a body without fracture, produced by a sustained stress beyond the elastic limit of the material due to dislocation movement.

Frictional & Plastic → microstructural deformation mechanisms

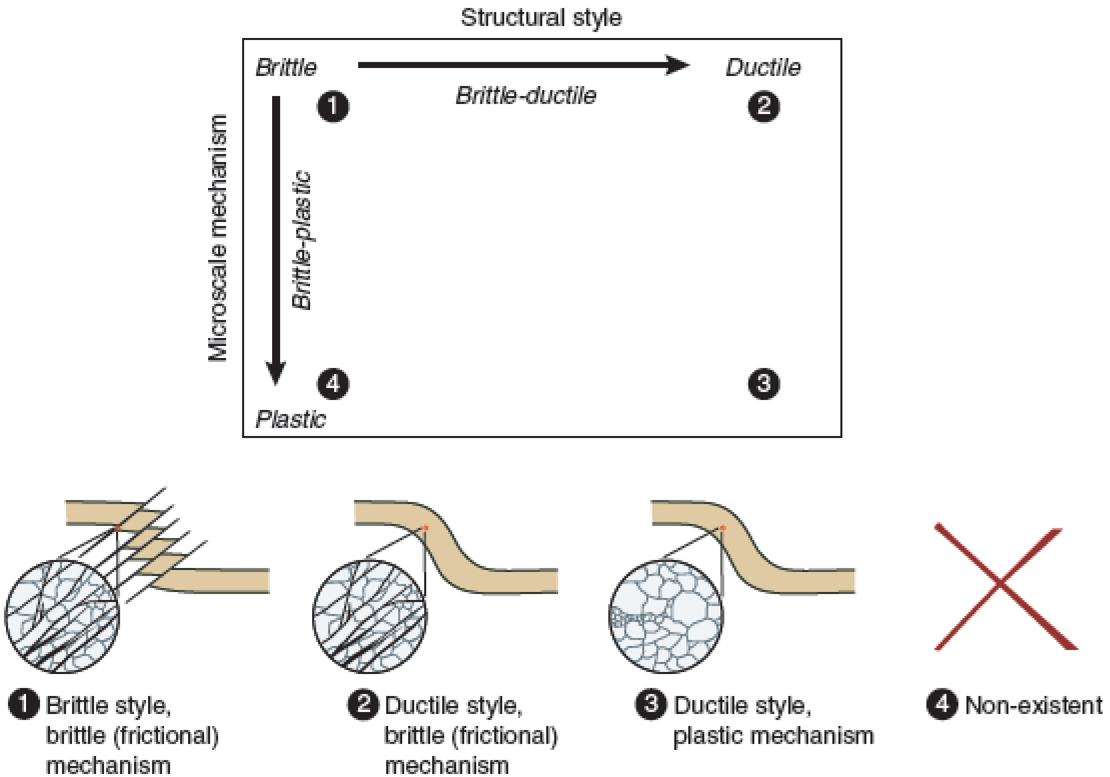

Figure 6.17 Illustration of the relationship between ductile and brittle deformation styles and plastic and brittle (frictional) microscale mechanisms. Example 4 is impossible because we cannot form a brittle deformation style by means of 100% plastic mechanisms.

Frictional Deformation &

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Concept of Scale

Folds: Wave-like bending of rock layers (Macroscale)

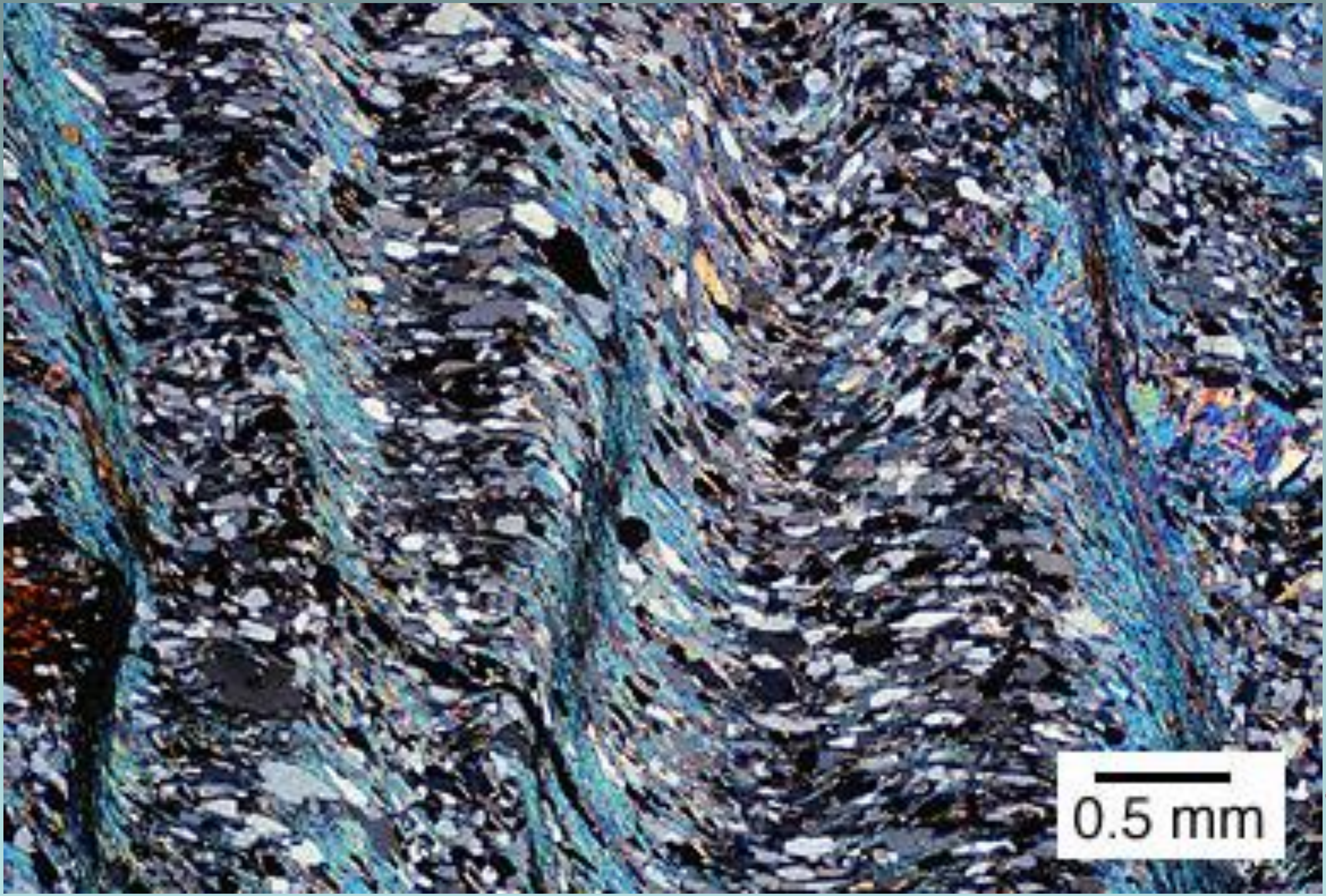
Features that can be traced over a region encompassing several outcrops to whole mountain ranges

Folds (Mesoscale/outcrop scale)

Features visible in rock outcrops but cannot necessarily be traced from outcrop to outcrop

(https://www.researchgate.net/figure/Examples-of-mesoscopic-folds-in-the-orthogneisses-and-metasediments-of-the-study-area-A_fig1_239280387)

Folds (Microscale)



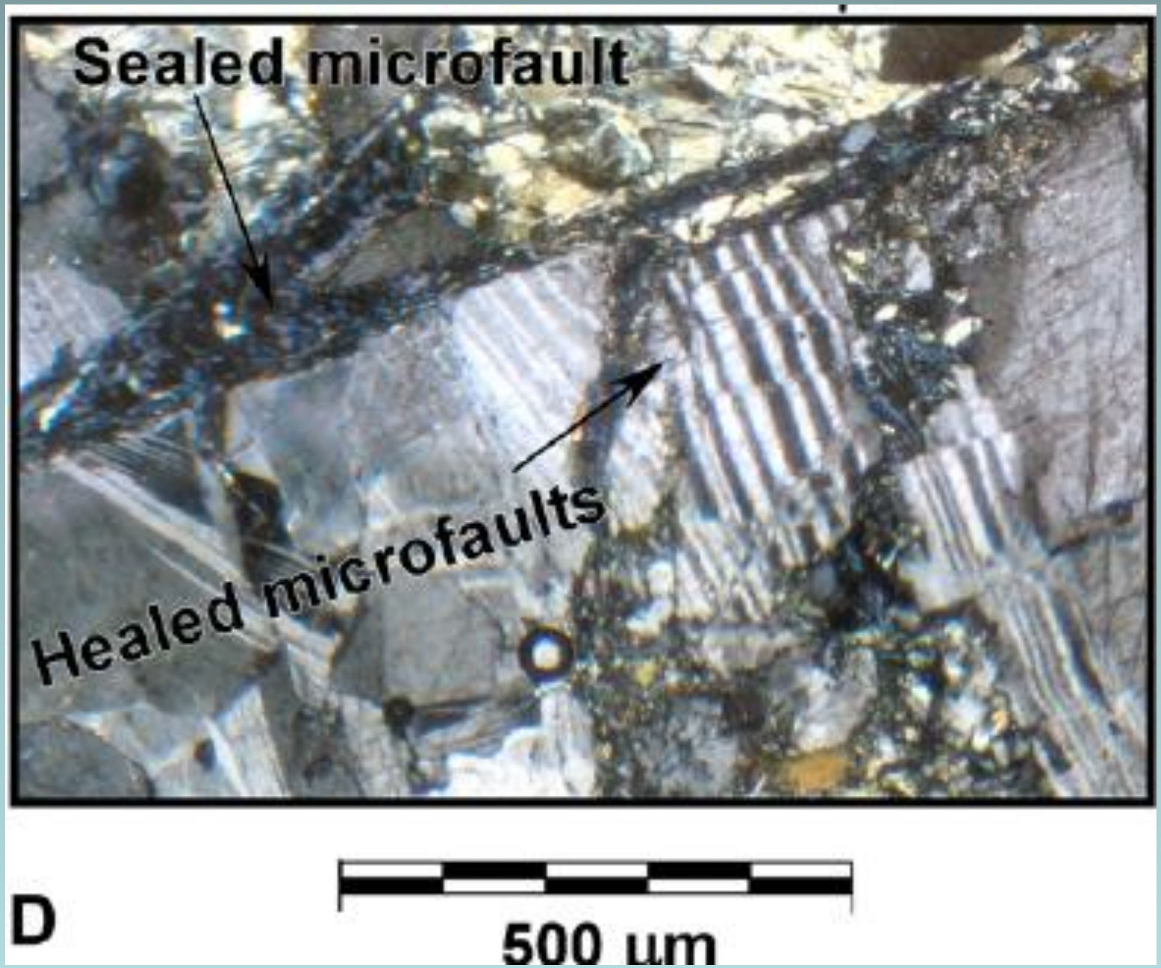
Faults: A fracture or fracture zone (generally planar) between two blocks of rock along which the opposite walls have moved past each other parallel to the fracture.

(Macroscale)

(https://en.wikipedia.org/wiki/Fault_(geology)#/media/File:Piqiang_Fault,_China_detail.jpg)

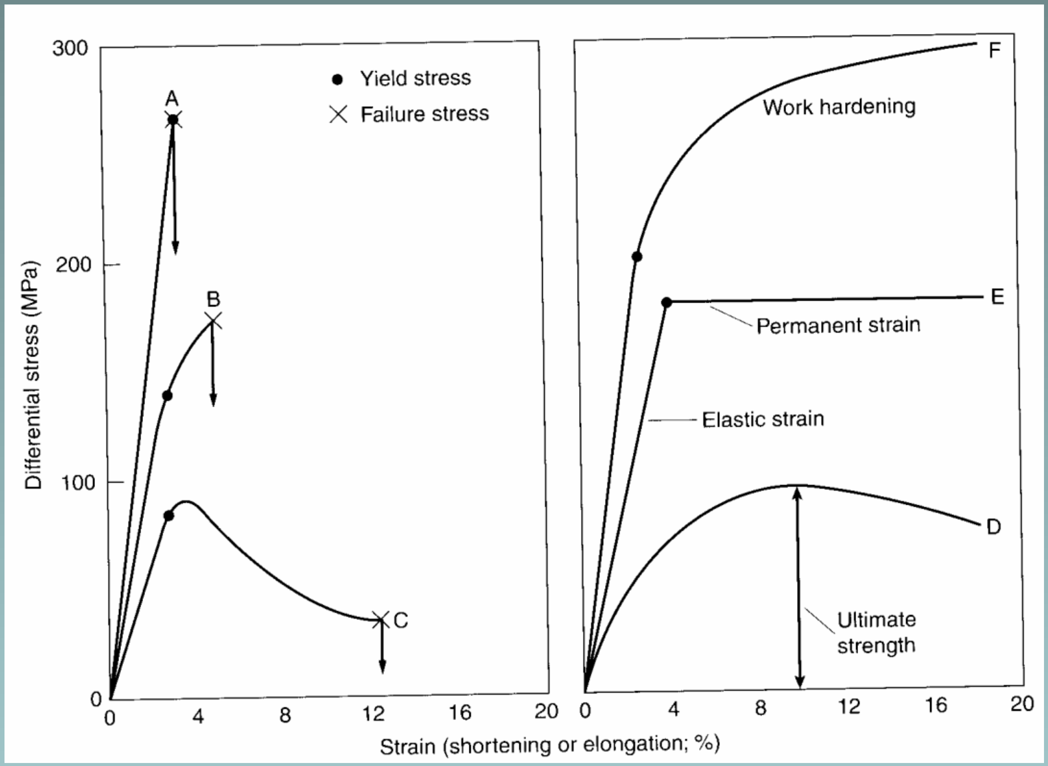
Faults (Mesoscale)

Faults (Microscale)



(https://www.researchgate.net/figure/Photomicrographs-made-in-the-thin-section-on-Fig-5-Right-Open-nicol-Left-Crossed_fig7_229474280)

• **Failure:** Rock is unable to support stress increase without permanent deformation



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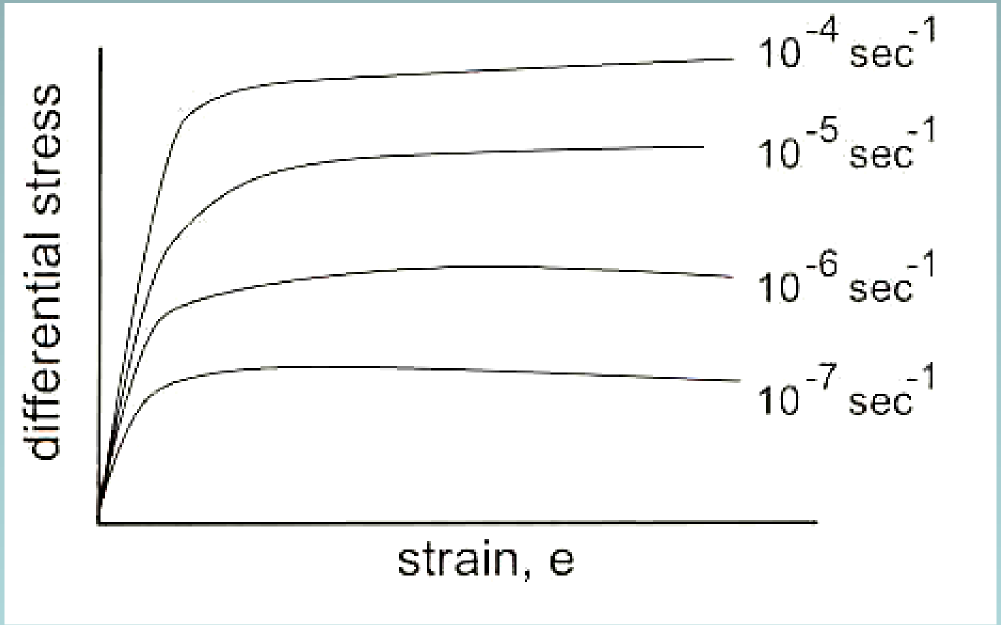
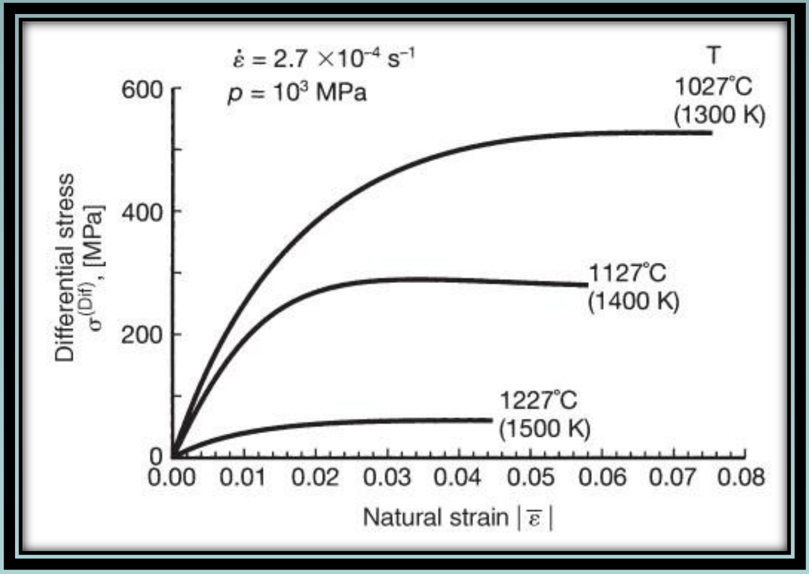
Ductile deformation experiments

Constant Strain Rate Experiments

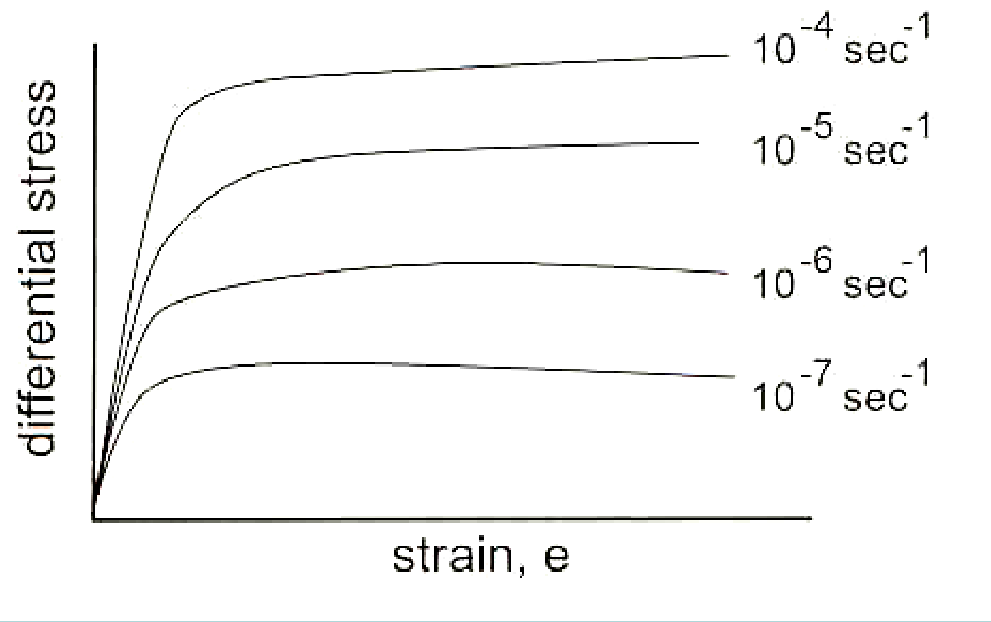




Therefore, rock experiments conducted at very high T

Ductile deformation experiments

Constant Strain Rate Experiments



Extrapolations to geologically meaningful lower strain rate

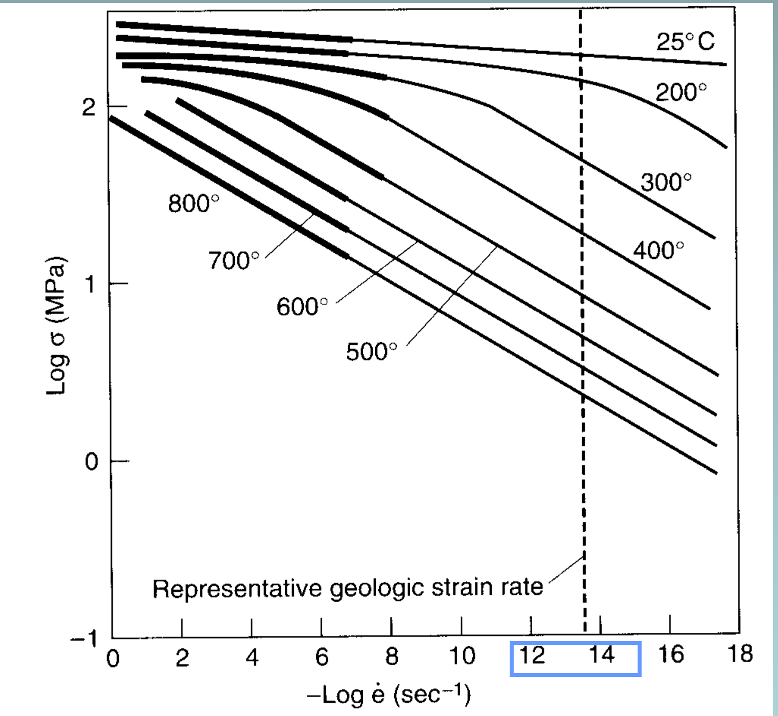


Figure 5.13 Log stress vs. –log strain-rate curves for various temperatures based on extension experiments in Yule marble. The heavy lines mark the range of experimental data; the thin lines are extrapolations to lower strain rates.

Ductile deformation experiments

Constant Strain Rate Experiments

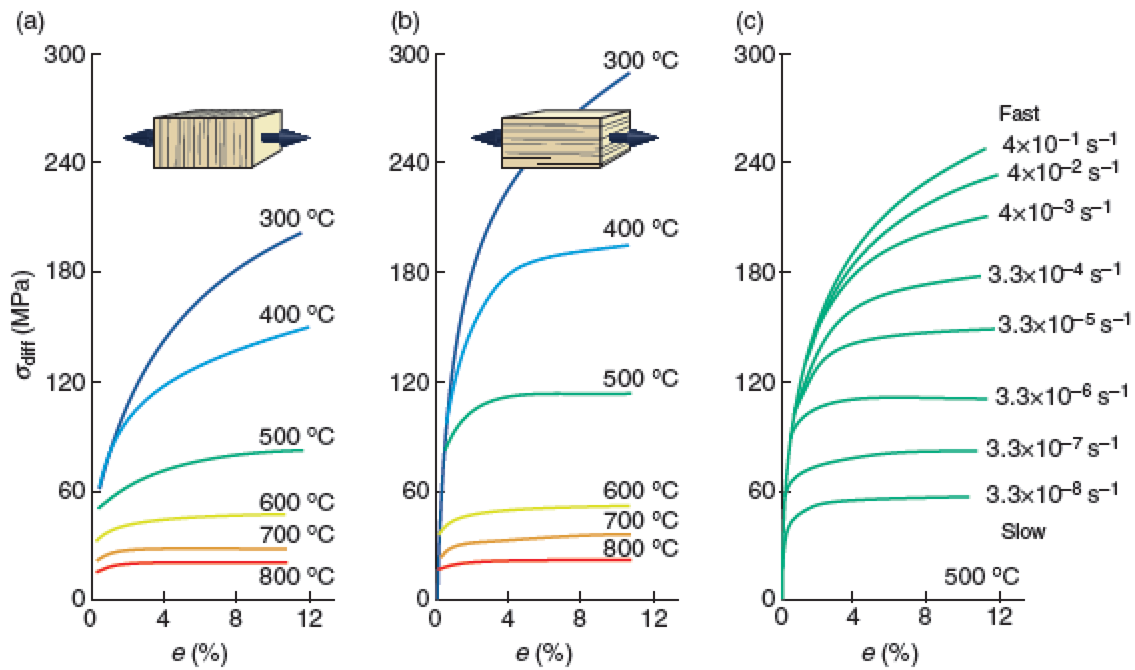


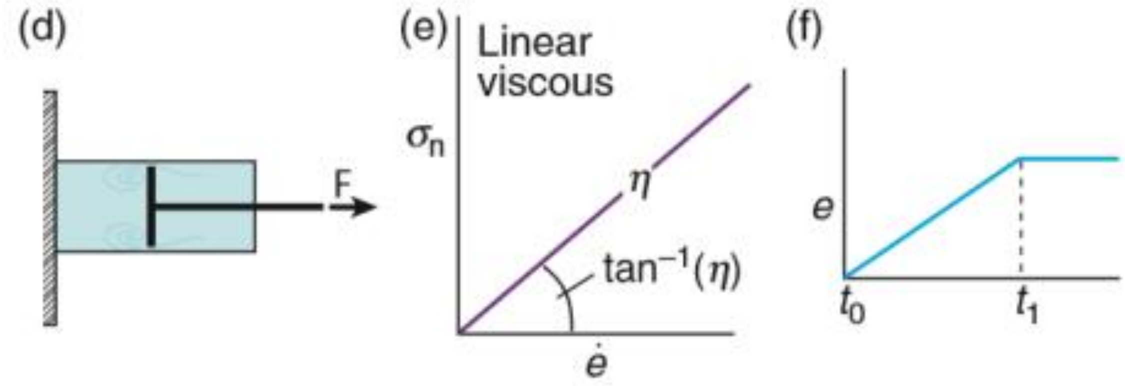
Figure 6.14 Stress–strain curves for Yule marble extended (a) normal and (b) parallel to the foliation. Data from Heard and Raleigh (1972). (c) Stress–strain curves for Yule marble at 500 °C for a variety of strain rates. From Heard (1960).

Strength of a rock depends on its structural fabric (anisotropy)

Nonrecoverable

Newtonian viscous behavior (fluid flow)

Movement of fluids under deviatoric stress



• Linear stress–strain rate relationship
• Stress depends on strain rate
• Delayed response to stress (the more time, the more strain)
• Permanent strain

$$\sigma = \eta * \dot{e}$$

time-dependent deformation

Coefficient of Viscosity (ease with which fluids flow)

- **When stress is removed strain rate goes to 0; strain does not.**
- **Permanent deformation**
- **Any stress can produce large strain, if "t" is high** ***(no relationship b/w strain & magnitude of stress)***

More viscous?

Relative viscosity → competency

$$\sigma = \eta * \dot{e}$$

$\eta = kgm^{-1}s^{-1}$; 1 poise=0.1Pas

Mantle ~10^{21} Pas