

Useful online resources

Dissemination of IT for the Promotion of Materials Science by Cambridge University

<https://www.doitpoms.ac.uk/index.php>

- ▶ Creep: Introduction
- ▶ Creep: Mechanisms
- ▶ Creep: Constitutive models
- ▶ Stress analysis and Mohr's circle
- ▶ Brittle fracture

Brittle and Ductile Deformations

- ▶ Rocks are elastic: they deform under loading and go back to the original shape (reference configuration) when the loading is removed.
- ▶ However, when the applied loading exceeds a certain critical value, rocks start to develop **permanent deformation**.
 - ▶ Linear and non-linear rheologies of rocks are used to describe permanent deformation as viscous flow.
 - ▶ Another mode of permanent deformation is fracturing: e.g., Faults and joints.
- ▶ We are going to study which mode becomes dominant under a given pressure and temperature condition. This understanding leads to a convenient way of representing both modes and required force in one plot: **yield strength envelope**.

Brittle Deformations

- ▶ Another related issue is what is the stress required for fracturing a rock and for causing the fractured surface to slip. Naturally, this question is related to the studies on faulting.
- ▶ Let's first get some intuition from these movies:
 1. Microscopic view to “permanent” deformation:
<http://www.youtube.com/watch?v=n7LXYyohmgg>
 2. Tension tests on metals:
<http://www.youtube.com/watch?v=D8U4G5kcpcM>

Brittle Deformations

- ▶ Stress-strain curves for linear and non-linear elastic materials.

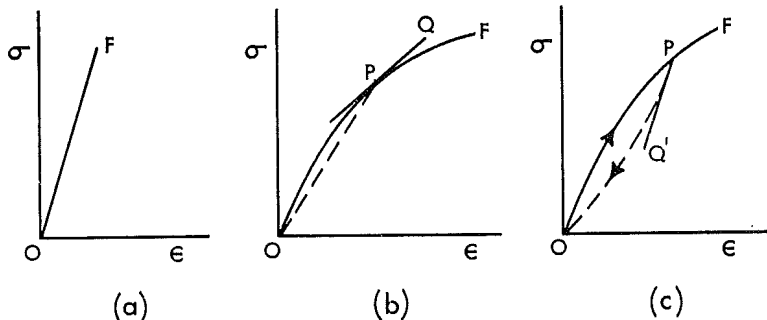


Fig. 4.2.1 (a) Linearly elastic material. (b) Perfectly elastic material showing tangent modulus PQ and secant modulus OP . (c) Elastic material with hysteresis, showing loading and unloading cycle.

Brittle Deformations

- ▶ A typical stress-strain curve for rock.

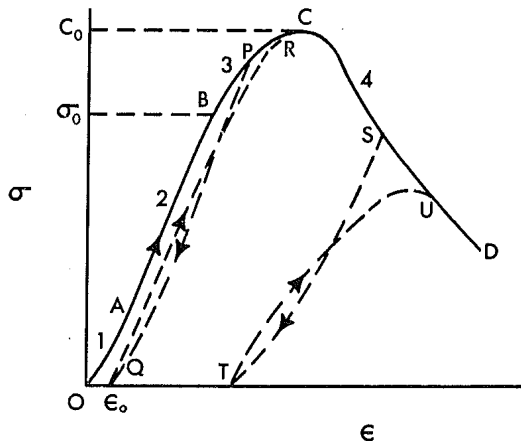


Fig. 4.2.2 The complete stress–strain curve for rock.

Brittle Deformations

(cont'd)

- ▶ The curve has 4 regions
 1. OA: Slightly concave upward. Nearly elastic (i.e. no permanent deformation when unloaded) although maybe with hysteresis.
 2. AB: Almost linear. Nearly elastic although maybe with hysteresis.
 3. BC: Concave downward. Usually, $\sigma_0 \sim 2/3 C_0$. Irreversible deformation starts in this region. Successive cycles of loading and unloading trace out different curves. For instance, paths PQ and QR leaves ϵ_0 .
 4. CD: Failing region. Starts from the stress maximum, C . Characterized by a negative slope. Unloading (ST) leaves a large permanent deformation and reloading (TU) approaches the curve CD at a lower stress U than S.

Brittle Deformations

(cont'd)

- ▶ A material is said to be **ductile** under conditions in which it can sustain permanent deformation without losing its ability to resist load. The ductile state corresponds to the region BC.
- ▶ A material is said to be **brittle** under conditions in which its ability to resist load decreases with increasing deformation. The brittle state corresponds to the region CD.
- ▶ If loading is cyclic, a reloading will attain a higher stress (as in PQR) if the material is in a ductile state while a lower stress (as in STU) if in a brittle state.
- ▶ The process of **failure** is regarded as a continuous one which occurs progressively throughout the brittle region CD, in which the rock steadily deteriorates. The stress value at C, C_0 is called *uniaxial compressive strength*.

Brittle Deformations

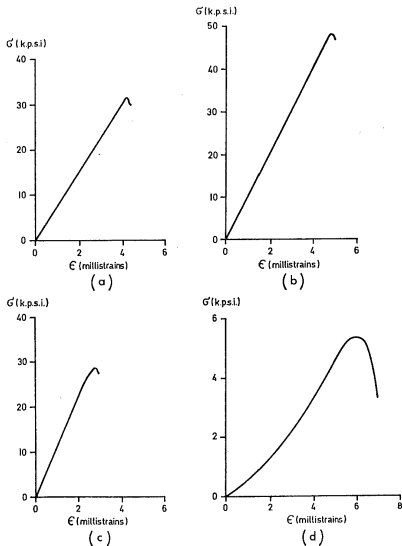
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- ▶ In actual testing, sudden failure often occurs at some point of the curve CD with **complete loss of cohesion across a plane** and this is known as **brittle fracture**. For instance (and for fun), watch

http://www.youtube.com/watch?v=PRF_ZJZksp4.

- ▶ The point B at which the transition from elastic to ductile behavior takes place is known as the **yield point** and the corresponding stress σ_0 as the **yield stress**.

Brittle and Ductile Deformations



- ▶ Some stress-strain curves of typical rocks for comparison with the idealized curve discussed earlier.
- ▶ These curves show how unimportant the regions OA and BC are in the practical cases.
- ▶ So, the assumption of linear elasticity up to failure is a good one in many cases.

Fig. 4.2.3 Stress-strain curves for uniaxial compression in a stiff testing machine. (a) Solenhofen limestone. (b) Karroo dolerite. (c) Rand quartzite. (d) Gosford sandstone

Brittle and Ductile Deformations

< Effects of Confining Pressure >

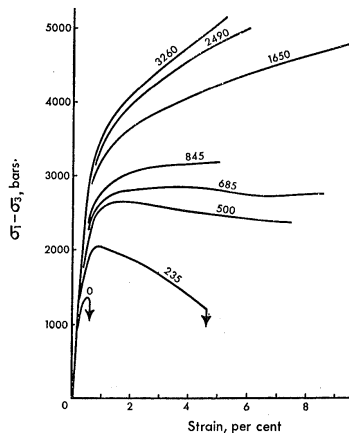


Fig. 4.3.2 Stress-strain curves for Carrara marble (after von Karman) at various confining pressures. The numbers on the curves are confining pressures in bars.

- ▶ Confining pressure up to 500 bars (50 MPa), brittle fracture occurs as before with an increase of strength and a small increase in permanent strain.
- ▶ The curve for 685 bars is completely different: It's a curve for a ductile state.
- ▶ The curve for 235 bars shows transitional behavior.
- ▶ Such a transition is called the **brittle-ductile transition**.

Brittle and Ductile Deformations

< Effects of Temperature >

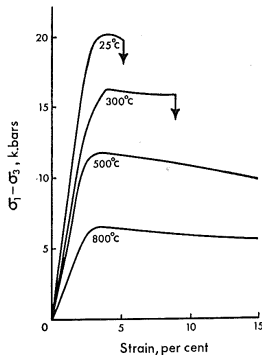


Fig. 4.3.3 Stress-strain curves for granite at a confining pressure of 5 kilobars and various temperatures (after Griggs, Turner, and Heard).

- ▶ The effect of increasing the temperature is to lower the brittle-ductile transition pressure.
- ▶ At room temperature, the brittle failure occurs.
- ▶ At higher temperatures, the substantial amount of permanent deformation is introduced without loss of load.

Brittle and Ductile Deformations

- ▶ Even the pervasively fractured rocks have a finite yield stress under confining pressure.
- ▶ Byerlee showed that the amount of shear stress (τ) required for the most favorably oriented fracture surface (or fault plane) is a linear function of the normal stress (σ_n) on that plane. This shear stress can be identified with the yield stress (τ_Y).
- ▶ Moreover, the linear relationship between τ_Y and σ_n holds regardless of rock type.
- ▶ Since the normal stress can be related to lithostatic pressure¹, $\rho g z$, this fact leads to a linear relationship between the yield stress of pervasively fractured brittle rock and depth: i.e., $\tau_Y \propto z$

¹The details will be worked out in the next class.

Ductile Deformations

- ▶ We can apply a general power-law rheology to ductile deformation. Then, for a given geotherm and an assumed value of strain rate, the shear stress becomes a function of depth, too.

$$\dot{\epsilon} = A(\sigma_1 - \sigma_3)^n \exp\left(\frac{Q}{RT(z)}\right), \quad (1)$$

where $(\sigma_1 - \sigma_3)$ can be related to the amount shear stress required for the assumed strain rate.

- ▶ If both brittle and ductile yield stresses are identified with $(\sigma_1 - \sigma_3)$, we can plot the stress difference $(\sigma_1 - \sigma_3)$ as a function of depth.
- ▶ At each depth, two stress difference values will be available: one for the brittle strength and the other for ductile strength. By picking the lower one, we get a single profile of strength, which is called the **yield strength envelope**.

Ductile Deformations

Table 6.4

$$\dot{\epsilon} = A_p (\sigma_1 - \sigma_3)^n e^{-Q_p/R_s T}$$

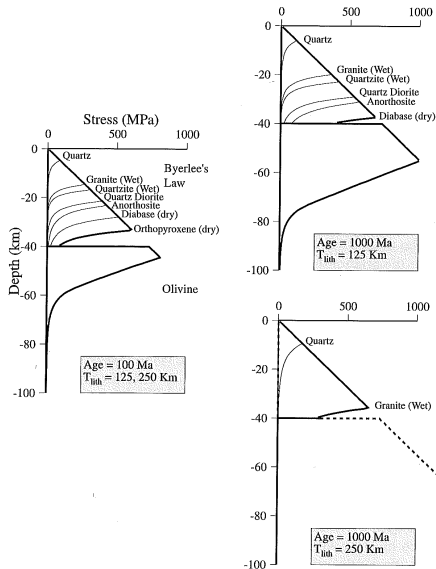
Steady State Flow Properties for Selected Rocks and Minerals

Rock/Mineral	Exponent <i>n</i>	<i>A_p</i> (Pa^{-<i>n</i>} s⁻¹)	<i>Q_p</i> (kJ mol⁻¹)	Primary Reference
Quartz	3.0	1.2×10^{-24}	92	Heard and Carter (1968)
Quartzite (dry)	3.0	6.1×10^{-24}	190	Brace and Kohlstedt (1980)
Quartzite (wet)	1.9	1.2×10^{-13}	173	Hansen (1982)
Granite (Westerly: wet)	1.9	7.9×10^{-16}	141	Hansen and Carter (1983)
Granite (Westerly: dry)	3.3	3.1×10^{-26}	186	Hansen and Carter (1983)
Anorthosite	3.2	3.2×10^{-22}	238	Shelton and Tullis (1981)
Diabase (dry)	3.05	3.1×10^{-20}	276	Caristan (1982)
Diabase (Columbia)	4.7	1.1×10^{-26}	488	Mackwell et al. (1998)
Diabase (Maryland)	4.7	5.0×10^{-28}	482	Mackwell et al. (1998)
Quartz Diorite	2.4	1.2×10^{-16}	212	Hansen (1982)
Orthopyroxene (wet)	2.8	1.0×10^{-19}	271	Rayleigh et al. (1971)
Orthopyroxene (dry)	2.4	1.2×10^{-15}	293	Ross and Nielsen (1978)
Clinopyroxene (wet)	3.3	2.3×10^{-14}	490	Boland and Tullis (1986)
Clinopyroxene (dry)	5.3	1.6×10^{-36}	380	Boland and Tullis (1986)
Olivine	3.0	7.0×10^{-14}	520	Goetze (1978)
Olivine (dry)	3.5	2.4×10^{-16}	540	Karato et al. (1986)
Olivine (wet)	3.0	1.9×10^{-15}	420	Karato et al. (1986)
Dunite(wet)	4.5	4.0×10^{-25}	498	Chopra and Paterson (1981)
Dunite(dry)	3.6	7.9×10^{-18}	535	Chopra and Paterson (1981)

Yield Strength Envelope

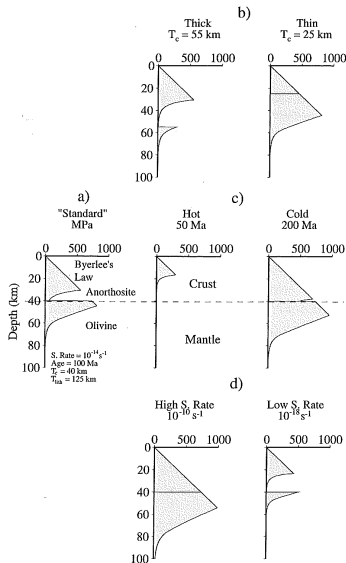
< YSE for continental lithosphere with $\dot{\epsilon} = 10^{-14} \text{ s}^{-1}$ >

(Fig. 6.28 in Isostasy and Flexure of the Lithosphere, Watts, A. B., 2001, Cambridge University Press, Cambridge).



Yield Strength Envelope

(cont'd) (Fig. 6.29 in *Isostasy and Flexure of the Lithosphere*, Watts, A. B., 2001, Cambridge University Press, Cambridge)



Yield Strength Envelope

Strength of Oceanic Lithosphere

