Notes V

Rheology part 2: Experimental rock deformation, stress-strain curves

Fall 2005

1 Reading assignment

The latter part of Chapter 18 in TM is essential reading for this section (pp. 369 – 385). Other useful sources are chapter 5 in Ranalli, G. (1995) *Rheology of the Earth* and Nicholas, A. and Poirier, J.P. (1976) *Crystalline Plasticity and Solid State Flow in Metamorphic Rocks*. Hobbes, et. al. (1982) *An Outline of Structural Geology* is the closest textbook to the order and logic of the lectures as presented in class.

These notes loosely correspond to material covered on Sept. 26 and Oct. 3

2 Experimental rock deformation

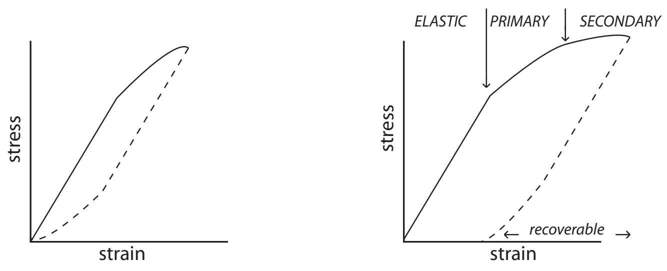
Most of the results of experimental rock deformation come from a fairly standard experimental set-up: a triaxial deformation apparatus.

The triaxial deformation apparatus is basically a pressure vessel surrounding a piston. This kind of apparatus allows careful control of the principal stresses, temperature and strain-rates. The effect of pore fluids or chemical solutions can also be controlled. Major limitations are: (1) the amount of finite strain that the apparatus can accommodate (on the order of 10%); (2) the slowest strain-rates possible (about $10^{p-7}\mathrm{sec}^{-1}$.

3 Experimental rock deformation: phenomenology

Figure 2 shows the relationship between stress (this is shorthand for "differential stress", i.e. $\sigma_1 - \sigma_3$) and (total, finite) strain. The first part of the curve shows a linear relationship between stress and strain – characteristic of elasticity. This strain is *recoverable*, meaning that the strain goes back to zero once the stress is removed. The second part of the curve is known as **primary creep**. Stress and strain are no longer linearly related; strain is recoverable, but the recovery turns out to be time-dependant. That is, this part of the curve shows behaviour characteristic of Kelvin visco-elasticity. The third part of the curve is referred to as

Figure 1: Stress-strain curves



secondary creep. When stress is removed, you recover the elastic part instantaneously, the secondary part in a time dependant part, but you accumulate permanent strain.

4 Ductile deformation: the effects of strain rate and temperature

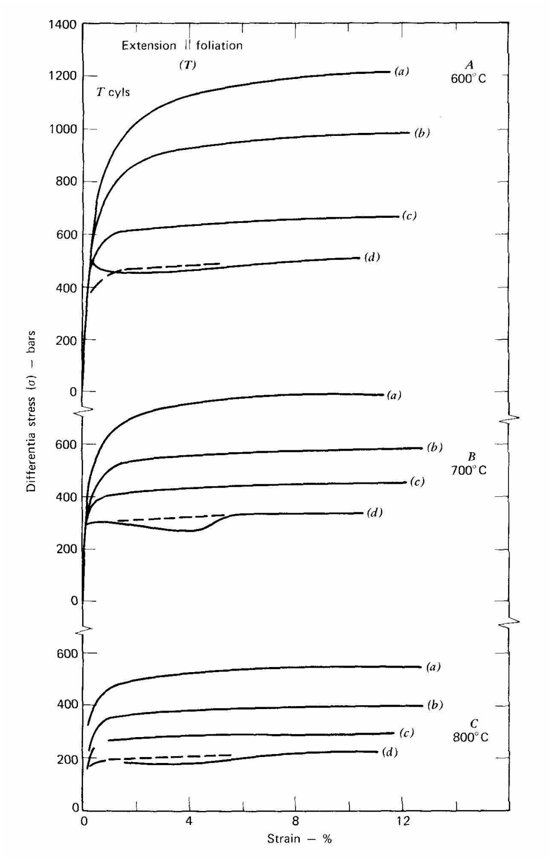
Consider a series of experiments (these results were first described by Heard and his colleagues from experiments on marble, see references in Hobbes, et. al. 1982). Figure 3 shows three plots. The first shows a family of curves corresponding to different temperatures at a constant strain-rate. The second shows a family of curves corresponding to different strain-rates at a constant (high) temperature. The first-order observation is that both increasing temperature and decreasing strain-rate have the effect of weakening the rock (less stress for the same strain). The third shows a plot of stress against strain rates for experiments on marbles. The thin black lines shows how the lines might be extrapolated to geological strain rates, but, more importantly since many of the lines are parallel, it suggests that for certain deformation mechanisms, temperature can substitute for strain-rate. Since we can heat up a sample much easier than we can control the passage of time, this represents a strategy for simulating natural deformation in the laboratory.

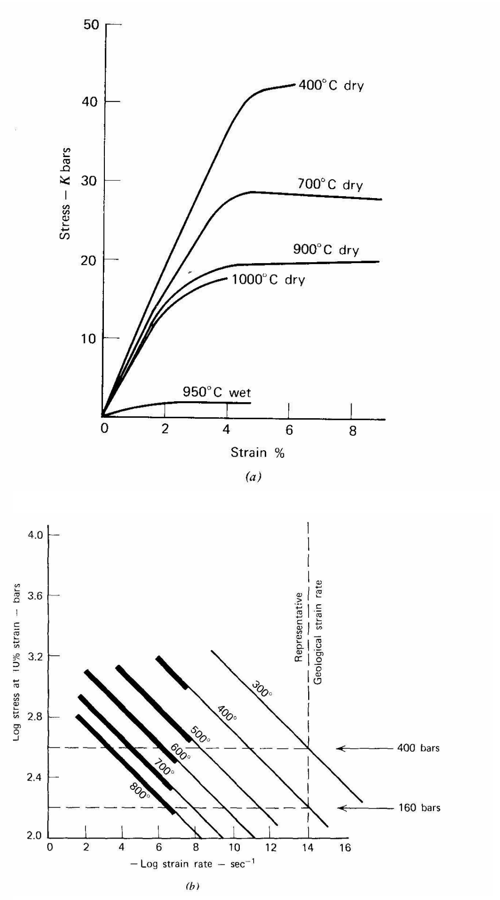
Experimental data can be fit by

$$\dot{\epsilon} = A \exp - \left(\frac{E}{RT} \right) \sigma^N$$

where T is the absolute temperature, R is the gas constant, E is the activation energy, and N is a constant ranging from 1 to 8. For materials deforming such that $N > 1$, this is called "power-law creep", since stress and strain rate are related by a power N. If $N = 1$, then strain rate is linearly proportional to stress, which is the definition of a Newtonian viscous body. For constant strain-rates or constant stresses, the equation can be manipulated to yield an "effective viscosity", which at the very least is a useful shorthand for the strength of materials deforming by ductile flow. The effective viscosity of the upper mantle, as inferred from studies of post-glacial rebound are in the 10^{21-22} range.

Figure 2: Experimental stress-strain curves





5 Review questions

What are typical strain rates for tectonic systems? What are the slowest strain-rates typically achievable in laboratory experiments? How can we safely extrapolate experimental results to natural systems?

In the plot with a family of temperature curves in stress vs. strain-rate space, not all the lines are, in fact parallel. This and similar plots are often subdivided into high, moderate and low stress regions.

Outline how the environmental variables of confining pressure, temperature and strain-rate affect the behaviour of rock deformation.