Repair examination Paper:

Mechanisms of Deformation and Transport in Rocks

Part II (Niemeijer) 19-05-2016 09.00 -12.30 hours HPTLAB

- The duration of this exam is 3.5 hours.
- Answer all questions given.
- All questions count with equal weight to the final grade.
- Answers may be given in English or Dutch.
- Make sure you **identify all mathematical symbols** used in answering the questions
- Use SI units unless otherwise specified.
- If you do not understand the English in any of the questions, raise your hand for help.
  Good luck !!!

Question 1

a) Explain what is meant by the term "superplasticity" (i.e. structural superplasticity).

b) Explain what microphysical mechanisms give rise to superplastic flow in metals, ceramics and rocks.

c) What ductile deformation mechanisms do not give rise to superplastic flow and why?

d) Go on to explain how you would determine if the processes responsible for superplastic flow behaviour operated in a fault zone rock found in a field study of a high grade shear zone.

e) Explain **three** ways in which the processes responsible for superplastic flow of rock can be initiated in shear zones and outline the implications for the localization behaviour of major shear zones.

Question 2

a) Explain what vacancies are and write down an equation for the equilibrium concentration of thermally produced vacancies in a pure elemental crystal maintained at a temperature T (K) and hydrostatic pressure P. Define all symbols appearing !!

b) Explain the statistical meaning of your answer to (a), with reference to the Boltzmann distribution law.

c) Derive an equation to show how the equilibrium concentration of vacancies is modified at a grain boundary transmitting a normal stress σ_n (superimposed on the hydrostatic component P), and hence explain the theoretical basis (driving force) for solid state diffusion creep.

d) Explain the most likely pathway for vacancy and atomic diffusion during deformation by solid state diffusion creep at temperatures of around 0.7 of the melting point in K. Then identify the physically possible rate limiting steps along this pathway, using an electrical circuit analogue diagram. Which of these steps do you expect to control deformation rate in a typical crystalline solid at the specified temperatures?

e) Write down the theoretical rate equations for ONE of the two best-known processes of solid state diffusion creep and name the process you choose and the associated diffusion path. Go on to obtain an expression for the viscosity of a solid deforming by this mechanism. Finally, identify which quantities in this expression will determine whether the process becomes more or less important with increasing depth in the lower crust or upper mantle.

Question 3

a) List at least 3 possible configurations for performing friction experiments, sketch them and list a possible disadvantage of each method.

b) Show why friction is *not* a material property using adhesion theory.

c) Go on to explain how shear stress should depend on (effective) normal stress if the contacts obey Hertzian contact mechanics and give a possible explanation why experiments almost always show that shear stress varies linearly with (effective) normal stress in a typical friction experiment.

d) Rate and state friction equations describe the evolution of friction with time (or displacement) and are given by:

$\mu = \mu_0 + a ln\left(\frac{V}{V_0}\right) + b ln(\frac{V_0\theta}{d_c})$ and the "slowness" evolution equation as: $\frac{d\theta}{dt} = 1 - \frac{V\theta}{d_c}$

Identify all terms in the two equations and derive an expression for determing the value of (a-b) from steady state friction measurements obtained at velocities V_0 and V_1.

e) Frictional sliding experiments were conducted on wet quartz gouge material over a range of temperatures from room temperature up to 600 °C. Microstructural observations of the experimental products show that grain size is significantly reduced at low temperature, whereas at elevated temperature a Lattice Preffered Orientation is observed in the quartz grains. List the deformation mechanisms that were operating at the different temperatures based on these microstructural observation and describe the steps you would take to derive a microphysical model for the evolution of friction from low to high temperature (actual derivation not required).

Question 4

a) Measured values of the tensile fracture strength (T_o) of brittle materials are usually much lower than the theoretical ("bond strength) value σ_T. Explain why this is.

b) Consider a flat "elliptical" crack (length 2a) within an infinite plate of elastic material (Young's Modulus E) and suppose that this plate (which is of unit thickness) is subjected to a remote uniaxial tensile stress (σ) oriented normal to the crack surface. The applied stress will give rise to a stored elastic energy U_e within the plate. Given that the rate of change of U_e with respect to crack length can be written as

$$\frac{d U_e}{da} = \frac{-2\pi a \sigma^2}{E}$$

derive the Griffith failure criterion for uniaxial tensile loading. **State any assumptions made.**

c) Go on to explain why the stress at which a brittle solid breaks, by say Mode I tensile failure, is not a material property.

d) Following on from your answer to Part (c), explain what is meant by the terms "stress intensity factor" and "fracture toughness", and re-write the Griffith criterion in terms of stress intensity factor and critical stress intensity factor.

e) A sample of low porosity but still permeable quartzite is loaded uniaxially, at room temperature and under dry conditions, to 80% of its brittle compressive failure strength. An initial instantaneous shortening of 0.2% occurs when the load is applied, but beyond that no further deformation occurs. The pores of the rock are then flooded with water at atmospheric pressure and the sample immediately fails catastrophically. Give an explanation for this behaviour.

Question 5

a) Write down an equation giving the chemical potential of a solid at a point on a fluid-filled grain-to-grain boundary experiencing a normal stress σ_n. Identify all of the symbols used and state their units. Assume the grain boundary contains fluid in the form of an island-channel structure or as an adsorbed film.

b) Use this equation to derive an equation for the rate of pressure solution creep of a material consisting of densely-packed cubic grains, subject to a pure shear stress of magnitude σ. Assume reaction control (i.e. dissolution/precipitation control).

c) Now write down an equation for the creep rate assuming diffusion control (no need to derive this).

d) By equating the two results you obtain, develop a criterion for determining the conditions under which pressure solution is controlled by reaction versus diffusion.

e) Assuming porosity has little influence on this criterion, use it to determine which mechanism you expect to control pressure solution creep in i) ultrafine fault rocks and ii) a very coarse-grained gas reservoir sandstone

Question 6

a) Write down the stress-strain relations for an anisotropic elastic material using **matrix** notation.

b) Taking into account the ***symmetry*** of the stiffness matrix (C_{rs}), the non-zero components of this matrix for a ***forsterite*** crystal (orthorhombic) are specified as follows:

$$\left.\begin{array}{lll} C_{11} = 3.284 & C_{22} = 1.998 & C_{33} = 2.353 \\ C_{23} = 0.738 & C_{31} = 0.688 & C_{12} = 0.639 \\ C_{44} = 0.6515 & C_{55} = 0.812 & C_{66} = 0.8088 \end{array}\right\} \times 10^{11}\ \text{Pa}$$

referred to the orthorhombic crystal axes x_1, x_2, x_3.

Write out the matrix C_{rs} in full.

c) Explain the physical meaning of the first vertical column of the matrix C_{rs}.

d) A forsterite single crystal is subjected to an elastic strain given by the tensor:

$$\varepsilon_{ij} = \begin{bmatrix} 3 & 0 & 1.5 \\ 0 & 0 & 0 \\ 1.5 & 0 & 1 \end{bmatrix} \times 10^{-4} \quad (\text{referred to } x_1, x_2, x_3)$$

Use C_{rs} to calculate the resulting state of stress, writing your answer in both matrix and tensor notations.

e) Calculate also the mechanical work done on the forsterite crystal when subjected to the above strain, making sure you state the units!!

f) Use the first and second laws of thermodynamics to **show** how this mechanical work changes the thermodynamic state of the crystal, if deformation occurs at constant temperature, and explain what would happen to the crystal if it is placed in contact with an unstrained forsterite crystal with a silicate melt layer between the two crystals.