Examination Paper: *Mechanisms of Deformation and Transport in Rocks*

12-04-2006 14.00 -17.00 hours C.116

Note:

- The duration of this exam is 3 hours
- The examination paper has two parts:
  -Part A (Deformation, Spiers) has 6 questions; <u>choose any 3</u>
  -Part B (Transport, Peach) has 4 questions; <u>choose any 2</u>
- Hence, answer 5 questions in total.
- Allow about 35 minutes per question.
- Answers may be given in English or Dutch.
- Make sure you identify all mathematical symbols used in answering the questions (marks will be deducted for unidentified symbols).
- Use SI units unless otherwise specified.

Good luck all !!!

PART A (Choose any 3 questions)

Question A-1

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

$$\left.\begin{matrix} C_{11} = 3.0 & C_{22} = 1.8 & C_{33} = 2.1 \\ C_{23} = 0.69 & C_{31} = 0.61 & C_{12} = 0.60 \\ C_{44} = 0.58 & C_{55} = 0.71 & C_{66} = 0.70 \end{matrix}\right\} \times 10^{11}\ \text{Pa}$$

referred to the orthorhombic crystal axes x_1, x_2, x_3. ***Write out the matrix C_{rs} in full.***

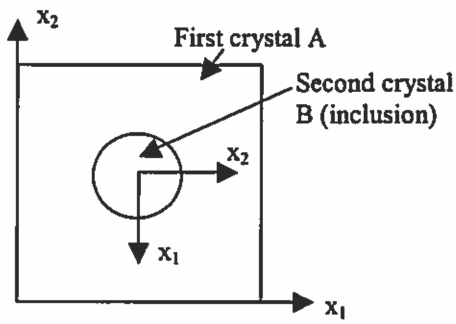
b) An olivine single crystal is deformed at constant temperature to an elastic strain given by the tensor

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

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

c) Calculate the change in the Helmholtz free energy of the crystal.

d) Suppose that the crystal (A) contains a second olivine crystal (B) as an inclusion, and that the crystal axes of this included crystal are orientated as shown in the figure on the right. If the strain applied to the first (outer) crystal is uniform throughout both crystals (homogeneous strain field), what is
-the state of strain in B, specified with respect to its own crystal axes?
-the state of stress in B, specified with respect to its own axes?
-the Helmholtz free energy of B?



e) If grain boundary migration is possible, in the above configuration, will B grow or shrink?

Question A-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 part (a), with reference to the Boltzmann distribution law.

c) 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) List the steps you would go through to derive a simple creep model for deformation of a polycrystalline material (grain size d) by Nabarro-Herring creep (lattice diffusion controlled creep). There is no need to derive the model in detail.

e) Write down the theoretical rate equation for Nabarro-Herring creep and show how the viscosity of mantle rock deforming by this mechanism is expected to depend on temperature and pressure.

Question A-3:

a) Explain what is meant by the terms "necking instability" and "superplasticity" (structural).

b) List the principal rheological and microstructural characteristics exhibited by crystalline materials that show superplastic deformation?

c) List the microphysical mechanisms that can give rise to superplastic flow .

d) Mylonitic shear zone rocks often show evidence for the operation of the processes responsible for superplastic flow. Explain **three** ways in which such behaviour can become localized in shear zones and outline the implications for ther strength of major shear zones compared to surrounding host rock.

e) Explain why superplastic deformation is important in materials science.

f) List the problems faced by materials scientists seeking to promote superplastic behaviour in metallic alloys and ceramics, and explain how these problems can be overcome!

Question A-4:

a) Gibbs' equation for the condition of chemical equilibrium at (any point on) a curved interface between a solid and its solution phase is written:

$$\mu_s = \mu_n^{eq} \equiv f^s + p\Omega^s + 2\gamma_{SL}\Omega^s / r$$

Identify all terms appearing and specify the units you use for each.

b) Go on to explain how the local equilibrium chemical potential of dissolved solid can be influenced by deformation of the solid phase.

c) Consider two grains (G1, G2), in a deformed polycrystal, separated by a grain boundary filled with a saturated solution phase in liquid film form. The grain boundary is straight (planar). G1 contains dislocations with a density ρ and energy per unit length W, *and hence has a stored energy of* ρW J/m^3 (!!!). G2 is free of dislocations. The thermodynamic state of the grains is otherwise identical. The fluid film thickness is S (m).

- i) If the grain boundary migrates, which way do you expect it will go? Illustrate your answer with a simple diagram showing the grain boundary configuration described.
- ii) Use Gibbs' equilibrium condition to derive an expression for the chemical potential difference tending to drive grain boundary migration.
- iii) Go on to obtain an expression for the velocity of fluid-assisted grain boundary migration for the limiting case of precipitation control, assuming a linear relation between precipitation (growth) velocity and driving force.
- iv) What would ultimately happen if the fluid film increses in thickness by accumulating fluid contained in fluid inclusions?

Question A-5

a) Explain, in terms of dislocation dynamics, what is meant by the terms "work hardening" and "recovery".

b) Go on to describe how these processes can lead to steady-state creep in rocks at elevated temperatures.

c) Develop a rate model for deformation by high-temperature, climb-controlled dislocation creep where the obstacles to dislocation glide are attractive junctions (dipoles) between edge dislocations of opposite sign (Weertman type model).

d) This model works well for dislocation creep at high temperatures, but breaks down at low-moderate temperatures. Why is this and how could you improve the model for the lower temperature range?

<u>Question A-6</u>

a) Measured values of the tensile fracture strength (T_o) of rocks and ceramics are usually much lower than the <u>theoretical</u> tensile fracture strength σ_T. Why is this?

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

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

<u>derive the Griffith failure criterion</u> for uniaxial tensile loading, **stating any assumptions made.**

c) Go on to explain what is meant by the terms <u>"stress intensity factor"</u> and <u>"critical stress intensity factor"</u> for a Mode I crack. Illustrate your answer with suitable equations and diagrams.

d) A wet rock sample is loaded at room temperature and at a stress which produces around 1% instantaneous shortening. The applied stress is too low to cause immediate fracture, but acoustic emissions are recorded immediately upon application of the load. Acoustic emissions subsequently continue with time and the sample deforms by slow, on-going creep. It finally fractures after 2 weeks. Offer an explanation for the behaviour observed, illustrating your answer with a strain-time plot and making use of any simple formulas that are relevant.

e) Explain how the type of behaviour described in (d) might be relevant to predicting seismic events – use your own imagination and background knowledge!

<u>PART B</u> (Choose any 2 questions)

<u>Question B-1</u>

a. What is Darcy's law in terms of hydraulic head, hydraulic conductivity and specific discharge (Darcy velocity)?
b. What assumptions are made for the fluid properties and porous rock properties in the formulation of Darcy's Law?
c. What are the limitations of Darcy's Law when applied to the flows in active hydrothermal fracture systems?
d. Define tortuosity. What role does tortuosity play in the formulation of Darcy's law from simple models of connected microscopic flow elements (capillaries, etc)?
e. What is the Dupoit-Forcheimer relation used for, in the construction of such permeability models?
f. What does a "representative elementary volume" (REV), in modelling hydro-geological transport processes mean? Do all transport processes (diffusion, heat conduction/convection, etc.), which may be coupled to fluid flow, share the same REV?
g. A rock has a hydraulic conductivity of 1 metre per day to a fluid with dynamic viscosity of 1 mPa.s and density of 1000 $kg.m^{-3}$. What is the rock's permeability in S.I. units? (Take g = 9.81 m^2s^{-1})
h. What is the permeability of the same rock to oil with a dynamic viscosity of 10mPa.s and density of 800 $kg.m^{-3}$?

Question B-2

a) With the aid of a Mohr circle diagram, describe how pore fluid pressure affects brittle shear-failure and faulting in upper-crustal rocks?
b) What changes to pore fluid pressure may be expected in deeper crustal rocks and how do these changes affect style and attitude of faulting?
c) Why are low-angle thrust faults rare in shallow, permeable, rock formations?
d) What are seismic pumping and fault valve behaviour?
e) Describe the geometry of extensional veins that are associated with thrust faulting.
f) At what stage in a seismic cycle are such extensional veins likely to form?
g) How are fluid pressure lambda values defined?
h) What is the most likely, immediate, consequence of a lambda value greater than 1, occurring at depth in a rock formation?

Question B-3

a) What processes give rise to crack-seal veins?
b) How can fluids be transported in lower-crustal and mantle rocks when the conduits to flow have a natural tendency to close by creep?
c) Describe three limitations to sub-critical crack growth that relate to the fluid transport properties of the host material and the properties of the crack filling fluid.
d) Why are fracture systems in hydrothermal fields often linked by fractal geometry?
e) What can equilibrium pore geometry and fluid/rock dihedral angle studies tell us about permeable connectivity in deep-crustal rocks?
f) To what degree, can laboratory measurements of permeability on such texturally equilibrated rocks provide us with values of permeability associated with deformation and metamorphism?
g) What methods of permeability measurement allow investigation of low permeability materials and explain their advantages over the methods pioneered by Darcy himself?

Question B-4

a) What can microscopic observations and spectral measurements of quartz rocks using infrared light, tell us about the fluids they contain?
b) What other methods can be used to determine the fluid transport properties of porous rocks besides direct permeability measurement?
c) What is percolation theory and how can it be used to quantify the effects of pore disconnection in low permeability rocks?
d) What percolation cluster structures are responsible for transport in percolating networks?
e) What method can be used to test percolation systems for proximity to a percolation threshold?
f) Outline how percolation theory may be applied to cases of dehydration veining to estimate the time to macroscopic hydraulic fracture?
g) What is the consequence of the fractal geometrical scaling of percolation systems for the estimation of fluid storage from small scale (e.g. laboratory scale) to large scale (e.g. field scale)?