GEO4-1410, Deformation Mechanisms and Transport in Rocks.

Tentamen:

Transport and Effects of Fluids

Docent: Dr. C.J. Peach
Datum: 17-04-2009, 09:00-12:00, C.116

Instructions:

- Read all questions through, thoroughly, before answering.
- Answer any **4** from the **6** questions and clearly label your answers with the question number.
- Use S.I. units, unless stated otherwise.
- Show any calculation steps clearly and use annotated diagrams where appropriate.
- Write your name clearly on each separate answer sheet.
- Duration of examination: 3 hours

Questions:

1.

a) What is meant by the term representative elementary volume (REV), in descriptions of transport properties used for hydro-mechanical modelling?

b) The permeability of fractured granite, in the form of a 50mm long cylinder with a 50mm diameter, was measured in the laboratory using suitable techniques. The value is to be used to assess the suitability of a geothermal energy extraction scheme, which is to be situated in the same material at depth within a geothermal region. The fracture system in the granite is mainly confined to regular joints with about 1 metre spacing together with a more variable fault related fracture system having a strong preferred alignment and intersections over tens of metres. Discuss the applicability of the permeability value and suggest what other parameters should be measured to enable a heat transfer assessment for extraction of hot water/steam from the hot formation.

c) What laboratory methods could be used to measure the permeability of the granite cylinder, given that the permeability is expected to be less that $10^{-18}m^2$ and what are their advantages over simple steady state Darcy flow through determinations?

d) What are the expected limitations of Darcy's Law when applied to the flows in active hydrothermal fracture systems?

e) Write Darcy's law in terms of hydraulic head, hydraulic conductivity and specific discharge (Darcy velocity) and state the units of each parameter?

f) Show the general structure of the permeability tensor for both an isotropic and an anisotropic porous medium, giving geological examples of such media.

g) A rock has a hydraulic conductivity of 10 metres per day to a fluid with a dynamic viscosity of 1mPa.s and density of $1Mg.m^{-3}$. What is the permeability of the rock in S.I. units? (take $\mathbf{g} = 9.81m^2s^{-1}$)

h) What is the permeability of the same rock to oil with a dynamic viscosity of 10mPa.s and density of $800kg.m^{-3}$?

2.

a) Define tortuosity. What rôle does tortuosity play in the formulation of Darcy's law from simple models of connected microscopic flow elements (capillaries, etc.)?
b) In the construction of such permeability models how is the Dupoit-Forcheimer relation used?
c) Why is the degree of connectivity taken to be more important than tortuosity in explanation of the critical permeability versus porosity behaviour seen in poorly connected, low permeability, materials?
d) What geometrical theory may be applied to poorly connected systems and how does it help with estimates of permeability?
e) What tests can be applied to systems of poorly connected transport paths to estimate their degree of connectivity?
f) Explain, by listing the process steps and connections, how the dehydration rate of certain rocks, that undergo prograde thermal metamorphism, may be used to estimate the time to failure by hydrofracture and thus to formation of mineral veins.
g) Why are fracture systems in hydrothermal fields often linked by fractal geometry?

3.

a) Show how pore fluid pressure affects shear failure of porous rocks by change of effective stress. Use Mohr diagrams to illustrate this.
b) How are rock pore fluid pressure "lambda" values defined?
c) What is the most likely, immediate, consequence of a lambda value greater than 1.0 occurring at depth in a rock formation?
d) Why do thrust faults generally occur deeper in geological formations than normal faults?
e) What parameters control the surface slope angle of accretionary wedges at convergent plate margins and what are their individual effects?
f) Why do deep crustal rocks show evidence for very high integrated fluid fluxes whilst their permeability is too low for continuous recycling by convection?
g) How can episodic fluid flow be maintained in fractures that have a natural tendency to close at deep crustal levels?

4.

a) Underground, in the northern part of the Netherlands, a 20m diameter vertical cylindrical cavity is made, by solution mining in a deep rock-salt (halite) formation. The base of the cavity is 3km deep and the cavity extends upwards for 100m from its base. The naturally impermeable salt formation (undisturbed permeability <= 10^{-21} m^2), has an average density of 2.22Mg.m^{-3}, is 2 km thick and lies beneath 2 km of sedimentary overburden with an average density of 2.55Mg.m^{-3}. The cavity is filled completely with a brine of density 1.10Mg.m^{-3} and is connected via a steel-cased borehole pipe to the surface where the brine is closed in by a valve. The brine fluid pressure at the time of shutting the valve is assumed to be hydrostatic throughout the fluid column. The brine has no direct access to the permeable overburden rock, since the borehole pipe is sealed against the salt formation it penetrates. However, as time proceeds, the halite host-rock of the cavern slowly creeps inwards, closing the cavern and causing the brine, which is shut in by the valve, to increase its pressure. Describe the mechanical evolution of the cavern and its brine content with reference to a diagram of fluid pressure (horizontal axis) versus depth (vertical axis, increasing downwards). Assuming the overburden is much stronger in compression than the polycrystalline halite, but also weak in tension, then predict how and where fluid may first escape by plotting the fluid pressure versus depth in the cavern as lines on the diagram, drawn relative to the hydrostatic and lithostatic gradients.

b) Given that the thermal conductivity of halite is twice the value of the overburden rocks. Given also, that the initial temperature of the brine was only 10°C at the time of shut-off and that the cavern experiences a typical continental regional heat flow (with typical granitic-crust geothermal gradients of 25°C per km). Then, describe what effects the thermal influence may be expected to have on the evolution of the cavern, its contents and its integrity as a long term fluid storage facility. Indicate, schematically, the evolution of fluid pressure in the cavern by a series of dotted lines on the pressure versus depth diagram.

c) Is the wall region of the cavern likely to remain impermeable? Describe what processes could occur there and why?

d) Comment on the possible use of such a deep cavern to store low compressibility fluid fuels (gasoline, diesel, liquid petroleum gas etc.) or high compressibility hydrocarbons (methane) or even hydrogen for long term strategic purposes. How would the stored-fluid compressibility alter the long term storage strategy?

5.

a) Explain why the bulk physical properties of fluids may not be applicable to thin films and narrow pores in meta-sedimentary rocks and how may we verify this?

b) What is a supercritical fluid and explain the significance of fluid phase properties for quartz transport and precipitation?

c) Why do the grain boundaries in quartzites often meet at triple junctions and what can the interfacial angles tell us?

d) What can equilibrium pore geometry and fluid/rock dihedral angle studies tell us about permeable connectivity in deep crustal rocks?

e) To what degree, can laboratory measurements of permeability on such texturally equilibrated rocks provide us with values of permeability associated with deformation and metamorphism?

f) What other methods can be used to determine the fluid transport properties of porous rocks besides direct permeability measurement?

6.

a) What are the stages of progressive hydration after fracture of a quartz crystal in a humid environment?

b) Why should the ionic concentration of a hydrous solution affect the ease of crack formation in stressed rock samples submerged in the solution?

c) What processes give rise to crack-seal veins?

d) Explain why the tensile strength of most deep crustal rocks can be considered to be negligible?

e) Describe three limitations to sub-critical crack growth that relate to the fluid transport properties of the host material and the crack-filling fluid properties.

f) What are seismic pumping and fault valve behaviour?

g) At what stage in a seismic cycle are extensional veins likely to form?

h) Describe the geometry of extensional veins that are associated with strike slip faulting.

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

Part I (Spiers) 12-03-2009 14.00 -17.00 hours Minnaert 019

Note:

- The duration of this exam is 3 hours.
- Answer any **4** of the **7** questions given.
- All questions count with equal weight to the final grade.
- Allow about 45 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 !!!

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a) Using MATRIX NOTATION, write down the stress-strain relations for an anisotropic elastic material.

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

$$\left.\begin{array}{lll} C_{11} = 3.00 & C_{22} = 1.80 & C_{33} = 2.10 \\ C_{23} = 0.69 & C_{31} = 0.61 & C_{12} = 0.60 \\ C_{44} = 0.58 & C_{55} = 0.71 & C_{66} = 0.70 \end{array}\right\} \times 10^{11} \text{ Pa}$$

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

c) An olivine single crystal is subjected to an elastic strain given by the tensor

$$\varepsilon_{ij} = \begin{bmatrix} 1 & 0 & 2 \\ 0 & 0 & 0 \\ 2 & 0 & 0 \end{bmatrix} \times 10^{-4} \quad \text{(referred to } x_1, x_2, x_3\text{)}$$

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

d) Calculate also the mechanical work done on the olivine crystal when subjected to the above strain.

e) Write down the first and second laws of thermodynamics and use these to show how the Helmholtz free energy of the crystal is changed as a result of the work done upon it, assuming that the strain is imposed at constant temperature (heat exchange with surroundings is easy).

f) Explain why the Gibbs free energy is not suitable for describing the thermodynamic state of an elastically deformed solid.

Question 2

a) Explain the concept of the Boltzmann distribution law and why this is important in determining the rate of processes such as vacancy migration.

b) 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 !!

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

d) 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.

e) Explain the possible pathways for vacancy and atomic diffusion during deformation by solid state diffusion creep, and identify the possible rate controlling steps.

f) Write down the theoretical rate equations for the two best known processes of solid state diffusion creep. Under what grain size and temperature conditions will the one dominate over the other, and why? Will these mechanisms become more or less important with increasing pressure (e.g. with depth in the mantle)?

Question 3

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

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

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

d) Why do materials deforming by glide or cross-slip controlled creep not show superplastic behaviour?

e) 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.

Question 4

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

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

Explain the meaning of the symbols and terms in this equation.

b) Draw a sketch of a planar segment of grain boundary penetrated by a solution phase in island-channel or thin film form. If the segment transmits a normal stress σ_n, write down an approximate expression for the average chemical potential of the solid within the grain boundary segment.

c) Consider a granular pack of quartz grains (diameter d) in which the pores are filled with a saturated solution phase. If the solid skeleton is instantaneously subjected to an externally applied hydrostatic stress P and the liquid to a lower hydrostatic pressure p, describe how the system will respond?
N.B. Assume i) that interfacial energy driving forces are negligible, ii) that grain contacts are penetrated by fluid in island-channel or thin film form, and iii) that deformation within the grains is elastic.

d) List the steps you would take to construct a model of the system response (do not derive models)

e) What is the application of such models in the Earth sciences?

Question 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?

Question 6

a) Explain what is meant by the term "dynamic recrystallization".

b) Use the Avrami relation to explain i) what competing processes are involved in dynamic recrystallization, and ii) how these lead to a systematic realtionship between recrystallized grain size and stress, during steady state flow involving dislocation creep.

c) It is commonly argued that dynamic recrystallization can lead to a switch in deformation mechanisms from dislocation creep to diffusion creep, and that this causes major weakening and shear localization. Discuss whether this idea is reasonable for i) a single phase material such as a pure olivine dunite, and ii) for an impure metamorphic rock consisting of quartz plus finely dispersed micas.

d) A more recent concept states that dynamic recrystallization involves a balance between diffusional and dislocation creep mechanisms, at the boundary between such mechanisms in the deformation map (i.e. an equal contribution to the total strain rate is provided by both mechanisms). Use this idea to obtain a relationship between recrystallized grain size and flow stress for a pure material deforming by high temperature, climb-controlled dislocation creep plus Nabarro-Herring Creep.

e) Does your result obtained in part (d) resemble experimental observations on recrystallized grain size stress relationships or not, and do you think the model is a good alternative to the Avrami aproach?

Question 7

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. 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

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

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

c) Go on to explain what is meant by the terms "stress intensity factor" and "critical stress intensity factor".

d) Explain what is meant by subcritical crack growth.

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 0.3% occurs when the load is applied. Over a period of 3 weeks thereafter, no time dependent deformation occurs – the sample length is unchanged. The pores of the rock are then flooded with water at atmospheric pressure and acoustic emission signals are detected, which continue with time. After 1 further week, the sample fails in a brittle manner with no increase in load. Draw a strain-time diagram illustrating how you think the sample behaved as a function of time, and provide an explanation for its behaviour.