Examination Paper: GEO3-1302

Continuum mechanics and rheology of the crust and mantle
PART II (SPIERS)

30-01-2015, 13.30-16.30, Educ-Beta

Note: an extra half hour is available to students who have registered special needs in advance

---

N.B.
- This exam paper consists of 5 questions. **Answer 4 of the 5 questions.**
- Take about 45 minutes to answer each question; each question carries equal points
- Answer in English or in Dutch
- Identify all mathematical symbols you use
- If you do not understand the English used in a question, raise your hand for help

Tip: - Read the questions carefully and answer what is asked. Check answers before leaving!

Good Luck!!!

Question 1

a) Describe the essential characteristics of the elastic behaviour of dry rock, illustrating your answer with sketches of i) stress-strain and ii) strain-time diagrams.

b) The elastic response of isotropic, porous rock containing a pore fluid at pressure P_f is given by the "poro-elastic" equation

$$2G\,\varepsilon_{ij} = \sigma_{ij} - \frac{1}{3}(1 - 2G/3K)\,\sigma_{kk}\,\delta_{ij} + \frac{2}{3}G(1/K_g - 1/K)P_f\,\delta_{ij}$$

where σ_{ij} and ε_{ij} represent the states of stress and strain respectively. Define the quantities G, K, K_g, δ_{ij} and σ_{kk} **fully**, using diagrams to illustrate the first three.

c) An isotropic reservoir sandstone, at 3 km depth in a new gasfield, experiences a state of total compressive stress defined by the tensor

$$\sigma_{ij} = \begin{pmatrix} 65 & 0 & 0 \\ 0 & 50 & 0 \\ 0 & 0 & 50 \end{pmatrix} MPa$$

where σ_{11} is the vertical stress and $\sigma_{22} = \sigma_{33}$ are the horizontal stresses. The gas pressure in the reservoir before production is 35 MPa. Assuming that the stress state remains constant, use the poro-elastic equation to calculate the change in the state of strain in the reservoir if the pore fluid pressure is reduced by gas production to 5 MPa.

d) If the reservoir is 200 m thick estimate the displacement of the reservoir top that would accompany the above reduction in gas pressure.

e) Use your results to estimate what would happen at the surface when gas is produced, and evaluate whether the assumption of constant stress in the reservoir is reasonable or not.

Question 2

a) Explain what is meant by the term "failure criterion" for brittle rock.

b) Write down criteria for the two main modes of brittle failure that can occur in regions of the Earth's crust where pore fluid is present at a pressure P_f. Make sure you identify all terms appearing and indicate any restrictions on the orientation of the failure planes involved.

c) Seismic events in an area of regional tectonic compression indicate reactivation of healed thrust faults at a depth of h ≈ 6000 m. Assuming (i) that the pore pressure at this depth takes a value equal to 50% of the lithostatic pressure (ρgh), (ii) that σ_3 is near-vertical and equal to the lithostatic pressure (ρgh), and (iii) that the local fault rocks are characterized by a (healed) cohesive shear strength of 10 MPa and a coefficient of internal friction of 6/10, obtain an estimate of the value of the horizontal stress (σ_1) and the differential stress associated with faulting. Take the overburden density (ρ)to be 2500 kg/m^3 and g = 10 ms^{-2}.

d) If the region was one of extension not compression, would earthquakes sourced at 6 km be associated with a smaller or larger differential stress and would they be smaller or bigger?

Question 3

a) Draw simple diagrams illustrating the main features of an edge dislocation.

b) Define the terms "dislocation self energy" and "line tension". Illustrate your answer with appropriate formulas, identifying all terms.

c) Explain what is meant by the term "slip system" and write down an expression for the force (per unit length) on a dislocation lying within its slip system in a stressed crystal.

d) Explain the operation of the Frank-Read source of dislocations. Make sure you mention the various competing forces involved and write down the equilibrium condition required to activate such a source.

e) Use the above equation and background knowledge obtained from the course to estimate the yield stress of a crystal containing pinned dislocation segments of length L = 0.5 µm.

Question 4

a) Explain what is meant by the term steady state creep, illustrating your answer with sketches of stress-strain and strain-time diagrams.

b) List the main mechanisms by which steady-state creep can occur in crystalline materials, indicating the essential characteristics of each mechanism.

c) Go on to explain briefly the concept of the deformation mechanism map, illustrating your answer with a schematic labelled diagram.

d) How is such a map constructed and what is the significance of the field boundaries?

e) How would you use a deformation mechanism map to estimate the flow behaviour of a calcite mylonite containing specific metamorphic minerals defining its metamorphic grade, assuming deformation at geological strain rates?

Question 5

a) Write down and explain what is meant by Byerlee's rule.

b) Indicate what deformation mechanisms and what type of constitutive equations are usually used to describe the ductile flow of quartz in the mid-lower crust and of olivine in the upper mantle.

c) Given Byerlee's law and suitable laboratory equations for the ductile flow behaviour of quartz and olivine, list the steps that you would take to construct a strength profile for a section of continental lithosphere undergoing rifting, assuming a uniform extensional strain rate of say 3 x 10^{-15} s^{-1}?

d) Finally, list and explain the main problems or weaknesses that you see in the classical approach to constructing a strength profile for a portion of lithosphere

Beer Award Borrel: All members of the class are invited for the beer award ceremony and borrel on Thursday 7 April, 17.00. Location follows via e-mail. **CHRIS**