Examination Paper: GEO3-1302

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

27-01-2016, 09.00-12.00, Educatorium-Megatron

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

N.B.
- The 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 **Good Luck!!!**

Question 1

a) Describe the essential nature 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 and δ_{ij} fully, using diagrams where needed.

c) A body of isotropic porous sandstone is subjected to an initial state of compressive stress defined by the tensor

$$\sigma_{ij} = \begin{bmatrix} 65 & 0 & 0 \\ 0 & 45 & 0 \\ 0 & 0 & 45 \end{bmatrix} MPa$$

and to a pore fluid pressure of 35 MPa. Use the poro-elastic equation to calculate the state of strain compared to the unstressed state, assuming G = 5 GPa, K = 10 GPa and K_g = 50 GPa.

d) Go on from part (c) to calculate the change in the state of strain if the pore fluid pressure is dropped to 10 MPa.

e) The initial state of stress and the fluid pressure given under (c), and the change in fluid pressure given in (d), are similar to those applying to the Groningen gas field before production and now. Is your result for the change in the state of strain obtained in (d) also relevant for understanding reservoir compaction in Groningen, Yes or No? Now explain your answer.

Question 2

a) Explain the terms "uniaxial compressive strength" and "failure criterion".

b) Indicate typical values of uniaxial compressive strengths for rocks.

c) Write down the Coulomb criterion for shear failure of dry rock and an expression giving the orientation (angle θ) of the failure plane normal with respect to the principal compressive stress σ_1 (identify ALL terms appearing and indicate any restrictions on θ).

d) The state of stress near a sealed normal fault in a 50 m-thick bedded anhydrite caprock formation overlying a carbonate reservoir (depth to top 2.9 km), into which natural gas imported from Russia is being actively injected for storage, is estimated (from numerical modelling) to be evolving with time t (years) in the following manner:

σ_1(vertical)	= 60 MPa (constant)	
σ_2(North-South)	= $(60 - a.t)$ MPa	where a = 0.2 MPa/year
σ_3(East-West)	= $(60 - b.t)$ MPa	where b = 1.0 MPa/year

These relations show that $(\sigma_1 - \sigma_3)$ will increase with time t and therefore that there is a risk of fault reactivation. Assuming that these relations for the principal stresses continue to hold, determine when (i.e. at what value of t) the fault in the anhydrite will be reactivated. DATA: Sealed faults in anhydrite typically have a cohesive shear strength of 5 MPa and a coefficient of internal friction of 2/3.

e) Draw a schematic geological cross-section of showing the reservoir, caprock and fault, and state what might the consequences of reactivating the fault be?

Question 3

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

b) Explain what is meant by the terms i) dislocation glide or slip, ii) dislocation climb.

c) In an unstressed crystal, a straight segment of edge dislocation is pinned between two obstacles, separated by a distance L, lying in the dislocation slip plane. In the region between the obstacles, the dislocation can glide in its slip plane. Explain how this configuration can act as a so-called Frank-Read source of dislocations (use diagrams).

d) Write down an equation for the critical shear stress required to activate a Frank-Read source, stating what equilibrium condition this equation represents.

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 = 1 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 nature 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?

e) What is the physical meaning of a boundary between two fields in such a map?

Question 5

a) Explain what is meant by Byerlee's rule and indicate for what portion of the continental lithosphere it is expected to apply.

b) Indicate what deformation mechanisms and constitutive equations are thought to describe the ductile flow behaviour of quartz in the mid-lower continental crust.

c) Explain how you would construct a strength profile for a section of continental crust assuming it is quartz-rich and taking a uniform extensional strain rate of say $10^{-15}\,s^{-1}$?

d) Sketch such a profile for a low and for a high geothermal gradient.

e) Use your profiles to predict what the effect of geothermal gradient should be on the depth and magnitude of seismicity during extension of the crust.

Beer Award Borrel: All members of the class are invited for the beer award ceremony and borrel on Thursday, 2 March, 17.00. Location follows via e-mail. **CHRIS**