

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 in carbonate rocks at a depth of $h \approx 6000$ m. Deep borehole measurements and sampling show (i) that the pore pressure at this depth takes a value equal to 60% 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 cohesive shear strength of 2 MPa and a coefficient of internal friction of 0.75. Use this information to determine the value of the horizontal stress (σ_1) and the differential stress causing faulting. Take the overburden density (ρ) to be 2500 kg/m^3 and $g = 10 \text{ ms}^{-2}$.
- d) If the region was one of extension not compression, would earthquakes sourced at 5 km tend to be smaller or bigger in magnitude? Explain why in giving your answer.

Question 3

- a) Draw simple diagrams illustrating the key features of an edge dislocation.
- b) Define the term "dislocation self-energy" and "line tension".
- 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) If the plastic yield behaviour of a crystal of calcite is controlled by the Frank-Read source mechanism, what length of pinned dislocation source segments is implied by a measured yield stress of 10 MPa at 300 °C? Take the shear modulus of calcite at this temperature to be 40 GPa and the Burgers vector of the active dislocations to be ~ 1 nm.

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) What aspects of microstructural change are not represented in a deformation mechanism map, and what kind of deformation map would you draw to assess the effects of such microstructural changes?

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 rule and laboratory equations for the 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 at a uniform strain rate of say 10^{-15} s^{-1} .
- d) Would this be accurate if ductile flow in the crust and upper mantle was not uniform but localized into a few large shear zones? Explain your answer in detail!

$$E = \frac{\sigma}{\epsilon} \quad G = \frac{c}{\gamma}$$

Examination Paper: GEO3-1302

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

26-01-2018, 13.30-16.30, Educ-Megaron

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 a porous rock containing pore fluid at a pressure P_f and subjected to a state of stress $\sigma_1 > \sigma_2 = \sigma_3$. Illustrate your answer with sketches of:
- i) axial stress (σ_1) v. axial strain (ϵ_1) at constant radial stress ($\sigma_2 = \sigma_3$) and pore pressure P_f , and
 - ii) volumetric strain (ϵ_v) v. P_f at constant σ_1, σ_2 and σ_3 .
- b) The elastic response of isotropic, porous rock containing a pore fluid at pressure P_f is given by the "poro-elastic" equation

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

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 and giving their units.

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

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

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, and taking $G = 3$ GPa, $K = 10$ GPa and $K_g = 75$ GPa, use the poro-elastic equation to calculate the change in the state of poro-elastic strain in the reservoir if the pore fluid pressure is reduced by gas production to 1 MPa.

- d) If the reservoir is 200 m thick, use the result of (c) to estimate the displacement of the reservoir top and hence the surface subsidence that would accompany the above reduction in gas pressure due to poro-elastic deformation. If you were the boss of the gas company, would you be concerned about this result, Y/N? Explain your answer.