Repair examination Paper: *Mechanisms of Deformation and Transport in Rocks*

Part II (Niemeijer) 25-05-2023 Earth Simulation laboratory

- The duration of this exam is 2.5 hours.
- Answer question **1** plus any **3** of the remaining 5 questions given.
- Each question is worth 25 points.
- Allow about 30 minutes per question.
- Answers may be given in English or Dutch.
- Make sure you **identify all mathematical symbols** used in answering the questions
- Use SI units unless otherwise specified.
- If you do not understand the English in any of the questions, raise your hand for help.
- Read the question carefully!
- **Note that pages are printed double-sided!**

Good luck!

Start 12:50

Question 1

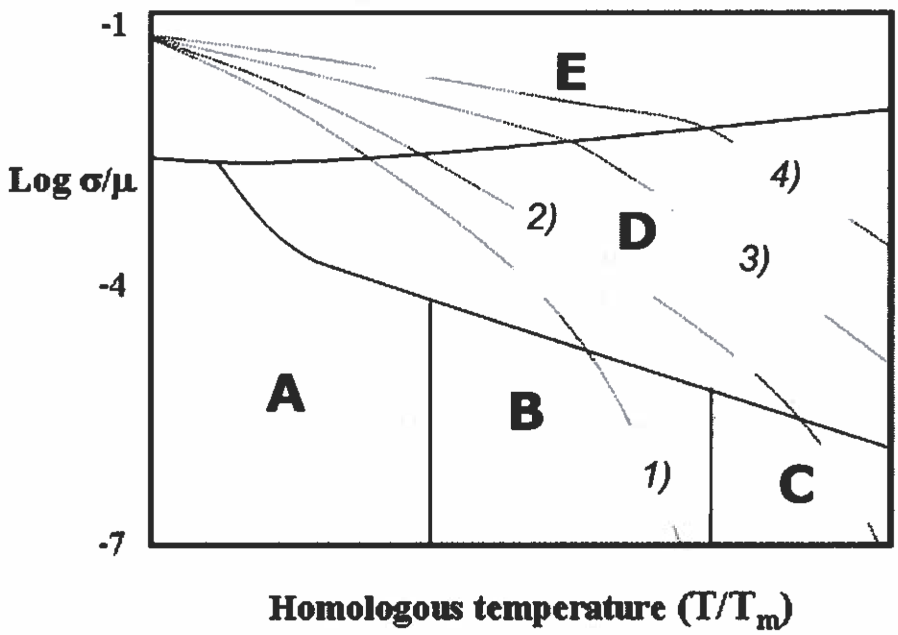


Figure 1: Deformation mechanism map.

1) Figure 1 shows a generic deformation mechanism map in which the different fields have not been labelled. Label de fields A-E with the appropriate deformation mechanism.
2) With reference to Figure 1, what parameter do the lines with numbers 1) to 4) represent and how should these numbers be ordered from small to large? Give examples of appropriate values.
3) Still with reference to Figure 1. Which additional parameter do we need to know the value of before we can use this deformation mechanism map?
4) Indicate for the following 4 statements whether they apply to dislocation creep or diffusion creep. Shortly motivate your answer. **Without motivation, no points will be given!**
   a) very dependent on stress (n >>> 1)
   b) Cob
   c) Weertman equation
   d) Grain size sensitive (GSS)

Question 2

a) Write down the stress-strain relations for an anisotropic elastic material using **matrix** notation.

b) Taking into account the ***symmetry*** of the stiffness matrix (C_{rs}), the non-zero components of this matrix for a ***Topaz*** crystal (orthorhombic, $Al_2(SiO_4)(F,OH)_2$) are specified as follows:-

$$\left.\begin{array}{lll} C_{11} = 2.8136 & C_{22} = 3.8495 & C_{33} = 2.9452 \\ C_{23} = 0.8815 & C_{31} = 0.8464 & C_{12} = 1.2582 \\ C_{44} = 1.0811 & C_{55} = 1.3298 & C_{66} = 1.3089 \end{array}\right\} \times 10^{11}\ \text{Pa}$$

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

c) Explain the physical meaning of the first vertical column of the matrix C_{rs}.

d) A topaz single crystal is subjected to an elastic strain given by the tensor

$$\varepsilon_{ij} = \begin{bmatrix} 4.5 & 0 & 2 \\ 0 & 0 & 0 \\ 2 & 0 & 3 \end{bmatrix} \times 10^{-4} \text{ (referred to } x_1, x_2, x_3)$$

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

e) Calculate also the mechanical work done on the topaz crystal when subjected to the above strain, making sure you state the units!!

f) Use the first and second laws of thermodynamics to **show** how this mechanical work changes the thermodynamic state of the crystal, if deformation occurs at constant temperature, and explain what would happen to the crystal if it is placed in contact with an unstrained anhydrite crystal at a high temperature (T / Tm > 0.8).

Question 3

1) 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!!

2) Explain the statistical meaning of your answer to (a), with reference to the Boltzmann distribution law.

3) Derive an equation to 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.

4) Explain the most likely pathway for vacancy and atomic diffusion during deformation by solid state diffusion creep at temperatures of around 0.7 of the melting point in K. Then identify the physically possible rate limiting steps along this pathway, using an electrical circuit analogue diagram. Which of these steps do you expect to control deformation rate in a typical crystalline solid at the specified temperatures?

5) Write down the theoretical rate equations (flow law) for ONE of the two best-known processes of solid state diffusion creep and name the process you choose and the associated diffusion path. Go on to obtain an expression for the viscosity of a solid deforming by this mechanism. Finally, identify which quantities in this expression will determine whether the process becomes more or less important with increasing depth in the lower crust or upper mantle.

Question 4

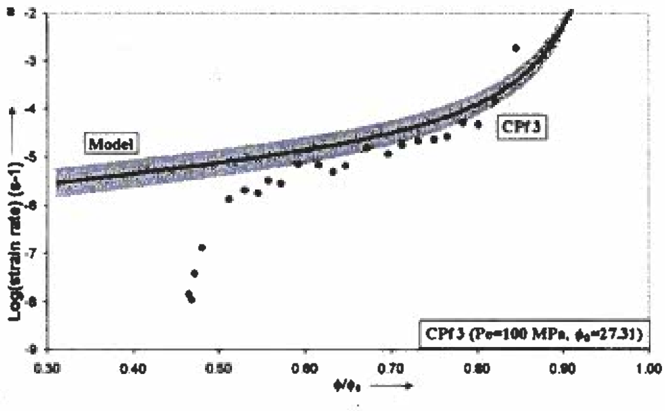
1) Name two major differences between the general flow laws and derivation thereof for compaction via pressure solution within a granular pack vs. deformation via pressure solution of a zero-porosity rock.
HINT: consider the driving force

2) Consider a granular pack of quartz grains (diameter d) in which the pores are filled with a saturated solution phase. The grain pack is contained in a vertical steel cylinder. If the grain pack is instantaneously subjected to a vertical stress σ and the liquid to a lower hydrostatic pressure p, describe how the system will respond in the short and longer term? Use diagrams.
N.B. *Assume i) that interfacial energy driving forces are negligible, ii) that grain contacts are penetrated by fluid in island-channel form, and iii) that deformation within the grains is elastic.*

3) Explain what processes might control the rate at which the system would respond in the long term, and which ones you would expect to be slowest under upper crustal conditions for this quartz aggregate.

4) Describe how you would experimentally test which process is rate-controlling, specifically addressing which data can be acquired and how these need to be processed to obtain the plot needed to identify the rate-controlling process. Sketch this plot.

5) One example of the output of such an analytical model is plotted in the figure below together with some experimental data. Name at least two assumptions of the analytical model that might be considered to help explain the discrepancy with the data at lower porosity.



Question 6

1) List at least 2 possible configurations for performing friction experiments, sketch them and list a possible disadvantage of each method.
2) Consider that friction is the ratio of shear stress over normal stress. Show why friction is *not* a material property.
3) Rate and state friction equations describe the evolution of friction with time (or displacement) and are given by:

$$\mu = \mu_0 + a ln\left(\frac{V}{V_0}\right) + b ln\left(\frac{V_0\theta}{d_c}\right)$$

$$\frac{d\theta}{dt} = 1 - \frac{\theta V}{d_c}$$

Derive an expression for determing the value of (a-b) from steady state friction measurements.
Define all symbols in the equations.
HINT: Steady state so the state variable is no longer changing.

4) What is the physical reason for the time dependence of friction as expressed in the RSF equations and what type of mathematical relation is assumed to describe this?
5) Sketch a simple fault model and use your sketch to explain why the parameter *(a-b)* is important in determining under what conditions earthquakes are possible.
6) With reference to your model of the previous question, which other two parameters are important in controlling whether an earthquake can nucleate or not?

Question 7

a) Derive an expression for the flow strength of a crystal in the absence of linear defects and give an order of magnitude estimate for typical crystals.

b) Sketch what an edge dislocation might look like in a crystal and use your sketch to explain why the presence of linear defect helps to explain the flow strength of materials at high temperature.

c) Give the basic equation that describes the strain rate when deformation is controlled by the movement of dislocations. What is it called?

d) Use the equation in d) to derive a general flow law for materials deforming via climb-controlled creep.

e) What are typical conditions within the Earth under which your flow law derived in d) would apply for ***olivine***?