Structural Analysis of Deformed rocks (GEO4-1411) - Exam 25-01-2018

Time: 09.00 – 11.30 hr. (2.5 hours)
Place: KBG Pangea

House rules:

- You may not leave the room during the first 30 minutes of the exam.
- Latecomers will be admitted until 30 minutes after the start of the exam
- All electronic equipment needs to be switched off (including phones!!), except for equipment which the examiner has allowed.
- Put coats and bags on the floor. Bags need to be closed.
- If you need to use the toilet, you have to let the invigilator know. Leave your mobile phone behind. You cannot go to the toilet after the first student has left the exam.

Answer all 4 questions

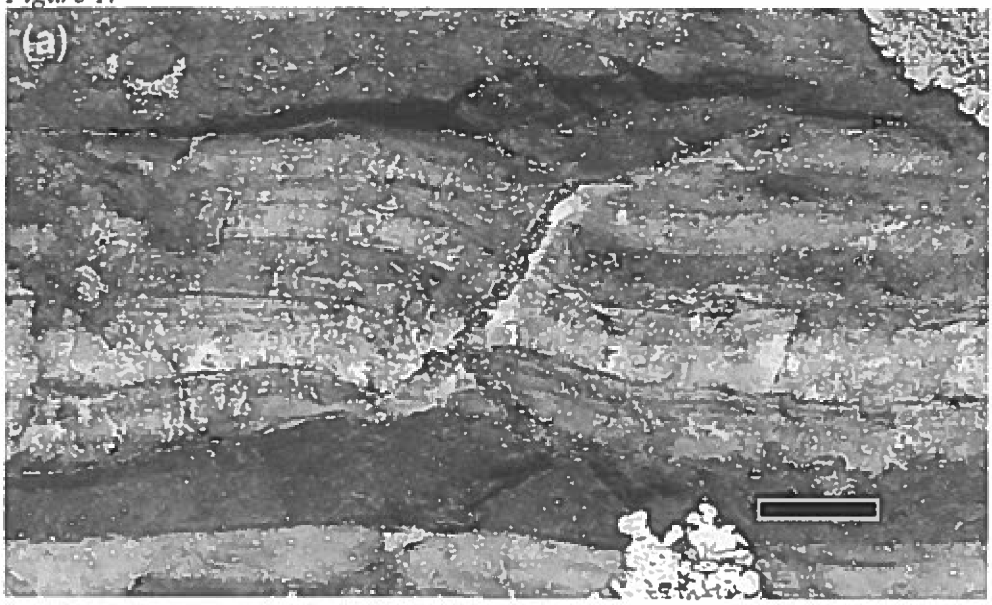
Please read carefully! And please answer every question on a separate page.

Also, **please reserve some time to fill in the course evaluation form.**

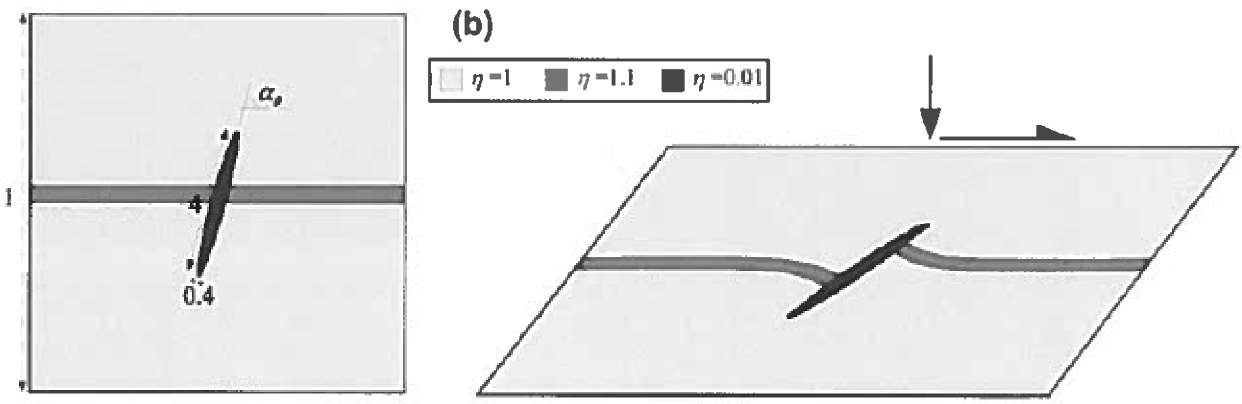
Question 1 – **On faults and flow in rocks**

Gomez-Rivas et al. (2007) studied "drag folds" associated with small-scale faults. Such drag structures could also be named "flanking folds". The authors looked at natural structures (Fig. 1a) at Cap de Creus, Spain, and performed numerical simulations (b) using the code BASIL. For the numerical silumations, they used a homogeneous isotropic layer with a defined viscosity (η) of 1, a single layer of η=1.1 representing the foliation of in the host rock, and a narrow ellips with η=0.01 representing the fault.

Figure 1:



scale bar: 10 mm



The following velocity gradient tensor has been defined for the experiment of Fig. 1b.:

$$\mathbf{L} = \begin{pmatrix} 1.0x10^{-10} & -1.0x10^{-10} \\ -4.0x10^{-10} & -3.0x10^{-10} \end{pmatrix} \quad [s^{-1}]$$

a) (5 points)
   i) What is special in terms of kinematics of a flanking/drag fold of the type of Fig. 1a?
   ii) Given de viscosity ratio of the layer versus the host rock (Fig. 1b), one might have expected the geometry of the drag fold to be different from the actual result of the simulation. What structure is more likely (make a drawing and explain)?

b) (6 points) Given that you have enough faults like that of Fig. 1a, including the 3D orientation and actual slip sense, one could perhaps determine the paleostress direction using a stress inversion tool.
   i) Explain briefly what the basics are of determining paleostress on the basis of fault slip.
   ii) Discuss whether or not you find this a useful analysis in case of a set of faults of the type of Fig. 1a

c) (7 points) Make a Mohr circle representation of the tensor **L** for the drag fold experiment. Carefully (!) label all axes and explain what the intersections of the Mohr circle and the axes mean. Also, determine the mean instantaneous stretching rates and the stretching rates along the flow apophyses.

d) (7 points)
   i) Determine the kinematic vorticity number of tensor **L**. You may use the Mohr diagram of question 1c) or calculate on the basis of the tensor.
   ii) Give a meaningful interpretation of your results of c) and d-i) in relation to the modelled drag folds (i.e. Fig. 1b).

Question 2 – On mechanical instabilities and structure development

a) (6 points) Explain briefly, in terms of kinematics and dynamics,

- what geological structures represent
- the principle that governs their formation
- what factors lead to structure development in practice (make a simple list).

b) (6 points) Explain what "stability analysis" is, and specify the basic steps followed in conducting a standard stability analysis. Use the break-up of a linear streak (long cylinder) of fluid into isolated droplets as an example to illustrate each step taken in performing such an analysis.

c) (6 points) Describe the main characteristics of the following structures (illustrate with simple diagrams) and explain with the aid of a feedback diagram how these structures develop:

- Pinch and swell
- Crenulation cleavage with metamorphic segregation in a slate.

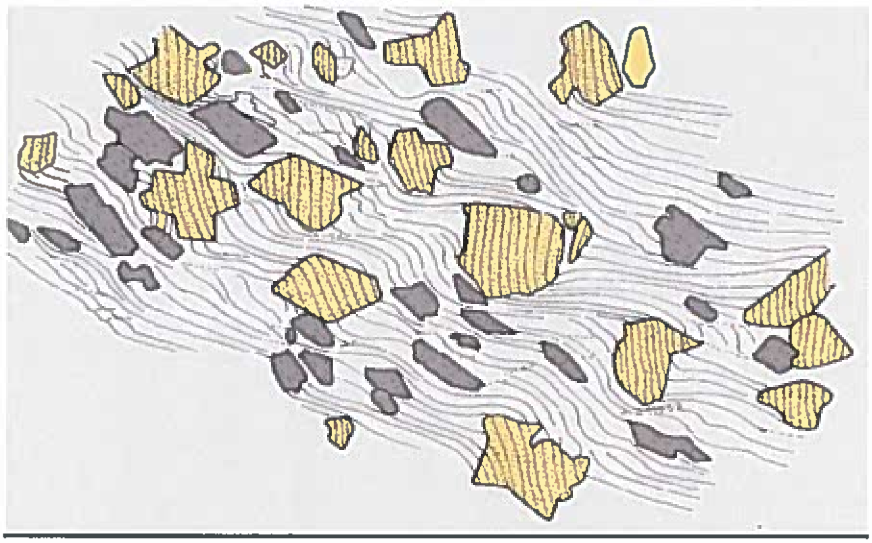
d) (7 points) You are in the field in a faulted terrain dominated by organic rich shales. You discover a narrow fault zone, around 5 cm thick, cutting these. The fault zone shows a prominent and highly reflective (shiny), internal, principal slip surface exposed in a fault scarp. The fault zone and slip surface itself are characterized by a scaly (foliated) gouge-like material containing high concentrations of graphite. The host rock, or protolith, on each side of the fault is cut by small cracks and veins but is otherwise relatively undeformed.

- Make a 3-D sketch showing the fault scarp, the fault zone and the surrounding rock.
- Sketch also a "close-up" of the fault zone, labelling the internal principal slip surface and microstructures seen.
- Propose an explanation for the development of the fault zone microstructure.
- Go on to use the concept of "positive feedback" to offer an explanation of how the fault localized.

Question 4: On the analysis of Deformation histories.

a) (5 points) What microstructures can be used to estimate the stress during ductile deformation and what are the limitations of using such microstructures to estimate stress?

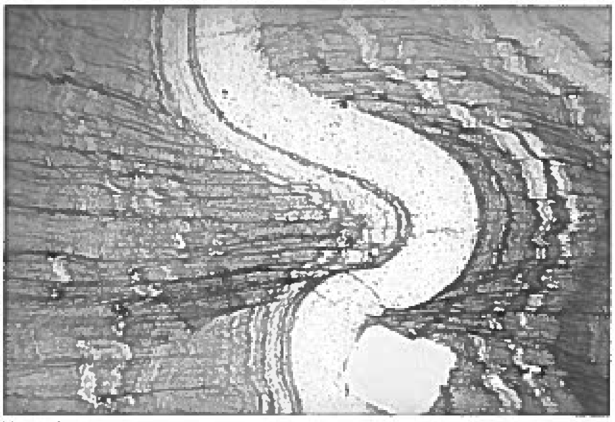
b) (10 points) The line drawing of a whole thin section below shows the external foliation and internal foliation in porphyroblasts in a schist from the Pyrenees from a paper by Aerden (1995). The lighter (yellow if printed in colour) shaded porphyroblasts are staurolite and grey shaded porphyroblasts are biotite.



i) What is the deformation history of this sample ?
ii) What was the timing of porphyroblast growth and deformation?
iii) What can you deduce about the kinematics of deformation?

c) (5 points) Are the folds in the two images formed by soft-sediment flow or solid-state deformation?

i) Field image of folded sediments



ii) Light microscope image of folded sediments.

d) (5 points)

i) What are the typical characteristics of structures formed by magmatic flow, sub-magmatic flow and sub-solidus flow?

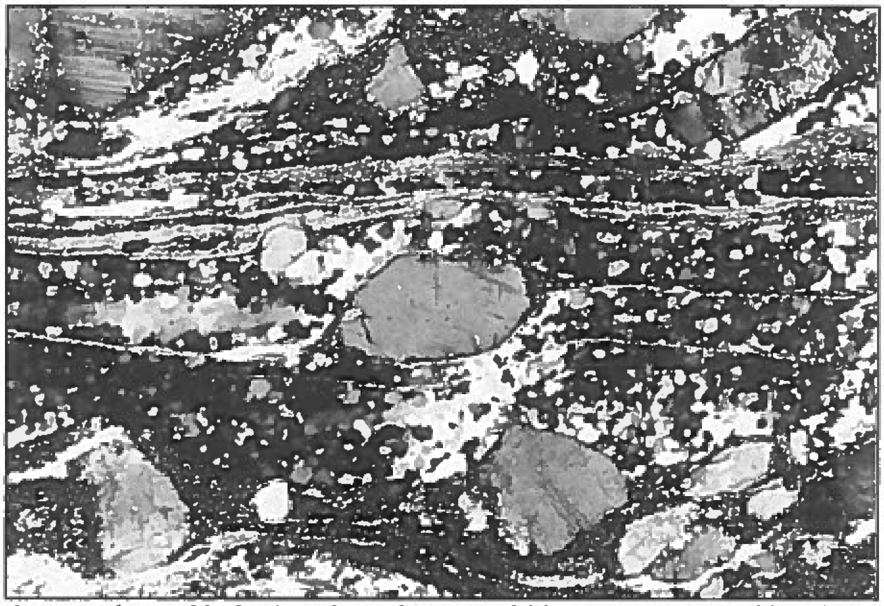
ii) This image shows a polished section of a granitic rock exposed as polished slabs on the outside of the Tweede Kamer in Den Haag. Has this foliation formed by subsolidus, sub-magmatic or magmatic flow? The width of the field of view is 20 cm.

Question 4 – **On fault zone structure and deformation microstructures**

a) (7 points) Sketch a schematic cross-section of a strike-slip fault zone in the continental lithosphere, indicating typical distributions of fault rocks, deformation mechanisms, and relative strength. Explain these distributions based on how the mechanical/rheological properties of the rocks depend upon particular environmental conditions.

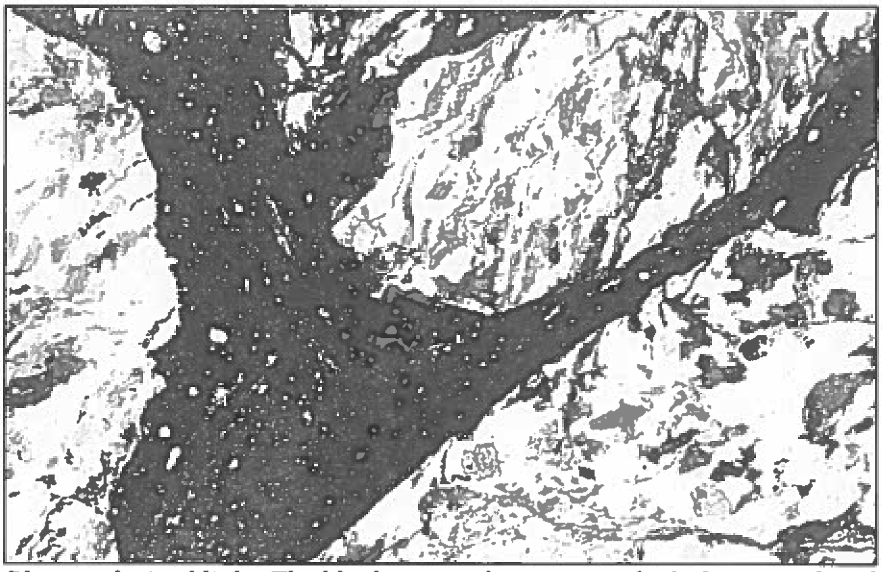
b) (6 points) Identify the fault rocks below, describing your key microstructural observations and how your interpretation of them supports your identification.

Rock 1:



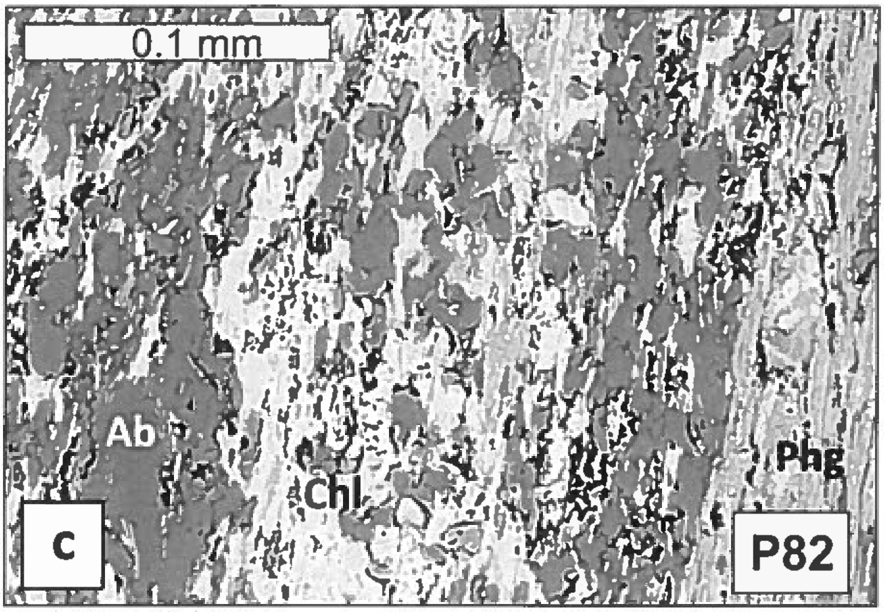
Cross-polarised light. Porphyroclasts are feldspar, fine-grained bands in the matrix are feldspar and mica, and the coarser-grained bands in the matrix are quartz.

Rock 2:



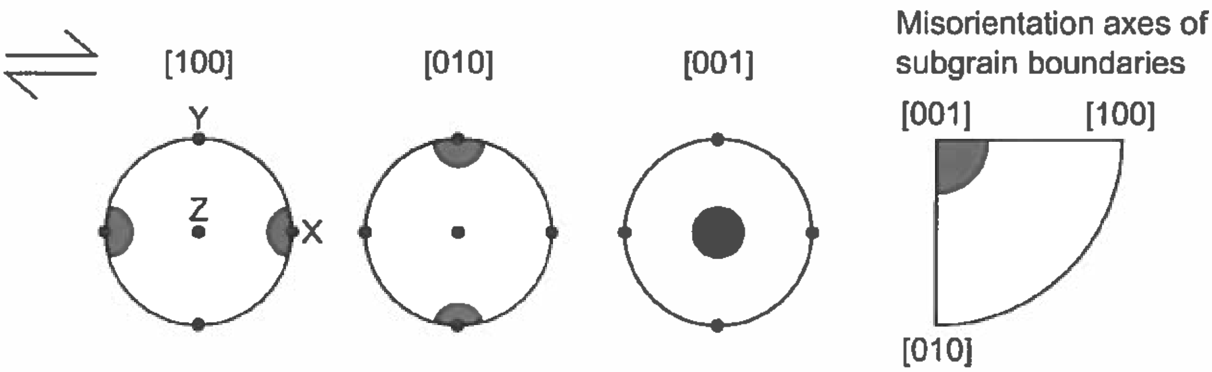
Plane-polarised light. The black material is opaque, the light mineral in the wall rock is feldspar, and the grey mineral in wall rock is amphibole.

Rock 3:



Backscattered electron image. Ab = albite, Chl = chlorite, Phg = phengite (white mica)

c) (6 points) The pole figures and misorientation inverse pole figure below summarise common observations from olivine deformed to high strains in simple shear in mantle shear zones. Interpret the dominant deformation mechanism and slip system. Explain how the observations provided support your interpretation, sketching figures if necessary. X = mineral stretching lineation, Y = pole to grain shape foliation.



d) (6 points) The occurrence of faults and shear zones provides evidence for strain localisation at various depths within the lithosphere. Briefly explain the geodynamic significance of strain localisation and outline some (hypothesised) mechanisms by which it occurs.