Structural Analysis of Deformed rocks (GEO4-1411) - Exam 29-01-2015

Time: 09.00 – 12.00 hr.
Place: UNNIK.211

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.

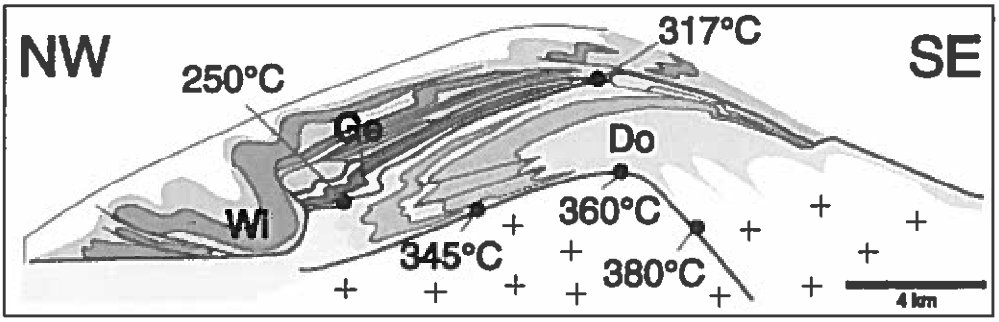
Answer 4 out of the 5 questions (make your own choice)

Please read carefully! Answer every question on a separate page. DO NOT answer 5 questions!

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

Question 1 – On flow in rocks

Herwegh *et al.* (2005) studied the Helvetic Nappe Stack in the western Alps, Switzerland. The area investigated is characterized by three major nappes, which are, from bottom to top, Doldenhorn (Do), Gellihorn (Ge) and Wildhorn (Wi) (see figure below). Nappe emplacement occurred during the Alpine orogeny during Early Oligocene to Miocene. Thrust direction was SE to NW. Herwegh *et al.* (2005) estimate that the strain rates during deformation were in the order or $10^{-10} - 10^{-11}\ s^{-1}$.



At the spots denoted 317°C and 250°C, analysis of rock microstructures has made it possible to describe the flow in terms of the following velocity gradient tensors L:

$$\mathbf{L}\ (\text{spot } 317) = \begin{pmatrix} 1.0x10^{-11} & -0.5x10^{-11} \\ -9.0x10^{-11} & -3.5x10^{-11} \end{pmatrix} \quad [s^{-1}]$$

$$\mathbf{L}\ (\text{spot } 250) = \begin{pmatrix} 3.0x10^{-11} & -4.0x10^{-11} \\ -4.0x10^{-11} & -5.0x10^{-11} \end{pmatrix} \quad [s^{-1}]$$

a) (5 points)
   i) Describe the fold structure that can be seen in the internal parts of the nappes, <u>using appropriate terminology</u>.
   ii) Give a short explanation of what is meant with "vorticity" in a geological context.

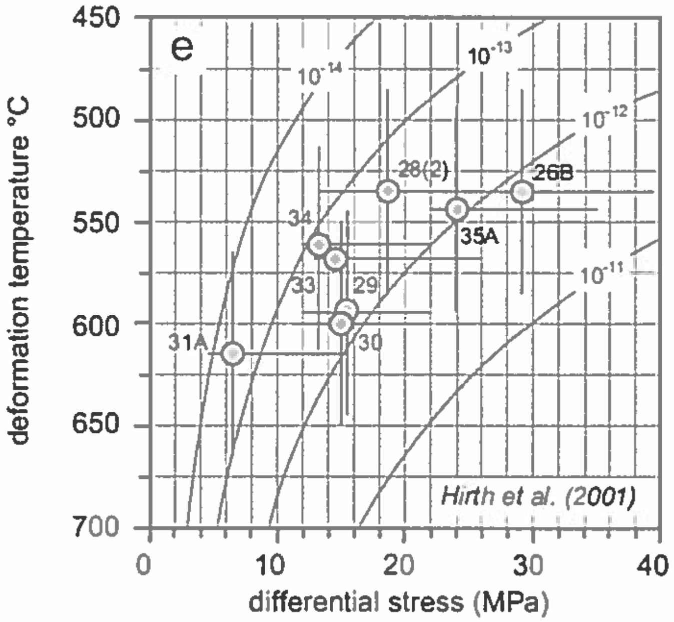
b) (10 points)
   Make a Mohr circle representation of **L** for both spots. Carefully (!) label all axes and explain what the intersections of the Mohr circle and the axes mean. Also, determine the <u>mean instantaneous stretching rate</u> and the <u>stretching rates along the flow apophyses</u>.

c) (10 points)
   i) Determine the kinematic vorticity number for the two locations. You may use the Mohr diagram of question 1b) or calculate on the basis of the tensors.
   ii) Give a meaningful interpretation of the results for the kinematic vorticity number. In other words, what do the results tell you about the Helvetic Nappe stack structure or history?

<u>Question 2</u> – On the analysis of paleostress and layered rocks

a) (9 points) Consider stress analysis using fault slip data:
   i) The so-called 'stress shape ratio' plays an important role when analyzing fault slip data. Explain <u>what</u> it is and briefly discuss <u>why</u> it is of importance in slip along faults.
   ii) Give a short explanation of three different indicators that can tell you about the kinematics of faults.
   iii) Name three drawbacks of the fault slip inversion method.

In a study of Law *et al.* (2013), high grade, quartz-rich metamorphic rocks from the so-called Greater Himalaya series, India, have been analyzed for the magnitude of the paleostress. For this, the quartz paleopiezometer of recrystallized grain size has been used. The figure below shows the obtained paleostresses in relation to the deformation temperatures. Also, the data can be compared with the predictions from an experimentally determined flow law for quartzite (after Hirth *et al*, 2001; numbers refer to strain rates in s^{-1}).



b) (8 points) Analyse the graph of Law *et al* (2013). Use your knowledge of flow laws (viscosity) and piezometric relations for dynamical recrystallization to respond to the following statements:
   i) The graph does <u>not</u> form proof that the size of dynamically recrystallized grains is temperature dependent.
   ii) The graph illustrates that we still do not fully understand how flow behaviour is related to the development of recrystallized microstructures in quartz rocks.

c) (8 points) Assume that samples 35A and 26B represent two slightly different types of quartz rock. Also assume that the two rock types can be found in a folded multilayer.
   i) How would such a folded multilayer look in outcrop. Explain your drawing.
   ii) Why is it in fact difficult to use the above figure to analyse structures that include two different types of quartzitic rock?

<u>Question 3</u> – On mechanical instabilities and structure development

a) (6 points) Explain why geological structures develop in rock bodies even when uniform displacement boundary conditions (uniform strain measured at the boundary of a given volume of the material) apply to the body of material considered. Illustrate your answer with a list of the factors that lead to structure development.

b) (6 points) Stability analysis is the principal method of analyzing the mechanics of structure development in complex systems. Explain what "stability analysis" is, and specify the basic steps followed in conducting a standard stability analysis. Choose any structure you like as an example to illustrate the steps taken in performing such an analysis.

c) (6 points) Explain with the aid of a feedback diagram why coarse grained rock materials deforming by plastic flow mechanisms at moderate or low temperatures are expected to be more prone to localized deformation than very fine grained rocks deforming by ductile flow mechanisms at high temperatures.

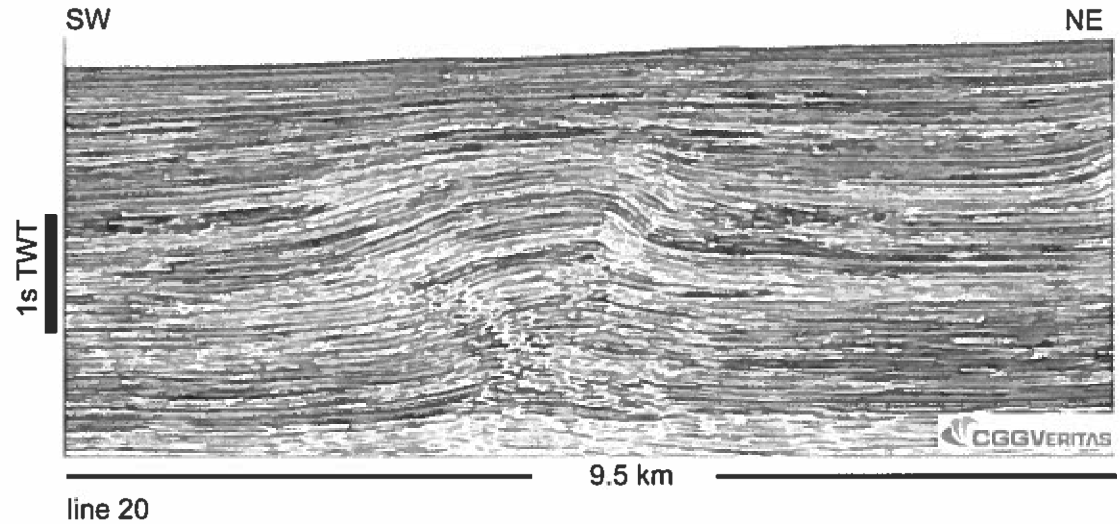
d) (7 points) You are in the field and discover a semi-brittle fault zone, around 5m thick, that shows a high concentration of weak clay minerals, compared with the surrounding rocks. The surrounding rocks are very low grade meta-sediments, consisting mainly of fractured siltstones. These siltstones are significantly richer in quartz cement and in quartz-filled veins on one side of the fault than on the other side of the fault. Far away from the fault, the siltstones typically contain 15-20% clay – more or less the original sedimentary composition.

- Make a sketch of the fault and its surroundings.
- Propose an explanation of the observed pattern of clay versus quartz enrichment.
- Go on to use the concept of "positive feedback" to offer an explanation of how the fault localised. Feel free to propose a <u>sequence</u> of feedback loops if needed.

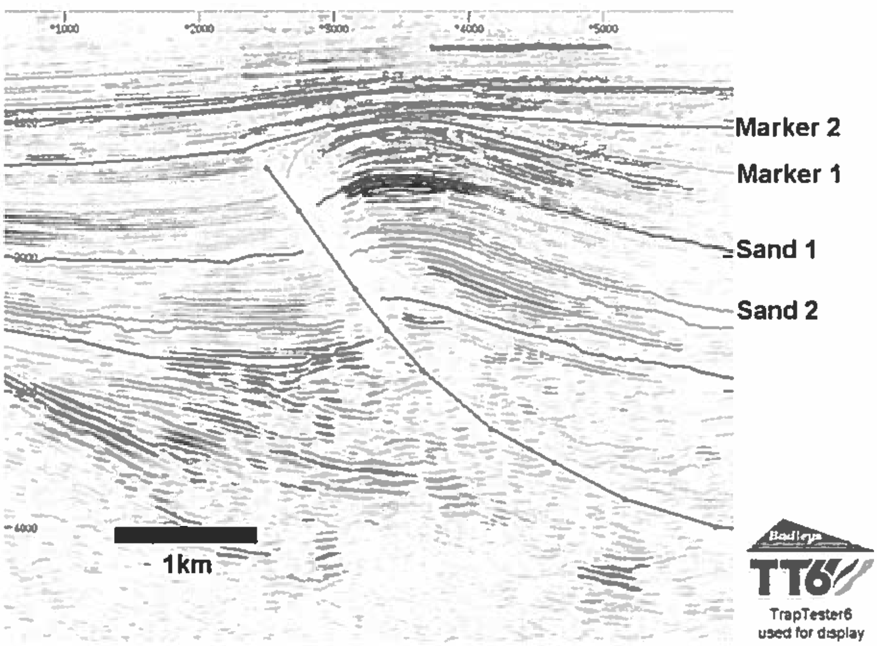
$$\dot{\varepsilon} = A \exp\left[\frac{\Delta H}{RT}\right]\frac{\sigma}{d^m}$$

<u>Question 4:</u> On the analysis of Deformation structures and histories.

a) (10 points) The images below show two reflection seismic sections of sediments in the Niger Delta and from Venezuela. Draw an interpretation of the sections showing any pre-tectonic, syn-tectonic and post-tectonic sediments. Which of these layers could have deformed by soft-sediment flow?

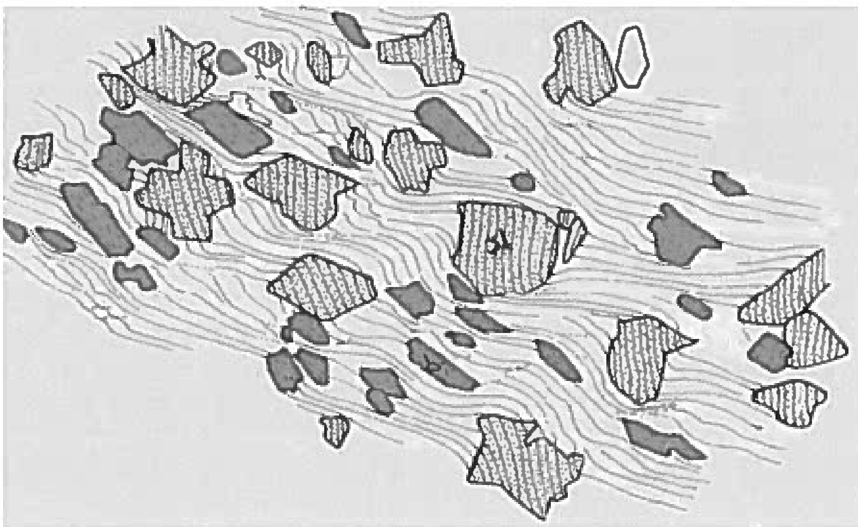


Niger Delta



Venezula

b) (10 points) The line drawing of a whole thin section below (next page) shows the external foliation and internal foliation in a schist from the Pyrenees from a paper by Aerden (1995). The lighter shaded blasts are staurolite and grey shaded blasts 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) The diagram below shows the foliation and lineation pattern in and around the Cauterets Intrusion in the Central Pyrenees. The foliation in the granodiorite intrusion was produced by magmatic flow; the foliation in the country rocks (mainly slates, phyllites and schists) was produced by solid-state flow.

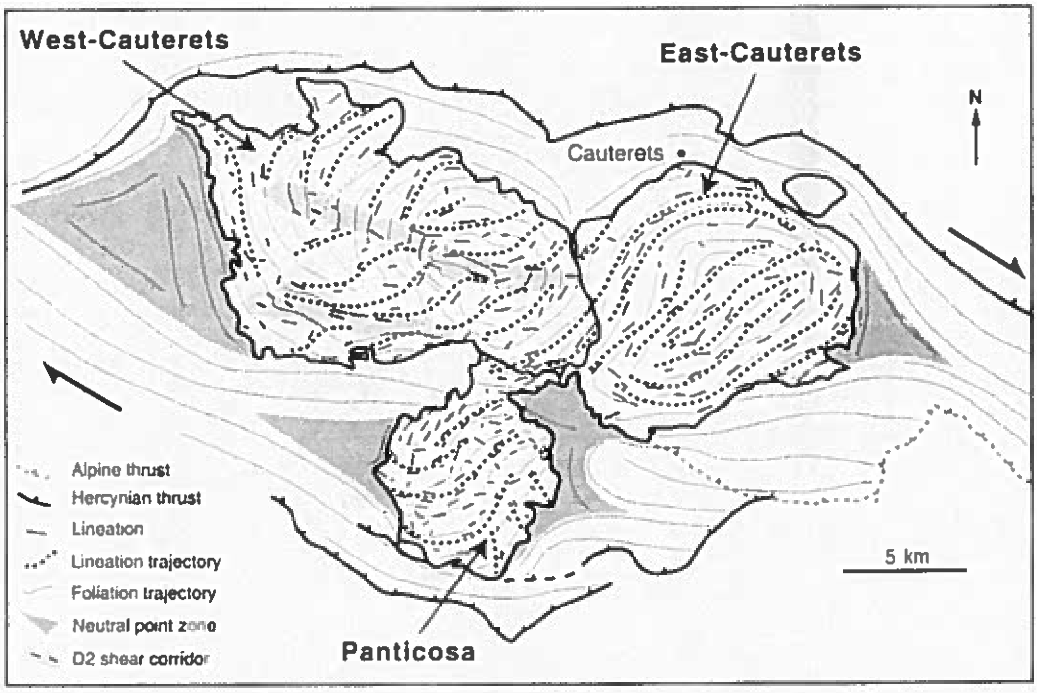


Fig. 3. Structural map of the Cauterets–Panticosa plutonic complex (AMS measurements) and its country rocks (after Santana *et al.* 1992; Leblanc *et al.* 1996*b*). The two shaded corridors in the West Cauterets body are D2 magmatic dextral shear zones.

i) What are the typical characteristics of structures formed by magmatic flow, sub-magmatic flow and sub-solidus flow?
ii) On the basis of the foliation patterns was the Cauterets intrusion pre-tectonic, syn-tectonic or post-tectonic?

<u>Question 5</u> - On structural analysis of crustal and mantle terranes

a) (6 points) How can exhumed crustal scale fault zones be recognized in the field? Describe some examples.

b) (6 points) What is the role of erosion and tectonic exhumation in producing the typical fault rock sequence found at a large scale thrust zone or a large scale extensional detachment zone.

c) (7 points) The diagrams below show the fold geometry developed in the Moine mylonites and schists of the Moine nappe in NW Scotland from the study of Evans and White (1984). Different fold geometries are found depending on the orientation of the fold axis relative to the stretching lineation Lm. The stereonet shows the orientations of fold axes and the orientation of Lm which plots in the area outlined by a dashed line. Note that some folds with axes parallel to Lm are re-folded by folds with axes perpendicular to Lm.

What deformation histories can explain the development of these structures?

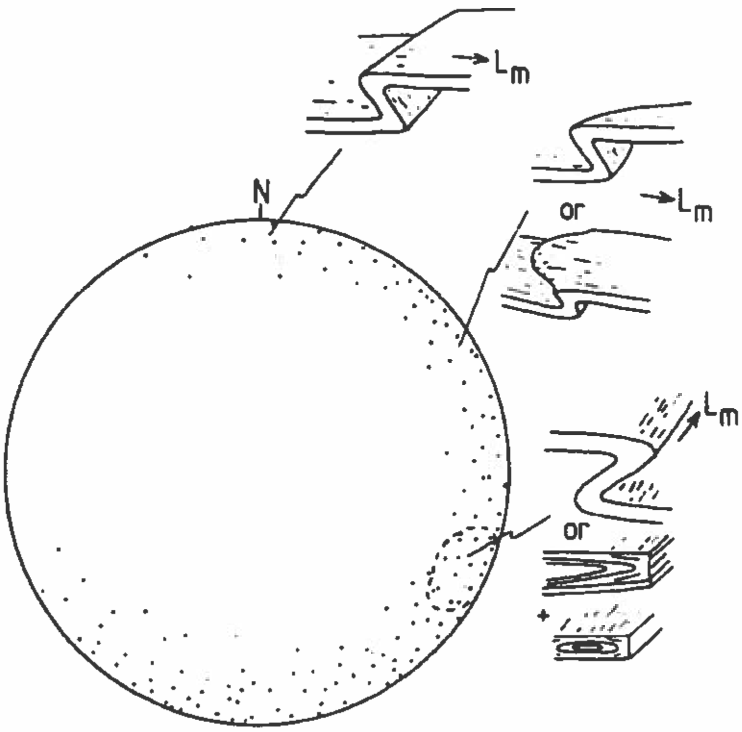


Fig. 11. Plot of minor fold plunge directions from the quartz mylonites (see text) with sketches illustrating their attitudes. The outlined area represents the area in which the extension lineation plots.

d) (6 points) The images below show the microstructures in upper mantle xenoliths from alkali basalts. How can the strain and flow stress be estimated from the olivine microstructures (upper row of images a, c, b)? How can the strain be estimated from the spinel microstructures (lower images a,b and f). What criteria could be used to determine if the deformation occurred in the lithosphere or asthenosphere?

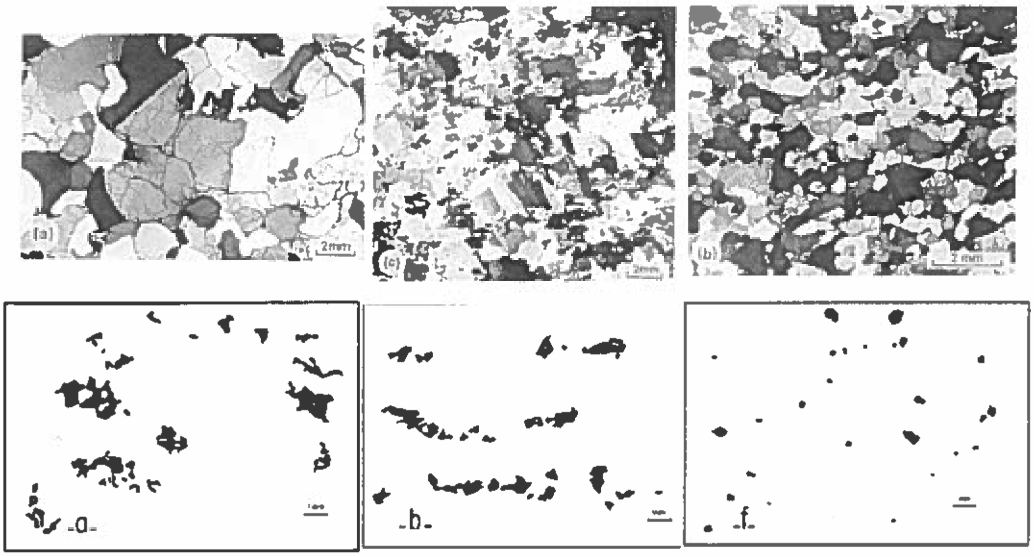


Figure caption: The upper three images are cross polarised light images mainly showing the shape, size and internal structures of olivine grains. The lower three images are line drawings of the spinel grain in the same xenoliths.