Structural Analysis of Deformed rocks (GEO4-1411) - Exam 28-01-2016

Time: 09.00 – 11.30 hr. (2.5 hours)
Place: Educatorium Alfa

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.

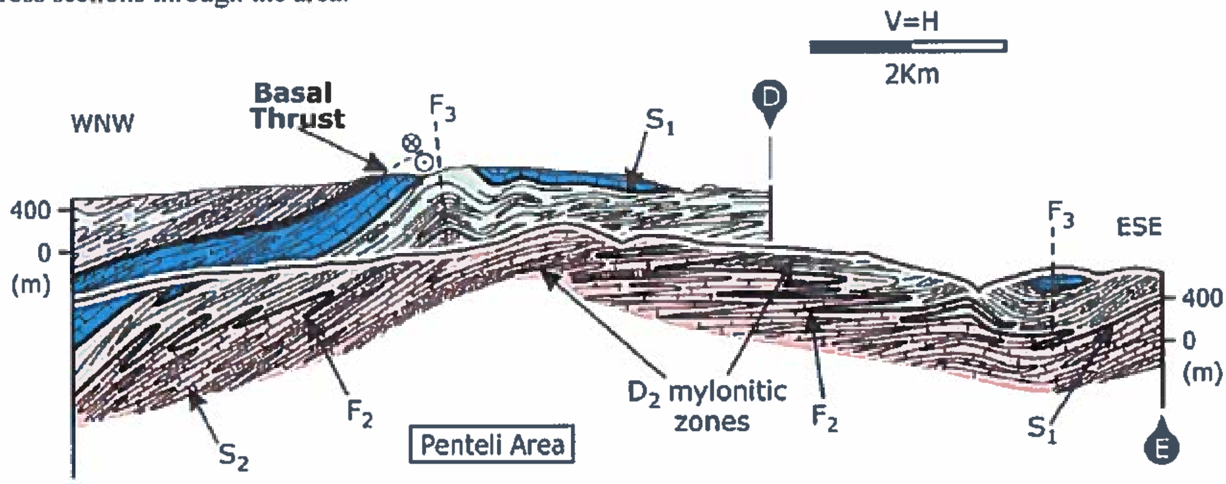
Answer 4 out of the 5 questions (make your own choice)

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

Spanos *et al.* (2015) studied calcite tectonites in the Attico-Cycladic massif in Greece. They used microstructural observations to determine vorticities and kinematics. The figure below shows one of the cross sections through the area.



One of the SADrocks lecturers has used the results of Spanos et al for the "D2 mylonitic zones" to describe the flow in terms of the following velocity gradient tensor L:

$$\mathbf{L} = \begin{pmatrix} 1.0x10^{-11} & -0.5x10^{-11} \\ -5.0x10^{-11} & -3.0x10^{-11} \end{pmatrix} \qquad [s^{-1}]$$

a) (8 points)
   i) Describe the fold structure that can be seen in the internal parts of the nappes, using appropriate terminology.
   ii) Give a short explanation of what is meant with "vorticity" in general and what it means in a geological context.
   iii) In the description of flow, use is sometimes made of "flow apophyses". What are these?

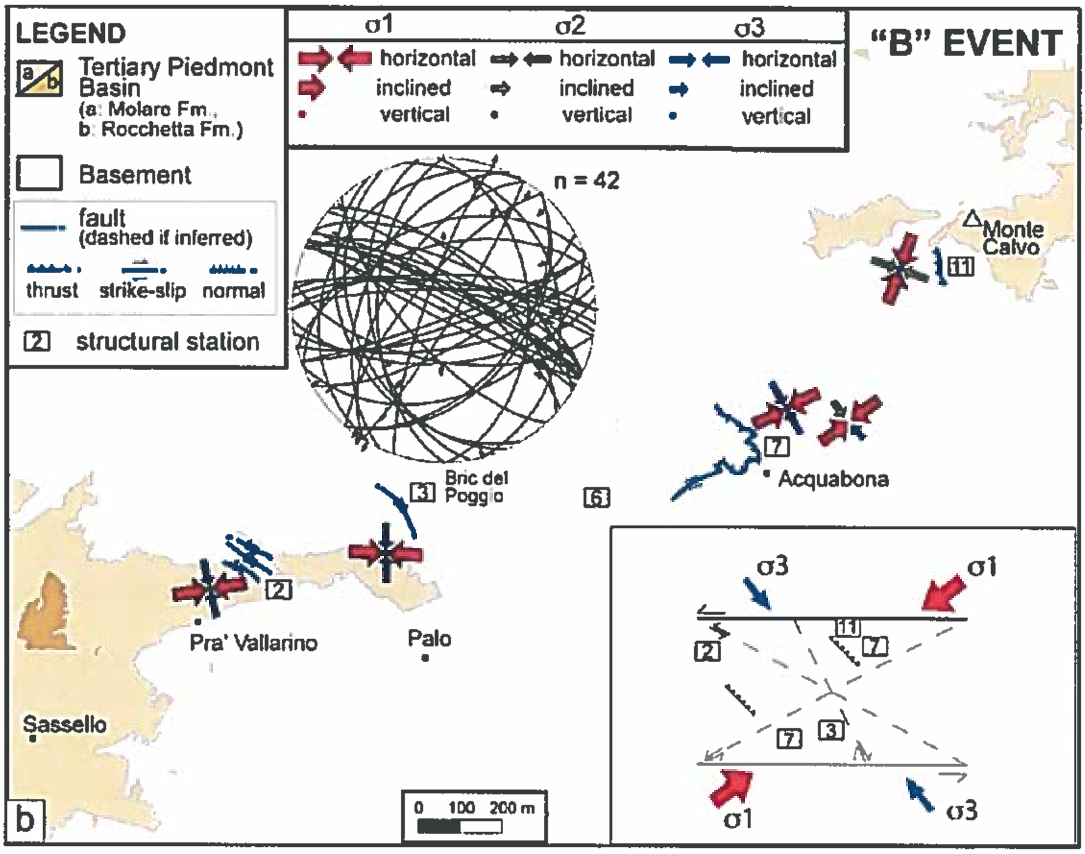
b) (9 points)
   Make a Mohr circle representation of **L** for the mylonitic zone. Carefully (!) label all axes and explain what the intersections of the Mohr circle and the axes mean. Also, determine the mean instantaneous stretching rate and the stretching rates along the flow apophyses.

c) (8 points)
   i) Determine the kinematic vorticity number for the location. You may use the Mohr diagram of question 1b) or calculate on the basis of the tensor.
   ii) Give a meaningful interpretation of the results for the kinematic vorticity number. In other words, what do the results tell you about the structure or history Attico-Cycladic massif?

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

a) (8 points) Consider stress analysis using fault slip data:
   i) Explain briefly what the basics are of determining paleostress on the basis of fault slip.
   ii) 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.

b) (8 points) The figure below shows results of fault slip analysis in the Voltri area, western Alps (Italy), taken from Federico *et al.* (2014).
   i) Describe what you <u>observe</u> on the figure in terms of faults and stress orientation.
   ii) Use your knowledge of this kind of analysis to infer the work flow of the authors (i.e. the steps they have taken to come to an interpretation).



c) (9 points) Assume that your dealing with a folded multilayer consisting of two different rock types with viscosities that only slightly differ. Also assume that the deformation temperature was high enough to allow ductile deformation processes to have taken place:
   i) How would this folded multilayer look in outcrop. Explain your drawing.
   ii) Critically evaluate methods that can be applied to estimate the paleostress magnitude in such deformed multilayer?
   iii) Do you expect a difference in paleostress between the two rock types? If yes, explain. If no, also explain.

Question 3 – On mechanical instabilities and structure development

a) 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).

   (6 points)

b) 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 each step taken in performing such an analysis.

   (6 points)

c) 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 and why they are periodic:
   - Crenulation cleavage with metamorphic segregation in a slate.
   - An array of evenly spaced fluid inclusions present in a healed, originally planar microcrack seen in a metamorphic quartzite.

   (6 points)

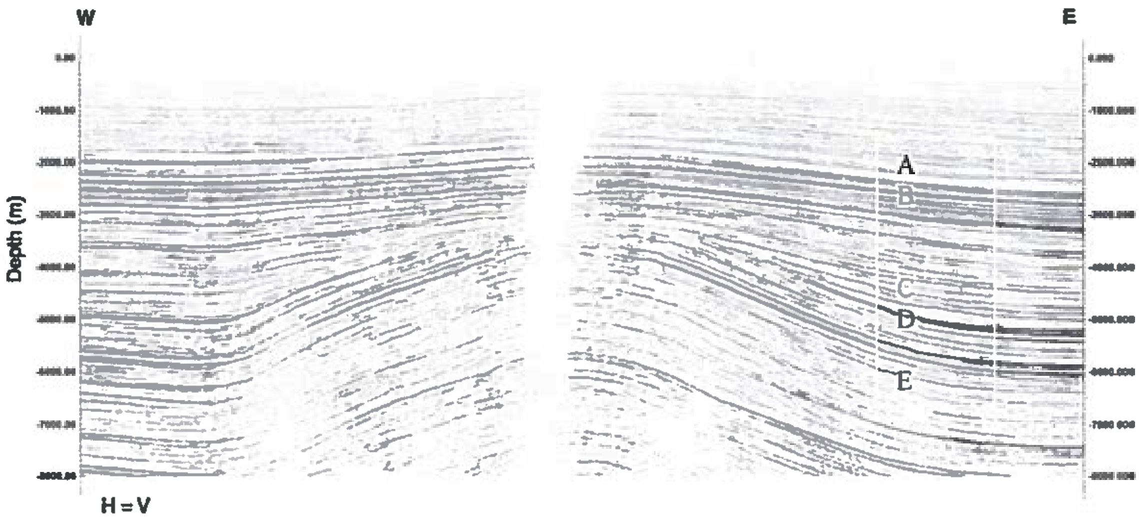
d) You are in the field in a limestone-dominated orogenic terrain prone to natural earthquakes. You discover a very narrow calcite-rich fault zone, around 5 cm thick, cutting dense crystalline limestones. The fault zone shows a prominent and highly "polished" or reflective, internal, principal slip surface exposed in a well-developed fault scarp. The fault zone and slip surface itself are characterized by a fine-grained, polygonal, recrystallized calcite microstructure that is typical of the microstructure developed during high temperature superplastic flow. You have read, in a paper about the area, that CO_2-rich fluid inclusions are abundant in the fault rocks exposed at this locality. The host rock, or protolith, is a well-cemented, coarse grained, carbonate grainstone containing widespread fossil fragments and cut by numerous small cracks and veins.
   - 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, taking into account the regional tectonic context.

   (7 points)

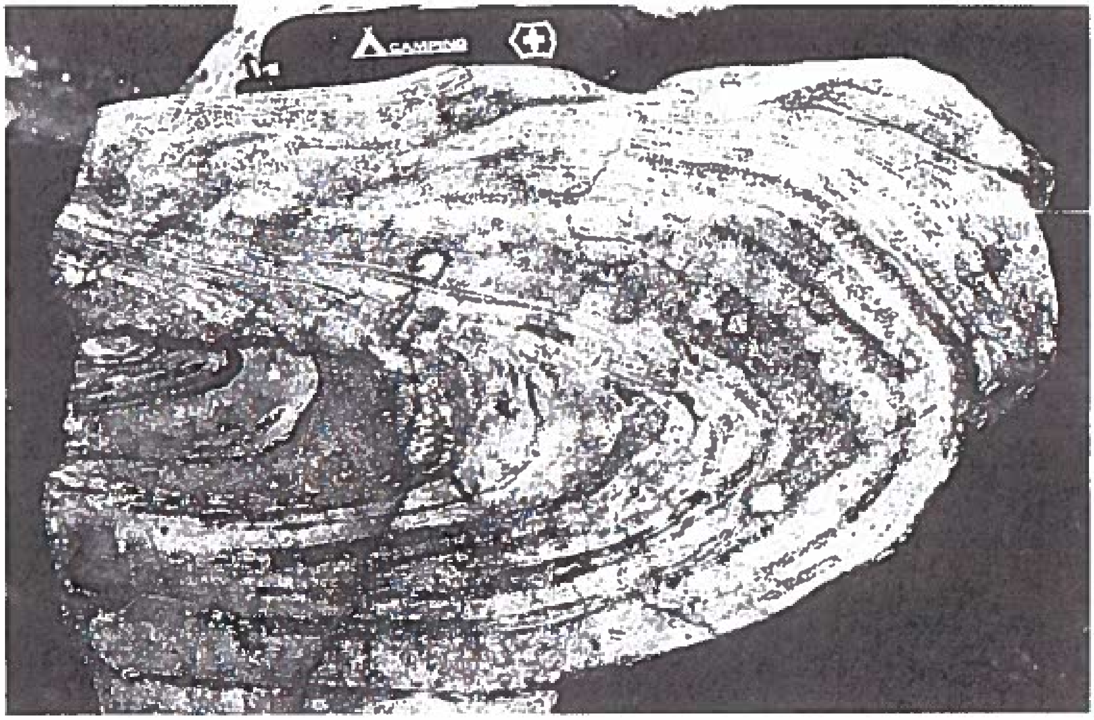
Question 4: On the analysis of Deformation structures and histories.

a) (9 points) The images below show reflection seismic sections of sediments in the Persian Gulf. Draw an interpretation of this section showing any pre-tectonic, syn-tectonic and post tectonic sediments. From well information the ages of the horizons A to E in millions of years, are A=10 Ma, B= 26 Ma, C= 68 Ma, D= 93 Ma and E = 145 Ma. Use the stratigraphic age information to discuss the timing of deformation and sedimentation.

a)



b) (8 points) Are the structures in the images below (this and next page) formed by soft-sediment flow or solid-state deformation? How in general can you tell the difference?



c) (8 points) The image below shows a garnet crystal in a metamorphic rock.

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?

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

a) (6 points) What criteria are used to describe different types of fault- rocks? Describe the Sibson (1977) and the IUGS (2007) classifications.

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.

c) (8 points) Images of highly deformed rocks from a crustal terrane are shown below. i) What deformation processes are involved in the formation of the rocks in figures 1 to 4? ii) The rocks shown in fig. 2,3 and 4 occur in a localised fault/shear zone 500 m thick, with north-south strike and shallow dip to the west. Fig 2 shows rocks next to the hanging-wall of the structure, figure 3 rocks in the centre of the zone and figure 4 next to the footwall. Is this fault/shear zone structure an exhumed thrust zone or extensional detachment zone?

Figure 1) light microscope image of granodiorite.

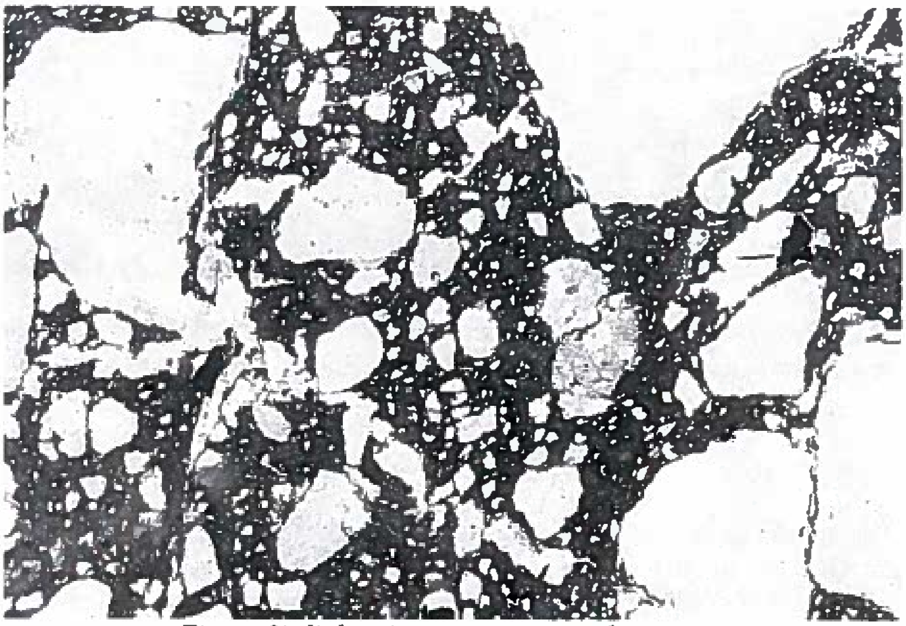


Figure 2) light microscope image of quartzite.

Figure 3) light micrograph of deformed granodiorite. Large clasts are feldspar and lighter matrix grains are quartz.

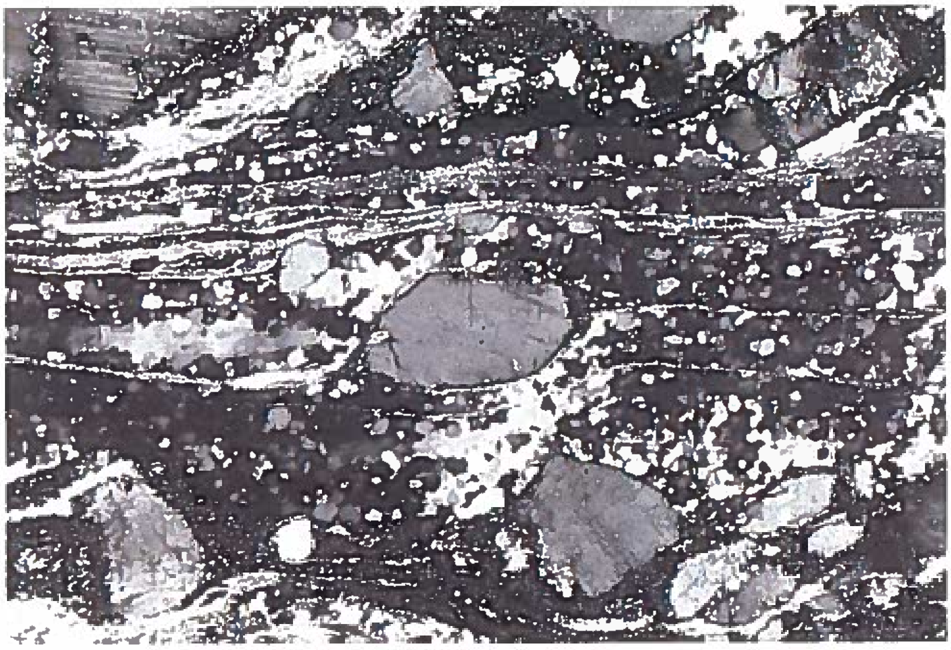


Figure 4) light microscope image of deformed granodiorite. Large clasts are feldspar, fine-grained bands in the matrix are mica and feldspar, coarser grained bands in matric are quartz.

d) (5 points) The images on the next page 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?

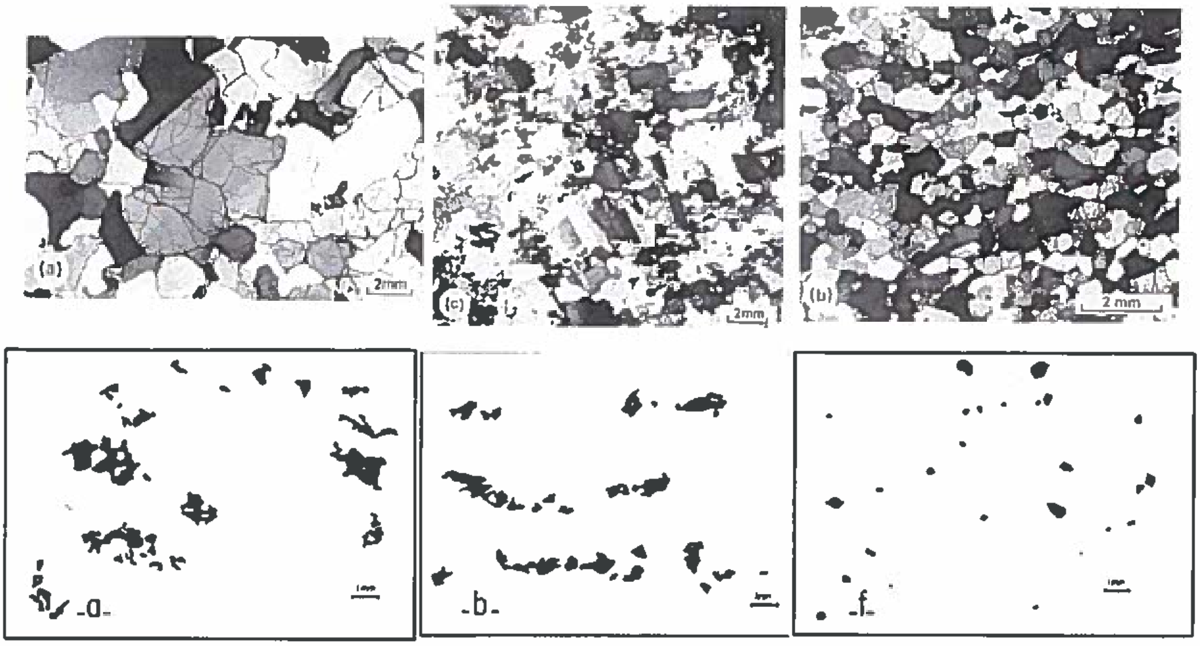


Figure caption: The upper three images are cross polarised light images mainly showing the shape, size and internal structures of olivine grains. The lower three images are line drawings of the spinel grain in the same xenoliths.