Structural Analysis of Deformed rocks (GEO4-1411) - Exam 27-01-2014

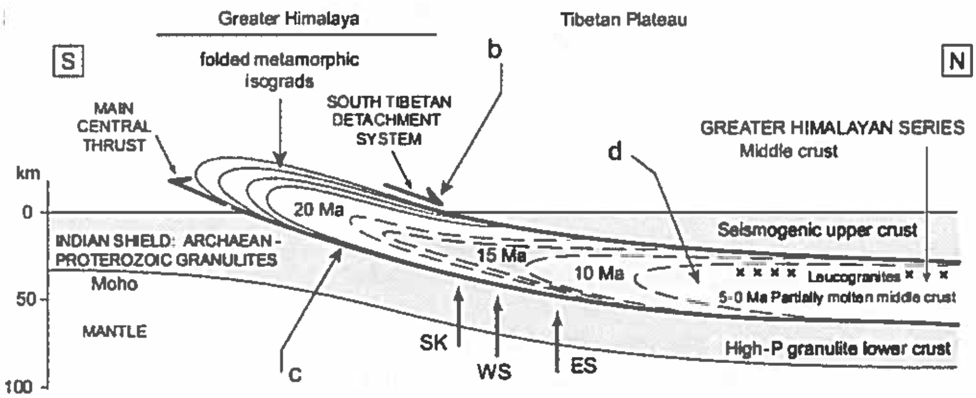
Time: 13.30 – 16.30 hr.
Place: UNNIK.211

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

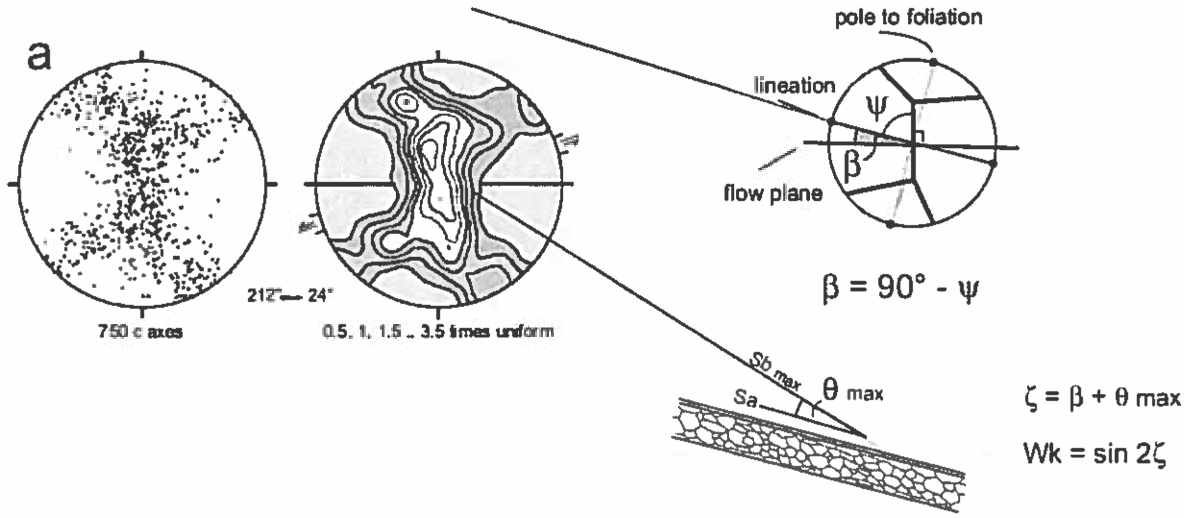
Please read carefully! Answer every question on a separate page. DO NOT answer 5 questions!

Question 1 – On flow in rocks

Law *et al.* (2013) studied high grade metamorphic rocks that form part of the so-called Greater Himalaya series in India. These rocks are positioned in the hanging wall of a major thrust (the "main central thrust"). A schematic model is shown below.



Quartz c-axis patterns have been measured in various recrystallized rocks. They show typical cross-girdle patterns as given below on the left. Such 'skeleton' patterns contain information on the vorticity of the rock. The kinematic vorticity number Wk can be determined by measuring 1) the angle β between the flow plane and the Instantaneous Stretching Axis (ISA), and 2) the angle θ between the macroscopic foliation in the rock (Sa) and direction of the long axes of the recrystallized grains (Sb). The ISA is assumed to be parallel to Sb. Values obtained for Wk range 0.8-1.0.



a) (5 points)
   i) Explain what the difference is between "vorticity" and "kinematic vorticity number".
   ii) Why do we need both?

b) (7 points) Study the figures above.
   i) Make a clear drawing showing the relationship between flow plane, direction of long grain axes and macroscopic foliation, consistent with the above method of Wk determination.
   ii) What can you conclude about the rocks with Wk=0.8-1.0 in relation to the model of the Himalayan series?
   iii) What will be the values for β and θ in case of true simple shear? Explain!

Let's assume that the flow of the Greater Himalyan can be described by the following velocity gradient tensor L:

$$\mathbf{L} = \begin{pmatrix} 1.0x10^{-12} & -0.5x10^{-12} \\ -9.0x10^{-12} & -3.5x10^{-12} \end{pmatrix} \qquad [s^{-1}]$$

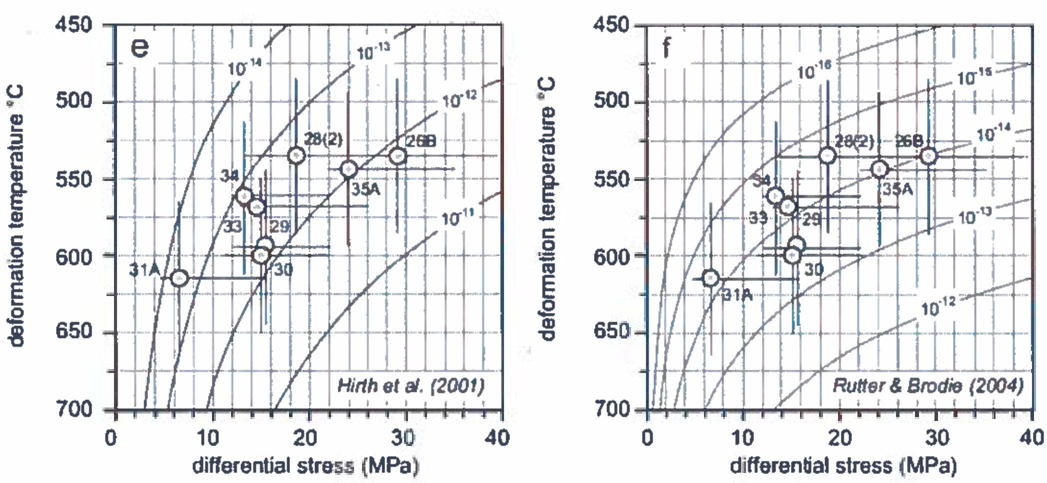
c) (7 points) Make a Mohr circle representation of **L**. Carefully (!) label all axes and explain what the intersections of the Mohr circle and the axes mean. Also, determine the mean instantaneous stretching rate and the stretching rates along the flow apophyses.

d) (6 points) Discuss in detail whether or not tensor **L** could indeed fit the flow of the quartz-rich metamorphic rocks in the Greater Himalaya rocks.

Question 2 – On the analysis of paleostress and layered rocks

a) (6 points) Consider stress analysis using fault slip data:
   i) explain briefly what the basic assumptions are behind this type of analysis,
   ii) what is meant with the 'stress shape ratio' and why is this ratio of importance?
   iii) what are the main drawbacks ("con's") of this method?

In the study of Law *et al.* (2013), introduced at Question 1, the high grade, quartz-rich metamorphic rocks from the so-called Greater Himalaya series, India, have also been analyzed for paleostress magnitude. For this, the quartz paleopiezometer of recrystallized grain size has been used. The figures below show the differential stresses obtained, plotted as a function of deformation temperature and compared with the predictions from experimentally determined flow laws for quartzite (lines; numbers refer to strain rates in s^{-1}).



b) (6 points) Make a list of pro's and con's ("voors en tegens") regarding the use of dynamically recrystallized grain size to estimate paleostress.

c) (7 points) Analyse the graphs of Law *et al* (2013). Use your knowledge of flow laws (creep, viscosity) and piezometric relations for dynamical recrystallization to respond to the following statements:
   i) The graphs do <u>not</u> form proof that the size of dynamically recrystallized grains is temperature dependent.
   ii) The graphs form a good illustration of the lack of understanding regarding the relationship between the piezometer for quartz and the flow behaviour of this material.

d) (6 points) Assume that the flow behaviour of sample 31A and of sample 26B belongs to two slightly different types of quartz rocks. Also assume that the two rock types can be found in a folded multilayer. How would such a folded multilayer look in outcrop. Explain your drawing.

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

a) (6 points) Explain <u>in detail</u> what is meant by the following terms:
   - unstable deformation process
   - stability analysis.

b) (6 points) Sketch stress-strain curves for plastically deforming materials showing i) strain hardening and ii) strain softening. Explain with the aid of a feedback diagram why work hardening materials do not show strain localization whereas strain softening materials often do. Explain also what kind of strain softening behaviour will be most effective in producing localization. <u>Assume throughout</u> that the stress-strain behaviour of the materials considered is insensitive to strain rate.

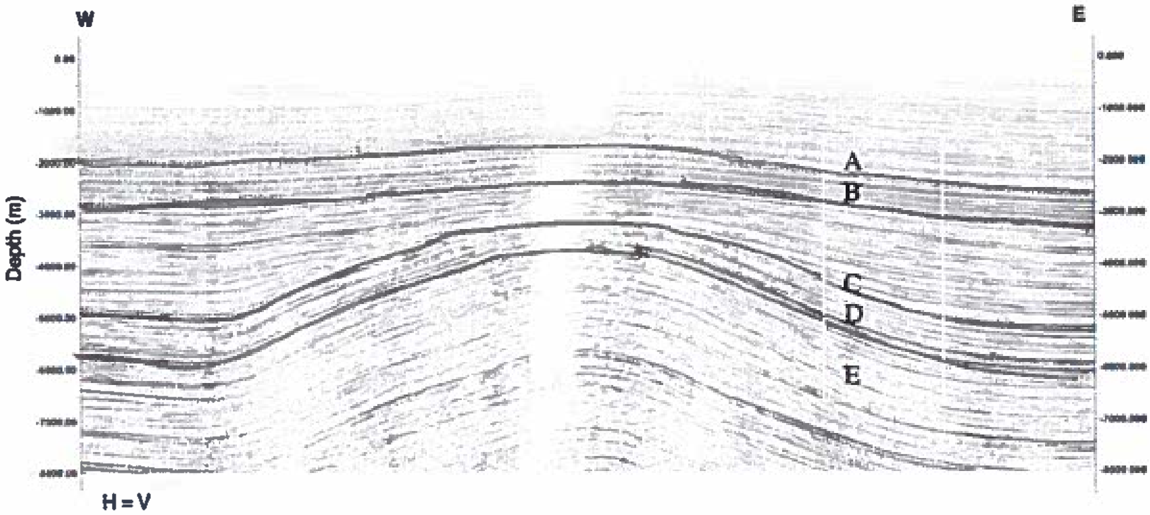
b) (6 points) Describe the main characteristics of the following structures (illustrate with simple diagrams) and explain how these structures can develop and why they are periodic:
   - Pinch and swell
   - Crenulation cleavage with metamorphic segregation in a slate.

d) (7 points) Define the term "ductile shear zone" from the point of view of a structural geologist who is working in the field.
   - Go on to outline three different ways in which ductile shear zones can dynamically localize in a deforming rock mass.
   - What features would you look for in the field to verify which of these localization mechanisms might be responsible for the formation of a given shear zone?

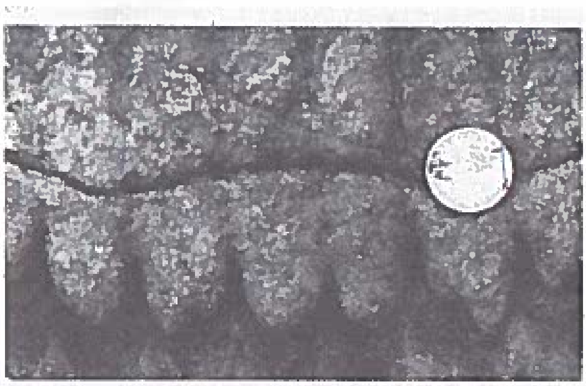
<u>Question 4:</u> On the analysis of Deformation Histories.

a) (10 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.

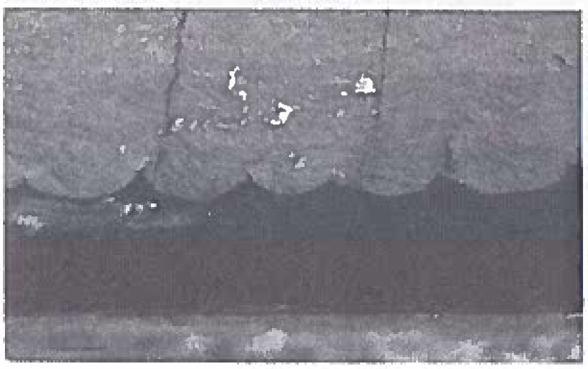
a)



c) (5 points) Are the structures in two images formed by soft-sediment flow or solid-state deformation? How can you tell the difference?



(e)



d) (10 points) Image a) and b) are micrographs showing porphyroblasts in a schist from the Cristallina pass in the Swiss Alps. Define the deformation history and determine the growth periods of garnet (Gt) and staurolite (St). Note that image b) is rotated by 90 degrees compared to image a). Image b) shows a higher magnification view of part of image a.

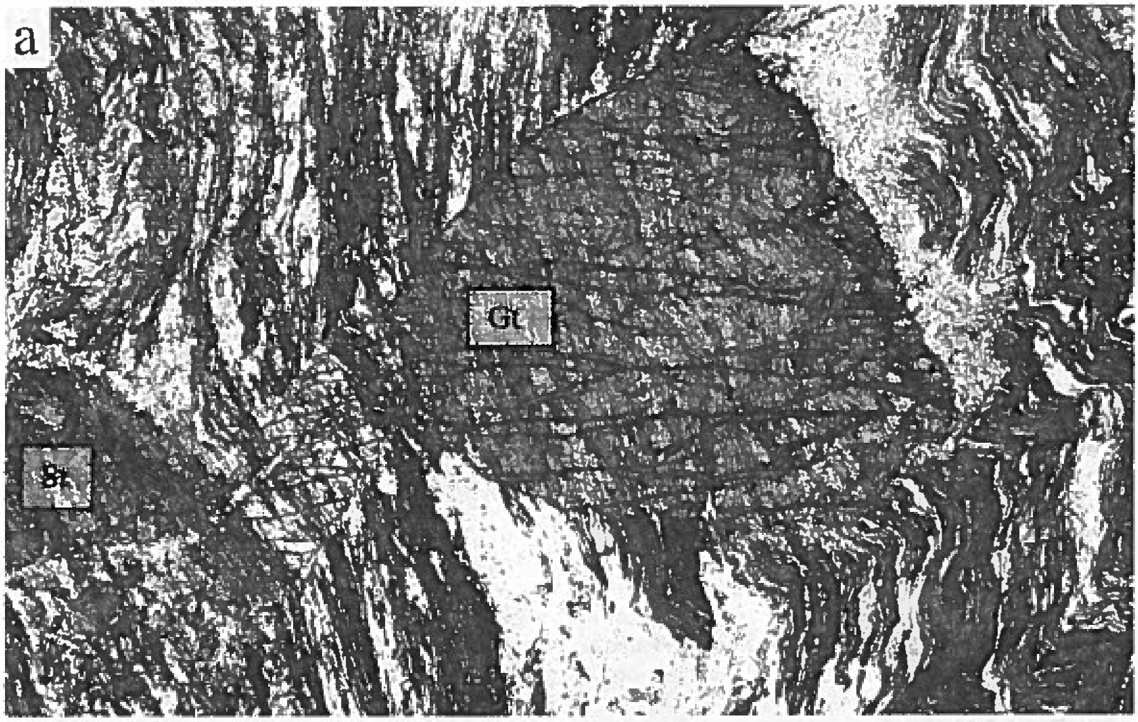
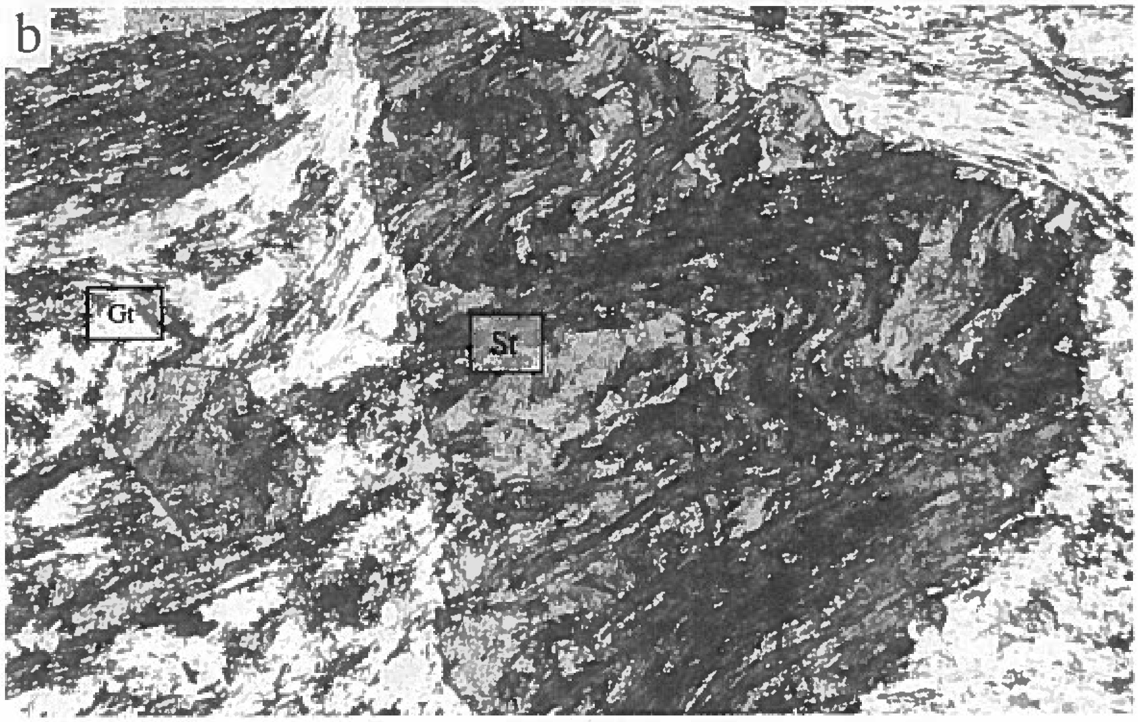


Fig. 11.19a,b. Garnet-staurolite micaschist; **a** shows a large garnet crystal in the centre and two staurolite crystals at *left*. Width of view 13 mm. Polarisers at 25°; **b** shows a detail of **a** with one of the staurolite porphyroblasts and a small garnet at *left*. Width of view 4 mm. PPL. Notice that, because of space restrictions, **b** has been rotated over 90° clockwise with respect to **a**. Cristallina, Alps, Switzerland

Problem 19 – Define deformation phases and determine the growth periods of garnet and staurolite.



<u>Question 5</u> - On Structural Analysis of Faults and Shear Zones

a) (5 points) What criteria are used to describe different types of fault-rocks? Describe the Sibson (1977) and the IUGS (2007) classifications.

b) (5 points) What type of fault rocks are shown in the images below and what deformation and grain size reduction processes are likely to be involved in the formation of these fault rocks?

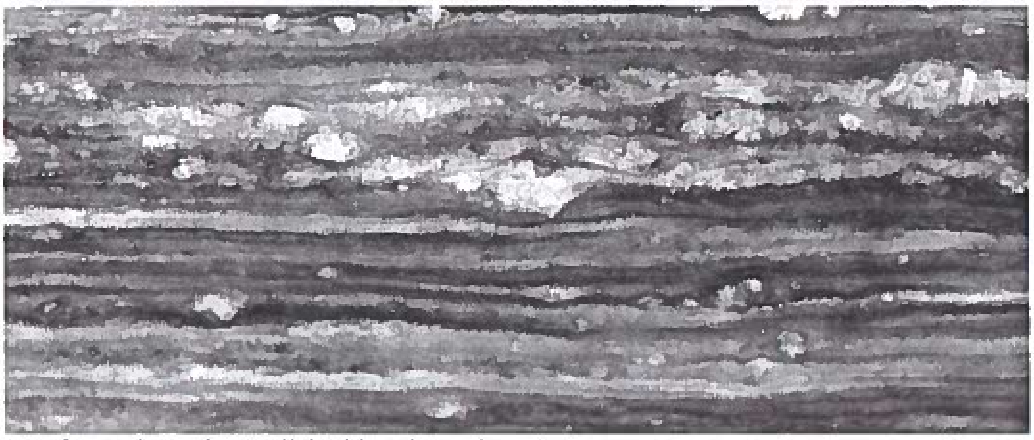


Fig. 5a-1 Deformed granite (polished hand-specimen).

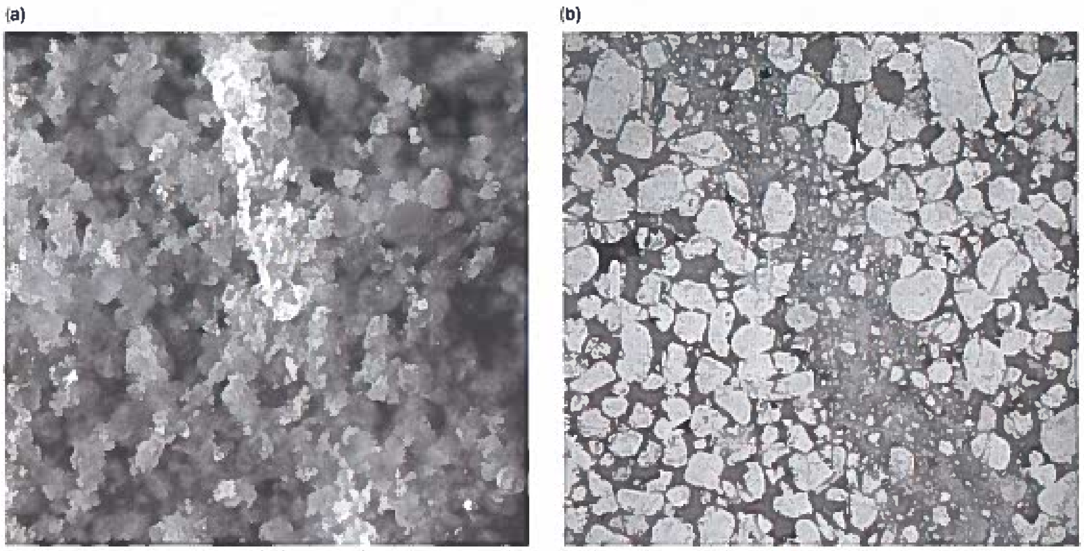


Figure 5a-2 Sandstone. Left image is hand-specimen, right image is microscope image with pores filled with dark resin.

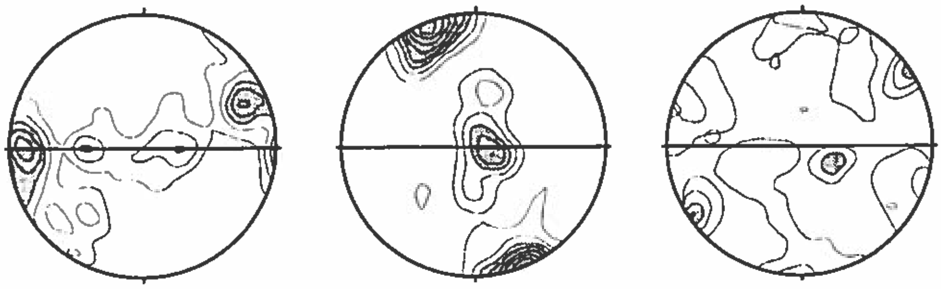
c) (5 points) Describe the structure of a typical exhumed thrust fault zone, such as the Outer Isles Thrust in NW Scotland or the Alpine fault zone in New Zealand. Discuss how these exhumed sections have been used to develop a model for the depth structure of major crustal fault zones.

d) (5 points) How can episodes of fault zone re-activation be recognized from field and other types of data?

e) (5 points) The crystallographic preferred orientation (LPO) of the olivine grains in an upper mantle rock from the Oman ophiolite is shown below. The diagrams are orientated with the vertical foliation, with E-W strike and with a horizontal lineation with E-W azimuth. The stereonets show the contoured density of the [100], [010] and [001] directions in olivine.

A25
n=384
(hzb)

W



E

290 m

Explain how the LPO can be used to work out the shear sense of deformation.
(Note that at high temperature T> 1000°C the easy slip system in olivine is [100](010), i.e. slip in the [100] direction on the (010) plane).