Structural Analysis of Deformed rocks (GEO4-1411) - Exam 21-01-2019

Time: 17.00 – 19.30 hr. (2.5 hours)
Place: Educatorium Gamma

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**.

<u>Question 1</u> – On flow in rocks

Langille *et al.* (2010) have studied middle crustal ductile deformation patterns in southern Tibet. The figure below (Fig. 1) shows a model of the area including a southward-flowing low-viscosity middle crustal channel (gray) bounded by an normal-sense upper shear zone (STDS) and a thrust-sense lower shear zone (MCT). The two shear zones thus separate the channel from higher viscosity material above and below. Double-barbed arrows indicate velocity vectors; single-barbed arrows indicate relative sense of displacement.

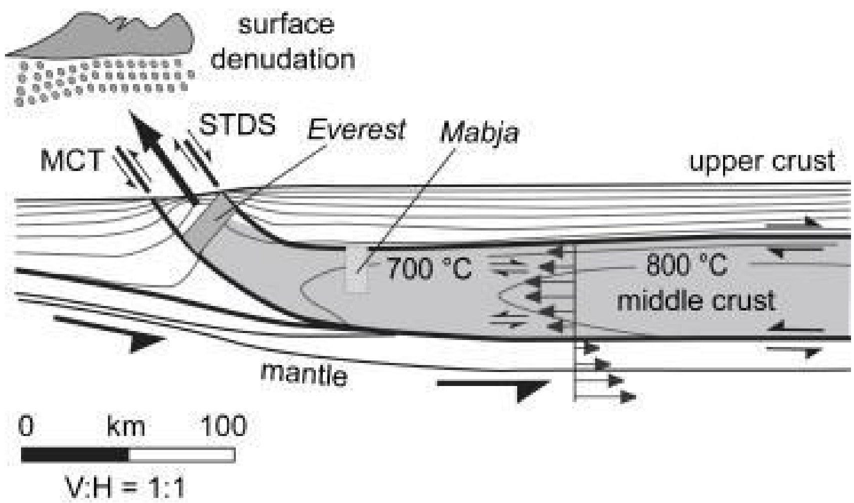

Fig.1 From Langille et al. (2010)

The following velocity gradient tensor L has been determined for the rocks sheared in the Mabja region:

$$\mathbf{L} = \begin{pmatrix} 3.0x10^{-11} & -4.0x10^{-11} \\ -4.0x10^{-11} & -7.0x10^{-11} \end{pmatrix} \quad s^{-1}$$

a) (6 points)
   i) Explain what is meant with a Kinematic Vorticity number.
   ii) Design a flow pattern of material particles for a Kinematic Vorticity number of 0.5.

b) (4 points)
   Looking at the velocity vectors in the figure, describe <u>qualitatively</u> the type of flow bottom to top, using simple shear – general shear – pure shear terminology

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

d) (8 points)
   i) Determine the kinematic vorticity number for tensor. You may use the Mohr diagram of question 1c) or calculate on the basis of the tensor.

ii) Give a meaningful interpretation of the results presented above for **L**. Do the results fit the expected flow pattern for Mabja? Compare with your answer for b).

<u>Question 2</u> – On the analysis of faults and folds

Riller *et al.* (2017) performed an elaborate study of the Sudbury Igneous Complex, Ontario, Canada. This was an initially flat melt sheet that was deformed into a fold basin, the Sudbury basin. The area shows metamorphic foliations as well as brittle faults. Figure 2 below shows a characteristic fault and the result of a fault inversion exercise. Figure 3, next page, shows a map of the interpreted strain field, following from the fault inversion analysis. The Figure also shows the foliation pattern.

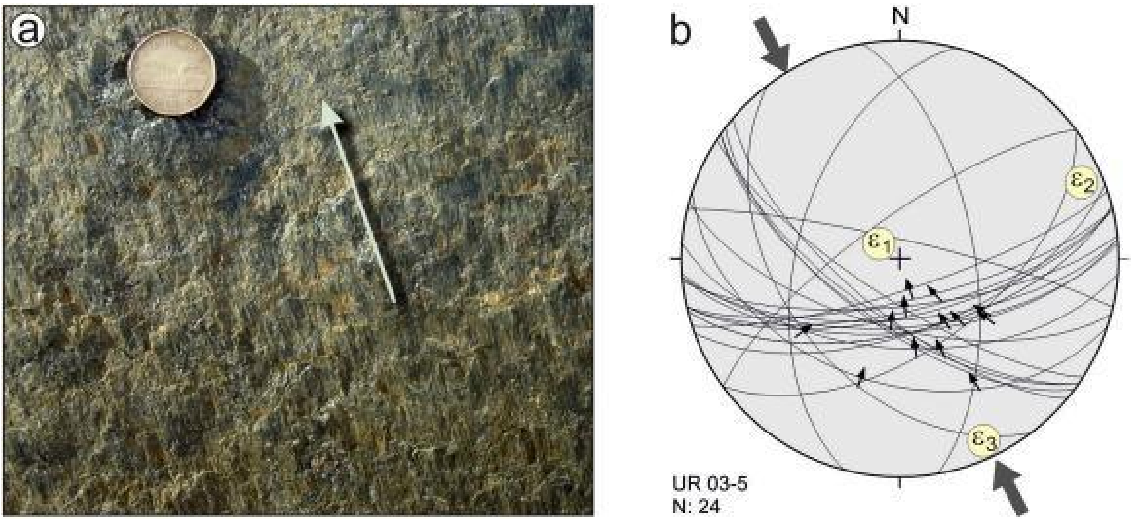

Fig.2. On the left side a brittle fault decorated with chlorite fibres. On the right side fault-slip data are presented, in lower-hemisphere, equal-area projection. Great circles represent fault surfaces. Arrows on great circles indicate the senses of slip of hanging walls with respect to footwalls along a measured slip lineation. $\varepsilon_1 \geq \varepsilon_2 \geq \varepsilon_3$ *are, respectively, maximum, intermediate and minimum principal strain axes. From Riller et al. (2017).*

a) (9 points)
   i) Explain briefly what sort of data you need and how these data are used to come to a fault slip analysis as Fig. 2.
   ii) Why would the authors use principal <u>strain</u> axes rather than principal stress axes?
   iii) What do you think the value of the 'stress shape ratio' is for the faulting? Explain your answer by including what is meant with this ratio.

b) (8 points)
   i) What approaches might be taken to estimate the viscosity contrast of the rocks?
   ii) Looking at the outcrop pattern of lithologies (Fig. 3), what can you say about viscosity contrasts in the area?

c) (8 points)
   Use Fig. 3 to analyse the area in terms of deformation phases. What do you expect in terms of fold vergences? Do you expect to find refolded folds (explain)? Etc.

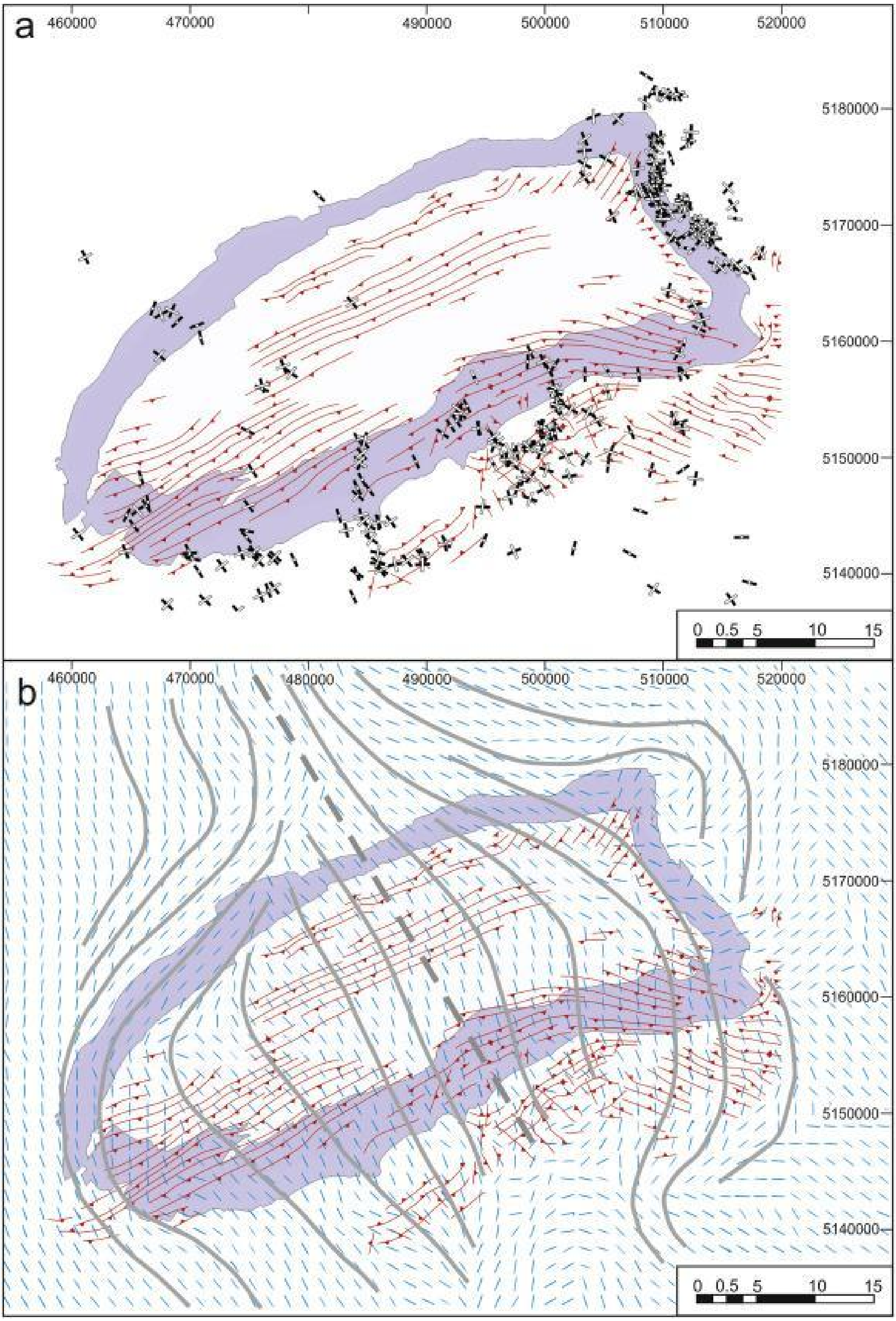

Fig. 3. Map-view of the Sudbury area. Red lines with barbs are manually constructed trajectories of the metamorphic foliation. The barbs indicate the dip direction. The purple band represents a zone of mainly quartz gabbro´s. TOP: Projected directions of maximum shortening (ε_3) and maximum extension (ε_1) inferred from fault-slip inversion indicated by black bars and white bars, respectively. BOTTOM: Superposition of foliation trajectories and interpolated shortening directions (short blue lines).

<u>Question 3</u> – 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:
   - Pinch and swell
   - 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)

<u>Question 4</u> – On fault zone structure and deformation histories

A crustal-scale, strike-slip fault zone was active in an orogenic region for 15 million years. During this time, erosion exhumed rocks from the lower crust, through the frictional-viscous transition zone, and into the upper crust. Today, the rocks are exposed at the surface.

a) Make a geological sketch map of a portion of the fault zone indicating:
   - the fault rock types present,
   - their overprinting relationships, and
   - the approximate ranges of depths and conditions under which they formed.
   (8 points)

b) Choose one fault rock that typically forms in the lower crust and one that typically forms in the upper crust. For each fault rock:
   - state the microstructures that identify it,
   - state the deformation mechanisms commonly associated with it,
   - describe its typical mechanical/rheological behaviour, and
   - explain the relationships between these characteristics.
   (10 points)

c) Metapelites within the fault zone contain garnet porphyroblasts. Figure 4 presents an electron micrograph of a typical example of one of these garnets. Analyse the microstructure and interpret:
   - the number of deformation phases,
   - the relative timings of deformation and garnet growth.
   Explain the evidence for your answers.
   (7 points)

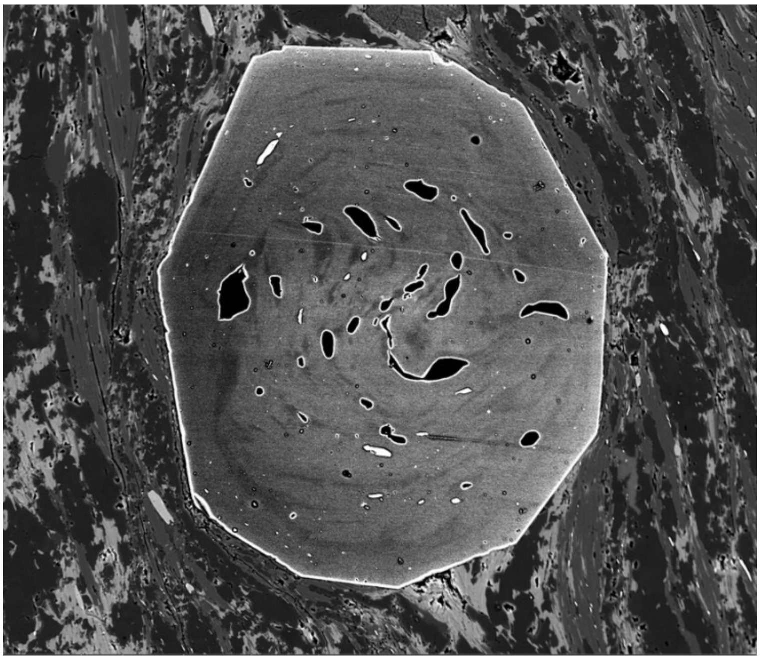

Fig. 4. Backscattered electron image of a garnet porphyroblast. Grey level is controlled by the mean atomic number of the material.

<u>Question 5</u> – On palaeopiezometry and crystallographic preferred orientations

You have collected a set of samples from an orogenic peridotite body. The peridotite body contains layered harzburgites and dunites in its centre, bounded by shear zones of finer-grained, mylonitic harzburgites. Structural data indicate that simple shear dominated within the shear zones.

a) Why can reliable piezometric estimates based on the size of dynamically recrystallised grains only be obtained from the dunites?
(4 points)

b) Which paleopiezometers could instead be applied to the harzburgites and what are the limitations/pit falls of each?
(8 points)

c) What methods could you use to obtain the basic microstructural information required for each piezometer discussed in parts (a) and (b)?
(4 points)

d) Measurements of olivine from the marginal shear zones reveal the crystallographic preferred orientation (CPO) presented in Figure 5.
- Interpret the dominant slip system that formed the CPO.
- Suggest two physical properties of the peridotite that CPO impacts and briefly explain why CPO impacts them.
(9 points)

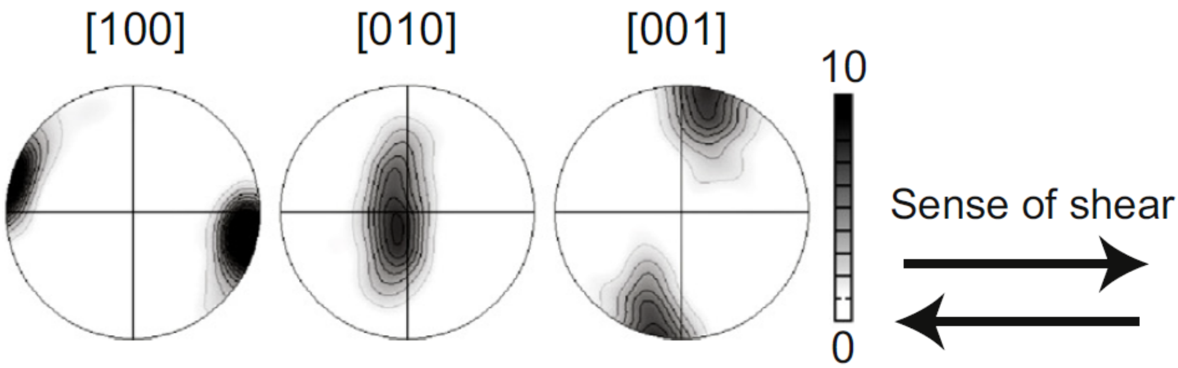

Fig. 5. Typical CPO of olivine within the shear zones (Skemer et al., 2013). Contours are in multiples of uniform distribution.