Solid Earth Discuss., 5, C292–C305, 2013
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Interactive comment on "The microstructural record of porphyroclasts and matrix of serpentinite mylonites – from brittle and crystal-plastic deformation to dissolution-precipitation creep" *by* J. Bial and C. A. Trepmann

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Received and published: 12 July 2013

Reply to comments by anonymous referee #2

We thank the anonymous referee for the critical and constructive review. We appreciate all suggestions and comments and will carefully consider them when preparing a revised manuscript. In the following we respond to all raised points one by one, answer questions and discuss the suggestions. The comments of referee #2 are given in quotation marks.

General comments

“While the title and the abstract of this manuscript explain clearly the aim of this study, the microstructures of the samples and the interpretation in terms of deformation mechanisms are not sufficiently described and documented through the paper. The conclusions on the successive deformation regimes through geological history are mostly based on general statements. The authors should describe more precisely and clearly their results and analysis using existing literature to support their conclusions. I address some points in some parts of the manuscript and recommend a major revision of the paper. The aim of this study - clearly enunciated in the title and in the abstract - is to show the difference in the microstructural records in serpentinite mylonite samples from the Voltri Massif (Italy) and relate them to independent successive episodes of deformation during geodynamical history. I was then expecting a detailed description of the microstructures linked to appropriate literature. Because of this too short microstructural description and lack of references to previous studies, the conclusions are not always supported by the results. The transition between deformation regimes suggested in the title of the article is not clearly demonstrated. In the case of antigorite microstructures the presented data do not support the conclusion largely based on general assumptions that are not documented in the text.”

In the revised manuscript we will describe the microstructures more comprehensively, especially the antigorite microstructure, as also requested by the first referee. We will add two more polarized light micrographs of antigorite microstructures to strengthen our discussions (see uploaded Figure 8). In the case of the antigorite microfabrics observed here, inferences on the crystallographic preferred orientations (CPOs) can be made by the orientation of the cleavage plane, i.e., the (001) basal plane, which is parallel to the foliation plane as observed by polarization microscopy (e.g., Fig. 6b, c and Fig. 8) and by the investigations with the compensator plate inserted (see below). EBSD data are not necessary to show this associated SPO and CPO with the basal plane in the foliation plane. The introduction will completely be rewritten with consideration of literature on the use of microfabrics of metamorphic mafic to ultramafic rocks related to deformation processes and stress, strain-rate conditions during burial and exhumation (see below). One of our main points is the documentation of an example, where the deformation record of porphyroclast in mylonites is not associated with the deformation record of the matrix, but where the microstructures of the porphyroclasts are inherited from a completely independent earlier deformation than the microstructure of the matrix. This is opposed to the general approach, where the microstructures of porphyroclasts are correlated with the microstructure of the mylonitic matrix - which is certainly valid for many mylonites, but not necessarily for all. This study shows one example, where such a correlation is not valid, as such it is a new and original contribution to understanding microstructures and their use to unravel the geological history. The main conclusions are focusing on the rheology of the rocks and the recorded stress conditions during the different stages of deformation. We will strengthen our main points throughout the revised manuscript.

1. Introduction: “The introduction describes very shortly the context of the study and the Erro-Tobbio Unit. The title and the abstract of the paper suggest that microstructures and EBSD textures were used to determine the processes (mechanisms and deformation regimes) that have taken place during the successive episodes of deformation as well as the associated stress-states (from rheological laws). However, no reference of previous works on the use of deformation microstructure as P, T and stress gauge for olivine, pyroxenes and serpentines are reported. I was expecting a large part of the introduction on these aspects.”

We completely revised the introduction considering literature on the use of microfabrics of metamorphic mafic to ultramafic rocks related to deformation processes and stress, strain-rate conditions during burial and exhumation, as also requested by the first referee:

In this study, we focus on the so far not widely used microstructural record of grain-scale

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deformation processes provided by partly serpentinized peridotite mylonites from the Erro-Tobbio unit (Drury et al., 1990; Hoogerduijn Starting, 1991; Scambelluri, 1991; Hoogerduijn Starting and Vissers, 1991; Hoogerduijn Starting et al., 1993; Vissers et al., 1991; 1995; Hermann et al. 2000) to obtain information on the rheology and the stress condition during the different deformation stages. These rocks dramatically changed their mineral content and thus their rheological behaviour during the complex geodynamic history. In comparison with experimental studies on the rheology of rock-forming minerals in metamorphic mafic to ultramafic rocks (omphacite: e.g., Avé Lallemant, 1978; Ingrin et al., 1992; Orzol et al., 2006; Zhang et al., 2006; Zhang and Green, 2007; Moghadam et al., 2010; olivine: e.g., Chopra and Paterson, 1981; Hirth and Kohlstedt, 2001; Zhang et al., 2000; Jung and Karato, 2001; Jung et al., 2006; Druiventak et al., 2011; 2012; antigorite: e.g., Hilariet et al., 2007; Chernak and Hirth, 2010) microfabrics can yield information on the deformation mechanisms, as well as the stress and strain-rate conditions during burial and exhumation (e.g., Skrotzki et al., 1991; van der Wall, 1993; Altenberger, 1995; Jin et al. 1998; Zhang et al, 2000; Jung & Karato, 2001; Piepenbreier and Stöckhert, 2001; Stöckhert, 2002; Andreani et al., 2005; Auzende et al., 2006; Jung et al., 2006; Wassmann et al., 2012; Matysiak and Trepmann, 2012). The aim of this study is to use the successively overprinted and modified microfabrics of the partly serpentinized peridotite mylonites to differentiate between the potential record of independent grain-scale deformation processes and implications on the stress conditions. On the basis of the findings we discuss the implications for the inferred superposition of features associated with initial brittle and crystal-plastic deformation of the original mantle peridotites with features indicating dissolution-precipitation creep of the serpentinized peridotites.

4. Sample description and microfabrics “This part describes the microstructures in olivine and diopside porphyroclasts and in antigorite. In the discussion these microstructures are used to infer the geological history. Then I expect a clear and more detailed description of microstructures in the samples. From page 369 line 24 to page 370 line 22: This part consist of a description of olivine porphyroclast in terms of mi-

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crostructures and chemical composition. This paragraph refers to five figures composed of more than 15 images and pole figures. As a reader I would have appreciate some help inserted directly on the images to show what you want me to see."

We extend the sample description and description of the microstructural data, which are now divided in two separate Chapters (4. Sample description, 5. Microfabrics).

"Page 370 line 20 : Whereas the SPO is associated with a crystallographic preferred orientation (CPO) for antigorite with the (001) basal plane in the foliation plane, olivine grains show no marked CPO (Fig. 6c, e). There is no measurement of CPO in antigorite in the sample so the authors suppose (which is reasonable) that basal planes are in the foliation plane?"

The reviewer correctly describes the subject. The associated SPO and CPO is obvious from the polarized light micrograph (Fig. 6b) and in the EBSD image (Fig. 6c) showing the antigorite cleavage plane, i.e., (001) basal plane, parallel to the foliation plane. Therefore, in this case, the crystallographic preferred orientation of the (001) plane can directly be inferred from the microstructure. We will state this more clearly in the text.

"From Page 370 line 23 to page 371 line 3: It is not clear for me on the images and pole figure whether diopside deformed in the plastic regime by kinking and (100) mechanical twining, which is dominant in this temperature range, or by dislocation glide, which is dominant above 800 _C or in some sample deformed at low stress below 800_C (e.g. Raleigh & Talbot, 1967; Ave Lallemant, 1978; Kolle & Blacic 1982; Kirby & Kronenberg, 1984; Ingrin et al.,1992)?"

All diopside porphyroclasts show exsolution lamellae parallel (100) with a relative constant spacing and a width of a few μm (Fig. 7), are commonly fractured (Fig. 7a), kinked and bent (Fig. 7b, c). The stereographic projection of bent crystals shows that the orientation of the [010] is a common axis and thus probably representing the rotation axis (i.e., the normal to the glide direction within the glide plane) during glide-controlled deformation. The relative misorientation at the kink bands is high with approximately

50° to 70° (Fig. 7). Also in kink bands, the [010] axis is the common axis. These microstructures indicate dislocation glide, but evidence of dislocation climb and dynamic recrystallization is not observed. This observation is in accord with TEM observations of experimentally and naturally deformed pyroxene that show the dominance of kinking and dislocation glide over dislocation climb processes, with the system for gliding being predominantly (100) [001] (e.g., Green and Radcliff, 1972; Skemer et al., 2006; Skrotzki et al., 1990; 1994; Moghadam et al., 2010). Microstructures that represent unequivocal indication of dynamic recrystallization of pyroxene are not always easy to recognize, e.g., a commonly occurring CPO of pyroxenes in natural rocks may be related to anisotropic growth rather than deformation (Mauler et al., 2001; Wassmann et al., 2011). Dynamically recrystallized pyroxenes are reported from nature to occur localized and at high stresses (e.g., Piepenbreier and Stöckhert, 2001; Müller and Franz, 2008; Raimbourgh et al., 2008). Twinning of clinopyroxene would indicate very high differential stresses, as discussed by Raleigh & Talbot, 1967; Kirby & Christie, 1977; Kolle & Blacic 1982; Trepmann and Stöckher, 2001; Orzol et al., 2003, however, no mechanical twins are observed in pyroxene of these rocks. This might indicate that stresses and strain rates were not sufficiently high to generate twins. However, the overall presence of (100) exsolution lamellae in porphyroclasts may have inhibited (100) twinning. This will be discussed in the revised text, see below.

“Page 371 Line 12: The pronounced SPO of antigorite corresponds to a CPO with the (001) basal plane in the foliation plane (Fig. 8). How the authors can be sure that the SPO of antigorite corresponds to a CPO with basal plane in the foliation plane?”

As stated above, the associated SPO and CPO is obvious from the polarized light micrographs (Fig. 8a, b) showing the antigorite cleavage plane, i.e., (001) basal plane, parallel to the foliation plane, as described for Fig. 6b, c. Furthermore, the polarized light micrographs with inserted compensator (Fig. 8c, d) show the pronounced CPO with additional colours when the basal plane oriented in the diagonal 45° position (i.e., nx of antigorite perpendicular to the main refractive index of the compensator plate)

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and yellow subtractional colours 90° to this orientation (i.e., nx parallel to the main refractive index of the compensator plate and the foliation plane at 135°). Therefore, in this case, the crystallographic preferred orientation of the (001) plane can directly be inferred from the microstructure in the polarization microscope. No EBSD data are necessary to show this associated SPO and CPO. We will state this more clearly in the text.

5. Discussion "5.1 Deformation of olivine and diopside porphyroclasts Page 371 line 17: The deformed diopside porphyroclasts (Fig. 7) record brittle and crystal-plastic deformation by dislocation glide. The bent (100) plane, the common rotation axis and kink band axis parallel to [010] indicate that the glide system (100) [001] was active. Could the authors explain if this glide system is common in diopside? Is the activation of the dominant (100)[001] glide system permits to precise the P-T conditions or the stress-state during deformation? Is this result different from previous microstructural observations in clinopyroxenes porphyroclasts? I expect a comparison with previous studies on both experimental and petrological aspects."

As stated above, our observed pyroxene microstructures are consistent with TEM observations of experimentally and naturally deformed pyroxene from previous studies that show the dominance of kinking and dislocation glide over dislocation climb processes, with the system for gliding being predominantly (100) [001] (e.g., Green and Radcliff, 1972; Skemer et al., 2006; Skrotzki et al., 1990; 1994; Moghadam et al., 2010). Dynamically recrystallized pyroxenes are reported from nature to occur localized at high stresses (e.g., Müller and Franz, 2008; Raimbourgh et al., 2008) and temperatures as low as 500°C (e.g., Piepenbreier and Stöckhert, 2001), consistent with experimental studies (e.g., Orzol et al., 2006; Zhang et al., 2006; Zhang and Green, 2007; Moghadam et al., 2010). Twinning of clinopyroxene would also indicate high differential stresses, as discussed by Raleigh & Talbot, 1967; Kirby & Christie, 1977; Kolle & Blacic 1982; Trepmann and Stöckhert, 2001; Orzol et al., 2003, however, no mechanical twins are observed in these rocks. This might indicate that stresses and strain rates were not sufficiently high to generate twins. However, the overall presence of (100) exsolution lamellae in porphyroclasts may have inhibited (100) twinning.

“Page 371 line 25: Both observations suggest subgrain rotation recrystallisation in the regime of dislocation creep, where the new grains inherit a crystallographic orientation similar to that of the replaced original grain. Dynamic recrystallization has taken place during deformation by dislocation GLIDE. If so, maybe the extrapolation of the rheological law determined in the dislocation creep regime (Chopra & Paterson, 1981) to infer the stress-state needs to be done with some precautions?”

Dynamic recrystallization is taking place during deformation in the regime of dislocation CREEP. The trade temperature for rate is commonplace in experimental rock deformation, being the only way to achieve measurable deformation at stress levels corresponding to those prevailing in nature (e.g. Paterson, 1987, 1990; McLaren, 1991; Evans and Kohlstedt, 1995). The extrapolation to natural conditions, yet, is only valid if processes occurring in nature and experiment are comparable (e.g. Hirth et al., 2001; Stöckhert et al., 1999; Stipp et al., 2002). As such, the evidence of deformation and recrystallization of olivine in the regime of dislocation creep at upper mantle conditions, as observed here, would justify the application of the flow law for olivine deformed experimentally in the regime of dislocation creep of Chopra and Paterson (1981).

“Page 372 line 18: A temperature above 600_C is also in accord with the general assumption that dynamic recrystallisation of olivine in the regime of dislocation creep at reasonable strain rates of 10-13 – 10-15s-1 requires temperatures considerably higher than 600_C as based on observations from natural systems (e.g. Skrotzki et al., 1990;Altenberger, 1995; Jin et al., 1998) and the extrapolation from experimentally derived flow laws (Fig. 9, Chopra and Paterson, 1981; Hirth and Kohlstedt, 2003). I am not sure to understand this part. of the rheological law by Chopra and Paterson (1981) is used: i) to conclude that the temperature was higher than 600_C or ii) to conclude that the stress was below 250 MPa ?”

The extrapolation of the flow law by Chopra and Paterson (1981) is used to estimate temperatures in the range of 650°C to 800°C at the stresses inferred from recrystallized grain size paleopiezometers (see below) and considering strain rates on the order of 10-13 – 10-15s-1 reasonable for the observed evidence of dislocation creep (Fig. 9). These conditions are accordance with observations from naturally deformed olivine (e.g. Skrotzki et al., 1990; Altenberger, 1995; Jin et al., 1998).

“Page 372 line 24: The recrystallisation grain size paleopiezometers of Van der Wal et al. (1993) for the observed recrystallised grain sizes of 10–50 _m would indicate differential stresses on the order 70–250 MPa. Assuming that an extrapolation of the experimentally derived flow law to relevant strain rates of 10-13 – 10-15s-1 is valid and that the grain size paleopiezometer is applicable, temperature conditions of 650–800_C are thus indicated for dynamic recrystallisation. Other experimental piezometers at different temperatures and for different water contents have been proposed for olivine since Van der Wall study (e.g. Zhang et al, 2000; Jung & Karato, 2001; Jung et al., 2006), can we expect a large variation in stresses with the use of other paleopiezometers?”

Jung et al. (2006) and Zhang et al. (2000) investigate the role of stress, strain and the presence of water on the activation of different glide systems and on the development of different CPO patterns in olivine. Zhang et al. (2000) found smaller recrystallized grain sizes at similar stress levels compared to van der Wall et al. (1993). Jung and Karato (2001) describe how grain boundary migration in olivine is facilitated by the presence of fluids, as well-known e.g. also for quartz (e.g., Drury and Urai, 1990; Mancktelow and Pennacchioni, 2004). Grain-boundary migration after deformation has to be expected to modify recrystallized grain size; as such the given differential stresses have to be considered as minimum values. Yet, our observations rather indicate subgrain rotation recrystallization (dynamic recovery), for which the effect of water was proposed by Jung and Karato (2001) to be less relevant. An experimental calibration on the diameter of recrystallized grains and differential stress, alternative to that by van der Wall (1993) is given by Karato (1980). This paleopiezometer reveals slightly higher differential stress of ca. 300 MPa and 76 MPa for 10 μm and 50 μm grain diameters, respectively. We will discuss this more clearly in the revised text.

5.2 Deformation of serpentinite "P 374 line 3: In monomineralic antigorite aggregates, a characteristic grain size variation with fine-grained antigorite at sites of stress concentrations showing a marked CPO around porphyroclasts and sutured grain boundaries (Fig. 8c, d) point to deformation by dislocation creep. The conclusion of antigorite deformation by dislocation creep is not supported by the presented data. In serpentine minerals a marked CPO (not presented for monomineralic antigorite in this study) do not mean that deformation was controlled by dislocation glide. This is a highly debated subject (Hilairet et al., 2007; Chernak & Hirth, 2010; Auzende et al., 2011). At a high stress-state (laboratory strain-rates), the fine-grained regions formed by grain size reduction in antigorite result mainly by activation of glide along basal planes and kink-band formation. But at tectonic strain-rates, dissolution-precipitation could play a major role (e.g. Andreani et al., 2005; Wassmann et al., 2011). I expect a more substantiated interpretation of microstructures in antigorite with detailed references."

We greatly appreciate this comment and discuss this point more comprehensively in the revised manuscript:

The fine-grained olivine and antigorite aggregates in strain shadows (Fig. 7b, c) around olivine and diopside porphyroclasts indicate that they were precipitated from the pore fluid during deformation. In almost monomineralic antigorite layers with the antigorite cleavage (001) plane parallel to the foliation, fine-grained olivine can be enriched in asymmetric multilayer folds (Fig. 8a, b). This indicates that either olivine crystallized during folding from the pore fluid, possibly on the expense of antigorite, or that olivine was present before folding and was redistributed by dissolution along the phase boundaries to antigorite. The microstructure in the strain shadows as well as the crenulation cleavage indicate that the phase boundaries between antigorite and olivine act as sites of preferred dissolution during deformation by dissolution-precipitation creep (Wassmann et al., 2011). The presence of secondary olivine in fine-grained aggregates together with antigorite as well as pyroxene (fine-grained, no exsolution lamellae) in strain shadows along the minimum shortening direction (x) of the strain-ellipsoid and perpendicular to the maximum shortening direction (z) indicates precipitation of new material from the pore fluid and dissolution-precipitation creep. The observations from this study is in accord with previous studies on naturally deformed antigorite (e.g., Andreani et al., 2005; Auzende et al., 2006; Wassmann et al., 2011) that demonstrate the importance of dissolution-precipitation processes during ductile deformation of antigorite, especially in polyphase aggregates, where phase boundaries between antigorite and olivine act as sites of preferred dissolution. The general importance of phase boundaries as preferred sites of dissolution during dissolution-precipitation creep is evident from many natural rocks (e.g., Groshong, 1988; Knipe, 1989; Tada and Siever, 1989; Schwarz and Stöckhert, 1996; Stöckhert, 2002; Trepmann and Stöckhert, 2009; Trepmann et al., 2010; Wassmann et al., 2011). In polyphase rocks undergoing dissolution-precipitation creep, monomineralic inclusions can deform by crystal-plastic processes as observed for folded quartz veins indicating dislocation creep within metagreywacke deformed by dissolution-precipitation creep (Trepmann and Stöckhert, 2009). The observed characteristic grain size variation with fine-grained monomineralic antigorite aggregates at sites of stress concentrations in additions to a marked CPO deflected around porphyroclasts (Fig. 8c, d) and sutured grain boundaries (Fig. 8e, f) suggest also some contribution of crystal-plastic deformation. Auzende et al. (2006), report on sutured grain boundaries and recrystallization of antigorite from serpentinites of the Erro-Tobbio unit Alps on the scale of high-resolution transmission electron microscopy. Antigorite deformation is controlled by the anisotropy of the crystal structure, with dislocation glide along the antigorite (001) basal plane being a very effective deformation mechanism at low temperature. The von Mises criterion, which states that five independent slip systems are required to accommodate homogenous flow of a polycrystalline material, however, has been proposed to limit the accommodation of strain by dislocation glide of antigorite (Chernak and Hirth, 2010; Hirth and Guillot, 2013). Deformation experiments on antigorite serpentinites by Hilairet et al. (2007) and Chernak and Hirth

(2010) demonstrate the low strength of antigorite during ductile and semi-brittle deformation at high temperature and pressure, respectively. Hilairet et al. (2007) represent a flow law for ductile deformation of antigorite that would indicate differential stresses on the order of 5 MPa assuming a strain rate of 10-14 s-1 and 50 MPa for a strain rate of 10-10 s-1. Chernak and Hirth (2010) report on semi-brittle deformation with contributions of crystal-plastic deformation and their findings likewise show a low strength of antigorite aggregates. However, these experiments have been performed at laboratory strain rates of 10-4 s-1 to 10-6 s-1.

6 Implications

"Page 375 Line 13: The observed secondary olivine and enstatite crystals occurring in strain shadows of diopside and olivine porphyroclasts (Fig. 6) as well as olivine in foliated antigorite aggregates (Fig. 8a, b) are assumed to have formed by these reactions and during deformation by dissolution-precipitation creep during alpine subduction and exhumation. How the authors relate enstatite and olivine in the samples with the dehydration reactions of antigorite?"

The presence of secondary olivine (fine-grained, internally not deformed) and pyroxene (fine-grained, no exsolution lamellae) in strain shadows indicates precipitation of new material from the pore fluid during dissolution-precipitation creep. The observation that olivine and pyroxene in the strain shadows are not crystal-plastically deformed – as opposed to the porphyroclasts - indicates insufficiently high stresses to accumulate significant strain by dislocation creep since precipitation. As such porphyroclasts and matrix minerals represent two successive deformation stages. Dissolution-precipitation creep requires the presence of a free fluid phase. Dehydration reactions of antigorite according to the reactions (1, 2) have been proposed to be recorded by the HP-LT metamorphic mineral assemblage of the Erro-Tobbio serpentinites (e.g., Hoogerduijn Strating and Vissers, 1991; Scambelluri et al., 1991; 2004; Ulmer and Trommsdorff, 1995; Hermann et al., 2000; Healey et al., 2009). These antigorite breakdown reactions can provide a considerable amount of fluid to depth of up to 200 km (Ulmer and Trommsdorff,

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1995, Bromiley and Pawley, 2003, Scambelluri et al., 2004). It is suggested that fluid provided by these reactions also contributed to the recorded dissolution-precipitation processes. Furthermore, in this case the precipitation of olivine and enstatite on the expense of antigorite might even further promote dissolution-precipitation processes due to the enhancement of preferred sites of dissolution, i.e. phase boundaries. We will enhance this discussion accordingly in the revised manuscript to avoid confusion and to strengthen our argumentation.

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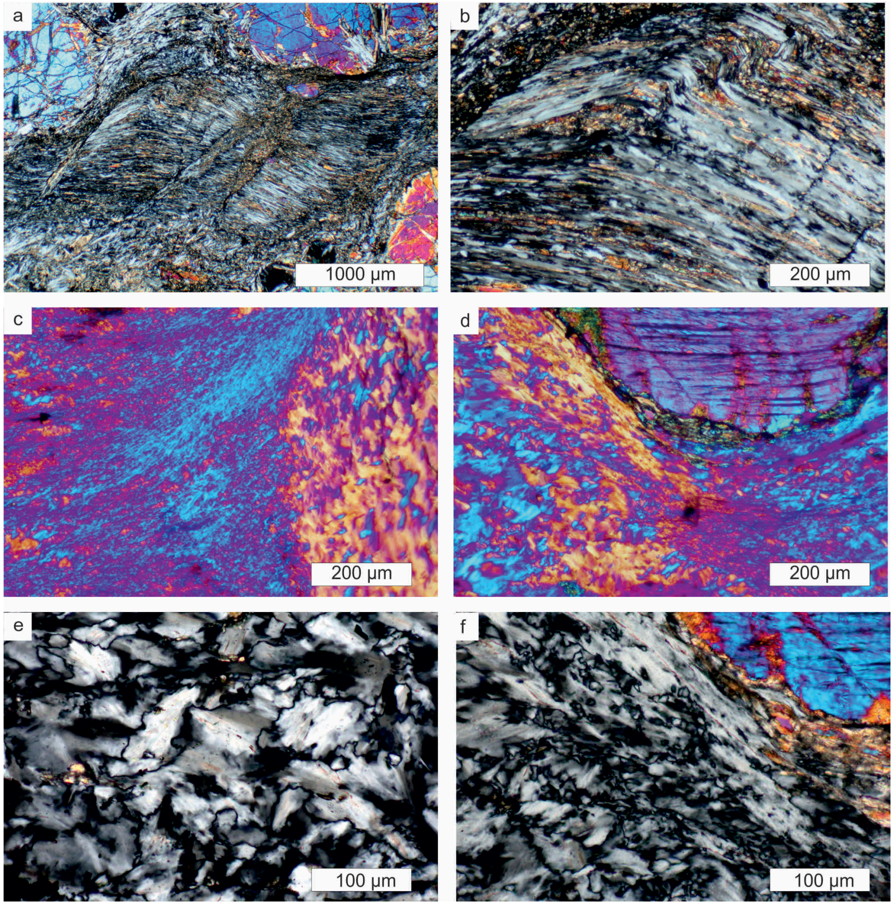

Fig. 1. Fig-08

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