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Small quantity but large effect — How minor phases control strain localization in upper mantle shear zones

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ABSTRACT

Low viscosity domains such as localized shear zones exert an important control on the geodynamics of the uppermost mantle. Grain size reduction and subsequent strain localization related to a switch from dislocation to diffusion creep, is one mechanism to form low viscosity domains. To sustain strain localization, the grain size of mantle minerals needs to be kept small over geological timescales. One way to keep olivine grain sizes small is by pinning of mobile grain boundaries during grain growth by other minerals (second phases). Detailed microstructural studies based on natural samples from three shear zones formed at different geodynamic settings allowed the derivation of the olivine grain-size dependence on the second-phase content. The polymineralic olivine grain-size evolution with increasing strain is similar in the three shear zones. If the second phases are to pin the mobile olivine grain boundary the phases need to be well mixed before grain growth. We suggest that melt–rock and metamorphic reactions are crucial for the initial phase mixing in mantle rocks. With ongoing deformation and increasing strain, grain boundary sliding combined with mass transfer processes and nucleation of grains promotes phase mixing resulting in fine-grained polymineralic mixtures that deform by diffusion creep. Strain localization due to the presence of volumetrically minor minerals in polymineralic mantle rocks is only important at high strain deformation (ultramylonites) at low temperatures (<~800 °C). At smaller strain and stress conditions and/or higher temperatures other parameters like overall energy available to deform a given rock volume, the inheritance of mechanical anisotropies or the presence of water or melts needs to be considered to explain strain localization in the upper mantle.

1. Introduction

Experimental studies on the most important rock forming minerals of the crust and upper mantle such as quartz, feldspar and olivine have led to the formulation of flow laws for monomineralic aggregates that are of fundamental importance for rheological models of the Earth's crust and mantle (e.g. Bai and Kohlstedt, 1992; Bai et al., 1991; Gleason and Tullis, 1995; Hansen et al., 2011; Hirth and Kohlstedt, 1995; Mei and Kohlstedt, 2000a, 2000b; Rybacki and Dresen, 2000). These flow laws show that deformation can occur by various mechanisms, which can be grain size insensitive (dislocation-accommodated creep) or grain size sensitive (diffusion accommodated creep) as described by the constitutive equation:

$$\dot{\varepsilon}= Ad^{-m}\sigma^{n}\exp(-Q/RT) \quad (1)$$

where $\dot{\varepsilon}$ is the strain rate, A is a constant, d is the grain size, m is the grain size exponent, σ is the differential stress, n is the stress exponent, Q is the activation energy, R is the gas constant and T is the temperature.

The most recent development in experimental deformation of olivine shows that dislocation-accommodated grain boundary sliding (disGBS) is an important olivine deformation mechanism at a range of temperature conditions in the dry upper mantle (Hansen et al., 2011). The activity of grain boundary sliding has not yet been observed in olivine deformation experiments at “wet” conditions (Hirth and Kohlstedt, 2003). DisGBS, in contrast to dislocation creep, has a slight grain size dependence (grain size exponent of 0.7 ± 0.1). In addition to dislocations, disclinations (rotational defects) are shown to be an important grain boundary accommodation mechanism during olivine deformation (Cordier et al., 2014).

These flow laws are all based on a monomineralic upper mantle, which is only an approximation of natural systems given the generally polymineralic nature of most upper mantle rocks. It has been shown in experimentally (Farla et al., 2013; Hiraga et al., 2010a; Ji et al., 2001; Mcdonnell et al., 2000; Sundberg and Cooper, 2008; Tasaka et al., 2013) and naturally deformed upper mantle rocks (Linckens et al., 2011b; Skemer et al., 2010; Tasaka et al., 2014; Toy et al., 2010; Warren and Hirth, 2006), as well as in theoretical models (Bercovici

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and Ricard, 2012) that the presence of secondary minerals may lead to substantially different rheological behavior.

When the extrinsic physical conditions are similar (e.g. temperature, stress, strain rate) a pronounced decrease of olivine grain size, by recrystallization or brittle deformation, induces a change from dislocation via disGBS to diffusion creep, resulting in a reduced viscosity of the upper mantle (Hansen et al., 2011; Hirth and Kohlstedt, 2003; Precigout and Gueydan, 2009). This reduction in viscosity due to the activation of diffusion creep is thought to be short lived as olivine grain growth kinetics are fast (Karato, 1989), and grain growth is expected in the diffusion creep field, forcing the grains to grow until becoming stabilized by dynamic recrystallization in the disGBS or dislocation creep field (De Bresser et al., 2001). However, second-phases help to preserve the small grain sizes by inhibiting grain growth (Evans et al., 2001; Herwegh et al. 2011; Hiraga et al., 2010b; Ohuchi and Nakamura, 2007; Olgaard and Evans, 1986) and can induce and maintain a change in the dominant deformation mechanism (Bercovici and Ricard, 2012; Farla et al., 2013; Hiraga et al., 2010b; Linckens et al., 2011b; Skemer et al., 2010). Based on naturally deformed peridotites from two different mantle shear zones, and comparing the results with a previously analyzed mantle shear zone (Linckens et al., 2011b), we determine the effect of second phases on the grain size of olivine, the dominant deformation mechanisms and the resulting strain localization behavior. In addition, we discuss the possible processes that can lead to the mixing of the different phases. The data set allows for a more accurate microstructural and therefore rheological description of mantle shear zones.

2. Geological settings and sample descriptions

In order to quantify the grain size evolution with progressive deformation in mantle shear zones, we studied two different large-scale mantle shear zones (Fig. 1; Othris, Greece; Lanzo, Italy). These results will be compared and discussed with previous results derived from a third shear zone located at Semail, Oman (Fig. 2, Linckens et al., 2011a, 2011b). For easy comparison, the data of the Oman shear zone will be included in the result figures.

The shear zones formed either under a strike-slip (Othris, Semail) or extensional (Lanzo) geodynamic framework. Their microstructures represent different deformation intensities, from relatively undeformed porphyroclastic tectonites to extensively deformed ultramylonites (Fig. 3). The width of the deformation zones decreases with increasing deformation intensity (Figs. 1 and 2, Boudier et al., 1988; Dijkstra et al., 2002b; Kaczmarek and Müntener, 2008; Linckens et al., 2011b).

2.1. Othris

The Othris ophiolite is part of the Hellenic Tethyan ophiolite belt. The ophiolite is thought to have formed near a transform fault at a slow-spreading ridge (Barth, 2003; Dijkstra, 2001) or above an intra-oceanic subduction zone at a mid-oceanic ridge (Barth and Gluhak, 2009; Barth et al., 2008; Rassios and Smith, 2000). It consists mainly of spinel–harzburgites and plagioclase–lherzolites with minor amounts of spinel–lherzolites and dunites (Dijkstra, 2001; Dijkstra et al., 2002b; Menzies and Allen, 1974). The samples analyzed in this study are from a mylonitic harzburgite (Fig. 1), which locally turns into ultramylonites. The mylonite is part of a km-wide N–S trending shear zone (Fig. 1, Dijkstra (2001)). The mylonites consist of monomineralic olivine and polymineralic domains on a thin section scale. Polymineralic domains formed by melt–rock reactions (Dijkstra et al., 2002b), after which solid-state deformation took place. With increasing deformation the fine-grained bands coalesced and are increasingly elongated resulting in continuous bands of fine-grained polymineralic aggregates in the mylonite (Dijkstra et al., 2002b).

2.1.1. Mylonite

The grains in the monomineralic olivine domains are strongly elongated (axial ratio of up to 1:10, see Fig. 4A). They have subgrain boundaries oriented subvertically with respect to the foliation. Some fine-grained (<50 μm) spinels and pyroxenes occur between the olivine grains in these aggregates (Fig. 4A). Porphyroclasts of orthopyroxene (0.4 to

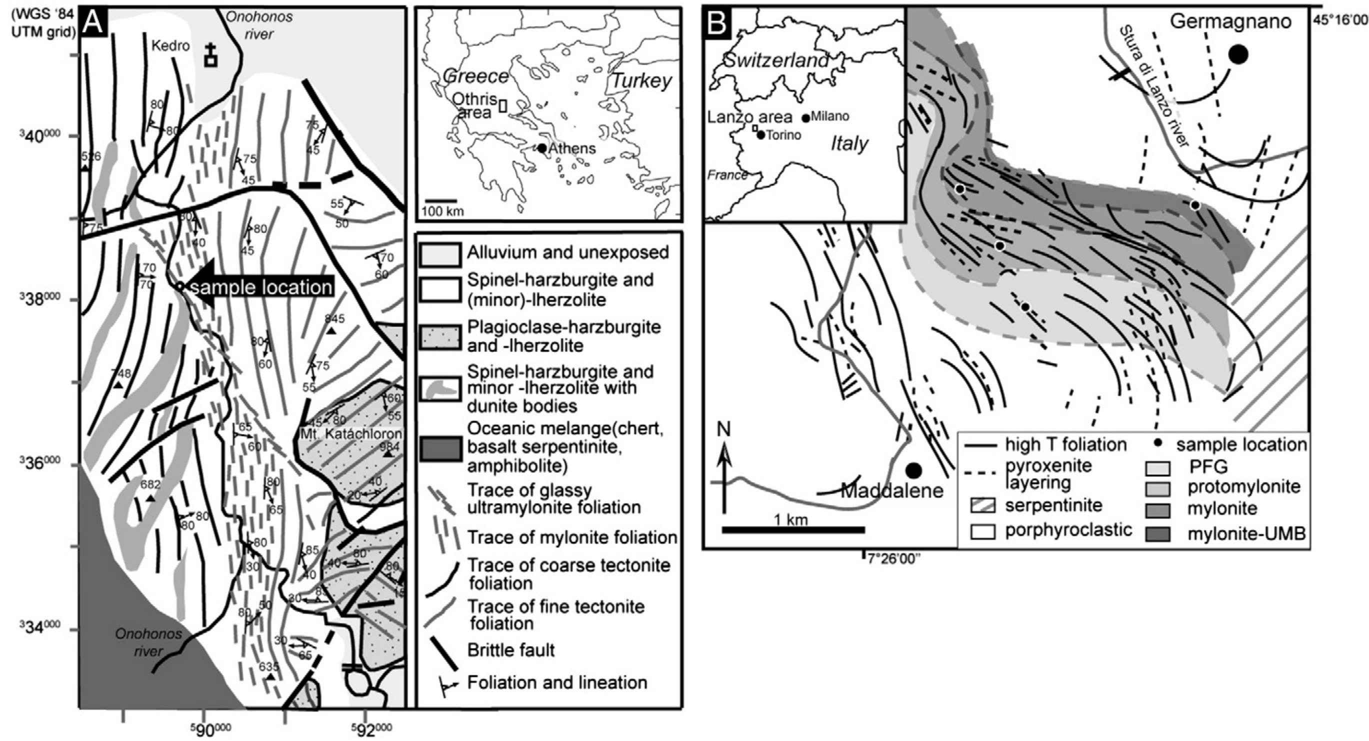

Fig. 1. Geological maps of (A) Othris (Greece) and (B) Lanzo (Italy) with sample locations, after Dijkstra et al. (2002a, 2002b) and Kaczmarek and Müntener (2008), respectively. PFG = porphyroclastic fine-grained texture, UMB = ultramylonitic bands.