Dynamic recrystallization and phase mixing in experimentally deformed peridotite

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ABSTRACT

Ductile shear zones evolve through complex feedbacks between microstructure and rheology. In the mantle, shear zones often display mylonitic or ultramylonitic microstructures, characterized by extensive grain-size reduction and well-mixed polymineralic domains. The feedback between the formation of these microstructures and grain-size sensitive deformation is often considered an important weakening mechanism in high-temperature mantle shear zones. To understand better the processes that transform coarse-grained tectonites into fine-grained and well-mixed mylonites, we have performed triaxial deformation experiments on synthetic peridotite samples comprised of mm-scale olivine and orthopyroxene clasts. Experiments were conducted in a Griggs apparatus at a confining pressure of $\sim$1 GPa, temperatures of 1400 to 1550 K and strain rates of 10^{-5}–10^{-6} s^{-1} under nominally dry conditions. Experiments yield deformed samples with macroscopic natural strains ranging from 0.31 to 0.74. Samples are partially recrystallized, with neoblasts ranging in grain size from 2–25 μm. At these deformation conditions, unrecrystallized mm-sized clasts deform by grain-size insensitive dislocation creep, while recrystallized grains deform by grain-size sensitive dislocation accommodated grain boundary sliding (disGBS). Using electron-backscatter diffraction (EBSD) we investigate the interfaces between recrystallized olivine and orthopyroxene domains. At the majority of these interfaces no mixing is observed. However, many boundaries are serrated, which is interpreted to be the result of surface tension driven phase boundary migration. In a few cases we observe small degrees of mixing, with enclaves of one phase completely surrounded by the other phase. This mixing occurs only within a few recrystallized grain length scales of the interface. These results demonstrate that the serial processes of dynamic recrystallization, phase boundary migration and disGBS deformation are a plausible mechanism for solid-state phase mixing. However, more extensive deformation may be needed to reproduce the near steady-state microstructure observed in highly deformed mantle shear zones.

1. Introduction

The strength and dynamics of the lithosphere, the initiation of subduction, and the generation of Earth-like plate tectonics are all strongly influenced by the ability of the lithosphere to localize deformation (e.g. Bercovici, 2003; Bercovici and Ricard, 2012, 2013; Bürgmann and Dresen, 2008; Carter and Tsenn, 1987; Kirby, 1985; Précigout et al., 2007; Regenauer-Lieb et al., 2001; Tommasi et al., 2009; Vauchez et al., 2012; Vissers et al., 1995; Warren and Hirth, 2006). High temperature ductile shear zones, which are considered manifestations of shear localization, are typically characterized by grain sizes that are significantly smaller than the grain size in the associated host rock (Drury et al., 1991; White et al., 1980). The smaller grain size is generally interpreted

to be the product of dynamic recrystallization, as mechanical work associated with deformation is converted to additional grain boundary area (e.g. Austin and Evans, 2007; Rozel et al., 2011). Grain-size reduction is also often associated with an inferred transition in deformation mechanism, from dislocation creep to diffusion creep or dislocation accommodated grain boundary sliding (disGBS) (Dijkstra et al., 2002; Handy, 1989; Jaroslow et al., 1996; Jin et al., 1998; Linckens et al., 2011; Newman et al., 1999; Précigout et al., 2007; Skemer et al., 2010; Toy et al., 2010; Vissers et al., 1995; Warren and Hirth, 2006).[1]

The activation of grain size sensitive deformation mechanisms is expected to promote rheological weakening (Hansen et al., 2011; Hirth and Kohlstedt, 2003; Rutter and Brodie, 1988; Walker et al., 1990). However, weakening caused by a reduction in grain

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[1] In the present study, we use the term disGBS to denote the phenomenon observed experimentally in olivine by Hirth and Kohlstedt (2003) and Hansen et al. (2011) at conditions intermediate between dislocation creep and diffusion creep.

size is countered by the tendency of grains to coarsen with time (De Bresser et al., 1998). When grain growth kinetics are rapid in comparison to dynamic recrystallization, as is the case for olivine (Karato, 1989), a material's ability to localize deformation is strongly inhibited. However, it is well known that secondary phases inhibit grain growth (Evans et al., 2001; Olgaard and Evans, 1986; Smith, 1948) and the inhibition of grain growth by well-mixed primary and secondary phases may therefore facilitate long-lived weakening in polymineralic shear zones (Farla et al., 2013; Herwegh et al., 2011; Linckens et al., 2011; Michibayashi et al., 2013; Précigout et al., 2007). Indeed, intermixed olivine and pyroxene are commonly observed in peridotite mylonites and ultramylonites (Dijkstra et al., 2002; Linckens et al., 2011; Newman et al., 1999; Skemer et al., 2010; Toy et al., 2010; Warren and Hirth, 2006). However, the processes that lead to phase mixing are not readily inferred from the geologic record. Some authors have speculated that grain boundary sliding (cf. Ashby and Verrall, 1973) may promote phase mixing (Linckens et al., 2011; Warren and Hirth, 2006). Others have argued that mixing occurs through particular metamorphic or melt-rock reactions (Dijkstra et al., 2002; Furusho and Kanagawa, 1999; Kelemen and Dick, 1995; Newman et al., 1999) or by entrainment of adjacent materials (Toy et al., 2010). Recent experimental studies designed to evaluate the development or preservation of phase mixing in fine-grained olivine–pyroxene aggregates show conflicting results: Hiraga et al. (2013) interpret their results as evidence of phase coalescence with progressive strain, while Farla et al. (2013) interpret their results as evidence of phase mixing.

To improve our understanding of phase mixing and the conditions at which it occurs, we performed high pressure, high temperature deformation experiments on synthetic peridotite samples, consisting of coarse-grained (mm-size) olivine and orthopyroxene clasts, embedded in a fine-grained (<10 μm) olivine matrix (Fig. 1). Previous deformation experiments on synthetic olivine–orthopyroxene aggregates started with fine-grained, well-mixed olivine and pyroxene powders (Farla et al., 2013; Hiraga et al., 2010, 2013; Hitchings et al., 1989; Ji et al., 2001; Lawlis, 1998; McDonnell et al., 2000; Sundberg and Cooper, 2008). Due to the small grain size and homogeneity of the starting materials in these studies, recrystallization and phase mixing or phase coalescence are difficult to identify on the basis of microstructure alone. In contrast, the starting materials in our experiments are coarse-grained, with mineral domain length scales that are initially two-three orders of magnitude larger than the recrystallized grain-size. This experimental design has a number of benefits. First, we are able to compare recrystallization processes in olivine and orthopyroxene directly with no complexity introduced by the mutual pinning of the two phases. Second, we are able to make unambiguous observations of the mixing process along initially unmixed mineral domain interfaces.

Our results demonstrate that the processes leading to a well-mixed microstructure are inefficient at the conditions achieved in these experiments. The serial processes of grain-size reduction by dynamic recrystallization, phase mixing, and subsequent deformation by disGBS likely contribute to the long-lived weakness of ductile shear zones, but may not play a major role in the initiation of shear localization.

2. Methods

Triaxial deformation experiments were conducted in a Griggs apparatus at a confining pressure of ~1 GPa, temperatures of 1400 to 1550 K and strain-rates of 10^{-5}–10^{-6} s^{-1} (Table 1). The experimental charges consisted of large (~0.5–2 mm) sub-spherical clasts of olivine and orthopyroxene embedded in fine-grained (<10 μm) matrix of olivine powder (Fig. 1). Starting materials were

Table 1

Experimental parameters. The confining pressure for all experiments is ~1 GPa.

Experiment	Temperature (K)	Strain rate ($\times 10^{-5}$ s^{-1})	Natural strain[1]
WUG_64	1400	3.9	0.48
WUG_67	1400	4.0	0.43
WUG_69	1450	4.0	0.54
WUG_73	1450	4.0	0.58
WUG_18	1500	4.4	0.52
WUG_113	1500	0.6	0.74
WUG_115	1500	0.7	0.64
WUG_76	1500	3.9	0.45
WUG_119	1525	0.4	0.31
WUG_124	1525	0.4	0.48
WUG_121[2]	1550	n/app	0.34

[1] Defined as $-\ln(l_f/l_0)$, where for l_f and l_0 sample length after and before the experiment, respectively, are taken. Includes compaction of the fine-grained olivine matrix.
[2] Experiment aborted upon reaching experimental pressure and temperature conditions, but before starting advancing the deformation piston.

synthesized from one to three mm diameter, inclusion-free olivine (Fo$_{90}$) and orthopyroxene fragments hand-picked from xenoliths of San Carlos peridotite. Smooth-surfaced sub-spherical clasts of both olivine and orthopyroxene were produced by running the rough fragments through a fluid energy mill and selecting clasts with an aspect ratio (i.e. longest axis over shortest axis) smaller than 1.5.

Olivine powder was also synthesized from inclusion-free olivine fragments. These fragments were crushed with an agate mortar and pestle and subsequently ground in a Syalon^{TM} ball mill for several hours in water, until the maximum particle size of the powder was <10 μm. The olivine and orthopyroxene were packed in a nickel capsule in a 60:40 volume ratio. Simultaneously, olivine powder was sequentially added to fill the void space between the clasts. Porosity of the experimental charge prior to experiments is estimated to be ~15%.

Samples were deformed in a Griggs apparatus using a solid-medium assembly with a crushable MgO inner pressure medium and pyrophyllite outer pressure medium. A 2 mm thick disk of barium carbonate was inserted above the experimental charge to reduce deformation during the initial stages of compression and heating. The assembly was stored in a vacuum oven at 363 K for a minimum of 14 hours prior to experiments to remove any water adsorbed on mineral surfaces during synthesis. Experiments were initiated by raising confining pressure to 0.5 GPa. Pressure and temperature were then raised simultaneously to 1 GPa and 1173 K. Finally, temperature was increased to the target temperature for the experiment, while pressure was maintained (Table 1). The temperature was monitored by a Pt/13%Rh thermocouple located at the middle of the sample. Once experimental conditions were attained, the sample was annealed for two to five hours to allow the olivine powder to compact and sinter. Constant strain-rate deformation was imposed by advancing a piston at constant speed. Samples were deformed until the desired axial strain was achieved. Experiments were quenched and thin-sections cut parallel to the shortening axis.

Bulk natural strain (ε_b) for each experiment (Eq. (1)) was calculated from the initial (l_0) and final (l_f) sample length.

$$\varepsilon_b = -\ln\left(\frac{l_f}{l_0}\right) \tag{1}$$

For each pair of adjacent and unlike clasts, the strain of each clast was calculated individually (ε_c). Most clasts are ellipsoidal in shape after deformation, with a minor axis that is subparallel to the macroscopic sample shortening. Dimensions of clasts were determined by the software package ImageJ 1.46r (http://rsbweb.nih.gov/ij/) using digitized cross-polarized photomicrographs. The strain of each clast was calculated from the length