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Temperature dependence of [100](010) and [001](010) dislocation mobility in natural olivine

Lin Wang [a,*], Stephan Blaha [a], Zsanett Pintér [a], Robert Farla [a], Takaaki Kawazoe [a], Nobuyoshi Miyajima [a], Katsuyoshi Michibayashi [b], Tomoo Katsura [a]

[a] *Bayerisches Geoinstitut, University of Bayreuth, 95440 Bayreuth, Germany*
[b] *Institute of Geosciences, Shizuoka University, Shizuoka 422-8529, Japan*

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ABSTRACT

Dislocation recovery experiments were conducted on pre-deformed olivine single crystals at 1450 to 1760 K, room pressure, and oxygen partial pressures near the Ni–NiO buffer to determine the annihilation rates for [100] and [001] dislocations on the (010) plane. Olivine single crystals were first deformed to activate the desired slip systems under simple shear geometry and then annealed at target conditions. The edge and screw dislocations with Burgers vectors, **b**, of [100] and [001], respectively, both elongated in the [001] direction were produced by the deformation. The dislocation annihilation rate constants of both types of dislocations are identical within 0.3 log unit. The activation energies for both dislocations are also identical, i.e., ~400 kJ/mol, which is also identical to that of the Si self-diffusion coefficient. This correspondence suggests that olivine dislocation creep controlled by a diffusion-controlled process under low-stress and high-temperature conditions. This study offers a potential insight into the formation of AG-type fabric in olivine.

1. Introduction

Formation of lattice preferred orientation (LPO) in mantle minerals is a consequence of the dominant slip systems activated by dislocation creep. Dominant slip system changes depending on chemical and physical conditions (Karato, 2008). Therefore, knowledge of conditions of LPO formation is useful to understand the chemical and physical conditions in the Earth's interior. In addition, LPO causes seismic anisotropy, which provides insight into the direction of upper mantle convective flow by combining observations about seismic anisotropy and conditions of formation of LPO in mantle minerals.

A number of seismic studies have shown seismic anisotropy in the upper mantle (Dziewonski and Anderson, 1981; Montagner and Kennett, 1996; Gung et al., 2003; Nettles and Dziewoński, 2008; Visser et al., 2008). These studies showed that the magnitude of seismic anisotropy decreases with depth. For example, the frequently cited one-dimensional global model, PREM (Dziewonski and Anderson, 1981), demonstrated that anisotropy in Vs and Vp gradually diminishes with depth. Montagner and Kennett (1996) suggested that horizontally polarized S-wave velocity (V_{SH}) is faster than vertically polarized S-wave velocity (V_{SV}) at the shallow part (<250 km) of the upper mantle, but this difference decreases with depth. Visser et al. (2008) reported similar results.

Since olivine is the most abundant mineral in the Earth's upper mantle, the LPOs of olivine from natural specimens and experimentally deformed samples have been extensively studied (Karato, 1988; Jung and Karato, 2001; Katayama et al., 2004; Katayama and Karato, 2006; Ohuchi et al., 2011; Jung et al., 2006). An abundance of olivine in peridotite, originating from the deep lithosphere and upper mantle, shows concentrations on the ***a***-axis in the direction of lineation and ***b***-axis in the direction normal to the foliation (e.g., Ben Ismail and Mainprice, 1998; Nicolas et al., 1971; named as A-type fabric after Jung and Karato, 2001). Peridotites from convergent boundaries (e.g., Dobrzhinetskaya et al., 1996; Mizukami et al., 2004; Skemer et al., 2006) show concentrations on the ***c***-axis in the direction of lineation and the ***b***-axis in the direction normal to the foliation (named as B-type fabric after Jung and Karato, 2001). AG-type fabric (Ben Ismail and Mainprice, 1998, categorized by Mainprice, 2007), in which the ***a***- and ***c***-axes show a girdle structure parallel to the foliation with concentration on the ***b***-axis normal to the foliation, were also found in upper mantle samples (Michibayashi and Mainprice, 2004; Hidas et al., 2007; Satsukawa et al., 2011). These natural olivine fabrics have been reproduced in deformation experiments under different chemical and physical conditions (Jung and Karato, 2001;

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* Corresponding author.
E-mail address: lin.wang@uni-bayreuth.de (L. Wang).

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Holtzman et al., 2003; Karato, 2008). A-type fabric forms under high-temperature conditions and B-type fabric forms under low-temperature and/or high-stress conditions (Jung and Karato, 2001; Karato, 2008). AG-type fabric forms with coexistence of melt (Holtzman et al., 2003).

However, we note that olivine LPO fabrics obtained in the laboratory generally formed under higher stresses and many orders of magnitude higher strain rates (Hirth and Kohlstedt, 2003). Competition between dislocation glide and climb and slip system activation under those conditions may not be the same as under low stress, moderate to high temperature conditions in the Earth. Therefore, it is necessary to investigate the origin of these fabrics using a different strategy.

Orowan's equation (Hull and Bacon, 2011) is a simple formula to describe dislocation creep, in which the dislocation creep rate is a product of the Burgers vector, average mobile dislocation density, and average mobile dislocation velocity. Generally, the average mobile dislocation velocity is the product of average dislocation mobility, which is independent of force, and a function of force acting on dislocations per unit length. Therefore, compared with dislocation velocity, dislocation mobility is more representative to express the rheology property of a material. This study focuses on variations in climb mobility in edge dislocation and cross slip mobility in screw dislocations, among different slip systems as function of temperature. Although glide velocity contribute much lager to the total strain, the climb/cross slip velocity is typically much slower than glide velocity. Therefore, dislocation climb/cross slip are the rate limiting process for olivine deformation (Poirier and Vergobbi, 1978) and should control the temperature and pressure dependence of strain rate. Thus, whether temperature and pressure can cause fabric transition is determined by the temperature and pressure dependences of climb/cross slip in different slip systems. Since climb and cross slip are controlled by thermal activated processes, we investigate the temperature dependence of them in two different slip systems. Hereafter, we use dislocation mobility to refer dislocation climb/cross slip mobility and use dislocation motion to refer climb in edge dislocation and cross slip in screw dislocation.

Dislocation recovery is one experimental technique to estimate dislocation mobility. In this technique, a sample containing a certain dislocation density is annealed under hydrostatic conditions, causing a reduction in dislocation density due to annihilation. The rate constant of dislocation annihilation should be proportional to the dislocation mobility. The primary advantage of this technique is that no external stresses, which are many orders of magnitude higher in deformation experiments than in natural conditions, are applied. Hence, the physical environment in annealing experiments is more representative of the mantle than those in the deformation experiments. Another advantage of this method is that it allows much wider physical and chemical conditions than the deformation experiments, making it possible, for example, to precisely determine temperature dependence. Strictly speaking, the dislocation annihilation rate is not identical to the dislocation velocity in dislocation creep, because the driving force of dislocation annihilation is the internal stress field created by dislocations themselves, whereas the dislocation motion in dislocation creep is driven by external stresses. However, we assume that the temperature derivatives over their absolute values are identical between the dislocation motions by annihilation and the creep. In other words, the activation energies are identical for these two cases.

The A-, B-, and AG-type fabrics are the most common fabrics in nature and should be produced by the [100](010) slip system, which is called ***a***-slip in this study, and/or the [001](010) slip system, which is called ***c***-slip in this study. Therefore, we conducted dislocation recovery experiments on oriented single crystal olivine deformed producing ***a***- and ***c***-slips at ambient pressure and temperatures of 1455 to 1763 K. The experimental results obtained in this study provide information on the temperature dependence of dislocation mobility for the most important olivine slip systems. They also offer insights into the nature of dislocation motion under low-stress conditions. Although there are many studies on dislocation recovery of olivine at high temperatures and pressures (Goetze and Kohlstedt, 1973; Kohlstedt et al., 1980; Karato and Ogawa, 1982; Karato et al., 1993; Farla et al., 2011), there is currently no study to compare dislocation annihilation rates and their temperature dependences between ***a***- and ***c***-slip systems. Therefore, this study provides unique data to investigate dislocation processes in the upper mantle rheology.

2. Experimental procedure

2.1. Sample preparation

The samples used in this study are single crystals of natural olivine from Pakistan. The same olivine has been describe by Gose et al. (2010) and the major and trace element, including water content, of the olivine has been reported there. The b-axis orientation of each crystal was determined using a Huber single-crystal diffractometer operated by SINGLE2014 (Angel and Finger, 2011). The oriented olivine crystals were mounted in epoxy resin with the (010) plane exposed to the surface and then polished using diamond powder with a grain size of 0.25 μm. The [100] and [001] directions were determined via electron backscattered diffraction (EBSD) in the scanning electron microscope (SEM). Cubes with 1.5 mm edge length were shaped from the oriented crystal along its crystallographic planes. The orientations of the crystals were checked again by EBSD after shaping the crystals. For the next step, inclusion- and crack-free cubes were handpicked under an optical microscope.

2.2. Production of high dislocation densities

High dislocation densities with dislocations of either [100] or [001] Burgers vector on the (010) plane were produced by experimental deformation in a Kawai-type multi-anvil apparatus at a pressure of 3 GPa and a temperature of 1600 K. Fig. 1 shows the experimental setup. A cubic hole was made at the center of an MgO slice to accommodate the cubic olivine crystal in a unique orientation. The MgO slice with the olivine crystal was sandwiched between two crushable alumina pistons, cut at an angle of 45° for simple shear deformation of the olivine single crystal. The shear geometry was in the [100] or [001] direction on the (010) plane for producing dislocations from the ***a***- or ***c***-slips, respectively. The sample and pistons were placed in a Pt tube, and another two columns of crushable alumina were placed on both ends of the inner crushable alumina pistons. Tungsten carbide anvils with 17 mm truncated edge lengths were used to generate high pressure together with a Cr_2O_3-doped MgO octahedron with a 25 mm edge length as a pressure medium. The furnace comprises a stepped cylindrical graphite heater and a ZrO_2 thermal insulator. Sample pressures were estimated from the hydraulic oil pressure based on calibrations using the phase transitions of Bi and Mg_2SiO_4 polymorphs. Temperatures were measured using a W97%Re3%–W75%Re25% thermocouple whose junction was located near the end of one of the alumina pistons.

The cell assembly was first pressurized to 3 GPa using a press load of 3.7 MN at ambient temperature for 2 h. The temperature was then increased to 1600 K for 15 min. The target temperature and press load were kept constant for 15 min to sinter the crushable alumina. The sample was then further compressed to a press load of 3.9 MN for 15 min to deform the sample. After deformation, the sample was quenched by switching off the heating power, and then decompressed to ambient pressure for more than 16 h.