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High pressure and temperature fabric transitions in olivine and variations in upper mantle seismic anisotropy

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ABSTRACT

The effects of pressure on crystallographic preferred orientation (CPO) of olivine aggregates were investigated through simple-shear deformation experiments at pressures between 2.1 and 7.6 GPa and temperatures of 1493–1673 K under dry conditions using a deformation-DIA apparatus, and the variations in seismic anisotropy were evaluated under the Earth's upper mantle conditions. We found that the monotonic decrease in seismic anisotropy with depth is caused by the pressure-dependency of the seismic properties of A-type (developed by the (010)[100] slip system) olivine fabric, while the rapid decrease is caused by the fabric transition from A-type to B/C-type (by the (hk0)[001] slip systems) at 7.6 GPa and 1673 K. Moreover, an alternative transition, from A-type fabric to B-type-like fabric (by the (010)[001] slip system), occurs at 7.6 GPa and lower temperature. These two temperature-dependent fabric transitions occurring at 7.6 GPa result in low seismic anisotropy with V_{SH}/V_{SV} (the ratio of horizontally and vertically polarized shear waves) > 1 at low temperatures (i.e., old-continental mantle conditions) and V_{SH}/V_{SV}<1 at high temperatures (i.e., oceanic mantle conditions) at greater depths, consistent with seismological observations. Thus, the variations of CPO with pressure and temperature in olivine under dry conditions can explain the seismic anisotropy signatures observed in the upper mantle, without invoking other mechanisms.

1. Introduction

Crystallographic preferred orientation (CPO) of olivine, which is developed by dislocation creep, controls the seismic anisotropy in the upper mantle. It has been reported that strong seismic anisotropy observed in the oceanic lithosphere decreases monotonically with depth, and it rapidly decreases below 200 km depth (Gung et al., 2003; Montagner, 1998; Montagner and Kennett, 1996). The low seismic anisotropy in the deep upper mantle has been attributed to the transition from dislocation to diffusion creep (Karato, 1992) or the development of an olivine CPO with low seismic anisotropy (Courvy et al., 2004; Mainprice et al., 2005). It has recently been reported that the easiest slip system in olivine changes depending on pressure (Raterron et al., 2007, 2009), suggesting a pressure-induced transition of CPO type in olivine. However, the effect of pressure on the CPO patterns of olivine has been controversial: Simple-shear deformation experiments on olivine aggregates at 11 GPa and 1673 K using stress-relaxation techniques show that C-type fabric (developed by the (100)[001] slip system) can be developed in the deep upper mantle (Courvy et al., 2004). However, these experiments were conducted under wet conditions (289–2248 ppm H/Si of water in olivine) (Courvy et al., 2004), and some authors pointed out that the development of C-type fabric is due to the water effect (Jung et al., 2009; Karato et al., 2008). More recently, a series of simple-shear deformation experiments reported a pressure-induced fabric transition in olivine from A-type (developed by the (010)[100] slip system) to B-type (developed by the (010)[001] slip system) at 3 GPa under dry conditions (Jung et al., 2009), while deformation experiments on orientated single crystals of olivine showed a change of the dominant slip direction from **b** = [100] to [001] at higher pressures (5–7 GPa) under dry conditions (Raterron et al., 2007, 2009).

Some petrological observations support the possibility of a fabric transition from A-type to B-type at high pressures (>5 GPa): A-type olivine fabric is dominant in the shallow upper mantle (<150 km) (Skemer and Karato, 2008; Vauchez et al., 2005), while B-type fabric is found in a garnet peridotite, which experienced high-*P* and low-*T* metamorphism (up to 7 GPa and 1023–1223 K) in a dry continental mantle (Sulu Terrane, China) (Xu et al., 2006). It has been reported that samples from garnet peridotite terranes (Alpe Arami, Switzerland), which carry evidence of very high pressure (10–13 GPa), show C-type-like fabric (Buiskool Toxopeus, 1976, 1977; Dobrzhinetskaya et al., 1996; Möckel, 1969). In contrast, the deformation microstructure of one of the ultradeep (>300 km) peridotites shows a relatively strong A-type olivine fabric (reported by Jin (1995); see also a review by Karato et al.

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(2008)), implying no pressure-induced fabric transitions in olivine. Moreover, apparently "dry" natural olivine-rich rocks can show wet fabrics (e.g., B- and C-types) because of water loss due to diffusion after the development of olivine fabrics (Karato, 2008; Katayama et al., 2005). The influence of pressure on olivine fabrics has not been fully explored in experimental studies or in petrological observations, and thus further extensive studies are needed to clarify the effects of pressure and temperature on the CPO of olivine under deep upper mantle conditions.

2. Experimental procedure

The starting materials for olivine aggregates were prepared from a sample of San Carlos olivine (Fo_{90}). Inclusion-free crystals of olivine were carefully selected and crushed using an agate mortar. The dried fine-grained powders of olivine were placed into a nickel capsule and were sintered at 2.0 GPa and 1373 K for 1.5 h using a Kawai-type multi-anvil high-pressure apparatus (Orange 3000) at Ehime University. The average grain size of the hot-pressed samples was 34 μm. The hot-pressed samples were core-drilled with a diameter of 1.5 mm, and then sectioned to have a thickness between 200 and 250 μm.

Simple-shear deformation experiments on olivine aggregates were conducted at pressures $P=2.1$–7.6 GPa, temperatures $T=1493$–1673 K, and shear strain rates of 1.5–$7.5\times10^{-5}\ s^{-1}$ using a deformation-DIA apparatus with the MA-6-6 system (Nishiyama et al., 2008; Ohuchi et al., 2010). The experimental procedures for the shear deformation experiments are based on Ohuchi et al. (2010). A semi-sintered cobalt-doped magnesia (Mg, Co)O cube with edge length of 7 mm was used as the pressure medium. A sectioned sample of olivine aggregates was placed into a platinum capsule and then sandwiched between two alumina or tungsten pistons (Table 1). The alumina pistons were coated with platinum (thickness of a few hundred nanometers) to avoid chemical reaction between alumina pistons and olivine samples. The platinum capsule was surrounded by a hexagonal boron nitride (hBN) or MgO sleeve. Temperature was monitored by a $W_{97}Re_3$–$W_{75}Re_{25}$ thermocouple placed along one of the diagonal directions of the cubic (Mg, Co)O pressure media. The temperature gradient between the central part and the edge of the sample was less than 50 K at ≤1673 K (Ohuchi et al., 2010). The difference in temperature between the hot junction of the thermocouple and the central part of the sample was in the range of 80–100 K at 1493–1673 K. Temperatures at the center of the samples were estimated from the temperatures monitored by a thermocouple. After the temperature reached the desired value, the sample was annealed for 1 h. Then the upper and lower anvils were advanced at a constant rate by operating the deformation rams. Shear strain was measured by the rotation of a nickel (used for experiments at 1493 K) or platinum (for experiments at 1673 K) strain-marker, which was initially placed perpendicularly to the shear direction. Strain rate was calculated under the assumption that the strain-maker rotated at a constant rate during the deformation experiment. The uncertainty in the strain rate, which resulted from the shape of the strain-marker, was within 15%. Shear strains of 0.7–1.3 were achieved in most of the experiments. The differential stress is in the range of 191–457 MPa, which is comparable to the previous experimental studies conducted at ≤2 GPa (Jung and Karato, 2001; Jung et al., 2009; Katayama et al., 2005; Zhang and Karato, 1995). The generated pressure was estimated from the relationship between the sample pressure and the press load for the cell assembly reported by Ohuchi et al. (2010). The uncertainty in pressure was ±0.4 GPa (Ohuchi et al., 2010).

We used the dislocation density of olivine to infer the stress magnitude using an SEM technique where the total length of the dislocation lines per unit volume is measured (Karato and Lee, 1999). The dislocation density was measured in each olivine polycrystalline sample after oxidation at 1173 K for 1 h. The oxidized dislocations were observed by the back-scattered electron (BSE) images using an FE-SEM (JEOL JSM-7000F). The detailed processes of the dislocation density measurements are shown in Ohuchi et al. (in press). The uncertainties of the stress estimation are about ±10–15% from the calibrations and the heterogeneity of the dislocations in a sample. We measured dislocation densities from 20 to 30 grains and averaged them. The relationship between applied stress and dislocation density can be described empirically as follows:

$$\rho=\beta\cdot\sigma^{m} \tag{1}$$

where ρ is density of free dislocations; β, and m, constants; and σ, axial differential stress ($=\sigma_1-\sigma_3$) (Kohlstedt et al., 1976). Substituting the obtained values of ρ and the reported values of the constants ($\log_{10}\beta=9.21\pm0.16$ and $m=1.39\pm0.07$ in the case of σ in MPa and ρ in m^{-2}: (Ohuchi et al., in press)) into Eq. (1), we calculated the values of σ.

The recovered samples were cut with a low-speed saw. These were then impregnated with epoxy under a vacuum and polished using 1.0 μm alumina powder followed by 0.06 μm colloidal silica suspension. The BSE images of the deformed samples were observed with an FE-SEM. The CPO of olivine grains was evaluated by the indexation of the electron backscattered diffraction (EBSD) patterns using a JEOL JSM-7000F at Ehime University. EBSD patterns were generated via the interaction of a vertical incident electron beam with a polished sample inclined at 70° with respect to horizontal. The samples were coated with carbon to prevent charging in the CPO measurements. The EBSD patterns were indexed using the CHANNEL5 software from HKL Technology. The EBSD pattern of each forsterite grain was obtained at

Table 1
Experimental conditions and results.

Run no.	P (GPa) [a]	T (K) [b]	Fabric type	Shear strain (γ)	Shear strain rate (s^{-1})	Dislocation density ($10^{12}\ m^{-2}$)	Stress (σ_1–σ_3) (MPa) [c]	Mean grain size (μm)	Water content C_{OH} (ppm H/Si) [d]	Piston material
M0175	2.1	1493	A	1.2 (±0.2)	2.9 (±0.4)×10^{-5}	2.54 (±0.38)	208 (±23)	4.9	<40	Alumina
M0152	3.0	1493	A	1.2 (±0.2)	5.0 (±0.7)×10^{-5}	4.19 (±0.63)	304 (±32)	5.3	<40	Tungsten
M0147	5.2	1493	A	1.2 (±0.2)	7.5 (±1.1)×10^{-5}	6.29 (±0.94)	425 (±47)	6.0	46 (±13)	Tungsten
M0181	5.2	1673	A	1.3 (±0.2)	3.1 (±0.5)×10^{-5}	2.05 (±0.31)	191 (±21)	6.4	107 (±35)	Alumina
M0183	7.6	1493	B′	0.2 (±0.05)	1.5 (±0.2)×10^{-5}	4.70 (±0.71)	362 (±40)	9.9	<40	Alumina
M0203	7.6	1493	B′	0.7 (±0.1)	2.0 (±0.3)×10^{-5}	6.53 (±0.98)	457 (±50)	5.4	<40	Alumina
M0178	7.6	1673	B/C	0.8 (±0.1)	3.4 (±0.5)×10^{-5}	2.78 (±0.42)	248 (±27)	5.4	<40	Alumina

[a] Uncertainty in pressure was 0.4 GPa (estimated based on the relationship between the sample pressure and the press load: Ohuchi et al. (2010)).
[b] Temperature at the center of the sample.
[c] Estimated values of the axial differential stress using the dislocation density piezometer.
[d] Water content in the recovered samples. Water contents were measured by the unpolarized infrared absorption spectra of the polycrystalline samples on the basis of Paterson (1982).