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Lattice-preferred orientation of olivine found in diamond-bearing garnet peridotites in Finsch, South Africa and implications for seismic anisotropy

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ABSTRACT

Seismic anisotropy in the upper mantle provides important constraints on mantle dynamics, continental evolution and global tectonics and is believed to be produced by the flow-induced lattice-preferred orientation (LPO) of olivine. Recent experimental studies at high pressure and temperature have suggested that the LPO of olivine is affected by pressure in addition to water and stress. However, there has been no report yet for the pressure-induced LPO of natural olivine because samples from the deep upper mantle are rare and often unsuitable for study due to ambiguous foliation and lineation. Here we show evidence of the pressure-induced LPO of natural olivine in diamond-bearing garnet peridotites from Finsch, South Africa. We found that the [010] axes of olivine are aligned subnormal to foliation and that the [001] axes are aligned subparallel to lineation, which is known as B-type LPO of olivine. The equilibrium pressure of the samples, as estimated using geobarometer, was greater than 4 GPa, indicating that the samples originated from a depth greater than ~120 km. In addition, FTIR spectroscopy of the olivine showed that the samples are dry, with a water content of less than 90 ± 20 ppm H/Si (5.5 ± 1.2 ppm wt. H_2O). These data suggest that the samples are the first natural examples of olivine displaying B-type LPOs produced due to high pressure under dry condition. Our data indicate that the trench-parallel seismic anisotropy observed in many subduction zones in and below subducting slabs at depths greater than ~90 km under dry condition may be attributed to the pressure-induced olivine fabrics (B-type LPO) and may be interpreted as the entrainment of the sub-lithospheric mantle in the direction of subduction rather than anomalous trench-parallel flow.

1. Introduction

Seismic anisotropy is a powerful tool for understanding the global tectonics of the upper mantle in the Earth (Becker et al., 2012; Fouch et al., 2000; Long, 2013; Long and Silver, 2008; Silver, 1996; Song and Kawakatsu, 2012) and has been observed in many subduction zones worldwide (Long, 2013; Park and Levin, 2002; Russo and Silver, 1994; Savage, 1999; Wang and Zhao, 2013). Trench-parallel seismic anisotropy has been observed in the mantle wedge above subducting slabs (Long, 2013; Long and Silver, 2008; Smith et al., 2001), as well as below subducting slabs at a deeper portion of the upper mantle (Long and Silver, 2008, 2009; Russo and Silver, 1994; Tian and Zhao, 2012). Proposed mechanisms for the source of this trench-parallel seismic anisotropy include water-induced B-type LPO of olivine in the mantle wedge (Jung, 2009; Jung and Karato, 2001a; Karato et al., 2008; Katayama and Karato, 2006; Kneller et al., 2008; Mizukami et al., 2004), LPO of serpentine in serpentinite altered from peridotite (Ji et al., 2013; Jung, 2011; Katayama et al., 2009; Soda and Wenk, 2014; Watanabe et al., 2011), trench-parallel mantle flow due to slab roll back (Long and Silver, 2008, 2009; Russo and Silver, 1994), rapid toroidal flow around slab edge (Jadamec and Billen, 2010), pressure-induced B-type LPO of olivine due to slip transition at high pressure greater than $P = 3$ GPa (Jung et al., 2009; Ohuchi et al., 2011; Raterron et al., 2011), aligned faults by hydration in subducting oceanic plate (Faccenda et al., 2008) and an effective orthorhombic symmetry for the oceanic asthenosphere, which is translated to the depth beneath the subducting slab (Song and Kawakatsu, 2012). However, the origin of seismic anisotropy remains poorly understood.

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Because olivine is the dominant mineral in the upper mantle and is elastically anisotropic (Abramson et al., 1997; Kumazawa and Anderson, 1969), seismic anisotropy may be attributable to the LPO of olivine (Ben Ismail and Mainprice, 1998; Long and Silver, 2008; Mainprice, 2007; Nicolas and Christensen, 1987). Previous studies have shown that the LPO of olivine is affected by the physical and chemical conditions of deformation, including water, stress, and temperature (Jung and Karato, 2001a; Jung et al., 2006; Karato et al., 2008; Katayama and Karato, 2006). Various types of LPOs have been observed in olivine depending on water content (C_{OH}) and stress at pressures less than 2.3 GPa (Jung et al., 2006). Both A- and D-type LPOs were found under dry conditions (C_{OH} < 200 ppm H/Si), while B- C-, and E-type LPOs were found under wet conditions. Among these LPOs, the B-type is particularly important to understand the trench-parallel seismic anisotropy of the mantle wedge, and it is characterized by the alignment of the [001] axes subparallel to the shear direction and of the [010] axes subnormal to the shear plane. Additionally, recent high pressure experiments on olivine aggregates under dry conditions have revealed that a change in the LPO of olivine from A-type to B-type is induced by high pressure greater than $P = 3$ GPa (Jung et al., 2009) and $P = 5$ GPa (Ohuchi et al., 2011). Although numerous studies have been conducted on the LPO of natural olivine at shallow depths ($P \leq 2$ GPa) (Jung, 2009; Jung et al., 2014; Kim and Jung, 2014; Mizukami et al., 2004; Palasse et al., 2012; Park et al., in press; Park and Jung, 2014; Skemer et al., 2010; Tasaka et al., 2008; Tommasi et al., 2008; Warren et al., 2008), studies on the LPO of olivine from the deep upper mantle ($P > 3$ GPa) have been very limited (Baptiste et al., 2012; Skemer and Karato, 2008; Wang et al., 2013a; Xu et al., 2006). In the present study, we demonstrate that pressure-induced B-type LPO of olivine does occur at high pressure in natural rocks, a finding with significant implications for seismic anisotropy and global tectonics.

2. Sample descriptions

We studied garnet peridotites from Finsch, South Africa, which is located at the western margin of the Kimberley block (Fig. 1) (Gibson et al., 2008). The garnet peridotites displayed a porphyroclastic texture and are strongly foliated (Fig. 2a), with a composition of primarily olivine with minor amounts of elongated enstatite and garnet (Table 1, Fig. 2a). Samples showed compositional layering of olivine-rich and orthopyroxene-rich layer. The thickness of olivine-rich and orthopyroxene-rich layer was ~10–32 mm and ~6–21 mm, respectively. Olivine-rich layer consists of olivine ~70–90 % while orthopyroxene-rich layer consists of orthopyroxene ~40–60 %. The foliation of the rock specimens was determined by the compositional layering of orthopyroxene and olivine with the variable ratios. Lineation(X) was determined by the shape preferred orientation of all grains on foliation (Panozzo, 1984). Thin sections were made in 3 orthogonal planes (XZ, XY, and YZ) where Z is the direction normal to foliation and Y is the direction normal to both X and Z, and the grain aspect ratios in these 3 planes were determined and shown in Table 1. The aspect ratio of all grains in the XZ plane was the largest. The aspect ratios of olivine and orthopyroxene were also determined separately in specimens and are shown in Table 2. It is found in general that orthopyroxene has bigger aspect ratio than olivine.

3. Methods

3.1. Determination of the LPO of olivine and calculation of seismic anisotropy

The samples were cut parallel to their lineation and perpendicular to their foliation for the microstructure analysis. The LPO of olivine was measured by electron back-scattered diffraction (EBSD; using the HKL system with Channel 5 software) at an accelerating voltage of 20 kV and a working distance of 15 mm using the scanning electron microscope JSM6308 of the School of Earth and Environmental Sciences (SEES) at Seoul National University (SNU), Korea. The EBSD pattern was indexed manually at each grain to obtain an accurate solution. We measured the LPO of ~230–700 grains of olivine for each sample. The misorientation index (M-index) (Skemer et al., 2005) was calculated to estimate the fabric strength of the sample using the uncorrelated grain pairs determined from the EBSD data. The seismic velocity and seismic anisotropy were calculated from the orientation data for olivine

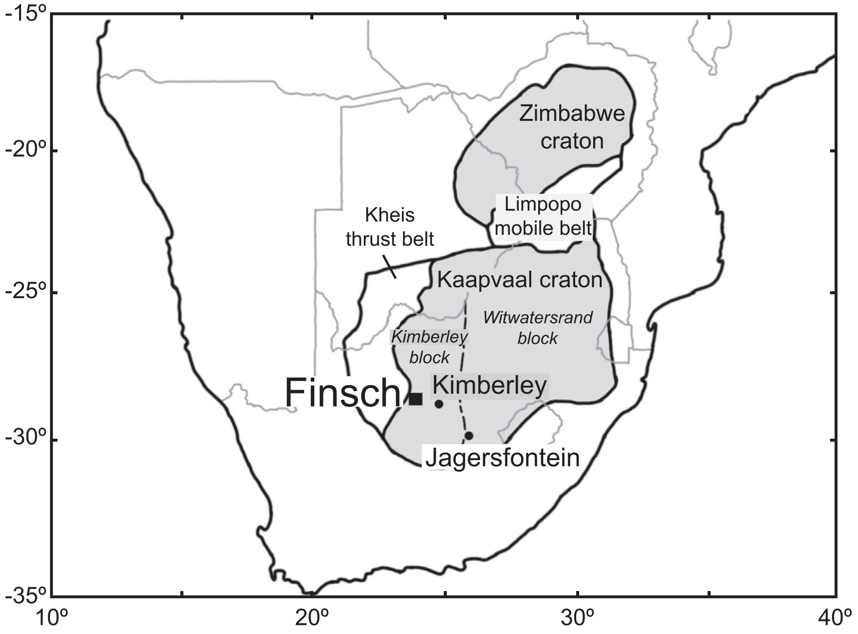

Fig. 1. Geologic map of the study area, Finsch in South Africa. Modified after Gibson et al. (2008).