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Development of A-type olivine fabric in water-rich deep upper mantle

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ABSTRACT

Water controls the activity of slip systems in olivine resulting in various types of olivine crystallographic preferred orientation (i.e., fabric) in mantle rocks. The A-type olivine fabric is the most commonly observed olivine fabric in natural peridotites. Development of A-type olivine fabric (developed by the (010)[100] slip system) is known to be limited to the water-poor conditions of the shallow upper mantle (<200 km depth). We have performed simple-shear deformation experiments of olivine at 7.2–11.1 GPa and 1400–1770 K. Here we show that A-type olivine fabric was developed under water-rich conditions (>2130 ppm H/Si in olivine), while B-type fabric (by the (010)[001] slip system) was observed under moderately wet conditions (750–2130 ppm H/Si). Developments of C-type (by the (100)[001] slip system) fabric was limited to water-poor conditions (<220 ppm H/Si). We found that monotonic decrease in the seismic anisotropy V_{SH}/V_{SV} (the ratio of horizontally and vertically polarized shear waves) with depth in the global one-dimensional models is well explained by the olivine fabrics developed in the horizontal flow of a water-poor mantle. Only A-type olivine fabric can explain the vertical mantle flow which associates the seismic anisotropy of $V_{SH}/V_{SV}<1$ in the deep upper mantle (>200 km depth). A strong anomaly of $V_{SH}/V_{SV}<1$ observed in the deep upper mantle beneath the East Pacific Rise is well explained by the distribution of water-rich regions (in which A-type olivine fabric is dominantly developed) in the deep upper mantle and upwelling mantle flows.

1. Introduction

The characteristics of the seismic anisotropy, such as the direction of shear wave splitting and the V_{SH}/V_{SV} (i.e., ratio of horizontally polarized shear waves and vertically polarized shear waves), vary depending on the types of crystallographic preferred orientation (CPO) of olivine (Jung and Karato, 2001; Katayama et al., 2004). Therefore, the pattern of the seismic anisotropy has been interpreted by taking into account the water-induced olivine fabric transitions in recent studies (Kneller et al., 2005; Ohuchi et al., 2012). It has been reported that the developments of the A-type fabric, which is the most commonly observed olivine fabric in natural peridotites (Ismail and Mainprice, 1998), is limited to water-poor conditions and various types of olivine fabrics such as the B-type, C-type, and E-type (developed by the (001)[100] slip system) are formed under wet conditions (at 0.5–2 GPa) (Jung and Karato, 2001; Katayama et al., 2004). In fact, some peridotite samples from convergent boundaries and collision zones show B-, C-, or E-type fabrics (Frese et al., 2003; Mizukami et al., 2004; Sawaguchi, 2004). Olivine fabric transitions are controlled not only by water but also by pressure. Recent experiments demonstrated that B-type, C-type or the intermediate B/C-type is predominant under the conditions of the water-poor (or nominally water-poor) deep-upper mantle (>200 km depth) (Couvy et al., 2004; Ohuchi et al., 2011). However, the effect of water on olivine fabrics at high pressures (i.e., deep upper mantle conditions) has not been fully explored. Simple-shear deformation experiments on olivine aggregates at 11 GPa and 1673 K using stress-relaxation techniques showed that C-type-like (or B-type-like) fabric was predominant under wet conditions (289–2248 ppm H/Si in olivine) (Couvy et al., 2004). However, total strain is limited to small values ($\gamma \sim 0.3$) in Couvy et al. (2004) and the exact values of stress at which much of CPO develops are unknown in stress-relaxation tests (Karato et al., 2008).

Olivine fabrics are important not only for the interpretation of seismic anisotropy but also for reading the history of water contents from natural mantle samples (Katayama et al., 2005). Water content in the Earth's interior can be estimated from olivine fabrics because it is difficult to modify the CPO by subsequent annealing (Heilbronner and Tullis, 2002), and thus CPO may record deformation conditions. Therefore, type of olivine CPO would be a usable tool for evaluating the water content in the place where the deformation of olivine proceeded. It has been reported that the water content of olivine in upper-mantle xenoliths is in the range of ~ 0 and 2300 ppm H/Si (Ingrin and Skogby, 2000). However, it is not clear if the measured water contents reflect "in situ" values in Earth's interior because water

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can be lost or added easily during transport of rocks to the surface (Katayama et al., 2005). The water content in the typical MORB source, which is estimated from a petrological approach, is reported to be between 800 and 3200 ppm H/Si (Dixon et al., 2002; Hirschmann, 2006; Hirth and Kohlstedt, 1996). Geophysically observed electrical conductivity data are important in estimating the "in situ" water content in Earth's interior, and water content in the typical oceanic asthenosphere is estimated to be 1500 ppm H/Si (Karato, 2011; Wang et al., 2006). Heterogeneous water distribution in the upper mantle ranging from ~0 to 10,000 ppm H/Si has been reported from electrical conductivity observations (Karato, 2011; Lizarralde et al., 1995; Yoshino et al., 2006).

Recently, we have developed experimental techniques for simple-shear deformation experiments under wet conditions using a D-DIA apparatus (Ohuchi et al., 2010). In this study, we demonstrate that a new type of water-induced fabric transition takes place under deep upper mantle conditions. From the viewpoints of the seismological properties of olivine fabrics, we discuss the directions of mantle flows and water distribution in the Earth's upper mantle.

2. Experimental procedure

2.1. Starting materials

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 apparatus at Ehime University. The entire cell assembly, which was stored at 383 K for ~12 h in a vacuum oven, was used for the synthesis of an olivine aggregate (OT733). The entire cell assembly for the synthesis of another olivine aggregate (OT786) was not stored in a vacuum oven before the sintering experiment. The average grain sizes of the hot-pressed samples were 34 μm (OT733) and 63 μm (OT786). The hot-pressed samples were core-drilled with a diameter of 1.2 or 1.5 mm, and then sectioned to have a thickness between 200–250 μm. In order to remove water dissolved in the OT786 sample, some sectioned parts of the OT786 sample (OT786F) was fired at 0.1 MPa and 1170 K under reducing conditions ($\log f_{O_2} \sim -16$ bars) for 6 h.

2.2. Deformation experiments

Simple-shear deformation experiments on olivine aggregates at pressures P=7.2–11.1 GPa, temperatures T=1400–1770 K, and shear strain rates of $(1.1–6.7)\times10^{-5}\ s^{-1}$ were performed using a deformation-DIA apparatus installed at SPring-8. The experimental procedures for the deformation experiments are based on Ohuchi et al. (2010). The MA6-6 system (Nishiyama et al., 2008) with a truncated edge length (TEL) of the second-stage tungsten carbide anvils (Fujilloy-TF05, Fuji Die Co. Ltd) of 4 or 5 mm (former: used for the 6.5-4 type cell assembly; latter: for the 7-5 type cell assembly) was adopted for the experiments. The cross-sectional views of the cell assemblies used for experiments are shown in Fig. S1. A semi-sintered cobalt-doped magnesia (Mg, Co)O cube with edge length of 6.5 or 7 mm (former: used for the 6.5-4 type cell assembly; latter: for the 7-5 type cell assembly) was used as the pressure medium. A boron nitride (BN) composite heater (i.e., TiB_2+BN+AlN: Kanzaki, 2010) or a graphite heater is located at the inner bore of a tubular $LaCrO_3$ thermal insulator.

Table 1
Experimental conditions and results.

Run no.	P[a] (GPa)	T[b] (K)	Fabric type	Shear strain (γ)	Shear strain rate (s^{-1})	Dislocation density ($10^{12}\ m^{-2}$)	Stress $(\sigma_1-\sigma_3)$[c] (MPa)	Mean grain size (μm)	Water content C_{OH}[d] (ppm H/Si)	Starting material[e]	Cell assembly[f]	Addition of water[g]
Deformation experiments[h]												
M0134	7.6	1400	B	0.8 (±0.1)	4.0 (±0.6)×10^{-5}	7.73 (±1.16)	516 (±57)	8.7	1730 (±292)[i]	OT733	7-5 type	Yes
M0155	7.6	1490	B	0.8 (±0.1)	5.5 (±0.8)×10^{-5}	5.30 (±0.79)	394 (±43)	11.1	842 (±132)	OT733	7-5 type	Yes
Y0802b	7.6	1670	B	0.3 (±0.1)	1.2 (±0.2)×10^{-5}	5.66 (±0.85)	413 (±45)	8.3	1295 (±136)	OT786	6.5-4 type	No
Y0803a	7.6	1670	B	0.5 (±0.1)	4.1 (±0.6)×10^{-5}	4.02 (±0.60)	323 (±35)	12.2	1673 (±52)	OT786	6.5-4 type	Yes
Y0804a	9.6	1670	B	1.2 (±0.2)	4.2 (±0.6)×10^{-5}	4.18 (±0.63)	345 (±38)	10.3	2129 (±65)	OT786	6.5-4 type	Yes
Y0312b	9.6	1770	B	2.1 (±0.3)	6.7 (±1.0)×10^{-5}	6.78 (±1.02)	488 (±54)	3.2	757 (±99)	OT786F[j]	6.5-4 type	No
MK2-04	7.2	1670	A	0.8 (±0.1)	2.8 (±0.4)×10^{-5}	5.10 (±0.77)	380 (±42)	9.7	2147 (±377)	OT786	7-5 type	Yes
Y0802a	7.6	1670	A	0.9 (±0.1)	2.8 (±0.4)×10^{-5}	4.23 (±0.63)	335 (±37)	16.0	2138 (±129)	OT786	6.5-4 type	Yes
Y0805	9.6	1670	A	0.8 (±0.1)	2.7 (±0.4)×10^{-5}	4.45 (±0.67)	361 (±40)	13.0	3511 (±248)	OT786	6.5-4 type	Yes
Y0806a	11.1	1670	A	0.9 (±0.1)	4.3 (±0.6)×10^{-5}	6.71 (±1.01)	497 (±55)	11.3	7075 (±222)	OT786	6.5-4 type	Yes
Y0803b	9.6	1670	C	1.3 (±0.2)	4.6 (±0.7)×10^{-5}	7.59 (±1.14)	529 (±58)	5.7	175 (±26)	OT786F[j]	6.5-4 type	No
Y0809	9.6	1770	C	0.3 (±0.1)	1.1 (±0.2)×10^{-5}	6.83 (±1.02)	491 (±54)	10.8	216 (±19)	OT786F[j]	6.5-4 type	No
Annealing experiments[h]												
M0230	7.6	1490							7401 (±540)	OT733	7-5 type	Yes
MII150	7.6	1670							3555 (±222)	OT786	6.5-4 type	Yes
MII148	9.6	1670							10,594 (±584)	OT786	6.5-4 type	Yes
MII149	11.1	1670							15,495 (±753)	OT786	6.5-4 type	Yes

[a] Uncertainty in pressure was 0.4 GPa.
[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 sample.
[e] Run numbers of the hot-pressed samples used for the experiments. Mean grain size of olivine: 34 μm in OT733; 63 μm in OT786. Water content C_{OH} in olivine: 111 (±17) ppm H/Si in OT733; 1301 (±125) ppm H/Si in OT786; <40 ppm H/Si in OT786F.
[f] Type of the cell assembly used for the experiment.
[g] Addition of water to the platinum capsule.
[h] After the temperature reached the desired value, the sample was annealed for 0.5 h.
[i] Although water content of the sample was reported in Ohuchi et al. (2010), the water content was re-analyzed in this study.
[j] A fired sample of OT786. The OT786 sample was fired at 0.1 MPa and 1170 K under reduced conditions ($\log f_{O_2} \sim -16$ bar) for 6 h.