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Seismic anisotropy in the mantle transition zone induced by shear deformation of wadsleyite

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ABSTRACT

Mantle flow in the Earth's mantle transition zone (between 410 and 660 km depth) plays a key role to understand the nature of mantle convection, which can be mapped by observed seismic anisotropy combined with crystallographic preferred orientations of mantle minerals. Although wadsleyite is the most important mineral to cause seismic anisotropy observed in the mantle transition zone, there have been limited experimental data on its crystallographic preferred orientation because of experimental limitations. We experimentally evaluated the preferred orientation of wadsleyite developed by shear deformation at pressure–temperature conditions of the mantle transition zone (17.6 GPa and 1800–1900 K) using a deformation-DIA apparatus. The deformation experiments reveal that the [001] axis and the (010) plane of wadsleyite tend to be subparallel to the shear direction and the shear plane during deformation, respectively. These results demonstrate that polarization seismic anisotropy (velocity contrast between horizontally-polarized and vertically-polarized S-waves, V_{SH}/V_{SV}) observed in the mantle transition zone might be attributed to the preferred orientation of wadsleyite caused by horizontal mantle flow.

1. Introduction

The nature of anisotropic structures in the mantle transition zone (MTZ: between 410 and 660 km depth) can be inferred from seismological observations, and carries important information on dynamics of the mantle. Geometry of mantle flow is determined based on interpretation of observed seismic anisotropy by using a relationship between crystallographic preferred orientation (CPO) of mantle minerals and flow geometry (Karato, 2008; Mainprice, 2007). The seismic anisotropy in the upper mantle is interpreted in terms of CPOs of olivine (Jung and Karato, 2001; Katayama et al., 2004; Ohuchi et al., 2011) and serpentine (Katayama et al., 2009), which indicates that style of upper mantle convection is dominated by horizontal flows and flow directions are nearly parallel to plate motions in subduction zones (Katayama et al., 2009; Nakajima et al., 2006) and on a global scale (Becker et al., 2003). The seismic anisotropies in the MTZ are classified as polarization anisotropy (velocity contrast between horizontally-polarized S-wave (SH) and vertically-polarized S-wave (SV) (Montagner and Kennett, 1996; Visser et al., 2008)) and azimuthal anisotropy measured from surface wave dispersion (Trampert and van Heijst, 2002) and splitting of shear-wave from deep earthquakes (Foley and Long, 2011). However, an interpretation of the MTZ seismic anisotropy as the flow geometry has not been fully understood because of little information on the CPO of minerals in the MTZ.

The CPO of wadsleyite is a key factor to interpret the MTZ anisotropy because only wadsleyite can produce detectable seismic anisotropy among major minerals in the MTZ (Karato, 2008; Mainprice, 2007). Presence of ringwoodite and majoritic garnet, which are the other dominant minerals in the MTZ, has only marginal effect on the MTZ seismic anisotropy because these minerals show elastic anisotropies which are much weaker than that of wadsleyite. In order to study the wadsleyite CPO, a shear deformation experiment on wadsleyite in simple shear geometry is needed because it provides a direct constraint on a relationship between the wadsleyite CPO and the flow geometry, and is accordingly critical in understanding dynamics of the MTZ.

Shear deformation experiments on wadsleyite were performed at pressure–temperature conditions of 15 GPa and ~1600–1700 K using a rotational Drickamer apparatus (RDA) (Xu et al., 2005), however, the CPO patterns of wadsleyite did not clearly develop in that study. The wadsleyite CPO was also studied by stress relaxation tests using a Kawai-type apparatus and two types of the CPO

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patterns were found (Demouchy et al., 2011), however, it is difficult to apply the CPO to mantle dynamics because of large uncertainties in stress and strain rate in the experiments. A variety of slip systems were identified in wadsleyite crystals deformed in a Kawai-type apparatus by transmission electron microscopy (TEM) (Sharp et al., 1994; Thurel and Cordier, 2003; Thurel et al., 2003), and were applied to interpretation of the MTZ seismic anisotropy through a deformation simulation of a wadsleyite aggregate (Tommasi et al., 2004). However, the simulation result was not definitive because relative activities of the wadsleyite slip systems have been uncertain, which are key factors for the CPO development.

Recently, we have expanded pressure–temperature conditions of the uniaxial deformation experiments in a deformation-DIA apparatus (Wang et al., 2003) from those of the upper mantle to the MTZ conditions by optimizing experimental techniques for high-pressure generation (Kawazoe et al., 2010b). In the present study, we extended the available pressure condition in the shear deformation experiments with the deformation-DIA apparatus to 17.6 GPa, which corresponds to ~530 km depth. Here we show the experimental results on the wadsleyite CPO developed at controlled strain rate at the pressure–temperature conditions of the MTZ.

2. Methods

2.1. Experimental methods

Shear deformation experiments on wadsleyite were conducted in the simple shear geometry using the deformation-DIA apparatus (Wang et al., 2003), *MADONNA*-1500, combined with newly-designed multi-anvil 6–6 system (Kawazoe et al., 2010b). We adopted second-stage anvils made of tungsten carbide with ultrafine grains (Fujilloy TF05, Fuji Die Co. Ltd.) with a truncated edge length of 3.0 mm, and no preformed gasket was used in the present study. The cell assembly used in the present study was similar to that developed in our early study (Kawazoe et al., 2010b) except for the shear deformation mechanism (Fig. 1). Starting material was a thin slice (~100 μm thick) of a single crystal of San Carlos olivine, and the [0 0 1] and [0 1 0] axes of the single crystal were oriented parallel to the shear direction and normal to the shear plane in the simple shear geometry, respectively. The starting material was sandwiched between tungsten pistons that cut at 45° from compression axis, and the pistons were placed with platinum foils in a central part of the cell assembly. Generated temperature was measured with a $W_{97}Re_3$–$W_{75}Re_{25}$ thermocouple, whose hot junction was placed near the end of one of the tungsten pistons, and uncertainty in temperature was determined as ±5 K based on its fluctuation during deformation. Generated sample pressure was calibrated against an applied press load by a quench method using a phase transition between wadsleyite and ringwoodite in $(Mg,Fe)_2SiO_4$ at 1700–1800 K (Gasparik, 2003), and uncertainty in pressure was estimated as ±0.4 GPa.

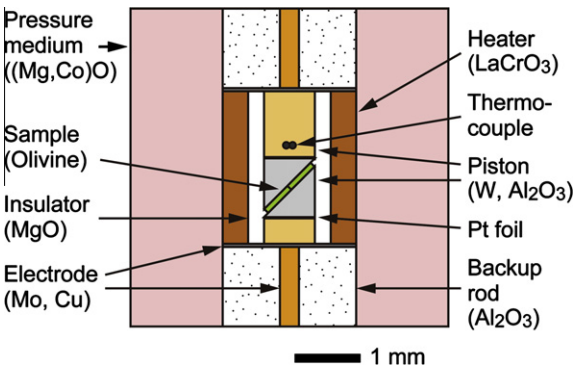

Fig. 1. A cross section of the cell assembly used for the shear deformation experiments using the deformation-DIA apparatus.

The sample was first compressed to a target press load (1.00 MN) at room temperature, and temperature was increased to 1700–1900 K at the press load. In the deformation experiments, temperature was kept at 1800–1900 K for 20 min, and then the sample was deformed at 17.6 GPa and 1800–1900 K by advancing upper and lower anvils controlling loads of deformation-rams manually. Additional runs with no deformation process were conducted at 17.6 GPa and 1700–1800 K in order to observe the CPO pattern and dislocation microstructure of the wadsleyite sample prior to deformation and determine the experimental pressure by phase observation. In the experiments with no deformation process (runs M0187 and M0169), the samples were quenched after keeping temperatures of 1800 and 1700 K for ~1 and 20 min, respectively.

2.2. Analytical methods

Shear strain γ was measured from rotation of an Mo strain marker in the sample, which was initially oriented normal to the shear plane, and calculated using the following equation: $\gamma = \tan\theta$, where θ is the rotation angle of the strain marker. Uncertainty in strain was evaluated as ±~0.1 by shape of the strain marker. Shear strain rate $\dot{\gamma}$ was calculated from the determined strain and duration of the deformation when the upper and lower anvils had been advanced. The calculated strain rate was an average during the deformation because the shear strain was determined from rotation of the strain marker in the recovered sample. Crystallographic orientation of a wadsleyite grain was measured by the electron backscatter diffraction technique (EBSD). An electron backscatter pattern was taken and indexed with Channel 5 software from HKL technology at an accelerating voltage of 15 kV and a probe current of 1.0 nA in a field emission scanning electron microscope (FE-SEM, JEOL JSM-7000F). In order to obtain an accurate solution, the crystallographic orientation of the wadsleyite grain was determined in an operator-controlled indexing mode. Half-widths of 30° and 20° were used to draw pole and inverse pole figures, respectively. Grain size was measured with a secondary electron image taken with the FE-SEM after etching a polished surface of recovered samples with 35% HNO_3.

Dislocation microstructure of wadsleyite in selected samples (runs M0162, M0180 and M0187) was observed with a transmission electron microscope (TEM, JEOL-2010). TEM foils were prepared with Ar ion beam using an ion slicer (JEOL EM-09100IS). Samples were first ion-milled at an accelerating voltage of 6 kV and then finally thinned at 2–4 kV. TEM observation was conducted at 200 kV using a two-axis folder. Water content in the samples was measured by Fourier-transform infrared (FT-IR) spectroscopy based on the Paterson's calibration (Paterson, 1982). FT-IR spectra were taken with unpolarized light using an aperture of 50 × 50 μm after the sample was kept at 383 K in a vacuum oven for more than 12 h. Phases of the samples were identified by micro-Raman spectroscopy using an Ar ion laser. The phase of the selected samples (runs M0162, M0180 and M0187) was also identified by selected area electron diffraction (SAED) using TEM.

An elastic constant tensor of the deformed sample and a three-dimensional relationship between elastic wave speeds and the deformation geometry were calculated using the software written by Mainprice (1990) and the elastic constant tensor of wadsleyite single-crystal (Zha et al., 1997). In the calculation, elastic wave speeds were evaluated at room temperature and high pressure because temperature effect on the elastic constant tensor of single-crystal wadsleyite was not available. The polarization