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Elasticity of single-crystal olivine at high pressures and temperatures

Zhu Mao[a,b,c,*], Dawei Fan[c,d,e], Jung-Fu Lin[c,e], Jing Yang[c], Sergey N. Tkachev[f],
Kirill Zhuravlev[f], Vitali B. Prakapenka[f]

[a] *Laboratory of Seismology and Physics of Earth's Interior, School of Earth and Space Sciences, University of Science and Technology of China, Hefei, Anhui 230026, China*
[b] *National Geophysical Observatory at Mengcheng, Anhui 233500, China*
[c] *Department of Geological Sciences, Jackson School of Geosciences, The University of Texas at Austin, Austin, TX 78712, USA*
[d] *Key Laboratory for High Temperature and High Pressure Study of the Earth's Interior of Institute of Geochemistry, CAS, Guiyang, Guizhou 550002, China*
[e] *Center for High Pressure Science and Technology Advanced Research (HPSTAR), Changchun, Jilin 130012, China*
[f] *Center for Advanced Radiation Sources, University of Chicago, Chicago, IL 60637, USA*

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ABSTRACT

Elasticity of single-crystal San Carlos olivine has been derived from sound velocity and density measurements at simultaneous high pressure–temperature conditions up to 20 GPa and 900 K using in situ Brillouin spectroscopy and single-crystal X-ray diffraction in externally-heated diamond anvil cells. These experimental results are used to evaluate the combined effect of pressure and temperature on full elastic constants of single-crystal olivine to better understand its velocity profiles and anisotropies in the deep mantle. Analysis of the results shows that the shear moduli display strong concave behaviors as a function of pressure at a given high temperature, while the longitudinal modulus, C_{11}, and the off-diagonal moduli, C_{12} and C_{13}, exhibit greater temperature dependence at higher pressures than at relatively lower pressures. Using a finite-strain theory and thermal equation of state modeling for a pyrolitic mantle composition along an expected mantle geotherm, our results show that the magnitude of the V_P and V_S jumps at the 410-km depth are 6% and 6.4%, respectively, which are greater than that found in seismic observations, suggesting a mantle olivine content of 40–50 vol%, which is less than what is expected for the pyrolite model. Our modeled velocity profiles for a metastable olivine wedge in the subduction slabs along a representative cold slab geotherm are 6% and 10% lower than those of wadsleyite and ringwoodite, respectively, at corresponding depths of the normal mantle. Our modeled results also show that metastable olivine in the cold slabs could have strong V_P and V_S anisotropies. The maximum V_P anisotropy is estimated to be 19–22% at transition zone depth, whereas the maximum V_S splitting is 13–23% and increases with depth. As a result, the presence of a metastable olivine wedge at the transition zone depth would exhibit a seismic signature of low velocity and strong seismic anisotropy which are consistent with recent seismic observations for various locations of the slabs and can be used as mineral physics constraints for future seismic detections of the metastable olivine wedges in the deep mantle.

1. Introduction

Seismological studies have provided some of the most direct information for understanding the physical properties of the Earth's deep interior (e.g. Dziewonski and Anderson, 1981; Kennett et al., 1995; Romanowicz, 1991; van der Hilst et al., 2007). Interpretation of seismic images and profiles requires detailed knowledge of the elasticity of major mantle minerals at relevant pressure–temperature (P–T) conditions (Bass et al., 2008; Cammarano et al., 2005a; Duffy and Anderson, 1989; Ita and Stixrude, 1992; Marquardt et al., 2009; Murakami et al., 2012). As one of the most abundant minerals in the Earth's upper mantle, olivine has the volume percentage of 60% in a pyrolitic mantle composition (Ringwood, 1975). Studying the elasticity of olivine at P–T conditions relevant to the Earth's mantle is of fundamental importance in constraining the composition and understanding the structure of the region.

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[*] Corresponding author at: Laboratory of Seismology and Physics of Earth's Interior, School of Earth and Space Sciences, University of Science and Technology of China, Hefei, Anhui 230026, China.
E-mail address: zhumao@ustc.edu.cn (Z. Mao).

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Experimental studies on the elasticity of olivine date back to 1930s when Adams (1931) studied the compressibility of fayalite, an Fe-endmember olivine (Fe_2SiO_4), at ambient temperature. With the development of high pressure techniques, the elasticity of olivine was extensively studied at high pressures and 300 K or high temperatures and 1 bar in the past few decades (Abramson et al., 1997; Duffy et al., 1995; Webb, 1989; Zha et al., 1996, 1998). Although Liu et al. (2005) reported the aggregate bulk and shear moduli of San Carlos olivine at simultaneous high P–T conditions up to 8 GPa and 1073 K using ultrasonic interferometry technique, in situ high P–T measurements on the elasticity of single-crystal olivine remain unavailable. Much of our understanding of upper-mantle seismic structures and mineralogy still heavily relies on the extrapolated elasticity of the candidate upper-mantle minerals, including olivine, enstatite, and garnet (e.g. Abramson et al., 1997; Chai et al., 1997; Duffy and Anderson, 1989; Duffy et al., 1995; Jackson et al., 2007; Jiang et al., 2004a; Li and Liebermann, 2007; Webb, 1989; Zha et al., 1996, 1998). It is widely accepted that the olivine content in the upper mantle can be constrained by comparing the velocity contrast across the olivine–wadsleyite phase transition to seismic observations for the 410-km discontinuity (Cammarano et al., 2005b; Duffy et al., 1995; Liu et al., 2005). In this case, the olivine content in the upper mantle is estimated to be 30–50 vol%, a value much lower than 60 vol% in the pyrolite model. Such a low olivine content model challenges the traditional pyrolite compositional model and calls for an answer in order to reliably understand the upper mantle mineralogy (Cammarano et al., 2005b; Duffy et al., 1995; Li and Liebermann, 2007; Liu et al., 2005). The difference in the olivine content between these models could be attributed to our limited knowledge of the combined effect of P–T on the elasticity of olivine and wadsleyite at relevant mantle conditions. Therefore, high P–T measurements on the elasticity of olivine and other candidate mantle minerals are needed to provide a better constraint on the upper mantle mineralogy.

A considerable number of seismic studies have shown that Earth's upper mantle is seismically anisotropic in various locations (e.g. Assumpcao et al., 2006; Ekstrom and Dziewonski, 1998; Long and Becker, 2010; Long and van der Hilst, 2005; Marone and Romanowicz, 2007). In the upper 200–250 km depth, shear waves with horizontal polarization travel faster than waves with vertical polarization. This difference between two shear waves $[(V_{SH} - V_{SV})/V_{Voigt}\%]$ can reach up to 4% (Ekstrom and Dziewonski, 1998; Long and Becker, 2010; Marone and Romanowicz, 2007; Nettles and Dziewonski, 2008). Since olivine as a major mantle phase has been shown to be strongly anisotropic in both compressional (V_P) and shear wave (V_S) velocities, the observed anisotropy has been suggested to be caused by the preferred alignment of olivine fabrics (Jung et al., 2009; Karato et al., 2008; Mainprice et al., 2005). Knowledge of the elasticity of single-crystal olivine is thus the key to understanding the anisotropic seismic structures of the upper mantle (Mainprice, 2007; Mainprice et al., 2000; Nunez-Valdez et al., 2010; Zha et al., 1996). Furthermore, seismic anisotropies have also been observed in the subduction slabs in the transition zone and used as potential evidence for the presence of the metastable olivine wedge in the region (Chen and Brudzinski, 2003; Liu et al., 2008; Sandvol and Ni, 1997; Tono et al., 2009). We note that the phase transition of olivine to ringwoodite has been proposed to be a potential mechanism for occurrence of the deep earthquakes (e.g. Green et al., 2010; Green and Houston, 1995; Kirby, 1995). Knowing the elasticity of single-crystal olivine at P–T conditions relevant to the cold slab geotherm is thus essential for deciphering the seismic properties of the metastable olivine wedge. To date, there is no data available for the elasticity of single-crystal olivine at simultaneous high P–T (Abramson et al., 1997; Speziale et al., 2004; Webb, 1989; Zha et al., 1996, 1998), significantly hindering our progress in understanding the observed seismic anisotropy in the upper mantle and subduction slabs in the transition zone.

In this study, we have investigated the single-crystal elasticity of San Carlos olivine at simultaneous high P–T conditions using Brillouin spectroscopy combined with single-crystal X-ray diffraction (XRD) and externally-heated DACs (EHDAC) up to 20 GPa and 900 K. Using our experimental results, we have constructed a new velocity model in a pyrolite mantle composition to explore the nature of the 410-km discontinuity. We have also modeled the velocity and anisotropy profiles of the metastable olivine wedge in the subduction slabs to better understand its potential seismic structures in the transition zone.

2. Experimental details

Natural single-crystal San Carlos olivine $[(Mg_{0.9},Fe_{0.1})_2SiO_4]$ from Arizona, USA, was examined for the chemical composition using the electron microprobe at The University of Texas at Austin. The single crystal was cut into two pieces orthogonal to each other with random crystallographic orientations of (0.96, 0.12, 0.24) (platelet 1) and (0.49, −0.87, −0.03) (platelet 2), instead of with the principle orientations. For low-symmetry minerals, such as the orthorhombic olivine with nine independent elastic constants, a large number of velocity measurements from different crystallographic planes are typically needed to fully determine the elastic moduli of single crystals at a given P–T condition, though obtaining such measurements at extreme P–T is difficult in terms of the quantity of sample pieces and collection time needed. Compared to principle planes, crystal pieces in random orientations normally exhibit two polarized shear waves and one compressional wave velocity, which can be simultaneously used to greatly reduce the need for conducting extensive velocity measurements in various orientations. Such velocity measurements from two random orientations also provide excellent constraints on the values and uncertainties of the derived single-crystal elastic moduli (Mao et al., 2007; Speziale et al., 2004). Both of the randomly cut sample pieces were double-side polished to platelets of 30–35 μm in thickness and broken into several small platelets with a size of ∼80 × 100 μm for the high P–T Brillouin and XRD measurements. Single-crystal XRD patterns were used to determine the orientations, crystal structure, and density of the sample at GeoSoilEnviroCARS (GSECARS) of the Advanced Photon Source (APS), Argonne National Laboratory (ANL). The starting sample had an orthorhombic structure with a density of 3.343(3) g/cm^3 at ambient conditions. Re–W alloy, which is more stable at high P–T conditions than typical Re gasket, was used as the gasket material for high P–T experiments. The gasket was pre-indented to a thickness of ∼65 μm by a pair of diamonds of 500 μm culet size in an EHDAC, and a hole of 300 μm was subsequently drilled and used as the sample chamber. One selected platelet from each representative orientation of the olivine crystal was loaded into an EHDAC together with Pt powder which served as the pressure calibrant at high P–T (Fig. 1) (Fei et al., 2007). A ruby sphere of approximately 5 μm was also loaded into the cell and used as the pressure indicator for loading a Ne pressure medium as well as for high-pressure and room-temperature experiments. The temperature of the sample was determined by an R-type thermocouple attached to one of the diamond anvils approximately 500 μm away from the diamond culet. The EHDAC was equipped with an alumina ceramic heater that was coiled by two Pt wires of 200 μm in diameter and 30 cm in length (Kantor et al., 2012).

High P–T Brillouin measurements were conducted at up to 14 GPa at three given temperatures of 500 K, 750 K, and 900 K at GSECARS of the APS, ANL, while complimentary high-pressure