Single-crystal elastic properties of dense hydrous magnesium silicate phase A

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ABSTRACT

The single-crystal elastic properties of phase A have been investigated by Brillouin spectroscopy at ambient conditions. The Voigt-Reuss-Hill average for the adiabatic bulk and shear moduli are $K_s = 106(1)$ GPa and $\mu = 61(1)$ GPa, respectively. The present acoustic measurements resolve discrepancies between the bulk moduli obtained in earlier compression studies. The axial compressibility of the hexagonal ($P6_3$) structure is highly anisotropic with the $c$-axis, which is perpendicular to the distorted close-packed layers, approximately 21% stiffer than the $a$-axis, in agreement with previous compression studies. The hydration of forsterite to phase A decreases the bulk and shear moduli by about 18 and 21%, respectively, while both compressional $V_p$ and shear $V_s$ wave velocities decrease by about 7%. These results suggest that water could be identified seismologically if phase A is present in abundance in cold subducted slabs.

Keywords: Single-crystal elasticity, phase A, Brillouin spectroscopy, water in subduction zones

INTRODUCTION

Dense hydrous magnesium silicates (DHMS) may be hosts for H$_2$O under hydrous conditions in the Earth’s mantle and subduction zones, and their dehydration is a possible cause for deep focus earthquakes (Thompson 1992; Hacker et al. 2003). The DHMS mineral group comprises several complex structures with a wide range of water (2–18 wt%) and silica contents, such as the 10 Å phase (Sclar et al. 1967), the 3.95 Å phase (Rice et al. 1989) or the so-called “alphabet phases” (phase A, B, C, D, E…) (e.g., Frost 1999; Angel et al. 2001). Knowledge of the physical properties of DHMS phases is therefore important for determining their stability field and their relevance for the storage of water in the Earth.

Phase A, which can contain up to 12 wt% water, was first synthesized by Ringwood and Major (1967) and by Sclar et al. (1967) at conditions ranging from 525 to 1100 °C and 7.5 to 18 GPa. The chemical composition of phase A, Mg$_7$Si$_2$O$_8$(OH)$_6$, lies along the forsterite–brucite join (Yamamoto and Akimoto 1974) but its structure differs significantly from that of the humite group. For instance, the crystal structure of phase A consists of two types of layers which are stacked alternately along the direction of the $c$-axis in a hexagonal array (space group $P6_3$, Horiuchi et al. 1979); the chains of edge-sharing Mg octahedra, which are the key structural units in the humites, are absent.

Phase equilibrium experiments suggest that water can be retained in phase A beyond the dehydration of antigorite and then be carried into the stability fields of phase E and wadsleyite under cool subduction conditions (typically 550 °C at 5.1 GPa) (Luth 1995; Wunder 1998; Komabayashi et al. 2005a). Despite the interest in phase A as a potential carrier of water into the transition zone, substantial uncertainties persist in the determination of its equation of state and thermodynamic parameters such as the compressibility. Pawley et al. (1995) obtained an isothermal bulk modulus of $K_t = 145(5)$ GPa (assuming $K_t = 4$) from energy-dispersive powder diffraction experiments to 9.85 GPa, whereas Crichton and Ross (2002) reported $K_t = 97.5(4)$ GPa with $K_t = 5.97(14)$ from single-crystal $P$-$V$ measurements to 7.6 GPa. Later measurements using single-crystal X-ray diffraction by Kudoh et al. (2002) and Kuribayashi et al. (2003) yielded intermediate values of $K_t = 105$ GPa (assuming $K_t = 4$) and 105(4) with $K_t = 3.9(8)$, respectively. More recently Holl et al. (2006) performed compression experiments in powdered phase A to 33 GPa and reported $K_t = 107.2(2.8)$ GPa with $K_t = 5.7(3)$. Beyond providing an independent measure of the bulk modulus by a technique other than the static compression methods used thus far, our work is motivated by a lack of any reported information on the shear elastic properties, single-crystal elastic properties, or sound velocity anisotropy of phase A.

To determine the shear elastic properties of phase A and hopefully resolve discrepancies in the previously reported elastic data, we have conducted single-crystal measurements of sound velocities and elastic moduli ($K_s$ and $\mu$) at ambient conditions using Brillouin scattering. In this technique, $K_s$ is obtained without compressing the sample, and the results are not subject to errors that may result from non-hydrostatic conditions or from the fit of the $P$-$V$ data to a particular equation of state. The results of this study are used to examine the effects of hydration on the elastic properties of phases along the forsterite-brucite mineralogical series, as well as the implication for the seismic low velocity zone within slabs and possibly other areas at depth in the Earth.

EXPERIMENTAL METHODS

The single crystals of phase A used in this study are from the same bulk sample used by Holl et al. (2006) for $P$-$V$ measurements. They were synthesized from a 1 mm single-crystal cube of San Carlos olivine plus a mixture of brucite and for...