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The elastic properties of β-Mg_2SiO_4 from 295 to 660 K and implications on the composition of Earth's upper mantle

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Abstract

New, high quality data are presented on the elastic properties of β-Mg_2SiO_4 (wadsleyite) from 295 to 660 K at ambient pressure. Elasticity measurements were carried out on a sintered polycrystal using resonant ultrasound spectroscopy (RUS). Room temperature values for the adiabatic bulk (K_S) and shear (G) moduli are 170.2(1.9) and 113.9(0.7) GPa, respectively. The K_S data exhibit linear dependence on temperature (T) with $(\partial K_S/\partial T)_P = -1.71(5) \times 10^{-2}$ GPa K^{-1}. Our result for $(\partial K_S/\partial T)_P$ is consistent with a relatively high magnitude for this derivative which contrasts with -1.20×10^{-2} to -1.30×10^{-2} GPa K^{-1} reported in some earlier studies. The average $(\partial G/\partial T)_P = -1.57(3) \times 10^{-2}$ GPa K^{-1} over the temperature range studied. This result is consistent with most earlier measurements of $(\partial G/\partial T)_P$ for wadsleyite. The $(\partial K_S/\partial T)_P$ and average $(\partial G/\partial T)_P$ for wadsleyite over 295–660 K are not measurably affected by the presence of iron as seen from comparing our results with those from a RUS study on β-$(Mg_{0.91}Fe_{0.09})_2SiO_4$. Further, our results for $(\partial K_S/\partial T)_P$ and average $(\partial G/\partial T)_P$ are consistent with olivine content of 44–54% at 410-km depth in Earth, given other assumptions made in recent studies about properties of the α- and β-olivine phases for P, T conditions at that depth. Our $G(T)$ data appear to exhibit small, but persistent, nonlinear behavior; the magnitude of $(\partial G/\partial T)_P$ increases with T. We discuss the important implications on upper mantle mineralogy if this nonlinear effect is confirmed and is demonstrated to apply when extrapolating beyond the temperature range of 295–660 K.

Keywords: Wadsleyite; Elastic properties; Mantle composition; Resonant ultrasound spectroscopy; Seismic discontinuities

1. Introduction

The elasticity of olivine [α-$(Mg, Fe)_2SiO_4$] and its high pressure polymorphs, wadsleyite (β) and ringwoodite (γ), are of significant interest because olivine is a primary mineral in many petrologic models of the Earth's upper mantle. Accurate data on elasticity of the olivine and wadsleyite phases are critical for investigating the role of the olivine [α-$(Mg, Fe)_2SiO_4$] to wadsleyite [β-$(Mg, Fe)_2SiO_4$] phase transition on the 410-km seismic discontinuity and for determining the olivine content of the Earth's upper mantle by comparing laboratory elasticity data for the α- and β-phases of $(Mg, Fe)_2SiO_4$ with the seismic velocity jumps (discontinuities) at 410-km depth.

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The elasticity of the low pressure α-phase [Mg_2SiO_4 and (Mg, Fe)$_2SiO_4$] has received considerable experimental attention in the past few decades (e.g., Isaak et al., 1989; Isaak, 1992; Zaug et al., 1993; Li et al., 1996; Zha et al., 1996, 1998; Abrahamson et al., 1997; Darling et al., 2004). However, precise modeling of the 410-km seismic discontinuities also requires accurate data on the elastic properties of the wadsleyite phase. Several studies on end member wadsleyite (β-Mg_2SiO_4) agree on values of the adiabatic bulk (K_S) and shear (G) moduli. Brillouin scattering measurements on single-crystals and ultrasonic interferometry studies using polycrystalline specimens generally yield ambient values for K_S and G in the range of 170–174 and 112–115 GPa, respectively (Sawamoto et al., 1984; Li et al., 1996; Zha et al., 1997; Li et al., 1998, 2001). Sinogeiken et al. (1998) reported comparable values of $K_S = 170(3)$ GPa and $G = 108(2)$ GPa for Fe-bearing wadsleyite from Brillouin scattering measurements on single-crystal. Katsura et al. (2001) and Mayama et al. (2004) both conducted resonant ultrasound spectroscopy (RUS) measurements on a hot-pressed polycrystalline specimen of β-$(Mg_{0.91}Fe_{0.09})_2SiO_4$ and obtained $K_S = 165.7$ GPa and $G = 105.4$–105.7 GPa. Current data on the pressure dependence of the elasticity of wadsleyite indicate values of $(\partial K_S/\partial P)_T$ and $(\partial G/\partial P)_T$ cluster near 4.2 and 1.5, respectively (Zha et al., 1997; Li et al., 1996, 1998, 2001). Liu et al. (2005), however, found $(\partial K_S/\partial P)_T = 4.56(23)$ and $(\partial G/\partial P)_T = 1.75(9)$, from a reanalysis of Li et al. (2001) data, which are near 4.8 and 1.7, respectively, found in the first direct measurements for these pressure derivatives of β-Mg_2SiO_4 (Gwanmesia et al., 1990a,b).

There are fewer and relatively more dispersed data of the temperature effects on K_S and G for the wadsleyite phase. Katsura et al. (2001) measured K_S and G for β-$(Mg_{0.91}Fe_{0.09})_2SiO_4$ over a limited temperature range of 278–318 K, obtaining $(\partial K_S/\partial T)_P = -1.6(3) \times 10^{-2}$ GPa K^{-1} and $(\partial G/\partial T)_P = -1.2(1) \times 10^{-2}$ GPa K^{-1}. These results contrast with $(\partial K_S/\partial T)_P = -1.2(1) \times 10^{-2}$ GPa K^{-1} and $(\partial G/\partial T)_P = -1.7(1) \times 10^{-2}$ GPa K^{-1} reported by Li et al. (1998, 2001) from ultrasonic interferometry studies on polycrystalline β-Mg_2SiO_4 and with $-1.29(17) \times 10^{-2}$ and $-1.58(10) \times 10^{-2}$ GPa K^{-1}, respectively, cited by Liu et al. (2005) from their reanalysis of Li et al. (2001) results. Mayama et al. (2004) re-measured Katsura et al. (2001) specimen over 298–470 K and obtained $(\partial K_S/\partial T)_P = -1.75(3) \times 10^{-2}$ GPa K^{-1} and $(\partial G/\partial T)_P = -1.59(1) \times 10^{-2}$ GPa K^{-1}. There appears near convergence in $(\partial G/\partial T)_P$ for a limited temperature range if Katsura et al. (2001) data are discounted, and there remain discrepancies in $(\partial K_S/\partial T)_P$ for any temperature range.

Our purpose is to present new, precise data on the temperature derivatives $(\partial K_S/\partial T)_P$ and $(\partial G/\partial T)_P$, of synthetic hot-pressed polycrystalline wadsleyite (β-Mg_2SiO_4) end member obtained by the resonant ultrasound spectroscopy technique. These data are over 295–660 K, thus, more than doubling the temperature range of previous RUS measurements for wadsleyite K_S and G. We compare our data with those from previous studies and discuss their implications on estimates of the olivine content of the Earth's upper mantle.

2. Experimental procedures

The polycrystalline specimen of wadsleyite (β-Mg_2SiO_4) used in this study was hot-pressed in the 1500-tonnes multi-anvil (Presnall Press) apparatus (Haemyeong et al., 2006) at the Geophysical Laboratory of the Carnegie Institution of Washington, DC using hot-pressing techniques described in Gwanmesia et al. (1990a, 1993). Starting material was very fine powder (<2 μm) obtained by crushing single crystal α-Mg_2SiO_4 grown by Toru Inuoe at Ehime University in Matsuyama, Japan. The powder was first dried at 250 °C for 24 h and then loaded into a Pt capsule. The capsule was cold-sealed in air and placed inside a NaCl sleeve. The sample was hot-pressed at 14 GPa and 950 °C for 2 h inside the 14/8 standard cell assembly. Synchrotron X-radiation diffraction was used to verify complete transformation of the recovered sample to the wadsleyite structure. The bulk density of the specimen ($\rho = 3.468$ g/cm^3) measured by the Archimedes' immersion method was within 99.9% of the X-ray density.

The original wadsleyite polycrystal was cylindrical in shape, about 3 mm in diameter and length. The specimen was ground and polished into a precise right-rectangular parallelepiped using 9, 6, 3, 1, and 1/4 μm diamond compounds in succession. The final edge lengths (in mm) of the prepared rectangular parallelepiped specimen were 2.167(1), 2.107(4), and 2.042(2), where the parenthetical numbers indicate uncertainty in the last digit.

The adiabatic bulk and shear moduli of the prepared wadsleyite specimen were determined using the right-rectangular parallelepiped resonance (RPR) version of resonant ultrasound spectroscopy. In RPR, the elastic properties of a right-rectangular parallelepiped specimen are determined from measurements of its mechanical resonance spectrum, edge lengths, and density (Ohno, 1976). The parallelepiped wadsleyite specimen was placed between a pair of shear PZT transducers, touching the two transducers with specimen corners diagonally