Single-crystal elasticity of (Al,Fe)-bearing bridgmanite up to 82 GPa

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ABSTRACT

Thermoelastic properties of mantle candidate minerals are essential to our understanding of geophysical phenomena, geochemistry, and geodynamic evolutions of the silicate Earth. However, the lower-mantle mineralogy remains much debated due to the lack of single-crystal elastic moduli ($C_i$) and aggregate sound velocities of (Al,Fe)-bearing bridgmanite, the most abundant mineral of the planet, at the lower mantle pressure-temperature ($P$-$T$) conditions. Here we report single-crystal $C_i$ of (Al,Fe)-bearing bridgmanite, Mg$_{0.88}$Fe$_{0.12}$Si$_{0.90}$O$_3$ (Fe10-Al14-Bgm) with Fe$^{3+}$/2Fe = ~0.65, up to ~82 GPa using X-ray diffraction (XRD), Brillouin light scattering (BLS), and impulsive stimulated light scattering (ISLS) measurements in diamond-anvil cells (DAs). Two crystal platelets with orientations of (~0.50, 0.05, ~0.86) and (0.65, ~0.59, 0.48), that are sensitive to deriving all nine $C_i$, are used for compressional and shear wave velocity ($v_p$ and $v_s$) measurements as a function of azimuthal angles over 200$^\circ$ at each experimental pressure. Our results show that all $C_i$ of single-crystal Fe10-Al14-Bgm increase monotonically with pressure with small uncertainties of 1–2% ($\pm1\sigma$), except $C_{55}$ and $C_{33}$, which have uncertainties of 3–4%. Using the third-order Eulerian finite-strain equations to model the elasticity data yields the aggregate adiabatic bulk and shear moduli and respective pressure derivatives at the reference pressure of 25 GPa: $K_s = 326 \pm 4$ GPa, $\mu = 211 \pm 2$ GPa, $K'_s = 3.32 \pm 0.04$, and $\mu' = 1.66 \pm 0.02$ GPa. The high-pressure aggregate $v_p$ and $v_s$ of Fe10-Al14-Bgm are 2.6–3.5% and 3.1–4.7% lower than those of MgSiO$_3$, bridgmanite end-member, respectively. These data are used with literature reports on bridgmanite with different Fe and Al contents to quantitatively evaluate pressure and compositional effects on their elastic properties. Comparing with one-dimensional seismic profiles, our modeled velocity profiles of major lower-mantle mineral assemblages at relevant $P$-$T$ suggest that the lower mantle could likely consist of about 89 vol% (Al,Fe)-bearing bridgmanite. After considering uncertainties, our best-fit model is still indistinguishable from pyrolitic or chondritic models.

Keywords: Single-crystal elasticity, bridgmanite, lower mantle, pyrolite, pyrolyte, chondrite

INTRODUCTION

Earth’s lower mantle, the most voluminous region of the planet, plays a key role in regulating physical, chemical, and dynamic interactions between the core and upper mantle as well as the crust. Geochemical and petrological observations indicate that the upper mantle likely consists of pyrolite with approximately three portions of peridotite and one portion of basalt (Ringwood 1975). If one assumes the whole mantle is chemically homogenous in major elements, a pyrolitic lower mantle would have ~75 vol% (Al,Fe)-bearing bridgmanite [(Mg,Fe,Al),(Fe,Al,Si)O$_3$, Bgm], ~18 vol% ferropericlase [(Mg,Fe)O, Fp], and ~7 vol% CaSiO$_3$, dawsonite (Irifune et al. 2010; Tschauer et al. 2021). However, such a pyrolitic model with Mg/Si = ~1.25 has much less Si than the chondritic bulk Earth model with Mg/Si = ~1.0 from cosmochemical constraints (McDonough and Sun 1995). To address the “missing Si” conundrum in the silicate Earth, Si as a light element in the core (Allègre et al. 1995) and/or a Si-rich lower mantle (Hofmann 1997) have been proposed previously. Moreover, some recent studies suggest that comparisons of velocity and density profiles between seismic observations (Dziewonski and Anderson 1981; Kennet et al. 1995) and mineral physics models (Irifune et al. 2010; Kurnosov et al. 2017; Mashino et al. 2020; Murakami et al. 2012) could provide important insights into the lower-mantle mineralogy. This would require a complete and reliable elasticity data set of the lower-mantle candidate minerals with small uncertainties.

Bridgmanite is suggested to be the most abundant lower-mantle mineral (Ringwood 1975). Despite extensive theoretical studies on its elasticity at high $P$-$T$ (Karki et al. 1997; Shukla and Wentzcovitch 2016; Wentzcovitch et al. 2004), experimental investigations on this subject are still limited to polycrystalline samples or single crystals at relatively low pressures. In addition, as much as 10 mol% Fe$^{3+}$ and Al$^{3+}$ could substitute the dodecahedral-site (A-site) Mg$^{2+}$ and octahedral-site (B-site) Si$^{4+}$ in the crystal structure of bridgmanite via charge-coupled substitution (e.g., Frost et al. 2004; McCammon 1997), whose effects on the elastic properties also need investigation. Of particular examples are the reports by Murakami et al. (2012).