Influence of aluminum on the elasticity of majorite-pyrope garnets

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Abstract

The effect of aluminum (Al) on the elasticity of majorite-pyrope garnets was investigated by means of ultrasonic interferometry measurements on well-fabricated polycrystalline specimens. Both velocities and elastic moduli increase almost linearly with increasing Al content within analytical uncertainty. No significant variation of the velocities and elastic moduli is observed across the tetragonal-to-cubic phase transition at majorite with the pyrope content up to 26 mol% along the majorite-pyrope system. The elasticity variation of majorite-pyrope garnets is largely dominated by the Al content, while the phase transition as a result of cation ordering/disordering of Mg and Si via substitution of Al on octahedral sites are therefore dominated by garnet composition (e.g., Al, Fe, Ca, and Na) rather than the tetragonal-to-cubic phase transition because of cation ordering/disordering.

Keywords: Aluminum, garnet, phase transition, velocity, elastic modulus, mantle transition zone; Physics and Chemistry of Earth’s Deep Mantle and Core.

Introduction

Garnet, X$_2$Y$_2$SiO$_{12}$ (where X$^{2+}$ = Mg, Fe, Ca, and Mn in a dodecahedral site; Y$^{3+}$ = Al, Fe, and Cr in the octahedral site), is one of the most abundant rock-forming minerals in the Earth’s crust and mantle (e.g., Novak and Gibbs 1971; Ringwood and Major 1971; Anderson and Bass 1986). With increasing depths from the upper mantle to the mantle transition zone, an aluminum deficient garnet called majorite forms from the gradual dissolution of clinopyroxenes into the garnet (Ringwood and Major 1971). Petrological studies have demonstrated that majoritic garnets represent up to 40 and 60% by volume of pyrolite and mid-ocean ridge basalt (MORB) compositions in the mantle (Novak and Gibbs 1971; Ringwood and Major 1971; Anderson and Bass 1986). Majorite (Mg$_3$Al$_2$Si$_2$O$_{12}$)-pyrope (Mg$_3$Al$_2$Si$_2$O$_{12}$) system is considered the most relevant to the upper mantle and transition zone (e.g., Irifune and Ringwood 1987). According to the physical and chemical properties of majorite-pyrope garnets are indisputable for constructing the mineralogy of the Earth’s mantle.

An increase of pyrope content to 25 mol% (M$_{30}$P$_{20}$, Mj = majorite; Py = pyrope) in majorite leads to a phase transition from a tetragonal (I4/a) to cubic (Ia3d) symmetry along the majorite-pyrope system, which is caused by the effect of cation disordering of Mg and Si on two distinct octahedral sites after Al substitution (Parise et al. 1996; Heinemann et al. 1997; Liu et al. 2017). Because of its potential ferroelastic properties, former studies speculated that the tetragonal-to-cubic transition in majoritic garnets may explain observed seismic scatterings in the mantle transition zone (Heinemann et al. 1997). Although the elastic properties of majorite-pyrope garnets have been widely studied by Brillouin spectroscopy (e.g., Bass and Kanzaki 1990; Yeganeh-Haeri et al. 1990; Pacalo and Weidner 1997; Sinogeikin et al. 1997, 2002a, 2002b; Pamato et al. 2016) and ultrasonic interferometry (Rigden et al. 1994; Liu et al. 2000; Gwanmesia et al. 2000, 2006, 2009; Zou et al. 2012; Liu et al. 2015; Chanel et al. 2016), the dependence of their elasticity on chemistry remains controversial. Sinogeikin et al. (1997) proposed two models to explain the variation of elastic moduli as a function of the pyrope content in this system: (1) a small linear decrease of $K_S$ (bulk modulus) and $G$ (shear modulus) from pyrope to majorite; (2) constant $K_S$ and $G$ from pyrope to Mj$_{30}$P$_{20}$, followed by a step-like decrease at Mj$_{30}$P$_{20}$ and a gradual increase to majorite. The latter model was proposed based on earlier results reported by Bass and Kanzaki (1990), Yeganeh-Haeri et al. (1990), and Pacalo and Weidner (1997). However, these data are relatively scattered due to different sample qualities and experimental techniques. It thus cannot draw a firm conclusion about the scattering nature of the compositional dependency of garnet’s elastic moduli. Furthermore, the potential effects of the tetragonal-to-cubic symmetry transformation on garnet’s elastic moduli also remain unclear. Therefore, it is required to clarify the effect of Al content on the elasticity of majorite-pyrope garnets.

In this study, we investigated the variation of P- and S-wave velocities and elastic moduli of a series of majorite-pyrope...