Pressure-induced velocity softening in natural orthopyroxene at mantle temperature

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ABSTRACT

In this study, we have measured the compressional and shear wave velocities of (Mg,Fe)SiO3 natural orthopyroxene up to 13.5 GPa and 873 K using ultrasonic interferometry in conjunction with in situ synchrotron X-ray diffraction and imaging techniques. Previous acoustic experiments on orthoenstatite (OEn) MgSiO3 indicated that both compressional and shear velocities (Vp and Vs) of OEn undergo continuous velocity softening above 9 GPa at room temperature, which has been attributed to the phase transition from OEn to the metastable, high-pressure clinoenstatite HPCEn2. For the first time, our results suggest that pressure-induced velocity softening can occur in natural orthopyroxene at high-temperature conditions relevant to the Earth’s cold subduction zones. Estimates of the impedance and velocity contrasts between orthopyroxene (Opx) and high-pressure clinoenstatite (HPCpx) have been calculated, and the possibility of this phase transformation being a plausible candidate for seismic X-discontinuities at depth around 250–350 km is re-evaluated.

Keywords: Orthopyroxene, velocity softening, high pressure and high temperature, ultrasonic interferometry

INTRODUCTION

Orthopyroxene (Mg,Fe)SiO3 is one of the most abundant minerals in the pyrolite compositional model of Earth’s upper mantle (Ringwood 1975). Several polymorphs of pure Mg end-member enstatite (MgSiO3) are thermodynamically stable under the pressure (P) and temperature (T) conditions of the upper mantle (see Fig. 1), including orthoenstatite (OEn; space group: Pbcn), protoenstatite (PEn; space group: Pbnm), low-pressure clinoenstatite (LPCEn; space group: P21/c), and high-pressure clinoenstatite (HPCEn; space group: C2/c) (Gasparik 1990, Pacalo and Gasparik 1990). Recently, a metastable, high-pressure monoclinic polymorph with space group P21/c (designated as HPCEn2) has been discovered and reported to be persistent at least up to 673 K (J. Zhang et al. 2012, 2014). Given the abundance of pyroxene in the Earth’s upper mantle, investigating the phase transformation behavior and physical properties of pyroxene-structured groups has attracted the attention of many research groups (e.g., Angel and Hugh-Jones 1994; Angel and Jackson 2002; Finkelstein et al. 2015; Frisillo and Barsch 1972; Hugh-Jones and Angel 1997; Jackson et al. 2004; Iahn 2008; Kung et al. 2006; Lin 2003; Xu et al. 2018; J. Zhang et al. 2012; Zhao et al. 1995).

Kung et al. (2004) observed a substantial softening of both the compressional and shear velocities (Vp andVs) in OEn above 9 GPa at room temperature. Subsequent experimental and computational investigations (Li et al. 2014; J. Zhang et al. 2014) suggest that the softening behavior may be related to the phase transformation from OEn to the newly discovered monoclinic phase HPCEn2 with space group P21/c. At room temperature or moderate high temperature, due to the reconstructive nature of the phase transition from OEn to HPCEn [which requires reorientation of the stacked layers], the phase transformation is always kinetically inhibited by energy barriers (Dera et al. 2013; J. Zhang et al. 2014); see black dotted line below 700 K in Figure 1. Thus, OEn would transform to the metastable phase HPCEn2. A recent study has shown this metastable phase transition could occur at high temperatures up to 700 K. The velocity softening observed in MgSiO3, at around 9 GPa, has also been observed in FeSiO3-orthoperovskite at room temperature at ~5 GPa (see Kung and Li 2014). However, prior to the current study, no attempt has ever been made to experimentally investigate if this pressure-induced velocity softening can persist at high temperature. Li et al. (2014) speculate that if such a softening behavior occurs at high temperatures in natural orthopyroxene compositions, the velocity and impedance contrast between Opx and HPCpx at mantle depths would be enhanced, which could, in turn, increase their detectability in seismic studies.

The phase transition from Opx to HPCpx has been proposed to explain the seismic X-discontinuity (e.g., Revenaugh and Jordan 1991; Woodland and Angel 1997) for a long time because the transition pressure from Opx to HPCpx is well consistent with the depth of the seismic discontinuity (Angel et al. 1992), and the phase transition boundary is sharp enough to generate the discontinuity (Woodland 1998). Previous acoustic studies on Opx have been conducted at high temperature and ambient pressure (e.g., Jackson et al. 2007; Kung et al. 2011) or at room temperature and high pressure (e.g., Chai et al. 1997; Flesch et al. 1998; Kung et al. 2004; D. Zhang et al. 2013; J. Zhang and Bass 2016).

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