Elasticity of single-crystal Fe-enriched diopside at high-pressure conditions: Implications for the origin of upper mantle low-velocity zones

DAWEI FAN\(^1\),\(^2\),\(^*\), SUYU FU\(^2\), CHANG LU\(^2\), JINGUI XU\(^1\), YAN-YAO ZHANG\(^2\), SERGEY N. TKACHEV\(^3\), VITALI B. PRAKAPENKA\(^3\), and JUNG-FU LIN\(^2\),\(^*\)

\(^1\)Key Laboratory of High-Temperature and High-Pressure Study of the Earth’s Interior, Institute of Geochemistry, Chinese Academy of Sciences, Guiyang, Guizhou 550081, China
\(^2\)Department of Geological Sciences, Jackson School of Geosciences, The University of Texas at Austin, Austin, Texas 78712, U.S.A.
\(^3\)Center for Advanced Radiation Sources, University of Chicago, Chicago, Illinois 60647, U.S.A.

ABSTRACT

Diopside is one of the most important end-members of clinopyroxene, which is an abundant mineral in upper-mantle petrologic models. The amount of clinopyroxene in upper-mantle pyrolite can be \(\sim\) 15 vol\%, while pyroxenite can contain as high as \(\sim\) 60 vol\% clinopyroxene. Knowing the elastic properties of the upper-mantle diopside at high pressure-temperature conditions is essential for constraining the chemical composition and interpreting seismic observations of region. Here we have measured the single-crystal elasticity of Fe-enriched diopside (\(\text{Di}_{15}\)\(\text{Hd}_{20}\), Di-diopside, and Hd-hedenbergite; also called Fe-enriched clinopyroxene) at high-pressure conditions up to 18.5 GPa by using in situ Brillouin light-scattering spectroscopy (BLS) and synchrotron X-ray diffraction in a diamond-anvil cell. Our experimental results were used in evaluating the effects of pressure and Fe substitution on the full single-crystal elastic moduli across the Di-Hd solid-solution series to better understand the seismic velocity profiles of the upper mantle. Using the third- or fourth-order Eulerian finite-strain equations of state to model the elasticity data, the derived aggregate adiabatic bulk and shear moduli \((K_{SO}, G_0)\) at ambient conditions were determined to be 117(2) and 70(1) GPa, respectively. The first- and second-pressure derivatives of bulk and shear moduli at 300 K were \((\partial K_{SO}/\partial P)_T = 5.0(2), (\partial^2 K_{SO}/\partial P^2)_T = -0.12(4)\) GPa\(^{-1}\) and \((\partial G/\partial P)_T = 1.72(9), (\partial^2 G/\partial P^2)_T = -0.05(2)\) GPa\(^{-1}\), respectively. A comparison of our results with previous studies on end-member diopside and hedenbergite in the literatures shows systematic linear correlations between the Fe composition and single-crystal elastic moduli. An addition of 20 mol\% Fe in diopside increases \(K_{SO}\) by \(\sim\) 1.7\% (\(\sim\) 2 GPa) and reduces \(G_0\) by \(\sim\) 4.1\% (\(\sim\) 3 GPa), but has a negligible effect on the pressure derivatives of the bulk and shear moduli within experimental uncertainties. In addition, our modeling results show that substitution of 20 mol\% Fe in diopside can reduce \(V_P\) and \(V_S\) by \(\sim\) 1.8\% and \(\sim\) 3.5\%, respectively, along both an expected normal mantle geotherm and a representative cold subducted slab geotherm. Furthermore, the modeling results show that the \(V_P\) and \(V_S\) profiles of Fe-enriched pyroxenite along the cold subducted slab geotherm are \(\sim\) 3.2\% and \(\sim\) 2.5\% lower than AK135 model at 400 km depth, respectively. Finally, we propose that the presence of Fe-enriched pyroxenite (including Fe-enriched clinopyroxene, Fe-enriched orthopyroxene, and Fe-enriched olivine), can be an effective mechanism to cause low-velocity anomalies in the upper mantle regions at the 410 km discontinuity at cold subducted slab conditions.

Keywords: Fe-enriched diopside, Single-crystal elasticity, Brillouin light scattering, high pressure, Low-velocity zone, 410 km discontinuity

INTRODUCTION

Ca-rich clinopyroxene (Cpx) in the Di-Hd solid-solution series is one of the most abundant constituent minerals in the upper mantle, along with olivine, orthopyroxene (Opx), and pyrope-rich garnet (Fumagalli and Klemme 2015). The volumetric proportion of Cpx is in the range of \(\sim\) 15–75 vol\% depending on its mineralogical abundance in different rock types (Duffy and Anderson 1989; Ringwood 1991). For example, mantle-derived peridotite commonly contain \(\sim\) 15 vol\% Cpx (e.g., Takazawa et al. 2000; Davis et al. 2009), while mantle-derived pyroxenite xenoliths in alkali basaltic or kimberlitic lavas contain up to \(\sim\) 60 vol\% Cpx (e.g., Lambart et al. 2013; Yang et al. 2016). As the most abundant end-member of Cpx in the deep Earth (Ringwood 1982), previous phase transformation studies have indicated that monoclinic diopside (\(\text{CaMgSi}_2\text{O}_6\)) with C2/c space group at ambient conditions was thermodynamically stable up to \(\sim\) 18 GPa and 1400 K (e.g., Kim et al. 1994; Oguri et al. 1997; Akaogi et al. 2004). Furthermore, recent studies have demonstrated that the dissolution of pyroxenes into majoritic garnet is slow in some subducted slabs (Nishi et al. 2013; van Mierlo et al. 2013), suggesting the presence of metastable pyroxene even below 660 km...