High-pressure behavior of liebenbergite: The most incompressible olivine-structured silicate

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ABSTRACT

Nickel is an abundant element in the bulk earth, and nickel-dominant olivine, liebenbergite, is the only igneous nickel-rich silicate found in nature. In this study, we used high-pressure single-crystal diffraction to explore the compressional behavior of a synthetic liebenbergite sample up to 42.6 GPa at ambient temperature. Over the studied pressure range, the liebenbergite sample retains the orthorhombic \( Pbnm \) structure, and no phase transition is observed. A third-order Birch-Murnaghan equation of state was used to fit the pressure behavior of the unit-cell volume, lattice parameters, the polyhedral volume, and the average bond length within each polyhedron. The best-fit bulk modulus \( K_0 = 163(3) \) GPa and its pressure derivative \( K'_0 = 4.5(3) \). We find that liebenbergite is the most incompressible olivine-group silicate reported thus far, and Ni\(^{2+}\) tends to increase the isothermal bulk modulus of both olivine- and spinel-structured silicates. Consequently, Ni-rich olivine has a higher density compared to Ni-poor olivine at the upper mantle \( P-T \) conditions; however, enrichment of Ni in mantle olivine is generally too low to make this density difference relevant for fractionation or buoyancy.

Keywords: Olivine, Ni, high pressure, equation of states, single-crystal diffraction

INTRODUCTION

Nickel is the most abundant of the minor elements in the bulk earth. It is less common than iron, oxygen, silicon, and magnesium, which make up 94% of the atoms in the Earth, yet slightly more common than calcium and aluminum (McDonough and Sun 1995; Allegre et al. 2001). A geochemical study of the distribution of nickel in the Earth can constrain our understanding of the Earth’s evolution, for example, core segregation (Ringwood 1959; Siebert et al. 2012; Fischer et al. 2015). Though one cannot directly measure the composition of the Earth’s core, it is estimated that the core contains ~5 wt% nickel, and the core is the largest reservoir of this element (McDonough 2014). This estimate is based on two premises: (1) the assumption that the abundance of nickel in the bulk earth is chondritic, and (2) the calibrated relationship between nickel concentration in mantle rocks and their MgO content (McDonough and Sun 1995; McDonough 2014; Palme and O’Neill 2014). However, most of the research on the nickel concentration in mantle rocks has thus far focused on the shallow materials (McDonough and Sun 1995; Korenaga and Kelemen 2000; Matzen et al. 2013; Palme and O’Neill 2014), and the partitioning coefficients of nickel between minerals and melts are strongly influenced by pressure (Li and Agee 1996; Siebert et al. 2012; Matzen et al. 2013, 2017; Fischer et al. 2015; Pu et al. 2017). Under certain geological settings, nickel could be enriched in mantle materials without directly interacting with the Earth’s core (Ishimaru and Arai 2008; Straub et al. 2008; Matzen et al. 2013), so it is possible to have some nickel-rich reservoir in the deep part of the silicate mantle.

To quantify the possibility of deep reservoirs of Ni-rich silicates, one needs to understand the high-pressure behavior of nickel-rich silicates. Systematic research on Ni-rich silicates is still lacking. From a mineralogical perspective, one cannot assume that nickel behaves the same as iron in silicates. For example, there are no nickel end-members of garnet and pyroxene (Back et al. 2017; Burns 1973; Campbell and Roeder 1968; Gentile and Roy 1960), while iron end-members of garnet (almandine) and pyroxene (ferrosilite) both exist. Nickel is highly compatible with mantle peridotites (Griffin et al. 1989; Hart and Davis 1978; Mysen 1979; Palme and O’Neill 2014). Geological surveys show that nickel tends to be enriched in olivine under natural conditions (Ishimaru and Arai 2008; Straub et al. 2008), and liebenbergite, the nickel end-member of olivine (De Waal 1968; Gentile and Roy 1960), while iron end-members of garnet (almandine) and pyroxene (ferrosilite) both exist. Nickel is highly compatible with mantle peridotites (Griffin et al. 1989; Hart and Davis 1978; Mysen 1979; Palme and O’Neill 2014). Geological surveys show that nickel tends to be enriched in olivine under natural conditions (Ishimaru and Arai 2008; Straub et al. 2008), and liebenbergite, the nickel end-member of olivine (De Waal and Calk 1973), is the only igneous nickel-rich silicate found in nature (Supplemental Table S1, Back et al. 2017). Considering the abundance of olivine in the mantle, studying the high-pressure behavior of liebenbergite will provide insights into nickel-bearing silicates at deep earth conditions.

Studies, described below, were previously carried out to constrain the phase diagram and stability field of liebenbergite.