Thermal conductivity of single-crystal brucite at high pressures: Implications for thermal anomaly in the shallow lower mantle

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Abstract

Brucite [Mg(OH)₂] is an important hydrous mineral in the MgO-SiO₂-H₂O system and also a key component in the process of hydrothermal metamorphism. Due to its large water storage capacity and presence within a sinking slab, the study of brucite’s physical properties under relevant extreme conditions could shed new light on its potential impacts on the slab’s thermal profile and geodynamics, as well as seismic anomaly observed around a subduction zone. For example, seismic tomography has revealed slab stagnation and low-velocity zones in the shallow lower mantle that is conventionally attributed, respectively, to large contrasts of physical properties between the slab and mantle as well as dehydration melt. However, the effect of hydrous minerals on slab dynamics and seismic anomalies remains poorly understood. Here we study thermal conductivity of brucite at high pressures and room temperature as well as at ambient pressure and elevated temperatures. We further model thermal conductivity of brucite along a representative geotherm and find an ~6-fold to 19-fold increase in the thermal conductivity as brucite decomposes to periclase in the shallow lower mantle (~800 km depth). This result implies that the subduction and decomposition of brucite-rich aggregate within a slab may create a local high-temperature anomaly that would both enhance the slab’s buoyancy, leading to stagnation, and facilitate dehydration melting, contributing to seismic low-velocity zones. Our findings offer mechanisms associated with brucite decomposition that could influence the slab dynamics and seismic structures in the shallow lower mantle.

Keywords: Brucite, hydrous mineral, anisotropic thermal conductivity, slab stagnation, dehydration melting, Physics and Chemistry of Earth’s Deep Mantle and Core

Introduction

Brucite is one of the key hydrous phases in the complex MgO-SiO₂-H₂O (MSH) ternary system (Hacker et al. 2003; Ohtani et al. 1995, 2000). It contains large amounts of water (~30 wt%) and can coexist with other hydrous minerals, e.g., phase D, at pressure-temperature (P-T) conditions within a subducting slab at mantle transition zone and top of lower mantle (Irfune et al. 1998; Nishi et al. 2014; Ohtani et al. 1995, 2000). The presence of brucite in Earth’s deep interior could play a crucial role in affecting Earth’s deep water circulation and water budget. In the past decades, many physical properties of brucite under extreme conditions have been extensively investigated, including: (1) phase stability (Fukui et al. 2005; Hacker et al. 2003; Hermann and Mookherjee 2016; Nishi et al. 2014; Pawley and Wood 1996); (2) elastic properties and seismic velocities (Hermann and Mookherjee 2016; Jiang et al. 2006; Mainprice and Ildefonse 2009); (3) crystal structure and equation of state (Catti et al. 1995; Hermann and Mookherjee 2016; Mookherjee and Stixrude 2006; Nagai et al. 2000; Parise et al. 1994; Raugei et al. 1999; Xia et al. 1998); (4) molecular vibrational spectrum (Duffy et al. 1995; Kruger et al. 1989; Zhu et al. 2019); and (5) thermal properties (Hofmeister 2014; Horii 1971; Saxena et al. 1993; Zhu et al. 2019). Importantly, using structure search and ab initio calculations, Hermann and Mookherjee (2016) predicted that brucite is stable along the P-T conditions of a subducting slab until about 30 GPa (~800 km depth), after which it decomposes to periclase (MgO) and H₂O. The stability of brucite would impact the relative stability of other minerals in the MSH system (Hacker et al. 2003; Ohtani et al. 1995, 2000). Potentially the drastic changes in physical properties across brucite’s decomposition to periclase and H₂O could trigger local seismic and geodynamic anomalies [see Hermann and Mookherjee (2016) and our discussion below].

Lattice thermal conductivity, the ability of a material to conduct heat, of minerals in the mantle and subducting slabs is crucial to control the thermal evolution and geodynamics in Earth’s interior (Chang et al. 2017; Dalton et al. 2013; Deschamps and Hsieh 2019; Hsieh et al. 2017, 2018, 2020; Marzotto et al. 2020). Recent studies suggested that a temperature anomaly within a subducting slab could be induced by large variations of thermal conductivity in the oceanic crust due to, for instance, the effect of hydration (Chang et al. 2017) or spin transition (Chao and Hsieh 2019; Hsieh et al. 2020). Since brucite could coexist with phase D in the peridotitic layer of a subducting slab, yet decompose to periclase in the shallow lower mantle, how its