The Mantle Convection in the Super-Earths; Implications from high-pressure experiments on silicate analogs

Brent Grocholski[1], Sang-Heon Shim[1], and Vitali Prakapenka[2], [1]Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, 77 Massachusetts Ave., Cambridge, MA 02139 USA, [2] GeoSoilEnvironCARS, University of Chicago, 5640 South Ellis, Chicago IL 60637, USA

Introduction

The tectonic activity at the surface of planets can be strongly coupled with processes in the deep mantle. This has been shown to be the case for the Earth, and potentially for the recently discovered Super-earth type planets. Furthermore, the scale of mantle convection strongly influences the thermal history of the planets. For example, the post-spinel boundary at 660-km depth in the Earth behaves as a permeable barrier for thermal mantle flow due to its negative Clapeyron slope (dP/dT) [1], regulating the thermal evolution of the mantle.

Computer simulations by Umemoto et al. [2] indicate a breakdown of the dominant mantle silicate at pressures achieved in the deep interiors of Super-earths (~1000 GPa) (Figure 1):

$$MgSiO_3 \rightarrow MgO + SiO_2. \quad (1)$$

They have predicted a strongly negative Clapeyron slope of the breakdown at least an order of magnitude larger than the post-spinel transition. This large negative Clapeyron slope would make the breakdown boundary completely impermeable for thermal mantle flow.

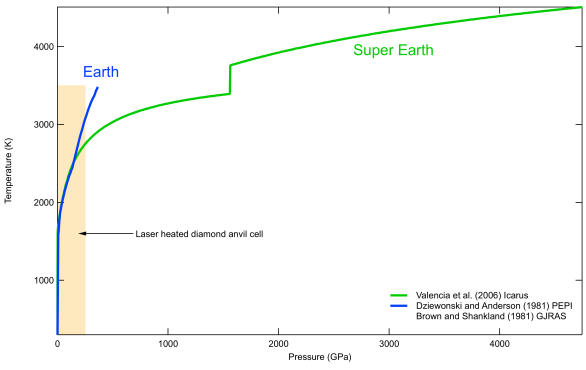

Figure 1: Comparison of pressures and temperatures at the interiors of the Earth and $10M_{\oplus}$ Super-earth.

While our current experimental methods using devices to generate static high pressure, such as the diamond-anvil cell, are not capable of reaching the predicted breakdown pressure, we can investigate analog materials which likely undergo the same sequence of phase transitions as mantle silicates but at much lower pressures. Umemoto et al. [3] predicted that $NaMgF_3$ (an $MgSiO_3$ analog) undergoes the same type of the breakdown above ~40 GPa, readily accessible for the diamond-anvil cell technique:

$$NaMgF_3 \rightarrow NaF + MgF_2, \quad (2)$$

where NaF is an MgO analog and MgF_2 is an SiO_2 analog. Indeed, $NaMgF_3$ is an isoelectronic and isostructural analog of $MgSiO_3$, and exhibits phase transitions such as the perovskite to post-perovskite, like mantle silicates, but at much lower pressure (~15 GPa) than $MgSiO_3$ (~120 GPa). Umemoto et al. [2] predicted that a phase transition in SiO_2 and MgF_2:

$$\text{Pyrite type} \rightarrow \text{Cotunnite type}, \quad (3)$$

which has a large volume collapse, drives the breakdown reaction of $MgSiO_3$ and $NaMgF_3$.

Here we report experimental measurements on the stability of $NaMgF_3$ in situ at high pressure and high temperature. We also investigated the phase transitions in MgF_2 (an SiO_2 analog), as it may play a critical role for the stability of $NaMgF_3$ [2].

Experimental Method

High pressure measurements on $NaMgF_3$ and MgF_2 were conducted in the diamond-anvil pressure cell at the GSECARS sector of the Advanced Photon Source, Argonne National Lab. The diamond cell is an opposed anvil device that uses brilliant cut diamonds to attain high pressures while allowing optical access to samples. The optical access allows us to heat our sample with a high-powered infrared laser and collect X-ray diffraction patterns to determine the stable phase assemblage at high pressure and temperature.

Thin foils (~10 μm) of sample material (either $NaMgF_3$ or MgF_2) mixed with 10 wt% platinum or gold (used as a pressure calibrant and laser absorber) were loaded into diamond-anvil cells with 200 μm culet with an argon quasi-hydrostatic pressure medium and thermal insulator. The fluorescence wavelength of ruby changes

with pressure and allows us to measure the pressure by placing a small ruby chip at the edge of the sample chamber [4]. We prepared a total of three samples of $NaMgF_3$ and two samples of MgF_2. The sample was brought to pressure at room temperature and laser heated at 1500–2500 Kelvin for at least 30 minutes while simultaneously collecting X-ray diffraction patterns every 2–3 minutes during the heating cycle.

Results

We do not observe the breakdown of $NaMgF_3$ (an $MgSiO_3$ analog) to NaF (an MgO analog) and MgF_2 (an SiO_2 analog) up to ~70 GPa and ~2500 Kelvin, much higher pressure than the breakdown pressure (40 GPa) prediction by Umemoto et al. [3]. X-ray diffraction patterns can be indexed as a combination of the perovskite and post-perovskite structures with some residual NaF from the starting material. Notably, the most intense diffraction line of MgF_2 is at a diffraction angle where neither perovskite nor post-perovskite is expected to produce strong intensities. The failure of the observation of the most intense lines of MgF_2 is unambiguous evidence for the stability of $NaMgF_3$ against breakdown at pressures at least up to 70 GPa.

In the computational simulations [2], the primary driving force for favoring the breakdown is a large decrease in volume at a phase transition in SiO_2 and MgF_2 from the pyrite-type to the cotunnite-type (reaction 3). In the experiments on MgF_2, we found a new phase of MgF_2, whose stability field exists between the pyrite-type and the cotunnite-type at 35–50 GPa and at temperatures >1500 K:

$$\text{Pyrite type} \rightarrow \text{Baddeleyite type} \rightarrow \text{Cotunnite type}. \quad (4)$$

This new phase has the baddeleyite-type structure found in ZrO_2 [5]. This structure is a distortion of the pyrite-type structure and has a very small decrease in volume (~1%) relative to the pyrite-type structure. The new baddeleyite-type phase was not observed in previous measurements of MgF_2 at high pressure and room temperature, suggesting that temperature is critical for the stability of this new phase at high pressure.

Implications

We have found that $NaMgF_3$ (an $MgSiO_3$ analog) is stable well above the computationally determined breakdown pressure. We also discovered that a previously unidentified phase becomes stable before the cotunnite-type phase in MgF_2 (an SiO_2 analog), which may expand the stability of the post-perovskite phase with respect to the breakdown products. This suggests that $MgSiO_3$ is stable much higher pressures and likely to pressures in excess of those found in the rocky mantle fraction of Super-earths [6, 7]. This finding would imply that the (at least most part of) mantles of Super-earths are not strongly stratified and silicates would remain the dominant constituent throughout their mantles.

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