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Mantle mixing over time

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Abstract

We evaluate under which conditions the ringwoodite-bridgmanite phase transition can separate Earth's mantle into two-layered convection and quantify the efficiency of material exchange between upper and lower mantle. Phase transitions and their Clapeyron slope depend on local composition (e.g. from primordial to depleted mantle material), temperature and pressure conditions [1].

1. Introduction

While Earth is a planet where for present-day processes in the interior and at the surface we have a wealth of information (with surface-mantle interactions as depicted in Fig. 1), data for the early evolution of the planet is sparse. Apart from few zircon inclusions that date back to Hadean times, first rock samples are limited to the end of the Eoarchaean and to the Archean time. These rock samples, while providing interesting single observations of early Earth's surface, are only some pieces of a much larger puzzle that we still need to solve to be able to explain why Earth developed to the unique habitable planet that we know.

Mantle temperatures have been estimated to exceed present-day temperatures by ~150-200 degree few Gyrs back into Earth's history [2], leading to the conclusion that the mantle may have been separated into two convecting layers [3], with few or no material exchange in-between (see Fig. 2). Such a layering would have strong implications for the thermal and chemical evolution of the upper and lower mantle, as well as for volatile cycles (if volatile recycling did exist on Hadean and Early Archaean Earth) from surface to the deep mantle. It is not clear, however, how strong the layering effect was in the past, and neither if a similar state would have occurred during Earth's earliest evolution after magma ocean solidification. It is therefore crucial to understand how changing temperature and pressure conditions for different Earth mantle compositions from primordial to depleted mantle may influence the Clapeyron slope of the ringwoodite-bridgmanite phase transition, and under which conditions and at which time (if at all) the mantle may have been separated into two mostly distinct layers.

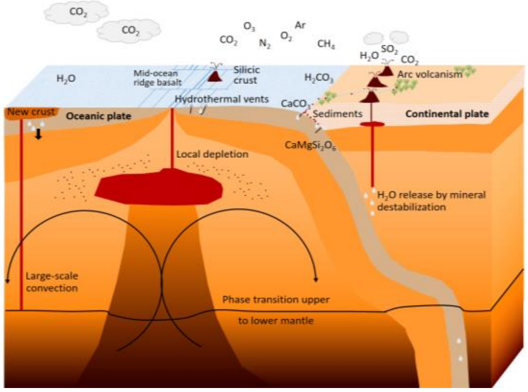

Figure 1: Sketch of Earth's present-day convective cycles from surface to interior. The depth profile of the sketch is logarithmic. [4]

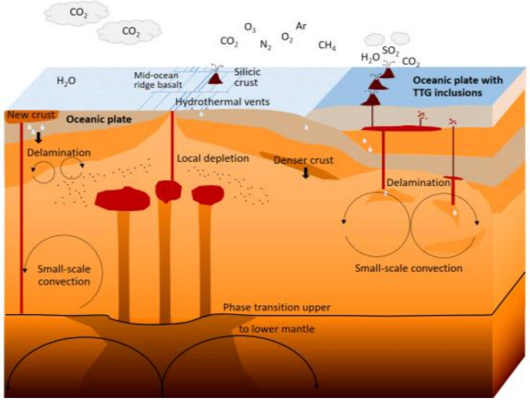

Figure 2: Sketch of possible Archaean's layered convection due to a hotter mantle. [4]

2. Model

The mantle convection code CHIC [5] solves the conservation equations of mass, momentum and energy in the compressible anelastic liquid approximation, to determine the mantle flow and thermo-chemical evolution of mantle rocks in a 2d spherical annulus. For all thermodynamic parameters (e.g. density ρ, thermal expansion coefficient α, specific heat capacity c_p), local values depending on the local composition (based on the Mg-Fe-Si-O-Al-Ca-Na system [6]), temperature and pressure are used.

We apply different initial temperature profiles varying from adiabatic profiles based on the melting temperature of the mantle (end of magma ocean phase) to non-adiabatic profiles assuming a magma ocean overturn after the solidification stage [7,8].

3. Mineralogy and phase transitions

The Clapeyron slope, which determines the strength of the mineral phase transitions, is evaluated locally depending on the entropy and density (and therefore depending on composition, temperature and pressure).

$$\gamma\left[\frac{Pa}{K}\right] = \frac{S_2 - S_1}{V_2 - V_1} * Mmol = \frac{S_2 - S_1}{\frac{1}{\rho_2} - \frac{1}{\rho_1}}$$

We use Perple_X [9] to determine the phase stability fields for the major mineral phases occurring on Earth [1], which are used in CHIC to define the phase transition pressures of Earth's dominant minerals.

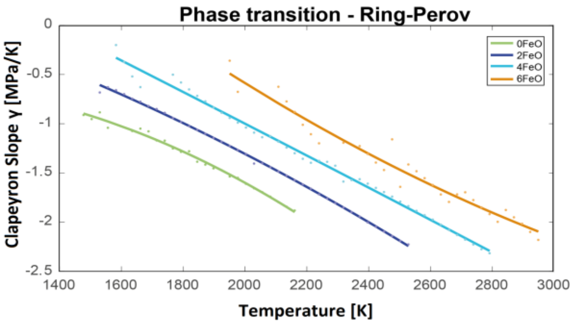

Figure 3: Clapeyron slope of the ringwoodite-bridgmanite phase transition depending on temperature and iron content calculated with Perple_X [9]. From [1].

EOS [6] are applied to obtain local information on thermodynamic properties for the mineral assemblage, including the Clapeyron slope (see Fig. 3) for accurate investigation of the influence of the phase transitions on the energy and momentum equation of the mantle. Figure 3 shows that the mantle composition (here looking at variable iron content based on pyrolite) strongly influences the strength of the Clapeyron slope. In addition, at lower temperatures, the negative Clapeyron slope is closer to zero, leading to a less strong effect on convective motion and temperature.

4. Summary and Conclusions

For a hotter (Archaean) Earth, the negative slope of the Clapeyron slope is larger, leading to a less efficient mixing between upper and lower mantle. In this study we quantify the effect of the ringwoodite-bridgmanite phase transition on mantle convection and mantle mixing. Changes in the convective style between two-layered and one-layered mantle convection can have global consequences due to a transition between heterogeneous mantle composition and efficient mixing consistent with the geological record [3].

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