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Influence of the viscosity of the early Earth's mantle on its cooling dynamics

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Abstract

1. Introduction

During its early evolution, the Earth's mantle likely experienced several episodes of complete melting due to giant impact heating, short-lived radionuclides heating, and viscous dissipation produced by metal/silicate separation [1]. After a first stage of rapid cooling and crystallization (i.e., Magma Ocean stage), the mantle cooling slowed down because the melt fraction reached a rheological transition occurring near a critical melt fraction of ≈30-40% [2, 3]. From this transition, the early mantle continued to crystallize from the bottom up to the surface, while thicker thermal boundary layers grew above and below this reservoir (i.e., Mushy stage). Once the mantle fully crystalized, large-scale geodynamical flows may eventually arise, resulting in global convection and modern tectonics [4].

2. Method

We develop a numerical model to monitor the thermal evolution of a cooling and crystallizing mushy mantle from an initially partially molten mantle [3, 5]. To this end, we use a 1D approach accounting for turbulent convective heat transfer occurring at a wide range of Rayleigh numbers. Our numerical model benchmarked with analytical solutions solves the heat equation in spherical geometry. This model also integrates recent and strong experimental mineral physics constraints, such as adiabatic temperature profiles and liquidus/solidus curves up 140 GPa, for a chondritic mantle composition.

3. Results

We followed the thermal evolution of a deep magma ocean with an initial temperature profile corresponding a temperature profile with a melt fraction of 40% throughout the whole mantle. Fig. 1 shows a reference case. Here the temperature initially rapidly decreases from the surface where heat is efficiently removed by conductive cooling and where a thin thermal boundary layer initially forms.

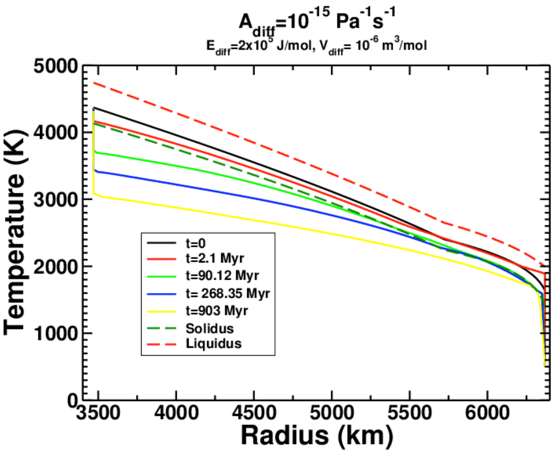

Figure 1: Time evolution of the temperature profile as a function of depth.

In the deepest part of the mantle, the temperature profile bends toward an adiabatic temperature profile. As a consequence, the deep solidification front starts from the CMB. After 100 Myr, most of the lower mantle temperatures are below the solidus, but two molten reservoirs remain. 270 Myr after the beginning of our simulation, the deeper one is located at a depth centered at 650 km, and the depth of shallower one ranges between 20 and 60 km. Finally, after 900 Myr of cooling, the entire temperature profile is below the solidus and the (i.e., the melt fraction is zero throughout the mantle). This solidification time scale is in agreement with the timescale proposed by [2], which proposed that the complete crystallization of the shallow early mantle could last more than 10^8 years.

4. Perspectives

Our preliminary results confirm that the cooling of the mushy mantle is strongly dependent on the rheological parameters of the solid fraction of the cooling mantle. In particular, depending on the activation energy, the activation volume and the viscosity pre-factor values, different regimes of mantle cooling arise, leading to important consequences for the characteristic timescales and the depths at which complete crystallization is achieved (Fig. 2).

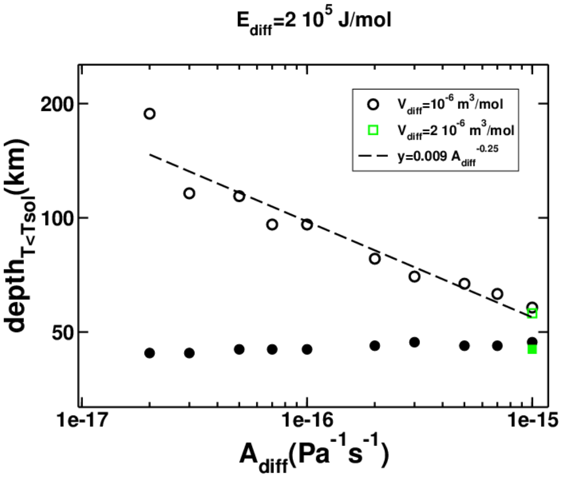

Figure 2: Depth at which the last layer of partially molten material solidifies as a function of the viscosity pre-factor value A_{diff}. In this figure, the activation energy E_{diff}= 2 10^5 J/mol. Open symbols represent the cases where no upper mantle is considered while solid symbols illustrate cases with an upper mantle. The cases with an activation volume V_{diff}=10^{-6} m^3 mol^{-1} are illustrated with black symbols and cases with V_{diff}=2 10^{-6} m^3 mol^{-1} are illustrated with green symbols.

The rheological parameters also strongly influence the thickness of the thermal boundary layers, which will govern the subsequent cooling of the early mantle from the end of the mushy stage up to present day. In this presentation, we will describe these processes and discuss the consequences of this early cooling event on the early mantle dynamics.

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