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Influence of Partial Melting on Mantle Convection in a Spherical Shell: Application to Mars

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Abstract

We present thermo-chemical 2D convection models that examine the influence of partial melt on the mantle dynamics of a one-plate planet such as Mars. In particular, the density decrease and the dehydration of the mantle associated with an increase of the viscosity due to partial melting have been studied. A major finding is that depleted buoyant mantle reservoirs that form by partial melting in the early evolution do efficiently remix with the lower mantle unless dehydration is considered.

1. Introduction

Partial melting plays an important role in the thermal evolution of terrestrial planets, being present during some period of planetary evolution [9]. In thermal evolution and convection models melt production has been considered by the release and consumption of latent heat, the formation of crust and the redistribution of radioactive heat sources [1, 2, 8]. When modeling partial melt it is important to consider the effects this process has upon mantle density and viscosity. Assuming fractional melting, where melt leaves the system as soon as it is formed, density of the mantle material ρ decreases with increasing degree of depletion due to compositional changes. Melt can also indirectly impact the viscosity of partially molten rocks through its influence on the water content [3]. Mantle material will be dried out due to partitioning of water from the minerals into the melt during the melting process resulting in an increase of viscosity. In the present study, we examine the influence of these effects on the mantle dynamics of Mars. In particular, we examine the existence of a depleted mantle layer and how long this layer can be stable during the evolution of Mars

2. Method

We use a 2D spherical convection model that can handle radial and lateral variations in the viscosity [4, 5]. We solve the equations for conservation of mass, momentum, energy and composition in a Boussinesq approximation with Newtonian rheology including latent heat consumption by partial melting. We further assume a cooling core boundary condition and decaying heat sources.
The density of solid residue varies between that of peridotite (3420kg/m^3) and harzburgite (3380kg/m^3), consistent to $\Delta\rho$= 36kg/m^3 upon 30% depletion - assuming further a linear variation with depletion [10]. Assuming a wet rheology and fractional melting, viscosity increases in the regions of partial melt due to dehydration. The viscosity of water depleted regions is a factor of 100 larger than the water-saturated rocks [3]. We use a partition coefficient of D=0.01 for accumulated fractional melting, i.e., for melt fractions larger than about 5 %, the remaining mantle material is depleted by about 90 % of the initial water content [6]. We further use D=0.1 consistent with some recent finding suggesting that dehydration is only effective for degree of melting larger than about 30 % [6].

3. Results

We have compared thermal evolution models with varying initial mantle temperatures and internal heating sources using parameters relevant to Mars. In the first cases, we only consider density changes but no changes on the viscosity due to dehydration. For high initial mantle temperatures T_m and internal heat sources H_0, a depleted and buoyant layer forms rapidly due to partial melting that convects separately early in the evolution. During the thermal evolution this buoyant layer is eroded – although a 'new' depleted layer is subsequently formed as long as partial melt is produced – and eventually efficient remixing with the lower mantle takes place. For initially smaller melt fraction, for instance due to lower initial mantle temperatures, the depleted layer is not buoyant and thick enough to convect separately and remixes faster with the lower mantle In Figure 1 we show a temperature and composition snapshot for a thermal evolution with T_m=2000K and H_0=7.3e-8W/m^3 at 2.25 Ga.

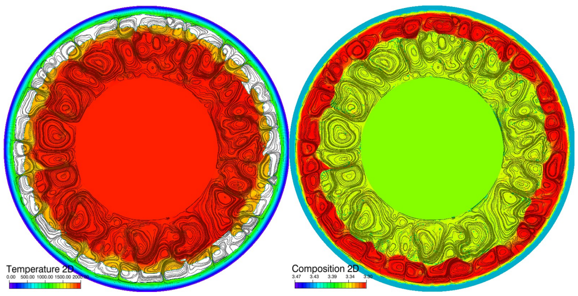

Figure 1: Temperature (left) and composition (right) for initial mantle temperature T_m=2000K and internal heat sources H_0=7.3e-8W/m^3. The white area indicates the partial melt zone. A two layered convection pattern evolves with a strongly depleted layer in the upper mantle and a less depleted lower mantle layer.

The depleted layer has also an insulating effect, which prevents an efficient cooling of the interior. This effect can be observed in Figure 2 for different initial mantle temperatures and internal heat sources.

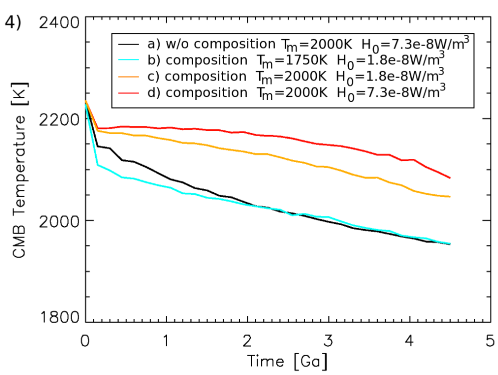

Figure 2: CMB temperature as a function of time for various initial mantle temperatures and internal heat sources

Remixing of the depleted layer with the lower mantle can be retarded or even prevented by a viscosity increase due dehydration. We will show the time scale for mixing dependent on the initial thermal conditions and the efficiency of dehydration.

3. Summary and Conclusions

In this preliminary study we investigate both, i.e. the effect of density and viscosity changes due to partial melting on the mantle dynamics using 2D spherical convection models [4, 5]. The results suggest that early mantle reservoirs will efficiently remix during the Martian evolution unless dehydration and the associated stiffening of the mantle material takes place. The formation of early mantle reservoirs that did not remix since their formation has been suggested by SNC geochemistry [7].

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