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Thermo-chemical Evolution of a One-plate Planet: Application to Mars

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Abstract

Melt generation in a planetary mantle is a complex process that has a strong influence on the thermo-chemical evolution of a planet. In most 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 (e.g., [1, 8]). In the present study we examine the influence of partial melt on the mantle dynamics of a one-plate planet such as Mars using 2D thermo-chemical convection models. All considered effects, i.e., variation of the solidus temperature, dehydration of the mantle and variation of the mantle composition due to melting tend to reduce the total amount of melting and the degassing of a one-plate planet.

1. Introduction

The thermo-chemical evolution of a one-plate planet like Mars strongly influences its atmospheric evolution via volcanic outgassing, which is linked to the production of partial melt in the mantle. When modeling partial melt it is important to consider the effects this process has upon the melting temperatures, the density and the viscosity of the mantle material. 1) Melt influences the melting temperature in case of melt extraction. Due to the loss of low-melting point components, the solidus increases with increasing degree of depletion by 150-200 K [5]. 2) Density of the mantle material decreases due to melting. A compositional mantle variation arises from the extraction of partial melt, which leaves behind a residuum modified in modal mineralogy. Mantle material depleted in crustal components is expected to be more buoyant than its fertile parent material. 3) Melting can indirectly impact the viscosity of the mantle [2]. Mantle material will be dehydrated due to partitioning of water from the minerals into the melt during the melting process. As a consequence, the viscosity of water depleted regions increases more than two orders of magnitude compared to the water-saturated rocks [4].

2. Method

We use the 2D-3D spherical convection code GAIA [3] to solve the conservation equations for an incompressible Boussinesq fluid assuming Newtonian rheology and an infinite Prandtl number considering a one-plate planet with cooling boundary conditions and decaying radioactive elements. We assume fractional melting, compositional variations, dehydration of a wet planetary and melting temperature changes as a consequence of mantle melting. A compositional field is used to track changes in the mantle mineralogy and adapt the melting temperature accordingly whereas a concentration field calculate the water concentration in the residual mantle at every time-step. The model was applied to Mars using constraints inferred by the observed volcanic history suggested by space mission data (e.g., Mars Express) and the data analyzed from the SNC meteorites [7].

3. Results

Increasing the solidus of depleted mantle material, results in a decrease of the melt production rates as compared to a model with constant solidus. Figure 1 shows the amount of depletion in percent for a model with and without solidus variation. The formation of a depleted buoyant mantle layer due to melting is shown in Fig. 2a. The presence of this buoyant layer reduces the melt production rate in contrast to cases where the mantle is homogenously mixed. However, it is interesting to note that the depleted layer is eroded with time by convection (Fig 2a). Eventually mixing takes place and separate mantle reservoirs cannot be sustained over the entire thermo-chemical evolution as suggested for Mars by the SNC meteorites. Assuming a wet rheology, dehydration of the mantle results in stiffening of the mantle material. Both composi-

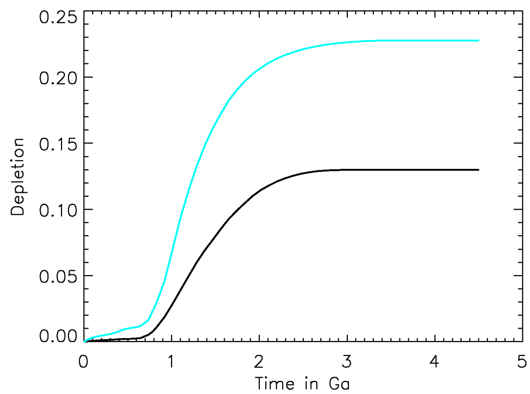

Figure 1: The melt extraction in percent: solidus temperature increases with increasing degree of depletion (black) and no changes in the solidus temperature due to depletion of mantle material(cyan).

tional changes and dehydration favour the formation of a buoyant depleted mantle layer and separate mantle reservoirs can be observed over the entire planet's evolution (Fig. 2b). Models considering dehydration and density changes on the mantle show reduced outgassing rates by a factor of about two in comparison to models which neglect the effects of dehydration.

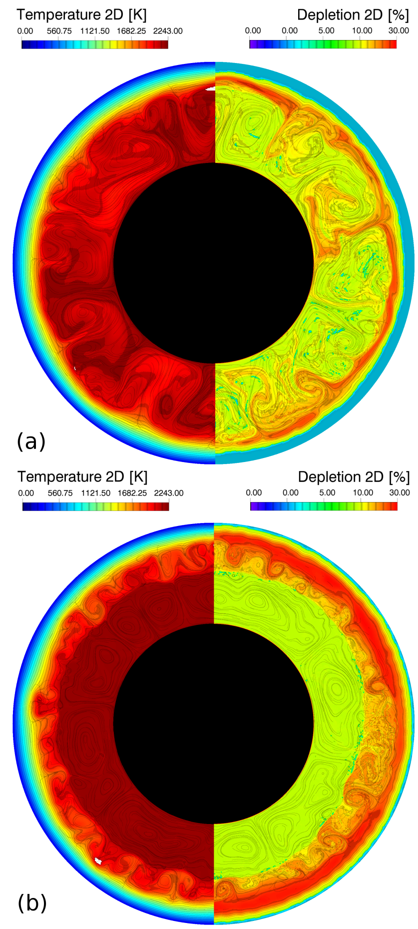

Figure 2: Temperature (left) and depletion (right) for a dry rheology considering density changes (a) and a wet rheology considering both density changes and dehydration due to partial melt (b) at 4.03 Gyr.

4. Summary and Conclusions

The results suggest that early mantle reservoirs formed by partial melting will efficiently remix during the Martian evolution unless dehydration and the associated stiffening of the mantle material take place. The effects of partial melt on viscosity and mantle density reduce the efficiency of outgassing of a one-plate planet. This implies that in the case of Mars the atmospheric conditions for fluid water at the surface are even less favourable than already suggested by thermo-chemical evolution models assuming a homogeneously mixed mantle [6].

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