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The Efficiency of Magma Ocean Cumulate Overturn using a strong temperature-dependent Viscosity

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The impact heat accumulated during the late stage of the planetary accretion can melt a significant part or even the entire mantle of a planetary body - producing a global magma ocean. The subsequent cooling of the interior causes the magma ocean to freeze rapidly from the core-mantle boundary to the surface due to the steeper slope of the mantle adiabat compared to the slope of the solidus. Freezing of a magma ocean is a highly complex process, which has been investigated by several authors [e.g. 1, 2].

In the present work, we assume fractional crystallization of such a magma ocean. For fractional crystallization, dense cumulates are produced with time close to the surface, largely due to iron enrichment in the evolving magma ocean liquid [2]. A gravitationally unstable mantle forms, which is prone to overturn. We investigate the cumulate overturn and its influence on the thermal evolution of Mars using the 3D spherical/2D cylindrical mantle convection code Gaia [3, 4]. We present different simulations using the initial conditions from [2] and a strong temperature dependence of the viscosity.

Our simulations show that using a rather weak temperature dependence of the viscosity (e.g. using an activation energy of 100 kJ/mol as in [2]) results in a complete overturn (i.e. dense cumulates from the surface sink to the core mantle boundary). A stable density gradient evolves in the mantle, in which the convection ceases and cannot be rejuvenated during the entire evolution of Mars even with heating by radioactive elements. The lack of convection, however, is not compatible with the observed long-standing volcanic activity and elastic thickness estimates on Mars.

When using a strongly temperature dependent viscosity (e.g. typical activation energy for mantle material of 300 kJ/mol), a stagnant lid forms rapidly on top of the convective interior preventing the uppermost dense cumulates to overturn. The formation of the lid is also given assuming the high surface temperatures due to the efficient greenhouse effect caused by the degassing of the freezing magma ocean [2]. Below the dense stagnant lid, an initially stable density gradient settles which is, however, less steep than in the previous case. In that case, convection continues and the mantle is continuously remixed. The convection pattern is dominated by small scale structures, which is not consistent with the large scale volcanic surface structures. Moreover, the global primordial high density crust as suggested by this scenario is at odds with the assumed low density of the southern hemisphere [5].

We conclude that a fractionated global and deep magma ocean seems to be difficult to reconcile with observations. Further investigations assuming for instance a hemispherical or shallow magma ocean will be studied.

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