Onset of solid-state mantle convection and mixing during magma ocean solidification

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I. INTRODUCTION

The initial compositional distribution of the mantle depends crucially on the crystallization sequence resulting from the solidification of a magma ocean[1]. Such distribution is important as it provides the starting conditions for the early dynamics of the mantle and its subsequent evolution[2,3]. Yet theonset of solid-state convection prior to complete solidification of a magma ocean (over timescales compatible with solidification under a thick atmosphere [4]) can partly or even completely erase the radial heterogeneity in the mantle by efficiently mixing the solid cumulates. Moreover, the temperature profile attained after the crystallization of a magma ocean is completed is likely to have a dramatic influence on the subsequent tectonic regimes and on the long-term evolution of the mantle[5]. Here we use numerical simulations of mantle convection to demonstrate the feasibility of the above scenario in the case of Mars.

2. MODEL

We simulate the convection of the solid cumulates underlying a magma ocean that crystallizes from the bottom up to the surface[1]. We use the code GAIA[6] to self-consistently solve the conservation equations of mass, momentum, thermal energy, and transport in a cylindrical domain whose upper boundary moves upward with time. The solidification front is defined as the intersection between the temperature profile and the solidus. We use a realistic temperature and pressure dependent Arrhenius rehology. In addition, we take into account the formation of an unstable compositional gradient that results from the preferential partitioning of heavy incompatible elements in the crystallising magma ocean (Fig. 1).

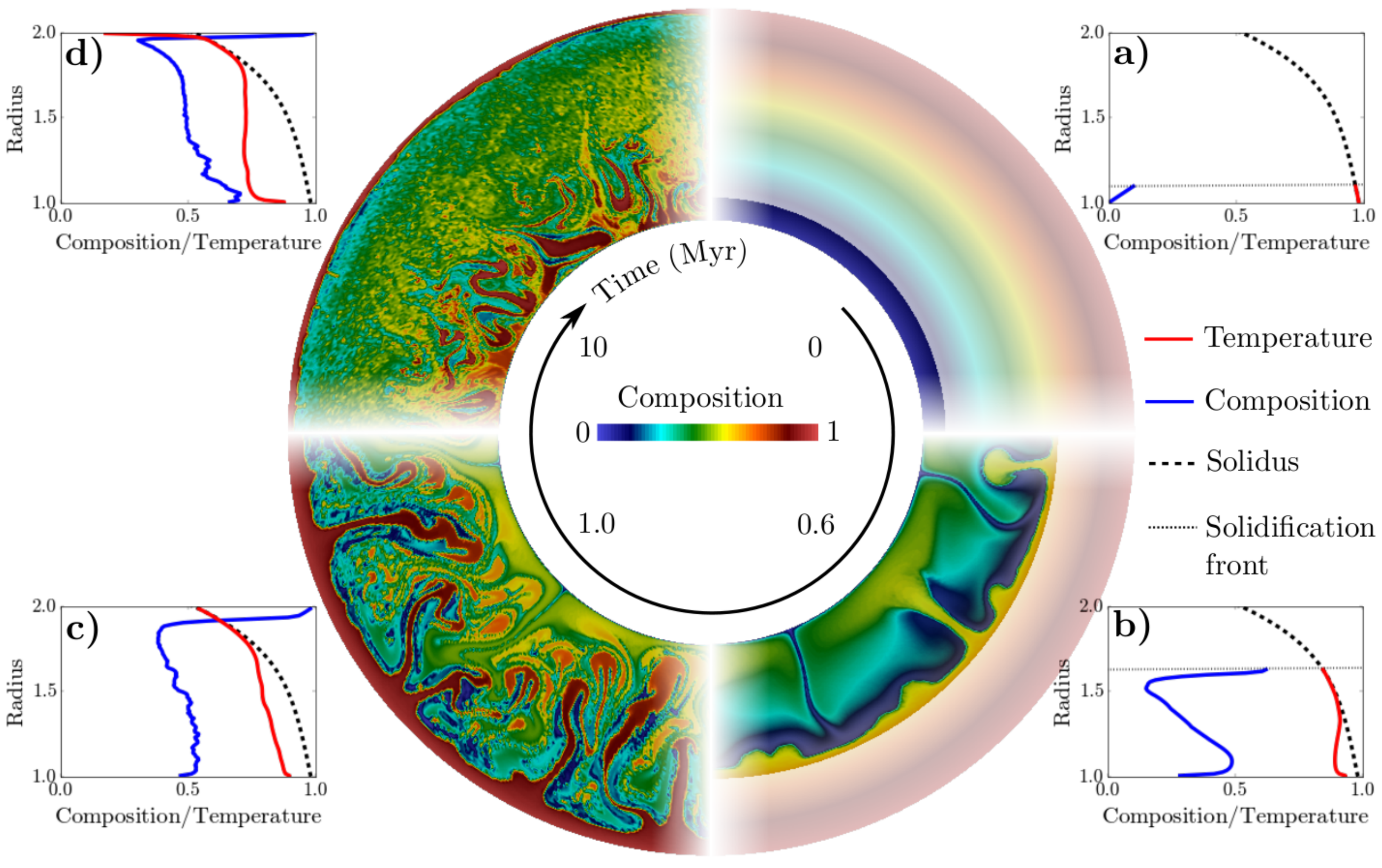

Figure 1. Time evolution of a simulation with Ra=10^9, B=1, t_{MO}=1 Myr, with temperature and composition profile at a) the bgining of the simulation, b) after 0.6 Mar, c) after 1 Myr (end of solidification) and d) after 10 Myr. The transparent part of the snapshot in a) and b) represents the domain of the solidifying magma ocean.

3. PARAMETERS

- **Rayleigh number** (Ra) at the CMB between 2x10^7 and 2x10^9 corresponding to reference viscosities at 3 GPa and 1600 K between 1.3x10^{20} Pa s and 1.3x10^{22} Pa s to account for diffusion creep in hydrated and dry olivine.

- **Buoyancy ratio** (B) between 0.2 and 0.8 (i.e. ratio of compositional to thermal buoyancy) to account for the effects of fractional crystallisation of the magma ocean.

- **Solidification time** (t_{MO}) between 0.1 and 10 Myr reflecting a possibly long lived magma ocean solidifying under a blanketing atmosphere generated upon magma ocean degassing.

4. RESULTS

- **Onset of solid-state convection** before complete solidification is acheived for long lived magma oceans and high Ra, and also enhanced by high values of B (Fig. 2).

- **Mixing** of the solid cumulates occurs through convective motions. An early onset of convection ensures a better mixing than a final global overturn because it progressively erases the compositional gradient (Fig. 3 and 4).

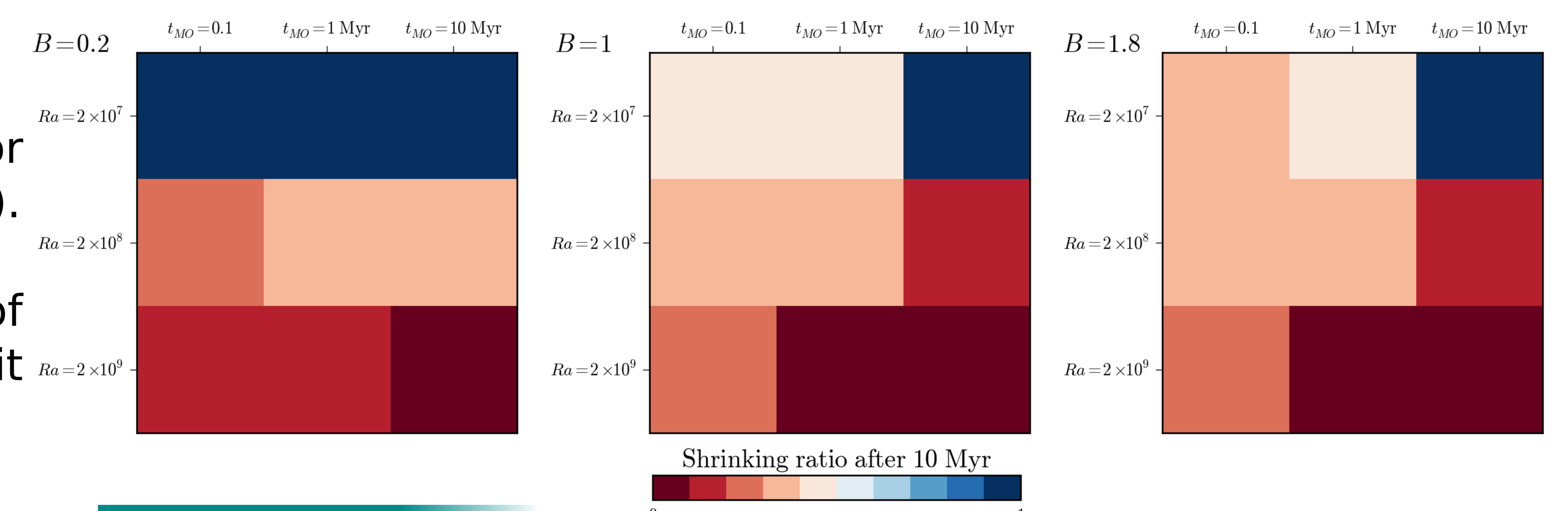

Figure 4. Mixing diagram covering the whole parameter space. Mixing is quantified by shrinking ratio, which expresses the amount by which the initial size of a mantle parcel has been reduced as a result of the deformation along its trajectory. A shrinking ratio of 1 means that the aspect ratio of such a parcel has remained unchanged while a shrinking ratio close to 0 marks an important deformation. Shrinking ratios are evaluated after 10 Myr.

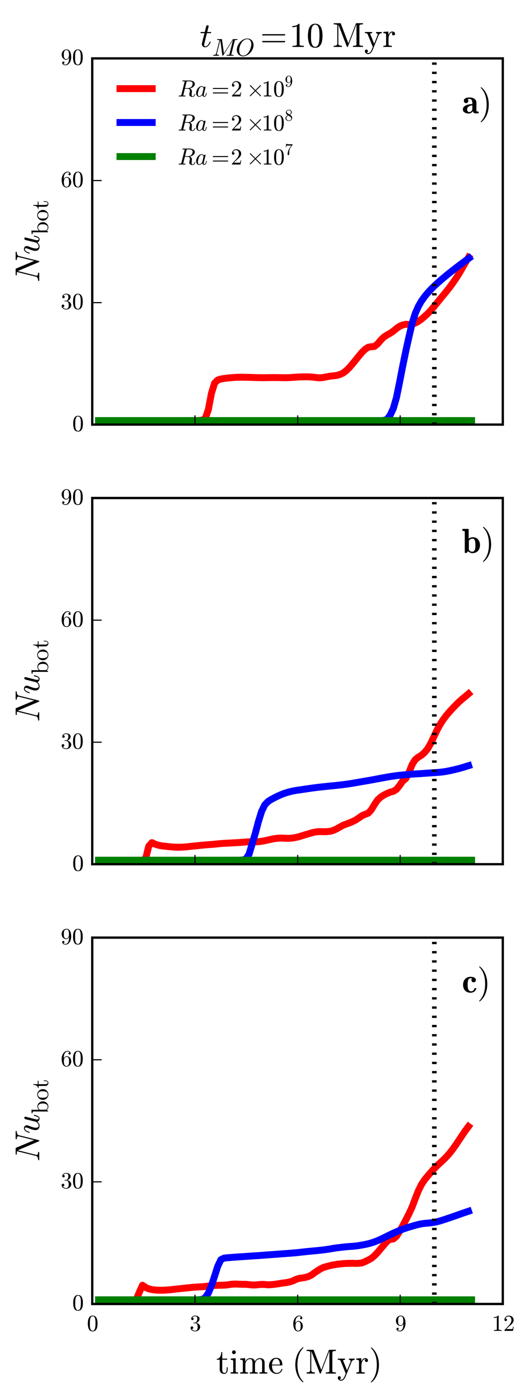

Figure 2. Time series of the Nusselt calculated at the CMB for t_{MO}=10 Myr, and a) B=0.2, b) B=1 and c) B=1.8. A Nusselt number greater than 1 is indicative of the onset of convection.

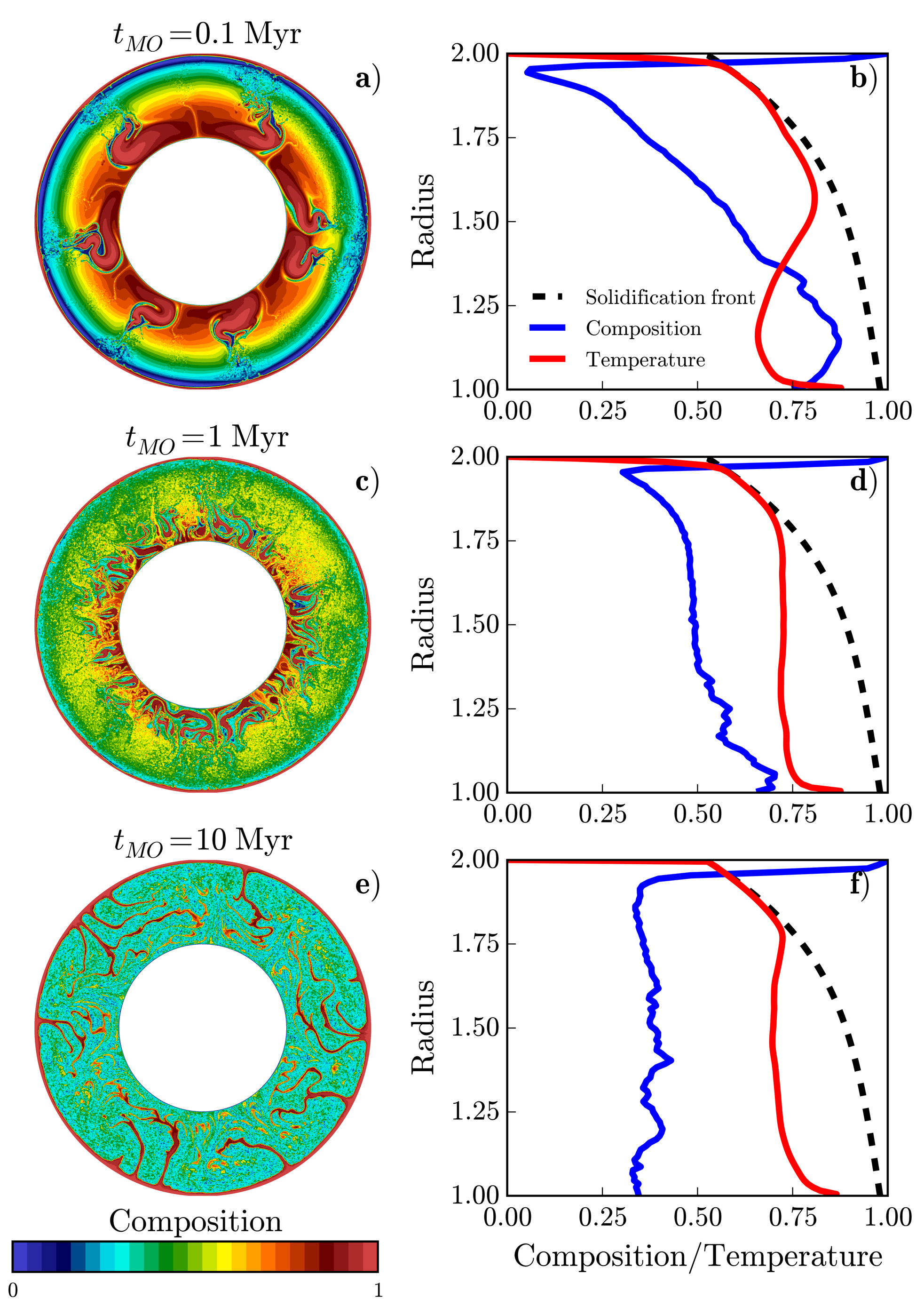

Figure 3. Snapshots and temperature and composition profiles after 10 Myr for 3 simulations: Ra=10^9, B=1 Myr and t_{MO}=0.1 Myr (a), b)), t_{MO}=1 Myr (c), d)) and t_{MO}=10 (e) and f)).

5. CONCLUSIONS

- Compositional mixing of the mantle can be acheived by solid-state convection during the magma ocean solidification, preventing a global mantle overturn.

- The thermal and compositional state of the post-magma ocean mantle depends on the reference viscosity, buoyancy ratio and crystallization time, which, in turn, can have a fundamental influence on the subsequent tectonic regime and thermochemical evolution.

References

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