ONSET OF SOLID-STATE CONVECTION AND MANTLE MIXING DURING MAGMA OCEAN SOLIDIFICATION. M. Maurice[1], N. Tosi[1,2], H. Samuel[3], A.-C. Plesa[1], C. Hüttig[1] and D. Breuer[1], [1]Deutsches Zentrum für Luft- und Raumfahrt, Berlin, Germany, [2]Technische Universität Berlin, Germany, [3]Institut de Recherche en Astrophysique et Planétologie, Toulouse, France.

Introduction: The energy sources involved in the early stages of the formation of terrestrial bodies can induce partial or even complete melting of the mantle, leading to the emergence of magma oceans [1,2]. Because of turbulent mixing in the low viscosity magma ocean, its temperature profile is likely adiabatic. Due to the steeper radial gradient of the liquidus relative to the adiabat, the solidification of the magma ocean occurs from the bottom up to the surface. Preferential partitioning of heavy elements in the melt causes the formation of an unstable density profile upon fractional crystallization of the magma ocean [2], which can eventually lead to a large-scale overturn resulting in a stably-stratified mantle [3,4]. Outgassing of an insulating atmosphere during the magma ocean crystallization can dramatically lower the radiative heat escape at the surface of the planet thereby slowing down the solidification process [5]. If the solidification is slow enough, solid-state convection can start mixing the deep solid cumulate before the end of the magma ocean solidification and hence progressively erase the density anomalies generated through the fractionation process. Instead of a post-solidification whole-mantle overturn [2,3,4], a largely homogeneous mantle, prone to long-term thermal convection, follows directly the magma ocean phase and provides an initial configuration for the study of early tectonics [6].

Model: We use the finite-volume code GAIA [7] to compute the dynamics of the growing solid cumulates [8]. We self-consistently solve the conservation equations of mass, momentum, energy, and composition in a 2-D quarter cylinder grid whose outer radius increases with time to simulate the rise of the crystallization front during magma ocean cooling and solidification. We use a temperature- and depth-dependent rheology and a parametrized yield stress to account for plastic yielding near the end of solidification. The initial temperature field is set at the solidus and we use an initial linear unstable profile for the compositional density to simulate fractional crystallization.

Results: We study the influence of three model parameters: the thermal Rayleigh number (Ra), the buoyancy ratio (B), which accounts for compositional density contrast due to fractionation, and the solidification time of the magma ocean.

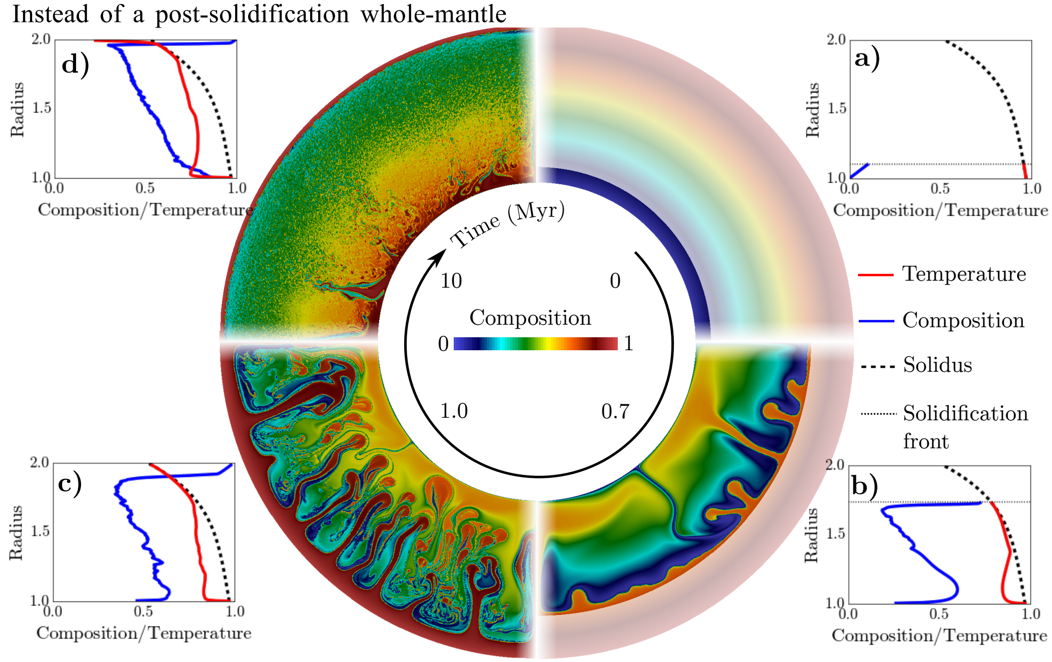

Figure 1: Snashots of the non-dimensional composition field and coresponding laterally averaged profiles of temperature (red), composition (blue) at four different times for a representative simulation characterized by the onset of convection during magma ocean solidification. The opaque domain in the snapshots represents the solid region where the equations of thermochemical convection are solved.

Onset of solid-state convection. For the sets of parameters least prone to convection (e.g. relatively low Rayleigh number and short solidification time), the mantle solidifies completely before the onset of convection, which then starts with a whole-mantle overturn occurring beneath a thin stagnant lid. However, for high Rayleigh numbers, corresponding to low reference viscosities, high buoyancy ratios and/or long solidification times of the magma ocean, the onset of solid-state convection in the cumulates occurs before complete solidification of the mantle (we term it then «early onset» of convection) and starts mixing the already solidified part (Figure 1).

Mixing. For each case, we compute the rate of mixing achieved in the mantle after 11 Myr (which is one million year after the complete magma ocean solidification of the slowest cases) in terms of the shrinking factor [9]. The shrinking factor decreases from one (in the case where no convective motion takes place) towards 0 when mixing increases. In Figure 2 we summarize the final values of the shrinking factor. Ra has a straightforward effect on mixing in that it promotes intense convection. A high value of B promotes progressive mixing in the case of early onset of convection, but also causes a rapid overturn that results in a very stable stratification in the case of late onset of convection, thus decreasing mixing efficiency. A long solidification duration also favours progressive mixing in the case of early onset of convection. However, it delays the initial overturn in the case of late onset of convection, reducing convective mixing time and resulting in less mixed mantle after 11 Myr.

Conclusion: This work shows that for realistic sets of parameters, solid-state convection is likely to begin during the solidification of the magma ocean and can progressively mix the fractionated solid cumulates. The mantle can be largely homogenized by the end of the solidification of the magma ocean resulting in a different structure of the early solid mantle in comparison with a post-solidification large scale overturn.

References:

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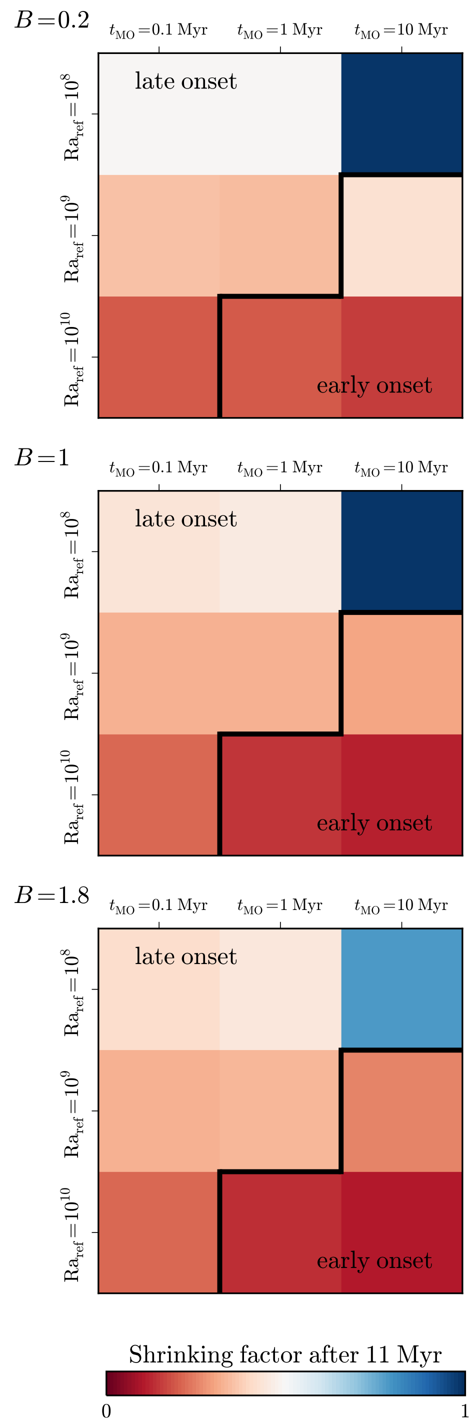

Figure 2: Final value of the shrinking factor for all parameter combinations tested. Small values are indicative of a well mixed mantle.