



Timing of mantle overturn during magma ocean solidification

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ABSTRACT

Solidification of magma oceans (MOs) formed early in the evolution of planetary bodies sets the initial condition for their evolution on much longer time scales. Ideal fractional crystallization would generate an unstable chemical stratification that subsequently overturns to form a stably stratified mantle. The simplest model of overturn assumes that cumulates remain immobile until the end of MO solidification. However, overturning of cumulates and thermal convection during solidification may act to reduce this stratification and introduce chemical heterogeneity on scales smaller than the MO thickness. We explore overturning of cumulates before the end of MO crystallization and the possible consequences for mantle structure and composition. In this model, increasingly dense iron-rich layers, crystallized from the overlying residual liquid MO, are deposited on a thickening cumulate layer. Overturn during solidification occurs if the dimensionless parameter, R_c , measuring the ratio of the MO time of crystallization τ_{MO} to the timescale associated with compositional overturn $\tau_{ov} = \mu/\Delta\rho gH$ exceeds a threshold value. If overturn did not occur until after solidification, this implies that the viscosity of the solidified mantle must have been sufficiently high (possibly requiring efficient melt extraction from the cumulate) for a given rate of solidification. For the lunar MO, possible implications for the generation of the Mg-suites and mare basalt are suggested.

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1. Introduction

Models of planetary accretion have shown that giant impacts during planet formation may likely melt terrestrial planets substantially (Safronov, 1964, 1978; Hostetler and Drake, 1980; Chambers and Wetherill, 1998; Canup, 2008; Nakajima and Stevenson, 2015). Evolution of such magma ocean(s) (MO) sets the initial conditions for long-term evolution of planetary interiors. Better understanding MO evolution is also motivated by geochemical evidence showing very early fractionation of the mantle of the Moon and Mars (Smith et al., 1970; Warren and Wasson, 1979; Blichert-Toft et al., 1999; Borg et al., 2003; Borg and Draper, 2003). Interestingly, it has been reported that the mantle sources of martian meteorites show strong similarities with lunar mantle sources. Sm/Nd, Rb/Sr and Lu/Hf systematics indicates that the composition of martian meteorites sources could be explained by a mixing of lunar-like compositions, similar to the depleted lunar mafic materials and the enriched KREEPy components (Borg et al., 2003). One of the key questions regarding mantle structure is the degree of mantle mixing and how dense components and heterogeneities containing heat producing elements are spatially distributed. Is the mantle

layered? If so, is it stably stratified? Mantle dynamics governs core cooling which is key for magnetic field generation by core dynamo. Surface and subsurface of planets are shaped by mantle dynamics through magmatism and tectonics. Constraining the structure of solid mantles that emerge from MO solidification is thus important but remains poorly understood.

The initial solid mantle structure depends on the details of how the MO (MO) solidified. Two key aspects are: (1) bottom-up/top down crystallization which controls where the solid mantle accumulate and (2) batch/fractional crystallization which controls extent to which solidification generates compositional heterogeneities. For planetary bodies smaller than the Earth or for those with shallow MOs, silicate MOs would crystallize from the bottom to the top as the liquidus first intersects the adiabat at the bottom of the mantle (Elkins-Tanton, 2012). For large silicate planets (Earth-size and larger), crystallization of a sufficiently deep MO might occur in a top-down fashion due either to the competition between liquidus and adiabat, or the density contrast between melts and solids (Labrosse et al., 2007; Stixrude et al., 2009; Boukaré et al., 2015; Boukaré and Ricard, 2017). In this study, we focus on the structure of solid mantle crystallizing from the bottom to the top by batch or fractional crystallization.

As the crystallization front moves towards the surface, the composition of mineral phases added on top of the solidified mantle evolves with pressure and composition of the residual liquid MO

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(Solomon and Longhi, 1977; Warren, 1985). For the Moon, bottom-up fractional crystallization has been proposed to generate an unstable chemical stratification in the solid mantle susceptible to overturn (Hess and Parmentier, 1995 and references therein). The lunar overturn model is a good candidate for explaining the deep origin of early magmatism (Hess and Parmentier, 1995; Shearer et al., 2006), the hemispheric asymmetry of mare basalts (Parmentier et al., 2002), and might be consistent with an early generation of a lunar core dynamo (Stegman et al., 2003). The cumulate overturn hypothesis has also been applied to other planetary bodies such as the Earth (Elkins-Tanton, 2008) and Mars (Elkins-Tanton et al., 2003, 2005).

Current models of lunar mantle overturn considered generally post MO overturn where the unstably stratified cumulates remain immobile until the end of MO solidification. However, cumulates are unstably stratified as they form. Whether it waits until after complete solidification to overturn, or overturns (or convects) during solidification is governed by a number of factors that we aim to determine in this study. Models of cumulate overturn have pointed out that the growth time of Rayleigh–Taylor instabilities – associated with unstable chemical stratification – may be smaller than the time of MO crystallization (Hess and Parmentier, 1995). If the cumulate overturns during its solidification, the early lunar mantle dynamics would differ from the post-solidification overturn models. In particular, the chemical layering created by fractional crystallization would be partially homogenized by mantle stirring. The driving forces for a post-MO solidification degree one overturn would be reduced.

This study aims to quantify the timing of mantle overturn relative to the time of MO crystallization and the amount of mantle mixing that occurs. We explore the behavior of a simple model in which a viscous cumulate layer thickens progressively by solidification of the overlying well-mixed liquid MO. In the case of fractional crystallization, fractionation of Fe/Mg between solid and liquid results in iron enrichment of residual liquid. Progressively iron enriched MO increases the density of solids forming from the liquid. We solve the Stokes flow in the solidifying MO cumulate in 2D Cartesian geometry.

Recently, two studies have investigated the onset of thermo-chemical convection in the cumulate for the case of Mars (Maurice et al., 2017) and the Earth (Ballmer et al., 2017b). These studies have shown that thermo-chemical convection in the cumulate layer can start before the end of MO solidification affecting the initial degree of mantle mixing. By varying the cumulate viscosity, the rate of MO solidification, the modes of crystallization (i.e., equilibrium vs. fractional) and the compositional density contrast between Mg-rich and Fe-rich mineral phases, Maurice et al. (2017) and Ballmer et al. (2017b) have shown that solid-state mantle convection during MO solidification can lead to various pictures of primitive mantle mixing. Maurice et al. (2017) have quantified the effects of convective vigor on mantle mixing during MO solidification. Such early mantle dynamics can affect the long-term preservation of deep geochemical reservoir (Ballmer et al., 2017b). In contrast to these previous works that have explored a relevant range of parameters, the present study aims to determine dimensionless criterion that characterize the timing of thermo-chemical convection relative to MO solidification. The competitive effects of cumulate viscosity and MO cooling rate, that has been pointed in these previous study (Maurice et al., 2017; Ballmer et al., 2017b), are here quantified. This dimensionless analysis allows to better illustrate the role of planetary size, MO cooling history and cumulate viscosity regarding the issue of early mantle mixing.

The simplicity of this approach allows the identification of two crucial aspects of the dynamics affecting the initial degree of mantle mixing. The degree of mantle mixing is controlled by the vigor of syn-solidification convection but also by the rate at which ma-

terials of distinct composition are added to the solid mantle. These two dynamic processes can be captured by the thermal Rayleigh number, Ra which is a measure of the convective vigor and a dimensionless parameter R_c , which is a measure of the ratio of MO crystallization time, τ_{MO} , and the timescale associated with chemical overturn. The dimensionless parameter R_c must exceed a critical value for having a syn-solidification overturn. For a given convective vigor, syn-solidification convection increases the degree of mantle mixing. Indeed, mixing progressively small amount of dense components is much easier than mixing instantaneously large amounts of dense materials. By quantitatively linking mantle viscosity, MO crystallization time and degree of mantle mixing, the present work offers a basic model to relate some aspects of early planet evolution such as timing and spatial distribution of magmatism, compositional variability of lavas and the amount of heat extracted from the mantle.

2. Model

2.1. General approach

To explore the role of mantle flow during MO solidification, a simple model is used in which a partially molten viscous cumulate layer thickens progressively by solidification of an overlying well-mixed, liquid MO. The top of the cumulate layer, defined by a freezing temperature that increases with depth, thickens with time as the remaining liquid layer cools. The freezing temperature being the liquidus temperature of the residual liquid layer. Here, the case of fractional solidification is adopted where Fe/Mg fractionation between solid and liquid results in iron enrichment of the residual liquid, thus progressively increasing the density of solids forming from this liquid. The case of batch crystallization (with no chemical fractionation) associated with the issue of retained melt in the cumulate is discussed later. Viscous flow in the cumulate layer occurs in response to the unstable compositional and/or thermal stratification. In turn, the viscous flow causes compositional mixing and convective heat transport. Rather than modeling a particular MO scenario, the goal of the current study is to investigate the effects of mantle thermal stratification resulting from the evolving freezing temperature, chemical stratification (generated by the mode of solidification) and MO solidification rate on the solid-state cumulate convection.

In this model, the MO cumulate grows by adding layers of small but finite thickness at a prescribed, constant rate. τ_{MO} is the time for solidification when the thickness of the cumulate layer, h , reaches the initial MO thickness, H . In an actual MO, this rate would vary and reflect the rate of heat loss from the planetary surface. The top of the cumulate layer corresponds to the rheologically critical melt fraction (RCMF) at which the cumulate viscosity becomes close to that of the solid (Goetze, 1977; Arzi, 1978; Costa, 2005). The upward velocity of this crystallization front is controlled by both the deposition rate and compaction rate of cumulates. If the crystallization front velocity is less than a critical value, compaction occurs in two zones, one near the crystallization front and the other at the bottom of the cumulates. These zones separated by a layer of uniform melt fraction (Shirley, 1986). The critical crystallization front velocity, v_i is controlled by the buoyant percolation velocity, $v_i \sim K \Delta \rho^{s-l} g / \mu_l$ where K is the permeability, $\Delta \rho^{s-l}$ is the density contrast between melt and solid, g is the gravity acceleration and μ_l is the melt viscosity. The thickness of the compaction zone just beneath crystallization front depends on the compaction length, and the residual melt fraction beneath it is controlled by buoyant melt percolation. The segregation of crystals and melt either by settling of dense crystals above the RCMF boundary or compaction in partially molten mantle beneath it is a process not treated explicitly in this model. Here, the upward

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