DID LUNAR MANTLE OVERTURN BEFORE THE END OF MAGMA OCEAN SOLIDIFICATION?

C.-E. Boukaré, E.M. Parmentier and S.W. Parman, Department of Earth, Environmental and Planetary Sciences, Brown University, Providence RI 02912 (charles-edouard_boukare@brown.edu).

Summary: Most models of the early evolution of the Moon's interior are based on post lunar magma ocean (LMO) overturn, in which the cumulate pile remains "immobile" until the end of magma ocean solidification [e.g., 1, 2]. However, geodynamic studies have shown that the time required for Rayleigh-Taylor instabilities to grow in the stratified cumulate may be smaller than that for magma ocean crystallization [1]. If the cumulate pile (i.e., comprising the young solid lunar mantle) overturns during its solidification, then the composition of the mantle sources for early lunar magmatism might differ significantly from the static crystallization models. This study uses coupled geodynamic and geochemical modeling to explore cumulate overturn before the end of magma ocean crystallization. The model is highly simplified, but provides fundamental insights into the cumulate dynamics.

Introduction: Since the earliest study of the Apollo lunar samples, the LMO hypothesis remains the cornerstone for explaining the current structure of the Moon and the ages of the returned rock samples [e.g. 3]. Here, fractional crystallization generates the first heterogeneities of the solid mantle. The current view of the LMO evolution relies generally on an idealized case where these heterogeneities pile up (i.e., stagnant crystallization) to form a primitive chemical layering, which then overturns due to the higher density of late stage, Fe-rich cumulates. If this assumption is correct, we must be able to link this primitive stratigraphy to the subsequent lunar magmatic episodes (i.e., age, composition and spatial distribution of magmatism). However, post-LMO overturn seems difficult to reconcile with the age of the oldest Mg-suite rocks which are almost contemporaneous with the ferroan anorthiste (FAN) crust [4,5]. Petrographic studies have also revealed that lunar crust formation may be much more complex than simple intrusion of young Mg-suite rock into old FAN [6]. Here, we explore the conditions under which the LMO could have experienced overturn prior to complete solidification.

Density stratification of the crystallizing mantle: The density stratification of the cumulate pile is the driving force of the overturn. In this study, we consider an simplified case where a liquid layer lies above a solid viscous layer (the cumulate mantle) (Fig. 1). We assume that the density stratification of the solid layer depends solely on its iron-content. As solidification occurs, the liquid layer becomes more enriched in iron (iron is slightly incompatible), as does the solid which crystallizes in equilibrium with this residual liquid. For simplicity, we consider at the interface between the idealized liquid layer and the solid layer (Fig. 1), follows thermodynamic equilibrium, $x_s(h(t)) = Dx_l(t)$ (1), where the thickness of the solid mantle, $h(t)$, depends on time, t, x_s is the iron content of the solid layer at the depth associated to the thickness$h$, $D$is the iron partitioning coefficient between melt and solid, and $x_l$is the iron-content of the residual well-mixed liquid layer.

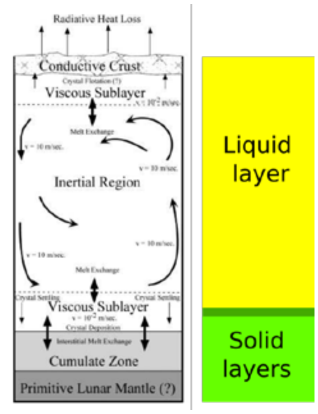

Figure 1. (Left) Schematic of the structure of the LMO [5]. (Right) Structure of the LMO idealized as a top liquid layer (yellow) and a bottom solid layer (green) that thickens with time. The newly crystallized solid layer (dark green) forms in equilibrium with the overlying liquid.

Physical description of the dynamics: We solve the Stokes flow within the growing mantle in 2D Cartesian geometry (behavior in spherical geometry should not differ significantly [2]). The thickness of the growing mantle increases by progressively adding layers of small, but finite thickness. The iron-content of each layer obeys the simplistic thermodynamic equilibrium imposed by (1). We neglect thermal density variations. In the infinite Prandtl number approximation, assuming a constant viscosity (we recognize this as an important aspect for further study [8]), the momentum equation is $-\nabla P + \mu\nabla^2\bar{v} + x_s\Delta\rho\bar{g} = 0$ [7] with pressure P, viscosity μ, velocity $\bar{v}$, and gravity $\bar{g}$. $\Delta\rho$ is the density contrast between iron-free silicates and pure iron silicates. The cumulate solid is assumed to be incompressible, so that $\nabla \cdot \bar{v} = 0$. Therefore, the iron-content x_s is advected using the advection equation, $\partial_t x_s + \bar{v} \cdot \nabla x_s = 0$. We nondimensionalize lengths by the thickness of the mantle H, time by τ_{MO} the magma ocean crystallization time, velocity by H/τ_{MO}, and pressures by μ/τ_{MO}. In the non-dimensional form, the body force due to density variation is $x_s R_{TI} h$, where h is the non-dimensional mantle thickness and $R_{TI} = \tau_{MO}\Delta\rho g\, H/\mu$.

When does overturn occur? In this highly simplified model, the occurrence of an overturn relative to the end of LMO solidification depends only R_{TI} and D. We can thus identify the range of values for R_{TI} and D which allows significant overturn when $h < 1$(i.e., the crystallization front has not reach the top of the LMO). This is mainly controlled by the non-dimensional number R_{TI}. This preliminary work suggests that the overturn begins during LMO solidification when R_{TI} is larger than 5 x 10^4. We depict in Figure 2 a case where the cumulate pile overturns after the end of LMO solidification and a case where the overturn occurs during solidification. The critical non-dimensional number R_{TI} should be seen as a ratio between τ_{MO}/μ where uncertainties remain large [1,2,9]. For instance, for a cumulate viscosity of about 10^{18} Pa.s this idealized model predicts that the overturn occurs during solidification if the LMO crystallizes in more than 0.2 Myrs (Fig. 3).

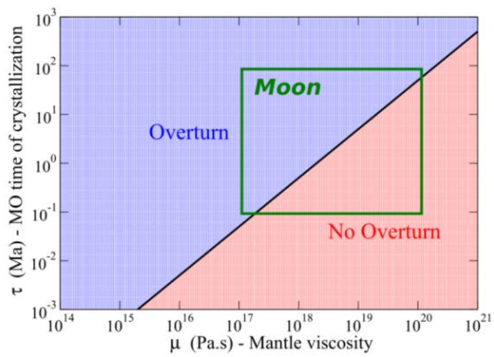

Figure 3. According to our idealized model, the question of whether mantle overturns before the end of magma ocean crystallization depends mainly on the ratio τ_{MO}/μ. In the blue region, the cumulate overturn occurs during LMO solidification.

Further modeling will add important processes not considered thus far: variable viscosity, flow due to thermal buoyancy, melt generation/percolation/retention. Melt retention in the mostly solid mantle at the solidification front and melt trapped in downwellings like those shown in Figure 2 can affect the both the density and viscosity of the cumulate mantle. Thermal convection within the cumulate mantle can occur if heating from below is sufficiently strong to overcome the stabilizing stratification from overturn. Remelting of upwelling cumulates at the solid-liquid interface could also facilitate early overturn [10].

The idealized model presented here shows that the extent of overturn depends strongly on both the time for MO solidification and the viscosity for the cumulate solid mantle. Early rapid solidification, controlled by primarily by heat flux radiated from the surface may later be reduced substantially by heat conduction through a buoyant crust. The extent of overturn may thus vary substantially during the evolution allowing a new perspective of the role of overturn in Lunar evolution. The simplicity of the present models also allows their application to the potential role of MO overturn on the evolution of other planetary bodies.

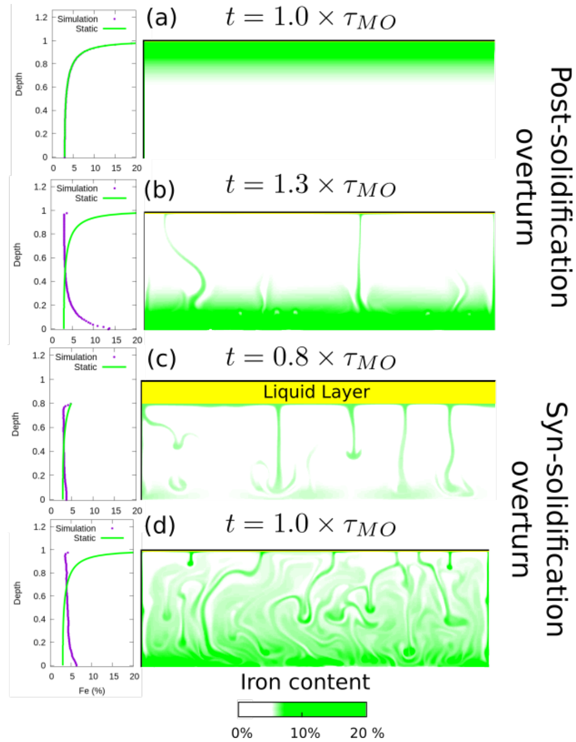

Figure 2. 2D fields of iron-content in the cumulate layer during LMO solidification (right) and associated horizontal averaged profile (left) for two values of R_{TI} (1x10^4 and 1x10^6) and at two times. (a) R_{TI}=1x10^4. At the end of the LMO solidification, the iron stratification (purple dots) follows exactly the stratigraphy predicted by the stagnant model (green line in the left panel). (b) R_{TI}=1x10^4. Iron stratification after the overturn, the stratigraphy corresponds to the commonly accepted post-overturn layering. (c) R_{TI}=1x10^6. The cumulate overturn begins during LMO solidification. The iron stratification (purple dots) differs from the stratigraphy predicted by the stagnant model (green line in the left panel). (d) R_{TI}=1x10^6. Iron stratification at the end of the LMO solidification. The stratigraphy differs significantly from the generally accepted post-overturn layering (shown in b.). Mixing progressively small amount of slightly dense components is much easier than mixing instantaneously a large amount of significantly dense materials.

References: [1] Hess PC, Parmentier EM (1995). [2] Parmentier EM, Zhong S (2001). [3] Smith JA *et al.* (1970). [4] Nyquist *et al.* (2001) [5] Shearer *et al.*, (2006). [6] Ryder G *et al.* (1997). [7] Turcotte DL, Schubert G (2002). [8] Elkins-Tanton LT *et al.* (2002). [9] Elkins-Tanton LT *et al.* (2012). [10] Morison A, Labrosse S (2017, personal communication).