

**IMPOSED SURFACE HEAT FLUX DOES NOT NECESSARY CONTROL MAGMA OCEAN SOLIDIFICATION TIMESCALE.** C.-E. Boukaré<sup>1</sup>, E.M. Parmentier<sup>2</sup> and S.W. Parman<sup>2</sup>. <sup>1</sup>Ecole Polytechnique Fédérale de Lausanne, Lausanne, Switzerland (charles-edouard\_boukare@epfl.ch), <sup>2</sup>DEEPS, Brown University, Providence, RI, USA.

**Introduction:** At the end of planetary accretion, magma ocean (MO) evolution is thought to set the initial conditions for the long-term evolution of terrestrial planets. Most aspects of MO dynamics are derived from the lunar MO based on data of the Apollo missions obtained more than forty years ago [e.g., 1,2]. However, crucial aspects of MO evolution are still highly debated.

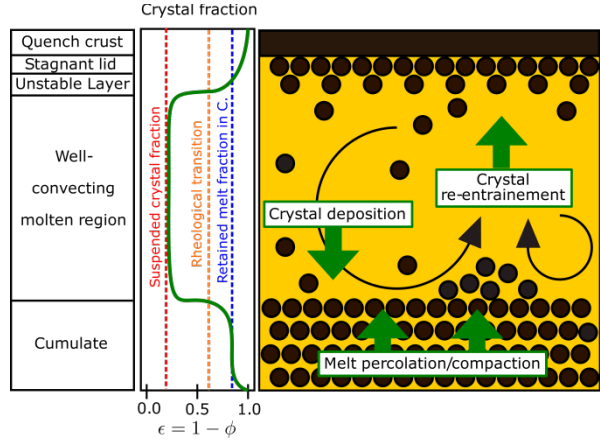
This study investigates the long-standing issue of MO time of solidification. Recently, several models have proposed mechanisms such as tidal heating [7], impact re-heating [8] or heat-piping [9] to delay the canonical timescale of several millions years [3] up to 200 Myrs. These allows to reconcile MO solidification timescale with a late solidification of the youngest anorthosite [e.g., 4,5,6].

Previous models that aim to determine the timescale of MO ocean solidification generally assume that MO cooling rate is controlled by surface conditions (e.g., radiative surface cooling). It is here argued that the MO timescale of solidification is not controlled by these surface conditions if the convective MO cannot sustain the heat flux imposed at the surface. This study proposes that such behavior could occur if the suspended crystal fraction in the magma ocean increases significantly during MO solidification. High suspended crystal fraction in the MO decreases the convective vigor of the MO and thus limits the efficiency of heat transport from the interior to the surface. Very mushy magma ocean cools slowly and could easily match the solidification timescale of 100s of Myr.

**Conceptual Model:** This work considers a MO that solidifies from the bottom to the top. The MO is composed of two main regions: a mostly molten convective region that overlies immobile cumulates (Figure 1). Crystals are formed in the molten region and the cumulate pile is built by progressive crystal deposition at the bottom of the MO. The suspended crystal fraction is assumed to be uniform in the whole top region consistent with efficient convective mixing and an adiabatic temperature that is expected to lies between the liquidus and solidus in a shallow lunar-like MO.

Previous work generally imposes a MO surface heat flux. This study investigates the MO surface heat flux that can be sustained by thermal convection in the crystal bearing convective region. The balance between the heat flux provided by the MO and the sum of the outgoing surface heat flux (potentially limited by

an opaque atmosphere) and incoming solar flux controls the MO surface temperature.



**Figure 1 : Sketch of segregation processes occurring in magma oceans (MOs). This study investigates the links between the timescales of MO solidification and crystal sedimentation. It is here proposed that high suspended crystal affects the MO solidification timescale.**

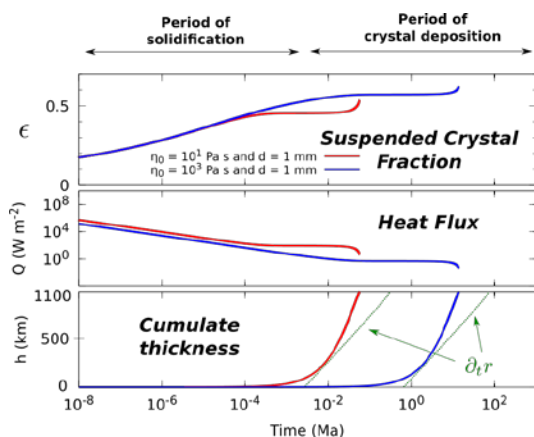
Thermal convection vigor controls the thickness of the thermal boundary layer. Very vigorous thermal convection, valid at low suspended crystal fraction, implies extremely thin thermal boundary layer and hot surface temperature, that do not favor the presence of a quenched crust. However, weak thermal convection, valid at high suspended crystal fraction, is expected to be associated with a thicker thermal boundary layer and lower surface temperature. In that case, the formation of a stagnant lid is likely (Figure 1). This model tests this second hypothesis by tracking the evolution of the suspended crystal fraction and MO heat flux in a self-consistent fashion as described below.

**Mathematical description:** The model couples a thermal budget with a mechanical description of crystal settling in vigorously convective fluid [10,11]. It can be shown that the evolution of the suspended crystal fraction in the MO can be approximated by,

$$\partial_t \epsilon = \frac{3r_0 Q(\epsilon)}{\rho L (r_0^3 - r^3)} - \frac{C_p}{L} \partial_t r \partial_r T_L + \frac{3r^2}{r_0^3 - r^3} \epsilon \partial_t r - \frac{3r^2}{r_0^3 - r^3} v_s (\epsilon - \epsilon_{eq}) \quad (1)$$

where  $Q(\epsilon)$  is the heat flux sustained by thermal convection in the MO,  $L$  is the latent heat of solidification,  $\rho$  is the silicate mean density,  $C_p$  the isobaric thermal capacity,  $r$  is the radius corresponding to the location of the top of the cumulate,  $v_s$  is the Stokes's settling

velocity,  $\epsilon_{eq}$  accounts for the flux of crystal reentrainment (but is set to 0 for now),  $\partial_r T_L$  the slope of the MO melting temperature.  $\partial_t r$  is the upward velocity of the top of the cumulates. Assuming that crystal fraction plays a similar role as temperature in a fluid with temperature-dependant viscosity, the scaling law of [12] is used to relate the MO surface heat flux with  $\epsilon$ . The first term on the RHS of eq. (1) accounts for the amount of heat extracted by the MO that can be used to form new crystals. The second term on the RHS of eq. (2) accounts for the amount of MO secular cooling constrained by the fact that the temperature at the top of the cumulate pile must follow the liquidus. The third term accounts for a dilution effect, i.e., the convective domain shrinks with time as the cumulate thickness grows. The last term on the RHS of eq. (2) accounts for the flux of crystal deposition. In this preliminary work, the presence of an opaque atmosphere is ignored and the MO is initially fully molten and crystal-free.

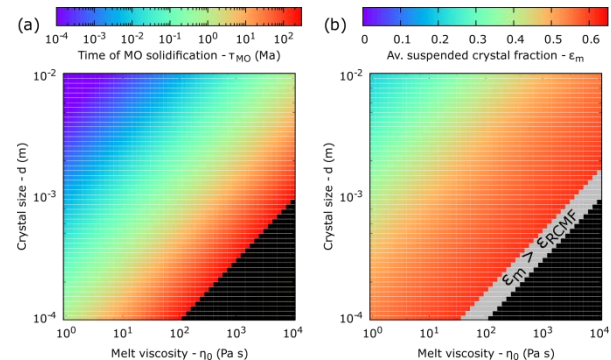


**Figure 2:** Time evolution of the suspended crystal fraction (top), heat flux (middle) and cumulate thickness (bottom). High crystal fraction decreases the efficiency of heat transport from the interior to the surface and thus delays MO solidification.

**Crystal sedimentation vs. crystal formation:** In this model, MO evolution is composed of two distinct periods as the solidification timescale, controlled by the MO output flux can differ from the crystal sedimentation timescale. For very high heat flux, i.e.  $> 10^3 W m^{-2}$  at the onset of MO solidification, crystal production is faster than crystal settling and the suspended crystal fraction increases in the MO (Figure 2, “period of solidification”). For lower output flux, i.e.  $< 10^2 W m^{-2}$ , the suspended crystal fraction can reach a temporary steady state when the rate of crystal production balances the rate of crystal sedimentation (Figure 2, “period of crystal deposition”). It is important to note that the MO evolves naturally from the period of solidification to the period of crystal deposition as the increase of

crystal fraction decreases the MO heat flux and increases the timescale of solidification.

**Time of MO solidification:** Small crystal grain and high melt viscosity act in the same direction in reducing crystal sedimentation rate that increases the suspended crystal fraction in the MO. High crystal fraction increases MO viscosity and can delay MO solidification up to few 100 of Myr (Figure 3).



**Figure 3:** (a) Time of MO solidification in function of crystal size and crystal-free melt viscosity. (b) Averaged suspended crystal. Small crystal grain or high melt viscosity induces long MO time of solidification.

**Conclusion and perspective:** High MO surface heat flux does not necessary imply fast MO solidification. The surface heat flux is a good proxy for the MO solidification timescale only if the heat convective transport in the MO can sustain the surface heat flux imposed at the surface. The suspended crystal fraction in the MO can significantly affect the efficiency of heat transport from the interior to the surface. Large MO surface heat flux i.e.  $> 10^3 W m^{-2}$  is expected to induce rapid crystal formation, i.e., solidification, but such mushy MO are expected to cool and fully solidify on much longer timescale.

Future work aims to apply this model to MO initially thermally blanketed by an atmosphere. Interestingly, an opaque atmosphere can decrease the surface heat flux below  $10^2 W m^{-2}$  that is, as indicated by this work, the limit at which the timescale of solidification becomes comparable to the one of crystal sedimentation. This work would provide a generic and flexible framework for studying MO solidification dynamics in our solar system and beyond.

**References:** [1] Solomon and Longhi (1977) *LPSC VIII* [2] Warren (1985) *AREPS*. [3] Elkins-Tanton (2008) *EPSL*. [4] Borg *et al.*, (1999) *GCA*. [5] Boyet and Carlson (2007) *EPSL*. [6] Nyquist *et al.*, (2010) *LPSC XXXI* [7] Meyer *et al.*, (2010) *Icarus*. [8] Perrera *et al.* (2018) *JGR Planets* [9] Maurice *et al.*, (2018) *AGU Fall Meeting*. [10] Martin and Nokes (1988) *Nature*. [11] Lavorel and Le Bars (2009) *Ph. Rev.*. [12] Davaille and Jaupart (1993) *JFM*.