CUMULATE MANTLE DYNAMIC RESPONSE TO MAGMA OCEAN COOLING HISTORY. C.- E.

Boukaré[1], E.M. Parmentier[1], S.W. Parman[1], [1]Department of Earth, Environmental and Planetary Sciences, Brown University, 02912 Providence, RI (charles-edouard_boukare@brown.edu).

Summary: Magma ocean (MO) fractional crystallization has been proposed to generate gravitationally unstable Fe-Mg chemical stratification capable of driving solid-state mantle overturn [1]. Fractional solidification and overturn hypothesis, while only an ideal limiting case, can explain important geochemical features of both the Moon and Mars. Fractional crystallization in MO can occur under very different mechanical regimes: (1) crystal settling in a turbulent magma ocean and (2) melt percolation in the viscous cumulate pile. Whereas the challenging issue of crystal settling/suspension in the MO has been investigated [2], very few dynamic studies have assessed the question of retained melt fraction in the cumulate pile and its effect on the cumulate convective dynamics. Here, we investigate the issue of the cumulate compaction during MO solidification. We show that the cooling rate history of the magma ocean affects the amount and distribution of retained melt in the cumulate layers. The retained melt controls the viscosity of the cumulates and the effective chemical partitioning between the residual magma ocean and the cumulate pile.

Introduction: Recent models of MO cumulate dynamics have shown that cumulate overturn can occur during MO solidification if the cumulate viscosity is low enough or the time of solidification is long enough [3,4,5,6]. Nevertheless, these models do not consider (1) the effect of retained melt on cumulate viscosity and (2) substantial variation in the rate of solidification during MO solidification. We compute an idealized model of the cumulate pile compaction. We show that the amount of retained melt fraction in the cumulates depends on the rate of crystal deposition at the top of the cumulates, a rate linked to the rate of MO solidification. This preliminary result shows that the timescale of melt extraction from the cumulate pile can be larger than that that for thermo-chemical convective motions. Under these conditions, solid-state mantle mixing may occur at a faster rate than chemical differentiation in the cumulates.

Compaction model: We consider an ideal case where a liquid layer lies above a viscous cumulates that contains interstitial melt (Fig 1). As solidification proceeds, layers of small but finite thickness are deposited at the top of the cumulate pile at a rheological critical melt fraction (RCMF) of ~ 35-40%. of melt. As the melt is buoyant in the cumulate, it tends to rise upwards towards the residual magma ocean by percolation limited by cumulate compaction.
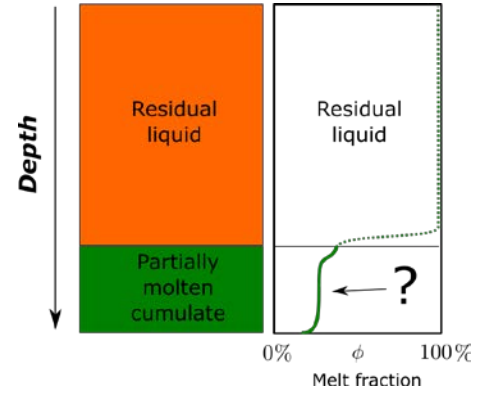

Figure 1 *: (Left) Structure of the MO idealized as a residual liquid and partially molten cumulate layers. (Right) Idealized melt fraction in the MO. Here, we focus on the evolution of the retained melt fraction in the cumulate layers.*

The bottom of the cumulate pile corresponds to the bottom of the original MO whereas the top of cumulate pile corresponds to the region where the melt fraction is at the RCMF. The temperature profile corresponds to the liquidus of the residual liquid. We solve the compaction problem in 1D in the cumulate layers in a similar approach as the one proposed by [7]. In the dimensionless form, the momentum conservation equation that describes melt/solid segregation is,

$$S^* = \phi^n \left((1 - \phi) + \delta^2 \left(\frac{H}{L} \right)^2 \partial_z \left((1 - \phi) \phi^{-m} \partial_z S^* \right) \right)$$

where ϕ is the melt fraction, S^* is the dimensionless segregation flux, δ is the compaction length, H is the thickness of the lunar mantle, L is the thickness of the cumulate pile, n is a constant exponent associated to the matrix permeability law and m is a constant exponent associated to the matrix bulk viscosity law. This non-dimensionalization uses a percolation velocity as reference, $S_{ref} = \frac{\Delta \rho g a^2}{c \mu_f}$ where $\Delta \rho$ is the density contrast between melt and solid, a is the crystals ter, g is the gravity acceleration, C is permeability constant and μ_f is the melt viscosity. The depth of the MO-Cumulate interface is updated using the following equation, $L(t + \Delta t) = L(t) + (v_{sed} - S(z = L(t), t)) \Delta t$ where v_{sed} is the crystal sedimentation velocity at the top of the cumulate pile. The main parameters that govern the dynamics are: the compaction length δ, the segregation flux of reference S_{ref} and the crystal sedimentation velocity, v_{sed}. If v_{sed} exceeds a critical value [7], (v_c ~ S_{ref}), the cumulates yers can-

not compact during crystal deposition. If v_{sed} remains below this critical value, the cumulate layers compact. In this case, lower v_{sed} results in lower retained melt fraction.
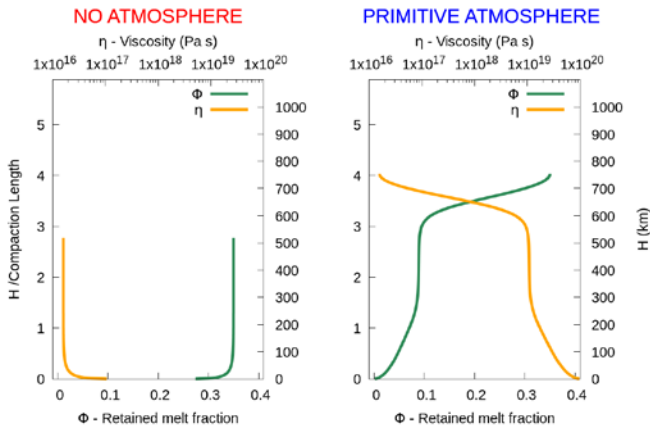

Figure 2 : *Melt fraction and viscosity stratification in the cumulates at the end of the no atmosphere stage (left) and in the presence of a primitive atmosphere that limits MO cooling (right).*

Application to Magma Ocean: The magma ocean cooling history is idealized as composed of three stages: no atmosphere (50 % of the MO solidifies in 10^{-2} Myr), primitive atmosphere (30 % of the MO solidifies in 1 Myr) and conductive lid (the last 20 % of the MO solidifies in 100 Myr). We assume that the rate of crystal deposition at the top of the cumulate pile reflects exactly the rate of MO solidification. We thus neglect that crystals can be suspended in the molten layer. Assuming H=1100 km, the three aforementioned stages correspond to crystals sedimentation velocities (in km/Myr): $v_{sed}^1 = {550}/{10^{-2}}$, $v_{sed}^2 = {330}/{1}$ and $v_{sed}^3 = {220}/{100}$. In the case where the MO cools by pure black body radiation, the rate of crystal deposition is so high that the cumulates do not have time to compact. The melt fraction in the cumulates remains at the RCMF, 35 % (Fig. 2, left). When the rate of crystal deposition is low enough, the cumulate layers compact and expel melt back into the overlying liquid layer. The melt fraction stratification tends to a steady-state profile (Fig. 2. right) that depends on the rate of crystal deposition [5]. The retained melt fraction in the cumulate layers can have significant effect on the cumulate viscosity. Fig. 2 shows the viscosity stratification associated with the melt fraction profile assuming $\eta(\phi) = \eta_{ref} \, \text{Exp}(-25\phi)$ [7]. The viscosity of the cumulate layers controls the vigor of its convective motions and the timing of overturn relative to magma ocean solidification [5,6]. In Fig. 3, we compare the timescale of compaction (green), the timescale of thermally driven convective motion (red) and chemically driven (iron enrichment overturn) convective motion (blue). The timescale associated with solid-liquid segregation (i.e., chemical differentiation) is always larger than the timescale of convective motions (i.e., convective mixing).

The idealized model presented here shows that the rate of crystal deposition at the top of the cumulate layer has important implications on the interstitial melt fraction. This interstitial melt fraction affects the effective chemical partitioning and the extent of convective mixing. The present study neglects the effects of crystal suspensions that might be required to better link rate of MO solidification and rate of crystal deposition.
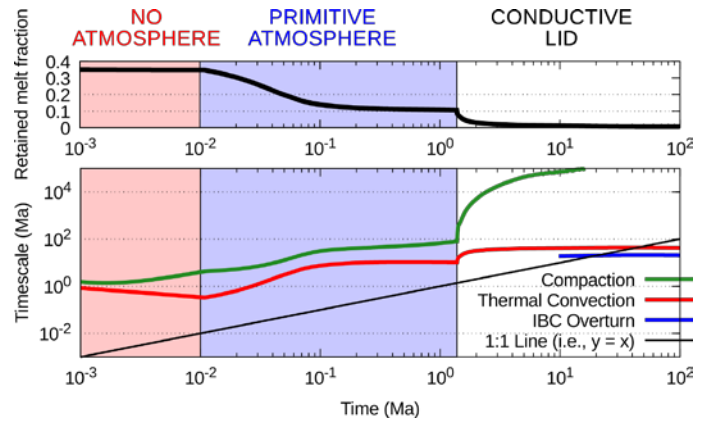

Figure 3 : *Evolution during MO solidification of the averaged melt fraction in the cumulate pile (black), the timescale of melt extraction (green) and the timescale of thermally driven (red) and compositionally driven (blue) convective motions. The horizontal axis corresponds to the time where t=0 corresponds to the onset of MO solidification.   The retained melt fraction depends on the rate of crystal deposition – that we assume equivalent to the rate of MO solidification. For a high crystal deposition rate, the retained melt fraction is high, decreasing the effective viscosity of the first cumulates. As the rate of crystal deposition decreases, the cumulate pile compacts and thus strengthens. The timescale of melt extraction remains larger than the timescale of convective motions throughout MO history.*

References: [1] Hess and Parmentier (1995) *EPSL 134,* 510-514. [2] Solomatov and Stevenson (1993) *JGR Planets 98,* 5375-5390. [3] Maurice *et al.,* (2017), *JGR Planets 122,* 577-598. [4] Ballmer *et al.,* (2017), G3 18, *2785 - 2806.* [5] Boukaré *et al.,* (2018), EPSL, in revision. [6] Boukaré *et al.,* (2017), *LPS XLVIII,* Abstract #2494. [7] Shirley (1986) J. Geol. 94, 795-809. [8] Shearer *et al.* (2006) *Rev. Min. Geo., 60.* [9] Hirth *et al.,* (1995) *JGR Solid Earth 100*, 15441 – 15449.