

**CONSTRAINING THE WETNESS OF THE MOON BY MODELING LUNAR MAGMA OCEAN CRYSTALLIZATION: INSIGHTS AND CHALLENGES.** A. Mallik<sup>1</sup> (mallika@arizona.edu), S. Schwinger<sup>2</sup>, P. Moitra<sup>1</sup>, A. Roy<sup>1</sup>. <sup>1</sup> Department of Geosciences, The University of Arizona (1040 E 4<sup>th</sup> Street, #208, Tucson, AZ 85721, USA), <sup>2</sup> Institute of Planetary Research, DLR Berlin (German Aerospace Center, Berlin, 12489 Germany)

**Introduction:** The H<sub>2</sub>O content of the Bulk Silicate Moon (BSM) is important not only to constrain the dynamics of Earth-Moon formation but also to understand the origin of hydrogen (H) in the Earth-Moon system. Using recent measurements of H or equivalent H<sub>2</sub>O contents on lunar materials, it has been shown that the Moon has tens to hundreds of ug/g H [1]. With such orders of magnitude difference in the existing estimates of bulk lunar H, an outstanding question arises: Can we constrain the bulk H content of the Moon better? Constraining the bulk H<sub>2</sub>O content of the BSM better requires consideration of several parameters such as initial bulk H content of the lunar magma ocean (LMO), partition coefficient of H between nominally anhydrous minerals crystallized from the lunar magma ocean and melt (ratio of concentration of H in the mineral to that in the melt), initial magma ocean depth, and the fraction of interstitial or trapped liquid during LMO crystallization [2]. Several of these parameters are poorly constrained w.r.t lunar formation and LMO crystallization. Thus, a sensitivity analyses are prudent to determine which parameter(s) need to be best constrained in order to effectively improve the bulk H estimates of the BSM. In addition, the degassing and outgassing of H bearing species during LMO crystallization guided by solubility laws need to be considered as well. Here we investigate the effect of the above-mentioned parameters to estimate the initial bulk H content of the LMO that would best explain the measured H contents in plagioclase grains from ferroan anorthosites (FANs; likely primary products of LMO crystallization) [3, 4]. We also investigate whether the crustal thickness of the Moon may be used as a reliable proxy for bulk H estimates.

**Methods:** We model LMO crystallization using a combination of the softwares SPICEs [5] and alphaMELTS [6]. We use the H<sub>2</sub>O contents in plagioclase from FANs [3, 4] as one of the observational constraints to determine the initial bulk H in the LMO. Given the appearance of plagioclase on the liquidus is dependent on the water fugacity of the system, we test whether crustal mass from GRAIL [7] (assuming it is anorthositic) may be sensitive to the initial bulk H in the LMO. We consider two end-member scenarios of LMO crystallization w.r.t volatile degassing and outgassing (Figure 1). In the first scenario, we consider that there is no net outgassing of dissolved H bearing species in a vigorously convecting LMO as bubbles formed by

decompression-induced degassing of dissolved volatiles at a shallow depth in the magma would be resorbed back in the LMO due to increased pressure as the convecting magma sinks to a deeper depth. In the second scenario, we test outgassing from a near-static LMO, where exsolved bubbles could efficiently escape the LMO. We vary initial dissolved H contents from 1-5000 ppm, initial LMO depths from 600-1350 km, interstitial liquid from 0 to 10 wt.% and partition coefficients between the minimum and maximum values reported in the literature. In the second scenario mentioned above, the two H bearing species considered are H<sub>2</sub>O and H<sub>2</sub>. In this scenario, we also vary the  $f_{O_2}$  of the system from IW to IW-2 (the range of  $f_{O_2}$  proposed for the lunar mantle [8]) since the proportions of H<sub>2</sub>O and H<sub>2</sub> in the LMO strongly depends on the  $f_{O_2}$  in this range [9]. We use the solubility laws of [10] for H<sub>2</sub>O and of [9] for H<sub>2</sub> to model their degassing behavior during LMO crystallization (Figure 2).

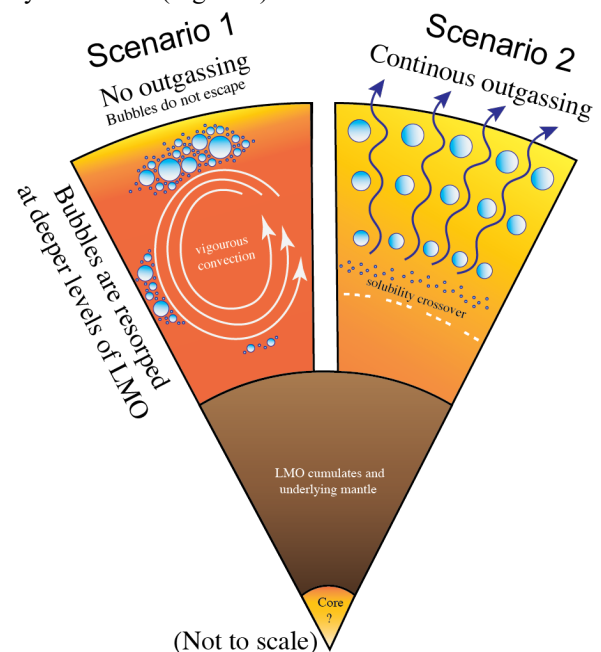


Figure 1. Two end-member scenarios w.r.t volatile outgassing considered in this study

**Results and Discussion:** In the first scenario, we find that the initial bulk H in the LMO is insensitive to the interstitial liquid fraction or initial LMO depth, rather is strongly dependent on the partition coefficient

of H between the LMO minerals and the melt [2] (Figure 3). This highlights the importance of experimentally

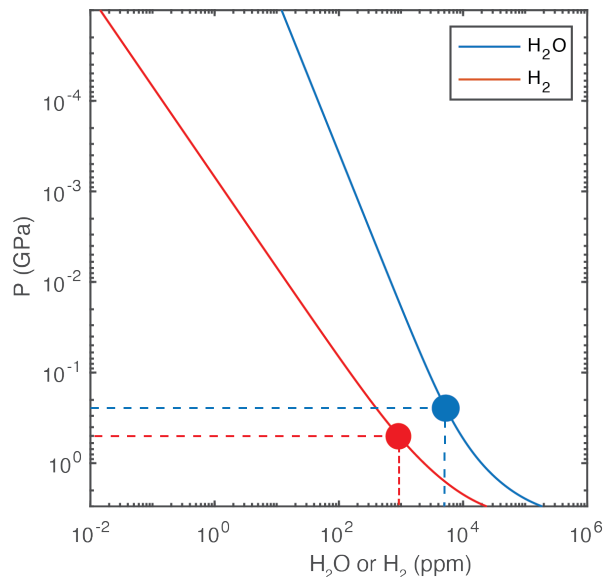


Figure 2. H<sub>2</sub>O [Moore et al] and H<sub>2</sub> solubility curves [Hirschmann 2012] as a function of pressure. The onset of degassing of these dissolved volatiles and formation of bubbles happens once the MO (dissolved volatile contents) intersects the respective solubility curves (marked with filled circles).

determining H partition coefficients specific to lunar conditions where the  $fO_2$  of the mantle is about 4-6 orders of magnitude more reduced as compared to the terrestrial upper mantle [8]. The partition coefficients of H reported in the literature are mostly for terrestrial conditions and may exhibit a dependence on  $fO_2$  due to the substitution mechanisms involved [see Mallik et al 2022 for more details].

In the first scenario, the H content in the plagioclase grains from ferroan anorthosites are best explained by 10 ppm initial bulk H and the maximum value of partition coefficients for each mineral-melt pair [2]. In the second scenario with efficient outgassing, a wetter Moon than that with 10 ppm initial bulk H would explain the H contents in ferroan anorthite plagioclase. We find that no unique combination of parameters converge to explain crustal mass rendering to be an unreliable hygrometer.

This study highlights (a) the need for experimental studies on H partitioning dedicated to lunar conditions given the strong dependence of bulk H estimates on partition coefficients; (b) the uncertainties in BSM bulk H estimates that arise due to assumptions about volatile outgassing during LMO crystallization (no outgassing versus 100% outgassing). If the partition coefficients

are well constrained in future studies, the range in bulk H BSM estimates would arise primarily from the extent of outgassing, which is poorly constrained for LMO crystallization.

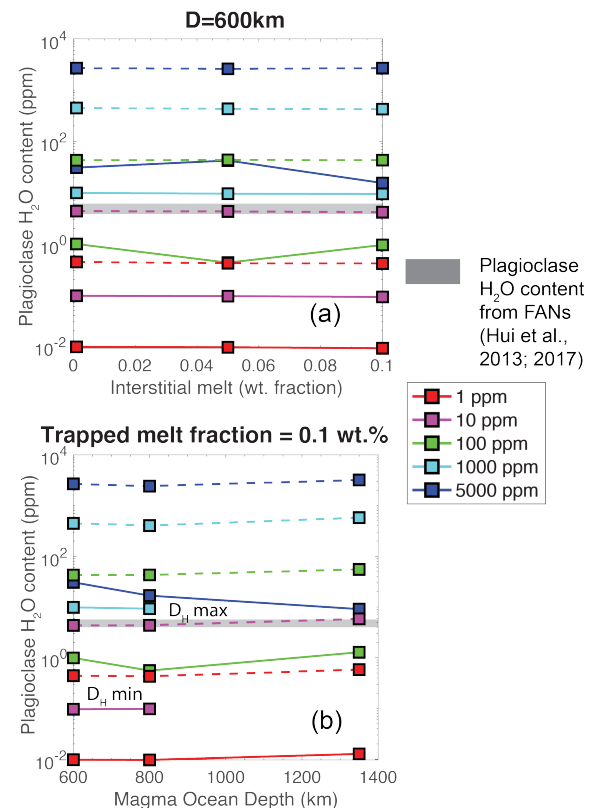


Figure 3. (a) Interstitial melt fraction versus plagioclase H<sub>2</sub>O content at initial LMO depth (D) of 600 km. (b) Initial LMO depth versus plagioclase H<sub>2</sub>O content at trapped or interstitial melt fraction of 0.1 wt.%. The curves are color coded based on the initial LMO bulk H contents. Dashed and solid curves represent maximum and minimum values of H partition coefficients, respectively [modified from 2]

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