WATER OUTGASSING DURING MAGMA OCEAN CRYSTALLIZATION AND THE POTENTIAL ENDOGENOUS ORIGIN OF WATER-ICE IN THE PERMANENTLY SHADOWED REGIONS OF THE MOON. A. Mallik[1] (mallika@arizona.edu), S. Schwinger[2], P. Moitra[1], A. Roy[1]. [1] Department of Geosciences, The University of Arizona (1040 E 4th Street, #208, Tucson, AZ 85721, USA), [2] Institute of Planetary Research, DLR Berlin (German Aerospace Center, Berlin, 12489 Germany)

Introduction: The detection of trapped water ice in permanently shadowed regions of the Moon [1] is of interest for water harvesting to support life and generate fuel from in-situ resource utilization perspective [2, 3]. The origins and mechanisms of delivery and emplacement of the cold trapped water ice are debated and will affect the distribution and abundance of ice, the knowledge of which is required for water harvesting [4]. The origins of water may include both endogenous sources such as volcanic outgassing and exogenous sources such as asteroid and cometary impacts and solar wind implantation [4, 5, 6, 7, 8, 9, 10]. Here we investigate a previously unexplored yet intriguing possibility that some fraction of the cold trapped water ice may have originated from lunar magma ocean (LMO) outgassing during its crystallization. This delivery of water ice likely occurred before true polar wander (TPW) i.e. the reorientation of the Moon's spin axis with respect to the present-day poles >3.5 billion years ago, contributing to the pre-TPW hydrogen deposits detected by the Lunar Prospector Neutron Spectrometer [11]. Using H_2-H_2O solubility laws and thermodynamic modeling of coupled degassing and crystallization, we provide estimates on the range of water masses that might have been outgassed during LMO crystallization.

Methods: We model LMO crystallization using a combination of the software SPICEs [12] and alphaMELTS [13]. This combination of codes best reproduces experimental data on LMO crystallization and hence has been successfully employed in recent studies [14, 15, 16]. Estimating the mass of water outgassed due to LMO crystallization depends on the initial bulk H_2O content of the lunar magma ocean (LMO), the partition coefficients 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), the initial magma ocean depth, and the fraction of interstitial or trapped liquid during LMO crystallization [15, 16]. The bulk H_2O content of the LMO and the partition coefficients of H_2O (for relevant LMO minerals and conditions) are currently poorly constrained [e.g. 15, 16, 17]. To assess the bulk H_2O content of the LMO and using the measured H_2O content in plagioclase from ferroan anorthosites [18, 19] as the observational constraint to validate their models, [15, 16] demonstrated that the model outputs are not sensitive to either the fractions of trapped interstitial liquid or the initial depths of LMO. Based on these previous findings, an initial magma ocean thickness of 600 km deep and an efficient extraction of residual liquid during crystallization (i.e. 0% interstitial liquid) are considered in this study. In our model, we vary the initial bulk LMO H_2O from 1-5000 ppm and the partition coefficients between the maximum and minimum values that are reported in the literature and reported by [15]. We consider two species of hydrogen dissolved and eventually outgassed from the LMO: H_2O and H_2. The proportions of H_2O and H_2 depend on the fO_2 of the system, hence we varied the fO_2 from IW to IW-2 as proposed for the lunar mantle [20]. We use the solubility laws of [21] and [22] to model outgassing of gaseous species during LMO crystallization. By integrating volatile exsolution over depth, the total amount of total degassed volatiles from LMO at a given temperature is calculated. Considering that a vigorously convecting LMO could lead to several convective cycles, we vary the number of degassing cycles (1 to 50) per degree decrease in temperature during crystallization to assess its effect on our model results. We bracket the range of realistic LMO crystallization scenarios based on the conditions required to explain the H_2O reservoir in the FAN suite and calculate the total H_2O released under such conditions and compare them with the polar ice inventory.

Results and Discussion: We find that when partitioning of H between the LMO minerals and melt is towards the minimum (D_{min}), the number of degassing cycles does not affect when bulk $H_2O \leq 100$ ppm but is important at higher bulk H_2O contents (Figure 1). The H_2O contents in crustal plagioclase are best explained by bulk H_2O contents ≥ 100 ppm. For D_{max} the amount of H_2O degassed in each cycle is small, hence, the crustal H_2O is not very sensitive to degassing cycles. However, only drier LMO (≤ 10 ppm bulk H_2O) can explain the crustal H_2O contents (Figure 1), a finding resonated in our previous studies [15, 16]. Accordingly, we provide estimates of the total amount of H_2O released during the entire sequence of LMO crystallization for ≥ 100 ppm bulk H_2O, 1-50 degassing cycles/K for D_{min}, and ≤ 10 ppm and only 50 degassing cycles/K for D_{max}.

We report the outgassed masses of both H_2O and H_2. For D_{min}, the outgassed H_2O ranges from $10^{16} - 10^{21}$ kg (up to 7 orders of magnitude higher than mare volcanic

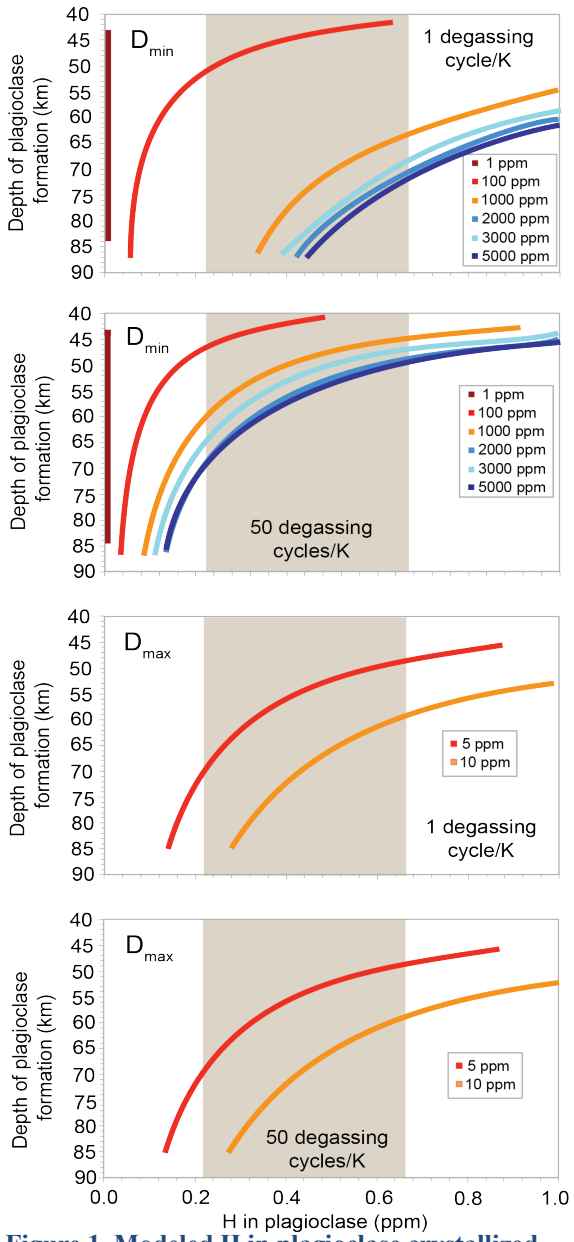


Figure 1. Modeled H in plagioclase crystallized versus depth of plagioclase formation during magma ocean crystallization for bulk H_2O contents of 1-5000 ppm, D_{min} and D_{max}, 1 degassing cycle/K and 50 degassing cycles/K each. The gray area is the measured H in plagioclase from ferroan anorthosites [18, 19]

H_2O outgassing estimates of ~10^{14} kg [5] and 10^{16} kg [23, 6]), and the outgassed H_2 ranges from 10^{15}-10^{20} kg. For D_{max}, the outgassed H_2O ranges from 10^3 – 10^4 kg, and the outgassed H_2 ranges from 10^{12}-10^{13} kg. We find that the species and mass of outgassed volatiles are very sensitive to the mineral-melt partition coefficient of H_2O which emphasizes the need to determine these partition coefficients specifically for lunar conditions in future studies. For D_{min}, if the outgassed H_2 does not oxidize to H_2O and only the outgassed H_2O contributes to water-ice, <0.001 % of the total H_2O released due to LMO outgassing, if condensed, can explain the entire estimated polar ice inventory of ~10^{11} kg [24]. For D_{max}, if all the outgassed H_2O condenses to water-ice, it may explain an insignificant amount of the estimated ice inventory. Future studies need to evaluate the lifetime of the transient atmosphere that would be formed as a result of outgassing during LMO crystallization and the effectiveness of the atmospheric water to be cold trapped in shadowed craters. However, this study raises an intriguing possibility that primordial outgassed endogenic volatiles during the very early stages of lunar chemical differentiation (~4370 Ma; [25]) likely contributed to the polar ice inventory and thus may be partially preserved to some extent on the Moon today. Cryogenic sample return (as proposed by the Artemis III Science Definition Team Report) from permanently shadowed regions and their geochemical analyses would validate the origin and delivery of the volatiles by magma ocean crystallization.

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