Revisiting the Lunar Magma Ocean Crystallization: Creating a Unified Hybrid Model. J. Davenport[1] and C. R. Neal[1], [1]Dept. of Civil Eng & Geological Sciences, University of Notre Dame, Notre Dame, IN 46556, USA (jdavenp1@nd.edu; neal.1@nd.edu).

Introduction: It is generally accepted that the lunar crust and at least the uppermost (500 km) mantle was formed by crystallization of a magma ocean [1,2]. The conditions under which the magma ocean cooled and crystallized, however, are still under debate. These conditions, among others, are the bulk composition, lunar magma ocean (LMO) crystallization (fractional vs. equilibrium), depth of the LMO, and time for LMO solidification (effects of tidal heating mechanisms, insulating crustal lid, etc.).

Lunar magma ocean theory has undergone extensive analysis and discussion throughout the past 40 years, ranging from observations by numerical modeling, lunar petrology and geochronology, to laboratory experiments. This study is a reexamination of the LMO crystallization model proposed by Snyder et al. (1992) and the incorporation of recent studies using numerical modeling of the LMO, geochronology of the anorthosite highlands, and experimentally derived LMO crystallization scenarios. We combine all of these factors into a new hybrid model.

Previous LMO Crystallization Models. Snyder et al. [3] based their LMO crystallization modeling on terrestrial analogues of mafic-layered intrusions. They proposed that any model attempting to accurately describe the crystallization of the LMO should include six factors: 1) Bulk composition of the initial LMO, 2) Relevant phase equilibria at required pressures in order to map crystallization paths of the LMO, 3) Amount and composition of a trapped liquid component, 4) Mineral and melt K_D values for major elements and partition coefficients for trace elements, 5) Depth of cumulate pile, and 6) Extent of equilibrium versus fractional crystallization that occurred as the LMO cooled. More recently, Elkins-Tanton et al. [4] have proposed a modified version of the Snyder model. A marginally different crystallization sequence, but a similar starting bulk composition for the LMO is used for modeling. They also used a density-driven equation to determine whether a mineral grain floats or sinks based on its diameter.

Elardo et al. [5] took a different approach. They used laboratory experiments to constrain the LMO solidification. In doing so, they were able to utilize a variety of pressures and temperatures as they mimicked the solidification process. Variations of the Taylor Whole Moon (TWM; [6]) and the Lunar Primitive Upper Mantle (LPUM; [7]) were used as bulk starting compositions. The starting LMO composition has a large controlling factor on the minerals that are crystallized. For example, assuming whole Moon melting, an initial composition enriched in refractory elements (TWM) crystallizes a deep mantle with garnet, Cr-spinel, olivine, and low-Ca pyroxene. An initial composition of LPUM will produce a deep dunitic mantle with low-Ca pyroxene *minus* an aluminous phase. The TWM compositions produce plagioclase and illmenite in greater quantities and much earlier in the crystallization sequence.

Using the Sept Iles layered intrusion of Quebec, Canada as an example, Namur et al. [8] focused on anorthosite formation by plagioclase floatation. They modeled this using Rayleigh fractional crystallization. They assumed that the majority of the LMO crystallization occurred from the bottom up, forming a lower mafic crust with a similar geochemical signature to rocks of the Mg-suite not exposed to KREEP contamination. Unfortunately, [8] did not describe how any cumulate overturn event can be incorporated into their model. Plagioclase flotation was the mechanism used to account for the formation of ferroan anorthosites in the upper crust. These conclusions led [8] to propose that two compositionally distinct Mg-suites exist in the lunar crust: one enriched in a KREEP component, locally restricted to the Procellarum KREEP Terrane, and another suite without the KREEP component. Namur et al. [8] suggested that both of the Mg-suites were produced by fractional crystallization of magmas with different origins: the KREEP-free suite is from melting of LMO cumulates; the KREEP-enriched suite originates from a similar magma assimilating KREEP components.

Revising the Model. This study has recreated the model proposed by [3], but incorporated some of the parameters from the more recent models outlined above. The parameters from [3] used were the specific crystallization sequence: 1) 0-40 Percent Crystallized Solid (PCS) = olivine, 2) 40-78 PCS = orthopyroxene, 3) 78-86 PCS = 53% plagioclase + 25% olivine +22% pigeonite, 4) 86-95 PCS = 38% clinopyroxene +36% plagioclase + 26% pigeonite, 5) 95-99.5 PCS = 34% pigeonite + 31% plagioclase + 24% clinopyroxene + 11% illmenite. These were modeled using equations 1-5 in [3]. Unlike [3], which used equilibrium crystallization to ~78% PCS and then fractional crystallization to 100% PCS, we used equilibrium crystallization throughout the whole scenario to create an initial end-member situation. This accounts for the

differences in the major element evolution of the LMO seen in Figure 1. Furthermore, 1% crystallization increments are used in this hybrid model, instead of 5% as in [3]. By using a smaller modeling increment we noted slight discrepancies with the Snyder et al. [3] model. It is concluded that the smaller the increment the more accurate the compositions of the crystallized minerals and residual liquids are. Another major factor contributing to uncertainty in the hybrid model was the
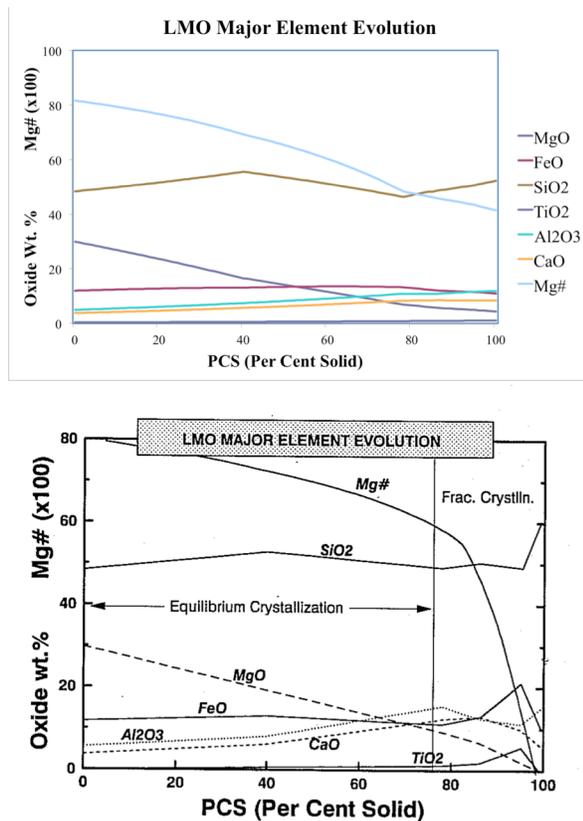
Figure 1. Major element evolution of the LMO, oxide wt. % (w/Mg# x100) vs. per cent solid (PCS). Figure 3 from Synder et al. [3] is included for comparison to our initial results.

connection between phase relationships and the depth of the magma ocean [5]. If we consider the depth to have been <500 km, garnet (for example) would not be stable and need not be considered. If the magma ocean depth is >500 km, garnet will crystallize if sufficient Al_2O_3 is present and, thus, needs to be included in the crystallization scheme. Therefore, we have made distinctions in the hybrid model to recreate both events and compare the results from both scenarios. A final, interesting and relatively recent discovery concerning spinel-rich lithologies, discussed briefly in [5], was researched more in-depth by Pieters et al. [10] with the discovery of OOS or orthopyroxene, olivine, and Mg-spinel via high resolution mapping. The presence of

spinel-rich lithologies are possibly linked to magmatic intrusions into lower lunar crust, caused by the remelting of LMO cumulates. Fractional crystallization and gravity settling in these intrusions can explain the presence of these mafic-rich components in specific zones in the lunar crust. We have used the hybrid model to connect these newly discovered spinel-rich areas to appropriate LMO cumulate source compositions.

To make the model more accurate and able to incorporate more variables, it has been programmed into MATLAB. With the help of MATLAB, the model includes the use of other initial LMO compositions, such as those listed in [3-5], the incorporation of equation (1) from Elkins-Tanton et al. [4], and the use of LMO depth equations and parameters from Khan et al. [11], for example. Along with the accuracy and adaptability of this versatile hybrid model, it allows us to more easily calculate the compositions of trapped instantaneous liquids at various stages during the evolution of the LMO. Furthermore, it allows comparative planetology studies to be undertaken as this model can be applied to the crystallization of magma oceans on other planets. Finally, the data obtained with these models was compared to remote sensing projects and whole rock compositions from the Apollo moon landing sites Using the remote sensing and whole rock composition data as a proxy to the hybrid model enables us to check the accuracy of each individual initial LMO composition. It then allows the determination of the most appropriate and feasible composition to have been the initial bulk moon composition.

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