MAGMA OCEAN COMPOSITION AND THE LUNAR MANTLE: IMPLICATIONS FOR THE SOURCE LITHOLOGIES OF THE HIGHLANDS MAGNESIAN SUITE.

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Introduction: The Moon-wide differentiation event known as the Lunar Magma Ocean (LMO) has been proposed as having been responsible for producing the source regions the mare basalts. Less clear is the relationship between LMO-produced source regions and the earliest stages of lunar magmatism represented by the Highlands Magnesian Suite (HMS). Here we illustrate the potential for understanding the nature of the early LMO cumulates from experiments and discuss the origin of the HMS within the context of these experiments.

Forming the Mg – Suite   This series of ancient plutonic rocks features the contrasting chemical signatures of Fe-Mg silicates with high Mg* (up to 94) coupled with the co-crystallization of high-Ca plagioclase (up to An 96) and an enrichment in incompatible elements (i.e. REE, Th). Various types of mixing models have been proposed to explain their origin. These models range from fertilizing early olivine-orthopyroxene cumulates with very late-stage incompatible element enriched cumulates (KREEP) during overturn to transport of these early, hot LMO cumulates to the base of the lunar crust where they are mixed with late-stage cumulates. However, in detail, these models are currently insufficient to explain observations in the most primitive HMS rocks (i.e. ultramafics, troctolites) such as low Ni, Co, and Cr contents in olivine relative to olivines in mare basalts, and the apparent co-crystallization of highly magnesian olivine and high-Ca plagioclase [e.g. 1-4]. Despite these apparent shortcomings, such mixing models better explain the Mg-suite's enigmatic features than do other proposed formation mechanisms (i.e. impact melting, direct crystallization from the LMO, remobilization of KREEP).

The Magma Ocean Connection   The composition of the LMO has been the subject of debate and much of the disagreement centers on whether the Moon is enriched in refractory elements (i.e. Al, Th) relative to Earth. The Taylor Whole Moon (TWM) composition [5] represents a 50% enrichment (6.1 wt. % Al_2O_3, Mg* 84) whereas the Lunar Primitive Upper Mantle (LPUM) composition [6] represents no such enrichment (3.9 wt. % Al_2O_3, Mg* 90).

Various authors [e.g. 7, 8] have proposed that LMO crystallization occurred in a roughly two step process: protracted equilibrium crystallization followed by fractional crystallization of the residual liq-

uid. As part of a larger effort to test this model and better understand how the LMO affected the structure of the lunar mantle, equilibrium crystallization experiments have been conducted on both of the aforementioned bulk Moon compositions from $0.5 - 2$ GPa, with higher pressure experiments to follow. These experiments allow us to investigate cumulates produced by two end member LMO compositions and to explore the potential for these cumulates to represent the source lithologies for the Mg-suite.
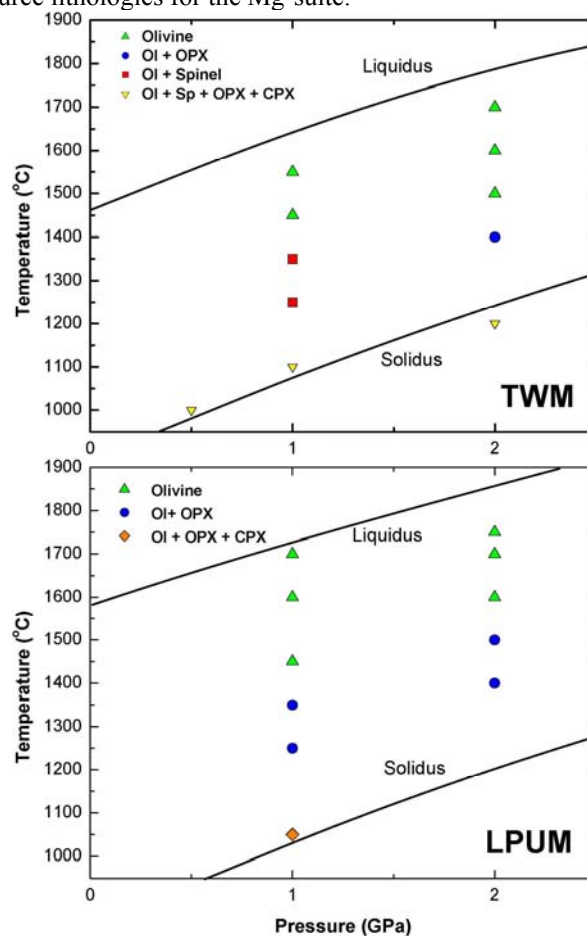
Figure 1: Equilibrium temperature vs. pressure phase diagrams for the TWM and LPUM bulk moon compositions with approximate liquidus and solidus.

Experimental Methods: Starting materials were partially crystallized glasses made from dried, anhydrous powered reagent-grade oxides. In addition to the major and minor elements defined by [5, 6], 250 ppm each of Ni, Co, Y and V were added to each mix.

Experiments from 0.5 – 2 GPa were run in graphite capsules using talc-Pyrex cells in a Depths of the Earth non-end loaded piston cylinder apparatus at the Institute of Meteoritics. Future runs to investigate LMO crystallization at higher pressure will likely be conducted using a Walker-style multi-anvil apparatus using ceramic octahedra. Run products were polished and then analyzed using a JEOL JXA 8200 electron microprobe and a Cameca ims 4f ion microprobe at the IOM.

Results: Initial results are shown in Figure 1. The TWM and LPUM compositions produce early cumulates with some similarities but which also exhibit stark differences. Both compositions produce highly-magnesian olivine as the sole phase for large degrees of crystallization with the LPUM olivine having a higher Fo content owing to the bulk composition's higher Mg*. The most Fe-rich olivine seen in any experiment to date was of the composition Fo89. A low-Ca pyroxene is the second phase to crystallize at 2 GPa for both compositions. However, unlike LPUM, the more Al-rich TWM crystallizes a Cr-rich spinel for ~100°C down temperature at 1 GPa before any pyroxene joins the assemblage. Though minor in modal abundance ($\leq 5\%$), the appearance of spinel marks a departure from the olivine to orthopyroxene crystallization sequence typically assumed for the LMO and demonstrated in our LPUM experiments and in the empirical model of [8]. A comparison of our results with this model is shown in Figure 2. A high-Ca pyroxene joins the equilibrium assemblage in both compositions, but not until very near the solidus in each case. It is also worth noting that plagioclase and ilmenite are not observed in any experiments to date. Partition coefficients (D) for Ni and Co in olivine have been calculated using EPMA data. D_{Ni} ranges from 2.2 - 5.6 for the TWM and 2.4 - 5.2 for the LPUM. D_{Co} ranges from 0.8 - 1.9 for the TWM and 0.5 - 1.8 for the LPUM. More precise determinations of these D-values are being made using secondary ion mass spectrometry (SIMS).

Discussion: The results of these experiments confirm that early LMO cumulates are sufficiently Mg-rich to act as the source regions for the Fe-Mg silicates observed in the HMS. Furthermore, it has been suggested by [2, 3] that the low Ni and Co abundances in Mg-suite olivines relative to mare basalts arise from initially low D_{Ni} and D_{Co} at high olivine Fo content. The preliminary results of these experiments are in agreement with recent experiments by [3] and demonstrate D_{Ni} increases with olivine Fe content and that D_{Co} also increases, though less dramatically, and that these early cumulates are capable of producing partial melts with low Ni and Co.

Comparing the cumulates produced by these two bulk compositions with each other and the empirical model of [8] demonstrates LMO composition and pressure regime have a non-trivial effect on cumulate composition. These observations may place better constraints on the duration of equilibrium crystallization and initial LMO composition. For example, in a TWM magma ocean, if equilibrium crystallization proceeds long enough, Cr-rich spinel is mixed into the cumulate pile by high Rayleigh number convection [7]. Low-degree partial melts of these cumulates, although rich in Mg and poor in Ni and Co, may be too rich in Cr to produce the low-Cr olivine of the Mg-suite.
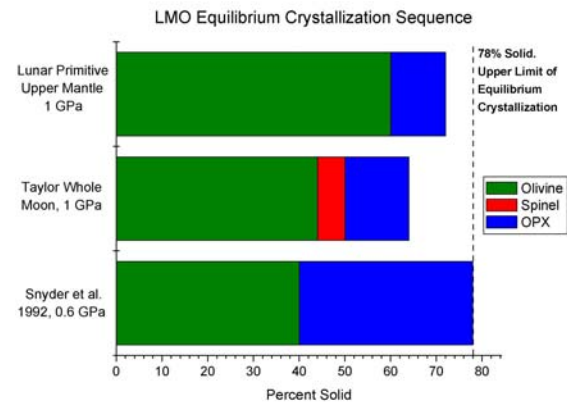
Figure 2: A comparison of the equilibrium LMO crystallization results presented here with the empirical model of [8].

Although partial melts of the early LMO cumulates may be capable of producing the mafic silicates of the Mg-suite, melting of these cumulates cannot produce other characteristics of the Mg-suite parent magmas such as the co-crystallization of highly magnesian silicates and Ca-rich plagioclase observed in troctolites and norites, the high CaO/Al_2O_3 and the enrichment in incompatible elements (KREEP). Other more complex processes must be invoked to explain these contrasting features if early LMO cumulates are the sources of the melts that crystallized the mafic silicates of the Mg-suite. Future work on these compositions will include higher pressure experiments as well as fractional crystallization experiments on the LMO liquid residual to equilibrium cumulates and will provide insight into potential differences between mare basalt and Mg-suite source regions.

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