

CRYSTALLIZATION OF A LUNAR MAGMA OCEAN: PRELIMINARY EXPERIMENTAL RESULTS.

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Introduction: Although the Lunar Magma Ocean (LMO) hypothesis has achieved wide acceptance in the lunar science community, it has never been fully tested experimentally. Presented here are the first results of equilibrium crystallization experiments using the Taylor Whole Moon (TWM) composition [1]. The first mafic cumulates in this LMO are dominated by forsteritic olivine, low-Ca pyroxene and, at near Moon center pressures, slightly majoritic garnet. These cumulates and the compositions of the residual liquids provide important insights into the constitution of the deep lunar mantle and constrain the maximum depth of crystallization in the LMO.

Methods: The TWM starting material was synthesized as a mechanical mixture of anhydrous powdered reagents and conditioned at the IW fO_2 buffer at 1000°C for ~24 hr in a Deltech gas mixing furnace. Experiments were conducted using graphite capsules in a Walker-style multi-anvil press. Cell assemblies, procedures and calibrations are identical to those described by Agee et al. [2]. Run products were analyzed using a JEOL 8200 electron microprobe.

Early Crystallization in the LMO: Our experiments simulate equilibrium crystallization in a LMO that represents whole Moon melting. Experimental phase assemblages are shown in figure 1. At 4.5 GPa, just below the Moon center pressure (4.7 GPa), TWM appears to be multiply saturated with forsteritic olivine and slightly majoritic garnet. Olivine is the sole crystallizing phase at 3.7 GPa, 1800°C and the remaining experiments reported here contain olivine + low-Ca pyroxene.

Several physical models suggest that early LMO crystallization did not occur at the base of the magma ocean, but rather in an inertial zone created by vigorous convection [3,4,5]. In such models, equilibrium crystallization is thought to prevail until some critical crystallinity is reached (~60-80%), after which fractional crystallization takes place. These early formed crystals make up the deeper lunar mantle and become the source regions for mare basalts and picrite glasses.

Presence of Garnet in the Lunar Mantle: Arguments regarding whether garnet is present in the lunar mantle have largely focused on garnet's effect on trace elements [6, 7]. In our experiment at 1800°C and 4.5 GPa (~1600 km depth) garnet makes up ~13% of the crystalline assemblage but is absent at pressures of 4.1 GPa and below. Thus garnet appears to be stable under a comparatively narrow range of conditions. If the Moon experienced slightly less than complete

melting, the base of the magma ocean may not have reached the garnet stability field. However, even if the Moon did experience complete melting, the inertial zone of crystallization may not have extended to depths as great as this narrow window of garnet stability and thus garnet would not have crystallized.

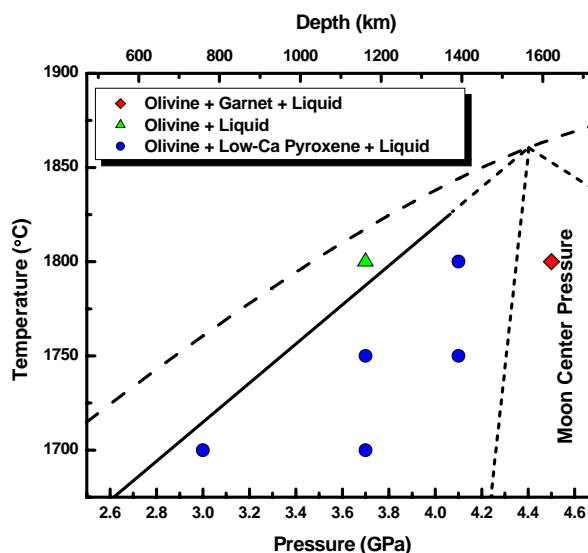


Figure 1. Pressure vs. Temperature plot of experimental results with inferred, approximate mineral in-curves and liquidus.

Effects of Garnet on LMO Evolution: Although the precise composition of the bulk Moon can be only estimated, most such estimates agree that its ratio of CaO/Al_2O_3 is close to chondritic (CI ~0.8; TWM = 0.75). If garnet crystallized in the early LMO, then it would increase the CaO/Al_2O_3 of the residual magma ocean, possibly affecting the subsequent liquid lines of descent. Removal of Al_2O_3 via early garnet crystallization might suppress the onset of plagioclase crystallization or even prevent its formation entirely. It would also impart an elevated CaO/Al_2O_3 ratio on subsequently-formed cumulate mantle. This elevation is demonstrated by our 4.5 GPa experiment. At a crystallinity of 55% (42% olivine, 13% garnet) at 4.5 GPa, the CaO/Al_2O_3 of the residual liquid is increased to 1.36 from 0.75 in the starting composition. Thus, cumulate mantle eventually formed from this liquid would retain a CaO/Al_2O_3 ratio around this value. However, mare basalts, whose petrogeneses likely do not involve phases that can significantly affect this ratio and thus probably preserve the CaO/Al_2O_3 of the lunar mantle, show a range of ~0.75 – 1.35.

In experiments lacking garnet, however, the $\text{CaO}/\text{Al}_2\text{O}_3$ values of the residual liquids are a closer match to the observed values in lunar basalts. The six experiments that do not contain garnet have a range of $\text{CaO}/\text{Al}_2\text{O}_3$ in the residual liquids of 0.50 – 0.74. At 3.7 GPa, the ratio goes from 0.51 at 1800°C where olivine is the only crystallizing phase to 0.70 and 0.69 at 1750°C and 1700°C, respectively, where low-Ca pyroxene has joined the assemblage. The range of $\text{CaO}/\text{Al}_2\text{O}_3$ in the garnet-free experiments is still lower than the observed mare basalt values, but none of the experiments contains any plagioclase, which will increase the $\text{CaO}/\text{Al}_2\text{O}_3$ of the residual liquid when it eventually begins crystallizing. The removal of plagioclase from liquids similar to the residual liquids of our garnet-free experiments could ultimately yield cumulate source rocks having a similar range of $\text{CaO}/\text{Al}_2\text{O}_3$ as do the mare basalts.

What would be the consequences of early garnet removal on the subsequent crystallization of LMO liquids? We argue that such a process would ultimately yield source rocks for lunar basalts having $\text{CaO}/\text{Al}_2\text{O}_3$ values much higher than the range seen in those basalts. To illustrate this notion, in figure 2 we plot the calculated ratio in liquids remaining after some fraction of removal of plagioclase (An90 or An95 as indicated in legend) or garnet (pyropic or mildly majoritic). If early LMO crystallization does not include garnet, the residual melts from which plagioclase should ultimately form retain a near-chondritic ratio until plagioclase onset, which then imposes their largely superchondritic values. If, instead, early garnet crystallization imposes a value ~ 1.36 , as in our run TWM1.009, subsequently-formed LMO liquids (green curve on fig. 2) will have their ratio driven to much higher values than is seen in any lunar basalt once plagioclase begins to form, if indeed it even does after sequestration of some alumina via garnet removal.

Constraints on the Depth of the LMO: As mentioned above, physical models of the LMO [3,4,5] suggest vigorous convection that inhibits crystallization at the very top or base of the LMO, but rather in an inertial zone between two viscous sublayers. The deepest extent of this inertial zone represents the maximum depth of crystallization in the LMO. Because garnet is unlikely to be present in the deep lunar mantle on the basis of its effect on the $\text{CaO}/\text{Al}_2\text{O}_3$ of the residual magma ocean and on its trace element partitioning behavior [7], the deepest crystallization possible in the LMO is between 4.1 and < 4.5 GPa (~ 1300 – < 1600 km), i.e. at a pressure lower than that defining the garnet stability field. Because the lower pressure limit of garnet stability in the TWM bulk composition is only slightly beneath Moon-center pressure (~ 4.7 GPa),

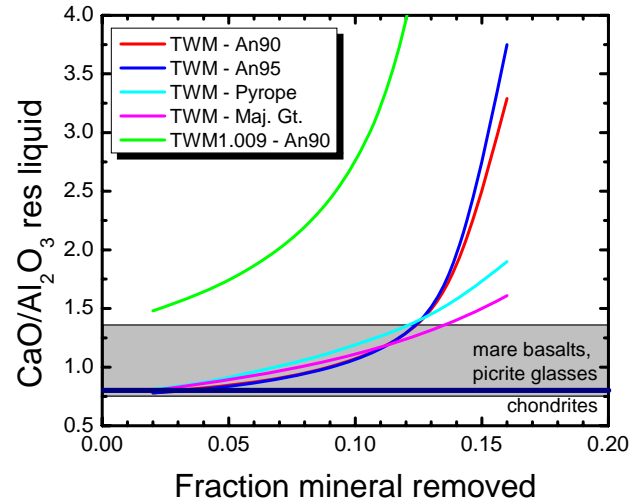


Figure 2: Impact of removal of plagioclase or garnet from LMO residual liquids. Grey field shows range of lunar basalts; blue line is chondritic value (0.80). See text

whole Moon melting cannot be ruled out, as the region between the center of the Moon and the lowest extents of inertial-zone crystallization can still be molten but not crystallizing, instead acting as a zone of crystal accumulation.

Future Work: Additional experiments conducted on TWM will better constrain the nature of the early cumulates of this possible LMO composition, including the precise conditions of the liquidus and of the stability fields for garnet and pyroxene. Experiments will also be conducted to 1) simulate the remainder of LMO crystallization, including a transition from equilibrium to fractional crystallization; 2) investigate the conditions at which plagioclase joins the assemblage and if its density allows flotation, and 3) whether KREEP is in fact produced at protracted degrees of LMO solidification (REEs will be added to the starting material for the fractional crystallization experiments). Ultimately, a similar study will be performed on the Lunar Primitive Upper Mantle (LPUM) composition of Longhi [8,9], which is also thought to be a possibility for the bulk Moon. That later study will help evaluate proposed ranges of refractory element (e.g. Al) contents of the LMO [10].

References: [1] Taylor S.R. (1982) *Plant. Sci. Lunar Perspective*. [2] Agee C. B. et al. (1995) *JGR*, 100, 17,725-17,740. [3] Spera, F. J. (1992) *GCA*, 56, 2253. [4] Tonks W. B. and Melosh H. J. (1990) *Origin of the Earth*, 151-174. [5] Snyder G. A. et al. (1992) *GCA*, 56, 3809 – 3823. [6] Neal C. R. (2001) *JGR*, 106, 27,865 – 27,885. [7] Draper et al. (2006) *GCA*, 70, 2400 – 2416. [8] Longhi J. (2003) *JGR*, 108, 16. [9] Longhi J. (2006) *GCA*, 70, 5919 – 5934. [10] Taylor S. R. et al. (2006) *GCA*, 70, 5904 – 5917.