

THE LUNAR MAGMA OCEAN: SHARPENING THE FOCUS ON PROCESS AND COMPOSITION.

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Introduction: The currently accepted model for the formation of the lunar anorthositic crust is by flotation from a crystallizing lunar magma ocean (LMO) shortly following lunar accretion. Anorthositic crust is globally distributed and old, whereas the mare basalts are younger and derived from a source region that has experienced plagioclase extraction. Several attempts at modelling such a crystallization sequence have been made [e.g. 1, 2], but our ever-increasing knowledge of the lunar samples and surface have raised as many questions as these models have answered.

This abstract presents results from our ongoing experiments simulating LMO crystallization and addressing a range of variables. We investigate two bulk compositions, which span most of the range of suggested lunar bulk compositions, from the refractory element enriched Taylor Whole Moon (TWM) [3] to the more Earth-like Lunar Primitive Upper Mantle (LPUM) [4]. We also investigate two potential crystallization models: Fully fractional, where crystallizing phases are separated from the magma as they form and sink (or float in the case of plagioclase) throughout magma ocean solidification; and a two-step process suggested by [1, 5] with an initial stage of equilibrium crystallization, where crystals remain entrained in the magma before the crystal burden increases viscosity enough that convection slows and the crystals settle, followed by fractional crystallization. Here we consider the fractional crystallization part of this process; the equilibrium cumulates having been determined by [6].

Experimental: Experiments are carried out using synthetic oxide mixes in piston-cylinder apparatus and 1 bar gas-mixing furnaces as NASA Johnson Space Center. The run products are analyzed for major and minor elements using electron microprobe.

Fractional crystallization experiments require an iterative approach similar to those outlined in [7, 8], in which we target, for each experiment, a temperature just below the liquidus to produce ideally 10% crystallization. Each run product is analyzed, and the composition of the quenched liquid is used as the starting composition of the next experiment, thus fractionating the crystals from the liquid. The pressure is decreased as the cumulate pile grows, and below 1 GPa (~75% crystallization) we switched to 1 bar experiments to mimic late stage low pressures, and to avoid the crystallization of metastable highly aluminous pyroxene. The experiments following on from the equilibrium

experiments of [6] use the same iterative process, but the initial composition is taken from the residual liquid after 50% equilibrium crystallization as determined in [6].

Results: Experiments have been completed for fractional crystallization of the TWM bulk Moon, and to 92% crystallization for LPUM. The fractional step after 50% equilibrium crystallization has reached ~70% crystallization, and so far the results indicate a markedly different cumulate pile compared to the fully fractional experiments.

Fully Fractional crystallization: The TWM cumulates are olivine-dominated at depth. 44% of the mantle cumulates are mono-mineralic olivine, after which Cr-rich spinel co-crystallizes as an accessory phase until Cr is exhausted in the bulk composition; some Al₂O₃ is thereby sequestered at depth in the mantle. Opx crystallization is of limited extent, crystallizing between 51 and 63 percent solid (PCS). After this point pyroxenes become increasingly Ca-rich, much earlier in the crystallization sequence than predicted by numerical models [1, 2], and producing lunar mantle cumulates much more enriched in high-Ca pyroxene than expected. Plagioclase crystallization begins at 78 PCS, co-crystallizing with high-Ca pyroxene, and later also with Fe-Ti oxides and phosphates. The crustal thickness of the plagioclase layer, assuming perfect separation of phases, would be ~47 km. Crustal thickness estimates like these are minimum values, given that crustal lithologies include less plagioclase-rich rocks as well.

By comparison, the LPUM cumulates are more rich in olivine and low-Ca pyroxene, with high-Ca pyroxene crystallization not beginning until 71 PCS. There is also no spinel crystallization observed in the lower mantle, therefore no Al₂O₃ storage at depth. However, plagioclase crystallization does not begin until 89 PCS, and although experiments are not yet complete we predict that ultimately plagioclase will be less abundant than in the TWM composition.

In both cases the mantle cumulates of the basalt source regions produced by fully fractional crystallization are less opx rich than suggested by the multiple saturation points of basaltic samples [9-11] – in the case of LPUM there is more olivine than expected, and depending on the source region depth more high-Ca pyroxene. In the case of TWM, however, the source region would be very rich in high-Ca pyroxene, which

is a phase not predicted by multiple saturation experiments.

Equilibrium followed by fractional crystallization:
 The TWM cumulates to 50 PCS predicted by [6] would be olivine plus approx. 10% opx, and may contain 1-2% garnet at the lowest depths. LPUM on the other hand would not, being predominantly olivine with approx. 10% opx. Our fractional crystallization experiments based on the residual liquids from these cumulate piles are pyroxene rich. As with the fractional experiments, TWM pyroxenes become Ca-rich much earlier in the sequence than in LPUM, reflecting the higher Ca content of the bulk composition. LPUM experiments to date have not yet produced the high-Ca pyroxenes seen in the other experiments, although some pigeonite coexisting with the low-Ca opx has been produced. In neither case has plagioclase yet been observed, although numerical models predict plagioclase crystallization at around 78 – 80 PCS [1, 2], which at the time of writing has not yet been reached for either composition.

Inferring LMO process and bulk composition:
 The suite of experiments discussed above investigate two end-member bulk lunar compositions, and two end-member crystallization models for the LMO. The results can help us to focus on the most likely process and composition for the magma ocean, by determining the cumulate pile that is most similar to that indicated by lunar samples, and producing a crust most similar to the recent determinations by GRAIL [12]. The fully fractional experiments indicate that TWM produces a crust of similar thickness to the GRAIL value, unlike

LPUM, which appears likely to produce an extremely thin crust. However, TWM fractionally crystallizes an extremely cpx-rich mantle, from which it would be difficult to produce the basaltic compositions observed in Apollo samples. Taken together, our observations to date suggest that fully fractional crystallization of the Moon probably did not occur. The equilibrium plus fractional experiments in the LPUM bulk composition have so far produced an olivine and opx rich mantle from which such basalts could be derived, although it remains to be seen if enough plagioclase crystallization can occur to produce the highlands crust. Such a result would further weaken the validity of a fully-fractional process for LMO solidification.

References:

[1] Snyder G. A., Taylor L. A., and Neal C. R. (1992) *Geochim. Cosmochim.* 56(10), 3809-3823
 [2] Elkins-Tanton L. T., Burgess S., and Yin Q.-Z. (2011) *EPSL* 304(3-4), 326-336. [3] Taylor, S.R., (1982) *Planetary Science, a Lunar Perspective*. [4] Longhi, J., (2006) *Geochim. Cosmochim.*, **70**, 5919. [5] Tonks, W.B. and Melosh H. J., (1990) *Origin of the Earth* [6] Elardo, S.M., et al. (2011), *Geochim. Cosmochim.*, **75**(11): 3024. [7] Villiger S. (2004) *J. Petrol.* 45(12), 2369-2388. [8] Villiger S., Ulmer P., and Muntener O. (2006) *J. Petrol.* 48(1), 159-184. [9] L.T. Elkins, V.A. Fernandes, J.W. Delano and T.L. Grove (2000) *Geochim. Cosmochim.*, 64, p. 2339 - 2350. [10] Longhi J. (1992) LPSC XXIII pp. 343-353. [11] Wagner T. and Grove T. (1997) *Geochim. Cosmochim.* 61(6), 1315-1327. [12] Wiczorek, M. A. et al. (2012) *Science* DOI: 10.1126/science.1231530.

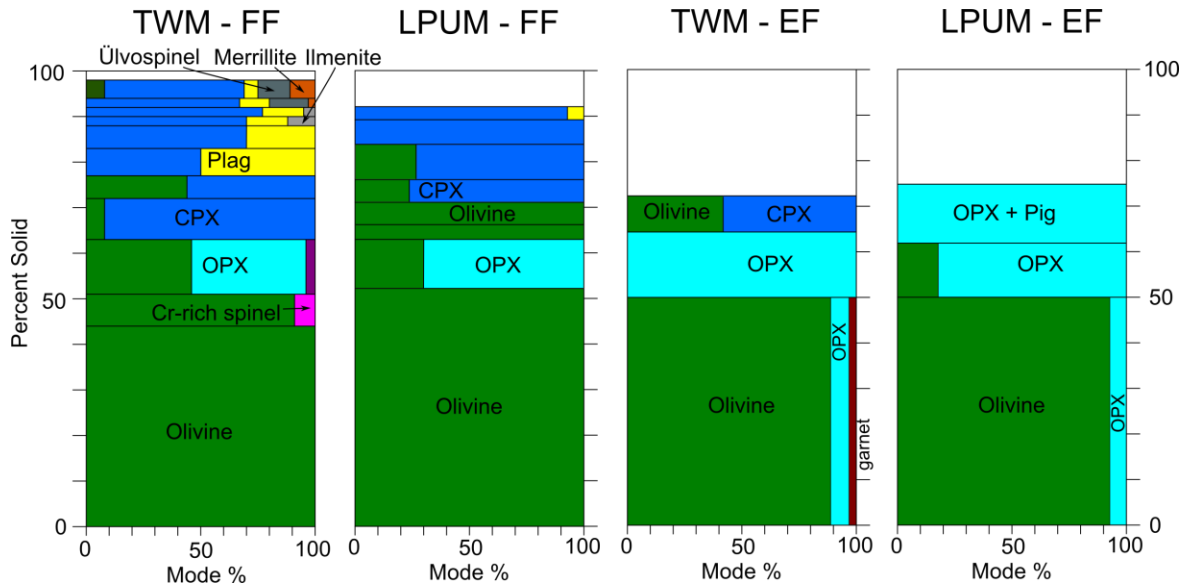


Figure 1: Comparison of experimental outcomes. FF indicates full fractional crystallization, and EF indicates 50% equilibrium crystallization followed by fractional crystallization.