EXPERIMENTAL FRACTIONAL CRYSTALLIZATION OF THE LUNAR MAGMA OCEAN.

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Introduction: The current paradigm for lunar evolution is of crystallization of a global scale magma ocean, giving rise to the anorthositic crust and mafic cumulate interior. It is thought that all other lunar rocks have arisen from this differentiated interior. However, until recently this paradigm has remained untested experimentally. Presented here are the first experimental results of fractional crystallization of a Lunar Magma Ocean (LMO) using the Taylor Whole Moon (TWM) bulk lunar composition [1].

Current models of LMO crystallization: Crystallization of a global-scale lunar magma ocean (LMO) is generally accepted as the best model to account for known lunar lithologies. There are two endmember processes by which crystallization of the LMO should proceed – fractional crystallization from the bottom up, or an initial interval of equilibrium crystallization followed by fractional crystallization. Physical models of magma viscosity and convection at this scale suggest that, under certain conditions, crystals could remain entrained in the magma for a significant period of time [2], resulting in equilibrium crystallization for the bulk of magma ocean crystallization. Alternatively, fully fractional crystallization results in a more pronounced change in residual liquid compositions in terms of decreasing Mg# and increasing SiO_2, potentially leading to plagioclase crystallization earlier in the sequence, and thus larger bulk proportions of plagioclase, in order to produce a flotation crust that is potentially up to 40 km thick [3]. Both possibilities have been computationally simulated [4, 5], and produce similar crystal assemblages (figure 1) although different bulk starting compositions were used. There are currently a number of different potential bulk lunar compositions, and it is impossible to distinguish between them with available data. TWM is a refractory enriched composition based on elemental abundance ratios, whereas LPUM reflects no such enrichment and is based on the terrestrial primitive upper mantle composition with alkalis adjusted to reflect lunar abundances [7]. Subsequent experimentation in this project will mimic fractional crystallization of an LPUM magma ocean.

The equilibrium crystallization case has been approached experimentally [6] using the TWM composition. These experiments equilibrated the TWM composition at 3 different pressures, and determined the crystallizing assemblages up to 80% solidification at each depth. We combine inferences from these experiments with those from our own in order to determine whether one model is more likely than the other to generate products most akin to the samples – i.e. an appropriate quantity of anorthitic plagioclase, appropriate mafic lithologies representing basalt sources, and a KREEP component.

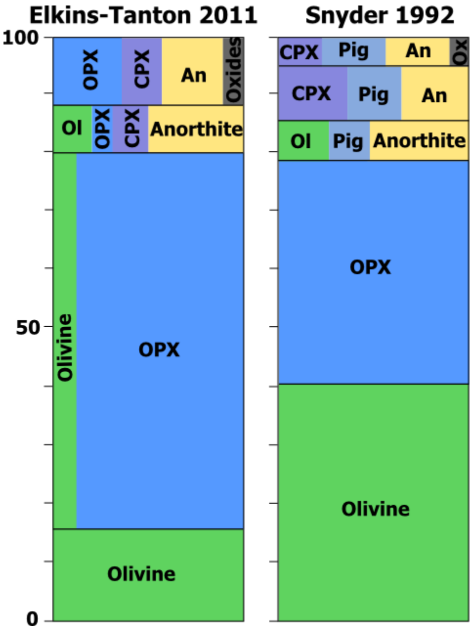

Figure 1 Block diagram showing the assemblages crystallized from two different computer simulations [4,5] (modified after [4]). The assemblage on the left represents a more fractional crystallization path, whereas the right hand diagram models equilibrium crystallization to 78%, followed by fractional crystallization. The two assemblages are broadly similar, with the Snyder model forcing the cessation of olivine crystallization with a recurrence further up the sequence. More anorthite is crystallized in the Snyder model, and CPX crystallizes later. However these must be compared with caution as differing bulk lunar compositions were used.

Methodology: The TWM starting composition was synthesized from a mechanical mixture of anhydrous oxides and stored at 110°C. Experiments were performed in a 10mm Depths of the Earth QuickPress piston cylinder apparatus at NASA Johnson Space Center, using graphite capsules and $BaCO_3$ as a pressure medium. Experiments were performed by heating to a superliquidus temperature for at least 15 minutes in order to homogenize the composition and condition it at fO_2 conditions close to the IW buffer, as stabilized by the graphite capsule. The temperature was then dropped in 1 – 3 minutes to the temperature of interest.

Experiments were quenched by switching off the power, which lowers the temperature below the glass transition in less than 1 minute. Run products were analysed using a Cameca SX100 electron microprobe. In order to synthesize fractional crystallization, experiments with approximately 10 volume % crystals were targeted. The composition of the glass from each step was used as the starting composition for the next set of experiments, simulating 10% of the crystals being fractionated from the melt. At each stage the total volume crystallized was calculated, and this value was used to calculate the pressure appropriate for the next set of experiments.

Crystallizing assemblages: Experimental phase assemblages are shown in figure 2, and compared to the calculated equivalent cumulate pile under equilibrium conditions [6]. Monomineralic olivine crystallizes for the first 50 volume % in our experiments, which is a much larger volume than in either of the modeled magma ocean or in previous experiments under equilibrium conditions by Elardo et al (2011). The second phase to crystallize is not OPX as predicted by the models, but Cr-rich spinel, followed by OPX/pigeonite only after 55% of the magma ocean has crystallized. CPX replaces OPX when 66% of the magma ocean has crystallized. At this point the spinel composition also changes from Cr-rich to Cr-poor (and Mg-rich), as Cr has been depleted from the system sufficiently to preclude chromite crystallization. The relatively early crystallization of Ca-bearing pyroxene and small but significant proportions of Al_2O_3-rich spinel in the crystallizing assemblages have strong implications for the amount of anorthite that is expected to crystallize after approximately 80% of the magma ocean has solidified. Depletion of both Ca and Al relatively early on in the crystallization sequence reduces the availability of these elements for anorthite crystallization. This depletion is counteracted somewhat by the much larger proportions of olivine formed than have been observed in previous models, producing a more plagioclase-rich melt composition relative to that observed by Elardo et al under equilibrium conditions (figure 3). It remains to be seen whether this melt composition will evolve to produce sufficient anorthite to account for the lunar crust, with a residuum representing KREEP. The outcome of this experimental investigation will enable us to put further constraints on the mechanisms by which the Moon evolved, in particular the extent, if any, to which equilibrium crystallization played an active role in LMO crystallization.

References: [1] Taylor, S.R., (1982) *Planetary Science, a Lunar Perspective*. [2] Tonks, W.B. and H.J. Melosh, (1990) *Origin of the Earth* [3] Wieczorek, M.A., (2009) *Elements* **5**(1): 35. [4] Elkins-Tanton, L.T., et al. (2011) *EPSL*, **304**(3-4): 326. [5] Snyder, G.A., et al. (1992) *Geochim. Cosmochim.*, **56**(10): 3809. [6] Elardo, S.M., et al. (2011), *Geochim. Cosmochim.*, **75**(11): 3024. [7] Longhi, J., (2006) *Geochim. Cosmochim.*, 70, 5919.

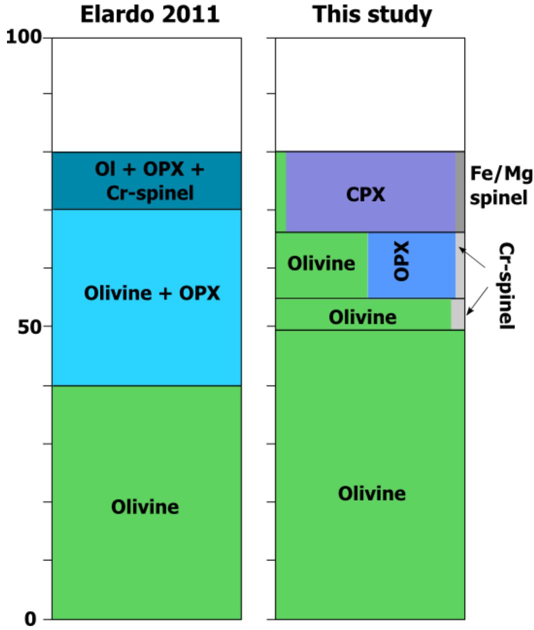

Figure 2 Block diagram showing the experimentally determined cumulate pile under equilibrium (left hand side – [6]) and fractional (right hand side – this study) conditions. The equilibrium assemblages are estimated based on the dominant assemblage crystallizing at each depth in the experimental study. The two scenarios show a marked difference in pyroxene abundance and composition, with the fractional case producing aluminous spinel and calcic pyroxene much earlier in the sequence.

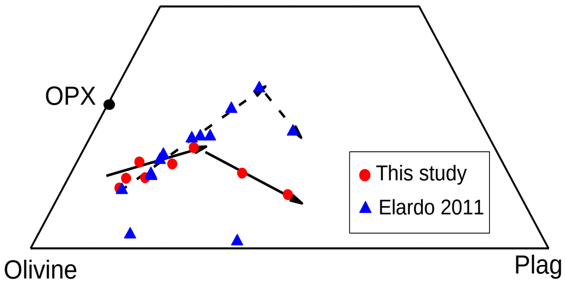

Figure 3 Liquid line of descent in the equilibrium and fractional case. Silica is at the apex of the ternary. The equilibrium experiments [6] (blue triangles, dashed line) produce a melt less enriched in the plagioclase component and more enriched in silica than the fractional experiments (red circles, solid line).