

**CAN FRACTIONAL CRYSTALLIZATION OF A LUNAR MAGMA OCEAN PRODUCE THE LUNAR CRUST?** J. F. Rapp<sup>1,2</sup> and D. S. Draper<sup>2</sup>, <sup>1</sup>Lunar and Planetary Institute, USRA Houston (jennifer.f.rapp@nasa.gov) <sup>2</sup>Astromaterials Research Office, ARES Directorate, NASA Johnson Space Center (david.draper@nasa.gov)

**Introduction:** New techniques enable the study of Apollo samples and lunar meteorites in unprecedented detail, and recent orbital spectral data reveal more about the lunar farside than ever before, raising new questions about the supposed simplicity of lunar geology. Nevertheless, crystallization of a global-scale magma ocean remains the best model to account for known lunar lithologies.

Crystallization of a lunar magma ocean (LMO) is modeled to proceed by two end-member processes – fractional crystallization from (mostly) the bottom up, or initial equilibrium crystallization as the magma is vigorously convecting and crystals remain entrained, followed by crystal settling and a final period of fractional crystallization [1]. Physical models of magma viscosity and convection at this scale suggest that both processes are possible. We have been carrying out high-fidelity experimental simulations of LMO crystallization using two bulk compositions that can be regarded as end-members in the likely relevant range: Taylor Whole Moon (TWM) [2] and Lunar Primitive Upper Mantle (LPUM) [3]. TWM is enriched in refractory elements by 1.5 times relative to Earth, whereas LPUM is similar to the terrestrial primitive upper mantle, with adjustments made for the depletion of volatile alkalis observed on the Moon. Here we extend our earlier equilibrium-crystallization experiments [4] with runs simulating full fractional crystallization.

Fractional crystallization should yield a more pronounced change in residual liquid composition than equilibrium crystallization, and therefore potentially the earlier and more extensive crystallization of plagioclase which is required to produce the plagioclase flotation crust represented by the anorthositic highlands. Both processes have been computationally simulated [5,6], and appear to produce broadly similar assemblages despite differences in bulk lunar composition and model parameters. However, an important limitation of theoretical models is the inability to constrain the last stages of LMO crystallization, in which both the plagioclase crust and KREEP component will form.

We present the results of fractional crystallization experiments on TWM and LPUM, and their implications thus far for the crystallization of a LMO and thickness of the anorthosite crust.

**Experimental:** Starting compositions were synthesized from mechanical mixtures of anhydrous oxides and stored at 110 °C. All compositions were doped with 100 ppm of trace elements (REE, Rb, Sr, Th, Hf),

for forthcoming mineral/melt trace element partitioning experiments to constrain the nature of the KREEP component. Experiments were performed in a 10mm Depths of the Earth QuickPress piston cylinder apparatus at NASA Johnson Space Center, under nominally anhydrous conditions using graphite capsules and BaCO<sub>3</sub> as a pressure medium. Experimental charges were heated 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 and run for 15 mins to 72 hours depending on temperature and pressure. 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 at 15kV and 20nA. A defocused beam of 10 µm was used on the glass phase. In order to simulate 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% fractionation of crystals from 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. After ~75% crystallization we switched to 1 bar experiments to mimic late-stage pressures. These experiments were buffered at IW using a Deltech CO- CO<sub>2</sub> gas mixing furnace.

**Results:** Experiments have been completed for 90% crystallization of the LMO using the TWM composition, and 50% using the LPUM composition (figure 1).

**TWM:** The first 50% of fractional LMO crystallization using TWM bulk composition produces monomineralic olivine – a much larger volume than predicted by theoretical models [5,6] or experiments under equilibrium conditions [4]. The next phase to crystallize with olivine is chromite, in small but significant proportions until Cr is exhausted, followed by opx/pigeonite. The crystallization of an aluminous phase at this early stage is significant, as it sequesters Al in the early-formed cumulates, reducing the availability to form plagioclase later in the crystallization sequence. In another deviation from modelled results and equilibrium experiments, the pyroxene composition soon changes to cpx, rather than a more extended

crystallization of opx, effectively sequestering Ca in the mantle also. At 78% LMO crystallization, plagioclase and cpx co-crystallize, and olivine is no longer present. The most recent experiments also contain ilmenite.

**LPUM:** Thus far, LPUM experiments are very similar to TWM, however with an important difference – they lack chromite. Paradoxically, although LPUM is poorer in Al than is TWM, Al is not sequestered by fractional crystallization of an aluminous phase, therefore plagioclase crystallization may in fact be enhanced in LPUM at a later stage. In addition, if opx crystallization is more extensive than in TWM, Ca would also be enriched in the late stage liquids, further favoring plagioclase crystallization. This result also confirms that chromite crystallization in the TWM experiments is not an effect of poor  $fO_2$  constraint in the capsule (or it would have also occurred in LPUM at the same conditions), but rather is a stable phase assemblage.

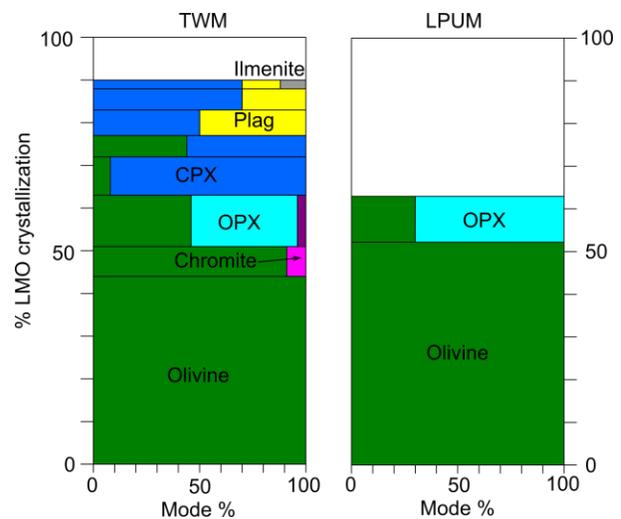
**Comparison with lunar samples:** Olivine- and orthopyroxene-rich mantle cumulates produced in our experiments are consistent with inferred mare basalt source regions [3]. Our late-stage cumulate assemblages are similar to predicted upper mantle cumulates, containing cpx, ilmenite and plagioclase. Late-stage ilmenite-rich cumulates are predicted in order to produce a density inversion in the mantle that drives overturn [5], provides a source of Ti for the high-Ti basalts and brings Mg-rich material to the surface to form Mg-suite rocks [4]. Pyroxene compositions are similar to those in FANs (figure 2), however plagioclase is at most  $An_{88}$ , which is much more Na-rich than plagioclase in lunar anorthosites of  $An_{95}$  [7] and above. We speculate that this is due to the poor constraint on Na in the lunar bulk composition, which could easily be at least an order of magnitude lower than used in TWM. This difference would result in significantly lowered abundances of Na in the magma ocean, and potentially higher An content of the crystallizing plagioclases. At the time of writing this notion remains to be tested experimentally.

**Implications for crustal thickness:** Although experiments to date have not completed 100% of LMO crystallization, the plagioclase produced after 90% crystallization constitutes some 25 km thickness of crust. The CIPW norm of the residual liquid contains around 30% plagioclase, 55% pyroxene, 9% Fe-Ti oxides, 5% apatite and 1% quartz. Assuming perfect separation of the phases, this plagioclase would produce a further ~15km of anorthosite crust. Data from the GRAIL spacecraft suggest that the average crustal thickness is 34 - 43km [8], somewhat thinner than previously predicted, but consistent with the predicted crustal thickness from our TWM experiments. As

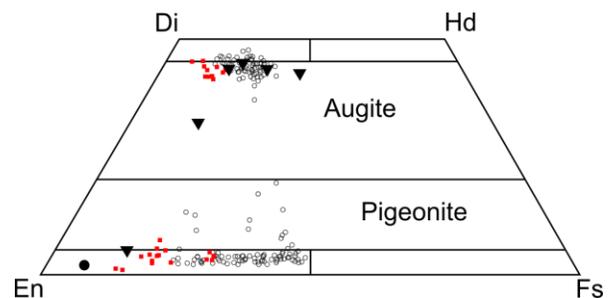
TWM is the most refractory element enriched bulk composition, one expects that a thicker crust will be produced from this composition. However, our data so far using LPUM suggest that although the bulk composition is initially less enriched in Al, it is also not sequestered into the early-formed cumulates, and is therefore available to produce a similar or thicker plagioclase crust. However, the effect of this different composition on the upper mantle cumulates and KREEP remains to be seen.

In summary, our experiments show that fractional crystallization of a lunar magma ocean produces cumulates consistent with our current understanding of lunar lithologies.

**References:** [1] Tonks, W.B. and Melosh H. J., (1990) *Origin of the Earth* [2] Taylor, S.R., (1982) *Planetary Science, a Lunar Perspective*. [3] Longhi, J., (2006) *Geochim. Cosmochim.*, **70**, 5919. [4] Elardo, S.M., et al. (2011), *Geochim. Cosmochim.*, **75**(11): 3024. [5] Elkins-Tanton, L.T., et al. (2011) *EPSL*, **304**(3-4): 326. [6] Snyder, G.A., et al. (1992) *Geochim. Cosmochim.*, **56**(10): 3809. [7] Warren, P. H. (1985) *Ann. Rev. Earth Planet. Sci.* **13**: 201 – 240. [8] Wiczorek, M. A. et al. (2012) *Science* DOI: 10.1126/science.1231530



**Figure 1:** Crystallizing assemblages in TWM (right) and LPUM (left) experiments.



**Figure 2:** Pyroxene quadrilateral comparing pyroxenes in TWM experiments (black triangles) and opx in LPUM experiments (black circle) compared to pyroxenes in Mg-suite (red squares) and FAN (open circles) lunar samples.