CRYSTALLIZATION OF THE LUNAR MAGMA OCEAN AND THE PRIMORDIAL DIFFERENTIATION OF THE MOON. B. Charlier[1,2,3], T. L. Grove[1], O. Namur[2], F. Holtz[2], [1]Massachusetts Institute of Technology, Department of Earth, Atmospheric, and Planetary Sciences, Cambridge, MA 02139 USA, [2]Institut für Mineralogie, Leibniz Universität Hannover, 30167 Hannover, Germany, [3]Department of Geology, University of Liège, 4000 Sart Tilman, Belgium (b.charlier@ulg.ac.be).

Introduction: The origin of the Moon has been generally attributed to a giant impact between a planet and the proto-Earth that ejected into orbit material from which the Moon accreted [1-3]. Energy liberated in the giant impact event was sufficient to produce melting of a substantial portion of the Moon, a likely cause of a "Lunar Magma Ocean" (LMO; [4]). Its crystallization appears to have structured the Moon into a mantle and a crust [5-6]. However, direct evidence on when the LMO formed and how it evolved chemically and physically as it cooled and crystallized remains a major issue.

To further the understanding of the evolution of the LMO and its crystallization products, we have performed a series of near-liquidus experiments to constrain the liquidus phase boundaries of a 600 km-thick lunar magma ocean with different bulk compositions. The 600 km depth was chosen based on evidence of a seismic discontinuity in the lunar mantle that could mark the base of the LMO [7]. Establishing the inital stratigraphy of the cumulates that formed during LMO crystallization is the main focus of this study as it is essential to understand the Moon's subsequent evolution and specifically potential cumulate overturn, remelting, and production of mare basalts and ultramafic glasses.

The early evolution of the LMO: We have selected a range of Whole Moon composition: the Taylor Whole Moon (TWM; [8]); Lunar Primitive Upper Mantle (LPUM; [9]), and the O'Neill composition (ON; [10]). These compositions lie in the stability field of olivine over the range of pressure relevant for LMO. The first steps of differentiation can thus be calculated by simulating crystallization of olivine. Liquid compositional evolution in each bulk composition was tracked by removing olivine to the point of low-Ca pyroxene saturation at the appropriate depth (pressure) in the crystallizing LMO, using existing experimental studies [9,11].

Experimental methods: We used graphite capsules in piston cylinder (1.35-0.80 GPa) and internally-heated pressure vessels (< 0.50 GPa), over 1580 to 1020°C. The experimental study aims at simulating the evolution of the lunar magma ocean during cooling, accumulation of crystallized material on the floor, and decreasing pressure with evolving residual liquid composition. We produced melt compositions that have evolved by fractional crystallization using a stepwise experimental approach, by synthesizing new materials having the composition of the residual melts after some degree of crystallization (Fig. 1). Each new experiment using a more evolved liquid composition is performed at da lower pressure, proportional to the fraction of crystallized minerals in the previous higher-temperature experiments. The main objective is to identify the position of phase boundaries in the appropriate compositional field and pressure range, and to build up a consistent dataset to constrain crystal-liquid partitioning for major elements.

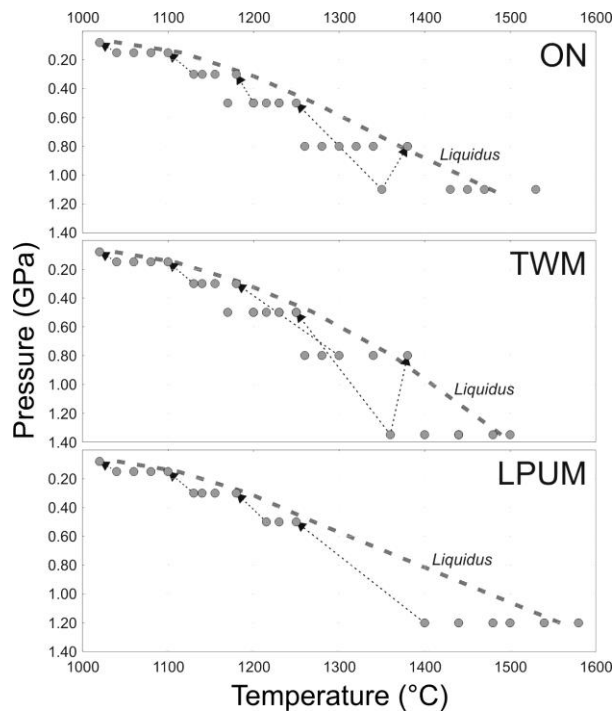

Figure 1: Pressure-Temperature conditions for stepwise crystallization experiments on LMO residual melts. Tie lines join successive experiments at decreasing pressure, proportional to the fraction of crystallized minerals. Lunar Primitive Upper Mantle (LPUM; [9]), O'Neill composition (ON; [10]), Taylor Whole Moon (TWM; [8]).

Phase assemblages: Experiments have been performed on a range of LMO compositions but systematic observations can be derived on phase equilibria (Fig.

2). Olivine is the first phase to appear followed by orthopyroxene. With decreasing temperature and pressure, olivine coexists with orthopyroxene, which is then replaced by pigeonite. The appearance of pigeonite is almost simultaneous with that of plagioclase (1280-1240°C). For two compositional suites, olivine then disappears and sub-calcic augite appears. The assemblage containing glass, pigeonite, subcalcic augite and plagioclase is complemented by the appearance of a silica phase (at 1080°C), and then by ilmenite. In our lowest temperature experiments (1020°C), olivine is stable again and pigeonite is not observed (Fig. 2).

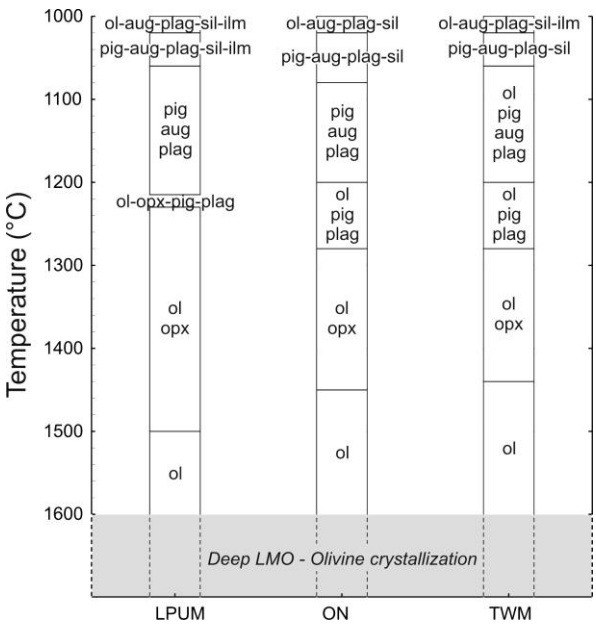

Figure 2: Crystallization sequence for the lunar magma ocean obtained experimentally for three Whole Moon compositions: the Lunar Primitive Upper Mantle (LPUM; [9]), the O'Neill composition (ON; [10]), and the Taylor Whole Moon (TWM; [8]).

Experimental liquids: Liquids show continuous MgO depletion with decreasing temperature from 32-38 wt.% in parental liquids to less than 1 wt.% in the most evolved residual melts at 1020°C. Silica remain approximatively constant (ca. 46-50 wt.%). The polybaric liquid lines of descent can be subdivided into two stages, before and after plagioclase saturation. Before plagioclase crystallization, the trends displays Al_2O_3 and CaO enrichment, with moderate increase in FeO_{tot}. After plagioclase saturation, the paths followed by the residual liquids show Al_2O_3 and CaO depletion and liquids record extreme iron enrichment up to 28 wt.% FeO_{tot}. Most noticeable is that residual melts do not show FeO_{tot} depletion even after ilmenite saturation. The amount of TiO_2 increases continuously, until ilmenite saturation (at 1080-1020°C). After plagioclase saturation, the different starting whole moon compositions lead to the same residual compositions with production of ferrobasalts.

Modeling: Our experimental dataset enables us to develop empirical equations for the prediction of equilibrium mineral compositions, cotectic proportions, and expressions for liquidus phase boundaries. Experiments will be combined with numerical models using forward approaches of fractional and equilibrium crystallization with various proportions of trapped liquid in crystallisation products. We will provide new constraints on the amount of alumina stored in the mantle, the timing for the saturation of plagioclase, the resulting crustal thickness, and density stratification with implications for potential overturn.

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