

SOLIDIFICATION EVOLUTION OF A DRY LUNAR MAGMA OCEAN: CONSTRAINTS FROM EXPERIMENTAL PETROLOGY. Y. H. Lin*, E. J. Tronche, E. S. Steenstra and W. van Westrenen, Faculty of Earth and Life Sciences, VU University Amsterdam, The Netherlands (y.lin@vu.nl)

Introduction: The Moon is thought to have been covered by a deep magma ocean shortly after its formation. The gradual solidification of this ocean yielded the plagioclase-rich highland crust, and shallow subsurface reservoirs rich in titanium and radiogenic heat-producing elements that control most of the Moon's subsequent geological and geochemical evolution. Full crystallization of a Lunar Magma Ocean (LMO) has been modeled numerically on the basis of a small subset of experiments in the classic work of Snyder et al. [1]. A recent experimental study focused on partial LMO solidification [2]. Here, we present a full experimental lunar magma ocean (LMO) crystallization study, simulating up to 99 per cent fractional crystallization of a dry, Al-poor, Fe-rich LMO composition. A 'two-stage' model of magma ocean solidification is assumed, which features early efficient crystal suspension in magma and corresponding equilibrium crystallization, followed by fractional crystallization of the later residual magma ocean. Our results differ in several ways from the classic numerical studies that are widely used in lunar magma ocean modeling [1], likely due to the fact that these ignored the pressure effect on crystallization.

Background: The crystallization of the LMO is thought to have created a series of concentric cumulate layers with different chemical compositions and different mineralogical assemblages. The crystallization sequence and composition of these cumulate layers are of primary importance for understanding key events in lunar evolution including the formation of a plagioclase-rich crust and an overturn in the mantle leading to mare basalt volcanism [3]. The aim of this work is to solve three main questions: (1) how thick is the anorthositic crust based on an experimental study of a dry LMO crystallization, (2) what is the crystallization sequence of the LMO and what are the corresponding P - T conditions in the ocean, and (3) how do the chemical compositions of cumulates and corresponding residual LMO vary with progressive solidification.

Experimental: We assume that the depth of the convecting part of the LMO is 700 km. From this starting point the process of LMO crystallization is investigated by adopting a 'two-stage' model of equilibrium crystallization persisting until 50% solids remains. This estimate is based on calculations of the ability of suspending crystals in a cooling magma ocean [4]. The starting composition of the LMO is based on the geophysical study of Khan et al. [5] with addition of TiO_2 . This composition is relative Al_2O_3 -poor compared with the Lunar Primitive Up-

per Mantle (LPUM) composition used for the classic LMO numerical model [1], instead having a aluminium abundance consistent with models for the composition of the Bulk Silicate Earth. Starting materials for subsequent crystallization steps are based on the composition of the residual liquid of the previous crystallization step with removal of the corresponding crystals. For comparison we show the LMO composition used by [1] and [2] in the table below.

	SiO_2	TiO_2	Al_2O_3	FeO	MgO	CaO
[1]	48.40	0.40	5.00	12.00	29.90	3.83
[2]	45.90	0.15	4.15	8.15	38.40	2.95
This study	45.42	0.54	4.35	10.65	37.10	3.19

We simulated fractional crystallization of the LMO using a stepwise experimental approach for the second part. The residual liquid remaining after the first ~50% of crystallization is synthesized (LMO_2). Crystallization of ~20.7% of this LMO_2 composition, which is equivalent to ~10.4% solidification in the whole LMO, is then studied in subsequent experiments. The residual liquid remaining after this crystallization of the LMO_2 composition, which is the residual after ~60.4% of LMO crystallization, is then synthesized (LMO_3), and so on. For each step, experiments were performed at 1 to 7 different pressures depending on the remaining depth of the magma ocean, and at as many temperatures as required to approach the targeted crystallization percentage.

Nominally dry starting materials are glassy powders produced by fusion of the appropriate high purity oxide and carbonate compounds. The samples were packed in graphite inner capsules which are inserted in outer platinum capsules subsequently welded shut. Experiments were performed in two piston-cylinder apparatus at VU University Amsterdam using a 0.5 inch diameter talc-pyrex cell assembly. Pressures range from 0.4 to 3 GPa and temperatures from 1000 to 1550 °C. The oxygen fugacity is around 1.1 log units above the IW buffer, so that iron is present in the 2+ valence state. Some experiments were also performed in a high temperature 1 atmosphere furnace (temperatures between 1000 and 1550°C). Experiment duration varied between 5 and 200 hours depending on the melting degree and temperature.

Analytical: All experiments were analyzed with JEOL electron microprobes at VU University Amsterdam or Utrecht University (15kV, 25nA for Si, Ti, Al, Fe, Mg and Ca), and checked for contamination and iron loss. The mineral and melt proportions

were determined both by mass balance calculations and area percentage using an EDAX EDS system in imaging mode.

Results: Results of our study are summarized in Figure 1a. There are significant differences in crystallized sequences with previous studies [1,2] apparent in Fig. 1. During the first stage of equilibrium solidification, olivine (0–40 per cent crystallisation, PCS) and orthopyroxene (40–78 PCS) have crystallized successively to 78 PCS in the Snyder et al. model [1]. In contrast, the Elardo et al. model [2] shows that Opx has not entered the phase assemblage by 50% solidification at 1 and 2 GPa, yet it has at 4 GPa, and subsequently garnet joins the assemblage of olivine and Opx. This implies that pressure has an important effect on the LMO crystallization sequence. In consideration of pressure effects, we used the same temperature and seven different pressures based on the whole LMO depth to model crystallization in the equilibrium stage. In our model, olivine and orthopyroxene crystallized together, and the Opx/olivine ratio increases with increasing pressure.

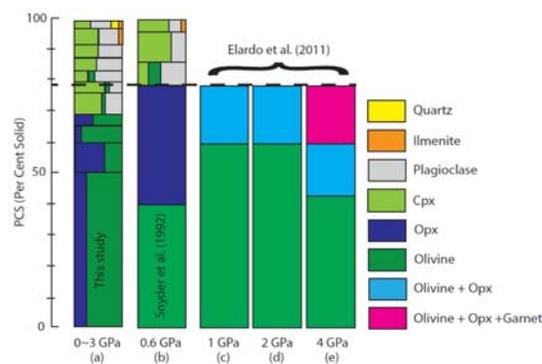


Figure 1: Comparison of the LMO solidification models ((a) this study, (b) from [1], (c–e) from [2])

The later fractional crystallization sequence also shows differences compared to the cumulate pile derived by Snyder et al. [1]. Plagioclase first appears between 68 and 76% of crystallization (78% for [1]) and floats in our experiments. At the same time, Ca-rich pyroxene starts crystallizing, and then olivine disappears at 83 PCS. Ilmenite starts to crystallize at 91 PCS. In the final experiments, β -quartz appears at 96 PCS coexisting with the assemblage of Cpx, plagioclase and ilmenite ending the LMO solidification at 99 PCS.

Discussion: At ~99% total dry LMO solidification the lunar crust consisting of pure plagioclase and later quartz has already reached a thickness of 67.5 km, which clearly exceeds the average crustal thickness (34–43 km) derived from recent GRAIL models [6]. We note that it is the case even though our bulk composition holds the same amount of al-

uminium as the bulk silicate Earth, which is less aluminium than many other bulk LMO compositional models. This provides independent support for the presence of water in the Moon at the time of LMO crystallization [7], as water is known to delay the crystallization of plagioclase in cooling magmatic systems [8–9]. In a companion abstract [10] we describe an experimental study into the effect of water on LMO crystallization.

Conclusions: The main conclusions of our fully experimental study of the crystallization of a dry lunar magma ocean are that (a) the shallow lunar interior could contain quartz (b) the LMO could have contained water.

References:

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