Solidification of the lunar magma ocean

E. J. Tronche and W. van Westrenen
Faculty of Earth and Life Sciences, VU University Amsterdam, The Netherlands (e.j.tronche@vu.nl)

Abstract

We investigated the crystallization of a model lunar magma ocean composition using experimental petrology. Our results differ from classic numerical studies that are widely used in magma ocean modeling, likely due to the fact that these ignored the pressure effect on crystallization.

1. Introduction

The Moon underwent a global magma ocean stage very early in its history [1]. The crystallization of this lunar magma ocean (LMO) is thought to have created a series of concentric cumulate layers with different mineralogical assemblages. The crystallization sequence and composition of these cumulate layers are of primary importance for subsequent key events in lunar evolution including the formation of a plagioclase-rich crust and an overturn in the mantle, with the latter triggering basaltic mare volcanism [1]. To date, numerical and petrological models studying cumulate overturn and other interior processes base their initial cumulate pile on the computations from Snyder et al. [2]. These authors used a simplified calculation path that does not incorporate the possible effect of pressure on crystallisation. In the present study, we determined in detail the crystallization behaviour of a magma ocean using experimental tools, simulating lunar interior conditions at depth and under shallow conditions. The aim of this approach is to solve three main questions: (1) can a thick anorthositic crust form, and if so, what is its mineralogical and chemical composition, (2) what is the extent of gravitational instability of the resulting cumulate pile, which forms a driving force for mantle overturn, and (3) how are the observed compositions of mare basalts and other volcanic products at the lunar surface linked to remelting processes of overturned cumulate piles.

2. Method

2.1 Calculation method

We assume that the depth of the convecting part of the LMO is 700 km. The magmasphere could have been deeper, but we consider that everything below 700 km is a mushy material that does not take part in convection. In their calculations, [2] considered equilibrium crystallization until the formation of plagioclase (78% of solidification in their case) at which point fractional crystallization begins. Other authors put this limit significantly lower, between 50 and 60% of crystallization [1]. We arbitrarily choose a 50% crystallization boundary between equilibrium and in situ crystallization. The starting composition (LMO_1) used for the first part of the crystallization is based on the study of Khan et al. [3] with addition of TiO_2 and a cocktail of trace elements (La, Ce, Nd, Sm, Eu, Dy, Er, Yb, Lu, Co, Ni, Ba, Sr, Nb, Sc, Mn, P, Cr, Na, K, U, Th, Hf and W). For comparison we show the composition used by [2] in table 1.

	SiO_2	TiO_2	Al_2O_3	FeO	MgO	CaO
This study	45.25	0.50	4.30	12.45	34.35	3.15
[2]	48.4	0.4	5	12	29.9	3.83

Table 1: Comparison between the starting compositions used experimentally in this study and numerically in Snyder et al. [2].

The compositions of subsequent starting materials are based on the composition of the residual liquid of the corresponding previous crystallization step. We choose steps of 5% of crystallization of the LMO for the second part. This means that after the first 50% of crystallization, the residual liquid of this first step is synthesized (LMO_2) and crystallized at 10% (5% of the whole magma ocean); the residual liquid after this step, which is the residual after 55% of crystallization, is then synthesized (LMO_3) and crystallized to 11.1% (5% of the whole magma ocean); the residual liquid from that step (LMO_4) is crystallized at 12.5% and so on. Composition LMO_{11} corresponds to the end of the LMO crystallization. For each step, experiments were performed at 3 to 6 different pressures depending on the remaining depth

of the magma ocean, and at as many temperatures as required to approach the crystallization amount needed. Because of the spherical shape of the Moon, crystallization occurring at depth in the LMO is volumetrically contributing less than at shallow levels. The amount of crystals over the whole pile for each step and the composition of the global residual liquid have all been scaled to their respective volumetric importance.

2.2 Experimental method

Sample materials are glassy powders produced by fusion of the appropriate high purity oxide and carbonate compounds. The samples are packed in graphite inner capsules which are inserted in outer platinum capsules subsequently welded shut. Experiments were performed in 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 1650 ℃. The oxygen fugacity is around 1.1 log units above the IW buffer, so that iron is present in the 2+ valence state as in the Moon. Some experiments were also performed in a high temperature furnace (between 1000 and 1650℃). Experiment duration varied between 5 and 200 hours depending on the melting degree and temperature.

2.3 Analytical method

All experiments were analyzed with a JEOL JXA 8800 electron microprobe at VU University Amsterdam (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. Trace element concentrations were measured by LA ICPMS when grain size allowed it.

3. Results

The first 50% of crystallization with our model is radically different from the study of [2]. In their model, only olivine crystallizes initially, with OPX joining after 40% crystallization. In our model, OPX and olivine crystallize together. At higher pressures, the OPX/olivine ratio increases. Since Snyder et al. [2] did not incorporate this pressure effect they did not see the importance of OPX in the lower cumulates. As trace elements have different affinities for olivine and OPX, later remelting of a dunitic or harzburgitic cumulate would create different volcanic compositions.

The later in situ crystallization also shows differences compared to the cumulate pile and residual liquid's trend of [2] (fig. 2).
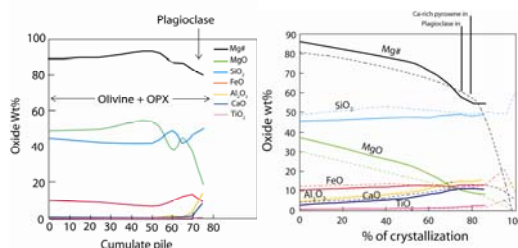

Figure 2: Compositions of cumulates (left) and residual liquid (right).

Plagioclase appears between 70 and 75% of crystallization (78% for [2]) and floats in our experiments, mechanically entraining pyroxenes. Ca-rich pyroxene starts crystallizing between 75 and 80%. At 85% of crystallization no ilmenite is formed yet.

4. Outlook

At this stage we have not finished the full LMO crystallization. Upcoming results will reveal the timing of ilmenite formation, the total thickness of the plagioclase crust (after 75% crystallisation it is 24 km thick) and place bounds on the enrichment of the KREEP layer.

References

[1] Shearer C. K. et al.: Thermal and magmatic evolution of the Moon. In New views of the Moon, Reviews in Mineralogy and Geochemistry volume 60., pp. 365-518, 2006.

[2] Snyder G. A., Taylor L. A. and Neil C. R.: A chemical model for generating the sources of mare basalts: combined equilibrium and fractional crystallization of the lunar magmasphere, Geochimica et Cosmochimica Acta, 56, pp. 3809-3823, 1992.

[3] Khan A. et al.: Joint inversion of seismic and gravity data for lunar composition and thermal state, Geophysical Journal International, 168, pp. 243-258, 2007.