

CONSTRAINTS ON THE BULK COMPOSITION OF LUNAR MAGMA OCEAN FROM CONDITIONS OF CRUST FORMATION; CRITICAL REEVALUATION OF SEPARATION MECHANISM OF ANORTHITE. R. Sakai¹, I. Kushiro¹, H. Nagahara¹, K. Ozawa¹, S. Tachibana¹, ¹Department of Earth and Planetary Science, The University of Tokyo, 7-3-1 Hongo, Tokyo 113-0033, JAPAN (rsakai@eps.s.u-tokyo.ac.jp).

Introduction: Recent observations by lunar explorations have shown that the lunar highland crust is highly anorthositic in composition and is $\sim 45 \pm 10$ km thick [1, 2]. The Moon has been thought to have undergone a global magma ocean very early in its history and the anorthositic crust was formed by accumulation of anorthite crystallized in the lunar magma ocean (LMO) [3]. The LMO hypothesis has been supported by geochemical observations, such as the ancient age (~ 4.5 Ga) of highland anorthosite, the complementarity of Eu anomaly between highland anorthosite and mare basalts, and the existence of KREEP rocks that are highly enriched in compatible elements, and geophysical modelings.

The bulk composition of the Moon has been estimated by previous studies on the basis of refractory trace elements in near surface rocks [4-6], composition of the mare basalts [7-9], and geophysical data such as the momentum inertia, the bulk density and the seismic velocity [10, 11]. There are, however, large disparities among the estimates, because of the lack of direct chemical and structural information on the Moon's interior right after the solidification of the magma ocean.

Elkins-Tanton et al. (2011) [12] recently evaluated the cooling process of LMO using physical and chemical model for solidification. They proposed that the initial LMO was as much as ~ 1000 km deep and that ~ 80 vol% of the LMO was solidified on the order of 1000 years before anorthite crystallization regardless of the initial composition. They further discussed the formation timescale of the anorthosite crust by floatation of anorthite with maximum efficiency. However, the floatation of anorthite is not always guaranteed because there are several factors that potentially prevent anorthite from floating to form the anorthositic crust, such as separation mechanisms of anorthite from the convecting LMO [13]. The initial composition of the LMO, particularly FeO and refractory elements, largely affects physical properties of melts as well as the phase relation of anorthite crystallization, and thus the dynamics of the cooling LMO.

We have investigated the conditions for the effective floatation of anorthite in the LMO to reproduce the observed critical features of the lunar crust to constrain the FeO and refractory element contents of the initial LMO. In this study, we refined our model [13] by applying the crystal separation model by [14], which is

more realistic than the model by [15], and by adopting an appropriate oxygen fugacity for the lunar interior. Here we report our new and more strongly constrained estimates of the contents of FeO and refractory element in the initial LMO.

Model: We divide the cooling process of the LMO into three stages: (1) The initial LMO, which is assumed to be 1000 km, (2) differentiation of mafic minerals, where olivine and pyroxene crystallize and settle down to make mantle, and (3) the crust formation stage, where anorthite crystallizes and floats to form the lunar crust. We assumed a Ca-Mg-Al-Si-Fe system for the bulk compositions of the initial LMO. The MgO/SiO₂ and CaO/Al₂O₃ ratios were set at those of the BSE and the solar abundances, respectively, and the abundances of FeO and refractory elements (CaO+Al₂O₃) were varied as parameters. Titanium was not considered because it did not affect significantly the LMO evolution. Alkali elements (Na₂O and K₂O) were not included either because they should be negligibly small to explain the anorthite content of lunar-highland plagioclase. The oxygen fugacity of the cooling LMO was kept close to the iron-wüstite buffer to match the estimated oxygen fugacity for the source of mare basalts and igneous glassed [16, 17]. Differentiation processes of mafic minerals were modeled as follows; (1) Crystallization of mafic minerals takes place at the middle depth of the well-mixed turbulent LMO. The phases and compositions of solidified components are calculated with MELTS/pMELTS [18, 19]. (2) At a certain crystal fraction in the LMO, the mafic minerals are instantaneously settled down to the bottom of the LMO. The critical crystal fraction for mafic mineral separation was varied from 0 to 0.4 as a parameter [20, 21]. After the separation of mafic minerals, we re-evaluate the depth of the LMO by mass-balance calculation and re-model the crystallization and separation of mafic minerals. This step was repeated until anorthite becomes a liquidus phase.

We then examined the LMO composition at the appearance of anorthite if it satisfies the following conditions required for the anorthosite crust formation; (a) the amount of anorthite, which can be crystallized from the LMO, is enough to form the crust with the thickness of ~ 45 km, (b) the pyroxene composition coexisting with anorthite is consistent with that of lunar highland rocks, and (c) anorthite can float in the turbulent LMO.

Results: The crystallization differentiation calculations showed that: (1) anorthite crystallizes in most cases except for the LMO highly enriched in refractory elements ($>2.3\times$ BSE), where spinel crystallizes as a major Al-bearing phase, (2) the degree of crystallization of a LMO reaches ~ 80 vol% at the time of anorthite crystallization after differentiation of mainly olivine and pyroxenes, and (3) the FeO content of the LMO at the appearance of anorthite increases with the initial FeO content, but shows little dependence on the initial abundance of the refractory elements and the efficiency of crystal separation of the mafic minerals.

A mass balance calculation using the CIPW norm showed that the LMO highly enriched both in refractory elements and FeO cannot produce the anorthosite crust with the thickness of 45 km from the initial LMO with the depth of ~ 1000 km.

The Mg# of clinopyroxene coexisting with anorthite at the timing of anorthite crystallization was compared with that of pyroxenes in FAN (ferroan anorthosite). The most magnesian cpx in FAN has the Mg# of 75 [24, 25], which gives the upper limit of ~ 20 wt% ($\sim 3\times$ BSE) for the initial FeO content in the initial LMO.

The compositional range of the LMO required for anorthite floatation was obtained by comparing the critical anorthite size for effective separation for each LMO composition with the size of anorthite in the Apollo-15 highland rock #15415 (1.8 cm) [22, 23]. It was found that the initial FeO content of the LMO should be larger than ~ 10 wt%, which is higher than the FeO content in the BSE.

A plausible range of the initial FeO and refractory element contents in the LMO is summarized in Fig. 1. The initial FeO content should be more abundant than that of BSE, and the degree of refractory element enrichment should be $<2.3\times$ BSE. The upper limit of the FeO content is constrained more strictly in this study than in our previous study because the oxygen fugacity was adjusted to the IW buffer, which prevented crystallization and separation of Fe metal maintaining high concentration of FeO in the melt.

Discussion: The evaluated range includes the estimates by Taylor [6], who estimated that the abundance of the FeO and refractory elements of the Moon to be 1.5 times as rich as the BSE; however, does not include those of Longhi [7] and Warren [5], who argued for the compositional similarity of the Earth and Moon. This discrepancy with previous studies might be mainly attributed to a strong bias of used lunar samples to particular regions or ages, which might not represent the global and initial features of the Moon. Our results showed that the BSE-like composition cannot produce the anorthosite crust because of its low

FeO content, which inhibits anorthite separation from the turbulent magma ocean owing to the smaller density contrast between the melt and anorthite, and its higher melt viscosity.

The higher FeO content estimated for the LMO than the BSE implies that the impactor that hit the proto Earth was enriched in FeO than the BSE or that the oxygen fugacity of the LMO was higher than the BSE. If the terrestrial magma ocean and the proto-lunar disk underwent turbulent mixing to maintain equilibration of oxygen isotopes [26], it may be implausible to assume that the oxygen fugacity of the Earth and Moon were different, suggesting the higher FeO model is favourable.

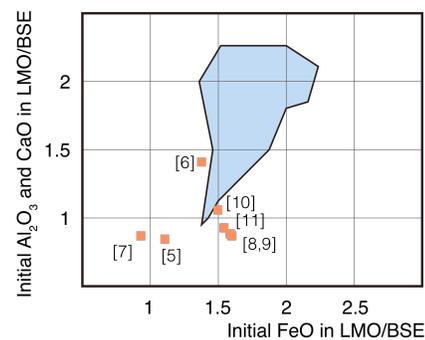


Fig. 1. Plausible ranges of FeO and refractory-element (Al_2O_3 and CaO) contents in the initial LMO (blue-colored region). The abundances of FeO and refractory elements are normalized to the BSE. The compositions estimated in previous studies (orange squares) are also shown for comparison.

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