

**CHEMICAL COMPOSITION OF LUNAR MAGMA OCEAN CONSTRAINED BY THE CONDITIONS OF CRUST FORMATION.** R. Sakai<sup>1</sup>, H. Nagahara<sup>1</sup>, K. Ozawa<sup>1</sup> and S. Tachibana<sup>2</sup>, <sup>1</sup>Department of Earth and Planetary Science, The University of Tokyo, 7-3-1 Hongo, Tokyo 113-0033, JAPAN ([rsakai@eps.s.u-tokyo.ac.jp](mailto:rsakai@eps.s.u-tokyo.ac.jp)), <sup>2</sup>Department of Natural History Sciences, Hokkaido University, N10 W8, Sapporo 060-0810, JAPAN.

**Introduction:** The Moon has been thought to have molten globally very early in its history and the anorthositic crust was formed by accumulation of anorthite crystallized in the lunar magma ocean (LMO) [1]. Previous studies revealed that the LMO extended to the whole Moon and anorthite began to crystallize from a residual melt after ~80% crystallization of the LMO [2, 3, 4]. The bulk composition of the Moon has been estimated by previous studies on the basis of refractory trace elements in near surface rocks [5-7], composition of the mare basalts [8-10], and geophysical data such as the momentum inertia, the bulk density and the seismic velocity [11, 12]. 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.

We have investigated the conditions of the effective flotation of anorthite in the LMO to reproduce the observed critical features of the lunar crust [13-16] to constrain the FeO and refractory element contents of the initial LMO. In this study, we refined our model [17] by applying the crystal separation model by [18], which is more realistic than the model by [19], 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 elements 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. The system consists of Ca-Mg-Al-Si-Fe-O, the MgO/SiO<sub>2</sub> and CaO/Al<sub>2</sub>O<sub>3</sub> ratios were fixed at those of the BSE and the solar abundances, respectively, and the abundances of FeO and refractory elements (CaO+Al<sub>2</sub>O<sub>3</sub>) were varied as parameters. Titanium was not considered, because it does not affect significantly the LMO evolution. Alkali elements (Na<sub>2</sub>O and K<sub>2</sub>O) were not included, because they should be negligibly small to explain the composition 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 glasses [20, 21].

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 [22, 23]. (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 [24, 25]. After the separation of mafic minerals, phase relations and the depth of the residual LMO were recalculated, and crystallized mafic minerals were separated again at the same critical crystal fraction as the previous step. These procedures were repeated until anorthite appears as a liquid phase.

We then evaluated the melt composition at the appearance of anorthite if it satisfies the following conditions required for the anorthositic crust formation; (a) the amount of anorthite, which crystallized from the residual melt, is abundant 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 except for cases with high enrichment of refractory elements (>2.3x 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 appearance after differentiation of mainly olivine and pyroxenes, and (3) the FeO content of the LMO at the appearance of anorthite increases with increasing initial FeO content, but shows little dependence on the initial abundance of the refractory elements and the critical crystal fraction for separation.

A mass balance calculation using the CIPW norm showed that the LMO highly enriched both in refractory elements and FeO does not produce the anorthositic 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 time of anorthite crystallization was compared with that of pyroxenes in FAN (ferroan anorthosite). The most magnesian cpx in FAN has the Mg# of 75 [15, 16], which gives the upper limit of ~20 wt%

(~3x BSE) for the initial FeO content in the initial LMO.

The compositional range of the LMO required for anorthite flotation 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) [26, 27]. It was found that the initial FeO content of the LMO should be larger than ~10 wt%, which is higher than the FeO content of 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, and the refractory elements should be also more enriched than those of BSE. The upper limit of the FeO content is constrained more strictly in this study than in our previous study [17] by considering a plausible  $f_{O_2}$ .

**Discussion:** The present results show that the BSE-like composition did not form the anorthosite crust observed, because its low FeO content prevented anorthite separation from a turbulent magma ocean owing to smaller density contrast between the melt and anorthite and a higher melt viscosity.

The present result is roughly consistent with Taylor [7], Jones and Delano [9], Wanke and Dreibus [10], Buck and Toksoz [11], and recent Khan et al. [12]. It is, however, inconsistent with Longhi [8] and Warren [6] who argued for the compositional similarity of the Earth and Moon. The discrepancy might be mainly attributed to the lunar samples they studied, which were derived from particular regions or ages and which might not represent the global and initial features of the Moon.

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 [28], it may be implausible to assume that the oxygen fugacity of the Earth and Moon were different, suggesting that the higher FeO model for the impactor is favorable.

Although the upper limit of the  $Al_2O_3$  and CaO contents is poorly constrained in the present study, their contents are much higher than the previous estimates by Longhi [8] and Warren [6]. Information of REE pattern in FANs is expected to give a much tighter constraint on the abundance of refractory element in LMO.

We will report a result in our ongoing evaluations: (1) the chemical composition analysis of Yamato-86032 to put a stronger constraint on the Mg# of LMO and/or the grain size of anorthite floated from LMO and (2) an examination of the REE in lunar highland

anorthosites to put a stricter constraint on the initial composition and the differentiation process of LMO.

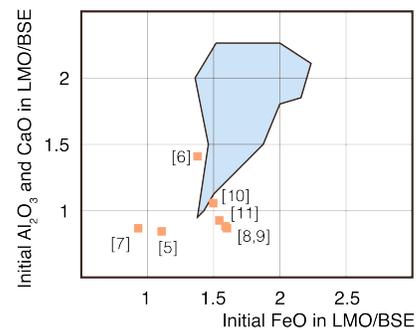


Fig. 1. Plausible ranges of FeO and refractory-element ( $Al_2O_3$  and CaO) contents in the initial LMO (blue-colored region). The abundances of FeO and refractory elements are normalized to the BSE. The compositions estimated in previous studies (orange squares) are also shown for comparison.

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