FeO AND REFRACTORY ELEMENTS OF LUNAR MAGMA OCEAN CONSTRAINED BY CONDITION OF ANORTHOSITE CRUST FORMATION. R. Sakai1, I. Kushiro1, H. Nagahara1, K. Ozawa1, and 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: Many previous works have estimated bulk composition of the Moon, where some insisted that the Earth and the Moon are compositionally alike [1, 2], whereas, some proposed that the Moon is rich in FeO and refractory elements [3, 4]. The contents of FeO and refractory elements such as Al₂O₃ and CaO are crucial for the formation and evolution of the Moon. The FeO content in the lunar magma ocean depends on the oxygen fugacity and/or the distribution between the core and mantle, and has a significant effect on the density and viscosity of magma. The Al₂O₃ and CaO are the main components of lunar anorthositic crust, and some studies insisted that these elements are enriched in the Moon compared to the Earth. We focus on the FeO and refractory elements in the composition of the lunar magma ocean (LMO) in this study.

The giant impact hypothesis suggests that the Moon was almost totally melted at the final stage of the Earth formation due to the release of enormous accretion energy [5, 6]. The dynamics and compositional evolution of a cooling magma ocean have been investigated specifically for the Earth [7-10], which suggested a low viscosity, turbulent magma ocean. There is, however, no consensus on the geochemical aspect of differentiation of a LMO, yet.

The present study tries to constrain the bulk LMO composition to be consistent with the observation of the anorthositic crust.

Model: The lunar crust has the average thickness of 45-60 km, the upper part of which is composed dominantly of almost pure anorthite, although the structure of the lower crust is unknown. Constraints for formation of such a lunar crust are: (a) anorthite crystallized and floated to accumulate in the differentiated magma ocean, (b) the amount of anorthite was abundant enough to form the anorthositic crust of the average thickness of 45 km, and (c) the composition of minerals, such as Mg# (= molar [MgO/(MgO+FeO)] x100) of mafic minerals and An content of plagioclase should be consistent with the observation. The constraint (a) has two aspects: one is chemical and the other is physical. The chemical requirement is that the magma has to be saturated with anorthite on the course of fractional crystallization in the LMO. The physical requirement is that the density of the magma is higher than anorthite at least at the time of anorthite crystallization and that the viscosity of the magma is low enough to allow floatation of anorthite crystals.

We first choose a bulk chemical composition, with which we calculate fractionation crystallization to find a melt composition saturated with anorthite after discarding cases that does not meet the requirement of anorthite saturation, we obtain the density and viscosity of the magma. We then evaluate whether the magma satisfies the constraints described above.

The bulk composition of the initial LMO is assumed to be that of the bulk silicate Earth (BSE), or FeO- and refractory element-enriched BSE. The enrichment factors, which are free parameters in the model, range 0.6-3 for FeO and 1-2.5 for refractory elements (Al₂O₃ and CaO). We do not consider TiO₂, Cr₂O₃, MnO, Na₂O and K₂O.

Differentiation of olivine and pyroxene is assumed to follow the incremental fractionation, of which compositional trajectory lies between the maximum fractionation and batch crystallization. The initial depth of the magma ocean is assumed to be 1000km. Crystallization is assumed to take place at the middle depth of the LMO up to the critical crystal fraction followed by instantaneous and complete crystal separation. Thus, the first separation of crystals takes place at 500km, the 2nd at 250km, and so on. A parameter in the differentiation process is the critical crystal separation fraction (X (=0 to 40)). The chemical composition, temperature, depth of the differentiated LMO, and the amount of melt at the first appearance of anorthite, and following crystallization of the melt are calculated thermodynamically with the MELTS/pMELTS models [11, 12]. The density and viscosity were determined in experiments conducted with a piston cylinder [13]. We finally evaluate whether the initial LMO composition satisfies the three constraints described above taking the effect of turbulence in the magma ocean into consideration. We also evaluate the chemical composition of clinopyroxene that appears after anorthite crystallization.

Results: The differentiation crystallization calculations showed that: (1) anorthite crystallizes in most cases except for highly refractory-enriched (> ~3x BSE) compositions, where spinel appears instead of plagioclase if the FeO content is more than twice of BSE, (2) the degree of crystallization of a LMO reaches ~80 vol% at the time of anorthite crystallization after differentiation of mafic minerals, where clinopyroxene ± olivine and/or spinel crystallize, and (3) The iron content of the melt at the time of anorthite
crystallization increases compared to the initial composition, however, the variation is more strongly dependent on the initial FeO content than differentiation. Fig. 1 shows the relationship between SiO$_2$ and FeO contents of the magma at the time of anorthite crystallization with varying the three parameters (initial FeO content, initial refractory contents, and critical crystal separation fraction $X$). The diagram shows that the compositional variations due to differentiation are within several wt% for FeO and less for SiO$_2$ for any initial FeO content and $X$.

The conditions for anorthite flotation in a turbulent LMO at the final stage of crystallization were evaluated with the model of Tonks and Melosh [10]. The result is that flotation was possible if the initial FeO content of LMO was $\sim$10 wt% or higher regardless of the number of $X$ assuming that the size of floated anorthite was 1.8 cm [14, 15].

The Mg$#$ of clinopyroxene coexisting with anorthite at the final stage of LMO crystallization in the present model was compared with that in FAN. The most magnesian cpx in FAN is Mg$#$=57 [16], which gives the upper limit of the FeO content in the initial LMO to be $\sim$20 wt% ($\sim$3x BSE) regardless of $X$ and the refractory element contents.

We have made a mass balance calculation whether the constrained magma composition can produce enough thickness of a lunar crust. Because the structure of the lower crust of the Moon is not known, it is difficult to make a more rigorous constraint for the initial LMO composition. Our model gives the upper limit of the FeO content, which can produce the anorthosite crust with the thickness of 45km.

**Discussions:** The present model suggests a plausible range of the initial FeO and refractory element contents in the LMO as shown in Fig. 2. The initial FeO content should be more abundant than that of BSE, and the degree of refractory element enrichment should be less than about three times of BSE. It is worth noting that the critical crystal separation fraction, that is, the mode of differentiation, does not affect the results significantly, which suggests the importance of the density and viscosity of the magma in the formation of the anorthosite crust.

The higher FeO content in the LMO than the Earth implies that the impactor had more FeO contents than the BSE, or the oxygen fugacity of the LMO was higher than the BSE. If the terrestrial magma ocean and the proto-lunar disk undergone turbulent mixing to maintain equilibration of oxygen isotopes between them [17], although this hypothesis is still under debate, it may be implausible to assume that the oxygen fugacity of the Earth and Moon were different. If the impactor was richer in FeO than the Earth, its metallic core should have been accumulated to the Earth’s core.


![Fig. 1. Chemical composition of the LMO at the time of anorthite crystallization for five initial FeO (color) and two initial refractory element contents (BSE: solid circle, FeO- and refractory element-enriched: cross) with varying critical crystal separation degree (numbers)](image1)

![Fig. 2. The plausible compositional range of the initial LMO. X denotes the critical fraction factor for the separation of crystals in the magma ocean, where zero means the maximum fractionation.](image2)