

**CONSTRAINTS ON THE BULK COMPOSITION OF LUNAR MAGMA OCEAN FROM THE RARE EARTH ELEMENT PATTERNS OF ANORTHOSITES.** R. Sakai<sup>1</sup>, H. Nagahara<sup>2</sup> and K. Ozawa<sup>3</sup>, <sup>1</sup>Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Chuo-ku, Sagami-hara, Kanagawa, 252-5210, Japan (miyazaki.risa@jaxa.jp), <sup>2</sup>Tokyo Institute of Technology, <sup>3</sup>The University of Tokyo.

**Introduction:** The widely accepted general picture of the lunar crust formation is differentiation during crystallization of an almost completely molten magma ocean (LMO) through heat loss from the surface. Such LMO models are supported by the chronology of the crustal rocks and geochemical observations, such as the complementarity of Eu anomaly between highland rocks and mare basalts and the existence of KREEP rocks rich in incompatible elements.

However, there are still many unresolved issues to establish quantitative model elucidating processes involved in thermal and material transportation in the evolving lunar interior supported by thermodynamics and recent observations from the remote sensing and surface samples. The key parameter that has to be constrained in modeling the thermal and material evolution of the LMO is the bulk chemical composition of the Moon (or the initial LMO). The FeO and Al<sub>2</sub>O<sub>3</sub> contents are particularly important which played critical role in the formation of the lunar crust, but they are still loosely constrained 0.8 ~ 1.8 times larger than the bulk silicate Earth (BSE) [1-2].

We have constrained the plausible ranges of FeO and Al<sub>2</sub>O<sub>3</sub> contents of the initial LMO to meet the conditions for the lunar crust formation [3]. We used MELTS and pMELTS, with the crystal separation efficiency as a free parameter and explored a wide range of the initial compositions to satisfy the following lunar data: (1) lunar crustal thickness, (2) composition of mafic minerals in anorthosite, and (3) grain size of plagioclase that can float in the LMO to reproduce the anorthosite lunar crust. We were successful in placing strong constraint on the FeO content, which ranges 1.3-1.8 x BSE (Bulk Silicate Earth). However, the obtained range of the Al<sub>2</sub>O<sub>3</sub> content is from 0.8 to 2.4 x BSE, which is far from satisfactory.

In this study, we incorporate an additional lunar data to better constrain the Al<sub>2</sub>O<sub>3</sub> content in the initial LMO. It is REE patterns of lunar highland anorthosites, which may reflect the history of the LMO differentiation process. The amounts of plagioclase and clinopyroxene crystallized and separated to produce a parental magma of the anorthosites were firstly estimated from the observed REE patterns and then they used to constrain the initial LMO composition.

**Methods:** The following procedure was adopted to constrain the initial LMO composition from REE data of lunar crustal plagioclase.

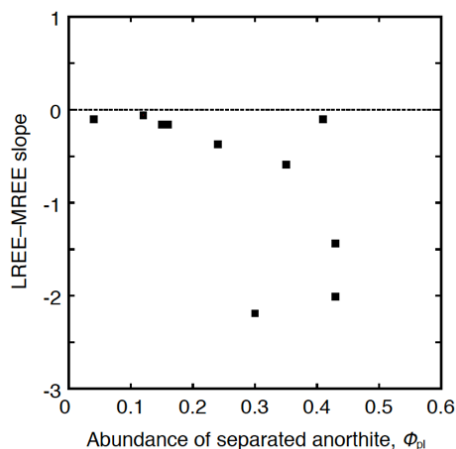
We identified plagioclase REE patterns involved in the early crust formation by screening 10 Apollo samples selected from the Apollo 16 FAN rocks reported by [4] and [5]. The REE pattern of the parent magma in equilibrium with plagioclase was estimated using the melt-mineral partition coefficients of REE for these minerals. We then estimated the amounts of plagioclase and clinopyroxene that had already separated from the LMO. This is based on that the marked negative Eu anomaly is caused by plagioclase fractionation and that the LREE-MREE slope is attributed to clinopyroxene fractionation. We assume that the REE pattern of the initial LMO is the same as that of the CI chondrite. Clinopyroxene is the unique mafic mineral that affects the slope of chondrite normalized REE pattern by its fractionation. Finally, we compared these results with our thermodynamic calculations of the LMO differentiation model to examine which initial composition can explain the estimated amounts of plagioclase and clinopyroxene separated from the LMO.

**Results:** Fig. 1 shows the relationship between the slope of LREEs-MREEs of the lunar anorthosite samples and the estimated amount of plagioclase ( $\Phi_{pl}$ ) that had separated from the initial LMO to eliminate the Eu anomaly. Six out of 10 samples have a large  $\Phi_{pl}$  (~0.2-0.4) suggesting that these rocks formed in a very later stage of lunar crust formation, and are not suited for our purpose. Therefore, the remaining 4 samples with low  $\Phi_{pl}$  (0.04-0.16) were selected for our study. The average slope of LREEs-MREEs for these samples is  $-0.12 \pm 0.05$ , which was used as an additional condition to better constrain the Al<sub>2</sub>O<sub>3</sub> content in the initial LMO.

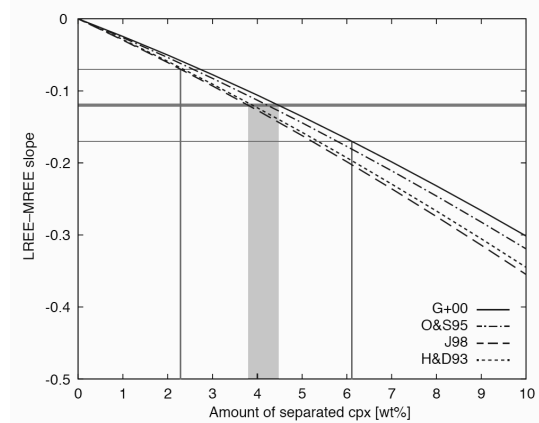
Figure 2 shows the relationship between the calculated slopes of LREE-MREE and the amount of separated clinopyroxene for partition coefficients of clinopyroxene from the literatures (4 line patterns in Fig. 2). The amount of clinopyroxene crystallized and separated from the initial LMO before the anorthosite crystallization is estimated as  $4 \pm 2$  wt% to be consistent with the FAN anorthosite estimated above ( $-0.12 \pm 0.05$ , horizontal line in Fig. 2). The actual values are smaller than this because of possible crystallization of clinopyroxene after the anorthite saturation.

Plausible range of FeO and  $\text{Al}_2\text{O}_3$  contents in the initial LMO is delineated in Fig. 3 by red shadow region. (1)-(3) in Fig. 3 are results of our previous works, where (1) is constrained by the crustal thickness, (2) by crystal size of anorthite separated from the LMO to form anorthite, and (3) by Mg# of orthopyroxene. (4) is the new constraint by the REE data of the highland plagioclase, which puts a tight upper limit on the initial  $\text{Al}_2\text{O}_3$  content. The range of the FeO and  $\text{Al}_2\text{O}_3$  contents of the LMO constrained in the present study is higher in FeO than and comparable in  $\text{Al}_2\text{O}_3$  to the BSE values and lies between that of the Earth and Mars. This study shows that the initial  $\text{Al}_2\text{O}_3$  content must be as low as that of BSE to satisfy both the phase relation of the LMO differentiation and the REE patterns of the highland plagioclase. If the initial LMO is rich in  $\text{Al}_2\text{O}_3$ , a large amount of clinopyroxene should have crystallized, which does not explain the observed LREE-MREE slope. Our study suggests that the chemical fractionation between the refractory elements and volatile elements during evaporation and/or condensation in the circum-Earth should not have played an important role in the formation of the Moon.

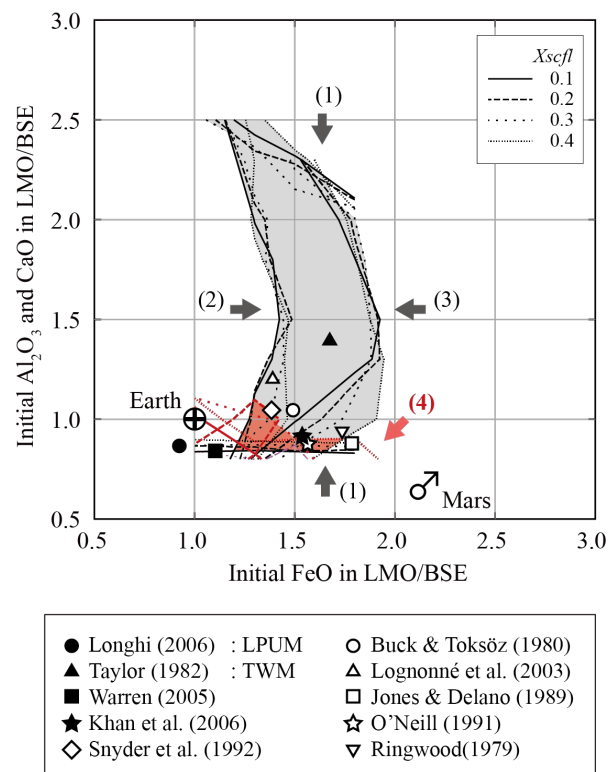
**References:** [1] Longhi J. (2006) *GCA*, 70, 5919-5934. [2] Taylor S. R. (1982) *PEPI*, 29, 233-241, [3] Sakai R. et al., (2014) *Icarus*, 229, 45-56, [4] Papike et al., (1998) *Planetary materials*, 719-952, [5] Floss et al., (1998) *GCA*, 62, 1255-1283.



**Fig. 1.** LREE-MREE slope plotted against the abundance of separated anorthite ( $\Phi_{\text{pl}}$ ). The average of LREE-MREE slope for 4 samples with low separation of anorthite ( $\Phi_{\text{pl}} < 0.2$ ) is  $-0.12 \pm 0.05$ .



**Fig. 2.** LREE-MREE slope of modeled REE patterns plotted against amount of crystallized or separated clinopyroxene. We estimated  $4 \pm 2$  wt% of clinopyroxene separation from LMO (gray shadow region).



**Fig. 3.** Plausible compositional range of the initial LMO constrained by lunar crust formation conditions ((1)-(3) are by our previous work, (4) is by this study). Solid, dashed, short-dashed, and dotted curves indicate the difference in the suspended crystal fraction limit  $X_{\text{scfl}}$  (The smaller the  $X_{\text{scfl}}$ , the closer to the maximum fractional crystallization). The estimations from the literatures are also shown for comparison. The region shaded by red is the most plausible compositional range satisfying all the constraints of the lunar crustal information examined in this study.