SOLIDIFICATION OF THE LUNAR MAGMA OCEAN OBSERVED BY MG NUMBER AND THORIUM ABUNDANCE CORRELATION OF THE HIGHLAND CRUST. M. Ohtake[1], S. Kobayashi[2], H. Takeda[3], T. Morota[4], Y. Ishihara[5], T. Matsunaga[6], Y. Yokota[6], J. Haruyama[1], S. Yamamoto[6], Y. Ogawa[7], Y. Karouji[5], K. Saiki[8], [1]Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Sagamihara, Kanagawa, 229-8510, Japan (ohtake.makiko@jaxa.jp), [2]National Institute of Radiological Sciences, [3]Chiba Inst. of Technology, [4]Nagoya University, [5]Lunar and Planetary Exploration Program Group, Japan Aerospace Exploration Agency, [6]National Institute for Environmental Studies, [7]The University of Aizu, [8]Osaka University.

Introduction: The Moon is known to be globally asymmetric in many properties including topography [1], crustal thickness [2], mare volcanic activity [3], and concentrations of incompatible elements and iron [4]. Knowing the origin of this lunar dichotomy is important for understanding both the evolution of the Moon and the solidification history of all planetary bodies.

We recently reported that highland materials with higher Mg# (Mg/[Mg+Fe] in mole percent in mafic minerals) (up to 80) than those on the lunar nearside were found on the lunar farside [5] by applying an empirical algorithm to lunar reflectance spectra. Mg# is a key geochemical parameter of lunar highland rock for addressing solidification of the lunar magma ocean because it provides a degree of differentiation of the magma ocean at the time of its solidification. Therefore, the observed higher Mg# on the lunar farside indicates that the farside crust consists of rocks that crystallized from less-evolved magma than the nearside crust. The results further indicate that the lunar dichotomy may be directly linked to crystallization of the magma ocean.

Most anorthosites of the lunar samples and lunar meteorites exhibit low Mg# relative to Mg suite, with a typical spread of 40 to 70 (ferroan anorthosite; FAN) [6, 7, 8]. The low Mg# imprinted on the few mafic minerals co-crystallizing with the plagioclase is interpreted to be due to the evolved, iron-rich nature of the magma ocean when the plagioclase crystallized. However, the higher derived Mg# than previously measured highland material, which is thought to be formed as the floating crust, may suggest that the bulk lunar magma ocean has a more primitive composition than FAN.

One of the other key parameters for evaluating solidification of the lunar magma ocean is Th abundance. Th is an incompatible element and concentrates in the liquidus phase when magma cools, therefore highland material that solidified earlier must have lower Th abundance than the highland material that solidified later. Th abundance distribution and its dichotomic nature were found to be lower on the farside than on the nearside [9] by using gamma-ray spectral data obtained by Kaguya [10]. The distribution matches the observed Mg# (higher Mg# on the lunar faside with lower Th abundance).

If the dichotomic distribution of lunar highland Mg# and the Th abundance were really formed by lunar magma ocean solidification, these two parameters reflect the chemical composition and solidification of the lunar magma ocean. As the solidification proceeds, Mg# will decrease while Th abundance will increase, giving the two parameters a negative correlation.

This study investigated the correlation of the two observed parameters of the lunar highland to validate the magma ocean origin of Mg# and Th abundance distribution on the lunar surface. We also tried to estimate the chemical composition of the lunar magma ocean from which the highland crust was formed by combining two remote-sensing data sets.

Method: Using Kaguya gamma-ray data, we derived the relative Th abundance (count of the observed gamma-ray data) map of the Moon as grided data with relatively lower spatial resolution (compared to the 450 km foot print on the lunar surface). We chose this resolution to achieve the best balance of highest sensitivity and highest spatial resolution resolvable for the farside highland formation process because this region has the lowest Th abundance and the lowest gamma-ray count, making it a challenge for an instrument. Kaguya gamma-ray data with high sensitivity enables us to resolve low Th abundance areas. The derived Th abundance (count rate data) was normalized by using the lowest Th count rate data of the data set to gain a relative trend (Th concentration ratio) of Th abundance after the highland crust began forming (plagioclase crystallization) by assuming that the lowest value observed represents the first solidified highland crust.

We then derived the Mg# map of the lunar highland so that it had the same grid as the Th abundance map by applying an algorithm to the global data set obtained by the Kaguya from the Kaguya Spectral Profiler [11]. The Mg# algorithm uses the spectral absorption angles between 920 nm and 950 nm that are most directly related to the Mg# (the absorption angle increases with increasing Mg# in assemblages with low-Ca pyroxene as a major mafic mineral component) [5]. The Mg# values are derived by applying this algorithm (including mafic mineral abundance correction) to a radiative transfer mixing model [12]. Mare regions and craters filled with impact melt were omitted when deriving the Mg# map because the Mg# estimation method only applies to an area of low high-/low-Ca pyroxene ratio and low olivine mineralogy areas.

For comparison with the derived Mg# and Th

abundance correlation trend, we calculated the Mg# of the lunar magma ocean starting with different bulk chemical compositions by using the MELTS program [13]. The calculated starting magmatic compositions were bulk silicate Earth by [14] and bulk lunar magma ocean by [15, 16]. Th concentration ratios after plagioclase solidification started (at that stage 80 % of the lunar magma ocean was thought to be already solidified) were calculated by using the mineral phase, composition, and volume at each solidification stage of the MELTS calculation and partitioning coefficient of Th between each mineral phase and melt [17,18].

Results: The derived Mg# and Th concentration ratio of the same location are presented in Fig. 1 (only the central farside highland was plotted to avoid areas close to the mare and Th-rich Procellarum KREEP Terrain [4] because they may be contaminated), which indicates a negative correlation of the two parameters. In addition to the negative correlation, another interesting feature is that there seems to be two separate trends with lower and higher Th concentration ratios. Note that although the highest Mg# of the farside highland is 80 in data sets with a 1 x 1 degree spatial resolution, the highest data point in Fig. 1 is less because it was blurred by averaging the surrounding area.

The calculated Mg# and Th concentration ratio with the bulk silicate Earth and the lunar magma ocean composition have distinct trends (Fig. 2), indicating sensitivity of this trend to the original chemical composition of bulk magma. Note that the calculation results starting with the bulk lunar magma ocean derived by [15] and [16] are very close.

Comparison of the observed Mg# and Th concentration ratio trend with that of the model calculation suggests that the observed data of the lower Th concentration ratio group matches the bulk silicate Earth composition better than the lunar magma ocean.

Discussion: The negative correlation of observed Mg# and Th concentration ratio suggests that current values of these parameters on the lunar surface are likely due to cooling of the lunar magma ocean as each location crystallized at a different solidification stage though the origin of the two apparent sets of the observed trends is not clear. The fact that the observed data of the lower Th concentration ratio group matches the bulk silicate Earth model better may imply that the chemical composition of the lunar magma ocean needs to re-evaluated and that the Mg# of the actual bulk lunar magma ocean may be higher than previously estimated [15, 16]. Although we need to further evaluate the effect of calculation conditions such as fractional crystallization degree on the resulting trend and the effect of slightly different chemical compositions (not only FeO and MgO abundance but also Al_2O_3 and CaO dependence) more closely to estimate the lunar magma ocean composition.

The possibly higher Mg# of the bulk lunar magma ocean agrees with the reported higher Mg# (up to 80) in the farside highland than previously estimated based on the nearside sampled FAN compositions.

Further study is required to understand the origin of the two apparent sets of the observed trends and to further constrain the bulk chemistry of the lunar magma ocean.

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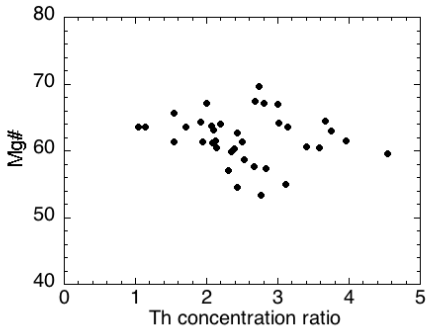

Fig. 1. Observed correlation between Mg# and Th abundance of the lunar highland.
Only the central part of the farside highland was plotted to avoid areas close to the mare and Th-rich Procellarum KREEP Terrain [4] because these areas may be contaminated.

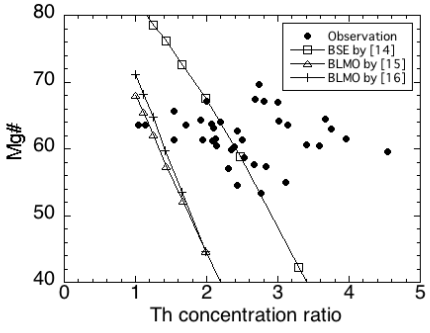

Fig. 2. Modeled correlation between Mg# and Th abundance with observation data of the lunar highland.
We calculated the values with starting magmatic composition of bulk silicate Earth by [14] and bulk lunar magma by [15 and 16].