MULTIPLE PLATEAUX DEVELOPMENT PRIOR TO LUNAR DICHOTOMY FORMATION.

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Introduction: Study of the formation of lunar crust is important for better understanding of lunar thermal evolution. To clarify the formation process, various hypotheses have been proposed [e.g., 1-4]. However, they were not sufficiently supported with real observation data on the lunar surface with high accuracy and precision. This situation has been changed by lunar explorers launched in the last decade. For example, missions of Kaguya [5], Lunar Reconnaissance Orbiter (LRO, [6]), and Gravity Recovery and Interior Laboratory (GRAIL, [7]) provide high-precision, high-resolution data sets including lunar farside data, and contribute greatly to the study of lunar crustal formation.

Using Kaguya gamma-ray spectrometer spectra, Kobayashi et al. [8] obtained a global Thorium (Th) abundance distribution map on the lunar surface. The Th element is hardly incorporated into initially crystallized plagioclastic crust because of incompatible behavior during crystallization of the Lunar Magma Ocean (LMO). Thus, a small Th abundance area is expected to correspond to old crust. Their results indicate that low Th abundance corresponds to the lunar farside highland area. Furthermore, Th abundance is inversely correlated with the Kaguya crustal thickness model [9] on the farside and the southern nearside.

In this study, the correlation between Th abundance and crustal thickness in the highland area was reinvestigated in more detail using the crustal thickness model obtained by the GRAIL gravity field model and LRO topography data [10] instead of the Kaguya model. After the launch of GRAIL, the precision of the lunar gravity field was improved by three orders of magnitude at long wavelengths. The vertical resolution of LRO topography is 20 times better than that of Kaguya's topography. Thus, more detailed analysis of the initial crustal formation process is possible compared to Kobayashi et al [8].

In this study, we first demonstrated that the spatial patterns of Th abundance and crustal thickness maps do not perfectly correspond on the farside. Next, we analyzed this difference and proposed a crustal formation scenario that consistently explains the spatial pattern difference. Finally, we compared our scenario with previously proposed crustal formation hypotheses or lunar dichotomy formation hypotheses, and checked consistency.

Data Analysis: Figure 2 (a) of Kobayashi et al.[8] was used in this study as a Th abundance distribution map on the lunar surface. Th distribution was obtained by analyzing the peaks at 2615keV of the Kaguya gamma-ray energy spectra, which are caused by ^{208}Tl of ^{232}Th decay chain. The original spatial resolution of the map was 100 km x 100 km; however, they degraded the resolution using the nearest-neighbor method with a radius of a 675 km bell-shaped filter to improve the precision of Th abundance and remove the effects of lateral material mixing caused by basin-forming impact events.

The GRAIL crustal thickness model (Model 1) in Wieczorek et al. [10] was used for crustal thickness. A crustal thickness map was created using GRAIL gravity model GL0420A and LRO topography data. The maximum degree and order of the original map was 310 in spherical harmonics, which corresponds to a 17km half-wavelength resolution at the lunar equator. The map was also degraded by applying a 675km bell-shaped filter for consistency with the Th distribution map.

Areas of maria and large impact craters were omitted from the calculation of correlation coefficients between the spatial patterns of Th abundance and crustal thickness because our concern in this study was the initially formed lunar highland area.

Results: Figure 1 depicts crustal thickness (a) and Th distribution (b). As stated in Kobayashi et al. [8], the spatial patterns of these two maps exhibit good negative correlation. The locations of the three local maximum spots (A, B, and C) in Fig. 1(a) correspond to those of the three minimum spots (a, b and c) in Fig. 1(b). However, the detailed spatial patterns on the highland area are not exactly the same. One notable difference between the two figures is that the crustal thickness of spot A is significantly greater than the other spots in Fig. 1(a), while some local minimum peak spots besides a, b, and c exist in Fig. 1(b); and the Th abundance of spot a is not so low compared to the other spots.

To investigate dominant spatial harmonic components that cause the spatial-pattern difference, we prepared several crustal thickness maps for which one or more components of spherical harmonics were removed from the original map, and calculated correlation coefficients with the Th distribution map of the highland area. The results confirmed that the crustal thickness map with 22 terms removed had the best correlation with the Th distribution map of the lunar farside. The correlation was higher than with the original crustal thickness map.

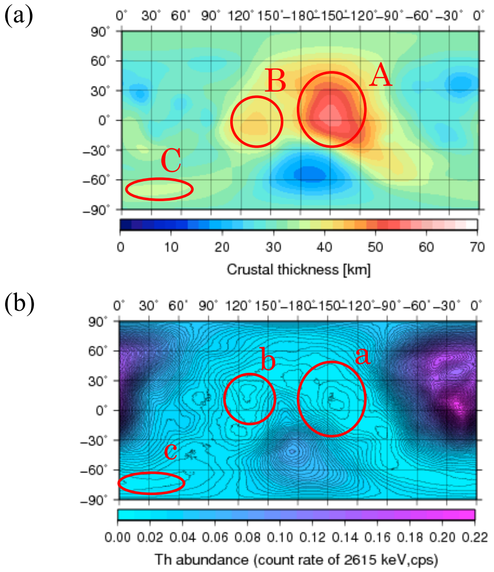

Fig. 1. (a) Crustal thickness and (b) Th abundance distribution maps of the moon.

Discussion: To clarify discrepancies between the two maps, we first determined what we could really see as Th distribution. Elkins-Tanton et al. [11] proposed a model to explain the solidification of LMO with chemical and physical constraints. Given this model, the oldest portions of the crust are located on top of the surface. The obtained Th distribution is assumed to correspond to the surface's oldest portions.

It should be noted that gamma ray observation detects surface Th abundance only, and not that of the whole crust. That is, the obtained Th distribution does not constrain growth of the crust in the radial direction. With uniform crust growth in the radial direction or radial mixing to make the concentration in the crust uniform, Th distribution and crustal thickness should exhibit high spatial correlation. However, in reality, some discrepancy exists between the two maps, as indicated in the result section.

To clarify this discrepancy, we considered the following hypothetic scenario. As already mentioned, Th is an incompatible element; therefore, it is assumed that plagioclastic floating crust formation began at spots of local minima of Th abundance (a, b and c in Fig. 1 (b)). The plagioclastic crust gradually grew using the initial spots as growth cores, and covered the lunar surface. At this stage, the 22 terms of crustal thickness were not as significant, and the Th distribution currently observed on the highland area preserves the state of this stage. After surface covering, the crust grew downward. During the downward growing stage, crust corresponding to the 22 terms developed significantly compared to other terms. Finally, some parts of the crust were modified by large impacts and eruption of lava, and the Th distribution of the corresponding parts were also disturbed.

The growth of the 22 terms means the development of crustal thickness on spot A in Fig. 1 (a), which is associated with formation of the lunar crust dichotomy. Various hypotheses have been proposed for dichotomy formation, but our scenario is consistent with the following hypotheses.

In Loper and Werner [2], plagioclastic floating crusts started to aggregate at one point on the farside and gradually grew to the nearside by global-scale convection. If spot A was even slightly cooler than the other growth cores in our scenario, downward crust growth started on spot A. With this growth, the lower part of spot A cooled further, and the aggregation centered on spot A became predominant by global-scale convection.

In Garrick-Bethell et al. [12, 13], the dichotomy was formed by early and frozen tidal heating. This hypothesis presupposes formation of a thin surface crust layer before development of the dichotomy. Thus, this hypothesis is consistent with our scenario.

Conclusion: The discrepancy in spatial patterns of Th distribution and crustal thickness on the highland can be explained by a two-step process of crustal formation: 1) formation of surface thin crust and 2) growth and development to the downside. This scenario is consistent with hypotheses of lunar dichotomy formation by Loper and Werner [2] and Garrick-Bethell et al [12, 13].

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