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研究課題名（和文）Asymmetric Crystallization of the Lunar Magma Ocean

研究課題名（英文）Asymmetric Crystallization of the Lunar Magma Ocean

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研究成果の概要（和文）：本研究の目的は、月の地殻の非対称性の起源を明らかにすることである。Fe/Mg比（Mg#）は経度で異なる。 鉄の原始マグマオーシャンの結晶時の液相分留が、月の地殻の非対称結晶化の原因であるかを検証した。
非対称性は、月の軌道が近接していた時期の初期地球上のマグマオーシャンの影響による可能性があった。 この影響を考慮にいれ、月の各半球の地殻成長速度を推計し、経度によるMg#を予測した。 さらに、衛星観測データから得られる地殻上層部の混合を再現すべく、月の成長初期の地殻混合度を与える海盆影響モデルを構築した。 本研究によりMg#の経度による多様性を説明できることを示した。

研究成果の概要（英文）：The purpose of the research was to investigate the origin of the asymmetry in the lunar crust. In particular, the ratio of Mg to Fe (Mg#) varies longitudinally. As Fe fractionates to the liquid phase as the primordial magma ocean crystallizes, we wanted to test if that longitudinal variation could be due to an asymmetric crystallization of the lunar crust.

The main driver of this asymmetry could be the influence of a magma ocean on the early Earth, while the Moon's orbit was closer. We used such a thermal forcing as a boundary condition to an energy balance calculation to estimate crustal growth rate on each lunar hemisphere and predict Mg# variation with depth. Then, we developed a basin impact model to characterize the degree of mixing of the lunar crust during its early evolution, as what is observed today from satellite observation is the result of the long-term mixing of the upper crust. We found that this scenario is able to explain the Mg# longitudinal variation.

研究分野：Planetary science

キーワード：moon　planetary science　magma　ocean

１．研究開始当初の背景

The lunar crust is asymmetric, as observed by crustal thickness and many elemental abundances including thorium, one of the leading heat sources for the long term evolution of planetary bodies. The origin of this asymmetry as long been debated and hypotheses have been proposed such as impact mixing and hydrodynamic instabilities in the crystallizing lunar magma ocean. However, due to recent rheological experiments on lunar material those scenarios seem unlikely to explain the observations and the question remains open.

Remote sensing measurements of the Mg# (Mg to Fe ratio) by the Japanese mission SELENE has shown a longitudinal variation pattern with the average Mg# being much smaller on the nearside than on the farside (Fig. 1). Iron being an incompatible element, it tends to concentrate in the residual liquid during magma ocean crystallization compared to magnesium. As a consequence, more primitive crust is expected to have higher Mg# values than later stage one, so it can therefore be used to track the evolution of the crystallization of the lunar crust. The authors of the study have suggested that the observed Mg# pattern (higher on the farside than the nearside) is the mark of the asymmetric crystallization of the lunar magma ocean, but that hypothesis was never tested.

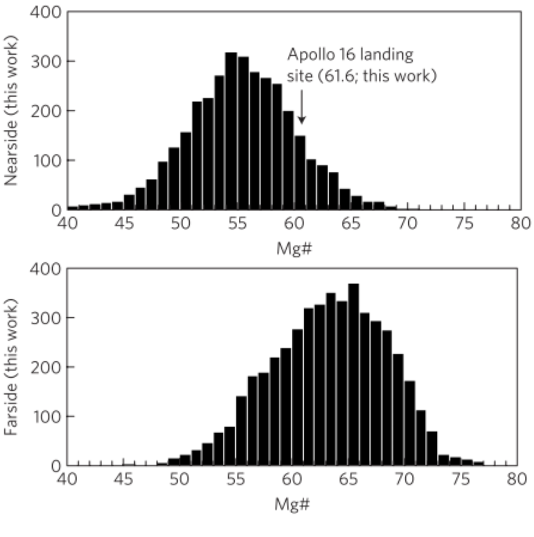

Figure 1. Mg# distribution on the lunar nearside (top) and farside (bottom) from Ohtake et al. (2012) based on SELENE data.

２．研究の目的

The main goal of this project is to characterize the radioactive heat sources distribution in the lunar interior. We will follow two independent approaches to address that question.

First, we will assess the role of the asymmetric crystallization of the magma ocean as way to generate the observed surface asymmetry. In particular, we want to quantify the strength of the thermal forcing required to explain the observations.

At the same time, we will model the subsequent long term evolution of the lunar mantle to test implications of different initial heat sources distribution against many other datasets (e.g., volcanism, magnetism, etc).

３．研究の方法

In order to assess the influence of magma ocean crystallization on the final radioactive heat sources distribution, we developed an energy balance model to estimate crystallization time depending on cooling rate.

Specifically, we studied the balance between energy input from solar radiation and thermal emission from Earth’s own magma ocean on the one hand, and secular cooling of the magma ocean, radioactive decay, as well as latent heat generated by crystallization of the crust on the other hand.

This allowed us to generate a synthetic Mg# profile with depth for both hemispheres. In order to be able to compare our results to observations (e.g., Fig 1), we also developed an upper-crust impact mixing model to take into account the diversity of depth of origin of material observed at the surface.

To construct this mixing model, we used scaling law developed over the years to consider the impact flux on the lunar surface and the morphology of basins as a function of impact diameter. This includes both basin depth and extent, but also its surrounding ejecta blanket.

As a complementary approach, we used 3D convection models of the mantle based on different heat sources distribution to understand which initial conditions lead to predictions consistent with other datasets.

The most constraining observables are the existence of long term volcanic and magnetic activity, as well as the surface heat flow as measured by the Apollo missions on the nearside and by remote sensing close to the North pole.

Those two approaches allowed us to study the heat sources distribution both from a formation perspective (which process could have generated the initial distribution) and from an evolution perspective (given an initial distribution, what are the long term consequences).

４．研究成果

We found that thermal radiation by Earth's magma ocean on the lunar nearside can delay crystallization of the crust on that hemisphere enough to explain the difference in crustal thickness between the two hemispheres of about 20 km. In addition, tracking crust composition as a function of time leads to Mg# differences comparable to that observed by the SELENE mission.

While a simple energy balance calculation can generate a synthetic Mg# profile, remote sensing observations depend on the upper crust mixing by impact over billions of years. We had not foreseen that complication in the proposal, which explains the delay in publication.

We have now developed an upper crust mixing model in collaboration with a researcher from the Curtin University in Australia, which allowed us to transform our predicted Mg# profile from magma ocean crystallization to a surface Mg# distribution directly comparable to the observations (Fig. 2).

In parallel, we have used 3D convection models to assess the coherence of several heat sources distribution with global observables. By integrating constraints from various observations (crustal thickness, remanent magnetism of the crust, gamma-ray spectroscopy and sample analysis), we constructed a range of possible initial radioactive heat sources distribution.

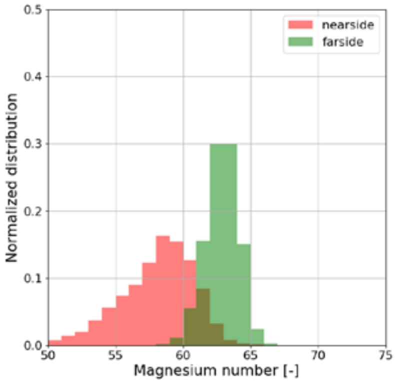

Figure 2. Predicted Mg# distribution at the lunar surface based on an energy balance model of magma ocean crystallization and subsequent crust mixing by impacts.

From that starting point, we simulated the global convection pattern for the duration of lunar history to understand the implications. We showed that models using remote sensing as their main constraint for the global distribution of heat sources cannot explain long term volcanic activity (Fig. 3).

We also generated several other predictions such as the thermal structure of the crust and mantle, which can have an influence on impact dynamics or reorientation of the Moon, the evolution of the magnetic field through inner core evolution. Many of those predictions can be tested by future missions to the Moon.

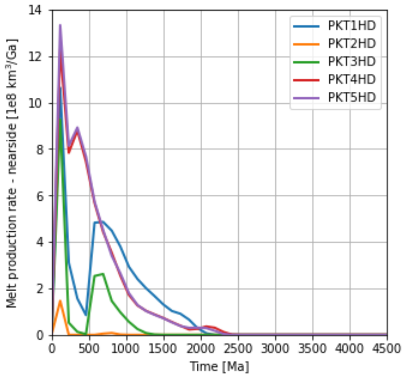

Figure 3. Melt production rate on the lunar nearside for different radioactive heat sources distributions.

５．主な発表論文等（研究代表者、研究分担者及び連携研究者には下線）

〔雑誌論文〕（計 0 件）

〔学会発表〕（計 6 件）

During the time covered by this grant, we made 6 presentations at international conferences, **one of which was a keynote** presentation.

[1] Laneuville M., Taylor J., Wieczorek M., Lunar Radioactive Heat Sources Distribution and Magnetic Field Generation, 49th Lunar and Planetary Science Conference, Houston, USA (2018).

[2] Laneuville M., Breuer D., Plesa A.-C., Schwinger S., Miljkovic K., Lunar Surface Mg# Distribution and Magma Ocean Crystallization, SELENE Symposium 2017, Tokyo, Japan (2017).

[3 (keynote)] Laneuville M., Heterogeneous Moon: Endogenous and Exogenous Processes in Lunar Evolution, Goldschmidt Conference, Paris, France (2017).

[4] Laneuville M., Breuer D., Plesa A.-C., Schwinger S., Lunar surface Mg# distribution and magma ocean crystallization, 48th Lunar and Planetary Science Conference, Houston, USA (2017).

[5] Laneuville M., Taylor J., Wieczorek M., Distribution of radioactive heat sources and magnetic field, New Views of the Moon 2 Workshop, Muenster, Germany (2017).

[6] Laneuville M., The heterogeneous formation of the lunar crust, Goldschmidt Conference, Yokohama, Japan (2016).

６．研究組織

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