論文の内容の要旨

論文題目：The long-term deformation of the Moon inferred from Kaguya geodetic data and implications for its thermal evolution

（かぐや測地データから示唆された月の長期変形と熱進化）

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The interior thermal state of a planet controls major processes that take place inside the planet, such as differentiation, magmatic and tectonic activities, and induction of magnetic field. While this fact poses a great importance of thermal evolution studies in planetary science, they also make such studies complex and difficult. The Moon can be considered as the smallest and simplest end-member of terrestrial planets, and evidences for geologic processes that took place billions of years ago are preserved on its surface. Because of this, detailed understandings of the early thermal evolution of the Moon are fundamental for general understandings of the thermal evolution of further complex planets.

Our understandings of the evolution of the Moon have been deepened and broadened with lunar exploration missions. Based on detailed analyses of Apollo data, fundamental concepts for the early lunar history, such as the global magma ocean, are proposed [e.g., 1]. The spatial coverage of high-resolution Apollo data, however, is highly restricted; the landing sites are confined to a nearside low-latitude region, and the orbital latitudes are also low. Since 1990s, global or nearly-global remote-sensing probes have been sent to the Moon and have revealed that the geology and geochemistry on the lunar surface vary greatly region by region [e.g., 2]. In addition, a wide range of ages is estimated for mare basalts based on analyses for global high-resolution images of the Moon [e.g., 3]. Furthermore, feldspathic meteorites, which are considered to originate from the lunar farside, have elemental composition significantly different from that for Apollo samples, suggesting a strong heterogeneity in the composition of the lunar crust [e.g., 4]. Such distinctive compositions may suggest distinctly different thermal histories, which are not predicted from lunar thermal evolution models previously proposed during and immediately following Apollo missions [5]. Although the amount of observational data has been increased, the thermal state of the early Moon has not been constrained well because of lack of information for subsurface structure and composition.

Large-scale topographies on the Moon deform in geologically long timescales since silicates, main constituents of the Moon, exhibit viscoelasticity. Because temperature increase reduces the viscosity of silicates greatly, surface topography relaxes faster when the Moon is hotter.

Similar to the surface, the lunar Moho (i.e., the boundary between the crust and mantle) also deforms viscoelasticity. The topography at the Moho is estimated based on gravity field data [e.g., 6]. Consequently, fundamental information for the paleo-thermal state can be obtained by comparing geodetic data and numerical calculation results for long-term deformation of large-scale topographies [e.g., 7].

Previous studies, however, suffer from two problems for conducting detailed analyses of viscoelastic state of large-scale topographies on the Moon, such as impact basins. The first problem is that the spatial resolution of gravity field data is low. The other problem is that long-term deformation calculations require the use of simple (few-layer, steady-state) viscosity profiles; detailed model calculations have not been conducted. The first problem is solved by the Kaguya mission; orbital tracking of the Main orbiter "Kaguya" on the lunar farside were conducted using a relay subsatellite "Okina." These data led to great improvement in lunar gravity field modeling [e.g., 8]. The second problem is resolved by the use of the new calculation scheme by [9]; costs for calculations using multi-layer time-dependent viscosity profiles are reduced greatly. We now can conduct both detailed analyses for the subsurface structure using high-resolution geodetic data and parametric studies of long-term viscoelastic deformation under a wide variety of calculation conditions with complex viscosity profiles.

The goals of this dissertation are to (1) investigate the long-term deformation of the Moon based on Kaguya geodetic data and detailed viscoelastic deformation calculations and then (2) extract information for the thermal evolution of the Moon.

In order to conduct a parametric study of long-term viscoelastic deformation under a wide variety of calculation conditions, a computationally efficient calculation scheme is necessary. As noted above, calculation costs for the second-order initial-value method proposed by [9] are much smaller than those for previous initial-value methods. Although an analytical approach called the normal-mode method can be used only for simple viscosity profiles, calculation costs for this method are much smaller than those for the second-order initial-value method. We report that calculation errors for the normal-mode method are significantly larger than those for the initial-value method when we consider long-term deformation modes even if we assume simple interior profiles. This result indicates that the use of the initial-value method is necessary when we consider deformation over geologically long timescales. Thus, we use the initial-value method in the following chapters.

We then conduct geodetic data analyses. We consider three types of major large-scale topographies on the Moon; fresh impact basins, degraded impact basins, and maria. Fresh impact basins, such as Orientale, exhibit large central positive free-air and Bouguer anomalies, suggesting that these impact basins have large mantle uplifts currently [e.g., 10]. If the lunar interior had been very hot around formation ages of these impact basins, substantial viscoelastic deformation would occur, and large mantle uplifts would not be maintained. In other words, if we assume such a hot early thermal state, unrealistic crustal structures around impact basins immediately after the impact are required from present-day structure; the Moho would go above surface. We reject such a hot early thermal state and constrain the hottest possible thermal state. Using thermal constraints, we obtain the upper limit for column-averaged radioactive element concentrations in the crust for each major geological province. Our results indicate that constraints on the early thermal state and those on subsurface radioactive element concentrations vary region by region (see Figure 1). For example, the lunar crust for the central anorthositic region of the Feldspathic Highlands Terrane requires surface temperature gradient $\lesssim 20$ K km^{-1} during basin formation ages and column-averaged Th concentration $\lesssim 0.5$ ppm. In contrast, the crust for the province called the Procellarum KREEP Terrane allows surface temperature gradient as high as 40 K km^{-1} during basin formation ages and column-averaged Th concentration as high as 5 ppm. The regional dependence of the upper limit for column-averaged radioactive element concentrations suggests a horizontally heterogeneous subsurface radioactive element distribution. Such heterogeneity may result from an early mantle overturn immediately after the solidification of the lunar magma ocean and/or asymmetric crustal growth.

Major impact basins classified as those older than pre-Nectarian (PN) 5, such as Australe, exhibit degraded surface topography and do not exhibit free-air and Bouguer anomalies [e.g., 11]. These observations indicate that the Moho around degraded impact basins is very flat. If degraded impact basins had initially large mantle uplifts similar to current mantle uplifts estimated for fresh impact basins, current flat Moho suggests the occurrence of substantial viscoelastic deformation. If this is the case, an extremely cold early thermal state needs to be rejected. We use current crustal structures around fresh impact basins as initial conditions and estimate the thermal state immediately after the formation of degraded basins. Our results indicate that a Moho temperature higher than the solidus of peridotite is necessary to reproduce a similar crustal structure currently observed for degraded impact basins. This result suggests that impact basins older than PN 5 were formed before the complete solidification of the lunar magma ocean. In other words, the timing of solidification of the lunar magma ocean may correspond to the PN 4/5 boundary.

Major maria fill the centers of large impact basins, such as Imbrium [e.g., 12]. Consequently, deformation of mare topographies would be relatively recent events in the lunar history. Apollo sample analyses have revealed that the viscosity of mare lava is smaller than those of terrestrial magmas significantly [e.g., 13]. This result suggests that the surface topography of maria may have been parallel to the equipotential surface called “the selenoid” immediately after the formation of maria. In order to quantify the amplitude of deformation, we measure slope angles and directions of the difference between the topography and the selenoid for major mare units. Our results indicate that topographies for most maria are inclined about 0.1° from the selenoid. We conduct a parametric study for viscoelastic deformation and found that a vertical loading stress of several ten MPa can account for the maximum slope angle of 0.1°. We found that the large-scale variation in crustal thickness satisfies the condition for the load. A dense ilmenite-rich layer, which may have been formed during the latter stage of the magma ocean solidification, may also satisfy this condition for the load. These results suggest that long-term large-scale deformations had continued for billions of years since the formation of the Moon.

Our results suggest that current viscoelastic states of major lunar large-scale topographies, such as impact basins and maria, reflect the upper thermal and compositional structure of the extremely early Moon.

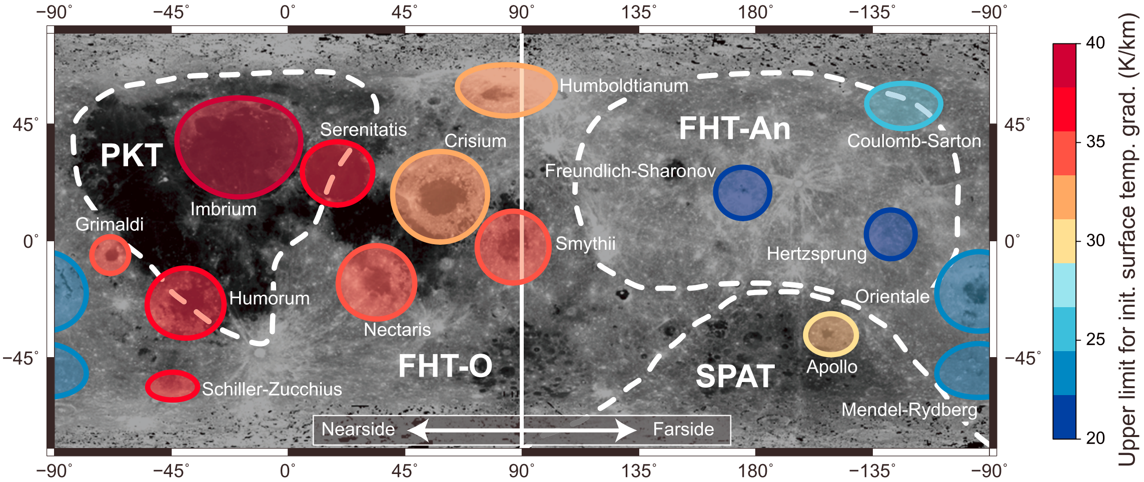

Figure 1: Upper limits for the initial surface temperature gradient. The geological classification by [2] is also shown; PKT, SPAT, FHT-An, and FHT-O indicates the Procellarum KREEP Terrane, the South Pole-Aitken Terrane, and the central anorthositic and the outer region of the Feldspathic Highlands Terrane, respectively. The background is the Kaguya Multiband Imager 750 nm reflectance map [e.g., 14]. (Submitted to *Journal of Geophysical Research Planets*.)

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