Study of lunar subsurface evolution based on the SELENE observation data and impact experiment

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博士論文

Study of lunar subsurface evolution based on the SELENE observation data and impact experiment

（SELENE観測データと衝突実験に基づく
月表層進化の研究）

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Abstract

Lunar surface topography and subsurface structure are important for understanding the geological condition of the lunar surface layer and thermal evolution of the Moon [e.g., *Solomon and Head*, 1980; *Namiki et al.*, 2006; *Ishiyama et al.,* 2013]. In order to investigate lunar subsurface structures, we performed analyses of datasets obtained by the Lunar Radar Sounder (LRS) onboard the SELENE spacecraft, which radiated the electromagnetic pulse in a frequency range of 4–6 MHz from the spacecraft at an altitude of ~100 km. The depth of subsurface reflector in the maria can be obtained from the time delay between arrivals of echoes from the surface and subsurface reflectors found in the LRS radargram. Using the LRS radargram, we focused on (1) the geological condition (i.e., bulk density and porosity) of lunar uppermost basalt layer, and (2) subsurface deflection structures in the nearside maria.

In Chapter 3, the geological condition of the lunar uppermost basalt layer to depth of a few hundred meters was investigated through the estimation of the bulk permittivity by using the SELENE/LRS, MI, and TC data [*Ishiyama et al.,* 2013; 2014]. The estimated bulk permittivities of uppermost basalt layer were 1.9–7.0 in Unit S15 of Mare Serenitatis, 1.6–14.0 in Unit S28 of Mare Serenitatis, and 1.3–5.1 in Unit P10 of Oceanus Procellarum. Since the bulk permittivity of rock depended on its bulk density [*Carrier et al.*, 1991], we could obtain the porosity from the estimated bulk permittivity. The estimated bulk densities of uppermost basalt layer were 1.0–3.0 g/cm^3 in Unit S15 of Mare Serenitatis, 0.7–4.0 g/cm^3 in Unit S28 of Mare Serenitatis, and 0.4–2.5 g/cm^3 in Unit P10 of Oceanus Procellarum. The grain (i.e., pore-free) densities of uppermost basalt layer were estimated to be ~3.3 g/cm^3 in Unit S15 and S28 of Mare Serenitatis and ~3.2 g/cm^3 in Unit P10 of Oceanus Procellarum from the TiO_2 and FeO abundance derived from the MI data. Based on the ratio of the bulk density and grain density, the estimated porosities were 9%–71% in Unit S15 of Mare Serenitatis, 0%–78% in Unit S28 of Mare Serenitatis, and 21%–86% in Unit P10 of Oceanus Procellarum. These results were consistent with the results of *Ishiyama et al.* [2013]. We found the common bulk permittivity range was 4.2–5.1, which satisfy the all estimated range of bulk permittivity reported in *Ishiyama et al.* [2013] and this study [*Ishiyama et al.*, 2014]. This value was smaller than the bulk permittivity used in several previous studies (~8) [e.g., *Peeples et al.*, 1978; *Oshigami et al.*, 2009]. In addition, the estimated porosity was 21%–33%, which was higher than typical porosity of Apollo basalt sample (~7%) [*Kiefer et al.*, 2012]. This high porosity results mainly from the impact-induced cracks. The voids in the lunar uppermost layers behave

as an insulator. This result will provide some constrains on the thermal conductivity of lunar surface in the discussions on cooling process in lunar mare region.

On the other hand, based on an effective medium theory, we must consider that the anisotropy of crack in rock with respect to the electric field of the radar pulse can change the measured permittivity even if their bulk densities are the same [e.g., *Kärkkäinen et al.*, 2000]. In Chapter 4, in order to (1) understand the bulk permittivity of the mare basalt layer affected by the macro cracks produced by meteorite impacts and (2) verify the validity of the estimation method of porosity and bulk density from permittivity measured in radar observation, we performed an impact experiment by using the two-stage light-gas (hydrogen) gun at JAXA, and derived the volume fraction of crack, bulk density, bulk permittivity, and loss tangent around two artificial impact craters produced by the projectiles with velocities of 3.586 km/s and 5.638 km/s. The measured volume fraction of crack decreased with increase of the distance from the crater's center, and showed clear inverse correlation with bulk density, bulk permittivity, and loss tangent. In addition, the volume fraction of crack increased with increase of projectile's velocity. As a result, the measured bulk permittivity and loss tangent decreased with increase of projectile's velocity. The measured bulk permittivity and loss tangent were also affected by the characteristic crack distribution (i.e., a concentric crack area and radial crack area) around two artificial impact craters. Based on the effective medium approximation theory, we could understand the measured permittivity as a result of the anisotropy of crack around impact crater; the cracks of perpendicular and parallel directions to the impressed electric field were produced within the concentric crack area, and the cracks of isotropic direction to the impressed electric field was mainly produced outside of the concentric crack area. The anisotropy of crack around impact crater makes it difficult to derive bulk density from the measured bulk permittivity, but this anisotropic crack effect was small. Thus, we could confirm that the estimation method of porosity and bulk density from permittivity measured in radar observation proposed by *Ishiyama et al.* [2013] was valid. In addition, we tried identification of anisotropic cracks in the LRS data, but we have not found them yet. It suggests that the crack around the actual impact crater is more complex than the models used in this study. A further investigation with the Finite-Difference Time-Domain (FDTD) method will be needed in future.

In Chapter 5, we have shown a new evidence of lunar mare deflection derived from basalt loading through statistical analysis of the slope angle of subsurface lava flow unit boundaries in five maria based on the LRS data. We identified subsurface boundary larger than lunar surface slope angle. The subsurface slope angle decreased with time, and we could identify a sudden decrease in slope angle at ~3.5 ± 0.1 Ga. The sudden decrease in slope angle at ~3.5 Ga was caused by the sudden decrease in lunar lava eruptive flux at ~3.3–3.6 Ga [*Weider et al.*, 2010; *Oshigami et al.*, 2014] without a sudden increase in lithospheric thickness. Based on a simple loading model, the large slope angle group can be explained by a large deflection of lithosphere due to thick basalt loading. In addition, the radial distribution of observed subsurface slope angle suggested that the basin-floor of Mare Imbrium were not similar with that of Mare Orientale used in the previous models. We finally pointed out that disappearance of the melt pool at the bottom of lithosphere can be a possible cause of sudden decreases of lava flow eruption flux and subsurface slope angle at ~3.5 ± 0.1 Ga. This melt pool is formed by a pressure reduction due to the excavation of lunar crust at basin formation [*Melosh et al.*, 2013; *Freed et al.*, 2014]. If the lithospheric thickness was enough thin, the melt pool kept providing magma to the lunar surface by buoyancy [*Wieczorek et al*., 2001]. But, the melt pool became unable to provide magma to lunar surface when the lithospheric thickness gradually increased through cooling process and reached a critical thickness. Therefore, the lunar loading-induced deflection becomes smaller steeply with time. As in the above discussion, the discovery of lunar loading-induced deflection structure would be provide some new constraints in discussion on tectonic processes in the maria and lunar thermal evolution.