Abridged Version of the Doctoral Thesis

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Title：Unveiling the Lunar Magma Ascent Process with Indigenous Volatiles via Radar Data Analysis
レーダーデータ解析に基づく内因性揮発性物質を伴う月のマグマ上昇過程の解明

Lunar indigenous volatiles are key constraints on both the formation of the Earth–Moon system and the subsequent evolution of lunar volcanism. Recent reanalyses of Apollo samples and many remote-sensing observations have increasingly suggested that the lunar mantle may be richer in volatiles than previously thought, marking a turning point for reconsidering our understanding of the Moon. However, evidence for the indigenous volatiles has so far relied primarily on sample analyses and surface observations, remaining limited to localized regions.

To obtain information on indigenous volatiles over a wider area, we use the Lunar Radar Sounder (LRS) onboard the SELenological and ENgineering Explorer (SELENE) spacecraft to identify subsurface gas voids at dike tips. These voids are expected to be tens to hundreds of meters in both horizontal and vertical dimensions, and to form when volatiles exsolve from intrusive magma. To detect such small-scale subsurface structures, it is essential to properly evaluate and subtract surface scattering echoes in LRS data. This study focuses on the presence of small-scale artifacts in a conventional DEM (SLDEM2015), which has been widely used for surface scattering simulations, and attempts to reduce these artifacts using a generative adversarial network (GAN) based on the high-resolution NAC images and NACDEM. As a result, the newly created GAN-based DEM (GANDEM) significantly improved multiple evaluation metrics (MAE, RMSE, RMSE slope, and SSIM) for short-wavelength topography (wavelengths shorter than 300 m), which strongly influences LRS surface scattering, compared to SLDEM2015. Furthermore, we performed surface scattering simulations using GANDEM and found that they reproduce the surface scattering component in the LRS data more accurately than simulations using SLDEM2015. By subtracting the improved surface scattering simulation results from the LRS observations, we successfully detected subsurface echo candidates (SECs) throughout Mare Tranquillitatis.

The detected SECs were more abundant in the eastern part of Mare Tranquillitatis, where the crust is thicker, and less abundant in the western part, where the crust is thinner. To interpret the observed SEC distribution, we assumed subsurface magma intrusion, varied the dielectric constant at the dike tip, and performed an analysis using the radar equation. We found that reproducing SEC reflection intensities greater than −25 dB requires a void or a highly porous structure at the dike tip. The SEC distribution and echo shape suggest that thicker eastern crust favored magma stagnation and subsurface gas void formation, while thinner western crust allowed continuous ascent and eruption, reducing the likelihood of subsurface gas voids. We then investigated whether volatiles are present in the magma of Mare Tranquillitatis. Using a magma ascent simulation method similar to those applied to terrestrial cases, we examined whether volatile-free magma could erupt through a crustal thickness of 34 km (model 1) or 40 km (model 3) in Mare Tranquillitatis. Even assuming the largest vertical extent of magma source and the highest melt fraction conceivable on the Moon, we found that the magma would penetrate the crust up to a height of 30.7 km from the crust-mantle boundary, making eruption in this region unfeasible without volatiles. Furthermore, we incorporated the volatile exsolution model for volatile-bearing magma (CO: 567 ppm, H_2O: 1100 ppm) based on the Apollo volcanic glass into the magma ascent simulation. The magma penetrated several kilometers higher into the crust compared to the volatile-free case but still failed to erupt through a crustal thickness of 34 km (model 1) or 40 km (model 3) in Mare Tranquillitatis. With 686 or 1976 ppm CO, the dike tip stalls at depths consistent with the SECs (130–300 m) within a crustal thickness of 34 km (model 1) or 40 km (model 3). To trigger an eruption in Mare Tranquillitatis, volatile gas concentrations of 692 or 1979 ppm CO were required. This CO concentration exceeds the maximum CO content (140 ppm) of the parent magma estimated from melt inclusions. Assuming that H_2 exsolved at depth in the lunar reducing environment compensates for this excess CO, the H_2 content would be 39–141 ppm. Therefore, it is possible that the magma source in Mare Tranquillitatis contains <140 ppm CO and 39–141 ppm H_2. This estimate implies a mantle H_2 abundance of 5.9–21 ppm, which cannot be explained by late accretion alone. This discrepancy suggests that a formation process capable of preserving volatiles operated during the formation of the Moon.

Taking these results together, we propose a scenario in which volatile-bearing magma ascended beneath the eastern part of Mare Tranquillitatis, where the crust is thick, and some magma stalled, forming subsurface voids via volatile exsolution. This is the first study to demonstrate the role of volatiles in lunar magma ascent using constraints from observations of subsurface structures. This finding provides an important new constraint on the distribution of indigenous lunar volatiles and has implications for the broader understanding of lunar formation and volcanism.