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学位(専攻分野)	博士(理学)
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学 位 論 文 題 目	Unveiling the Lunar Magma Ascent Process with Indigenous Volatiles via Radar Data Analysis
論 文 審 査 委 員	主　査　田中　智 宇宙科学コース　教授 高島　健 宇宙科学コース　教授 山本　幸生 宇宙科学コース　准教授 Jo Hilaire Agnes De Waele Department of Biological, Geological, and Environmental Sciences, University of Bologna, Full Professor Alessandro Simoni Department of Biological, Geological, and Environmental Sciences, University of Bologna, Associate Professor Sara Callegaro Department of Biological, Geological, and Environmental Sciences, University of Bologna, Full Professor

本学位論文研究は総合研究大学院大学と Alma Mater Studiorum – Università di Bologna（イタリア共和国）とのデュアル・ディグリー・プログラム [1] に関する協定に基づく国際共同指導により実施されたものである。

[1] コチュテル（デュアル・ディグリー）

海外の大学との協定に基づき本学に在籍する学生が、同時に相手大学に正規生として在籍し、両大学の教員から共同で学位論文指導を受けるもの。論文完成後、両大学による共同の論文審査に合格した場合は、両大学から単一の学位が授与され、各大学からそれぞれ両大学の共同論文指導によるものである旨を付記した学位記を交付する。

Summary of Doctoral Thesis

Name in Full：Hitoshi Nozawa

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.

(Separate Sheet)

Results of the doctoral thesis defense

Name in Full: Hitoshi Nozawa

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

The Defense Committee, having read applicant's PhD thesis and his publications, and having listened to the candidate's presentation, expresses its judgment as follows:

■ **Academic Merit and Contribution to the Field**

This dissertation investigates the ascent of lunar magma, with particular emphasis on the role of indigenous volatiles, using an integrated approach that combines radar sounding observations with numerical modeling. The topic is clearly situated within space engineering and planetary science, and it addresses questions that are scientifically significant and nontrivial.

A key contribution of the dissertation is the development and application of an improved surface-scattering correction framework for Lunar Radar Sounder data. In particular, the use of a high-resolution digital elevation model generated via a generative adversarial network enables the identification of subsurface echo candidates associated with small-scale geological structures—features that have been difficult to resolve using conventional approaches. Overall, the methodology is technically sound and represents a meaningful step forward for lunar radar-based subsurface investigations.

Furthermore, by integrating the spatial distribution of subsurface echo candidates with magma-ascent simulations, the dissertation proposes a volatile-assisted magma ascent model to account for volcanic activity in regions where magma ascent is not readily explained by crustal thickness or thermal structure alone. This interpretation offers a new perspective on lunar magmatic processes and is regarded by the committee as an original contribution to the field.

In summary, the committee assesses the dissertation to have sufficient originality, creativity, and academic significance, and to make a new and important contribution to the advancement of knowledge in lunar and planetary science.

■ **Independence and Role of the Candidate**

The dissertation is based on research conducted independently by the candidate, or on collaborative research in which the candidate played a principal and leading role. The candidate assumed primary responsibility for formulating the research objectives, developing the

analytical and numerical methodologies, conducting the data analysis and simulations, and integrating and interpreting the results.

The coherence and internal consistency of the dissertation indicate the candidate's ability to plan, conduct, and complete a research project autonomously. The work therefore satisfies the requirement that a doctoral dissertation be based on independent research, or on collaborative research with substantial individual contribution.

■ Scientific Validity and Completeness of the Dissertation

The scientific framework adopted in this dissertation is appropriate to the stated research objectives and is grounded in established physical and geological principles. The observational analyses and numerical simulations are conducted using assumptions that are reasonable in the context of the study; in most cases, these assumptions are stated explicitly and justified.

The dissertation is logically structured, and the progression from methodology to results and interpretation is coherent. The conclusions are supported by the analyses presented and remain consistent with the evidence provided.

From an academic standpoint, the committee judges that the dissertation meets the standards of scientific validity and overall completeness expected of a doctoral thesis in the field of space science.

■ Editorial Quality and Presentation

While the scientific content and overall structure satisfy the requirements for a doctoral thesis, the committee notes that the version submitted for the final examination contained a non-negligible number of typographical errors, formatting inconsistencies, and minor editorial deficiencies. These include, for example, issues related to equation numbering and textual accuracy.

These matters do not affect the scientific validity of the research or the principal conclusions of the dissertation. However, the frequency of such errors is regrettable and, in places, detracts from the level of precision and polish that would normally be expected of a final doctoral submission.

Accuracy and careful presentation are essential components of professional academic practice. It is therefore expected that these editorial issues be fully corrected in the final archival version of the dissertation.

■ Evaluation of Knowledge, Communication Skills, and Research Capability

Through the dissertation and the examination, the candidate has demonstrated a broad and advanced understanding of the relevant research domain, including radar engineering, lunar geology, magma dynamics, and the role of volatiles in planetary interiors.

The candidate is able to communicate complex scientific concepts clearly and appropriately in English, and to respond to technical questions in a logical and well-reasoned manner. In

the committee's view, these abilities indicate that the candidate is capable of engaging effectively in international academic activities.

The candidate has also demonstrated the capacity to conduct research independently and creatively, meeting the expectations required for the conferment of the doctoral degree.

■ **Final Assessment**

Based on the above evaluations, the committee considers that the dissertation:

- Is based on research conducted independently or with the candidate in a principal role
- Meets the academic standards of originality and scientific significance required in the field
- Demonstrates that the candidate has acquired the knowledge, communication skills, and research capability expected of an independent researcher

The editorial issues noted above are regarded as correctable and are not considered to undermine the academic merit of the dissertation.

Accordingly, the dissertation and the examination results are judged to be acceptable for the award of the doctoral degree.