学 位 論 文 内 容 の 要 約

博士（環境科学）　氏 名 Yu Meng

学 位 論 文 題 名

Mapping periglacial landforms in Daisetsuzan National Park, Japan

（大雪山国立公園における周氷河地形のマッピング）

1. Introduction

Periglacial environments are found in regions with frequent freeze–thaw cycles and cover approximately 25% of the Earth's land surface. A key feature of these environments is permafrost, which refers to the ground frozen at or below 0°C for at least two consecutive years. The distinct landforms in these environments are shaped by freeze-thaw processes such as solifluction, frost heave, cryoturbation, frost weathering, and sorting. These periglacial landforms are highly sensitive to climate change, which makes them vital for understanding past climate conditions and predicting future landform changes in the context of global warming.

Owing to its diverse and unique landforms, Daisetsuzan National Park in Hokkaido, Japan, offers an ideal setting for studying periglacial features. However, detailed geomorphological data for this region are limited because traditional mapping methods have struggled to capture the fine-scale characteristics and large-scale distributions of these landforms. This study employed uncrewed aerial vehicles (UAVs) combined with Structure from Motion (SfM) technology to produce high-resolution orthomosaic images and digital elevation models (DEMs) to address this limitation. The integration of UAV and SfM technologies can provide a precise, efficient, and cost-effective solution for mapping and analyzing periglacial landforms.

This study aims to advance the field of periglacial geomorphology by examining the distribution and characteristics of periglacial landforms in Daisetsuzan National Park using high-resolution UAV-SfM imagery and terrain maps. The primary morphological parameters of these landforms were extracted using Geographic Information System (GIS) tools, which offered a more comprehensive dataset compared to existing studies. This study also explored the formation mechanisms of these landforms, provided insights into related phenomena, and identified important parameters for future research. Additionally, the study highlights the advantages of the UAV-SfM approach for studying periglacial environments and proposes a framework for future studies based on these findings.

2. Study Area and Methodology

This study focuses on periglacial landforms within Daisetsuzan National Park. Volcanic activity in the region began in the Late Pleistocene and continued into the Holocene, creating gently sloping lava plateaus covered by extensive pyroclastic deposits. These volcanic landforms provide favorable conditions for periglacial processes because of their ability to retain substantial moisture in the surface layers. Consequently, the Daisetsu Mountains represent one of the largest areas in Japan with periglacial landforms and permafrost. Two lava plateaus within the park, Area A (Hokkai-daira) and Area B (Kumono-daira), were selected for detailed investigation. They are covered with lava and pyroclastic flow deposits from volcanic eruptions, forming gentle surfaces at approximately 2000 m, concurrent with the emergence of the Ohachi-daira.

Multiple data collection and analysis techniques were used in this study. High-resolution imagery data were generated using UAV-SfM technology, which enables the precise mapping and detailed identification of periglacial landforms. GIS tools were employed to analyze the terrain conditions and explore their relationship with landform distribution and morphology. Multi-directional hillshade maps and object-based image analysis (OBIA) methods were applied to improve the accuracy of landform identification and classification. A U-Net image segmentation model was also tested, and the potential of combining deep learning techniques with UAV-SfM imagery for automated landform recognition was demonstrated. This study also explored broader spatial distribution patterns of periglacial landforms within Daisetsuzan National Park by integrating UAV-derived data with satellite imagery. The preliminary results from this combined method are presented in this study.

3. Periglacial landforms in the Daisetsuzan National Park

This study identified several important periglacial landforms that reflect the region's active cryogenic processes. The key landforms documented include earth hummocks, nonsorted steps, sorted nets and stripes, thermal contraction cracks, and other sporadically distributed periglacial features.

Earth hummocks are among the most widespread landforms, covering extensive areas in both the study areas. These small cryogenic mounds create subtle microtopographic variations, significantly influence soil temperature regimes and water dynamics, and affect the local biogeochemical cycles.

Another prominent landform is nonsorted steps, characterized by step-like terraces composed of alternating vegetation strips and bare soil patches. Nonsorted steps commonly occur on gentle slopes and are notably concentrated around hiking trail areas.

Sorted patterned ground, which is frequently observed in periglacial environments, results from frost-induced fine and coarse material sorting. On relatively flat or gently sloping terrain, frost sorting produces patterns of circles, polygons, or irregular stone networks surrounding patches of finer soil. Within the study areas, sorted patterned ground transitions from sorted nets (an intermediate form between circles and polygons) to sorted stripes as the slope gradients increase.

Thermal contraction cracks were also observed. These features are fractures generated when the ground contracts rapidly under extremely low winter temperatures or sudden cooling events. In some areas, intersecting thermal contraction cracks create polygonal patterned ground called thermal contraction crack polygons.

Earth hummocks and nonsorted steps are the most extensive and significant features among the diverse landforms identified. Additional periglacial features observed included solifluction lobes, nivation hollows, and other less clearly defined forms of patterned ground. The spatial distribution and geomorphological characteristics of these features were thoroughly documented using UAV-SfM imaging and mapping.

4. Earth hummocks

The morphology of earth hummocks was analyzed in detail based on highly accurate distribution maps created with the UAV-SfM approach, visual interpretation methods, and GIS technology. These steps are documented throughout the workflow. The orthomosaic images and DEMs achieved resolutions of over 2 cm/pixel and 4 cm/pixel, respectively. Examination of the DEMs and multi-directional hillshade maps revealed 18,838 individual earth hummocks across 87 sites, indicating that Daisetsuzan National Park is the largest known area for earth hummocks in Japan.

For the first time, the individual shapes of these massive earth hummocks were identified using high-resolution imagery. Multi-directional hillshade maps derived from DEMs were used in both 2D and 3D formats to provide a more precise basis for delineating the earth hummocks' boundaries and collecting accurate morphological parameters of the hummocks. The average dimensions of the hummocks were 1.22 m in length, 1.03 m in width, and 0.15 m in height. Their shape generally resembles an elliptical base topped by an oblate dome-like protrusion.

This study also explored the relationship between the morphology of hummocks and various topographical factors. Maps of the topographical conditions, including slope, aspect, Topographic Wetness Index (TWI), and Geomorphon Landforms, were examined alongside the distribution of the earth hummocks. Statistical analysis indicated that the morphological features of the hummocks were closely linked to local topographic factors. Earth hummocks were primarily found in areas with gentle slopes and specific moisture conditions, and they were densely distributed in areas with slopes below 20° and particular moisture conditions, following clustered patterns. The distribution of hummocks was closely associated with the soil moisture levels and drainage networks, as indicated by the TWI maps.

This study enhances the understanding of earth hummock morphology and distribution in Daisetsuzan National Park and showcases the efficacy of UAV-SfM technology in periglacial landform research. Multidirectional hillshade mapping proved effective and offered greater precision than traditional measurements.

5. Nonsorted steps

Nonsorted steps represent another key landform studied in the study areas. These are important topographic and sedimentary indicators that offer valuable insights into the mechanisms of solifluction, subsurface structures, and past climatic conditions.

This study mapped the distribution of nonsorted steps and measured morphological parameters, including riser height, tread width, riser width, and terrace length. High-resolution DEMs and orthophoto data obtained using the UAV-SfM methodology were used to create detailed distribution maps. Consequently, 50 nonsorted step sites were identified. They covered approximately 105,552 m² across both study areas. This study enhanced the methodology by employing eCognition software for OBIA to accurately classify vegetated and bare ground areas. This classification is a critical step in distinguishing the treads and risers of nonsorted steps. The analysis showed that the average riser height was 0.20 m, with tread widths averaging 1.00 m, riser widths measuring 0.73 m, and terrace lengths averaging 5.08 m.

The distribution characteristics of nonsorted steps were analyzed using terrain condition maps. Nonsorted steps are more commonly found in areas with sparse vegetation, where solifluction processes are more likely to occur. The study also revealed a strong correlation between the morphology of nonsorted steps and local topographic factors. Terrain analysis showed that over 80% of the nonsorted steps are located on slopes with an incline of less than 10°, primarily near hiking trails in areas with sparse vegetation and low TWI values. Additionally, the riser height and slope angle had a significant positive correlation.

A comparative analysis with global studies suggested that the nonsorted steps in the study areas are generally smaller in scale, particularly with respect to the riser height. This difference is likely due to the lower soil moisture, reduced pore water pressure, shallow frost penetration, and distinct vegetation types in the Daisetsuzan region. These environmental conditions restrict soil movement and frost heaving, leading to smaller terrace features than in areas with higher moisture levels and deeper frost penetration. The combination of UAV-SfM methodology with multi-directional hillshade mapping and OBIA techniques also proved highly effective in recognizing and analyzing nonsorted steps by providing enhanced precision and efficiency.

6. Other periglacial landforms in the study areas

In addition to earth hummocks and nonsorted steps, this study documented several other periglacial landforms, including thermal contraction cracks, sorted nets and stripes, and irregular patterned grounds.

Thermal contraction cracks were formed by rapid surface cooling and intense thermal stress. The study documented a total crack length of 2991 m across the study areas, surpassing the measurements provided in earlier studies. High-resolution imagery demonstrated that active crack formation persisted despite the overall permafrost degradation in the Daisetsuzan region. This situation is driven by localized extreme cold events, altered snow cover, and intensified freeze-thaw cycles.

The sorted nets and stripes exhibited elongated irregular mesh patterns. These patterns arise from the interaction between fine and coarse materials, with gravity acting on different slopes. Sorted nets generally form flat terrains, whereas sorted stripes tend to appear at steeper inclines in the study areas. Additionally, labyrinthine and irregularly patterned grounds may suggest complex self-organizing processes influenced by stone concentration and vegetation distribution in the study areas. These features offer crucial insights into the sediment displacement and the underlying mechanisms that sculpt the landscape. Further investigations are required to fully understand their origins and evolution.

The concurrent presence of cracks and nonsorted steps provided evidence that the terraces of nonsorted steps adjacent to the cracks were originally part of a continuous and connected surface. This indicates that the non-sorted steps had already formed and maintained a coherent structure prior to the generation of cracks. The study emphasized the importance of long-term monitoring and detailed geomorphological mapping to track changes in landforms in sensitive environments, thereby providing additional fundamental data to support geomorphological research in periglacial areas.

7. General discussion

This chapter discusses the relationship between topographical conditions and the processes shaping periglacial landforms. Combining a review of the existing literature with the data obtained in this study highlights the role of slope, vegetation, and moisture factors in shaping periglacial landforms. For instance, the findings of this study align with the conclusion that earth hummocks are primarily formed by differential frost heave, with vegetation playing a key role in moisture retention and thermal regulation. Nonsorted steps develop through solifluction on gentle slopes, and temperature fluctuations and sparse vegetation influence thermal contraction cracks.

However, the study also revealed the complexity of periglacial processes and the need to consider a range of environmental factors, since the study found that topographical factors alone could not fully explain the formation of all periglacial landforms. This study outlines key parameters for future research, including climate, soil, snow, wind, vegetation, and topographical conditions. Climate influences freeze-thaw cycles and permafrost stability, while soil moisture and material properties affect frost heave and mass movement. Snow and wind impact thermal conditions, snow accumulation, and erosion patterns that shape landform development. Vegetation is critical for stabilizing soils, influencing moisture retention, and modifying the thermal properties. The interaction of these factors over time drives the evolution of periglacial landscapes, making interdisciplinary and high-resolution field monitoring essential for understanding these dynamic processes, particularly in a warming climate. Future research is expected to integrate additional data types with the detailed topographic and morphological data documented in this study, which could lead to new insights regarding how these factors work together to influence the formation and development of landforms in periglacial environments.

This study also demonstrated the significant benefits of using the UAV-SfM approach in periglacial research. It allows for high-resolution data collection without requiring researchers to access dangerous areas, thus minimizing the environmental impacts on fragile alpine ecosystems. Additionally, this technique improves data collection efficiency by capturing far more data than traditional methods, and the integration of multidirectional hillshade mapping enhances the precision of landform interpretation, revealing previously overlooked features.

Furthermore, this study explored the innovative potential of integrating high-resolution UAV-SfM imagery with advanced analytical techniques for periglacial studies. High-resolution UAV data allow automated feature extraction using deep learning methods such as U-Net. This approach reduces the manual interpretation time and enhances the accuracy and consistency in delineating features, such as earth hummocks. Moreover, combining UAV data with satellite imagery facilitates predictive mapping over broader regions, allowing researchers to identify potential periglacial landform distributions based on terrain and environmental criteria. The study then proposed a future research framework that builds on these advancements and potential by combining precise remote sensing technology, automated classification, and field investigation and validation while promoting interdisciplinary collaboration and citizen science.

8. Conclusions

This study successfully mapped and analyzed the distribution and morphology of periglacial landforms in Daisetsuzan National Park using the UAV-SfM approach, focusing on earth hummocks, nonsorted steps, thermal contraction cracks, and sorted patterned ground. These findings provide valuable insights into the relationship between the geomorphology of landforms and topographical conditions and the complex processes that shape these landforms. This study also demonstrated the advantages and potential of UAV-SfM for high-resolution mapping and analysis of periglacial environments, particularly in regions that are difficult to access.

The detailed workflow incorporated multidirectional hillshade maps and OBIA to map these landforms. Analysis of morphological parameters and their relationships with environmental factors provided crucial insights into landform formation processes. The study identified 18,838 earth hummocks across 87 sites, averaging 1.22 m in length, 1.03 m in width, and 0.15 m in height, with strong correlations between their morphology and terrain factors such as slope and aspect. These features predominantly occur on gentle slopes with specific moisture conditions. This distribution demonstrated the influence of microclimatic and topographical factors.

Nonsorted steps were mapped across 50 sites covering more than 100,000 m^2, with detailed morphological parameters extracted. The average riser height was 0.20 m, tread widths were 1.00 m, riser widths measured 0.73 m, and terrace lengths were 5.08 m. The analysis revealed significant differences in step morphology between the study areas, influenced by local environmental conditions. These features are primarily located on gentle slopes below 10°, with aspect and terrain moisture playing key roles in their distribution.

Thermal contraction cracks, with a total length of 2991 m, were observed. High-resolution imagery also facilitates the identification of sorted patterned ground, offering insights into their spatial patterns and interactions with other periglacial features.

The research suggests that topography alone cannot fully explain the periglacial features of Daisetsuzan. The topography in periglacial environments intricately interacts with climate, vegetation, snow, wind, and soil, creating diverse conditions that affect precipitation patterns, soil moisture, and vegetation distribution. It advocates the integration of high-resolution mapping with comprehensive field investigations and interdisciplinary approaches to better understand the complex interrelationships among these factors in landform evolution, ultimately leading to more precise insights into the geomorphological processes.

In this study, the UAV-SfM approach demonstrated clear advantages over traditional methods, including higher spatial resolution, flexibility, and the ability to capture small-scale features often missed by conventional field surveys. For future research, the study recommends a combination of long-term field monitoring, numerical simulations, and interdisciplinary approaches to better understand the dynamics of periglacial landforms. The integration of UAV data with deep learning, satellite imagery, citizen science 3D scans, and other new technologies will be crucial for improving efficiency, enhancing accuracy, and expanding the scope of research. A comprehensive research framework that combines high-resolution mapping with field investigations is essential to better understand the impact of climate change on periglacial environments and landforms, potentially leading to new insights and further innovations in periglacial geomorphology.