学位論文の要約

Controlling Factors for Hillslope Denudation by Soil Formation and Shallow Landsliding in Low-relief Landscapes under Contrasting Lithological Conditions

（土層形成と表層崩壊による斜面削剥を制御する要因：
対照的な地質条件をもつ小起伏山地での比較研究）

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Chapter 1: Introduction

It is essential to quantify denudation rates and identify the controlling factors to better understand the evolution of mountainous landscapes. Under the same tectonic and climatic conditions, rock properties such as the strength and permeability of rocks are the main control on hillslope denudation, which affect the hillslope relief and drainage density. However, previous studies do not consider the effects of soil layer that widely and persistently covers the hillslopes in humid temperate regions. This study aims to reveal the controlling factors of denudation along soil-mantled hillslopes, with a spatial emphasis on the lithological influences of hydro-geomorphological processes at various time scales, which consist of soil production, transport, and removal of the accumulated soil layer via shallow landsliding. Contrasting landforms that are underlain by granite and hornfels bedrock in Shiga-Kyoto and Hiroshima, western Japan were selected for this study purpose. The granite areas at both sites consist of low-relief, finely dissected terrain, whereas the hornfels areas consist of high-relief ridges with minor dissection. The long-term soil production and transport rates at the Shiga-Kyoto site were determined via a joint analysis of cosmogenic ^{10}Be and high-resolution digital terrain models. The short-term hydrological processes that trigger shallow landslides in each lithological setting at the Hiroshima site have been revealed via analysis of an extreme rainfall event in 2014. Finally, the recovery time of the soil depth and hillslope denudation rates were estimated via a simulation of soil layer development.

Chapter 2: Study area

2.1. Shiga-Kyoto site

The study areas at the Shiga-Kyoto site are located in Shirakawa watershed, at the eastern margin of Kyoto City, western Japan. The geology of this region consists of a Jurassic accretionary complex and Late Cretaceous granite. The accretionary complex has been subjected to contact metamorphism related to intrusion of a granite pluton, with the northern and southern edges of the granite body consisting of hornfels zones. The hornfels ridgelines are relatively weakly dissected, high-relief hillslopes whereas the granite hillslopes form a low-relief, hilly terrain with a high drainage density. Areas that possessed representative hillslope geometries in the granite and hornfels areas were selected for the detailed surveys for production and transport of soils, subsurface structure, hillslope material sampling, and hydrological monitoring.

2.2. Hiroshima site

The study site is located in the northern hills of Hiroshima City, western Japan where a heavy rainfall event on 20 August 2014 resulted in shallow landslides and debris flows. The bedrock in the region is mainly Triassic to Jurassic high-grade metamorphic rocks, Jurassic accretionary complexes, and Late Cretaceous granite. The metamorphic rocks and accretionary complexes underwent contact metamorphism during the intrusion of a granitic pluton, producing hornfels. The granitic hillslopes form a finely dissected landscape with a high drainage density and low-elevation ridges, whereas the hornfels hillslopes form a terrain with a low drainage density and high-elevation ridges. A typical shallow translational sliding of soil layer occurred in unchanneled hollows on each lithology was elected for detailed subsurface structure surveying, hillslope material sampling, and hydrological monitoring.

Chapter 3: Field and laboratory methods and results

3.1. Field survey

In this study, I surveyed longitudinal profiles along the selected hillslopes at the Shiga-Kyoto site and landslides at the Hiroshima site, and conducted cone-penetration soundings to investigate the shallow subsurface structures at each site. The soil and bedrock textures were observed along the vertical pit walls, and then were identified the depth of the soil–bedrock interface in the Shiga-Kyoto site and potential sliding surface along each profile in the Hiroshima site.

At the Shiga-Kyoto, the dynamic cone penetrometer soundings indicated that the thickness of the weathered material from the granite hillslope site varied based on the hillslope location, such as the nose and hollow, and upper and lower parts of the hillslope. The thickness of the weathered mantle along the hornfels hillslope is thicker than that in the granite hillslope. The saprolite holds its original bedrock texture, which indicates no evidence of physical movements, but chemical depletion at the depth. Although hornfels bedrocks are commonly recognized as a hard bedrock, the strength of the saprolite often drops enough low to excavate by a shovel.

At the Hiroshima site, the dynamic cone penetrometer soundings reveal that the granite hillslope site is draped by a thin soft soil layer, even in the landslide scar, whereas a thick soft soil layer covers the upslope area of the hillslope and thickens toward the ridge crest. Conversely, a set of soil layers overlies the hard bedrock substrate, with a distinct interface that is approximately parallel to the ground surface at the hornfels hillslope. The sliding surface of the shallow landslide formed along the boundary between the upper and lower soil layers in each lithology. The upper soil layer is well-mixed and topped with a thin organic-rich layer. The lower soil layer appears to be in a transitional state, with evidence of creep, but it also possesses residual bedrock features, such as decomposed rock fragments.

3.2. Geotechnical tests

Geotechnical tests were conducted to quantify physical, mechanical, and hydrological properties of soil, saprolite, and hard bedrock using undisturbed samples from both sites.

At both sites, the granite hillslopes are covered by coarse soils with a high permeability and low soil-water-retention ability whereas the hornfels hillslopes are covered by fine soils with a low permeability and high soil-water-retention ability. The granite-derived sandy soils possess a smaller cohesive strength and larger shearing resistance angle than the fine-grained and hornfels-derived soils. At the Hiroshima site, the saturated hydraulic conductivity in the granite hillslope was no discernible change across the sliding surface while that in the hornfels hillslope decrease with depth, with the sliding surface located at the hydraulic discontinuity between upper and lower layers.

3.3. Monitoring of the hydrological processes and ground temperature fluctuations

Tensiometers were used to monitor the pore-fluid pressure responses of the subsurface materials to rainfall infiltration at both sites. The ground temperature of the subsurface layer was monitored at the Shiga-Kyoto site using thermo sensors.

At the Shiga-Kyoto site, the pressure heads were negative throughout the monitoring period, except for the peaks during some of the rainfall events. The soil and saprolite layers along both hillslopes remained in an unsaturated state, even during an extreme rainfall event. The response times of the pressure heads at the deeper sensors were always delayed during the weak rainwater inputs, whereas there was a relatively rapid response in pressure at all depths during the heavy rainfall inputs under wet conditions in both lithology. The ground temperature fluctuations decreased with increasing depth. There tended to be a lag in the seasonal variations of the air temperature in the deeper layer. The subsurface layer in the granite hillslope is more sensitive to the seasonal variations in air temperature than that in the hornfels hillslope, due to its heat transmissivity.

At the Hiroshima site, the pressure heads were also primarily negative throughout the monitoring period except for the peaks during some rainfall events, indicating that the soil layers remained unsaturated. The pressure responses in the granite hillslope were characterized by a rapid pressure rise, with a short time lag that was dependent on rainfall intensity. During the heavy rainfall event with a wet soil condition, the pressure head at all depths rose rapidly and reached a peak value at approximately the same time as the peak rainfall intensity. Conversely, the pressure head responses in the hornfels hillslope were concordant with the depth migration of a wetting front through the soil layers. During the heavy rainfall event with a wet soil condition, the pressure heads in the upper soil layer responded more rapidly, with peak pressure heads observed for a time lag of less than half an hour after the peak rainfall intensity, whereas the pressures in the lower soil layer attained peak values with a time lag of 1–2 h.

3.4. Quantification of soil production and transport

At the Shiga-Kyoto site, the cosmogenic ^{10}Be that accumulated in the saprolite just beneath the soil layer was analyzed to determine the soil production rates along the granite and hornfels hillslopes. Also, the relationship between topographic curvature and soil thickness were defined using a 1-m resolution digital terrain model and the field survey.

The long-term soil production rates and transport coefficient were higher and larger in the granite hillslope than the hornfels hillslope. The soil production rates decline exponentially with increasing soil thickness for both bedrock lithologies, with the soil production rates along the granite hillslope being higher than those along the hornfels hillslope at any depth. Furthermore, the soil transport coefficient along the granite hillslope is four times larger than that along the hornfels hillslope, which is estimated from the soil production function and spatial distribution of soil thickness along the hillslopes.

Chapter 4: Data analysis and discussion

4.1. Factors controlling soil production and transport rate

At the Shiga-Kyoto site, systematic differences in the soil production and transport rates are observed under the same tectonic and climatic setting, but different underlying bedrock lithologies. Possible geological factors that influence these differences are the saprolite strength and soil layer effect. The soil production at these lithologies does not simply depend on saprolite strength because there is no systematic difference between the soil production rates and saprolite strength. Thus, the observed differences in the soil production and transport rates between the granite and hornfels hillslopes are likely associated with the soil coverage functions. The hydraulic and mechanical properties of the granite- and hornfels-derived soils are quite different, reflecting the different characteristics of these two protoliths.

The hydro-mechanical processes through the soil layers promote or inhibit soil production and transport along the granite and hornfels hillslopes. The higher permeability and larger fluctuation of soil moisture in the granite soil layer readily decompose the structure of saprolite, contributing most probably to result in rapid soil production and transport. The granite soil mass has undergone a larger fluctuation of temperature than the hornfels soil mass and thereby the different degree of thermal disturbance at the soil–saprolite regulates soil production rates. Also, the granite hillslope draped by cohesionless soil layer gets unstable condition under thin soil cover than the hornfels hillslope, which increases efficiency of soil transport and then leads to maintain that thinness of the soil cover. This feedback system results in rapid soil production and transport along the granite hillslope. The soil coverage effects play a key role to rates of soil production and transport.

4.2. Triggering factors of the shallow landslides

At the Hiroshima site, results of slope stability analysis indicate that the landslides on the granite hillslopes occurred without a large positive pressure, whereas those on the hornfels hillslopes required a certain positive pressure. Hydrological analysis based on the coupling of water storage capacities of the subsurface materials (S_c) and the radar-based total rainfall amounts at the storm event supports this analytical result. The rainfall amount at the event is much smaller than the S_c of the granite hillslopes, whereas it is comparable to that of the hornfels hillslopes. The regional rainfall thresholds for triggering landslides also support these results, with a smaller threshold on the granite hillslopes (~150 mm) than on the hornfels hillslopes (~180 mm). Thus, these results highlight that the hydrological critical conditions for landslide initiation are lithology-dependent.

The shallow translational sliding in the granite and hornfels hillslopes are triggered by the contrasting hydrological mechanisms. The formation of a sliding zone is related to the subsurface structures, hydraulic and mechanical properties of the hillslope materials, and the resulting subsurface hydrological processes. Only a weak positive pore-fluid pressure is required to potentially trigger landslides in the granite hillslope, which possesses a larger water storage capacity. Conversely, a large positive pore-fluid pressure acts on the potential sliding surface to trigger landslides in the hornfels hillslope, with a smaller water storage capacity resulting from the build-up of a perched groundwater zone above the hydraulic discontinuity between the upper and lower soil layers.

4.3. Landslide return periods and rates of elevation change

A simulation for spatiotemporal development of soil layer is conducted to reveal periods of soil layer development after shallow landslide events and rates of elevation change caused by soil production and transport on hillslope. Soil depth and elevation per each grid-cell were calculated with a one-year interval using the 1-m meshed DTM and a program established on model builder framework in ArcGIS.

The model simulation runs to get time period for soil restoration in the hollows at the Shiga-Kyoto site. In the granite hollows, the simulated soil depth develops ~1 m after 300 years of model running and then restored to the initial state after 500–600 years. In contrast, the hornfels hillslope develops no more than 1 m of soil depth after 1000 years of model running. After 8000–10,000 years of the model runs, the soil depth almost recovers to the present level. Lowering rates on hillslope nose is ~1.2 m kyr^{-1} in the granite and ~0.1 m kyr^{-1} in the hornfels. Also, the soil accumulation rates in the hollows represent about 0.9 m kyr^{-1} in the granite and 0.04 m kyr^{-1} in the hornfels hillslopes, respectively.

4.4. *Summary and future directions*

Here the long-term soil production and transport rates are revealed via a cosmogenic nuclide and high-resolution DTM analysis. The short-term hydrological processes that trigger shallow landslides are also revealed via investigations of an actual landslide event. The mechanical and hydraulic soil properties control these hydro-geomorphic processes. Such differences produce the difference of soil recovery time for shallow landsliding along each hillslope. The granite hillslope shows more than ten times shorter time for soil recovery in hillslope hollow than the hornfels hillslope due to rapid rates of soil production, transport and accumulation, and smaller threshold rainfall. Thereby, this system facilitates hillslope denudation and leads to the formation of contrasting landform between the granite and hornfels hillslopes.

Further studies are needed to reveal the evolution of soil-mantled hillslopes underlain by granite and hornfels bedrock, such as the effects of runoff processes on hillslopes, root reinforcement on slope stability, and the mineral and chemical composition, and grain size of the bedrock on weathering. Runoff processes should influence stream water generation and channel initiation mechanisms, and therefore catchment topography formation. Quantification of the mineral and chemical composition, and grain size of the underlying bedrock are needed to explain the differences in soil properties, such as the cohesion, angle of shearing resistance, and saturated hydraulic conductivity, between granite and hornfels soils, and the weathering processes of each bedrock type.

Chapter 5: Conclusions

This study focuses on the denudation processes along hillslopes, and reveals the soil production and transport rates, shallow landslide triggering mechanism, and soil recovery periods along hillslopes underlain by granite and hornfels at the Shiga-Kyoto and Hiroshima sites, western Japan. This study documents the geomorphic evolution of these two different hillslopes based on the coupling of long- and short-term hillslope denudation processes. The hydro-mechanical properties of soil control the soil production and transport rates, and hydrological condition for hillslope instability, resulting in different periods of soil recovery and hillslope lowering rates between the granite and hornfels hillslopes.

At the Shiga-Kyoto site, the different soil production and transport rates along hillslopes underlain by granite and hornfels bedrock are strongly influenced by soil layer effects due to different hydro-mechanical processes occurring in the soil layer. The soil production and transport rates along the granite hillslope are higher than those along the hornfels hillslope. These differences are related to the differences in soil properties. The coarse cohesionless soil, which possesses a limited soil–water, along the granite hillslopes experiences larger soil moisture and ground temperature fluctuations than the fine cohesive soil, which possesses a high amount of soil–water, along the hornfels hillslope. The larger fluctuations in the granite soil layer readily decompose the saprolite structure, which most likely contributes to rapid soil production and transport. Therefore, the soil layer effect facilitates the self-regulation of soil production and transport along soil-mantled hillslopes.

At the Hiroshima site, contrasting hydrological processes triggered shallow landslides along the hillslopes underlain by granite and hornfels bedrock during an intense 2014 rainfall event. The granite-derived high-permeability sandy soil allowed rainwater to quickly percolate to the underlying saprolite, whose low permeability and limited water storage capacity resulted in the development of a saturated zone that extended upward from the base of the soil layer. Shallow landsliding occurred along the mechanically weak section of the soil layer, as long as a weak positive pressure generates the potential sliding zone. Conversely, the hornfels hillslopes are covered by a cohesive soil whose permeability decreases with depth, which promotes the formation of a perched groundwater body above the lower soil layer. Shallow landslides are triggered along the hydraulic and mechanical discontinuity between the upper and lower soil layers when the certain positive pressure develops along the potential sliding zone.

A simulation of the spatiotemporal development of a soil layer is conducted to estimate the return periods and rates of elevation change along each hillslope. The rates of lowering of the hillslope noses and soil accumulation in the hollows are ten times higher along the granite hillslope than along the hornfels hillslope. The soil recovery time is estimated to be 500–600 years along the granite hillslope and 8000–10,000 years along the hornfels hillslope. The granite hillslope also exhibits a lower rainfall threshold for landslide initiation. Therefore, the rapid soil accumulation and smaller threshold rainfall along the granite hillslope promote a larger amount of soil evacuation from the watershed, which leads to rapid hillslope denudation. This feedback results in the formation of contrasting soil-mantled landscapes underlain by granite and hornfels bedrock.