1 **Lithological effects in soil formation and soil slips on weathering-limited**
2 **slopes underlain by granitic bedrocks in Japan**

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10
11 **Abstract**

12 Soil slips occur every few years due to heavy rains on biotite granite (Gb) and hornblende
13 biotite granite (Ghb) slopes in the Taga Mountains, Ibaraki Prefecture, Japan. The
14 occurrence density of soil-slips per unit area is 2.7 times greater in the Gb slopes than that
15 in Ghb slopes. We examined the chemical, mineral, physical, and mechanical properties
16 of two soil profiles on soil-slip scars in these slopes to study the effect of bedrock mineral
17 composition on the density of soil-slips. For a given size of mineral grain, the amount of
18 biotite (which is susceptible to chemical weathering) in granitic bedrocks strongly
19 influenced the density of soil-slips. In the Gb slope the soil layer becomes thinner because
20 of the smaller proportion of biotite in the bedrock; this restricts the downward movement
21 of soil water into the material below the slip plane. During heavy rainfall the water
22 surface then rises toward the slope surface above the slip plane. This promotes soil slips,
23 increasing the density of soil-slip scars. In contrast, in the Ghb slope, with more biotite in

the bedrock, the soil layer becomes thicker, so that soil water moves easily into the material beneath the slip plane. This limits the rise of water surface toward the slope surface above the slip plane even during heavy rainfalls. There are consequently fewer soil slips and density of soil-slip scars.

Key words: Granite; Soil slip; Mineral composition; Biotite; Weathering; Rock control

1. Introduction

Granitic rocks are defined as ‘light-colored coarse-grained plutonic rocks containing quartz as an essential component along with feldspar and mafic minerals’ (Glossary of Geology, American Geological Institute, 1987). They are generally weathered to grus. A soil slip occurs on steep granitic rock slopes when a soil layer of grus reaches a critical depth: i.e., these slopes correspond to a weathering-limited slope. Granitic rocks are of various types, including granite, granodiorite and quartz diorite, classified according to the volume ratio of quartz, alkali feldspar and plagioclase. The occurrence density of soil slips per unit area differs among distinct granitic zones, even if they are adjacent to each other and have experienced a similar weathering environment (e.g. Miura, 1966, 1967; Tanaka, 1983; Onda, 1992; Wakatsuki et al., 2005).

Soil-layer structures formed by weathering in granitic areas have been studied according to the deep weathering profiles on flat surfaces and ridges of mountains at which little or no erosion occurs (e.g. Ruxton and Berry, 1957, 1961; Lumb, 1962, 1965; Nakagawa et al., 1972; Kimiya, 1975; Suzuki et al, 1977; Eswaran and Bin, 1977a,b,c; Matsukura et al, 1983; Schulz and White, 1999; White et al., 2001; White, 2002; Migoń

and Thomas, 2002; Braga et al., 2002; Begonha and Braga, 2002; Lan et al., 2003). There are relatively few studies of soil-layer structures or relations between soil-layer structures and soil slips due to rock weathering on steep granitic slopes (e.g., Miura, 1966, 1967; Matsuo et al., 1968; Nishida and Aoyama, 1987; Tanaka, 1994; Wakatsuki et al., 2005). Nishida and Aoyama (1987) observed that plagioclase disappeared and kaolinite appeared near the slip surface in a granodiorite slope in the western region of Shimane Prefecture, Japan. Wakatsuki et al. (2005) examined the effect of mineral grain size on the rate of soil formation and the occurrence of soil-slips on two slopes underlain by coarse-grained granite and fine-grained granitic gneiss having similar mineral compositions near Seoul in the Republic of Korea. They found that coarse-grained rocks decompose to grus more easily, so that soil formation proceeds faster and soil slips are more common.

In the Taga Mountains in the southern part of the Abukuma Mountains in Japan, biotite granite and hornblende biotite granite are distributed widely. Both rocks have similar mineral grain sizes but different mineral compositions (species) and the occurrence density of soil slips is different (Tanaka, 1983). In this study we examine the effect of bedrock mineral compositions on soil-layer structures and its effect on the formation of the soil-slip plane and on the occurrence and density of soil-slips on these slopes. We investigated the depth of weathered soil layers using cone penetration testing, hammer seismic refraction sounding, and examination of some chemical, mineralogical, physical and mechanical properties of the layers.

2. Study area

The study site is located in the Taga Mountains in the southern part of the Abukuma Mountains, in the northern part of Ibaraki Prefecture (Fig. 1A). The altitude of the Taga Mountains increases from southeast to northwest (Fig. 1B). Oya (1972) indicated that the Abukuma Mountains have three planation surfaces at altitudes of 300–320 m, 380–400 m, and 500–520 m. Hayakawa and Mishima (1997) recognized seven planation surfaces in this region, having altitudes of 200–300 m, 320–400 m, 420–460 m, 480–560 m, 580–680 m, 700–740 m, 760–800 m. They found that the denudation rate in the catchment area of some reservoirs, estimated from sediment load, was 212.6 m³/km²/yr (over an observation periods of 28 yrs) in the Mizunuma Dam along the Hanazono River, and 272.4 m³/km²/yr (21 yrs) in the Hananuki Dam along the Hananuki River. The corresponding annual denudation thickness are 0.21 mm/yr and 0.27 mm/yr.

The Taga Mountains are composed mainly of four kinds of Late Cretaceous granitic rocks: biotite granite (Gb), hornblende-biotite granite (Ghb), granodiorite (GD) and fine-grained biotite granite (Gf) (Fig. 2). They are distributed in belts oriented northeast to southwest. We studied soil-slip scars in the Gb and Ghb areas. The Gf rock has finer grains than the Gb and Ghb rocks. Also, Tanaka (1983) indicated that, in the Gf area, soil-slip scars are sporadic and slope materials in the scars are composed exclusively of coarser grus than the finer grus in most of the Gf area. Soil-slip scars are rare on slopes with the finer grus. Tanaka(1983) also stated that geologic structures are complex in the GD area. The present study therefore excludes soil-slip scars in the Gf and GD areas. Biotite granite (Gb) and hornblende biotite granite (Ghb) are equigranular and have similar grain sizes; the median diameter is 1.4 mm in Gb and 2.1 mm in Ghb.

The mean annual temperature is 13.9°C, and the monthly mean ranged from

4.3°C in January to 24.6 °C in August over 22 years (1979–2000) at the AMeDAS station ‘Hitachi’ of Japan Meteorological Agency (Fig. 1B). The mean annual precipitation over 22 years (1979–2000) at ‘Hitachi’ was 1468 mm and over 16 years (1985–2000) at ‘Ohnou’ was 1883 mm (Fig. 1B).

3. Density of soil-slips

In the Taga Mountains, soil slips have occurred every few years due to heavy rains, stemming from the Baiu front, tropical or extratropical cyclones, typhoons, and the autumnal rain front. Many soil slips occurred during typhoon Catherine on September 15, 1947 (Hayakawa and Mishima, 1997), torrential rainfall in April, 1971 and typhoon #23 in August, 1971 (Oya, 1972; Shibahara, 1984) and typhoon #11 in September, 1977 (Hayakawa and Sakai, 1981).

Fig. 2 shows the distribution of soil-slips based on air photographs taken in 1966 and 1976 and on field surveys performed by Hayakawa and Sakai (1981) and Tanaka (1983) (summarized in Tanaka, 1983). The density of soil-slips in the Gb area was 3.94 per km², and is 2.7 times larger than that in the Ghb area (1.45 per km²). The drainage density is 15.3 km/km² in the Gb area and 12.2 km/km² density in the Ghb area. These data suggest that, in the Taga Mountains, an area with higher drainage density has higher soil-slip density.

4. Hillslope profiles, soil layer structure and slip plane depth

4.1. Hillslope profiles

Matsukura and Tanaka (1983) and Tanaka (1983) investigated the dimensions

(plan view, longitudinal section, and cross section) of two typical soil-slip scars from each area (Gb-1 and Gb-2 in the Gb area and Ghb-1 and Ghb-2 in the Ghb area), as shown in Figs. 1C,D and 2. The Gb-1 and Gb-2 slopes are located at an altitude of about 350 m; they have dissected the planation surface of approximately 390–570 m height (Fig. 1C). The Ghb-1 and Ghb-2 slopes were located at an altitude of about 370 m, and have dissected the planation surface of approximately 400–460 m height (Fig. 1D). These soil-slip scars were formed by soil slippage due to typhoon #11 in September, 1977.

The soil-slip scar on the Gb-1 slope was about 7 m wide, about 16 m long, with an angle of 39.5° (Fig. 3A). On the Ghb-1 slope the scar width was about 10 m, the length was about 13 m, and the angle was 47.2° (Fig. 3B). Shallow soil slips were common on a slope with a hollow-like shape. Approximate pre-slip slope profiles were reconstructed by taking into account the morphology of the entire slope and continuity between the head and foot of the scar. The results are shown by the dotted lines in the longitudinal sections and cross sections in Fig. 3.

4.2. Soil layer structure

The soil-layer structure on the Gb-1 and Ghb-1 slopes was measured by hammer seismic refraction sounding and cone penetration testing. Hammer seismic refraction sounding was conducted using a 3-channel seismograph, McSEIS-3 (Oyo Co., Japan). Nakagawa et al. (1981) classified weathering layers into eight zones according to the P-wave velocities (V_p) on granite slopes in Obara Village, Aichi Prefecture, Japan. They found that the slip surface of soil slips dominates in weathering zone Aw-1 ($V_p = 250\text{--}380$ m/sec), which is readily trenched by scoop, and zone Aw-2 (320–800 m/sec) which has

some joints and can be broken by a hammer, but cannot be trenched by a scoop. A three-layered structure was found on both the Gb-1 and Ghb-1 slopes (Fig. 3). In the Gb-1 slope, the V_p for the first layer (V_1) was 686 m/sec, for the second layer (V_2) it was 1031 m/sec, and for the third layer (V_3) it was 4135 m/sec (Fig. 3A). The seismic boundary surface between the first and second layers was at a depth of 0.4–0.5 m, and the boundary between the second and third layers was located at depths of 3.0–8.3 m. In the Ghb-1 slope, V_1 was 379 m/sec and V_2 was 708 m/sec and V_3 was 1946 m/sec (Fig. 3B). The seismic boundary surface between the first and second layers was at a depth of 2.6–3.3 m, and the boundary between the second and third layers was at depth 3.8–13.4 m. According to the classification by Nakagawa et al. (1981), on the Gb-1 slope, the first layer corresponds to zone Aw-2, the second layer to zones Aw-2 or Bw-2 (1250–2500 m/sec) and the third layer to zones Cw-1 (>3800 m/sec) or C-2 (>4000 m/sec), being bedrock. Soft zone Aw-1 was too thin to be detected. On the Ghb-1 slope, the first layer corresponds to Aw-1, the second layer to Aw-2 or Bw-1 (550–1100 m/sec), and the third layer to Bw-2. Zones Cw-1 and C-2 corresponding to bedrock were not detected. This is because these zones are located deeper in the soil profile so that the seismic pulse through the zone becomes too weak to be picked up.

Cone penetration testing was performed using a Doken-type simplified dynamic cone penetrometer. Results obtained from the cone penetration test are given by the N_{10} value. This is the number of impacts of a 5 kg iron weight falling from a height of 50 cm needed for penetration of a cone resister having diameter of 30 mm and tip angle of 60° to an incremental depth of 10 cm vertically downward (Fig. 3). Wakatsuki et al. (2005) recognized four soil layers based on the hardness obtained from the Tsukuba-Maruto type

simplified dynamic cone penetrometers (N_c) on granitic slopes. These are: $N_c < 5$ for the *upper layer* (denoted hereafter as UL), $5 \leq N_c < 10$ for the *middle layer* (ML), $10 \leq N_c < 30$ for the *lower layer* (LL), and $30 \leq N_c$ for the *weathered bedrock* (WB). The relation between N_{10} and N_c values on a granite slope is given by the equation $N_c \approx 0.5 N_{10}$ (Wakatsuki et al., 2003); we therefore classified the soil layers as follows: $N_{10} < 10$ for UL, $10 \leq N_{10} < 20$ for ML, $20 \leq N_{10} < 50$ for LL and $50 \leq N_{10}$ for WB.

At the head of the soil-slip scar (at sites L-0, L-20 and L-30 for Gb-1, and L-0, L-30 and L-44 for Ghb-1), the thickness of UL was 30–100 cm on both slopes. The thicknesses of ML and LL were smaller on the Gb-1 slope (0–20 cm and 10–30 cm) than on the Ghb-1 slope (>20 cm and >100 cm). At the side of the scar (at site S-38 for Gb-1 and S-62 for Ghb-1), the thickness of UL and ML was 100–130 cm and the thickness of LL was 0–20 cm on both slopes. In the soil-slip scars (at sites L-33.5, L-36, L-40, L-42.5, L-46, L-50 and L-54 for Gb-1, and L-50.2, L-56 and L-60 for Ghb-1), the thicknesses of UL and ML were only 0–20 cm on the Gb-1 slope and 20–60 cm on the Ghb-1 slope, and the thickness of LL was 0–40 cm on both slopes. Results from both cone penetration testing and hammer seismic refraction sounding indicate that the Ghb slope has a deeper weathered layer than the Gb slope.

The soil-layer structure was observed from a soil pit at the scar head (symbol ☆ in Fig. 3) on both slopes. The three soil layers (UL, ML and LL) on the Gb slope were thicker than those on the Ghb slope, according to Tsukuba-Maruto-type cone penetration testing (Fig. 4). Fig. 5 shows photographs of the soil profile. On the Gb-1 slope, the bedrock texture remained wholly in WB and LL, and slightly in the deeper part of UL. The color of the soil profile changed abruptly from white in WB and LL to light brown in

the deeper part of UL, and changed gradually to dark brown toward the surface. In the Ghb-1 slope, the bedrock texture remained in LL and ML. The color of the soil profile changed gradually from white in LL to yellow in ML, and changed abruptly to dark brown near the surface. These observations suggest that more chemical weathering has taken place in the shallower part of both slopes. The change in the soil-layer structure due to chemical weathering toward the surface proceeded abruptly on the Gb-1 slope and gradually on the Ghb-1 slope.

Based on the Geological Society (1995) classification of weathered rock, WB in the Gb-1 and Ghb-1 slopes corresponds to “Grade I-III” and LL of both rocks corresponds to “Grade IV/V”. In the Gb-1 slope, UL corresponds to “Grade V/VI”. In the Ghb-1 slope, ML corresponds to “Grade V”, and UL corresponds to “Grade VI”. According to the WRB soil correlation system (Driessen and Deckers, 2001), the soil profile in the Gb-1 slope is “Leptic Cambisol” and in the Ghb-1 slope is “Haplic Cambisol”. In the Gb-1 and Ghb-1 slopes, WB consists of Cr and R horizons, LL of Cr horizon, and UL of A and Bw (Cambic) horizons (Soil Survey Division Staff, 1993). In the Ghb-1 slope, ML consists of Bw (Cambic) horizon (Soil Survey Division Staff, 1993).

4.3. The depth of slip plane

The thickness of UL and ML in the soil-slip scars was thinner than at the side or head of the scars, indicating that UL and ML were removed by soil slips on both slopes (Fig. 3). In the soil profile in the soil pit (Fig. 4), the extension of the slip surface to the upper slope corresponds to 50 cm depth of the soil profile between UL and LL on the Gb-1 slope, and a depth of 60–70 cm in ML on the Ghb-1 slope. These values suggest that the

slip surface occurs at the boundary between UL and ML or LL, corresponding to N_{10} values around 10, i.e. N_c around 5. The average depth of the soil slips was estimated to be 70 cm on the Gb-1 slope, and 80 cm on the Ghb-1 slope. Table 1 shows the slip depth and the slope angle of these slips. The slope angles of the soil-slip scars and the slip depths are clearly similar at 40–48° and 70–100 cm on both Gb and Ghb slopes.

5. Soil sampling

For the measurements of physical, mechanical, mineralogical and chemical properties, soil samples were collected at the upslope side of the soil pit at the scar head (☆ in Fig. 3). The same properties were also measured for two fresh blocks of bedrock in the Gb and Ghb areas and a slightly weathered block of gravel on a river floor in the Ghb area. UL and ML soil samples were collected with a 100 cm³ soil sampler because of the soft grus; samples for LL were collected by quarrying out the soil as a block because of the hard grus. Soil sampling and *in situ* tests were carried out in these soil layers at every 10–40 cm depth, down to 60 cm on the Gb-1 slope and 130 cm on the Ghb-1 slope.

6. Mineralogical and chemical properties

6.1. Methods

Mineral composition and clay minerals in slope material were determined using X-ray powder diffraction. Bulk compositions were analyzed from samples of bedrock, gravel and from three soil layers (UL, ML and LL). The major elements (SiO₂, Al₂O₃, K₂O, Na₂O, CaO, MgO, FeO+Fe₂O₃, MnO, TiO, P₂O₅) and ignition loss were analyzed using a X-ray fluorescence spectrometer. Calibration was performed using pellets for 26

standard rock samples from the Geological Survey of Japan.

6.2. Results

The samples of Gb-1 bedrock contained mainly quartz, plagioclase (mainly albite), K-feldspar (mainly microcline) and biotite (Fig. 6A). Samples of Ghb-1 bedrock contained mainly quartz, plagioclase (mainly albite), K-feldspar (mainly microcline), and biotite as well as small amount of riebeckite (Fig. 6B). The Ghb bedrock was composed of more mafic minerals than the Gb bedrock (Table 2 and Fig. 6). In particular, there is more biotite in Ghb than in Gb.

Assuming that the X-ray diffraction intensity is proportional to the amount of included minerals, it is possible to estimate the amount by depth in the soil profile. The peaks used were the 101 peak (about 3.34 Å) for quartz, the 040 peak (about 3.24 Å) for K-feldspar, the 002 peak (about 3.19 Å) for plagioclase, the 001 peak (about 10.0 Å) for biotite, and the 110 peak (about 8.5 Å) for riebeckite (Fig. 6). Fig. 7 shows the ratio of X-ray diffraction intensities of each mineral in the soil layers to the corresponding intensities in the bedrock (Ratio of X-ray Diffraction Intensity, or *RI* for short). The *RI* values for quartz, K-feldspar, and plagioclase on the Gb-1 slope, and quartz on the Ghb-1 slope, were close to unity throughout the three soil layers, so that the amounts of these minerals do not change from the bedrock to the soil layers. The *RI* values for biotite on the Gb-1 slope decreased gradually from 1.8 at 60 cm depth to 1.1 at 50 cm depth (potential slip plane) in LL, and from 1.1 to 0.1 toward the surface in UL. The amounts of biotite therefore decreases gradually from LL to UL. The *RI* values for K-feldspar and plagioclase on the Ghb-1 slope fell greatly around ML (potential slip plane) with a small

change in UL. The *RI* values for biotite and riebeckite in the Ghb-1 slope were much less at 130 cm depth in the lower part of LL. The *RI* value for biotite could not be measured in ML because mica clay minerals having a strong peak at 10Å are abundant, and cannot be distinguished from biotite in the X-ray diffraction pattern.

The soil layers on both slopes contained clay minerals such as typically intergradient vermiculite-chlorite, kaolin minerals, mica clay minerals and gibbsite (Table 3). The amount of intergradient vermiculite-chlorite was higher in UL than in ML and LL, but there were less mica clay minerals in UL than in ML or LL on both slopes. On the Ghb-1 slope there were more mica clay minerals in ML than in LL and UL; biotite was less in LL on the Ghb-1 slope. These results indicate that biotite changes from mica clay minerals to intergradient vermiculite-chlorite toward the surface. The amount of kaolin minerals and gibbsite showed little change with depth in the soil profile on the Gb-1 slope, but on the Ghb-1 slope there were more of these minerals in UL than in ML or LL.

Fig. 8 shows the chemical compositions on the two slopes. The bedrock contained mainly SiO₂ (74.5 % for Gb-1, 65.5-67.4 % for Ghb-1), Al₂O₃ (15.6 %, 15.0–15.2 %), K₂O (2.9 %, 3.4–3.9 %) and Na₂O (3.8 %, 3.4–3.5 %). In the bedrock these four oxides made up 98.4 % in the Gb, 90.3–92.4 % in the Ghb, but decreasing in UL to 80.2–94.6 % on the Gb-1 slope, and 79.5–85.5 % on the Ghb-1 slope. Conversely, the levels of Al₂O₃, Fe₂O₃, and TiO₂ increased from the bedrock to UL on both slopes.

Fig. 9 shows the *ROT* values, which are the ratios of Oxide/TiO₂ in the soil layers and gravel to the amount in the bedrock (Wakatsuki et al., 2005). Assuming that TiO₂ is a stable constituent because of its immobility in aqueous solutions, the *ROT* value is a measure of the amount of oxides leached from the soil layers and gravel relative to the

bedrock. Leaching of all oxides increased gradually in LL, ML and UL in that order on both slopes. In the soil layers on the Gb-1 slope, $\text{FeO}+\text{Fe}_2\text{O}_3$ and MgO were heavily leached out; CaO , Na_2O and K_2O were moderately leached; and SiO_2 and Al_2O_3 were scarcely leached. In the soil layers and gravel on the Ghb-1 slope, CaO , K_2O and MgO were most highly leached out; SiO_2 and Na_2O were highly leached; and $\text{FeO}+\text{Fe}_2\text{O}_3$ and Al_2O_3 were slightly leached. Leaching was greater on the Ghb-1 slope than on the Gb-1 slope.

7. Physical and mechanical properties

7.1. Methods

The physical properties measured were the grain-size distribution, the dry unit weight (γ_d), the moist unit weight (γ_t), the saturated unit weight (γ_{sat}), the natural water content (w), the void ratio (e), the degree of saturation (S_r), the saturated hydraulic conductivity at a temperature of 15°C (K_{15}) and the infiltration capacity (I_c) of slope materials in the soil layers. The grain size distribution was determined by sieving and the hydrometer method of JIS (Japanese Industrial Standards) A 1204. The dry and saturated unit weights, the void ratio, and the degree of saturation of slope materials were obtained via JIS A 1225. The natural water content and the saturated hydraulic conductivity were measured according to JIS A 1203 and JIS A 1218, respectively. The infiltration capacity was measured using a flood-type cylinder infiltrometer. The apparatus is a steel cylinder of internal diameter 8 cm and length 4 cm. The soil layers to be tested were first scraped to produce a horizontal plane. The apparatus was then pushed 3 cm into the soil, allowing a 1 cm head of water to be maintained. The measurement time was 5–15 minutes and the

infiltration rate was measured every 0.5–1 minutes. The infiltration rate decreased gradually for 0.5–3 minutes and was then nearly constant; this constant value is regarded as the I_c value. The infiltration test can be applied to the hard grus in LL in addition to the soft grus in UL and ML, while the hydraulic conductivity can be measured only in the soft grus. The relation between K_{15} and I_c values on granite slopes is given by the following equation (Wakatsuki et al., 2004):

$$\text{Log}_{10}I_c = 0.497 \text{ Log}_{10}K_{15} - 0.071 \quad (1)$$

The mechanical properties, such as the cohesion under natural water conditions (c_{nat}) and saturated conditions (c_{sat}), angle of internal friction under natural water conditions (ϕ_{nat}) and saturated conditions and (ϕ_{sat}), and the Yamanaka-type cone penetrometer hardness (Daiki Co.) of the slope materials, were measured *in situ* in the undisturbed soil layer. Values of c_{nat} , c_{sat} , ϕ_{nat} and ϕ_{sat} were determined by vane shear-testing (Matsukura and Tanaka, 1983; Wakatsuki et al., 2005). The Yamanaka-type cone penetrometer hardness was expressed in terms of the penetration depth, X (mm), in which a cone having tip angle $25^\circ 20'$ attached to a spring with a strength 8 kg/40 mm was pressed vertically into the specimen; X is related to P (kgf/cm²) by the equation $P = 100 * X / 0.7952(40-X)^2$ (Yamanaka and Matsuo, 1962).

7.2. Results

The grain size distributions on both the Gb-1 and Ghb-1 slopes were similar. The median diameter of slope materials was between 0.42 and 1.09 mm in the Gb-1 slope, and

between 0.56 and 2.55 mm on the Ghb-1 slope (Fig. 10). Vertical changes in grain size were of two types. One type was observed in the deeper part of the soil profile such as LL on both slopes and ML on the Ghb-1 slope, where the grain size changed little. The other type was observed in the shallower part of the soil profile such as UL on both slopes, in which the grain size gradually became finer toward the surface. The natural water content decreased as the grain size became finer on both slopes (Fig. 11).

The dry, moist, and saturated unit weights (γ_d , γ_t , γ_{sat}), the void ratio (e), the porosity (n) and the Yamanaka-type cone penetrometer hardness (X or P) showed similar tendencies on both slopes, from the deeper zone to the surface (Fig. 11). The dry unit weights in both slopes were nearly identical: $>1.45 \text{ gf/cm}^3$ in LL, $1.16\text{--}1.55 \text{ gf/cm}^3$ in ML, $0.57\text{--}1.16 \text{ gf/cm}^3$ in UL. The degree of saturation increased in LL and decreased in ML and UL on the Gb-1 and Ghb-1 slopes.

The saturated hydraulic conductivity (K_{I5} value) was high ($4.6\cdot 10^{-3}\text{--}1.2\cdot 10^{-3} \text{ cm/sec}$) in UL on the Gb-1 and Ghb-1 slopes (Fig. 11). The infiltration capacity (I_c value) was high ($2.8\cdot 10^{-2}\text{--}2.0\cdot 10^{-1} \text{ cm/sec}$) in ML and LL on both slopes. Upon substituting the I_c values into Equation (1), K_{I5} was estimated to be $3.0\cdot 10^{-3} \text{ cm/sec}$ in LL on the Gb-1 slope, and $5.3\cdot 10^{-2} \text{ cm/sec}$ in ML, and $7.8\cdot 10^{-3} \text{ cm/sec}$ in LL on the Ghb-1 slope. These estimated values are higher than the measured values in UL.

The values of c_{sat} , ϕ_{sat} , c_{nat} , and ϕ_{nat} showed similar tendencies on both Gb-1 and Ghb-1 slopes; values decreased greatly from LL to the potential slip plane (ML), and were either unchanged or slightly decreased from the potential slip plane to UL (Fig. 12). However, the rate of change from LL to the potential slip plane differed between the two slopes: the values of c_{sat} and ϕ_{sat} on the Gb-1 slope changed mostly within a 10 cm

thickness, from 120.8 gf/cm² and 48.6° for LL-60 cm to 25.0 gf/cm² and 28.1° for UL-50 cm (potential slip plane). Changes in these values on the Ghb-1 slope were smaller and within a 40 cm thickness, from 100.2 gf/cm² and 42.6° for LL-110 cm to 66.4 gf/cm² and 35.6° for ML-70 cm (potential slip plane).

8. Discussion

8.1. Effect of bedrock mineral composition on chemical weathering

Figs. 7 and 9 show that some primary minerals in the bedrock have undergone chemical weathering on the Gb-1 and Ghb-1 slopes. On the Ghb-1 slope, the *RI* values for biotite and riebeckite were small (0.21 and 0.06) at the deepest 130 cm depth in LL (Fig. 7). This finding implies that these minerals have been heavily weathered in or below LL, and that K₂O, CaO and MgO have also been heavily leached (Fig. 9). On the Gb-1 slope, the *RI* value for biotite decreased gradually from 1.8 at 60 cm depth to 1.1 at 50 cm depth, and from 1.1 to 0.1 toward the surface (Fig. 7). This change indicates that the amount of biotite decreases gradually from LL toward the surface. Plagioclase and K-feldspar on the Ghb-1 slope were gradually weathered toward the surface from the upper part of LL (Fig. 8), so that CaO and Na₂O were leached out (Fig. 9). The weathering of K-feldspar and plagioclase was small on the Gb-1 slope and the weathering of quartz was insignificant on both slopes. All slope materials except quartz were more weathered on the Ghb-1 slope than on the Gb-1 slope, in all layers. In the potential slip plane there was more weathering on the Ghb-1 slope than on the Gb-1 slope.

Mafic minerals such as biotite and riebeckite are generally considered to be more susceptible to chemical weathering than felsic minerals such as quartz and feldspars (e.g.

Allen and Hajek, 1989). In LL, biotite was more leached on the Ghb-1 slope than on the Gb-1 slope (Fig. 7). Soils above the potential slip plane, i.e. UL, had similar thickness on both slopes, but those below the potential slip plane, i.e. ML and LL and zone Aw-1, were thicker on the Ghb-1 slope than on the Gb-1 slope. Soil water deriving from rainfall may permeate into deeper soil more easily, and weathering appears to proceed in the deeper soil on both slopes because the K_{15} values in UL, ML and LL were relatively high, at 10^{-2} – 10^{-3} cm/sec. Thus, the difference in the thickness of ML, LL and zone Aw-1 is due to the larger amount of biotite in Ghb rock than in Gb rock. Many researchers (e.g., Wahrhaftig, 1965; Eggler et al., 1969; Nettleton et al., 1970; Miura and Higuchi, 1974; Isherwood and Street, 1976; Bustin and Matthews, 1978; Dixon and Young, 1981; Matsukura et al., 1983; Birkeland, 1999) have asserted that alteration of biotite plays an important role in the deep weathering of granitic rocks. Some researchers (Wahrhaftig, 1965; Nettleton et al., 1970; Dixon and Young, 1981; Gerrard, 1994) have asserted that alteration of biotite to vermiculite or chlorite results in expansion, causing the rock to disintegrate so that a grus layer tens of meters thick can be formed. Consequently, slopes underlain by Ghb, containing a larger amount of biotite, should have been weathered deeper than those underlain by Gb, containing a smaller amount of biotite, so that ML and LL and zone Aw-1 in the Ghb slopes become thicker. This mechanism is reinforced by Matsukura et al. (1983), who showed that the alteration of biotite begins at the deeper part of a deep-weathering profile of granite near the present study site, whereas the alteration of plagioclase begins at the shallower part.

8.2 Effects of chemical weathering characteristics on changes in physical properties of

soil layer

The weathering materials in LL were composed of hard grus, in contrast to those in UL which decomposed to soft grus. This outcome of chemical weathering reflects the differing physical properties of soil layers, such as the dry unit weight (γ_d), the saturated unit weight (γ_{sat}), the natural water content (w), the void ratio (n), the degree of saturation (S_r), and the saturated hydraulic conductivity (K_{15}). Values of these parameters for weathering materials changed dramatically at the boundary between LL and UL on the Gb-1 slope, and in ML on the Ghb-1 slope, but the values gradually decreased toward the surface in UL on both slopes (Fig. 11). Since the bedrock on both slopes had mineral grains of a similar diameter, the weathering materials also had similar grain sizes (Fig. 10). The permeability is also similar on both slopes.

Assuming that TiO_2 is a stable constituent, the dry unit weight of weathering materials due to leaching alone ($L\gamma_d$) is given by the following equation (Wakatsuki et al., 2005):

$$L\gamma_d = \text{dry unit weight of bedrock} \times \frac{TiO_2 - \text{value of bedrock}}{TiO_2 - \text{value of soil layer}} \quad (2)$$

If the dry unit weight of the bedrock is taken as 2.6 gf/cm^3 on both the Gr-1 and Gn-1 slopes, the TiO_2 value of bedrock corresponds to the average value of bedrocks on both slopes. Assuming that the weathering materials did not suffer from any compaction or expansion, the volume of the original rock did not change and only the weight decreased due to leaching. The $L\gamma_d$ values of the weathering materials in or around the potential slip plane at depths of 30, 40, 50, and 60 cm from LL to lower part of UL, were 2.55–2.72

gf/cm³ on the Gb-1 slope (Fig. 13). The values were 1.64–1.99 gf/cm³ at depths of 60 and 70 cm for ML on the Ghb-1 slope (Fig. 13). The $L\gamma_d$ values on the Gb-1 slope were larger than on the Ghb-1 slope. The $L\gamma_d$ values for the Ghb-1 slope were similar to the γ_d values, of about 1.55 gf/cm³ (Fig. 13). This suggests that the potential slip plane (ML) is formed principally by leaching (chemical weathering) in the Ghb-1 slope, at which the weathering materials are not consolidated by the pressure of the weight of the upper soils, and the texture of the original rock remains. On the Gb-1 slope, the calculated $L\gamma_d$ values of the potential slip plane (2.55–2.72 gf/cm³) are 1.5–2.3 times larger than the actual γ_d of 1.16–1.67 gf/cm³ (Fig. 13). This suggests that slope materials in the potential slip plane in the Gb-1 slope had expanded. The expansion in the Gb-1 slope is explained by the following two processes: (1) less weathering in LL, with WB having little effect on γ_d but weakening grain bonding, and (2) bioturbation or soil creep, generally active near the surface, breaking the original texture, and increasing void space. Anderson et al. (2002) also examined soil expansion by assuming Zr immobility on the steep slopes of graywacke in Oregon. They believe that the expansion was caused by stress-releasing exfoliation fracturing and by bioturbation- and creep-driven mixing of rock and organic matter. We therefore suggest that the expansion in the upper layer on both slopes is due to bioturbation or soil creep.

The grain size became finer as the degree of chemical weathering increased. On the Gb-1 slope, as the weathering progressed gradually from deeper zones to the surface, the grain size of the slope materials became gradually finer (Figs. 7, 9 and 10). On the Ghb-1 slope, because the degree of weathering was similar throughout LL, the weathering materials contained grains of similar size in this LL layer (Figs. 7, 9 and 10). In contrast,

the grain size became gradually finer in ML and UL, where weathering proceeded gradually from deeper zones to the surface.

8.3. Effects of changes in physical properties on mechanical properties of soil layer

The vertical changes in γ_d , P , c and ϕ showed a similar pattern on both slopes (Figs. 11 and 12), decreasing from LL to the lower part of UL and changing little in UL. The packing of the soil (γ_d) therefore reflects the P , c and ϕ . Since γ_d in LL and ML changed more gradually toward the surface on the Ghb-1 slope than on the Gb-1 slope, these values also changed more gradually on the Ghb-1 slope. They decreased sharply within a 10 cm interval from LL-60 cm to UL-50 cm on the Gb-1 slope, but decreased gradually over a 50 cm interval from LL-110 cm to ML/UL-50 cm on the Ghb-1 slope.

8.4 Effect of changes in physical and mechanical properties on shearing resistance of soil layer, and difference in the return period of shallow soil slips on Gb and Ghb slopes

Soil-slip scars on the Gb-1 and Ghb-1 slopes have nearly uniform inclination and shallow depth. Soil slips occur when the shearing force overcomes the shearing resistance at the slip plane. The shearing force (F_D , gf/cm²) and the shearing resistance (F_R , gf/cm²) are given by the following equations (Wakatsuki et al., 2005):

$$F_D = W \cdot \cos i \cdot \sin i \quad (3)$$

$$F_R = c + (W - m \cdot \gamma_w \cdot z) \cdot \cos^2 i \cdot \tan \phi \quad (4)$$

$$W = \int_0^{z_0} \gamma_{sat}(z) \cdot dz \quad (5)$$

459

460 where W is the weight of soil slip materials per unit area (gf/cm^2), i is the slope angle, γ_w
461 is the unit weight of water (gf/cm^3), γ_{sat} is the saturated unit weight of soils (gf/cm^3), c is
462 the cohesion (gf/cm^2), ϕ is the angle of internal friction (degree), z is the vertical depth of
463 soil (cm), and z_0 is the vertical thickness of soil-slip materials (cm). Here m is a fraction
464 such that mz is the vertical height of the groundwater table above the slip plane. Equation
465 (4) are suitable under such conditions as a temporary perched water flow running parallel
466 to the slope, when infiltration through the soil exceeds the transmissive capacity of the
467 underlying rock. On similar steep slopes made of grus-regolith, Serizawa (1981) and
468 Terajima and Moroto (1990) have observed that the water table continues to rise
469 approximately parallel to the slope surface. A similar phenomenon must have occurred on
470 the present slopes during storms. The present analysis assumes that $m = 0.5$ (as a
471 temporary perched water table rises to the middle part of the soil zone between the ground
472 surface and the sliding plane) or $m = 1$ (when the water table has reached the slope
473 surface). We substitute into Equations (3), (4) and (5) the slope angle on the soil-slip scars
474 ($i = 39.5^\circ$ for the Gb-1 slope, $i = 47.5^\circ$ for the Ghb-1 slope), c_{sat} and ϕ_{sat} from Fig. 12, and
475 γ_{sat} from Fig. 11, supposing that the slip plane is located at depths of 15 cm, 50 cm and 60
476 cm in the Gb-1 slope and 10 cm, 50 cm, 70 cm and 110 cm in the Ghb-1 slope.

477 Fig. 14 shows the relation between the shearing force (F_D) and the shearing
478 resistance (F_R). The slope becomes more unstable as F_D approaches F_R , with soil slip
479 occurring when the values coincide. The value of F_D calculated from Equation (3),
480 increases with increasing soil depth on both slopes. However, F_R on the Gb-1 slope,
481 calculated from Equation (4), decreases sharply at the point where c_{sat} and ϕ_{sat} decrease

from LL to ML (Figs. 12 and 14). The F_R was minimized at the minimum of the c_{sat} and ϕ_{sat} in ML, at which depth the slip plane was created. It increases slightly as c increases again from ML to UL. On the Gb-1 slope, F_D coincides with F_R at a depth of 50 cm in ML when $m = 0.5\text{--}1.0$, so that the material of the soil profile reaches the critical value for soil-slippage before the temporary perched water flow rises to the surface. This calculated slip depth of 50 cm agrees well with the observed value of 70 cm (Fig. 14). At the same time, because LL is very thin in the Gb-1 slope, the temporary perched water table formed above WB will easily reach the potential slip plane and UL at the time of heavy rainfall and a soil slip will occur.

On the Ghb-1 slope, the F_R value falls sharply as the c_{sat} and ϕ_{sat} decrease from LL to ML as in the Gb-1 slope, but gradually decreases close to the ground surface because the c_{sat} and ϕ_{sat} values for ML and UL gradually decrease (Figs. 12 and 14). The material of the soil profile is stable to soil slippage because F_D is smaller than F_R at a depth of 70 cm depth in ML even if $m = 1$ (Fig. 14). Assuming that the values of c and ϕ at a depth of 100 cm are the same as the measured values at a depth of 70 cm, when $m = 1$, then F_R at the slip depth of 100 cm is 93.2 gf/cm^2 , which is close to the F_D value of 90.0 gf/cm^2 . This calculation indicates that a soil slip will occur when the weathering front progresses to greater depths and ML is close to a depth of 100 cm. This calculated depth coincides well with the observed slip depth of 80 cm. At the same time, because the Ghb slope has the thick permeable LL, the temporary perched water table is hardly formed even during heavy rainfall, and soil slips are uncommon. These estimated hydrological processes conform to hydrological observations by Onda (1992) in Obara Village, Aichi Prefecture, Japan. Onda(1992) indicated that the slopes underlain by

coarse-grained biotite granite had a thinner soil layer with small storage capacity for rain water, giving rise to soil layers that saturated more easily during heavy rainfall and more frequent soil slips than on slopes underlain by hornblende biotite granodiorite. The coarse-grained biotite granite slope corresponds to the Gb slopes, and the medium-grained hornblende biotite granodiorite slope corresponds to the Ghb slopes.

As mentioned above, the Gb slope is in greater danger of soil slippage than the Ghb slope. The density of soil-slip scars should therefore be higher, or the shallow soil slips should occur more often, on the Gb slope than on the Ghb slope. This claim is consistent with the fact that the density of soil-slip scars in the Gb area is higher than in the Ghb area.

9. Summary

The effect of differing bedrock mineral composition on the structure of the soil layer on soil-slip scars is summarized in Fig. 15. Although the mineral grain size is almost identical in the Gb and Ghb slopes, the Gb rock has less biotite than the Ghb rock.

In the Gb slope, the small amount of biotite in the bedrock leads to a thinner LL and ML, so that soil water is restricted to moving down into the deeper soil below the slip plane. This characteristic causes the water surface to rise toward the slope surface above the slip plane during heavy rainfall. The easy rise of water surface is favorable to the occurrence of soil slips and increases their density and frequency.

In the Ghb slope, because of the larger amount of biotite in the bedrock, LL and ML become thicker, so that soil water moves easily down into the deeper soil through the slip plane. This in turn restricts the rise of the water surface toward the slope surface

above the slip plane, even during heavy rainfalls. The limited rise of the water surface prevents the occurrence of soil slips, so that the density of soil-slip scars is less.

The difference in soil-layer structures and recurrence intervals of soil slips on the Gb and Ghb slopes is strongly influenced by weathering characteristics, via differences in the bedrock mineral composition. The biotite content is particularly important; biotite is highly susceptible to chemical weathering.

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