Underlying rock type controls of hydrological processes and shallow landslide occurrence

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Abstract Hydrological observations were conducted in the areas where the shallow landslide density varied with rock types, and determined that the difference in landslide occurrence density can be explained by the different hydrological environment. In Obara region, central Japan, where few landslides were observed in the Granodiorite area and many in granite area, occurrence of landslides was found not to be controlled by regolith shear strength, instead by regolith zone thickness, which determines storm water storage capacity. In Niigata region, central Japan, few landslides were observed in Paleozoic sedimentary rock area and many in granite area. Hydrological observation showed that in Paleozoic basin, storm water can be discharged by Hortonian overland flow, whereas in Granite basin storm water can infiltrate in the regolith, thereby the regolith would saturate, resulting in landslides.

INTRODUCTION

Hydrological processes such as runoff generation pattern is recognized to vary with underlying rock types (Hewlett & Nutter, 1970; Freeze, 1972; Onda, 1992), and the frequency of shallow landslides also known to vary with underlying rock types (e.g. Hayashi, 1985). Nonetheless, few studies have provided the conclusive field evidence for the differences. Since hydrological environment seems to be the most important control on landslide occurrence (e.g. Selby, 1979), hydrological researches of two areas, where the landslide density varies with rock types, were performed.

GRANITE AND GRANODIORITE

Study area

In the investigated area there were 200-500 m high granite hills that were underlain by two types of Cretaceous granitic rocks in sharp contact with each other (Nakai, 1974): (a) a medium grained granodiorite covered in the northern part, and (b) a coarse grained granite in the southern part. The granite has higher resistance to chemical weathering than the granodiorite (Iida *et al.*, 1986). Landslides due to a heavy rainfall (210 mm/3 hours) occurred in 1972 in Obara area, Aichi, Japan, where the landslide occurrence density varied with rock types; few landslides were observed in the granodiorite area and many in granite area (Fig. 1).

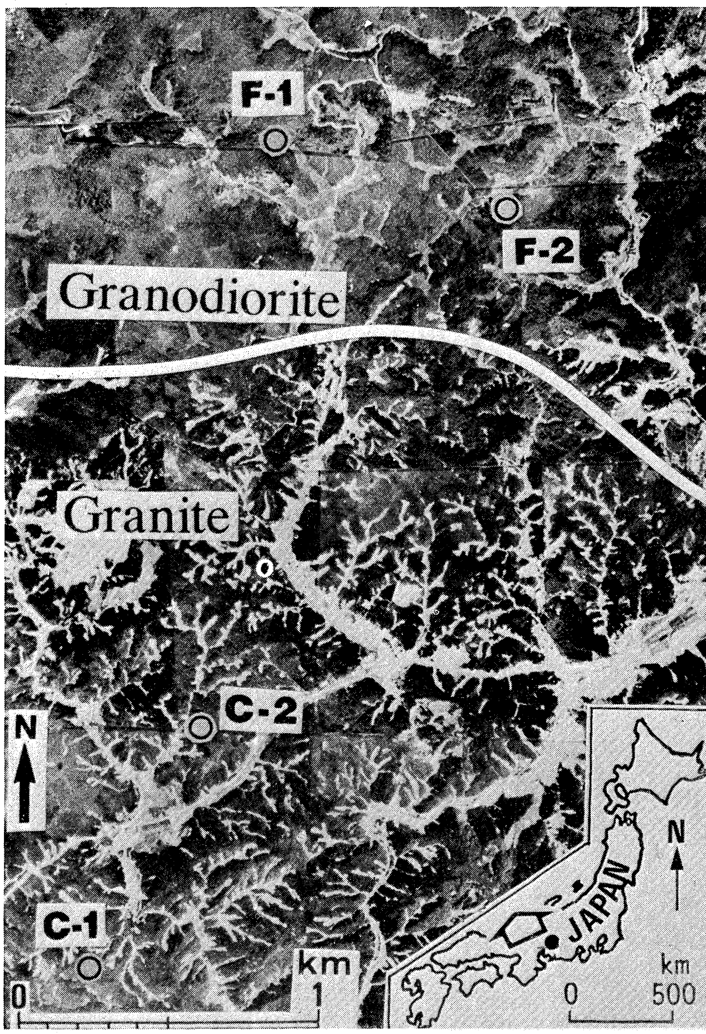

Fig. 1 Scars resulting from 12 July 1972 landslide (Photo date 19 July 1972) and location of the experimental basin.

Field observation has been performed since 1986 to explain this contrast, with two experimental basins (0.41 ~ 0.86 ha) being established in each area since 1986. Discharge was taken at the outlet of each basin by thin-plate V-notch weirs, located at C-1, C-2, and F-1 basins, and a partial flume, located at F-2 basin. Several manual tensiometers, vertically buried with different depths, were placed at the crest of in F-1 and C-1 basins. The experimental basins are located within a distance of 3 km; this approximates identical climatic conditions for the experimental basins. A raingauge was placed at C-2 basin.

Results and discussion

A regolith's shear strength, which can be measured by a direct shear test, is believed to be the catalyst in slope failures, and was determined using a 12-cm diameter shear box and saturated samples. The sampling was only performed in the F-2 and C-1 basins, because sampling was easier than the other basins, which were underlain by the same bedrock. Normal stresses were applied at 100, 300, 500, 900 kPa. Shear speed was 1 mm/min. The regolith was collected at the potential slope failure depth (Iida & Okunishi, 1983) of 1 m. The granodiorite and the granite regolith's saturated shear strength were respectively C = 37.2 kPa/∅' = 31.8° and C = 26.5 kPa/∅' = 48.2°. Since the granite's shear strength was greater than the granodiorite's, the difference in slope failure distribution cannot be attributed to the regolith's shear strength in saturated conditions.

Regolith shear strength normally decreases with respect to its water content (Selby, 1979), therefore hydrological observations must be performed to investigate regolith properties. Figure 2 shows hydrograph of the F-1 and C-1 basins during the 1986 rainy season (16 June-16 July), which had a total rainfall of 462 mm. Compared with the C-1 basin, the F-1 basin had lower peak runoff and relatively higher and more steady base flow. The runoff ratio during the rainy season was 12.6% for the F-1 basin, and greater than 39.8% for the C-1 basin. The runoff ratio for the F-2 basin was greater than 18.8% and in the C-2 basin was 39.7%, indicating that runoff characteristics depend on the underlying rock types.

The water budget equation (Freeze & Cherry, 1979) shows the remainder of the precipitation must be stored in the basin, thus the regolith acts as reservoir during the rainy season and afterwards supplies the base flow. It has been reported that the regolith structure may control the runoff characteristics (Hewlett & Nutter, 1970),

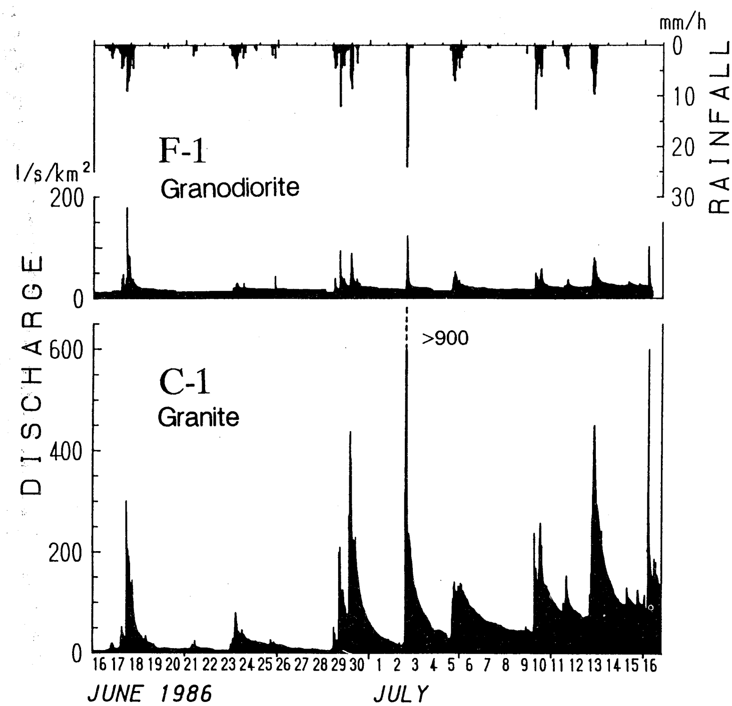

Fig. 2 Hydrograph of the F-1 and C-1 basins during 1986 rainy season.

therefore regolith zone thickness was investigated using a cone penetrometer. The regolith zone is defined as the depth that $N_{10} < 50$ (Iida & Okunishi, 1983). The N_{10} value is defined as a number of blows for a 10-cm penetration by a cone penetrometer with a cone diameter of 3 cm, a weight of 5 kg, and a falling height of 50 cm.

Figure 3 shows the subsurface structure and suction values in the F-1 and C-1 basins. The regolith thickness at the crest of the F-1 basin (Fig. 3a) was 5.9 m, however, the average thickness was 4 m, therefore 800 mm of storm water could be stored in the macro pores (Onda, 1989). In contrast, the C-1 basin's regolith zone thickness in the granite area was only 1 m, having a calculated water storage capacity of 210 mm (Onda, 1989). The regolith thickness also varied with underlying rock type in the C-2 and F-2 basins.

Figures 3b and 3c show the suction values during the 1986 rainy season obtained by manual tensiometers. After a rainfall the F-1 basin's suction value (Fig. 3b) in the regolith's shallow region abruptly decreased, however with increased depth the suction value only gradually decreased, i.e., the suction value at 300 cm decreased in a specific interval, followed by smaller values at 400 cm, 500 cm, and 590 cm. This implies a gradual lowering of the wetting front, whereas in the C-1 basin (Fig. 3c), the suction value decreased to 20 cm H_20 after each rainfall, indicating that the entire regolith zone is close to being saturated. However, after the rainfall, the suction value recovered, then decreased over time, demonstrating that the subsurface water movement and the regolith water content are primarily controlled by regolith thickness.

These results indicate that landslides were not controlled by regolith shear strength, instead by regolith zone thickness, which determines storm water storage capacity.

PALEOZOIC SEDIMENTARY ROCKS AND GRANITE

Study area

Landslides due to a heavy rainfall (350 mm/day) occurred in 1968 in Kaetsu region, Niigata, Japan; few landslides were observed in Paleozoic sedimentary rock area and many landslides and debris flow were found in granite area (Fig. 4). The mountains have approximately 900 m elevation and the granite covers the northern part and the Paleozoic sedimentary rocks (shale, sandstone etc.) cover the south. The elevation between the Paleozoic and the granite is about the same, caused by the similar mode of uplift (Watanabe & Une, 1985). Therefore the sediment budget in both regions is considered to be about the same.

A large ($1.95 \sim 2.04$ km^2) and a small ($0.03 \sim 0.04$ km^2) experimental basins have been established in each area since 1991. These basins are located within the distance of 3 km, and the Paleozoic and the granite basins are named PL and PS, and GL GS, respectively. Discharge and electrical conductivity (EC) was measured automatically in these basins.

Results and discussion

The observation showed that on the large Paleozoic basin, flows generated mainly from large springs, whereas flows generated as seepage from small seeps but a great deal

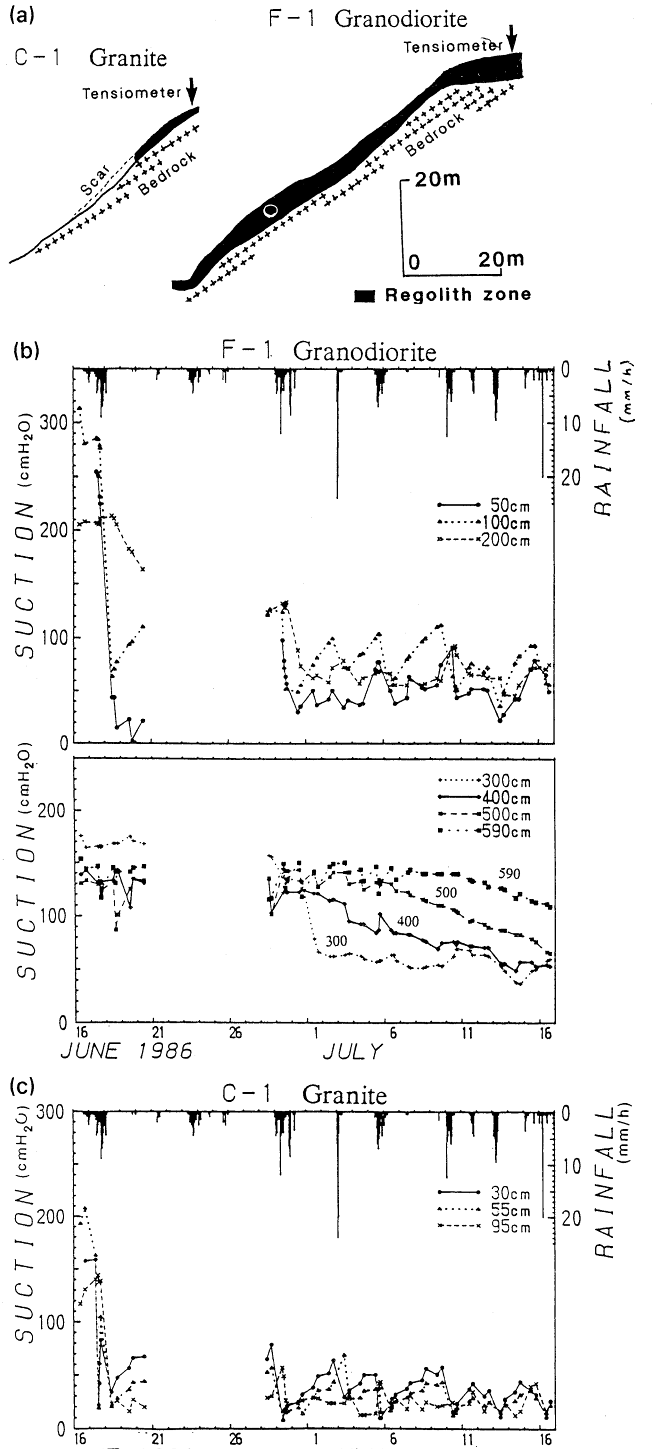

Fig. 3 Subsurface structure (a) and suction values in the F-1 basin in the granodiorite region (b) and the C-1 basin in the granite region (c) during rainy season in 1986. No observations were made from 22 to 26 June.

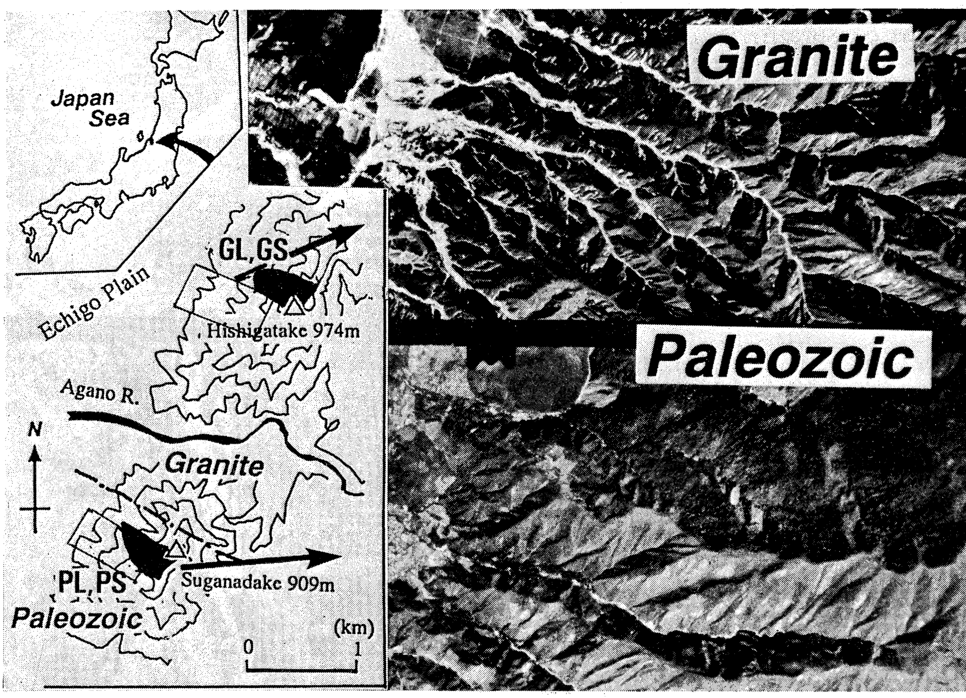

Fig. 4 Location of study site and landslides resulting from 28 August 1968.

of them can be found in the granite region. The thickness of the regolith, obtained by the soundings, and infiltration rate, measured by tube infiltrometer (tube diameter of 8 cm) are listed in Table 1. This shows the regolith thickness was about the same but the smaller infiltration capacity was measured in the Paleozoic basin.

Figure 5 provides hydrograph for PL and GL basins during 1-14 August 1991. The PL basin's hydrograph (Fig. 5a) shows that runoff did not respond to precipitation in smaller intensity of rainfall (7 August), but responded quickly with precipitation >30 mm/h (8-9 August), with the peak dissipating rapidly. The value of electric conductivity was generally constant during rainless periods but decreased abruptly with rainfall. The GL basin's hydrograph (Fig. 5b), on the contrary, responded quickly to each rainfall, having high discharge peak with delayed recession. The EC response to precipitation varied considerably from event to event.

Table 1. Regolith thickness, and infiltration capacity in the small watersheds.

	Regolith thickness (cm)	Sample number	Infiltration capacity (mm/h): Average	Minimum	Maximum
Paleozoic (PS)	60	5	310	96	618
Granite (GS)	60	4	833	425	1254

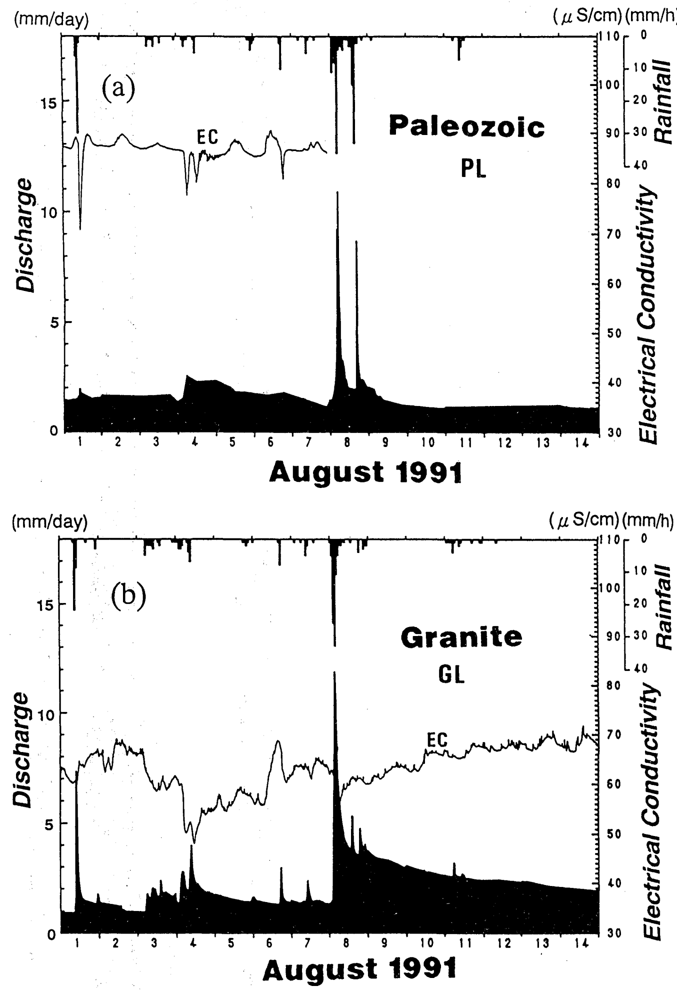

Fig. 5 Hydrograph of the PL and GL basins in August 1991. No EC data were obtained in PL basin from 8 August.

To quantify the contrasting EC response to precipitation, the plot of 1-hour rainfall against deviation of EC from average value is made (Fig. 6). The plot of the Paleozoic basin (PL) shows EC-value gradually decreases with rainfall intensity, whereas little correlation can be found between rainfall intensity and EC value in the granite basin (GL). This illustrates that marked dilution effect was observed in PL basin, but was not found in GL basin. The small infiltration rate (Table 1) and the dilution effect during rainfall peak (Fig. 6) suggest that Hortonian overland flow may occur during the rainfall peak in the Paleozoic basin.

In the light of above results, Hortonian overland flow would contribute much of the peak runoff at its peak, occurring at the time of the heavy rainfall (>30 mm/hour). In contrast to this, in the granite basins, flows were judged as generated as translatory flow (Pearce *et al.*, 1986) in terms of seepage outflow. The average regolith thickness in both area was the same (Table 1), suggesting that the difference in landslide

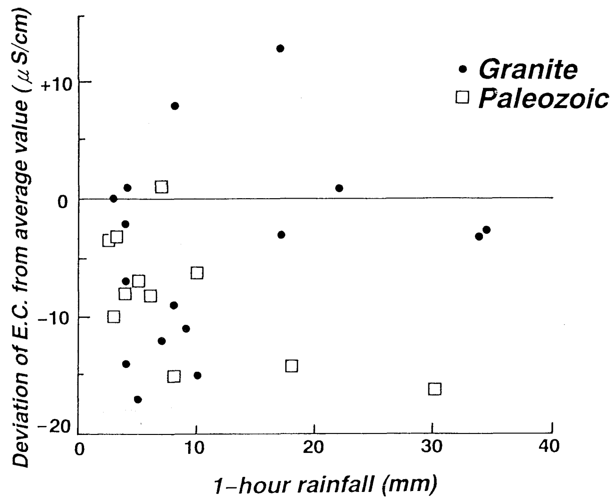

Fig. 6 The relationship between 1-hour rainfall against the deviation of EC from average value in PL and GL basins.

occurrence was explained as the difference in the runoff mechanisms; in the Paleozoic area, storm water can be discharged by Hortonian overland flow, whereas in the granite area storm water can infiltrate in the regolith, thereby the regolith would saturate, resulting in landslides.

CONCLUSION

The above two cases suggested that the difference in landslide occurrence density can be explained by the different hydrological environment, which is controlled by underlying lithologies.

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