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Geologic factors contributing to landslide generation in a pyroclastic area: August 1998 Nishigo Village, Japan

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Abstract

Vertical contrasts in permeability, particularly where permeable surface materials overlie impermeable materials that prohibit the downward infiltration of groundwater, concentrate the groundwater and become an important focus of landslides that are triggered by intense rainfall. Just such a hydrogeological structure is present within the pyroclastics in Nishigo Village in Fukushima Prefecture, Japan, where intense rainfall of 1200 mm in 6 days generated more than 1000 landslides in August 1998. Three types of landslides occurred. The first type occurred along the edges of small plateaus, where horizontal beds of permeable ash, scoria, and pumice overlie impermeable mudflow deposits consisting of tuffaceous fines and andesite blocks, and massive, weakly consolidated ignimbrites. The rainfall on the plateaus infiltrated downward first, then laterally within the permeable beds, finally gushing out at the plateau edges and triggering landslides. The second type of landslide occurred where weathered tuff of the same ignimbrite was present with a slip surface at the base of the heavily weathered zone. Within this heavily weathered zone, the tuff exfoliated into thin weak plates running parallel to the slope surface. The third type of landslide involved failure of colluvium or ash that filled hollows. This type occurred as a result of subsurface erosion caused by the groundwater infiltrating the superficial beds above the impermeable tuff.

Keywords: Landslide; Pyroclastics; Ignimbrite; Weathering

1. Introduction

Areas of pyroclastic flow or ignimbrite, a common rock in tectonically active regions such as USA, central and south America, Iceland, Italy, New Zealand, and Japan (Sparks et al., 1973; Fuller and Sharp, 1992; Moon, 1993; Cas and Wright, 1996), have experienced a great number of devastating landslides. One of the most recent disasters was the 1998 Fukushima disaster in Japan, which occurred in the area of vapor-phase crystallized ignimbrite. Before this disaster, vapor-phase crystallized ignimbrite had not been reported to have generated many landslides as a result of intense rainfall. It had previously been supposed to be rather stable to landslide. Non-welded ignimbrite, without intensive vapor-phase crystallization is typified by Japanese Shirasu, the local name for such ignimbrite in Kyushu, Japan. It is particularly sensitive to intense rainfall (Iwamatsu et al., 1989; Yokota, 1997; Yokota et al., 1997, 1998). Shirasu weathers quickly as rainfall penetrates the ground surface and the increasing thickness of the weathered zone leads to failure (Shimokawa, 1984; Yokota, 1997). After a landslide, which involves the removal of a weathered zone, weathering

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commences again at the landslide scar, preparing for the next landslide. Strongly welded ignimbrite, on the other hand, generally does not suffer from shallow landslides because it is dense and resistant to weathering. It is commonly separated by cooling joints into many columns, which sometimes topple. Weakly consolidated ignimbrite, typically ignimbrite that has been subjected to vapor-phase crystallization (Smith and Bailey, 1966) and that has characteristics that fall between non-welded and welded ignimbrites, is denser and hence more resistant to weathering than non-welded ignimbrite, but is almost free of cooling joints.

Shallow landslides or slope failures have been studied from the viewpoints of geomorphology, hydrology, geotechnology, and geology. Shear or tensile strength of soil and plant roots, groundwater table, and slope forms including hollows are particularly regarded as important for the landslide generation (Dietrich and Dunne, 1978; Selby, 1993; Montgomery et al., 2000). Geology, on the other hand, has generally been regarded as subsidiary, probably because bedrock geology is not thought to greatly affect the geotechnical and hydrological properties of overlying soil that slides.

This paper clarifies that the basic causes of the landslides during the 1998 Fukushima disaster were hydrogeological structures inherited from a history of eruption, erosion, and weathering.

2. Outline of the disaster and the landslides

Heavy rainfall occurred in northern Japan from 26 to 31 August 1998, causing disastrous floods and landslides. The rainfall was particularly heavy in Nishigo Village, Shirakawa City, and Nasu Town, with maximum hourly precipitation of 60 mm or more. The cumulative rainfall in these areas exceeded 1200 mm (Fig. 1), compared to an average August precipitation (1979–1990) of 200–280 mm (Ushiyama, 1998).

This rainfall generated numerous shallow landslides, which killed eight people in and around the welfare facilities of Taiyo-no Kuni in Nishigo Village. Many of the landslides occurred on 27 August (Umemura et al., 1999). Miyagi et al. (1998) reported briefly on these landslides on the basis of a survey performed immediately after the disaster. After that report, the present author made a geological investigation around Taiyo-no Kuni in Nishigo Village and also interpreted aerial photographs (scale of 1:8000) which were taken from 10 to 11 September 1998 in Nishigo Village by the Kokusai Kogyo (Chigira and Inokuchi, in press). As a consequence, more than 1000 landslides, which were controlled by bedrock geology, have been identified as having occurred over an area of 100 km^2 (Fig. 2). The highest frequency of landslides occurred in a zone trending northeast, approximately coincident with the area of more than 800 mm rainfall. The landslides occurred at densities up to 30 per 1 km^2. The largest case occurred at Dannohara (Fig. 2), and had a 50-m-wide source area and a total length of 500 m from the top to the distal edge. Apart from a few exceptionally large landslides like this, most landslides were relatively small, with widths and lengths of 10–30 m and depths of 1–3 m.

3. Geomorphology and geology

A geologic map of the area around Taiyo-no Kuni is shown in Fig. 3. Small plateaus, about 60–100 m high above the nearby fluvial plains, occupy a wide area of Nishigo Village. The tops of the plateaus are essentially depositional surfaces of pyroclastic flows covered by thin tephra layers. Slopes between the edges of the plateaus and the fluvial plains commonly have convex slope breaks about 20 m above the fluvial plains. The origin of these slope breaks is not known.

The bedrock of the plateaus is the early Quaternary Shirakawa pyroclastic flow (Yoshida and Takahashi, 1991; Suzuki et al., 1998) overlain by thin beds of pyroclastics, which are thought to have erupted from Nasu Volcano 200–350 thousand years ago (Suzuki, 1992).

The Shirakawa pyroclastic flow has been divided into several flow units (Yoshida and Takahashi, 1991; Saotome et al., 1999). According to this classification, the flow around Taiyo-no Kuni belongs to the Nishigo pyroclastic flow (Yoshida and Takahashi, 1991; Suzuki et al., 1998) or the Rakuoukei pyroclastic flow (Saotome et al., 1999). The Nishigo pyroclastic flow has been fission track dated to 780 ka (Suzuki et al., 1998). The Shirakawa pyroclastic flow around Taiyo-

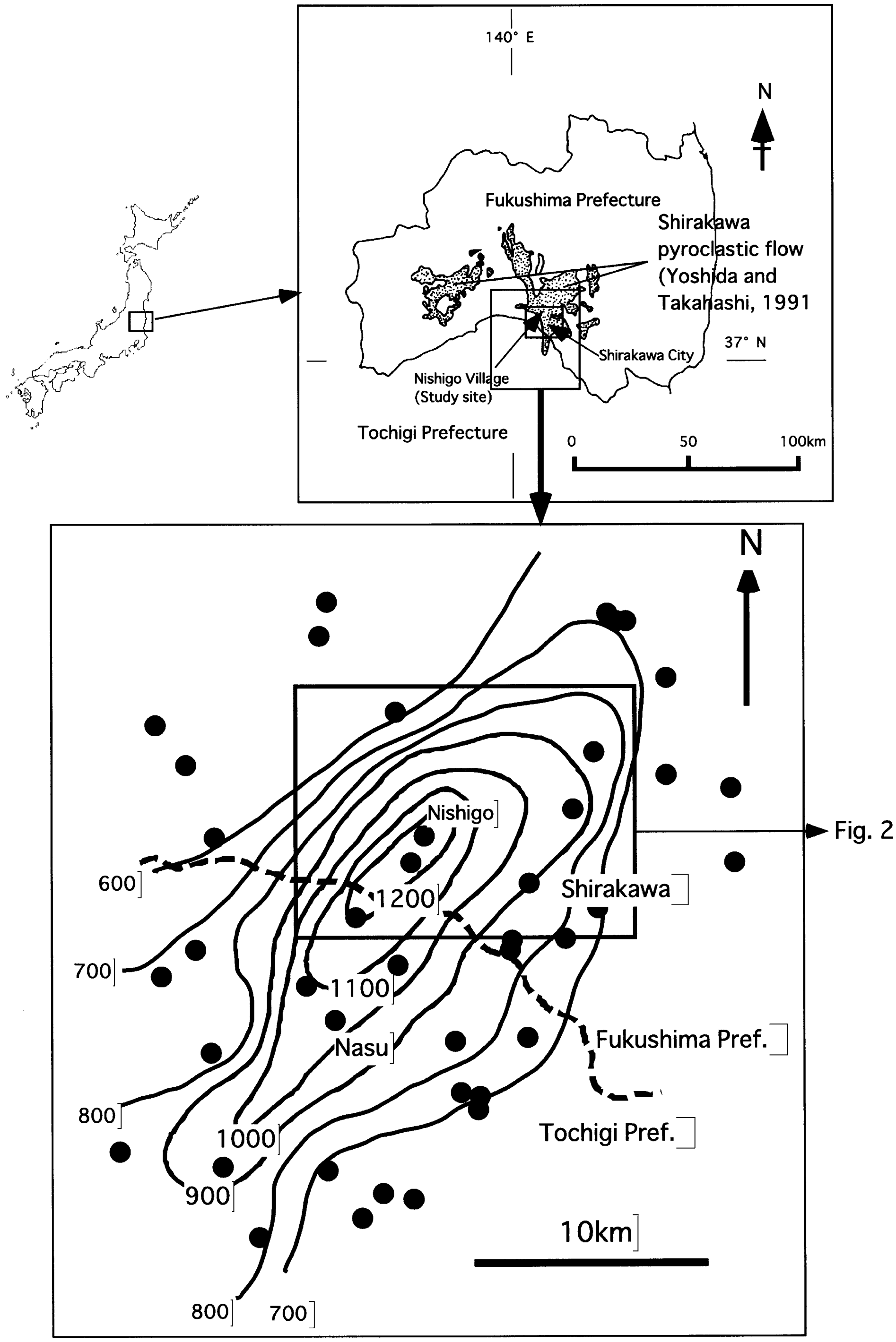

Fig. 1. Index map and the distribution of rainfall. The rainfall data (mm) are from Yamamoto et al. (1999). Location of rain gauges marked. Isohyet interval is 100 mm.

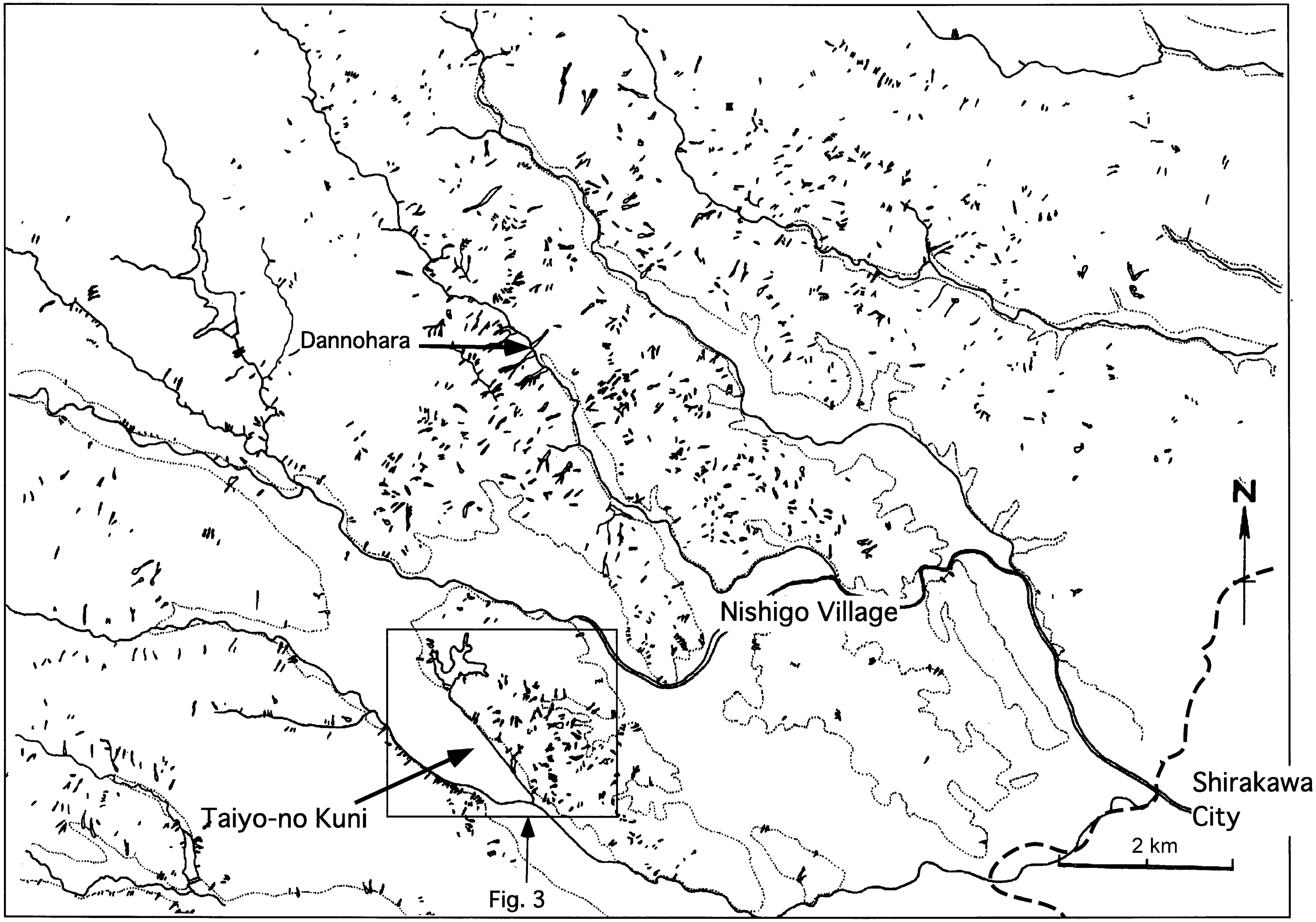

Fig. 2. Landslide distribution in and around Nishigo Village. The dotted line is the edge of the valley floor.

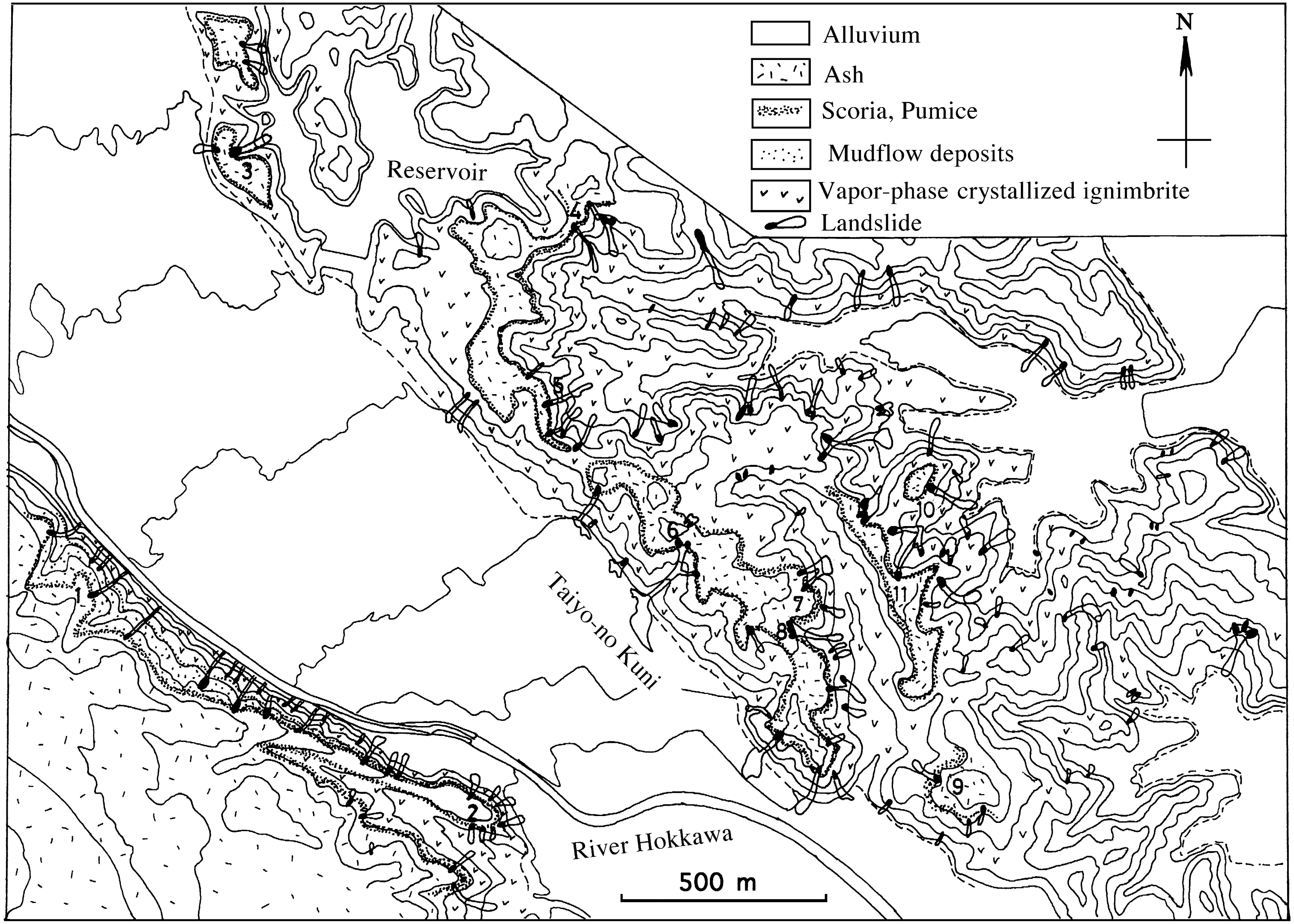

Fig. 3. Geologic map and landslide distribution around the Taiyo-no Kuni. Contour interval is 10 m.

no Kuni consists of ignimbrite (tuff), which is dacitic and poor in lithic fragments. It contains pseudomorphs of beta quartz with a diameter of up to 3 mm, hornblende, pyroxene, tridymite, and cristobalite. This is a weakly consolidated, massive, and intact tuff that had been subjected to vapor-phase crystallization, shown by the presence of tridymite and cristobalite. The tuff has few conspicuous glass lenses and joints but is estimated to have a uniaxial compressive strength of 5 MPa judging from the sound and the rebound of a hammer blow. It is essentially impermeable, with permeabilities on the order of 10^{-8} m/s (Nakata, E., unpublished data). In addition, this tuff has a very characteristic weathering profile, which renders it particularly sensitive to landsliding. Our preliminary survey of the Shirakawa pyroclastic flow in Nishigo Village indicates that for the most part, it has similar properties to the flows around Taiyo-no Kuni. Strongly welded tuff with columnar joints is exposed only locally, and is not important in considering the landslide distribution.

The pyroclastics overlying the Shirakawa pyroclastic flow are exposed in landslide scars and artificial cuttings; elsewhere they are covered by vegetation. These beds, which consist of mudflow deposits (diamicton made up of tuffaceous fines and andesite blocks), scoria, pumice, and ash, are nearly horizontal, hence their outcrop traces follow the contour lines. Their thicknesses vary considerably from place to place, which indicates that they have been deposited and also eroded locally (Fig. 3). The mudflow deposits range from 2 to 20 m thick. They are soft but essentially impermeable. The mudflow deposits are overlain by two types of pumice layers, one of which is white in color and the other is orange, with the latter being more porous and permeable than the former. The former has hydraulic conductivities in the order of 10^{-7} m/s (Oda et al., 1999). A scoria bed, which is laminated and ranges in thickness from several tens of centimeters to 2 m, consists of grains ranging from coarse-sand to granule size and has high hydraulic conductivities of 10^{-4} to 10^{-5} m/s (Oda et al., 1999). Volcanic ash, which is altered to brown or sometimes black soil, forms the top of the pyroclastic beds just beneath the plateau surface. The permeability of the ash should be greater than its measured hydraulic conductivity (10^{-4} to 10^{-5} m/s: Oda et al., 1999), because it is penetrated by plant roots and piping holes.

4. Landslides and geology

Most of the landslides were debris avalanches or debris slides–debris flows as described by Cruden and Varnes (1996), in which "debris" refers to soil containing coarse materials. The landslides were extremely rapid and highly mobile (Miyagi et al., 1998). Their equivalent friction angles (Scheidegger, 1973; Hsü, 1983) ranged from 0.2 to 0.35 with an average of 0.28 based on surveys of 18 cases. These values are between the values for saturated debris flows and unsaturated landslides (Okuda, 1984). A detailed geological investigation near Taiyo-no Kuni showed that these landslides had particular geologic causes. Three types of landslides were identified (Fig. 4). The landslides shown in Fig. 3 were identified by air photo interpretation and more than 20 landslides were investigated in the field. However, since I have not checked all the landslides, these landslides are not differentiated into three types in Fig. 3.

4.1. Landslides of pyroclastic deposits overlying weakly consolidated ignimbrite

These landslides involve pyroclastic deposits and also debris on mudflow deposits and weakly consolidated ignimbrite. They are located along the trace of the pyroclastic fall deposits (Fig. 3) and occurred on gentle convex breaks along the periphery of the small plateaus. The flat top surfaces of the plateaus gradually change to the lower slopes inclined 20°–30°. These landslides were identified initially on aerial photographs, and subsequently most of them were investigated by ground survey. Nine landslides occurred on the 1-km trace of the outcrop of the pyroclastic fall deposits on the southwest slopes of the River Hokkawa. Sixteen landslides occurred on the 2-km trace on the northeast slopes of Taiyo-no Kuni. The successions of the pyroclastic fall deposits, which were observed at landslide scars, are shown in Fig. 5.

The scar of this type of landslide is a spoon-shaped depression, in which almost no debris remains (Fig. 6A). In the upper parts of the scars, pyroclastic fall deposits were exposed and many piping holes were generally present in soft ash. In some locations, groundwater was still observed discharging from the porous scoria 1 week after the event of August 1998. At the base of the scars, impermeable mudflow deposits

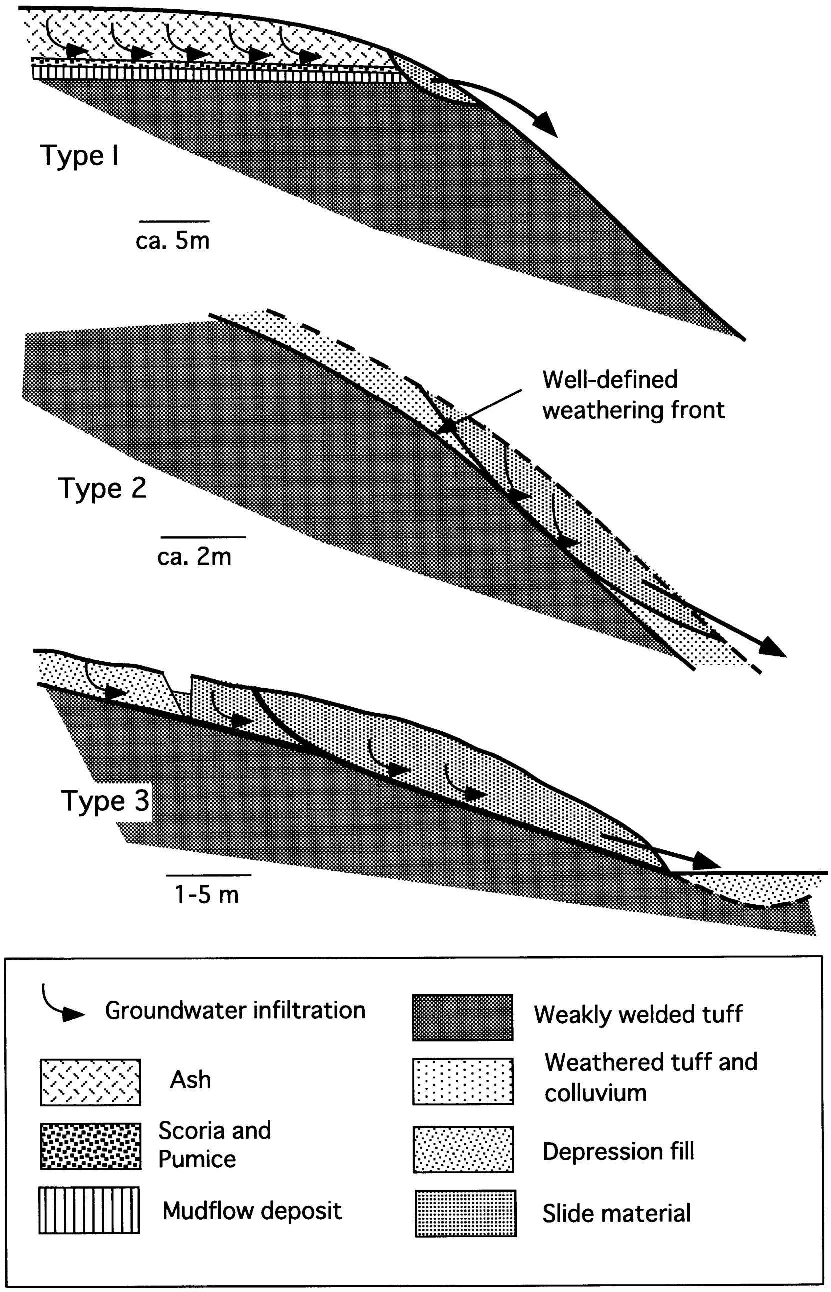

Fig. 4. Landslide types according to geology.

were usually exposed, suggesting that these had blocked the downward infiltration of the infiltrated groundwater. Groundwater resulting from widespread rainfall over a wide area of a plateau thus infiltrated downward through the ash, pumice, and scoria, then flowed laterally and gushed out to the ground surface at the outcrop trace of these beds along the edge of a plateau, generating the extremely rapid landslides. The high mobility of the debris was also indicated by the fact that moving debris hardly damaged grasses or trees

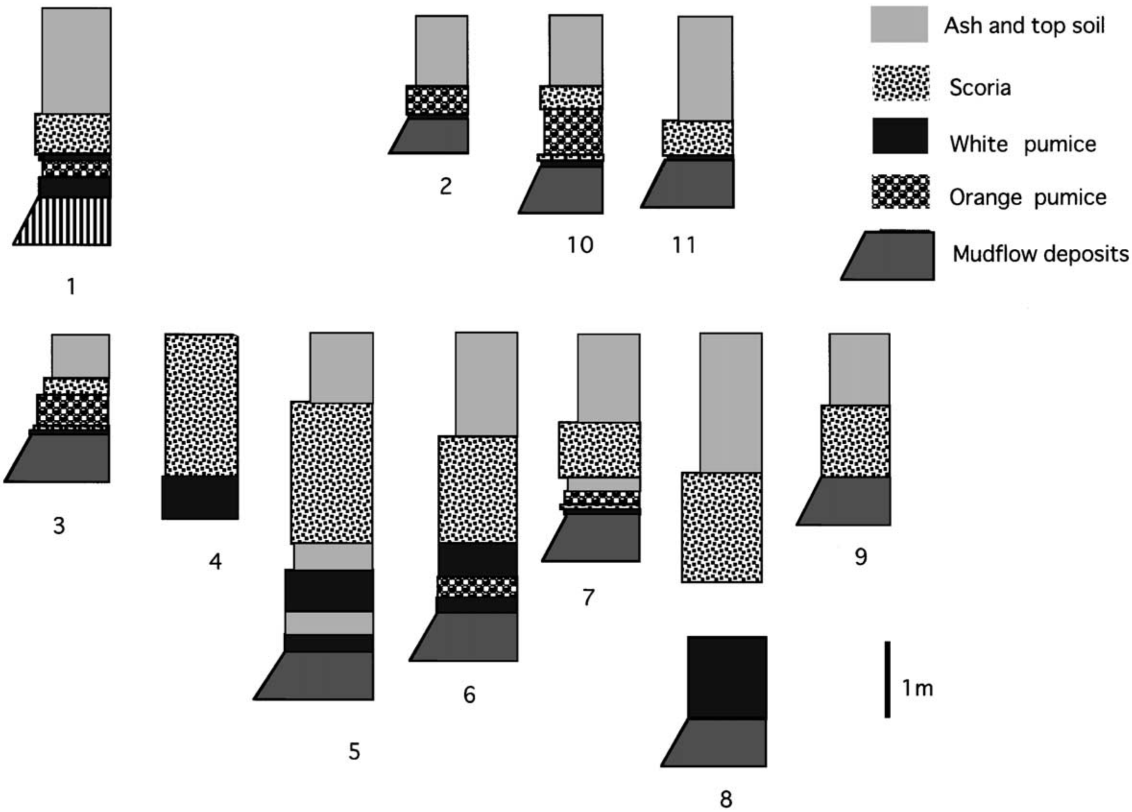

Fig. 5. Successions of pyroclastics overlying the Shirakawa pyroclastic flow. The top of each column is a slope surface. For the location number, see Fig. 2.

and only flattened them onto the ground surfaces along its path (Fig. 6A).

The locations of these landslides must be controlled by the concentration of groundwater in the limited flow paths represented by piping holes. The concentrating process is inferred to be determined by surface topography as well as by underground structures, as is suggested by the fact that many landslides were in hollows into which subsurface drainage concentrates. However, the underground morphology of the tops of the mudflow deposits and of the tuff cannot be known explicitly from the ground surface.

4.2. Landslides of weathered tuff and colluvium

Many landslides had scars that were easily identified by their bright color, a result of the exposed tuff (Fig. 7A). These landslides are less than a few meters deep and involve the failure of weathered tuff and/or accompanying colluvium. Their sliding surface is within the heavily weathered tuff. Most of the landslides away from the surface trace of scoria and pumice shown in Fig. 3 are of this type. These failures had three contributing geologic causes. First, the weathering front in the tuff is generally sharply defined by a conspicuous contrast of strength, above which the rock has deteriorated very much. Second, the tuff has few primary cracks so that groundwater does not infiltrate except in its upper weathered part. Third, because of the clearly defined weathering front and the absence of cracks, plant roots do not penetrate into its intact part to support the surface materials.

The weathering profile of the tuff that has been subjected to vapor-phase crystallization typically has an exfoliated zone, where the tuff separates into thin plates that are parallel to the ground surface, between the underlying less weathered part and the surface soil. This zone ranges from several tens of centimeters

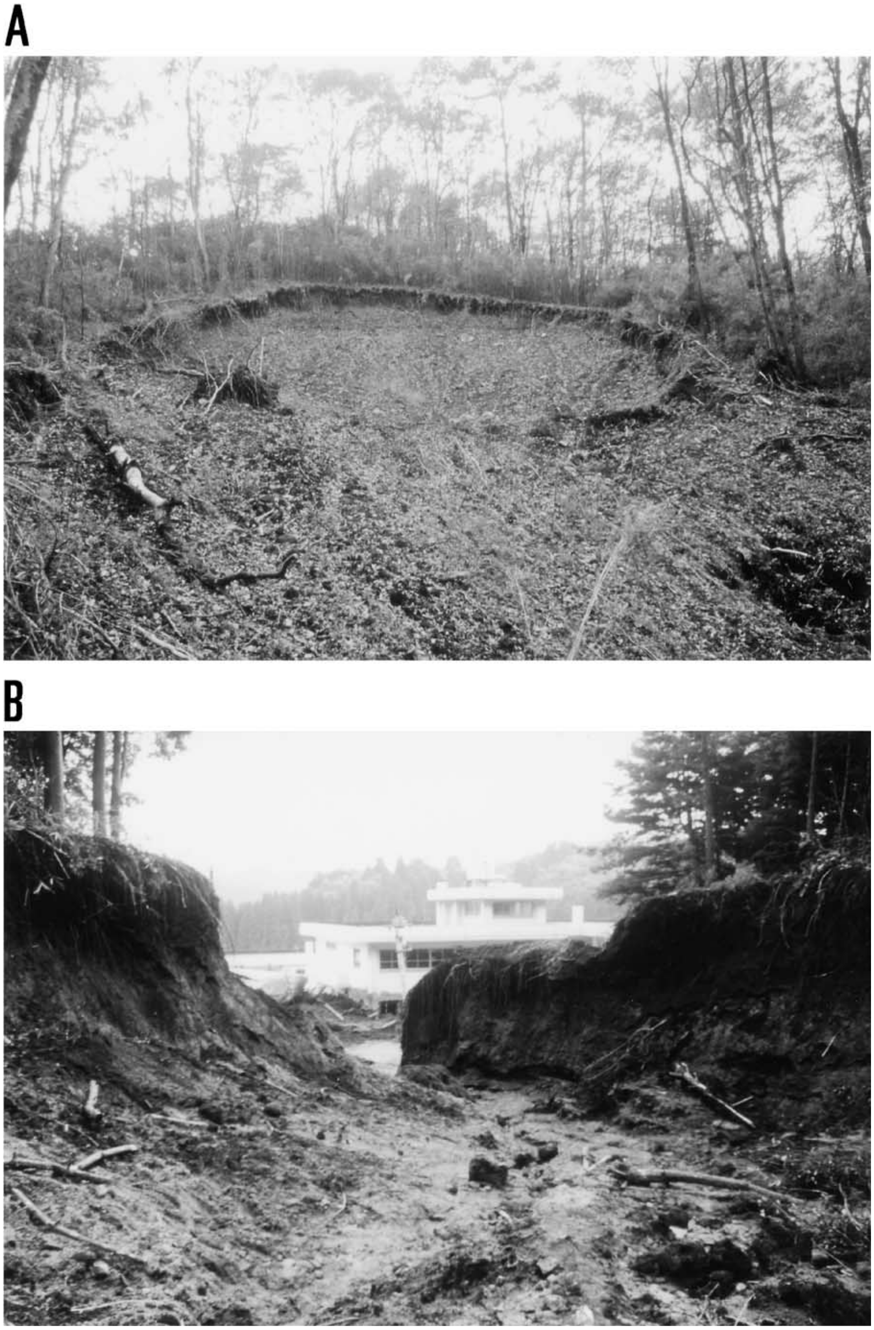

Fig. 6. Typical types of landslide. (A) Landslide of pyroclastic fall deposits overlying mudflow deposits and weakly welded tuff. The landslide scar is an amphitheater-like depression with a diameter of 10 m. Debris came down to the front, but no debris remains, flattened grasses are observable: photo taken 2 months after the event. (B) Landslide of colluvium and ash that filled a former stream near the Daishin Junior High School 15 km northeast of Taiyo-no Kuni. The previous ground surface smoothly connected the left and right top surfaces in the photo. The debris rushed into the building of the Junior High School (middle of the photograph).

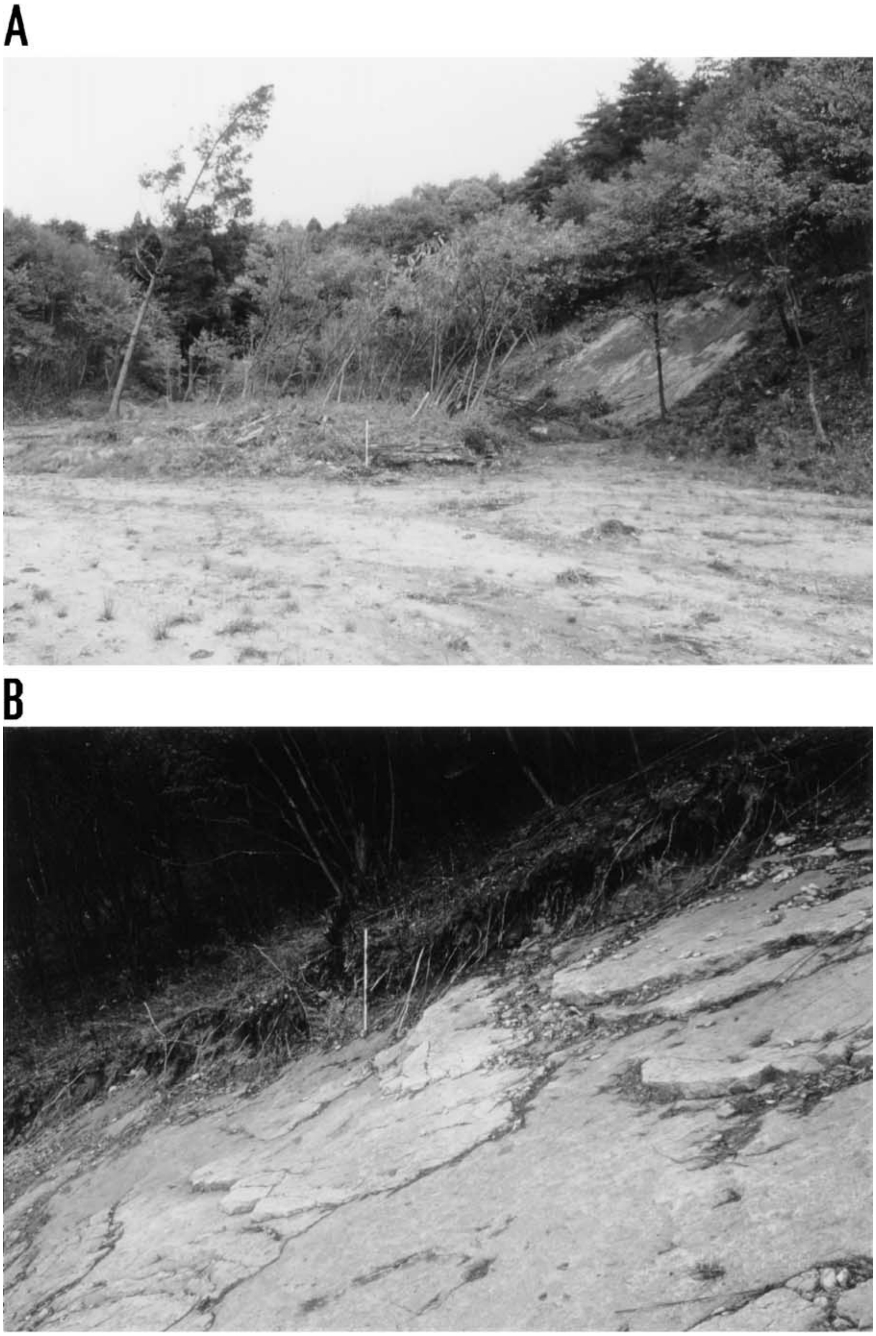

Fig. 7. Landslide of colluvium and weathered tuff with its sliding surface on the heavily weathered tuff. (A) Landslide on a 35° slope with its lobate deposit on flat ground. The scale is 1 m. (B) Sliding surface under which tuff is exfoliated with fractures parallel to the ground surface.

to about 1 m thick, with each plate being several centimeters thick. This zone is called the exfoliated zone. The tuff in the exfoliated zone and the overlying soil is much softer than the underlying tuff, although few clay minerals have been detected in them. The landslides made up of weathered tuff and colluvium have their sliding surfaces in this exfoliated zone, thus leaving some plates of tuff beneath the landslide scars (Fig. 7B). The mineralogical and chemical characteristics of the weathering profile are described in a separate paper (Chigira et al., in press).

The groundwater resulting from the intense rain infiltrated through the soil and along fractures in the exfoliated zones, but did not penetrate significantly into the underlying unweathered and less weathered rocks. Consequently, the soil and the weathered rocks became saturated with water, leading to a landslide.

The landslides of this type occurred on slopes of 20°–45°, sometimes with a convex break of slope downslope. Landslides on such slopes occurred on the southwestern side of the River Hokkawa. A conspicuous convexity is present about 20 m above the bed of the River Hokkawa. Above the convexity, the slopes incline 20°–25° with soil cover, while below the convexity, they are at 40°–45° without a soil cover. Debris on the tuff in the upper slopes slid because its support on the lower slopes had been removed.

4.3. Landslides of depression fill

Failure of colluvium or ash that filled depressions was also triggered by the intense rainfall, although this type of failure seemed less common than the other two types. A typical example of this was a landslide that occurred near Daishin Junior High School, 15 km northeast of Taiyo-no Kuni, where a former buried stream was exposed again by the landslide, leaving a scar 5 m deep and 80 m long (Fig. 6B). On the bed of the landslide scar, ignimbrite was observed to be overlain by horizontal beds of silt and sand, which in turn were overlain by ash. This landslide occurred as a result of subsurface erosion caused by the groundwater infiltrating the superficial beds above the impermeable tuff. Landslides of this type generally had piping holes around the tops of the landslide scars, which had a maximum size of 1 m in diameter.

5. Hydrogeology of pyroclastics that favor landslides

Pyroclastic flow and fall deposits are among the most widely distributed materials in tectonically active regions (Cas and Wright, 1996), and have suffered from disastrous landslides (Del Prete et al., 1998). The landslides described here are inferred to be typical ones triggered by intense rainfall. This is because the basic causes of the three landslide types are within the hydrogeological structures that had been made through the geological and geomorphological history of volcanic materials, which could be common in many volcanic regions. Landslides of the first type occurred along the edges of small plateaus, where permeable, horizontal beds rest on exposed impermeable rocks. This structure is a result of the history of pyroclastic flow, pyroclastic fall, and erosion, very common processes in volcanic regions. In fact, the non-welded ignimbrite of Shirasu in Kyushu, Japan is overlain by pumice beds in which landslides are common (Iwamatsu et al., 1989). The second type of landslide described in this paper was favored by weakly welded tuff with a weathering profile that includes a clearly defined weathering front above which the tuff was greatly deteriorated and exfoliated in layers. This type of weathering profile has not been reported before, but there is no reason to think it exceptional. The weathering profiles of non-welded ignimbrite have been well studied by Yokota and Iwamatsu (1999), who found that the weathered part gradually changes into the unweathered part without an exfoliated zone and without an abrupt change of rock properties. The weathering behavior of ignimbrite is strongly dependent on the degree of welding, and so the characteristic weathering profile reported in this paper might be typical of ignimbrite that has been subjected to vapor-phase crystallization. The third type of landslide described in this paper involves a slide of materials that fill depressions. This is a common type of landslides generated by rainstorms because it is triggered by the concentration of infiltrating groundwater along buried hollows (Montgomery et al., 2000). Although low permeability is favorable for the occurrence of landslides of this type, the type is independent of bedrock geology.

6. Conclusions

Heavy rainfall, as much as 1200 mm per 6 days, generated more than 1000 landslides in Nishigo Village, Fukushima Prefecture, Japan in 1999. According to hydrogeological structures, three types of landslides occurred. The first type occurred along the edges of small plateaus, where horizontal beds of permeable ash, scoria, and pumice overlay impermeable mudflow deposits and weakly consolidated ignimbrite (tuff). Rainfall on the small plateaus infiltrated downward and laterally within the permeable beds, gushing out at the edges and triggering landslides. The second type is a landslide of heavily weathered tuff with a slip surface along the bottom of a heavily weathered zone, where tuff is exfoliated into weak plates. The third type is a slide of materials that fills depressions on impermeable tuff.

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