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Erosion and Mudflows at Usu Volcano after the 1977–1978 Eruption: August 1977–December 1979

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1977–1978 噴火後の有珠山における侵食と泥流 (1977 年 8 月～1979 年 12 月)

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Introduction

The eruption of Usu Volcano in Hokkaido, from August 1977 to October 1978, caused severe and diversified disasters to the neighbouring areas due to direct impact of pumice and ash falls (Kadomura *et al.*, 1978 a) and crustal deformations, as well as due to accelerated erosion and repeated floods of mud or rock debris flows (rain lahars) from the volcanic body. Although no eruptive activities have occurred since the end of October, 1978, new tephra-covered slopes have been eroded vigorously and mud or rock debris flows have occurred repeatedly until the end of October, 1979. Coupled to the crustal deformations causing frequent landslides, accelerated erosion of new tephra-covered and devastated slopes, and unstable sediments accumulated in the valleys would give rise to a long-continuing menace to the piedmont areas. On October 24, 1978, large-scale mudflows were triggered by a localized downpour, and attacked spa towns on the north foot of volcano, resulting in 3 dead, 26 destroyed houses and more than 100 inundated houses.

This paper describes the aspects and sequences of erosion and the occurrence

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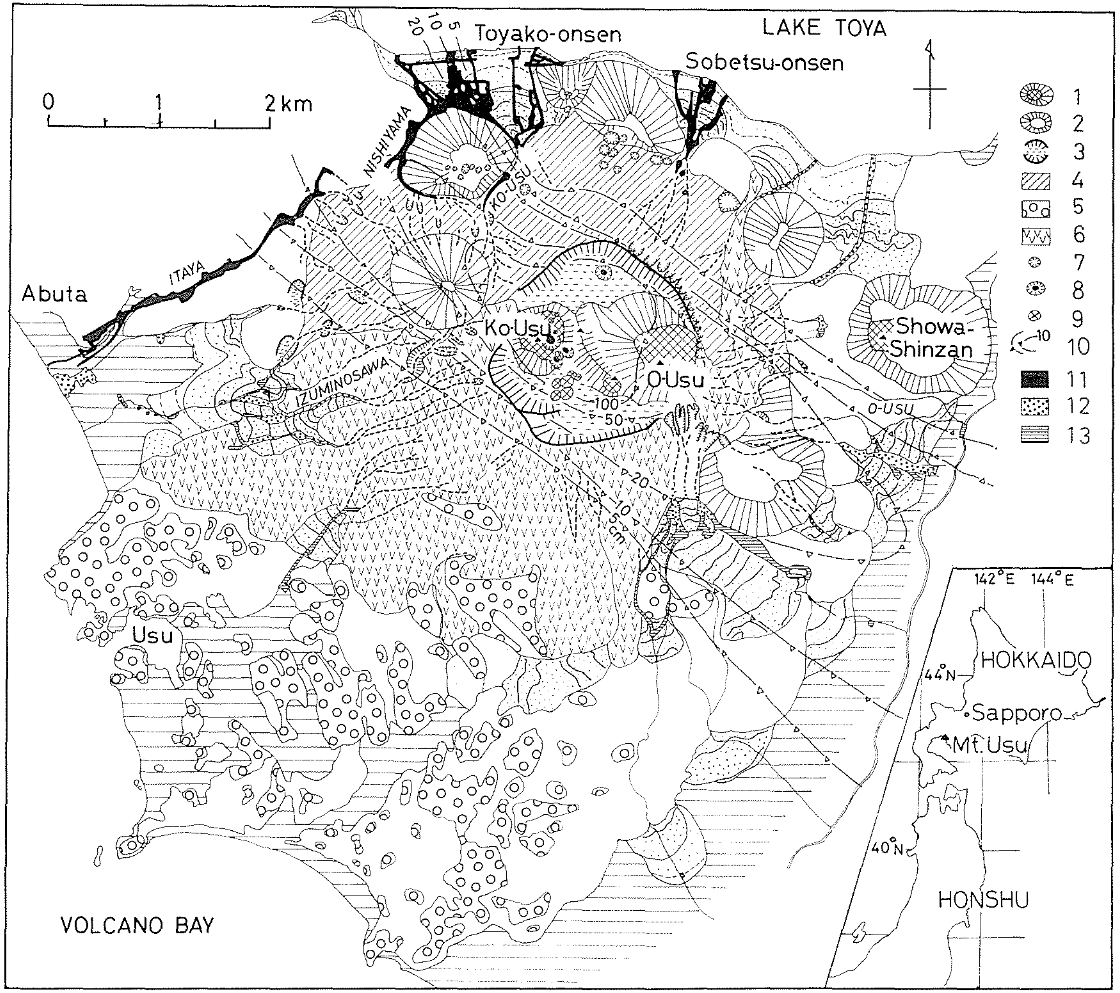


Fig. 1. Geology and geomorphology of Usu Volcano and its surrounding area

1: Lava dome, 2: Cryptodome, 3: Somma-atrio, 4: Slopes composed of Usu Somma lava, 5: Zenkoji mudflow hills, 6: Slopes covered with 1822 and 1853 nuées ardentes, 7: 1910 explosion craters, 8: Craters opened in August 1977, 9: Craters opened by phreatomagmatic eruptions during 1977–1978, 10: Isopach of new tephra produced in August 1977, 11: Mudflows occurred on the night of October 24, 1978, 12: Mudflows occurred in the morning of October 24, 1978, 13: Other mudflows occurred during August 1977-November 1978.

Geology is based on Katsui *et al.* (1978) and Niida *et al.* (1980).

of mud and rock debris flows at Usu Volcano since the biginning of the latest eruption, on the basis of work carried out by the authors from August 1977 to December 1979. Field work was partly supported by the Grant-in-Aid for Scientific Research (Natural Disaster Research) by the Ministry of Education, Science and Culture (Project No. 202035, No. 202038, No. 302044 and No. 402045).

Regional Setting

Usu Volcano, one of active volcanoes in Hokkaido, is situated on the southern rim of Toya Caldera, which is filled with waters, i. e., Lake Toya, and faces on Volcano Bay (Fig. 1). This volcano is a composite type consisting of a somma topped by an atrio being formed by the destruction of a stratovolcano during early Holocene, and some ten of dacite domes and cryptodomes protruding on the summit atrio and flank slopes. The highest peak, O-Usu was 727 m above the mean sea-level before the 1977-1978 Eruption.

Before the 1977–1978 Eruption, six historical eruptions were known to have occurred; in 1663, 1769, 1822, 1853, 1910 and 1943–1945 (Katsui *et al.*, 1978; Kadomura *et al.*, 1978 a). During the 1910 Eruption, 45 craterlets opened in the northern part of the volcano and a cryptodome (Meiji-Shinzan) with a relative height of 170 m was formed on the coast of Lake Toya. Associated with steam eruptions, five strips of eruption lahar flowed down onto the alluvial fans at the north foot of the volcano. The eruption of 1943–1945, which occurred in the eastern area, produced a cryptodome, named Roof Mountain, with a protruded lava dome 409 m in altitude (Showa-Shinzan).

Most of slopes of the volcano are covered with pyroclastic deposits composed of ashes, pumices and nuées ardentes, all of which were produced by the historical eruptions. The south-facing slopes are widely-covered with the deposits of the 1822 nuée ardente, while on the north-facing slopes the distribution of such deposits is limited and outcrops of somma lava are found to form cliffs and falls in many parts.

Surrounding the volcanic body, except for the west slope, alluvial fans which are composed of sediments derived from both dissection of hillslopes and eruption lahars are well-developed. Average slope of these fans is about 10% on the upper segment and 3–4% on the lower segment. The northern part of the volcano which seems to falling within Toya Caldera has been tectonically unstable. This has been revealed by the formation of new hills and associated land deformations in this part during recent eruptions. The 1910 eruptive activity was accompanied by the formation of a number of faults not only on the hilly areas but on the alluvial fans. Most of these faults were set in motion over again since the biginning of the 1977–1978 Eruption.

Climate of the area studied is humid cold temperate, with the mean annual temperature of 6–8°C and the mean annual precipitation of 1,200–1,400 mm (Table 1). While the minimum monthly temperature is as low as −7°C in January, the maximum monthly temperature reaches 21°C in August. Winter day continues for

Table 1. Temperature and precipitation around Usu Volcano (Data from Japan Meteorological Agency) (°C, mm)

Station		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual	Period
DATE	Temp.	−3.8	−3.6	−0.2	6.1	11.5	15.5	19.8	21.4	17.4	11.1	4.5	−1.9	8.1	1966–1975
	Precip.	70	113	49	59	87	83	100	181	163	97	112	54	1,168	
OTAKI	Temp.	−7.9	−7.7	−4.9	2.7	9.7	14.0	18.6	19.4	14.4	7.7	0.6	−6.0	5.1	1967–1975
	Precip.	120	141	94	90	141	139	115	226	272	188	202	102	1,830	
TOYA	Temp.	−6.2	−6.1	−3.2	4.2	10.5	14.5	19.0	20.2	15.7	9.2	2.3	−4.2	6.3	1967–1975
	Precip.	116	127	89	75	95	93	113	199	162	112	143	114	1,438	
OKISHI	Temp.	−4.5	−4.3	−0.9	5.5	10.8	15.0	19.7	21.4	17.0	10.8	4.1	−2.7	7.7	1966–1975
	Precip.	82	84	63	42	84	99	136	173	149	97	101	82	1,192	

150 days from November to March, with 60 ice days from mid-November to mid-February. In contrast to Honshu and other southern regions, there has been no remarkable rainy season like *baiu*, but rainy days tend to concentrate to three months from July to September. Snow covers the landsurface for five months from mid-November to mid-April. Although the maximum snow depth sometimes exceeds 1 m on the slopes of Usu Volcano, in the lowland areas it rarely reaches 50 cm. Less snow cover favours soil freezing, the maximum depth of frost penetration attaining 50 cm.

Before the 1977–1978 Eruption, most of the vlocanic slopes were covered with dense natural forest of summer-green broadleaf trees such as *Populus maximowiczii, Tilia maximowicziana, Acer mono, Ulmus davidiana* var. *japonica, Cercidiphyllum japonicum, Magnolia obovata, Betula* spp., etc. (Ito, 1978). Showa-Shinzan, born during 1943–1945 Eruption and still preserving high geothermal condition on its ground surface, has been free from forest vegetation. In contrast, Meiji-Shinzan, produced by the 1910 Eruption, is mantled with both by thick natural forest and planted trees of larch (*Larix kaempferi*) and fir (*Abies sachalinensis*). The tracts of plantation of such trees are also found here and there on the foot slopes of the volcano.

Two spa towns, Toyako-onsen and Sobetsu-onsen are located on the alluvial fans at the north foot of the volcano. These hot spas, having a population of 4,500 and the accommodation for more than 7,000 guests, have been developed as a central place of Shikotsu-Toya National Park in which Usu Volcano constitutes the main attractive landscape together with Lake Toya. For further details of social setting of the area see Kadomura *et al.*, 1978 a.

The 1977–1978 Eruption and Associated Changes in Terrestrial Environment

The 1977–1978 Eruption of Usu Volcano caused drastic changes in the terrestrial environment of the volcanic body itself and the surrounding areas. The first, changes were caused by the fall of ejecta during the First Stage eruption which lasted from 7 to 14 August, 1977. The total volume of ejecta consisting of ash and pumice produced mostly by the four major pumice eruptions was estimated at $8.3\times10^{13}\,cm^3$ (Katsui *et al.*, 1978), and the total thickness of tephra covering the landsurface was more than 1 m on the summit atrio and 0.5–1 m on the northwest and southeast slopes of the volcano (Fig. 1).

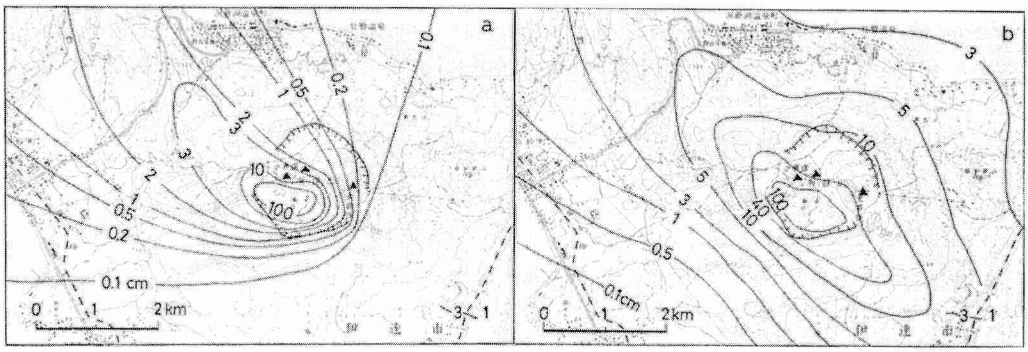


Fig. 2. Distribution of ejecta produced by the Second Stage eruption during November 1977-October 1978 (from Niida *et al.*, 1980)
a: By magmatic eruption of September 12/13, 1978. b: Cumulative thickness of tephra produced during the Second Stage eruptions.

The fallen ash and pumice not only buried the former landsurface with resulting naked surface, but destroyed vegetation by damaging trunks, branches, twigs and leaves of trees, and by burying undergrowth and herbs. This resulted in extremely devastated landscape similar to that found in a semi-arid environment during a dry season (*see* Photos 1, 4 and 5). Particularly, the forest vegetation was completely destroyed in and around the summit atrio where more than 20 new craters opened and the total thickness of new ejecta, including volcanic blocks and bombs larger than 30 cm in diameter, exceeded 1 m (Ito, 1978; Photo 1). On the upper slopes of the northwest part of the somma, the vegetation was also severely destroyed by the fall of new ejecta with a thickness of 0.5–1 m. In such areas, although the recolonization of scattered herbaceous vegetation, such as *Polygonum sachalinense* and *Petasites japonicus* var. *giganteus*, was found since early summer 1978, no trees have regenerated until autumn 1979.

As will be mentioned later, the surface of the deposited new tephra was covered with a cement mortar-like ash which fell during the rainy weather on August 8, 1977. This ash fall contributed not only to the destruction of trees and crops but to the formation of impermeable crust, leading to the drastic increase of overland flow.

Subsequent to the major pumice eruptions during August 1977, the Second Stage eruptions, consisting of a series of phreatic to phreato-magmatic and magmatic eruptions, occurred intermittently from November 16, 1977 to October 27, 1978

(Niida *et al.*, 1980). The ejecta produced during the Second Stage eruptions consisted mostly of fine-grained ash and was predominantly distributed to the northwest and southeast directions (Fig. 2 b), the total volume being $7.5 \pm 0.8 \times 10^{12}$ cm^3 (Niida *et al.*, 1980). Among the Second Stage eruptions, the magmatic eruption of September 12/13 was the largest and the slopes of the somma were covered with the new, fine-grained ash of 2-3 cm or more in deep. This event led to the drastic drop in the infiltration rate over again.

Accompanied to the eruptive activities, remarkable crustal deformations have proceeded on the summit atrio and north to northeast slopes of the somma, as well as on the alluvial fans at the north foot of the volcano. On the atrio, a new roof mountain (cryptodome) has been upheaving with accompanying numerous faults (Photo 1), as a result of the rise of subsurface magma beneath the atrio (Katsui *et al.*, 1978; Katsui and Yokoyama, 1979). In contrast, one of the summit domes, Ko-Usu has been successively sinking. The rise of magma has also caused remarkable northeastward thrust of the somma, resulting in densely-spaced faultings and large-scale landslidings of the upper slopes (Photos 2 and 3). The repeated precise distance measurements have revealed that the north rim of the somma has already moved about 160 m towards the northeast up to July 1979 (Katsui and Yokoyama, 1979; Fig. 3).

Slope deformations and rock falls have also been accelerated by the shock of

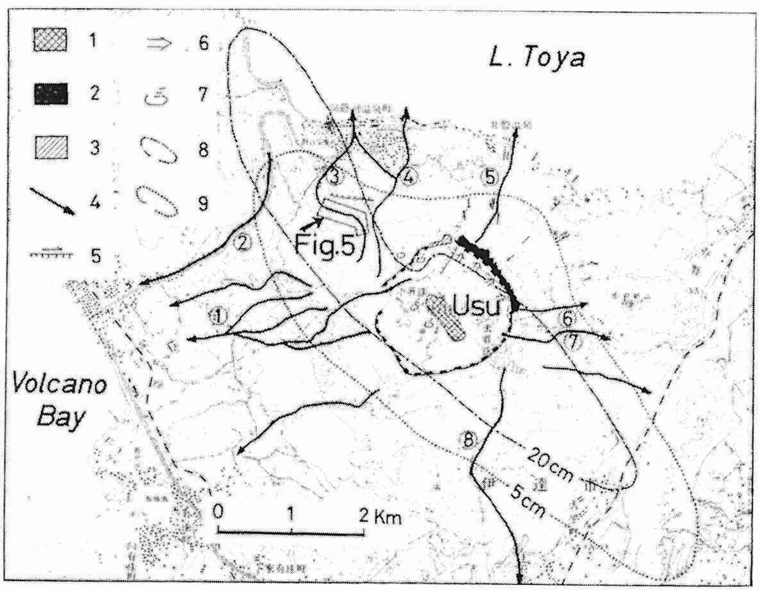


Fig. 3. Major geomorphic changes on Usu Volcano after the 1977 Eruption
1: Upheaved, 2: Slope failures due to crustal deformation, 3: "Tilled" due to earthquake vibration and crustal deformation, 4: Valleys where mudflow occurred, 5: Fault, 6: Horizontal displacement, 7: Fumarole, 8: Isopach of tephra deposited during pumice eruptions in August 1977, 9: Isopach of tephra produced by the Second Stage eruptions during November 1977-October 1978.

repeated earthquakes occurring beneath the volcano. These deformations producing a large volume of unstable sediments have continued even after the cease of the eruptive activities and progressively devastated the volcanic slopes, increasing the potential hazards from accelerated erosion and mass transport in the form of mud or rock debris flows.

Physical Characteristics of New Tephra

Composition

In the R. Nishiyama watershed falling within the northwest slope of the somma of Usu Volcano, one fall unit of big eruptions during August 1977 consists of coarser pyroclastics, i. e., pumice and lapilli, in the lower part, and ash in the upper part. The pumice, which is the most predominant essential ejecta, is hypersthene dacite (Katsui *et al.*, 1978). The ash consists of essential ejecta and montmorillonite clay derived from lake deposits in the summit atrio. In addition, fine ashes produced by phreato-magmatic eruptions during the Second Stage eruptive activities, covered earlier deposits of the new tephra with a depth of 2-3 cm or more.

Texture

A typical columnar section of the new tephra observed in August 1978 in the R. Nishiyama watershed is shown in Fig. 4. Two cycles of coarse and fine textural alternation can be found within the deposits of big eruptions. The new tephra is subdivided into four layers from the textural difference. Mean diameter of the 2nd and the 4th layers composed mainly of pumice is 4-5 mm (Fig. 4; Table. 2), while that of the 1st and the 3rd layers is 0.3-1 mm. The 1st layer contains 13% of silt and clay particles. The ash produced by the eruption of September 12/13, 1978 consists of 57% of silt and clay particles. Owing to the texture of these layers, solid phase ratio of the 1st and the 3rd layers is about 50% and that of the 2nd and the 4th layers is 34% and 40% respectively. Apparent and specific gravities are larger for the finer deposits than the coarser deposits consisting mainly of pumices (Table. 3).

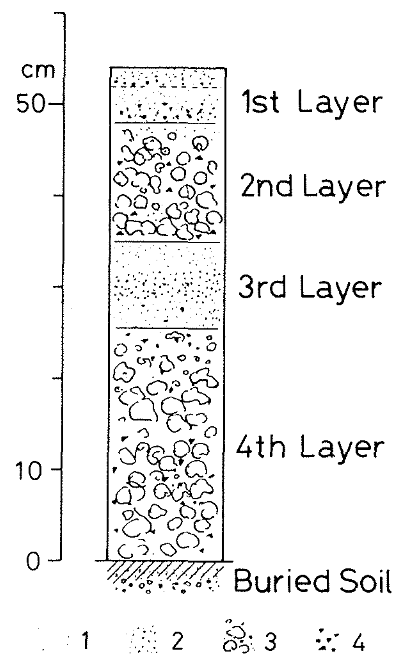


Fig. 4. A typical columnar section of new tephra on the experimental slope in the middle reaches of R. Nishiyama
1: Fine ash, 2: Volcanic sand, 3: Pumice, 4: Lapilli.

Infiltration Capacity

As mentioned earlier, the surface of hillslopes was covered with a cement mortar-like fine ash which fell with rain waters on August 8, 1977. Infiltration rate of this ash layer, which was measured on the flat land about 10 km northwest of Usu

Table 2. Grain size and consistency of new tephra and redistributed deposit

Materials	Grain Size					Consistency	
	No. of samples	Silt·clay % (<0.063 mm)	Sand % (0.063–2 mm)	Gravel % (2–64 mm)	Mean (mm)	No. of samples	Liquid limit W_L (V_L) %
New tephra 1st*	1	13	81	6	0.29	1	20.3 (25.4)
New tephra 2nd*	1	0.1	13	87	4.6		
New tephra 3rd*	1	0.1	73	27	1.1	1	18.3 (22.7)
New tephra 4th*	1	1	20	79	4.3		
New tephra fine ash**	1	57	42	—	0.095	1	20.0 (26.4)
Buried soil*	1	21	76	4	0.15	1	42.5 (31.5)
Talus deposit*	5	7	53	40	0.97	5	21.2 (24.0)
Mudflow deposit Aug.-early Sep. Main body	3	7	32	61	1.9	2	20.0 (17.6)
Sep. 26 Surface	5	0.2	1.2	98	16		
Sep. 26 Main body	5	7	37	57	1.2	5	25.0 (26.3)
Oct. 24 Surface	2	9	30	61	1.7		
Oct. 24 Main body	6	10	40	50	1.3		
Water-laid deposit	4	6	71	24	0.76		

* Sampled on October 13/14, 1978
** Produced by a magmatic eruption of September 12/13, 1978. Sampled on September 14, 1978

Table 3. Three-phase and specific gravity of new tephra and redistributed deposit

Materials	No. of Samples	Three-phase %			Porosity P %	Bulk density d_0	Specific gravity d	Remarks
		Air V_A	Solid V_S	Liquid V_L				
New tephra 1st*	9	33.9	49.9	16.0	50.1	1.21	2.42	Ash and sand
New tephra 1st**	6	28.8	51.0	20.3	49.0	1.32	2.60	Fine ash and sand
New tephra 2nd	11	48.9	34.3	16.9	65.7	0.70	1.87	Pumice and lapilli
New tephra 3rd	18	32.3	49.6	18.1	50.4	1.24	2.53	Ash and sand
New tephra 4th	7	41.5	40.6	17.9	59.4	0.80	1.98	Pumice and lapilli
Buried soil	10	41.9	29.9	28.2	70.1	0.74	2.47	A horizon
Talus deposit	5	28.9	48.7	22.4	51.3	1.13	2.31	
Mudflow deposit Aug.-early Sep. Main body	4	34.1	44.4	21.6	55.6	0.88	1.96	Small-scale, limited within valley
Sep. 26 Surface	5	50.0	29.2	20.9	70.8	0.47	1.61	Spread onto alluvial fan
Sep. 26 Main body	5	12.5	52.4	35.1	47.6	1.05	1.99	
Oct. 24 Surface	2	24.0	48.2	27.9	51.9	0.90	1.88	Spread onto alluvial fan and entered L. Toya
Oct. 24 Main body	5	19.7	54.6	25.7	45.4	1.20	2.20	
Water-laid deposit	4	11.6	58.7	29.7	41.3	1.52	2.58	

* Sampled from July to early September, 1978
** Sampled from mid-September to November, 1978, including fine ash produced by a magmatic eruption of September 12/13, 1978

Volcano on August 18/19, 1977, was as low as 0.78 mm/h in terms of basic intake rate (HNAES and HCAES 1978). However, with the lapse of time the surface layer gradually turned to porous due to such processes as rain splash, sheet erosion and infiltration runoff of soluble salts and finer materials. Soluble salts such as Na and Ca, abundant in the ash layer, were leached out rapidly.

For instance, at an experimental plot in the R. Nishiyama watershed, cumulative infiltration depth of surface layer for ten minutes was 41 mm on July 19, 1978, about 11 months after the deposition. But, fine ashes produced by the phreato-magmatic to magmatic eruptions during August-September 1978 resulted in drastic decrease of infiltration capacity again. Cumulative infiltration depths for ten minutes at the same plot were 2.9 mm on October 12/13, 1978 and 4.5 mm on July 7, 1979, showing long-continuing low infiltration capacity of the surface layer. This suggests that under the saturated condition surface runoff may occur when rainfall intensity exceeds 3-4 mm per ten minutes.

Changes during Winter-Spring

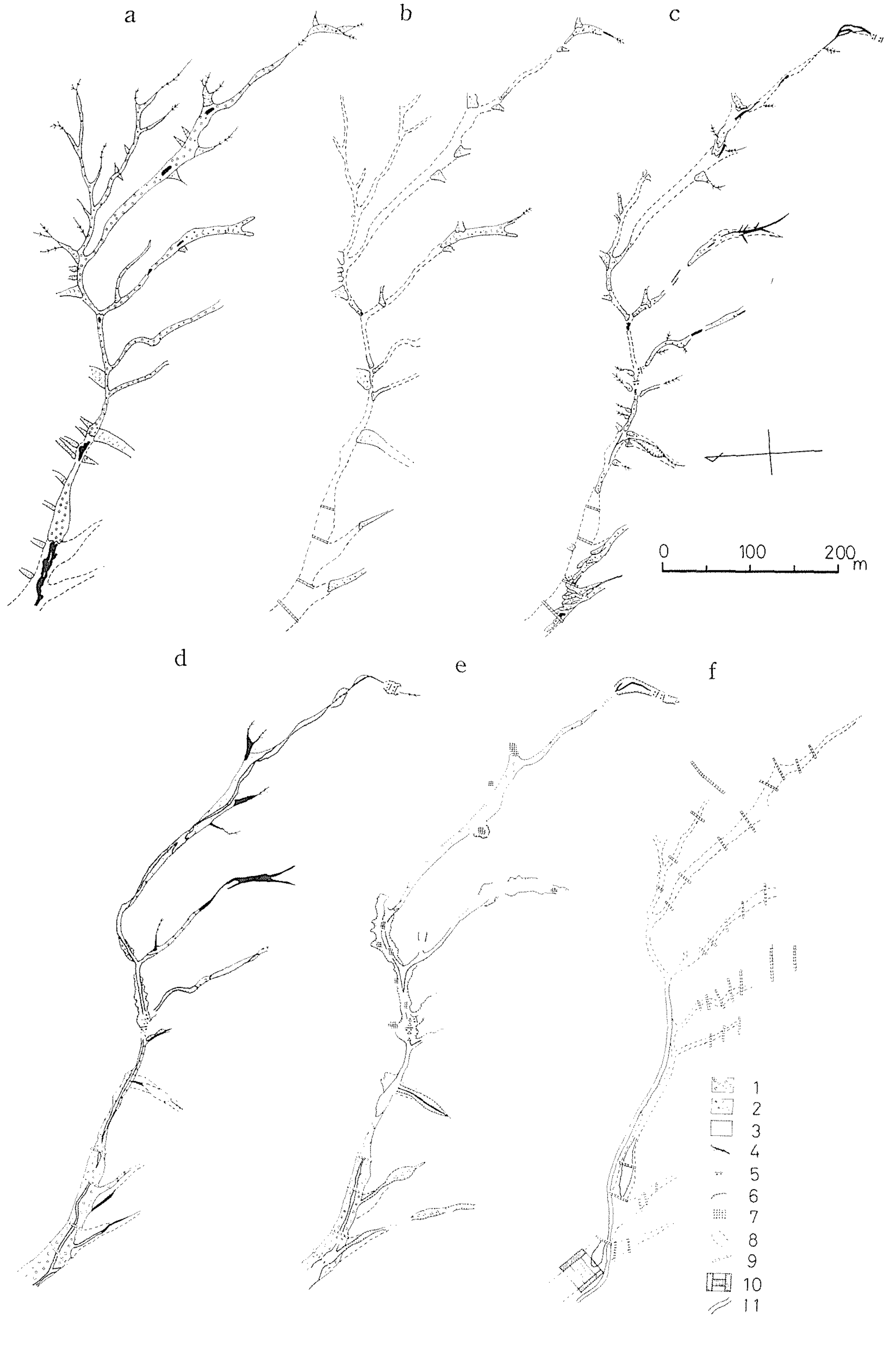
During two winter seasons from 1977 to 1979, the upper layer of new tephra freezed to the depth of 20-30 cm and an ice plate, 2-3 cm in thickness, was formed at the contact between snow cover and new tephra. This ice plate seemed to be formed by freezing of water supplied from thawing, since the upward movement of water within the pumiceous layer was unlikely. During the thawing period, the upper layer was almost in the condition of water saturated. However, no surface runoff appeared on the hillslopes except for on some of the lower slopes where melt water concentrated. The process of solifluction on the saturated layer was also limited, contrary to our expectations. Pumices, which experienced freeze-thaw alternation and exposed to the air after thawing, tended to disintegrate into sawdust-like fine fragments.

Erosion and Sediment Yield in the R. Nishiyama Watershed

Erosional processes operating in the new tephra-covered watershed of R. Nishiyama, which rises on the northwest slope of the somma of Usu Volcano, have been investigated by means of repeated observations, plane tablings, plot measurements and aerial photo interpretation, since late August 1977 (Kadomura *et al.*, 1978 b). Geomorphic changes occurred in the watershed have been mapped as shown in Fig. 5.

August-December 1977

Rapid erosion and redistribution of the new tephra began to proceed immediately after the deposition, due to rainfall and shock of repeated earthquakes. From the comparison of aerial photographs taken on August 23 and September 23, 1977, it was clarified that accumulation and removal of pumiceous deposits on most of tributaries and gullies running down from Mt. Nishiyama and Mt. Kompira occurred during the first month after the outbreak. We confirmed by a field survey of September 29 that most of rills, gullies, and talus and alluvial cones were already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formed before that day (Photos 4 and 5). On the upper slopes, especially on the narrow divide, thin (0.5-1 cm), hard crust was formed and Horton's "no erosion belt" was clearly observed everywhere. On the middle and lower parts of hillslopes with a slope of 30°, straight rills dissecting the surface layer of the new tephra were well-developed (Photo 4). Concentration of rills on the concave slopes in plane-profile led to the formation of gullies of 0.3-0.5 m wide and 0.3-0.5 m deep. Numerous talus cones were also formed in the lower steep slopes by the sediment derived from gullying. The volume of the sediment deposited in every talus cone, with a size of 5-15 m high and 0.3-0.5 m deep, was 3 to 20 m^3.

Diurnal rainfall as much as 20 to 50 mm occurred frequently from August to late September. It is considered that most of rills, gullies and talus cones which were found by the survey on September 29 were formed by these rainfalls. However, on the main valley floor with a gradient of 10°, no active sediment transport in the from of mass transport was observed until December 1977, except for a small-scale incision which was found intermittently at an interval of 50 to 150 m. Although remarkable erosion of pumiceous deposits was observed on the tributaries and on the hill-side slopes, the main valley was not yet covered with the considerable amount of sediment transported from the tributaries.

Due to snow cover, no changes of landsurface occurred during mid-December 1977 to late March 1978.

April-August 1978

Although some striking changes due to snow-melt and freeze-thaw alternation of the surface layer were at first expected, little changes occurred during and immediately after the thawing period. Immediately after the snow-melt, most of rills were made indistinct and were buried with removed pumiceous deposits. Since that time, the surface crust composed of fine-grained ashes became porous due to leaching of finer materials and soluble salts. This change led to the increase of infiltration capacity and contributed to the slow down of the rate of hillslope erosion and channel processes.

However, redeposited sediment on the tributaries repeated a short-distance advance during every rain after early June. A tongue-shaped front, which was characteristic of pumiceous flow (Photo 6), in one of the tributaries running down from Mt. Nishiyama, moved forwards for about 20 m during May 6 to July 16. Total amount of rainfall in this period was 217 mm, and maximum intensities for one hour and ten minutes were 22.0 mm and 13.5 mm respectively on July 12 (*see* Fig. 10). However, only a few talus cones were newly formed until July 16. In

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Fig. 5. Geomorphic changes in the valley of R. Nishiyama: August 1977-May 1979

Date of survey a: December 1, 1977; b: May 7, 1978; c: September 6, 1978; d: October 4, 1978; e: November 3, 1978; f: May 25, 1979, 1: Pumiceous mudflow deposit, 2: Talus cone, 3: Water-laid deposit, 4: Scouring of valley floor, 5: Nick point, 6: Slump, 7: Excavation of former ground surface, 8: Boundary of valley floor, 9: Sabo-dam, 10: Slit-dam, 11: Road.

correponding with the progress of the Second Stage eruptions which produced fine ashes, gully erosion and scouring of nickpoints along the main valley floor became active towards the end of August. Prior to September 6, pumiceous deposits from the two tributaries reached the floor of the main valley after moved 20-30 m as a small-scale mudflow. The sediment transported by each of such flows amounted 5 to 10 m^3. Small-scale talus cones were also developed in this period in the lower part of existing ones by the deposit issued from gullying.

Physical characteristics of mudflow deposits are summarized in Tables 2 and 3. Mudflow deposits, which first appeared in late August on the middle reaches of R. Nishiyama, were usually mantled with a porous pumiceous layer. The main body of mudflow deposits found in late August was also more porous and showed higher percentage of gravelly particles than succeeding mudflow deposits.

September-December 1978

The surface of hillslopes became impervious again by the deposition of ash produced by the eruption of September 12/13. On September 26, a mudflow was triggered and reached Toyako-onsen spa. This was the first mudflow spreading onto the alluvial fan. The amount of rainfall which is thought to be responsible for the occurrence of mudflow was very small, maximum hourly and ten minute rainfalls being 7.0 mm and 5.0 mm respectively on the middle reaches of R. Nishiyama (*see* Fig. 10). Geomorphic changes caused by this mudflow were surveyed along the main valley on October 4 (Fig. 5 d). On the valley plain and alluvial fan, the thickness of mudflow deposits was several ten centimeters. The deposits of mudflow were confusedly mixed with pumices and ashes and were capped by pumiceous layer (Photo 6). Undercutting of the new tephra at nickpoints of the main valley exposed the former valley fill composed of boulders and blocks of somma lava. Landslides of the upper layer of the new tephra were induced by scouring of basal slopes in some places.

Both on October 16 and 24, a large-scale mudflow occurred in the valley of R. Nishiyama, and spread onto the alluvial fan together with that issued from R. Ko-Usu, reaching Lake Toya and causing severe disasters to the spa town. The aspects of the destructive mudflow will be described in detail in later chapter. Geomorphic changes caused in the valley of R. Nishiyama by these two events have been mapped as shown in Fig. 5 e. From this map following changes may be pointed out:

On the upper and middle reaches, undercutting of the valley floor advanced upstream and a number of landslides occurred on the valley side-slopes. Former soils and boulders of somma lava, which were once buried by the deposits of the new tephra, were exposed on the bottom of gullies and tributaries in many parts. Sediments composing mudflows were supplied not only from the main valley floor but from hill-side slopes and gullies.

Mean diameter of mudflow deposits sampled from middle reaches to lake shore showed little change and was ranging from 0.8 to 4.6 mm (Tables 2 and 3). Percentage of finer materials smaller than silt size increased towards the lake shore. Specific gravity of the deposits was fixed within the range from 2.13 to 2.35, and almost equaled to that of the four layers of new tephra covering hillslopes. This may indicate that the mudflow went down to the alluvial fan without sorting of its composing materials. The volume of sediment deposited on the valley floor and alluvial fan is summarized in Table 4. Most of the sediment flowed out as a mudflow was derived from the upstream of the barrier dam No. 2.

No marked changes were recorded during late October to mid-December, and the snow cover avoided the surface processes until late March, 1979.

Table 4. Mudflow deposit of October 24, 1978 on a compound alluvial fan at Toyako-onsen spa

River	Volume (m^3)
Nishiyama	83,000
Ko-Usu	23,000
Zennikku-higashinosawa	14,000
Total	120,000

April-December 1979

During November 1978 to April 1979, 36 sabo-dams and debris barriers were constructed on the valley of R. Nishiyama. This has led to the slow down of the sediment transport and no mudflows, which could overflow a sabo-dam, occurred during this period. The considerable decrease in movable sediment as a result of large-scale mudflows occurred in autumn 1978, also seems to keep the sediment from a mass transport.

Destructive Mudflows of October 24, 1978

On October 24, 1978, large-scale mudflows were triggered in several valleys on the north and west slopes of Usu Volcano by a localized downpour (Kadomura *et al.*, 1979). Preceding seven days were mostly rainy (Fig. 10) and the total rainfall during these days amounted 30–40 mm. In addition, 20–30 mm of rain fell in the morning of October 24 and this rainfall triggered smale-scale mudflows in some valleys on the east and southwest slopes of the volcano (Fig. 1). Although rain once stopped in the afternoon, unstable atmospheric conditions continued through night because a cold front accompanying a group of strong convectional clouds was approaching from the west to Southwest Hokkaido.

Based on an analysis of a radar echo at Hakodate Marine Observatory at 21:00 JST, one of strong convectional cells with a height of 10,300 m and located at 30 km west-southwest of Usu Volcano seemed to proceed to the volcano at a speed of 60 km/h and to bring about a very localized thunderstorm (Fig. 6). The recorded maximum hourly rainfall on the north slope was 24.5 mm from 21:00 to 22:00 JST and the maximum intensity for ten minutes reached 21.0 mm from 21:25 to 21:35 (Fig. 7). As shown in Fig. 6, the area stricken by this downpour was limited to the west and north slopes.

Such an extreme downpour inevitably triggered large-scale mudflows in the valleys on the north and west slopes, namely R. Itaya, R. Nishiyama, R. Ko-Usu, and R. Sobetsu-onsen. Coupled to the concentration of overland flow facilitated by the high intensity of rainfall over impermeable, fine-grained ash-covered hill

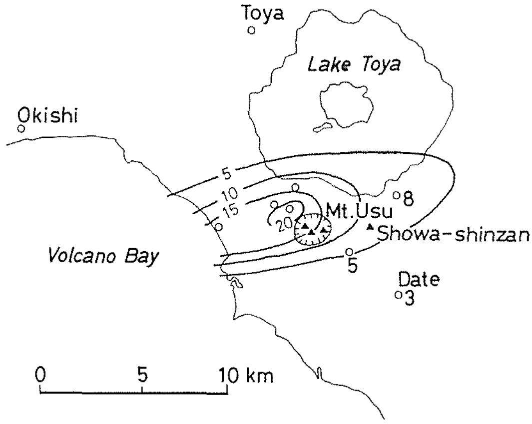

Fig. 6. Distribution of one-hour rainfall from 21:00 to 22:00 JST, October 24, 1978

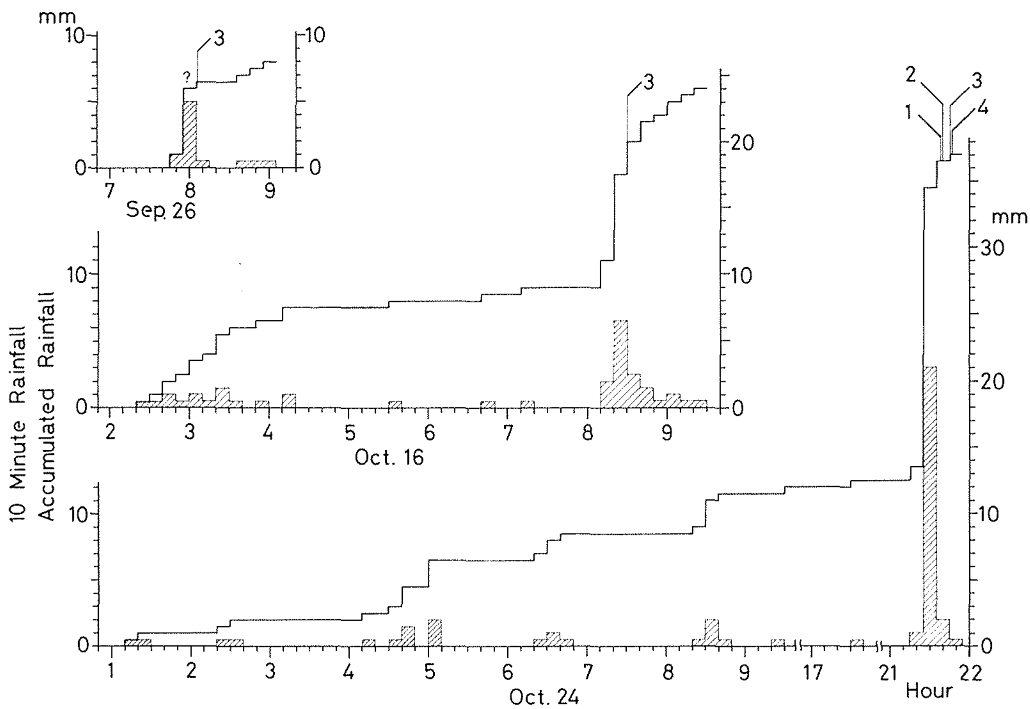

Fig. 7. Rainfall and the occurrence of mudflows of September 26 and October 16 and 24, 1978

Time of triggering for 1: R. Sobetsu-onsen; 2: R. Itaya; 3: R. Nishiyama, 4: R. Ko-Usu.

slopes, unstable sediments consisting mainly of redistributed tephra and well-saturated by the antecedent rains, would had contributed to the occurrence of large-scale mudflows. The torrent of floods removed not only the newly deposited tephra but also the former deposits containing large boulders of lava, by scouring valley floors and

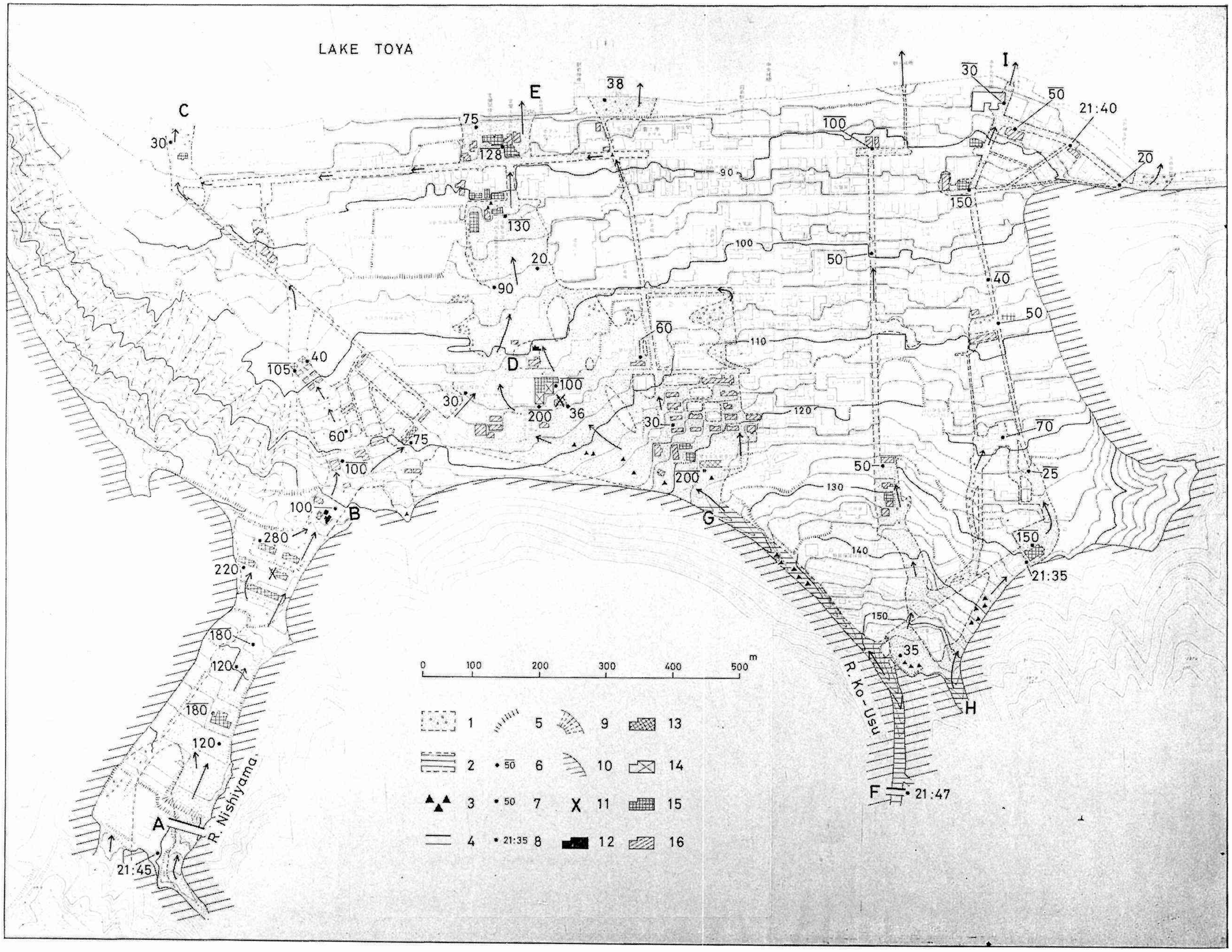

Fig. 8. Spread of muflows of October 24, 1978 on a compound alluvial fan at Toyako-onsen spa, with resulting damage

1: Deposition, 2: Scouring, 3: Boulders, 4: Sabo-dam, 5: Artificial cliff, 6: Depth of flood in cm, 7: Depth of deposit in cm, 8: Passing time of mudflow front, 9: Foot slopes, 10: Steep slopes, 11: Houses in which persons were killed or lost, 12: Completely destroyed houses, 13: Partially destroyed houses, 14: Slightly damaged houses, 15: Inundated above the floor-level, 16: Inundated below the floor-level.

undermining hill-side slopes; thus mud or rock debris flows grew downwards and attacked alluvial fans and/or valley plains with a destructive force. In most of valleys, mud or rock debris flows occurred between 21:35 and 21:47 JST, within about 10 minutes after the end of the highest intensity of rainfall (Fig. 7).

Toyako-Onsen Spa

Although a few check dams were already installed on the middle reaches of R. Nishiyama and R. Ko-Usu, they were filled up and overtopped by the flood of mudflows. According to the report by a fireman who was in charge of watching the occurrence of a mudflow at dam site A of R. Nishiyama (*see* Fig. 8), "It was at 21:45 when a surge of mudflow rushed down with a height of about 2 m and overtopped the dam with a great velocity and making a loud noise." "Downstream from the dam, the mudflow swept down in successive waves like ocean waves." The spread of mudflows and resulting disasters on the Toyako-onsen alluvial fan are mapped as shown in Fig. 8.

Toyako-onsen Spa, located on a compound alluvial fan of R. Nishiyama and R. Ko-Usu, was swept by the violent mudflows issued from the two valleys (Photos 7–10). Because there was neither natural stream nor discharge channel on this alluvial fan, muddy waters preceded the mudflow run off over road across contours. The behaviour of mudflow was also controlled by the network of roads, but it was largely modified by the distribution of micro-landforms and artificial structures. Hence, the velocity varied in time and space. According to eyewitness's account, the maximum velocity of mudflow was 30–40 km/h, i. e., c. 10 m/sec. Maximum depth of the flow exceeded 2 m on the valley plain and the upper part of alluvial fan. Peak discharge of the mudflow at R. Nishiyama valley plain was estimated at 115 m^3/sec (Yamaoka *et al.*, 1979). The main body of mass transport continued for 15 to 20 minutes, and was followed by muddy waters. Sediment transported from the valley of R. Nishiyama was composed mainly of the new tephra, mixed deposits of ashes and pumices, while on the traces of mudflow issued from R. Ko-Usu a lot of rock debris scattered, particularly on the upper part of the fan (Photo 10; Fig. 8).

The total area covered by mudflow deposits was 0.266 km^2, the total volume being estimated at 120,000 m^3 (Table 4). The specific sediment yield reached to over 126,000 m^3/km^2 for R. Nishiyama and 81,000 m^3/km^2 for R. Ko-Usu. These values are almost equivalent to the past maximum of specific sediment yield in Japan produced by a large-scale mud or rock debris flow due to an extreme downpour. Previous data have revealed that a large amount of sediment yield on the order of 100,000 m^3/km^2 was mainly reported from volcanic terrain.

The main losses caused by the mudflows of October 24 are as follows: 2 killed, 1 missing, 2 wounded 4 completely destroyed houses, 21 partially destroyed houses, and more than 100 inundated houses. Total number of sufferers reached 345, about 10% of the whole population of the spa town. It was said that some 15 vehicles were swept down by the mudflows, but no available data were obtained for this.

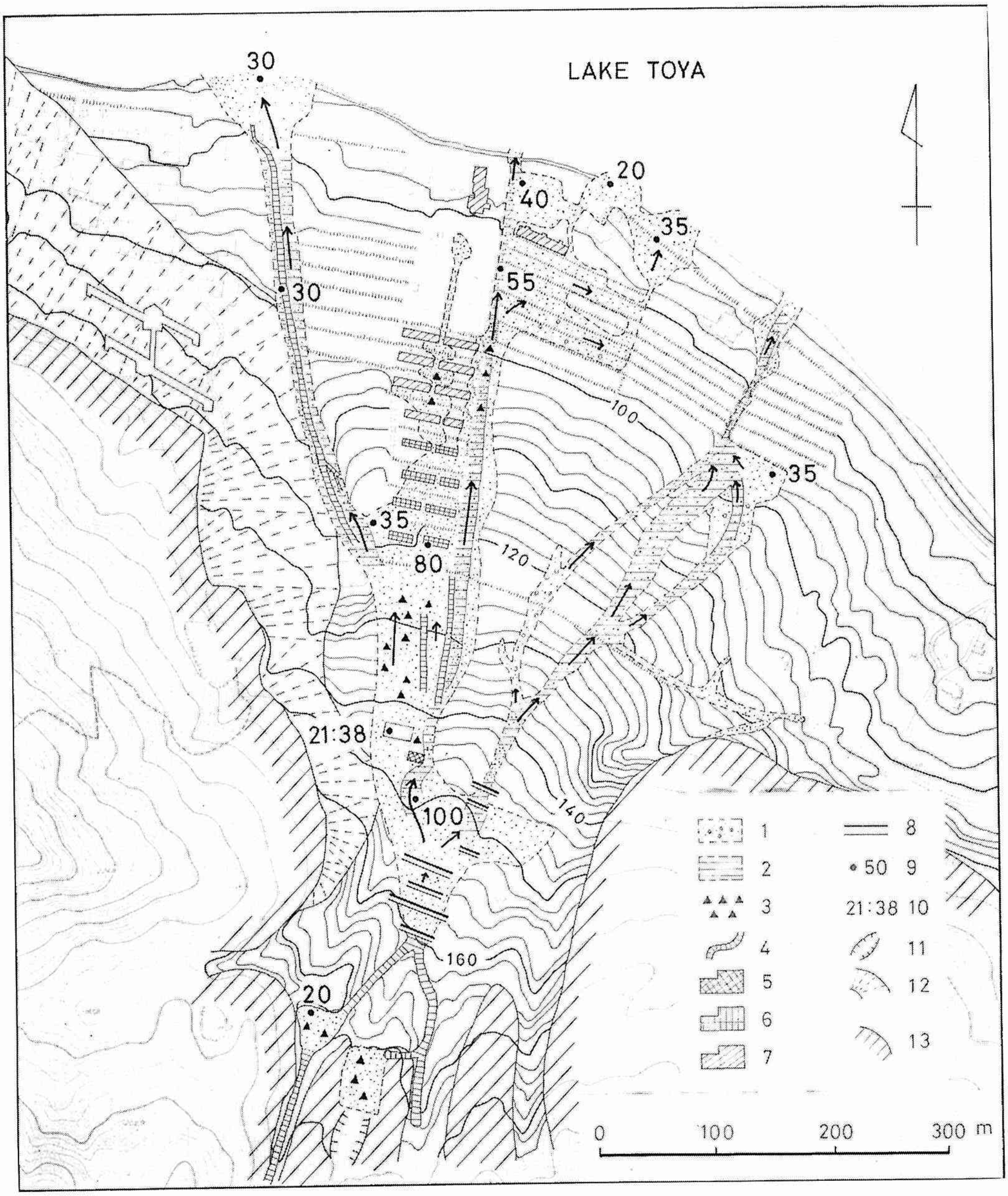

Fig. 9. Spread of mudflows of October 24, 1978 on an alluvial fan at Sobetsu-onsen spa, with resulting damage

1: Deposition, 2: Scouring, 3: Boulders, 4: Gully, 5: Partially destroyed houses, 6: Inundated above the floor-level, 7: Inundated below the floor-level, 8: Sabo-dam, 9: Depth of deposit in cm, 10: Passing time of mudflow front, 11: Landslide, 12: Foot slopes, 13: Steep slopes.

In spite of large-scale mudflows, destructive disasters such as the loss of human life and the destruction of houses and buildings were, fortunately, relatively small. This partly depends on the nature of the mudflows consisting mainly of pumices of low specific gravity ($d=2.0-2.2$) (Table 3) and ashes, and containing no large number of boulders. Although mudflows were able to penetrate into wooden houses, in case of reinforced concrete buildings they could only invade through windows. Timely evacuation to upstairs rooms and appointed refuges based on the order issued immediately before the occurrence of mudflows was also seemed to contribute to minimize the loss of human life. In addtion, it is probable that the experience of the mudflow which spread onto the alluvial fan on October 16, 1978, with less destructive force, as well as a training of evacuation from a supposed mudflow attack carried out on October 10, were effectively utilized by the inhabitants to take emergency self-countermeasures.

Sobetsu-onsen Spa

On October 24, 1978, an alluvial fan on which Sobetsu-onsen spa is situated was also attacked by violent mud and rock debris flows issued from small rivers rising on the north slope of the somma (Fig. 9; Photo 11). According to the record of the Usu Volcano Observatory of Hokkaido University, located just on the apex of alluvial fan, it was attacked by a series of mud and rock debris flows from 21:38 to 21:53 JST. Debris transported onto the alluvial fan were mainly older ejecta like the pumice produced by the 1663 Eruption and boulders of lava composing the somma, all of which were derived from scouring of valley fills and side-slopes.

The total volume of sediment deposited on the alluvial fan was estimated at 26,000 m^3. One house was partially destroyed by the debris flow at the apex, and 21 houses were flooded by the mudflow on the middle to lower part of the fan (Fig. 9).

Sequence and Spatial Variation of Mudflows

General Sequence

Figure 10 shows the sequence of eruptive activities and the occurrence of mudflows during August 1977 to November 1979 in the valleys around Usu Volcano. During this period, most of valleys around the volcano have experienced mud or rock debris flows (rain lahars) and the total number of the occurred mudflows reached 86, among which 29 flowed out from the valley and spread onto the piedmont alluvial fans.

Generally speaking, mudflows seem to occur in close relation to the progress of eruptive activities producing impermeable but erodible ejecta and the seasonal march of rainfall. The occurrence of a large-scale mudflow concentrated to the periods during mid-August to late September 1977, and late September to late October 1978. The former corresponds to the period immediately after the big pumice eruptions of the First Stage and the latter the culmination of the Second

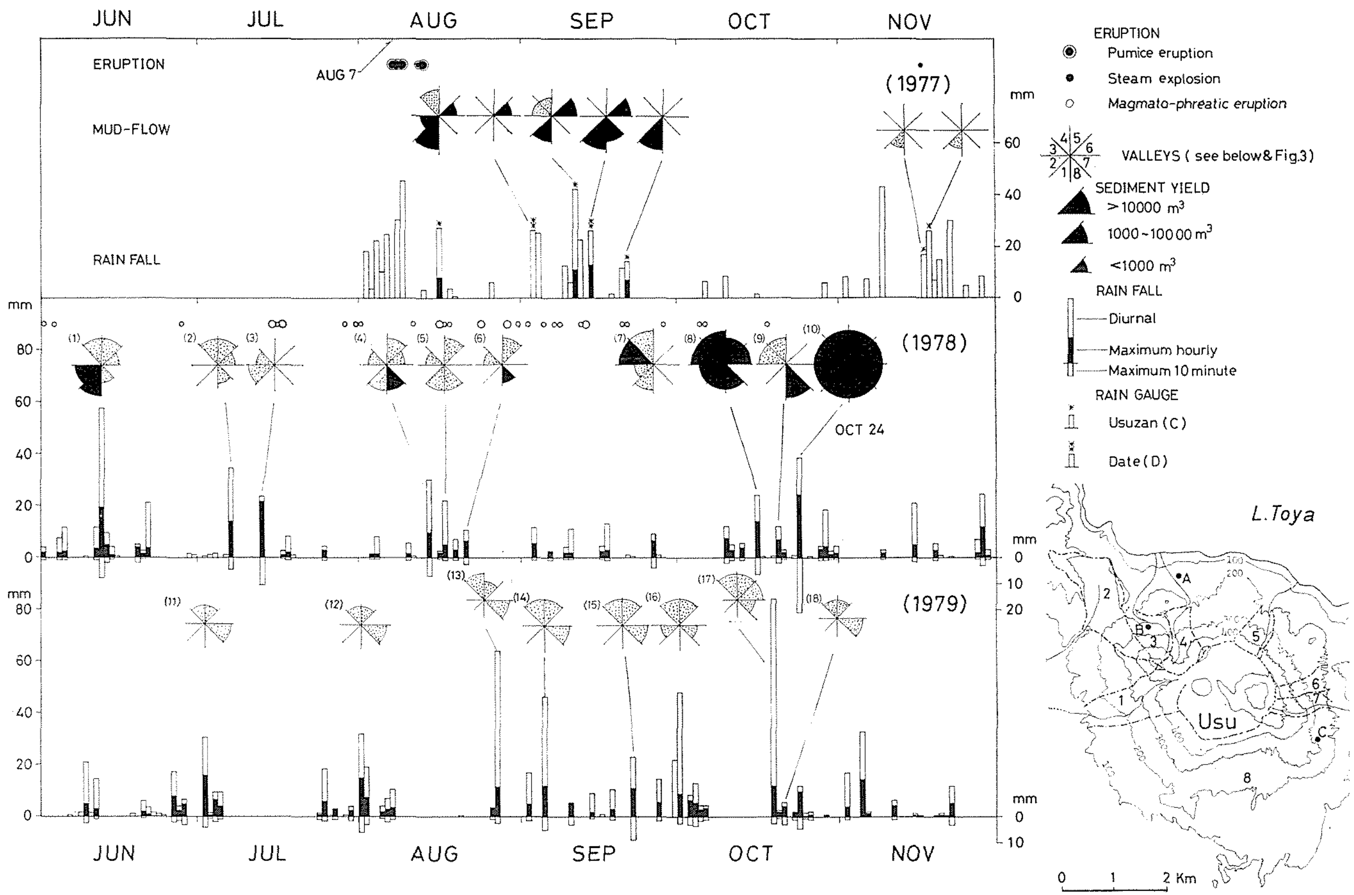

Fig. 10. Sequence of 1977–1978 Eruption and mudflow occurrence.

Rainfall data at Toyako-onsen Fire Station (A) for 1977 and at Nishiyama Gauge (B) for 1978–1979. Dotted symbol for sediment yield indicates a mass transport which did not flow out from a valley.

Stage eruptions. In particular, large-scale mudflows which could spread onto the alluvial fans occurred for all of the valleys during October 1978.

Intensive erosion control works aiming at preventing accelerated erosion and the occurrence of mud and/or rock debris flows have been carried out immediately after the outbreak of the 1977–1978 eruption. The construction of sabo-dams, debris barriers, hill-side fences and discharge channels has been accelerated for most of the valleys after the destructive mudflows of October 24, 1978. Such rapid progress made in erosion control works and artificial removal of unstable sediment from the valley bottoms are thought to be effective to check the occurrence of a large-scale mass transport. This may be one of the main reasons why during 1979 the sediment transport in the form of mudflow was limited to the valley bottoms and no mudflows spread onto the piedmont areas.

Spatial Variation

As shown in Fig. 10, the mudflow occurrence also varies from one valley to the other in terms of its time, scale and composing materials. As long as the mudflows which happened during August 1977 to October 1979, it seems probable that the variations in time and space seen in the mudflow occurrence relate to the spatial difference of the nature and depth of the new tephra, the mode of crustal deformations and rainfall patterns. The aspects of erosion and the occurrence of mudflows for each of the watersheds shown in Fig. 10 may be outlined as follows:

1) R. Izuminosawa: Although the thickness of the new tephra exceeded 1 m on the uppermost reaches, only a few centimeters thick ash fell on the lower reaches. From mid-August 1977, immediately after the First Stage eruption, to October 1978, large-scale rocky mudflows composed of a lot of rock debris derived from scouring of the former valley fills, occurred repeatedly and spread onto the alluvial fan, even on an occasion of light rainfall. Particularly, a large-scale debris flow ranging from 10,000 to 30,000 m^3 occurred four times during 50 days from mid-August to late September and the total amount of sediment produced by these four flows reached 68,500 m^3. Large-scale debris flows also occurred intermittently during 1978 (Photo 12). However, sediment yield has decreased with time, no mass transport being recorded during 1979.

2) R. Itaya: The upper reaches of this river were covered with new tephra of 30–50 cm deep, resulting in denuded hillslopes. Active sediment yield was found only during 1978, particularly in October. A lot of rock debris were produced by scouring of valley floor of tributaries, but they could only reach the main valley and the mudflow went down further downstream was composed mainly of the new tephra. No mass transport was observed during 1979.

3) R. Nishiyama (Photo 13) and 4) R. Ko-Usu (Photo 14): As mentioned in previous section, the upper and middle reaches of these rivers were covered with the thick deposits of the new tephra. Forest vegetation on the upper reaches was destroyed to a considerable degree. The new tephra covering hillslopes has been actively eroded by rills and gullies since its deposition and removed sediment has been stored as talus cones and valley fills. However, no large-scale mass trans-

port was recognized during 1977. In the following year, 1978, unstable sediment on the main valleys gradually advanced downstream, with the seasonal march of rainfall as well as the progress of the Second Stage eruptions producing fine, impermeable ashes. At length, a large-scale mudflow yielding the sediment on the order of 10,000–100,000 m^3 was triggered two times, on October 16 and 24, 1978. The main materials composing mudflows were derived from the deposits of new tephra.

It was calm during November 1978 to December 1979 and the occurrence of mass transport was limited in scale, time and space. In the valley of R. Ko-Usu, the sediment was removed in the form of a small-scale mudflow eight times, but its flow was used to be checked by the sabo-dams which were constructed at the mouth of the valley.

5) R. Sobetsu-onsen : This river rises on the northeast slope of the somma, on which only a few centimeters thick tephra fell. No mudflows were recorded during 1977, but since June 1978, with the progress of deformation of the upper slopes of the somma, the occurrence of mudflow has become frequent. A large-scale mudflow on the order of 10,000 m^3 occurred on October 24, 1978. The sediment consists mainly of older ejecta such as pumice produced by the 1663 Eruption and boulders of somma lava. Although the spread of a mudflow onto the alluvial fan was checked by the sabo-dams, during 1979 mudflows were triggered repeatedly by almost every rain (Photo 15). It may well be said that the potential of a large-scale mudflow would be continuously increased, as the deformation of upper slopes of the somma seems to proceed with time.

6) R. Showa-Shinzan and 7) R. O-Usu : The fall of new tephra was 10–50 cm on the upper reaches of both rivers. However, immediately after the First Stage eruption and during June to August 1978, the occurrence of a small-scale mudflow was concentrated in the valley of R. Showa-Shizan. The mudflow of October 24, 1978 was the largest in terms of sediment yield as in other rivers. No remarkable events happened during 1979.

On the contrary, in the valley of R. O-Usu, no marked changes were observed until the end of October, 1978, when a large-scale debris flow on the order of 10,000 m^3 occurred. However, with the lapse of time, eastward thrust of the somma has led to the frequent landslidings on the middle reaches of the river, producing a number of boulders and blocks of lava. This river, during 1979, has been most active in terms of frequency in the occurrence of mass transport and yielding rock debris, than any other river around Usu Volcano (Photo 16). The tendency of erosion and sediment yield seems to be continued as time goes on.

8) Several rivers rising on the south slope of the somma : In this section, most of rivers were most active during 1978, as in the case of R. Nishiyama. The sediment contained a large quantity of rock debris. No mass transport was recorded during 1979.

Rainfall Triggering a Mudflow

It is usually difficult to determine the critical rainfall triggering a mudflow, because the exact time of triggering and the rainfall data at the point very close to the watershed concerned can rarely be obtained. In the case of the area studied, until May 1978, no rain gauges, which were able to catch a localized downpour, were installed in the watershed experienced mud or rock debris flows. The rainfall data during 1977 which are shown in Fig. 10 are based mainly on the observations on the northern and eastern piedmont areas, 1 to 2 km apart from the rim of the somma. Therefore, these data should only be used for approximating the amount and intensity of rainfall which might be related to the occurrence of a mudflow.

Since early May 1978, rainfall has been continuously observed on the middle reaches of R. Nishiyama, by a rain gauge installed by our laboratory. An analysis of critical rainfall has been made using these data, leading to a tentative conclusion: As long as 18 mudflows which occurred during June 1978 to October 1979, critical rainfalls triggering a mass transport or a mudflow are more than 20 mm for continuous rainfall, more than 9 mm for one hour-rainfall and more than 2–3 mm for ten minute-rainfall. Thirteen cases meet all these critical values and the remains only one of them.

These values are almost comparable with those obtained at the other Japanese active volcanoes such as Mt. Yakedake and Sakurajima (Yamauchi, 1978) which have experienced frequent mud and rock debris flows in keeping with the eruptive activities. As has been revealed from these data, it should be emphasized that in the valleys of an active volcano, the slopes of which are devastated due both to the deposits of tephra and land deformations, a large-scale mud or rock debris flow tends to occur even by an ordinary rainfall. When an extremely high intensity of rain fell, as in the case of the mudflow of October 24, 1978 at Usu Volcano, an extraordinarily large-scale mudflow on the order of 100,000 m^3 has sometimes occurred.

Summary and Conclusion

The latest eruption of Usu Volcano during the period August 1977 to October 1978 produced a large quantity of pumices and ashes. The fall of the new tephra resulted in extremely denuded slopes which have been exposed to accelerated erosion, particularly on the summit domes and the upper slopes of the somma. The fine ashes deposited during a rainy weather of August 8, 1977 and those produced by the phreato-magmatic eruptions during July to September 1978, led to the drastic drop in infiltration capacity, contributing to the increase of overland flow. Moreover, the rise of subsurface magma body has caused domings in the summit atrio and northeastward dislocation of the somma. Such deformations accompanied by faultings and landslidings have also accelerated the devastation of upper slopes of east to north-facing somma wall.

Under these conditions, in most of all valleys around the volcano, rain-triggered mud or rock debris flows (rain lahars) have been caused repeatedly even by a light rain, and a total of 86 mudflows have already occurred until the end of October

1979. Out of 86 mudflows, 29 flowed out from the valleys and spread onto the piedmont alluvial fans. The minimum amounts of rainfall triggering a mudflow were 20 mm for continuous rain, 9 mm for one-hour intensity and 2–3 mm for ten-minute intensity, as long as 18 mudflows happened during 1978–1979.

An extreme downpour with the intensity of 21 mm/10 min., which fell on the night of October 24, 1978, triggered large-scale mudflows yielding the sediment on the order of 10,000–100,000 m^3 in most of valleys on the west to north slopes of the volcano, causing severe disasters to the spa towns. After this event, intensive erosion control works have been undertaken for most of valleys. As a result, the occurrence of mudflows has decreased through time in most of valleys. However, in the valleys on the north to east slopes of the somma, the occurrence of rocky mudflows has become more frequent towards the latter half of 1979, with the progress of crustal deformations associated with the rise of subsurface magma. It should be noted that the continuous doming in the summit atrio accompanying the northeastward thrust of the somma has provided the conditions favouring accelerated erosion and the occurrence of a large-scale mass transport in those valleys.

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Throughout this research, we have drown upon the help of many people and institutions. Among many institutions and individuals, we are particularly grateful to the following: Special Bureau for Arranging Countermeaures to Cope with Usu Volcano Disasters and Toya Branch, Muroran Division of Public Works, Hokkaido Government, and Town Offices of Abuta-cho and Sobetsu-cho, for providing relevant data; Prof. I. Yamaoka, Department of Civil Engineering, Hokkaido University, Prof. S. Higashi and Prof. T. Araya, Department of Forestry, Hokkaido University, Prof. I. Yokoyama, Department of Geophysics, Hokkaido University, Prof. Y. Katsui and Dr. K. Niida, Department of Geology and Mineralogy, Hokkaido University, Prof. S. Okuda, Institute for Disaster Prevention, Kyoto University, Prof. I. Moriya, Department of Geography, Kanazawa University and Mr. H. Yamagishi, Geological Survey of Hokkaido, for giving us useful materials and comments; Usu Volcano Observatory, Hokkaido University, for their kind cooperation during field work; Mr. M. Hanaoka and Mr. N. Takahashi, for drawing maps and diagrams.

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Summary

This paper describes the aspects and sequences of erosion and mudflows (rain lahars) at Usu Volcano after the burst of the 1977–1978 Eruption, on the basis of field work carried out by the authors from August 1977 to December 1979. An event of destructive mudflows of October 24, 1978, which were triggered by a downpour, is also mentioned.

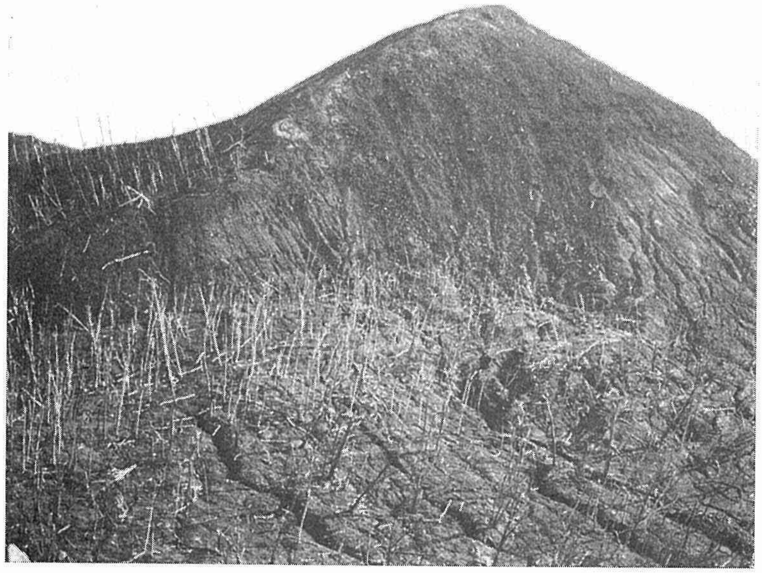

Photo 1. Forest vegetation in the summit atrio was completely destroyed by air-fall pumices and volcanic blocks and bombs ejected during the First Stage eruption in August 1977. Backing hill is a New Mountain (cryptodome) upheaved due to the rise of subsurface magma body underneath the atrio, accumulated upheaval reaching 120 m up to July 1979.
November 3, 1979. Photo by T. Imagawa.

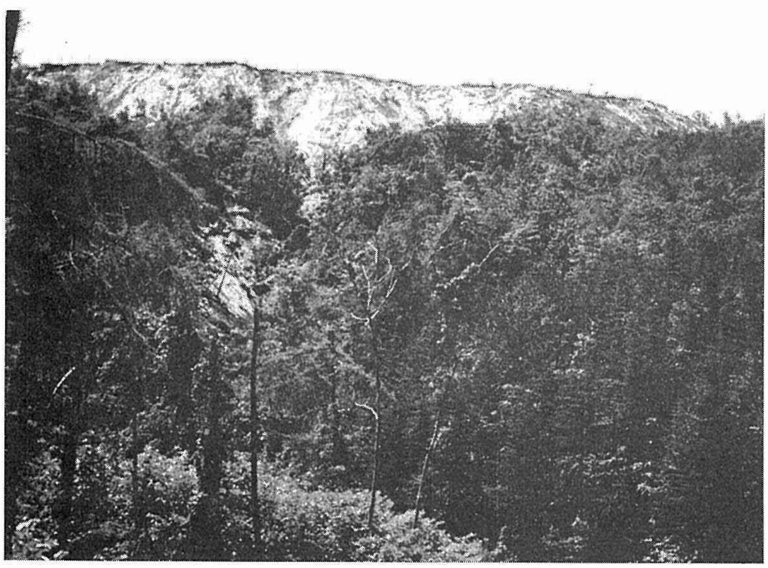

Photo 2. Northeastward thrust of the somma resulted in extremely deformed and devastated upper slopes of the somma. View from north. Landslide and rockfall have been accelerated due to over-steepening and faulting but also the shock of repeated earthquakes.
July 16, 1979. Photo by H. Kadomura.

Photo 3. Close up of deformed uppermost slope of the northern somma. On the right are Toyako-onsen spa and Lake Toya.
June 17, 1979. Photo by T. Imagawa.

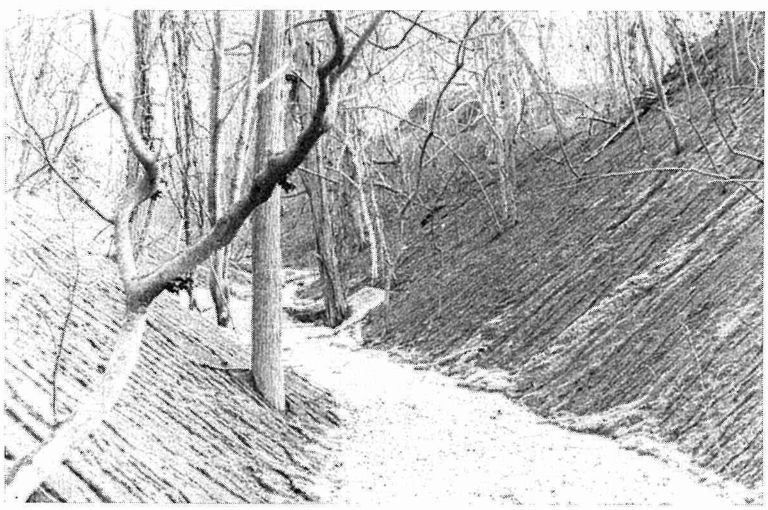

Photo 4. Forest damaged by air-fall tephra with a thickness of c. 60 cm, in the watershed of R. Nishiyama. Rills were rapidly developed on the new tephra-covered slopes immediately after the deposition. Some talus cones were found and the valley floor was buried by redeposited pumices.
September 29, 1977. Photo by R. Suzuki.

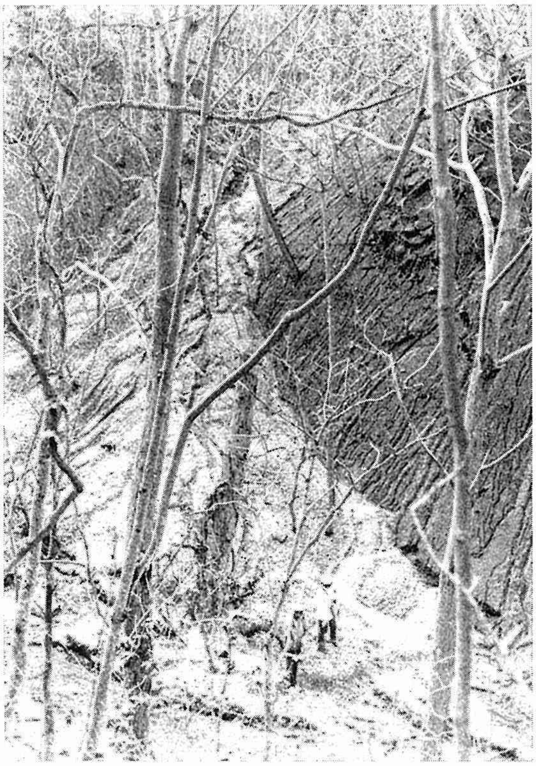

Photo 5. Alluvial cones consisting mainly of redistributed pumices were also formed here and there in the watershed of R. Nishiyamn. Note marks of miniature mudflows with levees and tongue-shaped front. *September 29, 1977. Photo by R. Suzuki.*

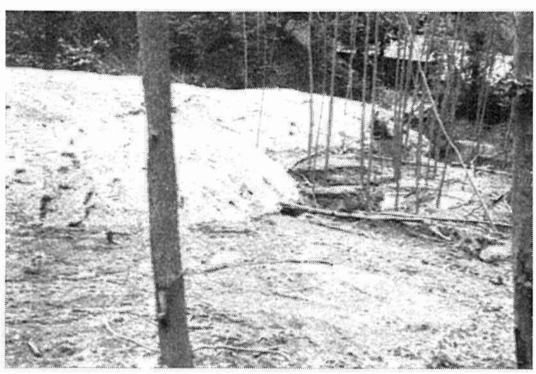

Photo 6. Tongue-shaped front of pumiceous flow issued from a tributary reached the main valley floor of R. Nishiyama in late August 1978. *26 August, 1978. Photo by H. Kadomura.*

Photo 7. Trace of the mudflow of October 24, 1978, in the valley plain of R. Nishiyama. The mudflow went over a sabo-dam and attacked the filtration plant in the middle and apartment houses in the distant view, with a depth of more than 2 m. Broken roof of a D-shaped hut in the foreground was caused by deposition of the 1977 tephra about 50 cm in deep.
October 26, 1978. Curtesy Publicity Section of Hokkaido Government.

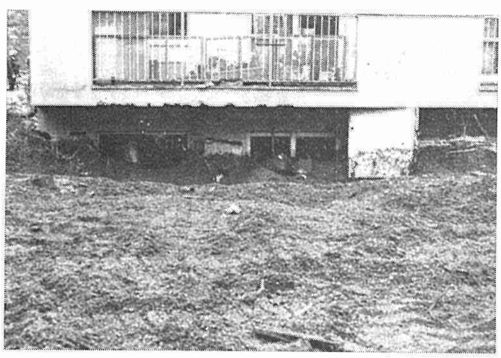

Photo 8. The ground floor of a three-storied apartment house, which is seen in the rearmost right in Photo 7, was penetrated and completely buried by the mudflow of new tephra with a depth of more than 2.5 m.
October 26, 1978. Photo by K. Arai.

Photo 9. A wooden house almost completely destroyed by the mudflow of October 24, 1978, near the apex of R. Nishiyama alluvial fan.
October 26, 1978. Photo by H. Kadomura.

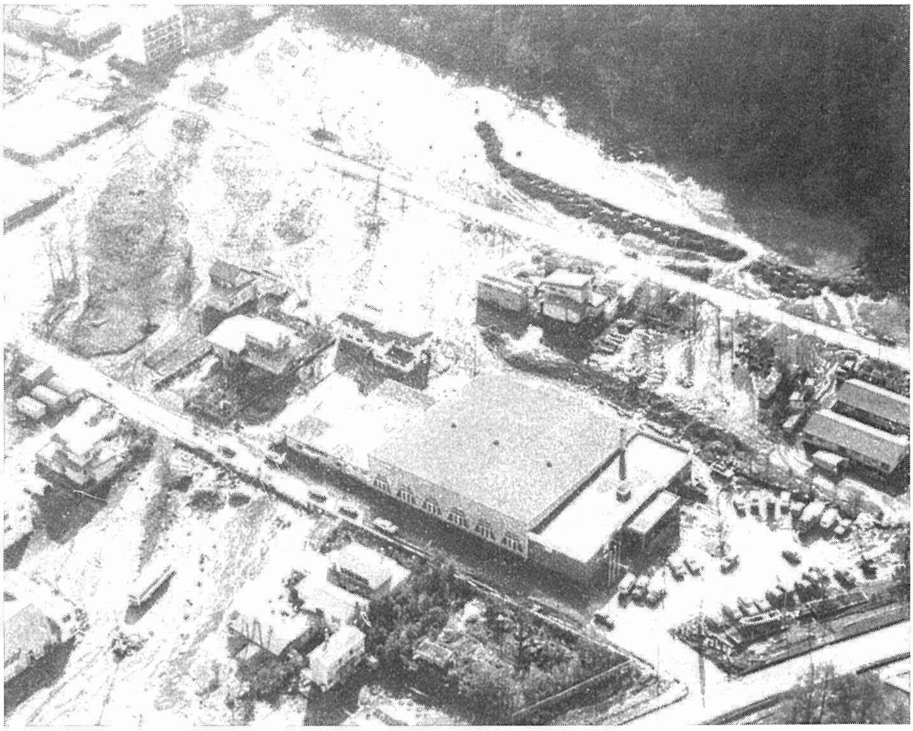

Photo 10. Spread of the destructive mudflow of October 24, 1978 issued from the valley of R. Ko-Usu. View from north-northwest. From the ground floor of a two-storied wooden house in the center of photograph, three persons were swept away, with one missing. *October 26, 1978. Curtesy Publicity Section of Hokkaido Government.*

Photo 11. Trace of the rocky mudflow of October 24, 1978 on the upper part of alluvial fan of Sobetsu-onsen. Most of houses in the upper right were inundated by the flood of mud. *October 25, 1978. Curtesy Disaster and Fire Prevention Section of Hokkaido Government.*

Photo 12. Boulders of lava which were derived from scouring of former valley fill in the upstream spread onto an alluvial fan of R. Izuminosawa, southwest foot of the volcano. *October 26, 1978. Curtesy of Publicity Section of Hokkaido Government.*

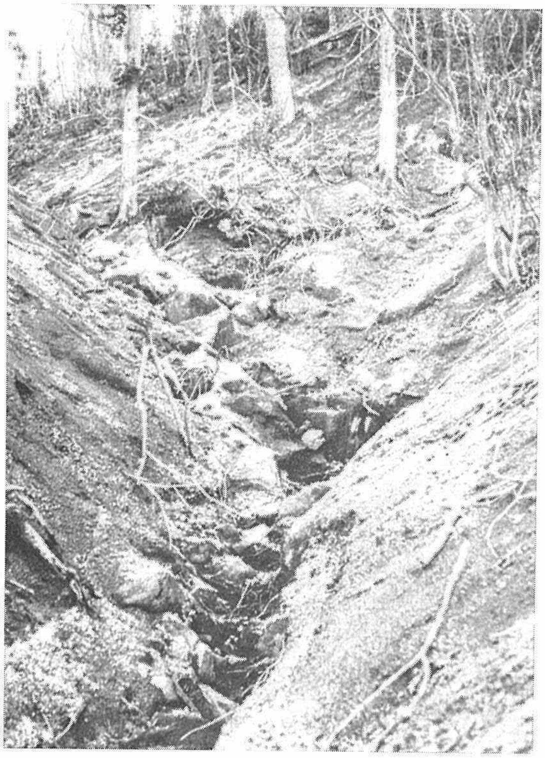

Photo 13. Exhumation of former valley fill resulting from removal of new tephra, on the upper reaches of R. Nishiyama. Only some herbs and shrubs have regenerated in autumn 1979. *September 14, 1979. Photo by T. Imagawa.*

Photo 14. Vigorous channel processes accompanying cut and fill have been operating up to the end of 1979, on the upper reaches of R. Ko-Usu. The depth of new tephra exceeds 2 m. Former ground surface is pointed with a finger.
September 14, 1979. Photo by T. Imagawa.

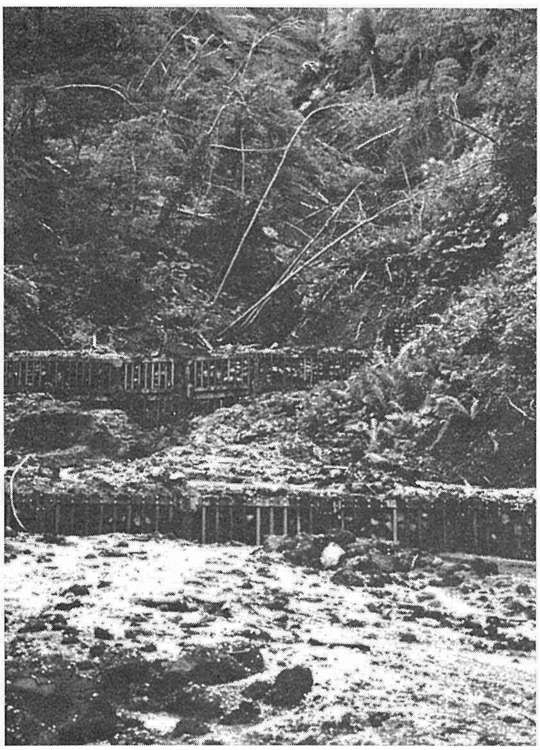

Photo 15. Rocky mudflow of September 5, 1979 went down one of valleys of R. Sobetsu-onsen rising on the extremely devastated northern somma slope. Tilted trees and scars in the background have been caused by faulting, landsliding and the shock of repeated earthquakes. *September 15, 1979. Photo by H. Kadomura.*

Photo 16. Rock debris flow passed throught a "slit-dam" installed in the main valley of R. O-Usu, the most active river during 1979 in terms of sediment yield and frequency of mass transport. The debris flow was triggered by a rainfall of 86 mm/24 h brought about by Typhoon No. 7920 which attacked the region on October 19, 1979. Valley-side slopes in the background have been progressively retreated due to landslide and rockfall, producing a large number of boulders.
October 22, 1979. Photo by T. Imagawa.