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Surface Erosion Associated with Tephra Deposition on Mt. Usu and Other Volcanoes

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Abstract

The 1977–1978 eruptions of Mt. Usu, Hokkaido, altered erosion regime of its summit atrio through destruction of pre-existing vegetation, new tephra deposition and crustal deformation, resulting in heavy rilling and gullying. Slope erosion rate in the atrio culminated on slopes of 15°–30° owing to severe gullying. The 4th Crater catchment, located on summit atrio, represented an extraordinarily high erosion rate at 13.6 cm/yr when averaged over the 4 post-eruption years. However, the erosion rate was decelerated within 3 years after the latest tephra deposition and before revegetation and erosion control works were done. The pattern, initial rapid erosion followed by an exponential decline, was observed for several other volcanoes, indicating rapid adjustment of a slope to the new erosion-sedimentation regime.

Key Words: Volcanic eruption, Tephra deposition, Surface erosion rate, Temporal variation.

1. Introduction

Volcanic eruptions often destroy vegetal cover and also produce huge quantities of tephra. The present study aims to discuss responses of slope erosion processes to a new tephra deposition with reference to the 1977–1978 eruptions of Mt. Usu, Japan and several other volcanic eruptions. Focuses are on time series of surface erosion rate after new tephra accumulation.

"Surface erosion", in this paper, means subaerial erosion and also excludes mass movement. Moreover, special attention is focused on water erosion such as slope wash, rilling and gullying.

2. Previous studies

Table 1 demonstrates previous main studies of surface erosion on newly tephra-covered slopes or catchments. The studies have been reported from several volcanoes: Parícutin (Mexico), Irazú (Costa Rica), Vulcan (New Guinea), Mt. Usu, Fernandina (Galápagos), and Mt. St. Helens (USA).

Swanson *et al.* (1983) reviewed hillslope erosion processes observed at Mt. St. Helens, Parícutin, Irazú, Vulcan and Fernandina where detailed and quantitative studies were done. As a result, they draw the following conclusions. Rates of

Table 1. Main studies of surface erosion on newly tephra-covered slopes or catchments

Volcano	Recent eruptive activity	Reference
Vulcan, New Guinea	1937	Ollier and Brown (1971)
Parícutin, Mexico	1943—1945	Segerstrom (1950) etc.
Irazú, Costa Rica	1963—1965	Waldron (1967) etc.
Fernandina, Galápagos	1968	Hendrix (1981)
Usu, Japan	1977—1978	Kadomura *et al.* (1978) etc.
St. Helens, USA	1980	Lehre *et al.* (1983) etc.

superficial erosion from tephra covered slopes in the vicinity of Mt. St. Helens are greatly variable in relation to slope gradient, thickness and texture of tephra, and lack of vegetation and organic debris. The rate appears to have peaked and declined during the first rainy season, which was related to such variables as removal of readily eroded material, exposure of layer of coarse particles and woody material resistant to erosion, increased infiltration capacity owing to exposure of coarser deposits and underlying soil. The pattern of a initial high rate of sheet and rill erosion, followed by a rapid decline, was also reported for other volcanoes.

Collins *et al.* (1983) in their study on Mt. St. Helens revealed that rapid erosion occurred on steep, thickly tephra-covered, barren slopes. They stressed an important role of fallen trees as a erosion-resistant control.

Following the 1943 eruptions of Parícutin, standing trees played an important role for an initiation of rilling by discharging collectively the stemflow in the form of concentrated flow (Segerstrom 1950). In this way, newly constructed surface, after a heavy rainfall, was soon cut by rill channels, resulting in the occurrence of small-scale mudflows (Segerstrom 1950, p. 84). Deep gullies cut into, not only the new tephra, but also the underlying pre-eruption ground surface (Lowdermilk 1947, Segerstrom 1950). "Softening" of landscape through time, for example, rounding of gully divides, had been evident during the 19-year study period (Segerstrom 1966).

According to Hendrix (1981), no change in gully pattern or size was observed in a barren area of Isla Fernandina, Galápagos, through successive visits during 1971-1977.

On Irazú Volcano, removal of new tephra from upper slopes mainly resulted from the headward and lateral growth of rills and gullies (Waldron 1967). He estimated that one-third to one-half of the new tephra (ashes) had been removed from the upper slopes by the end of 1964.

A number of studies of erosion processes following the 1977-1978 eruptions of Mt. Usu have been undertaken. Most studies have been concerned with debris and mud flow occurrences on the outer somma slopes and downvalley (e. g., Kadomura *et al.* 1978). On the slope of Nishiyama-gawa catchment, research on erosion processes was conducted by Yamamoto (1984), during 1977-1982, with reference to ground lowering and to physical properties of the new tephra. He found no clear relationships between slope gradient and erosion depth. Erosion rate, based on measurements of erosion pin exposure, was high during the period from 1978 to the mid 1979, followed by a subtle change until 1982 (Figure 3) ; 66 mm average erosion depth was observed during September 1978 - December 1979, equivalent to 54 mm/yr (Yamamoto 1984).

3. Surface erosion on Mt. Usu

1) *Regional setting*

Mt. Usu is located in the southwestern part of Hokkaido and it faces north where Toya Caldera Lake which has a 15 km diameter is located. The First Stage eruptions of Mt. Usu which took place August 7–14, 1977 produced thick tephra (ashes and pumices) (Niida *et al.* 1980). The Second Stage eruptions occurred intermittently from November 1977 to October 1978, mainly producing ashes (Niida *et al.* 1980). The ejecta of the 1977–1978 eruptions amounts to as much as $9 \times 10^7\ m^3$ (Katsui *et al.* 1978 a). The tephra accumulation, coupled with notable land deformations, altered the erosional regime of the atrio and surrounding

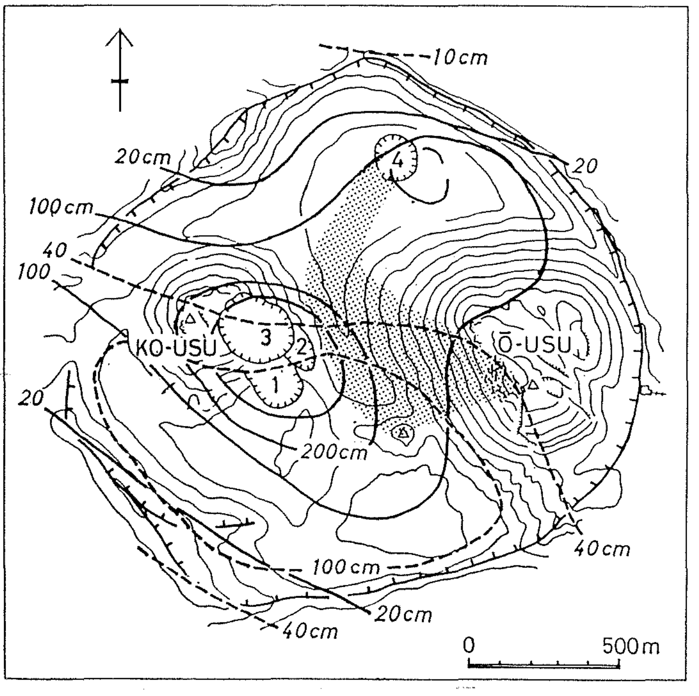

Figure 1. Map showing isopachs of the newly deposited tephra of 1977–1978 eruptions in the atrio of Mt. Usu (partly modified from Katsui *et al.* 1978 a, Niida *et al.* 1980.)

Solid and dashed lines mean the isopach of the First Stage (1977) and the Second Stage (1977–1978) tephra, respectively. Topographic contour as of before the eruptions. Numbers 1–4 denote craters opened during the First Stage eruptions. Shaded portion is the 4th Crater catchment.

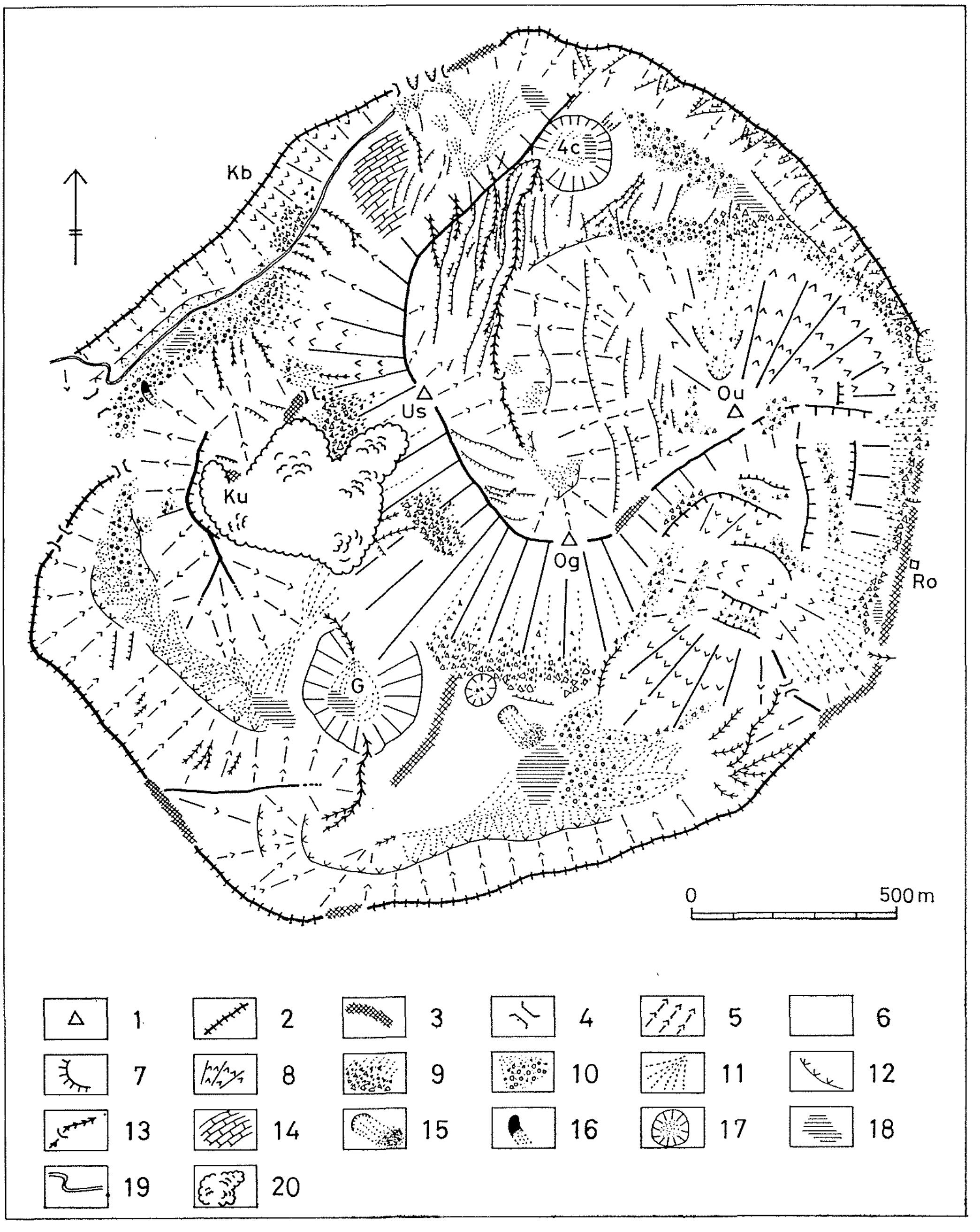

Figure 2. Geomorphological map of the atrio based on interpretation of 1 : 4000 aerial photography taken on 24 September 1981.

1 : Cryptodome 2 : Knife-edge ridge-like crest 3 : Rounded crest 4 : Col 5 : Severely rilled and gullied slope 6 : Lightly rilled slope 7 : Fault-scarp and flexure including landslide-scarp 8 : Block-covered slope 9 : Talus 10 : Alluvial cone and fan consisted chiefly of pumices 11 : Fan and floor infilled by ashes 12 : Break in slope 13 : Gully (top width larger than 6 m) with knick-point 14 : Artificial terraces 15 : Landslide 16 : Small-scale mudflow lobe 17 : Crater 18 : Pond or depression 19 : Road 20 : Area dissimulated by smoke Ou : O-Usu (731 m) Og : Ogari-yama (668 m) Us : Usu Shinzan (662 m) Ku : Ko-Usu (550 m) Kb : Kitabyobu-yama (633 m) 4c : 4th Crater G : Ginnuma Crater Ro : Ropeway station.

areas. Rapid surface erosion caused by the agents of rainfall and snow-melting sculptured the slopes thereafter (e. g., Kadomura *et al.* 1978, Imagawa 1984, Yamamoto 1984).

In this paper, I discuss and evaluate time series of erosion processes in the atrio where higher sediment yield was recorded. I also want to briefly examine the effects of erosion control works and vegetation recovery on erosion processes.

Dense forest, composed predominantly of *Populus maximowiczii*, which covered the atrio, was completely killed by the eruptions. The new tephra was more than 1 m thick in the atrio ; the tephra reached more than 4 m in thickness in the vicinity of craters (Fig. 1). In addition, the artio, except for the northern atrio, has been out of erosion control works ; erosion control works, e. g. terracing, consolidation dams, started in 1981 in the northern atrio. The summit atrio, when compared with the surrounding areas, is characterized by thicker new tephra and spectacular land deformations. Upheaval and thrust of the U-shaped block, namely the northeastern atrio, resulted in the tilting of the atrio surface by 11°. Maximum upheaval of the new cryptodome (Usu Shinzan — Ogari-yama rise) reached ca. 180 m. Detailed topographic changes of the atrio during August 1977 — February 1978 are presented in Katsui *et al.* (1978 b).

Figure 2 demonstrates the main features of geomorphic changes based on an interpretation of aerial photography taken in September 1981. Following the upheaval of the new cryptodome, rock fall process formed talus on the footslopes of O-Usu, southern footslope of Ogari-yama, and western footslope of Usu Shinzan. Slopes have been mainly sculptured by sheet wash, rilling and gullying ; thus densely spaced rills and gullies have characterized the atrio. Sediment delivered by such rilling and gullying formed alluvial cones and fans on footslopes and atrio floor ; lithic fragments as large as 0.5–1 m in diameter were also transported by gullying in the northern atrio. Deeply incised gully network was formed on the U-shaped block and in a small catchment which drains in Ginnuma Crater. Larger gullies reached more than 10 m wide and more than 5 m deep. High sediment yield was caused by such heavy rilling and gullying in the atrio.

The climate of this region belongs to the humid cold temperate zone. The monthly average temperatures in August and in January are 21°C and −4°C, respectively (J. W. A. 1982). Much rain falls in July, August and September, and snowfall occurs during the period November — April. The mean annual precipitation during the last 29 years has been 1030 mm.

2) *Erosion rate and its relation to slope gradient*

Sheet wash, rilling and gullying have been the dominant erosion processes in the atrio ; the prevailing erosion process has changed from sheet wash and rilling to gullying through time during 1977–1983 (Chinen and Kadomura in press). Wind erosion, gelifluction-type soil creep, and small-scale mudflows caused by over-saturation of subsurface layer had a minor effect.

Utilizing erosion pins, 205 in total number, I tried to detect erosion depth in the atrio during 1982–1984. Sites where the pins were installed range in gradient from 4° to 33°. As a result, ca. 2–4 mm of average erosion depth was observed during the period, although the erosion depth was highly variable in space. The amount of erosion probably reflected the combined effects of rainsplash, sheetwash, rilling and gullying. The erosion rate shows the same order of that was obtained during the period from the end of 1979 to 1982 by Yamamoto (1984) (Figure 3). Thus

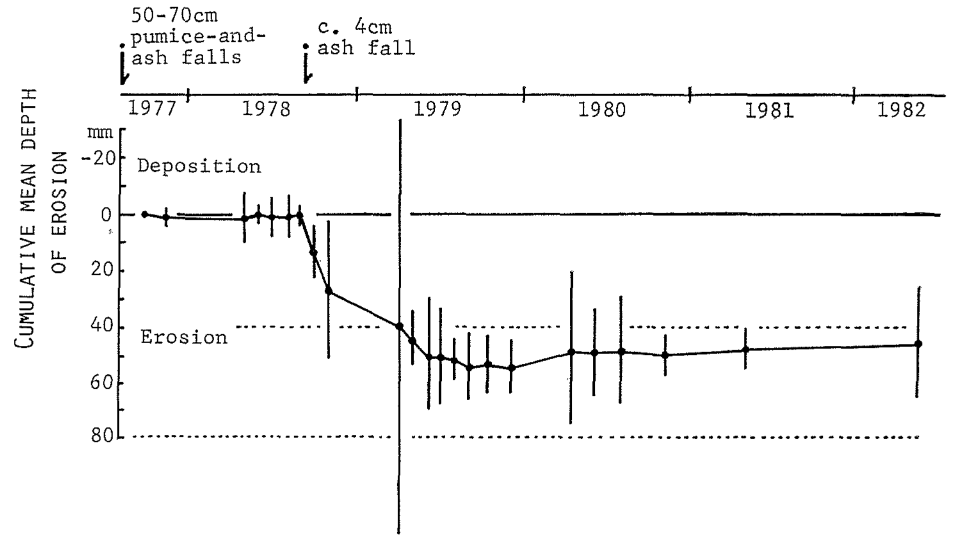

Figure 3. Temporal change in the cumulative mean depth of erosion during the period from 1978 to 1982 (modified from Yamamoto 1984).

Erosion pins were installed October 1978, on a slope (south-facing, 20°–30° in gradient). All values after the 1978 ash fall have had 4 cm of the re-accumulated ash subtracted. The pins used are 65 in total number.

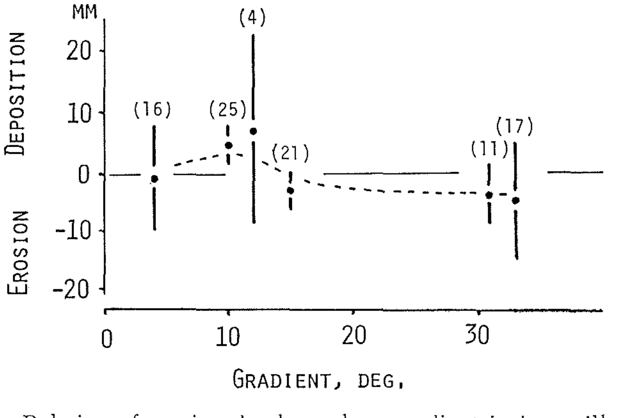

Figure 4. Relation of erosion depth to slope gradient in inter-rill and inter-gully areas based on measurements of erosion-pin exposure.

Bars denote 95% confidence range. Values in parentheses above the bars means number of erosion pins. Measurement period: November 1982–July 1984.

it is indicated that comparatively severe slope wash took place soon after the deposition of the new tephra, followed by little erosion until 1984.

Figure 4 indicates the general erosional trend on slopes steeper than 15°, while the depositional trend, though wide-ranged, on lowerslopes gentler than 15°. This relationship obtained from inter-rill and inter-gully areas does not entirely parallel that observed on a slope of Nishiyama-gawa catchment, 1 km northwest of the atrio, by Yamamoto (1984). Although erosion rate was magnified as slope gradient became steeper on the slope of Nishiyama-gawa catchment (Yamamoto 1984), the gentle sites were located only on the crestslope. Consequently, these findings indicate that the upper slope is subjected to erosion processes while the gentler lowerslope to deposition processes, and that no clear relationship between erosion depth and slope gradient is recognizable for slopes steeper than 15°.

The 4th Crater catchment (0.21 km^2), surrounded by the 4th Crater, O-Usu, Ogari-yama and Usu Shinzan (Fig. 1), represented a high erosion rate at 13.6 cm/yr when averaged over the first 4-year period (Chinen and Kadomura in press). This rate can be substituted with the gully erosion rate because gullying contributed more than 90% by volume to total sediment yield. The extraordinary gully erosion rate is attributable to faulting, tilting, and base level lowering due to the formation of the 4th Crater.

In order to examine the relationship between gully density and slope gradient, a sample area with ca. 0.3 km^2 was established in the northern atrio. Gully density in the area was measured on the basis of an interpretation of an aerial photo taken in September 1981. In addition, a slope map was made by using a topographic map. As a result, higher gully density is recognized on slopes ranging in gradient from 15° to 30° (Table 2). Field examination indicates that slopes steeper than 30° are subjected to gravity-governed erosion processes.

Table 2. Relation of gully density to slope gradient in the northern atrio of Mt. Usu

Gradient, deg.	Area, m^2	Gully length, m	Gully density, m/100 m^2
5>	3500	0	0.0
5—10	70400	4600	6.6
10—15	99400	7900	8.0
15—20	94400	10600	11.2
20—30	85100	10000	11.8
>30	27400	2700	9.8

Gradient and area measured on the topographic map (1 : 2500).
Gully length measured on the aerial photo (1 : 4000) taken September 1981.

In summary, total slope erosion rate, including both erosion on inter-rill and inter-gully areas and gully erosion, was generally magnified as slope gradient increased ; however, the erosion rate culminated at a slope gradient of 15°–30°.

3) *Temporal variation of sediment delivery*

A sediment budget analysis for the 4th Crater catchment during 1977–1982 revealed that sediment production and yield peaked during 1978–1981 and declined after 1981 (Chinen and Kadomura in press). Although natural erosion processes have not been observed in the catchment owing to erosion control works after 1982, field examination and measurements of erosion pin-exposure in the atrio showed very low erosion rate after 1982 onwards. Thus it is likely that the erosion rate in the 4th Crater catchment after 1982 was much slower than that during the 5 post-eruption years, even though the catchment had been prone to natural conditions.

Active erosion in the 4th Crater catchment terminated in October 1981. However, 17% of the total volume of new tephra was estimated to have been exported from the catchment whereas 83% remained chiefly on slopes of the catchment by 1982 (Chinen and Kadomura in press). Cumulative sediment production constantly increased through time during 1977–1982; nevertheless, the ratio of the volume of older tephra to the cumulative sediment production drastically increased during 1978–1982 (Figure 5). This trend is reflected in the ratio of the volume of eroded new tephra to original total volume of the new tephra, indicating a rapid removal of the new tephra at the initial stage (Fig. 5). The exponential decline of erosion rate through time, observed in the 4th Crater catchment, is proportional to the time series of erosion depth on the slope of Nishiyama-gawa catchment mentioned before.

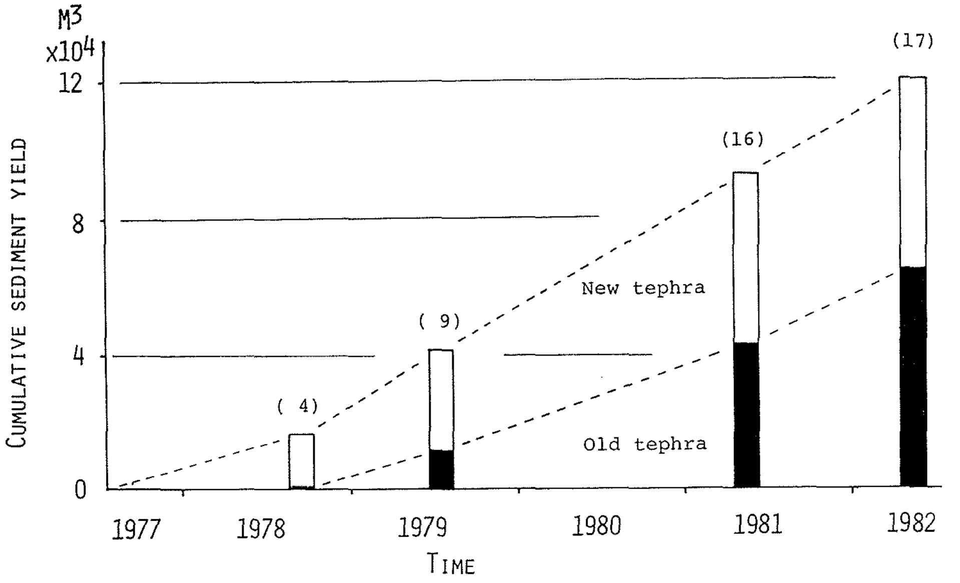

Figure 5. Time series of sediment production of the new and old tephra in the 4th Crater catchment on Mt. Usu.

Values in parentheses denote the ratio (%) of the volume of eroded new tephra to original total volume of the new tephra.

The deceleration of erosion rate over time is probably intrinsic; revegetation and erosion control works have little effect on the rate of superficial erosion of the new tephra on Mt. Usu. The construction of erosion preventive works might decelerate downvalley mass movement on outer somma slopes (Kadomura *et al.* 1983 a), but field examination and sediment budget analysis in the atrio indicated that superficial erosion rate had been exponentially declining before vegetation recovery and erosion control works were started in 1982.

The exponential decline of the erosion rate is probably a result of the formation of a more permeable, less erodible surface; porous and permeable new pumice layer and pre-existing organic soil were exposed through rilling and gullying. Porosity and hydraulic conductivity of the surface fine ash layer in Nishiyama-gawa catchment also increased through time during 1978–1982, resulting in less active occurrence of surface runoff (Yamamoto and Imagawa 1983). This finding supports the time series of erosion rate described above. Keeping in line with these trends, the effective rainfall amount and intensity for sediment production and yield increased over time during 1977–1981 (Kadomura *et al.* 1983 b, Chinen and Kadomura in press).

4. Comparison of time trend of sediment delivery among newly tephra-covered areas

Swanson *et al.* (1983) indicated that rapid decline of erosion rate was common to the newly tephra-covered slopes of several active volcanoes such as Mt. St. Helens, Parícutin, Vulcan, Irazú, and Fernandina. Time-sequential surface erosion rate observed on Mt. Usu shows the same trend. Although it is rather difficult to compare the decline process of the erosion rate among different areas, because of various study and environmental conditions involved. Figure 6 demonstrates a more rapid decline at Mt. Usu and Mt. St. Helens than at Parícutin. Rapid erosion terminated within 3 and 1 year after the latest tephra deposition on Mt. Usu and Mt. St. Helens, respectively. More interestingly, the erosion rate on slopes at Mt. St. Helens had declined before dense vegetation was established (Swanson *et al.* 1983). This finding is comparable to that obtained from the atrio of Mt. Usu. The erosion rate in the 4th Crater catchment on Mt. Usu, moreover, had also declined before erosion control works were done.

Table 3 shows the ratio of the volume of removed deposit to that of total deposit. Only 8% and 17% of the new tephra were removed at Mt. St. Helens and Mt. Usu, respectively, although the erosion rate had declined by the end of each study period; in contrast, nearly 50% of the new tephra was removed at Parícutin and Irazú. Deep gully incision brought about a large quantity of sediment removal of underlying older tephra in the 4th Crater catchment at Mt. Usu. However, little older tephra was mobilized and removed on Mt. St. Helens (Lehre *et al.* 1983). which was also the case with Parícutin and Irazú. Crustal deformation (faulting and tilting) and base level lowering in the 4th Crater catchment probably contributed to the volumious removal of the older tephra by gullying.

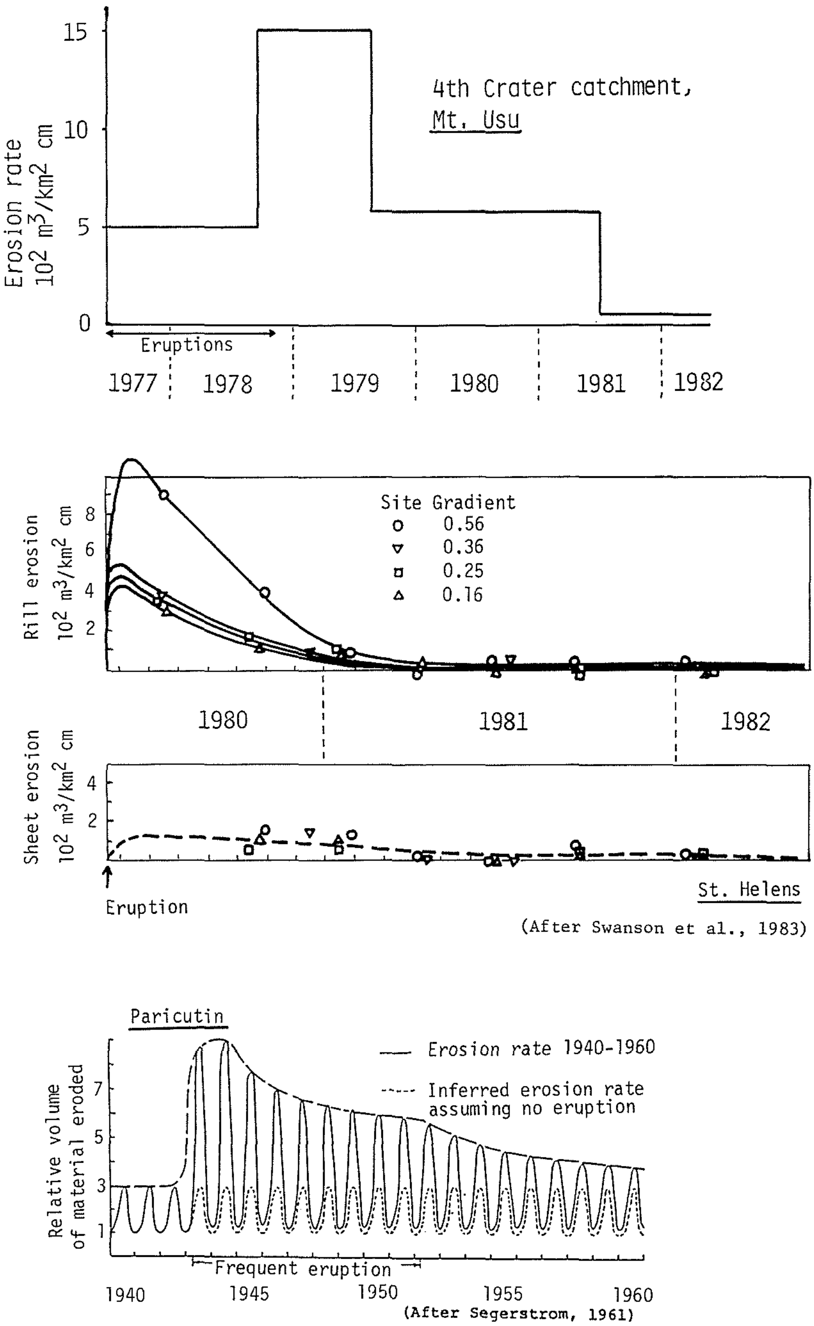

Figure 6. Erosion rate as a function of time observed at Mt. Usu (Chinen and Kadomura in press), Mt. St. Helens (Swanson *et al.* 1983), and Parícutin (Segerstrom 1961).

Erosion rates on Mts. Usu and St. Helens in sediment volume per km² and cm of rainfall.

Table 3. Removal of new tephra observed at Parícutin, Irazú, Vulcan, Mt. St. Helens and Mt. Usu

Volcano	Deposit Type	Processes	Deposit Removed (percent)	Period of Record (yrs)
Parícutin (Mexico)	Airfall	Sheet, rill	48	4
Irazú (Costa Rica)	Airfall	Sheet, rill	30—50	1
Vulcan (New Guinea)	Cindercone	Rill, Gully	—	5
Mt. St. Helens (USA)	Airfall	Sheet, Rill	8	2
Mt. Usu (Japan)	Airfall	Rill, Gully	17	4

(modified from Swanson *et al.* 1983)

In summary, it is indicated that adjustment of slopes to a new erosion-sedimentation regime, caused by a tephra deposition, is rapidly completed. It is also suggested that erosion control measures will work effectively soon after the tephra deposition. Nevertheless, study methods and site conditions are too various to draw a quantitative conclusion for overall comparative study. For example, sediment mobilization, sediment yield, and sediment storage generally vary with space and time. In addition, volcanic activity and its effect on land surface spatially vary, resulting in different modes of responses of slope erosion processes to the volcanic impact.

5. Concluding remarks

The summit atrio of Mt. Usu has been subjected to heavy rilling and gullying since the 1977-1978 eruptions. The rate of sheet wash was magnified as slope gradient became steeper, although no clear relationship between erosion depth and slope gradient was recognized for slopes steeper than 15°. On the other hand, higher gully density was recognized on slopes ranging in gradient from 15° to 30° in the northern atrio. Surface erosion rate was variable in space, although slope erosion rate, as a whole, culminated at a slope of 15°-30°.

An extraordinarily high erosion rate (13.6 cm/yr) was recorded mainly by gullying in the 4th Crater catchment on Mt. Usu when averaged over the 4 post-eruption years. However, the active erosion in the catchment terminated in Otcober 1981, 3 years after the latest ash deposition. Instead of a deceleration of erosion rate, 83% of the new tephra still remained in the catchment in 1982. The results, together with field examination during 1982-1985, indicate that surface erosion rate in the atrio had been declining before vegetation recovery and erosion control works were done.

These findings parallel with that of Swanson *et al.* (1983), indicating an exponential decline of erosion rate over time; this pattern was reported for several other volcanoes. Consequently, it is suggested that adjustment of slopes and catchments to a new erosion-sedimentation regime is rapidly completed. Volcanic impacts, study methods and site conditions are, however, too various to draw a quantitative conclusion for such a comparative study.

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