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Mud and Debris Flows on Mt. Usu After the 1977–1978 Eruption

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Abstract

During the course of this paper post-eruption erosion in the world is summarized, and the characteristics of mud and debris flows after the 1977–1978 eruption of Mt. Usu are discussed and its process of time-spatial sequence is explained. Accelerated erosion just after the eruption is common to active volcanoes in the world. This fact can be confirmed in the case of Mt. Usu because mud and debris flows continually and frequently occurred during the first four years. The sequence of mud and debris flow can be explained by its relation to ash fall, crustal deformation and rainfall.

Key Words: Post-eruption erosion, mud and debris flows, rainfall condition, sediment yield, time-spatial sequence, ash fall, crustal deformation.

1. Introduction

Mud and debris flows which started on Aug. 16, 1977 continued in the summit atrio and on somma slope for about four years, until Sept. 1981.

There are some papers about mud and debris flow after the 1977 eruption (i. e. Kadomura, et al. (1979, 1980, 1983 a & b), Imagawa (1984), Takagai, et al. (1982), Yamagishi et al. (1982), and Suekane (1978)). Most of papers described erosion and mass movement in a specified basin or a specified occurrence. However, all of the mud and debris flows which occurred after the eruption should be considered as a chain of events, because all of the events resulted from ash fall and crustal deformation that accompanied the 1977–1978 volcanism.

The purposes of this study are to summarize previous papers about other volcanoes concerning post-eruption erosion from the view points of dominant erosion processes, their duration, and rate; and to discuss the characteristics of mud and debris flows (i. e. time occurrence, rainfall condition and magnitude). Also to explain the process of the time-spatial sequence of mud and debris flows.

2. Post-eruption erosion on volcanoes in the world

There are some reports about post-eruption erosion concerning the following volcanoes; Mt. Irazu (Ulate & Corrales, 1966; Waldron, 1967) in Costa Rica, Mt.

Table 1. Characteristics of post-eruption erosion

Volcano	Vulcan	Barcena	Anak Krakatau	Paricutin
Main literature	Ollier & Brown (1971)	Richards (1965)	Bird & Rosengren (1984)	Segerstrom (1950)
Country	Papua New Guinea	Mexico	Indonesia	Mexico
Height	232 m	330 m	200 m	2350 m
The latest activity				
Year	1937	1952	1927	1943
Characteristics	Formation of scoria cone (Vulcan) Soria cone (Vulcan)	Ash fall	Formation of the volcanic body, Lava flow, Scoria	Formation of the volcanic body, Scoria, Ash fall, Lava flow
Surface condition	bare	bare	bare	bare
Climate				
Type	Af	BS	Af	Cw
Precipitation	2241 mm/yr	150 mm/yr	1755 mm/yr (Djakarta)	1638 mm/yr
Main erosion process reported				
Gully	D	D	D	D
Sheet	D			D
Wind		D		D
Creep				D
Landslide				D
Downvalley-mass movement				D
coastal		D	D	
Duration of dominant erosion	5 yrs	1 yr		1 yr
Erosion rate or Sediment yield	56 cm/31 yrs (whole slope)	90 cm/day (Aug. 11–Nov. 5, 1952, coastal erosion)	5–7 m/yr (coastal erosion)	5.5 cm/yr (first 4 yrs, sheetwash & rill erosion)

"D" denotes the erosion process described in that volcano.

and mass movement of active volcanoes in the world

Irazu	El chichon	St. Helens	Sakurajima	Yakedake
Ulate & Corrales (1966) Waldron (1967)	Tricart (1983)	Collins et al. & Lehre et al. (1983) Swanson et al. (1983)	Yamasaki (1980)	Okuda et al. (1978)
Costa Rica	Mexico	United States of America	Japan	Japan
3300 m	1015 m	2500 m	1110 m	2455 m
1963–1965	1982	1980	Present	1962–1963
Ash fall	Ash fall Pyroclastic flow	Ash fall, Pyroclastic flow	Ash fall	Steam explosion
bare in the upper slope	?	almost bare	bare in the upper slope	bare in the upper slope
Aw	Af	Cfb-Df	Cfa	Cfa
1600 mm/yr	4037 mm/yr	1048 mm/yr (Vancouver)	2432 mm/yr	1067 mm/yr (Matsumoto)
D		D		D
D		D		
		D		
		D		
D	D	D	D	D
1 yr				
1/3–1/2 of new tephra was removed from the upper reach		26.3 mm/yr (first year, slope) 31–38 × 10^6 m^3 flowed to downvalley	500,000 m^3/yr (1976–1979, Nojiri R.)	

Barcena (Richards, 1965), Mt. Paricutin (Segerstrom, 1950), Mt. El Chichon (Tricart, 1983), in Mexico ; Mt. St. Helens (Collins et al., 1983 ; Leher et al., 1983 ; Swanson et al., 1984) in the U. S. A. ; Mt. Vulcan (Ollier & Brown, 1971) in New Guinea, Mt. Anak Krakatau (Bird & Rosengrem, 1984) in Indonesia, Mt. Yakedake (Okuda et al., 1978), Mt. Sakurajima (Yamasaki et al., 1980) in Japan. Figure 1 shows the locations of these volcanoes. It is difficult to carry out comparisons on post-eruption erosions not only because of their different geographical locations, altitudes, relative heights and types of eruption but also because of disparity between investigations. Nevertheless, a few generalities could be found.

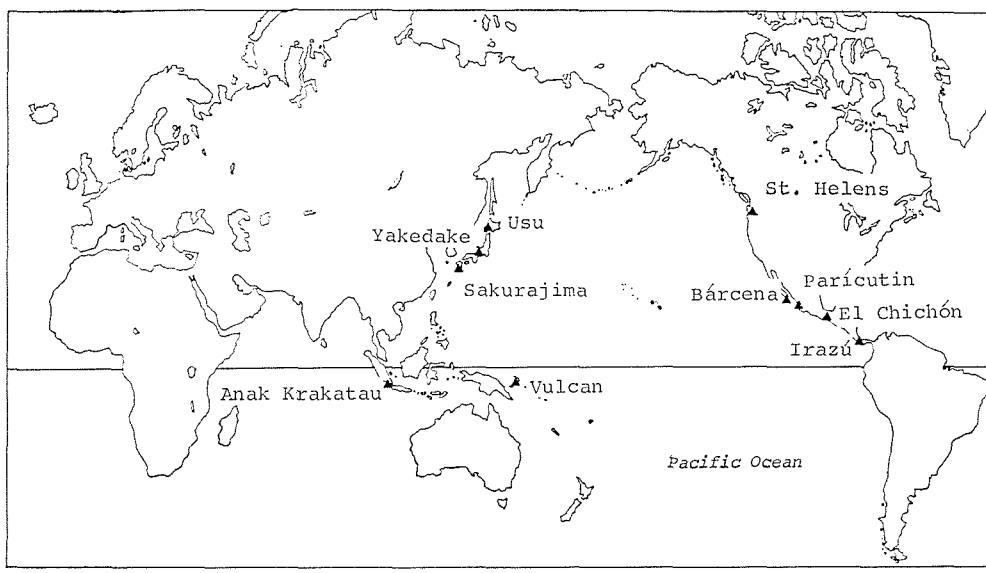

Figure 1. Active volcanoes where were studied about post-eruption erosion and mass movement.

Table 1 shows the characteristics of each volcano. It is generally indicated that erosion and mass movement progress rapidly a short time just after the eruption and the formation of cone. Duration of post eruption erosion was about one year in Barcena, Paricutin and Irazu. In Mt. St. Helens also rapid erosion progressed within one year after the 1980 eruption. Segerstrom (1961) reported that on Paricutin, the highest rates of erosion were attained just after the eruption of 1943, and that this rate substantially decelerated with cease of ash fall in 1952. It is estimated that the present valleys were formed during the five years which followed the eruption.

The causes for induced rapid erosion and mass movement are inferred as follows :

1) Hill slopes are covered with unconsolidated materials and are barren.

2) Sheet flow occurs when the rate of precipitation exceeds the infiltration capacity of the mantle, thus inducing the formation of rills and gullies. Where the surface layer consists of fine material, rill and gully develop, particularly rapidly

i. e. in Paricutin, Barcena and Irazu.

A few papers reported the process of rill and gully development in detail. It is thought that rill and gully develop in a short time, and in some cases in one event only. Rill and gully in Barcena developed for a week and were left untouched after that. In Mt. Irazu, Waldron (1967) estimated that during the 1964 rainy season alone, one-third to one-half of all tephra deposits were removed from the upper Reventado River.

Channel erosion is more intensive than slope erosion, and this does not only occur in new tephra, but also in old deposits. Channel depth can reach several meters. Eroded vallyes are U-shaped or box-shaped. Waldron (1967) regarded depth, width, and gradient of channel; as well as characteristics and quantity of sediment load, and material forming the channel, as factors of erosion. Channel erosion generally induces landslides of valley sides.

Debris flows, which result from channel erosion, are generally triggered by rainfall. In Irazu, more than 90 debris flows occurred soon after the eruption during the 1964 rainy season. Because of the quality of material accumulated, even light rainfall can trigger large debris flows i. e. the debris flow of Dec. 9, 1963. The rainfall which led to this event was 24.4 mm/day. This amount was much smaller than 154 mm/day when the largest debris flow took place before the eruption. However, the magnitude of the former was bigger than the latter. Tricart (1983) described debris flows just after the eruption of El Chichon in 1982. One of inducing factors was considered to be the total amount of rainfall which attained in only 4 months the annual average of 400 mm. Another factor was considered to be the erosion of a surficial ash crust. In Japan, the occurrence of debris flow was reported on Mt. Sakurajima and on Mt. Yakedake. Debris flows of Sakurajima occurred frequently since the eruption of 1975. The frequency of debris flows is high from May to November due to high precipitation and repeated ash falls. The sediment yield of R. Nojiri located on southwest slope reached 5×10^5 m^3/yr between 1976 and 1979 (Yamasaki et al., 1980). On Mt. Yakedake, debris flows were triggered by the steam eruption of 1962, and on 30 occasions were caused by rainfall between 1970 and 1977. It is considered that the formation of a vent on the valley head and thick unconsolidated volcanic ejecta made the occurrence of a debris flow easy (Okuda et al., 1978).

Rainfall conditions inducing debris flows and erosion rates were not discussed in detail. Erosion rate was estimated to be 56 cm/31 yrs in Vulcan by Ollier & Brown (1971) with the stipulation that most of this erosion occurred during the first 5 years after the eruption.

3. The characteristics of sequence

3. 1. *The time occurrence*

Characteristic features about the time occurrence of mass movements can be described on the basis of Figure 2 as follows:

1) The occurrence of mass movements were concentrated in the first 4 years

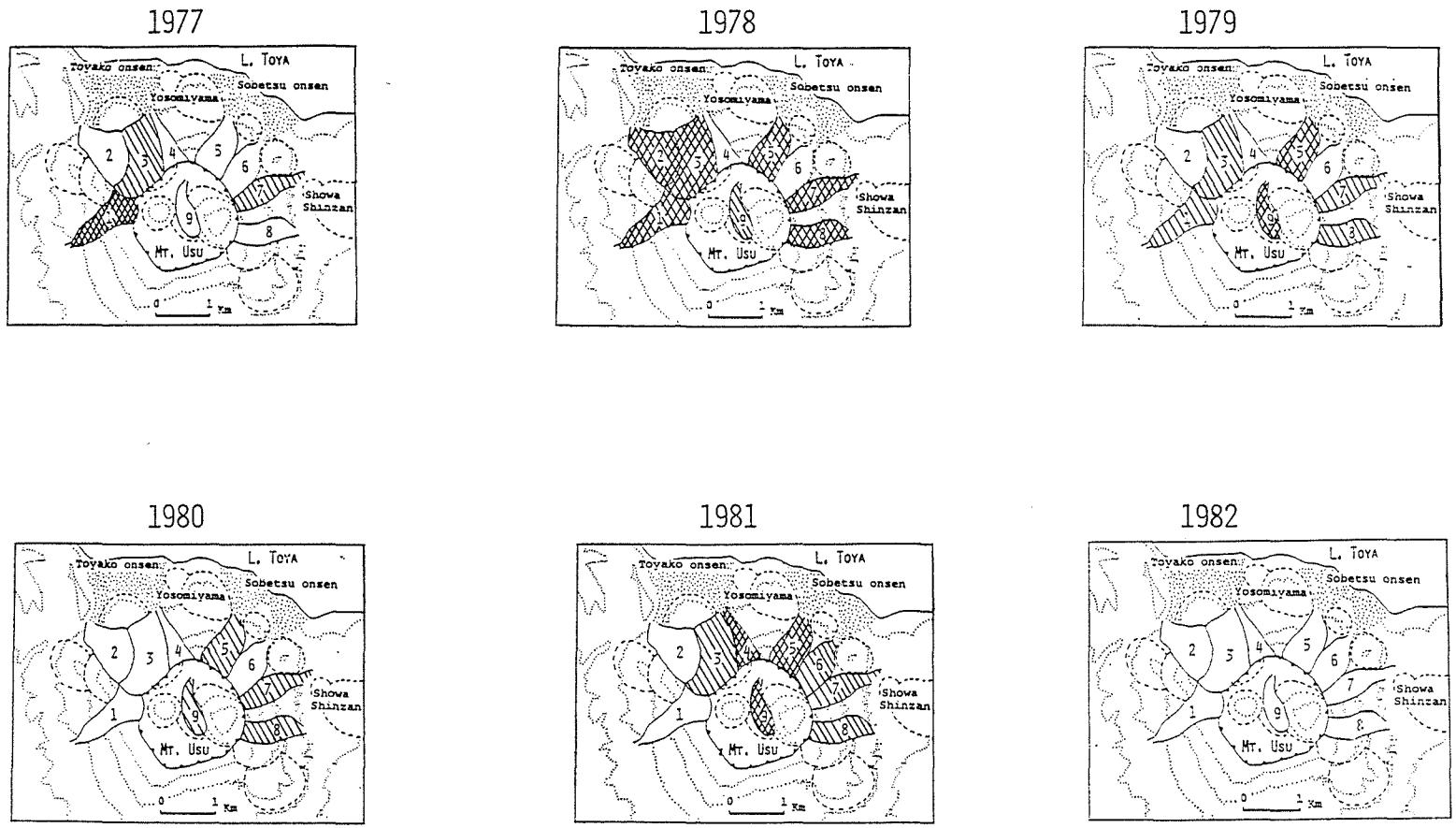

Figure 2. Spatical variation of mass movement occurring.

□ : <1000 m³ of sediment yield per a year,

▨ : <10000 m³, ▩ : >10000 m³.

and had peaked in 1978 and 1979. After 1981, mass movements occurred once in 1984 and twice in 1985. Each mass movement occurred in a limited number of valleys, i. e. Sobetsu-onsen R. and Ko-Usu R. and were small in scale.

2) Mass movement mainly occurred in the tephra covered basins between 1977 and 1979, and, on the contrary, occurred in the basins affected by crustal deformations between 1978 and 1981.

3) Large scale mass movements with a volume of more than 10000 m^3 occurred in the Izumiichinosawa R. in 1977, in all basins in 1978 and mainly in the basins affected by crustal deformations in 1981.

A duration of four years for mass movement occurring is considered to be a relatively short period when compared to the recurrence time of the volcanism in Mt. Usu which is approximately 30 years. In the case of other volcanoes, i. e. Paricutin, Irazu, Varcena and Vulcan, post-eruption erosion and mass movement also ceased after a short period. It can be said that this fact, namely the accelerated erosion just after the eruption, is a characteristics in active volcanoes.

3. 2. *Seasonal variation*

Precipitation in Mt. Usu consists of rain in Apr. -Nov. and snow in Dec. -March. Here, I examine rain and snow as factors triggering mass movements. All but one occurred from June to November which is the rainy season (Fig. 3). The mass movement triggered by melting snow occurred in April 1981 (Kadomura, 1983 b). Debris flow was seldom produced in winter season. Mt. Usu is normally covered with snow from Devember to April. From December to March no mass movement ever took place, although snow avalancing tracks were observed in tephra covered basins. In basins affected by crustal deformation, snow and debris avalanche with a volume of 10–100 m^3 were sometimes observed. Snow and debris

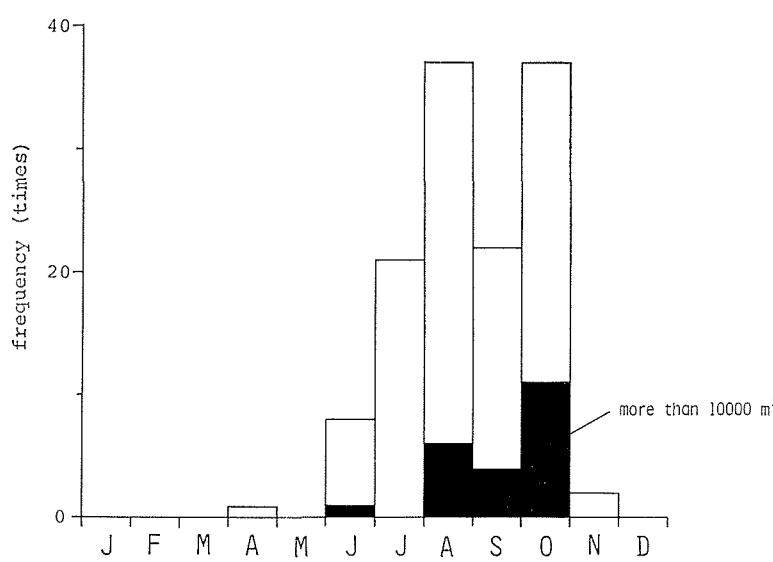

Figure 3. Monthly frequency of mass movement occurring during the period 1977–1982.

avalanches deposited on lower valleys within several tens meters in distance except for the debris avalanche of April 24, 1981 which deposited to a distance of about 700 m.

Most of mud and debris flows and particularly the large-scale ones, took place between July and October. It can be said that rainfall played an important role in production of debris and the occurrence of mud and debris flow.

4. Rainfall condition

When I discuss the rainfall condition which induced mud and debris flow, it is a matter for reflection that mass movements consist of mudflow and debris flow. However, both these types of mass movements cannot be distinguished as to their time occurrence.

Past mud and debris flows on Mt. Usu occurred during ordinary rainfall, except for a few cases such as those of October 24, 1978 and August 4 & 23, 1981 (Figure 4). The minimum amount of rainfall responsible for triggering a mass movement was 20–30 mm of continuous rainfall, 5–15 mm in one-hour and 2.5–5 mm in ten-minutes. These values increased somewhat after 1980 (Figure 4). Changes in occurrence may be brought about by the combined effects of sequential changes in related factors. In tephra covered basins, change resulted from a decrease of sediment on the valley bottom. In basins affected by crustal deformations, change was attributed to the move of the major sediment source from the middle to the upper reaches of the river. The effects of evacuation of unstable sediment that had accumulated on the valley floor by the preceding mass movements is generally quite considerable.

The above cited values are almost comparable with those obtained on active volcanoes in Japan such as Mts. Yakedake and Sakurajima (Yamauchi, 1978) which have experienced frequent mud and rock debris flows in relation to their eruptive activities. As it has been revealed from my data, it should be emphasized that in the valleys of an active volcano, with slopes devastated due both to the deposits of tephra and land deformations, large-scale mud or rock debris flows tend to occur even by an ordinary rainfall.

Consequently, the rainfall condition inducing mud and debris flow in Mt. Usu can be compared with rainfall inducing other debris flows in Japan. Data obtained in 1972 by Seo and Funazaki (1974), were used for this discussion, as well as rainfall data of Mt. Usu i. e. Oct. 24, 1978 and Aug. 23, 1981, which produced the largest and the secondary volume of sediment, respectively (Figures 5 and 6). Continuous rainfalls and maximum hourly rainfalls of Mt. Usu are much smaller than other regions of Japan. The 10 minute-rainfall of Oct. 24, 1978 is in the largest category, but that of Aug. 23, 1981 is relatively low.

Seo and Funazaki (1974) also estimated the risk of debris flow disaster based on rainfall and its intensity (Figure 7). The examples of Mt. Usu are not contained in the dangerous zone for debris flow disaster, thus showing that the mud and debris flows of Mt. Usu were induced by small-scale or ordinary rainfalls.

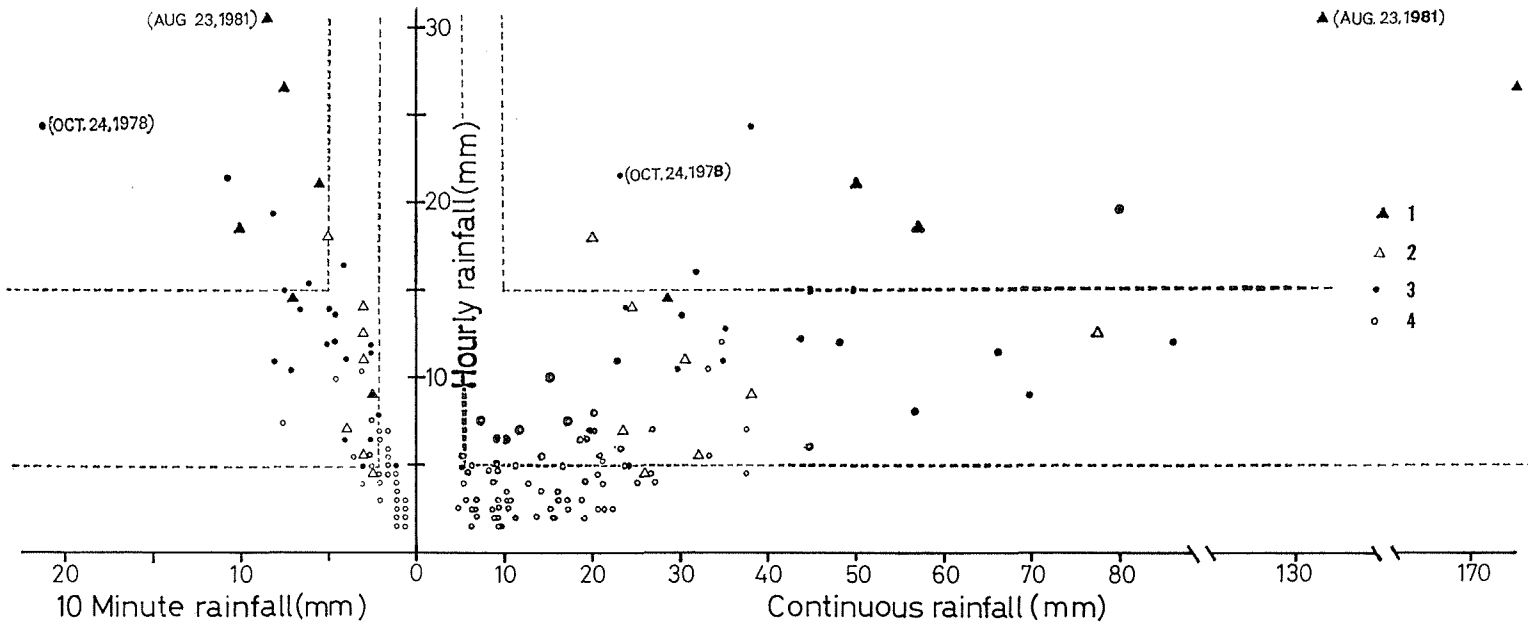

Figure 4. Rainfall and mass movement.

1: Movement in 1981. 2. No movement in 1981. 3: Movement in 1978–1980. 4: No movement in 1978–1980. Precipitation readings of more than 5 mm of continuous rainfall are shown.

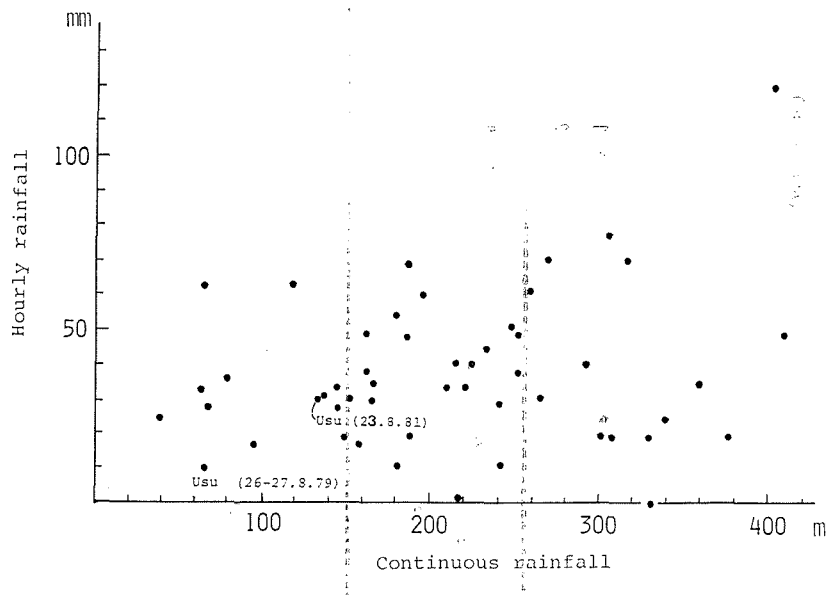

Figure 5. Relationship between continuous and hourly rainfalls related to mass movement occurring.

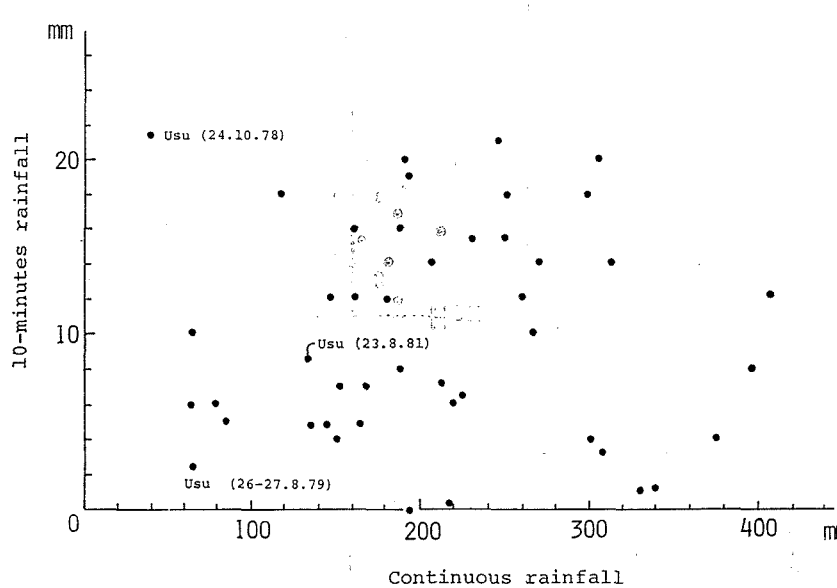

Figure 6. Relationship between continuous and 10-minute rainfalls related to mass movement occurring.

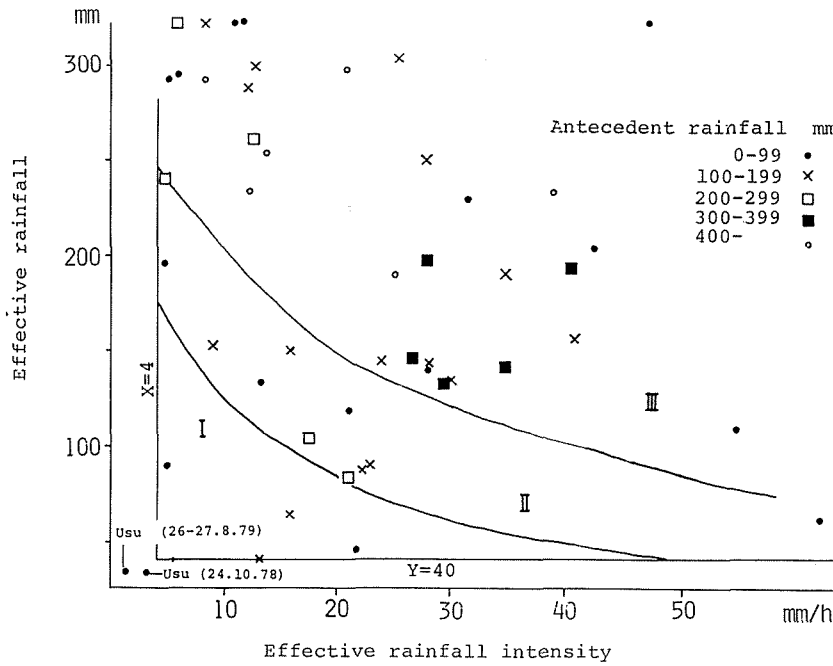

Figure 7. Relationship between the effective rainfall and the effective rainfall intensity related to mass movement occurring.

5. Sediment yield

Table 2 shows the sediment yield of selected valleys after the eruption. Total sediment yield reached over 10^5 m^3 in these valleys except for the O-Usu R. Figure 8 shows the sequence of sediment yield. Characteristic features of sediment yield can be described as follows:

1) Sediment yields of the first two years reached about 70% of the total yield.

2) The main basin, where sediment yields were produced, changed from tephra covered basins to deformed basins after 1979.

Annual sediment yields of the Nojiri R. at Mt. Sakurajima were about 5×10^5 m^3/yr from 1976 to 1979. Sediment yield of the North Fork Toutle R. at Mt. St. Helens reached $31\text{–}38\times10^6$ m^3 in the first year. On Mt. Usu, maximum annual sediment yield was 1.2×10^5 m^3 which is less than 1/5 and 1/10 respectively of the former cited volcanoes.

Ollier and Brown (1971) surveyed gully cross-sections and founded that they represented an average erosion rate of 16 mm/yr. They estimated that assuming a 5-year period of gully formation, the volume of gullies represents an erosion rate of 105 mm/yr. Collins et al. (1983) measured a slope erosion rate which represented 26.3 mm/yr during the first year. On Mt. Usu, average erosion rates are 20–130 mm/yr and maximum erosion rates are 50–280 mm/yr (Table 2).

Table 2. Sediment yields from selected basins on Mt. Usu, August 1977–October 1981. Figures in parentheses give the specific sediment yields per sq. km

	Watershed	Attributes	Total (1977–1981) $\times 10^3$ m^3	Annual yield mean $\times 10^3$ m^3	Annual yield max $\times 10^3$ m^3	Annual yield year	Single storm maximum amount $\times 10^3$ m^3	Single storm maximum date	Single storm maximum rainfall mm	Main transported material
Somma slope	Izumi-I*	n=4 s=1.458 km^2 l=2530 m h=365 m θ=9°	112 (76.8)	26.9 (18.4)	67.9 (46.6)	1977	26.0 (17.8)	14- 9-77	26 13/hr	Valley fill
	Nishiyama***	n=4 s=0.690 km^2 l=1620 m h=365 m θ=13°	121 (175)	29.1 (42.2)	121 (175)	1978	103 (149)	24-10-78	37.5 24.5/hr 21/10 min.	1977–78 tephra
	Ko-Usu**	n=4 s=1.054 km^2 l=1190 m h=370 m θ=18°	142 (135)	34.1 (32.3)	106 (101)	1978	37.0 (35.0)	24-10-78	37.5 24.5/hr 21/10 min.	1977–78 tephra, Valley fill
	Sobetsu-onsen†	n=4 s=0.467 km^2 l=890 m h=320 m θ=21°	124 (266)	29.8 (63.7)	70.0 (150)	1981	39.0 (83.5)	23- 8-81	133 30.5/hr 8.5/10 min.	Old tephra, Lava blocks
	O-Usu*	n=3 s=0.436 km^2 l=1200 m h=330 m θ=16°	38.0 (86.0)	9.12 (20.9)	22.7 (52.0)	1979	5.0 (11.0)	5- 9-79	46.5 14.5/hr 5/10 min.	Lava blocks
Atrio	Crater 4†***	n=2 s=0.230 km^2 l=1000 m h=175 m θ=10°	125 (543)	30.0 (130)	63.9 (278)	1979				1977–78 tephra, Old tephra

Tephra-cover ≧50 cm: *Upper reaches only, **Upper-middle reaches, ***Whole area; †Affected by strong crustal deformation; n: stream order at the mouth of the valley, s: catchment area, l: length of main stream, h: relative height of watershed, θ: average slope of main stream. Data on sediment yield from various sources. Rainfall data give continuous, maximum hourly and maximum 10-minute readings.

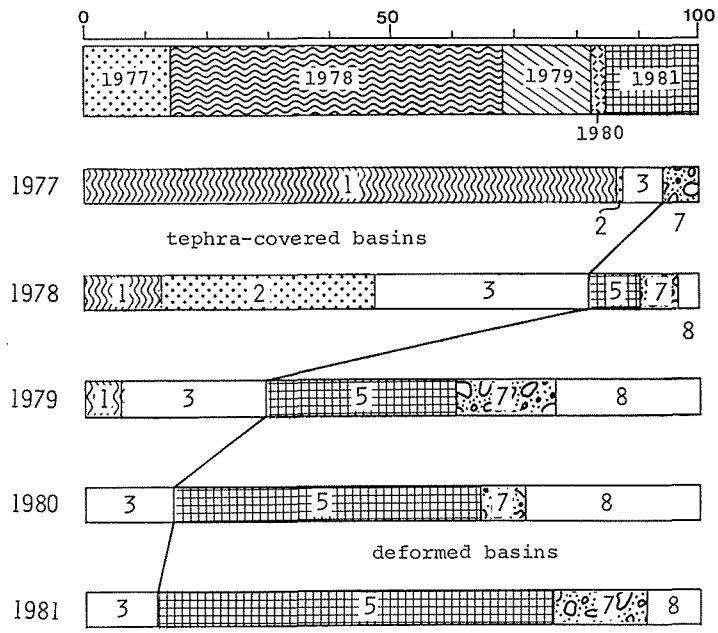

Figure 8. Sequence of rate of sediment yield in every year and every main valley. 1: Izumiichinosawa R., 3: Nishiyama R., 4: Ko-Usu R., 5: Sobetsu-onsen R., 8: O-Usu R., 9: Crater 4th Their locations are shown in Figure 2.

On the basis of the above results, it can be said that intensity of erosion on Mt. Usu was as much as or more than on other volcanoes, but the volume of sediment was small. This small volume of sediment on Mt. Usu is inferred to be due to small volume of the volcanic body.

The specific sediment yield of the Crater 4 basin in the atrio was 2–7 times larger than in the other basins. The 4th Crater basin was strongly affected both by ash fall and by crustal deformations. In valleys located on the somma slope, the Sobetsu-onsen R. basin reached 266×10^3 m^3/Km^2, a maximum value. On the contrary, the Izumiichinosawa R., Nishiyama R. and Ko-Usu R. which were tephra-covered basins reached $76.5-175 \times 10^3$ m^3/Km^2 and were smaller than the former. Generally speaking, crustal deformations contributed more strongly to the sediment production than ash fall.

Sediment yield by a single event is significant from the viewpoint of disaster science. The maximum sediment yield of mud flow was 103,000 m^3 in the Nishiyama R. on Oct. 24, 1978. In other basins, the maximum sediment yields ranged from 3×10^3 m^3 to 4×10^4 m^3. These volumes are not large when compared with volumes which were produced by past large debris flows in Japan. However, specific sediment yields (11×10^3 m^3 – 149×10^3 m^3) are of same order. Such large volumes were mainly recorded in the Quaternary volcanic regions. The characteristics of Mt. Usu are large specific sediment yields occurring repeatedly over a short period.

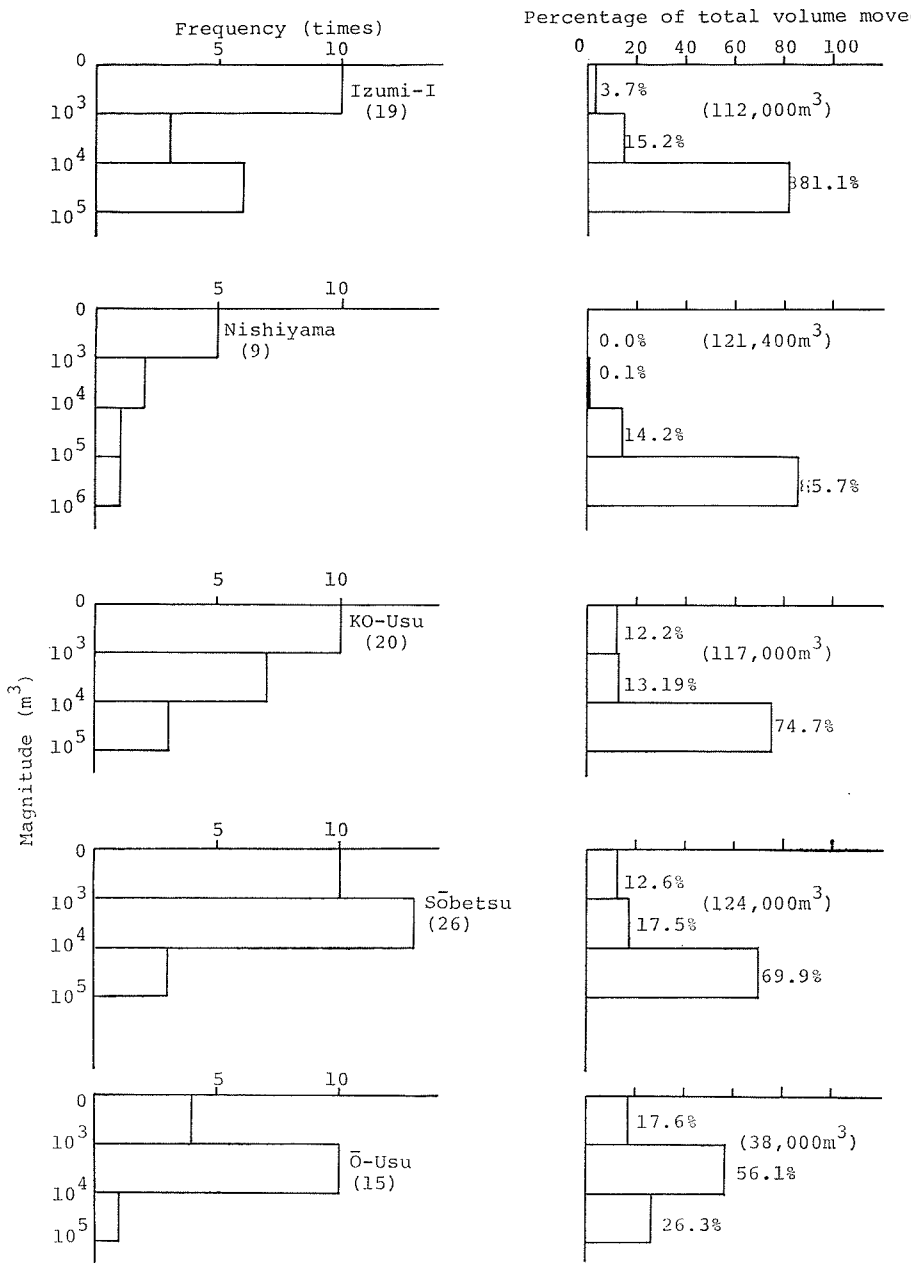

Figure 9. Frequency of mass movements of a given volume and percentage of the total volume of debris moved by mass movements of a given volume.

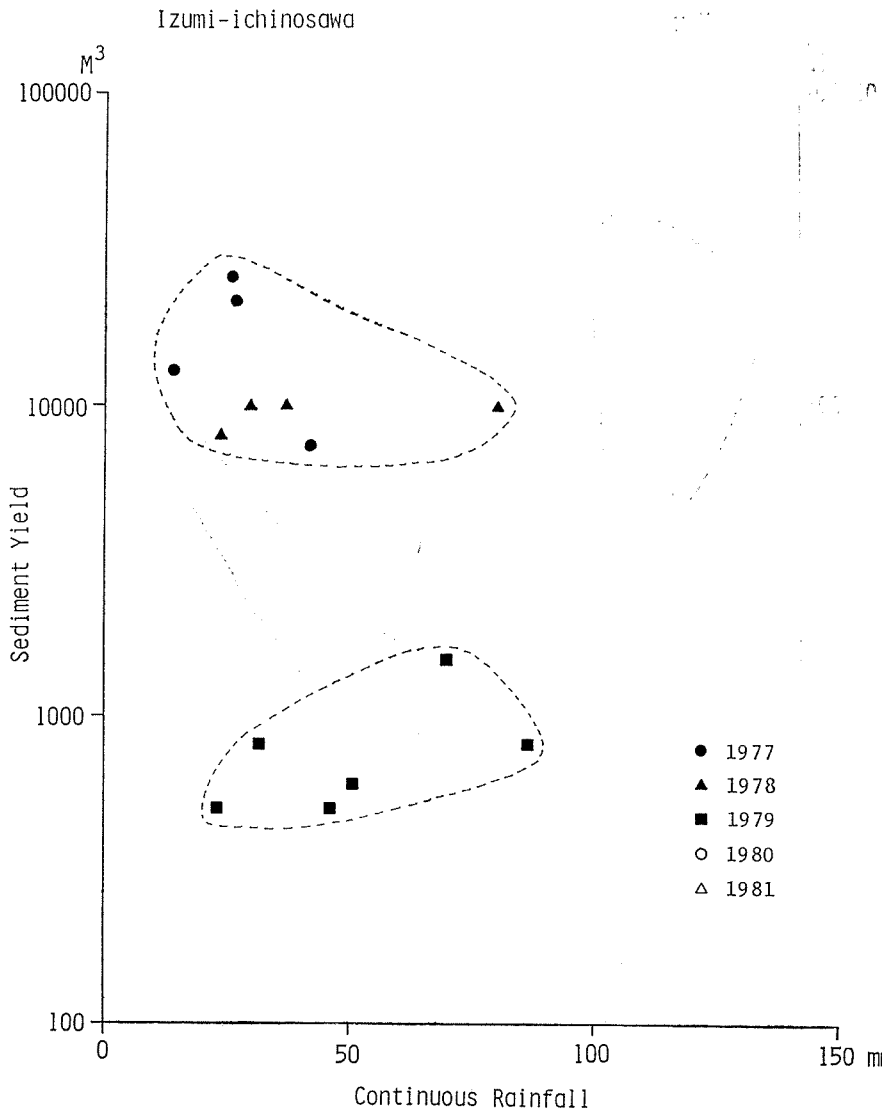

Figure 10. Relationship between sediment yield and continuous rainfall in Izumiichinosawa R. basin.

Figure 9 shows the frequency of mass movement of a given volume and the percentage of the total volume of debris moved by debris flows of a given volume.

Frequency of mass movement tends to decrease with magnitude. 70-85% of the total volume of debris were produced by mass movements with a volume of 10,000 m^3 and more each.

It can be said that large-scale events played an important role in the sediment yield. This is distinguishable in the Nishiyama R.

Now, I will discuss the relationship between sediment yield and rainfall. Figures 10 to 12 show examples of the Izumiichinosawa R., Ko-Usu R., and Sobetsu-onsen

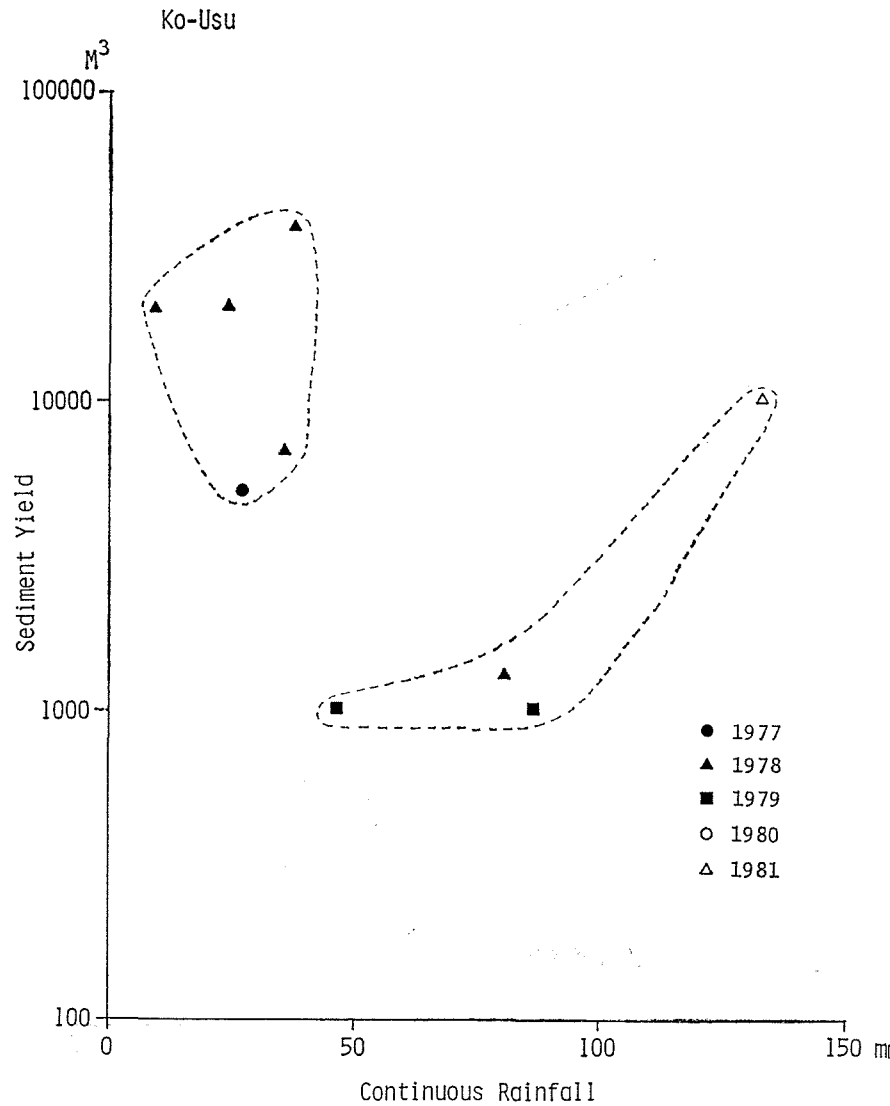

Figure 11. Relationship between sediment yield and continuous rainfall in Ko-Usu R. basin.

R. As a whole, the relationship that existed between sediment yield and rainfall seemed to change after 1979 : in the Izumiichinosawa R. sediment yield per one rainfall triggering debris flow decreased from the order of 10^4 m^3 to the order of 10^3 m^3 (Fig. 10) and in other basins similar relationships were recognized between them as shown in Figures 11 & 12. This change related to storage of sediment in each valleys as mentioned above. I suspected that the change after 1979 was produced by the event of Oct. 24, 1978 ; because this event cleared a large volume of sediment in most of the valley floors and because sediments remained in the most upper reaches.

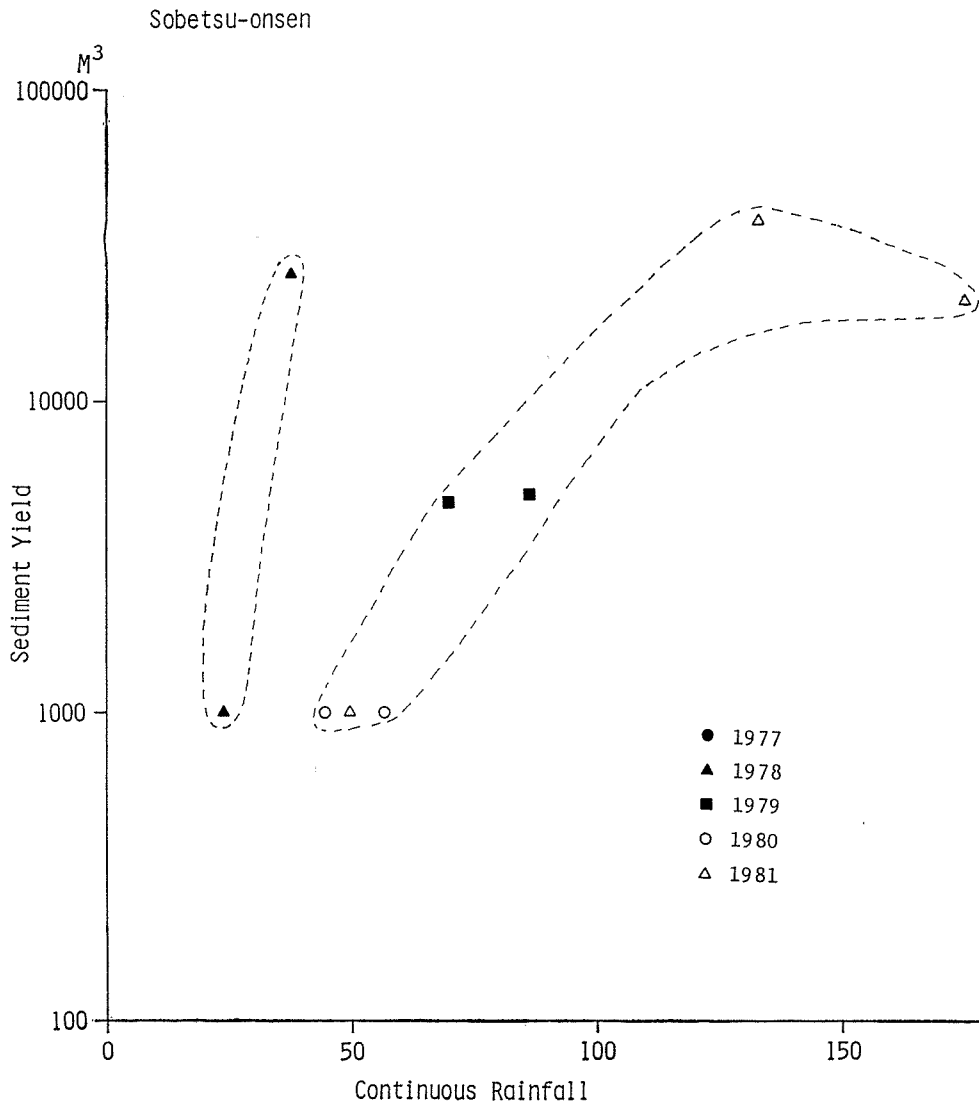

Figure 12. Relationship between sediment yield and continuous rainfall in Sobetsu-onsen R. basin.

6. The process of the time-spatial sequence of mud and debris flows

On the basis of the above results, it can be stated that mud and debris flow was concentrated in the rainy season, that rainfall induced mud and debris flow is small and that sediment yield, which is produced by mass movement, is not always dependent on rainfall. However, these results are not sufficient to explain the time-spatial sequence of mass movement (Figure 13). It is necessary to consider ash fall and crustal deformations which accompany volcanism.

First, it should be pointed out that a large-scale mud and debris flow occurred only in Izumiichinosawa R. just after the eruption. Mud and debris flow also

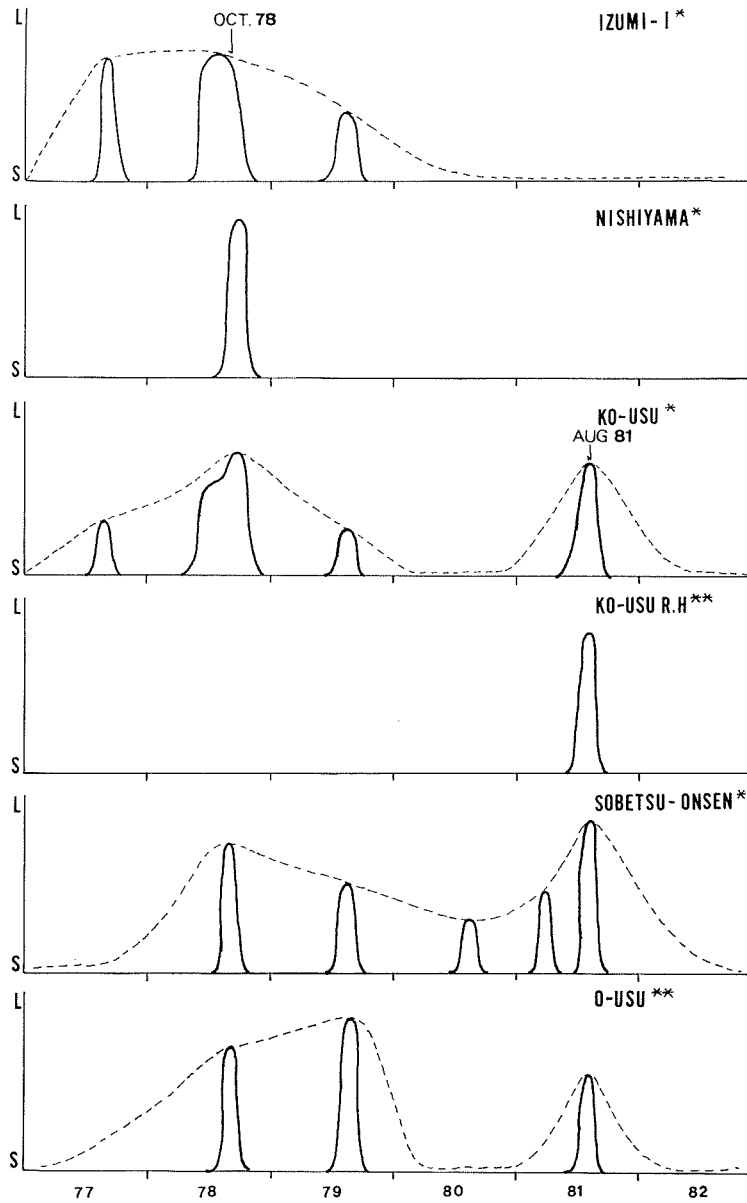

Figure 13. Diagrammatic representation of sediment yield on main valleys of Mt. Usu during the period 1977–1982. L: large-scale, S: small-scale, *: tephra covered basin, **: basin affected by crustal deformation.

occurred in the Ko-Usu R. at that time, but these were small-scale or flow confined to one valley. Suekane (1979) explained that large-scale mass movements in the Izumiichinosawa R. in 1977 were linked to the geomorphic characteristics of wide and steep valley slopes. However, landslides on the steep valley slope mentioned were seldom visible. This implies that most of mud and debris are not produced by landslides on steep valley slopes.

Thus, rainfall and characteristics of the watershed are regarded as the main factors causing large-scale mass movements. First I will discuss rainfall. There were only a few rain-gauge stations around Mt. Usu, consequently I discussed rainfall not on a small-scale, but on a mesoscale. The heavy rainfalls took place in and around Mt. Usu between Aug. 16 and Sept. 14. This distribution shows the possibility that rainfall of high intensity was concentrated on the southwest somma slope. However, rainfall on Mt. Usu was less than in the surrounding areas of Mt. Usu on Sep. 10–11 and 21 (Figure 14). According to this distribution of rainfall, rainfall cannot be considered to be the only main factor triggering debris flow in the Izumiichinosawa R.

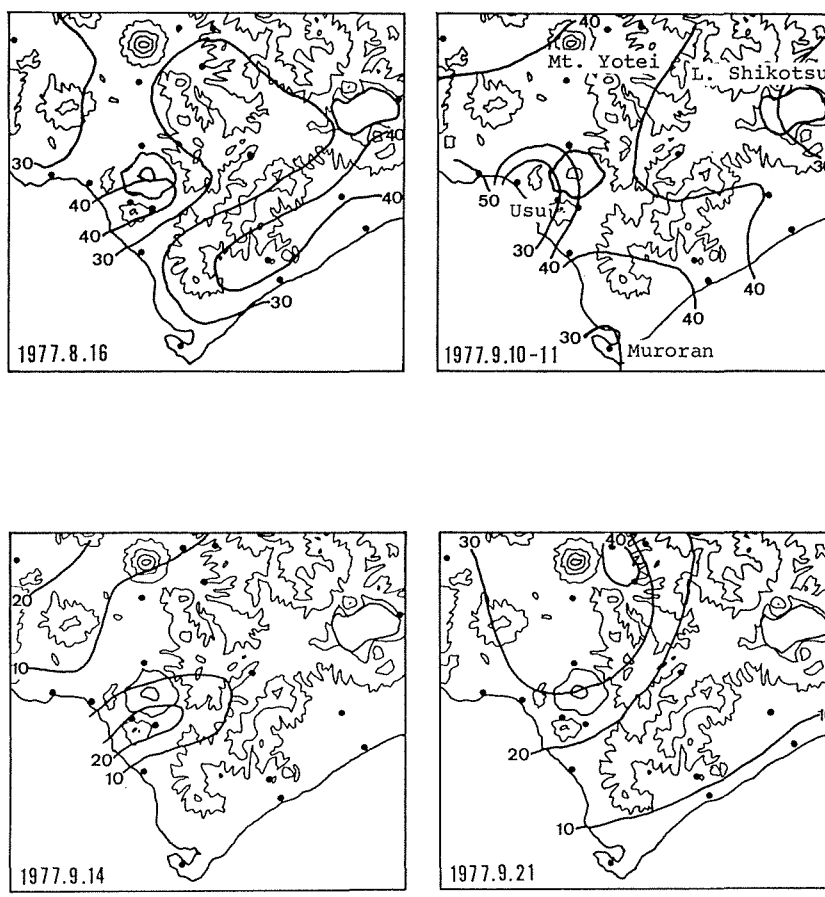

Figure 14. Distributions of rainfall triggered debris flow in 1977.

The second factor is the characteristics of the watershed and the following three characteristics were pointed out.

1) The upper reaches located on the atrio were covered by thick tephra.

2) The valley bottom was filled with sediments by past debris flow and formed terraces.

3) The shape of the basin is narrow.

As mentioned above, it is reasonable to consider as a factor of debris flow that overland flow which resulted from rain on the upper reaches scoured the valley bottom and terraces.

Second, it should be pointed out that in most of valley around Mt. Usu mud and debris flow occurred in late September and late October, 1978. Particularly large-scale mud and debris flow with more than 10,000 m^3 of sediment occurred in almost all the valleys on Oct. 24. The factors which triggered large-scale mud and debris flow in this period are summarized as follows;

1) A fine ash fell on Sept. 12/13, and a hard crust was formed on the surface. This helped to generate overland flow which resulted in erosion and mass movement.

2) The rainfall was an intense local storm. The recorded maximum hourly rainfall on the north slope was 24.5 mm and the maximum intensity for ten minutes reached 21.0 mm. The area stricken by this downpour was limited to the west and north slopes.

This large-scale mass movement significantly affected the following mass movements: In basins covered with thick tephra such as the Nishiyama R., the Izumi-ichinosawa R. and the Ko-Usu R. mass movements drastically decreased in number and magnitude after the mudflow of Oct. 24, 1978. This contributed to the removal of sediments from the valley bottoms. On the contrary, in basins affected by crustal deformation debris flows increased, because mud and debris were directly

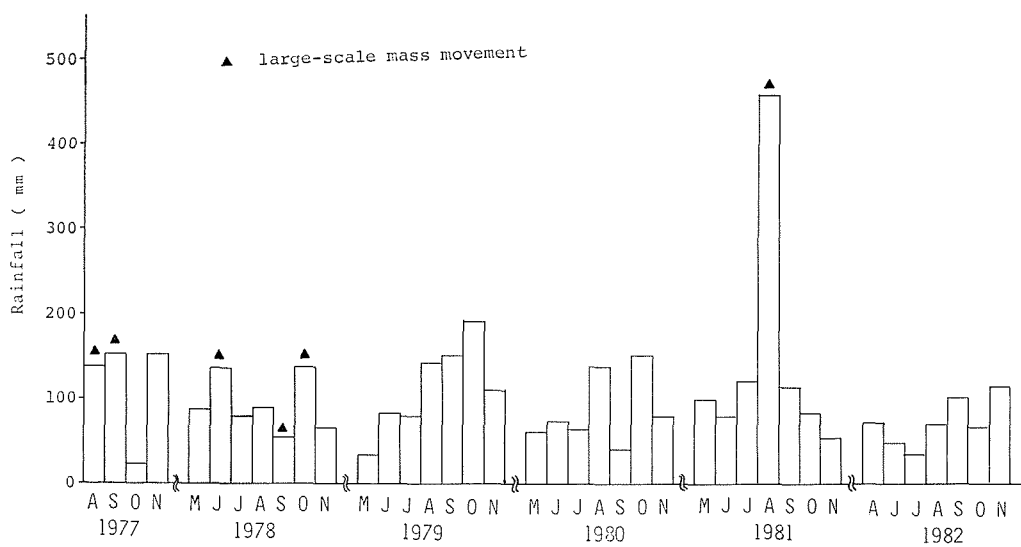

Figure 15. Monthly rainfalls between May and November in each year.

supplied from landslide scars on the upper reaches. As mentioned above, it can be said that mass movements occurred mainly in Izumiichinosawa R. during 1977 in relation to the First Stage eruptions and that large-scale mass movements occurred from Sep. to Oct. in 1978 in relation to the Second Stage eruptions.

Third, it should be point out that large-scale debris flow occurred mainly in basins on the northern somma slope affected by crustal deformations in the summer of 1981. The factors which triggered large-scale debris flow in the summer of 1981 are considered to be rainfall and continuous crustal deformations. Figure 15 shows monthly rainfall after the eruption. The amount of rainfall in Aug., 1981 was more than double that of other months. In August, these were four rainfalls with more than 50 mm of continuous rainfall including two rainfalls with 100 mm. It can be concluded that these climatic events contributed to triggering large-scale mass movements and that the continuous crustal deformation, although weak, also helped mass movements to occur (the northern somma slope was unstable due to crustal deformations which took place just after the eruption). The faults and fissures which developed on the somma slope particularly helped landslides to occur.

Mass movement hardly occurred since 1982. It can be concluded that the supply of mud and debris to valley bottoms ceased. However, the potential of mass movement would be continued as long as the sediment exists on the valley bottoms.

As mentioned above, it is reasonable to explain the sequence of mass movement after the eruption by its relation to ash fall, crustal deformation and rainfall.

7. Conclusion

The purposes of this study were to summarize the post-eruption erosion in other volcanoes, to discuss the characteristics of mud and debris flows after the 1977 eruption of Mt. Usu and to explain the process of the time-spatial sequence of mud and debris flow.

It is common to volcanoes in the world that erosion and mass movement progress rapidly on slopes covered with new tephra and newly formed cones for a short time after the eruption. However, their duration, magnitude and dominant processes are different in case of each volcano due to the difference of their geographical location, scale and activity.

I have verified that in the case of Mt. Usu after the 1977–1978 eruption mud and debris flows frequently occurred during the rainy seasons of the first four years, and accelerated erosion proceded for the same duration. Mud and debris flows were triggered even by ordinary rainfall. Maximum sediment yield by a single occurrence reached $3\text{–}4 \times 10^4$ m^3, but these values are not large when compared with volumes which were produced by other volcanoes and past large debris flows in Japan. It is characteristics in the case of Mt. Usu that large specific sediment yields occurred repeatedly over a short period.

The sequence of mud and debris flow after the eruption can be explained by its relation to ash, crustal deformation and rainfall.

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(JE): in Japanese with English abstract

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