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Seismic Activity Immediately before and in the Early Stage of the 1977 Eruption of Usu Volcano, Hokkaido, Japan

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Abstract

The first eruption of Usu Volcano occurred near the summit at 09:12 a.m. (JST) on August 7, 1977 after 32 years' dormancy. This eruption was not only preceded by a number of earthquakes, but also followed by remarkable earthquake swarms. During the early eruptive stage four large and two moderate eruptions occurred accompanied by both volcanic tremors and high seismic activity. The data on the earthquakes were obtained from two routine stations, HSS ($\Delta=58$ km) and ERM ($\Delta=167$ km), and a temporary station, SSU ($\Delta=2.5$ km), and these seismic activities were studied.

Thirty-two hours before the first eruption premonitory earthquakes began to occur and for 9 hours before the eruption exponential increase in earthquakes was observed. For 4 to 7 hours before the outbreak, stations near and distant from the volcano also observed premonitory variation from high frequency to low frequency in seismic wave form. A series of the six eruptions occurred through the following five stages: (i) cloud with ash and pumice ascending up high, (ii) seismic activity diminishing in intensity, (iii) successive tremors which lasted to the end of the eruption increasing and decreasing in amplitudes, (iv) ejection of ash and pumice coming to rest, and (v) a calm state with no earthquakes and no tremors dominating for a while. The later the eruption occurs, the slower the decline of seismic activity as well as the growth of tremors becomes. A linear relationship was found between the height of volcanic cloud up to 10 km and the amplitude of tremors.

1. Introduction

In the morning (09:12, JST) of August 7, 1977 the first eruption of Usu Volcano, Hokkaido, Japan (Fig. 1) which had been dormant for 32 years since the formation of Showa-Shinzan lava dome in 1943–1945 took place at a newly opened crater on the summit of the volcano. During the early eruptive stage from August 7 to 14, there were four large and two moderate eruptions, which were accompanied by pumice and ash shower[1]. These eruptions were followed

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by remarkable earthquake swarms and crustal movements. The remarkable crustal movements including formation of new mountains in the area around the summit of volcano and horizontal compression in the northeastern foot of the volcano are still in progress[2]. The earthquake swarm is also continuing up to August, 1979 (Fig. 2).

For prediction of eruptions in Usu Volcano, Yokoyama et al. (1973)[3] have indicated the importance to keep on watching the seismic activity based on the study of historic activities of the volcano. This 1977 eruption was also preceded by a remarkable earthquake swarm for 32 hours before the outbreak of the eruption[4]. Half a day after receiving the emergency reports from Japan Meteorological Agency (JMA), that informed a rapid increase of small earthquakes occurring near the volcano, Hokkaido University set up three temporal stations with seismographs around Usu Volcano and began to observe the earthquakes. The seismographs recorded many earthquakes before the outbreak of the eruption. The data for the earthquakes have served for not only studies of prediction of eruptions but also for understanding the mechanism of eruption.

This paper is to present some results derived from analyses of seismograms and also to introduce a relationship between eruptive and seismic activities during time from August 6 to 20, 1977.

2. Data

Fig. 1 shows the locations of Usu Volcano and seismographic stations installed near the volcano. There are five seismographic stations near the volcano, three of which, SSU, YSE, and ODR are the temporal stations operated by Hokkaido University and one of which, JMA-SH, also a temporary station operated by JMA. Another station, JMA-A located on the somma had been operated by JMA from 1966, but the seismographs at the station stopped to record on August 7, 1977 because of a breakdown caused by pumice falls. At station SSU, which is located about 2.5 km east of the new crater at the southeastern foot of the Ko-Usu lava dome, three component geophones are installed. This station installed also three vertical geophones which were placed to form a tripartite array. Observations at the four temporary stations started from the evening of August 6, the day before the first eruption.

The parmanent stations, HSS and ERM, telemetering to Hokkaido University in Sapporo are located about 58 km northeast and about 167 km

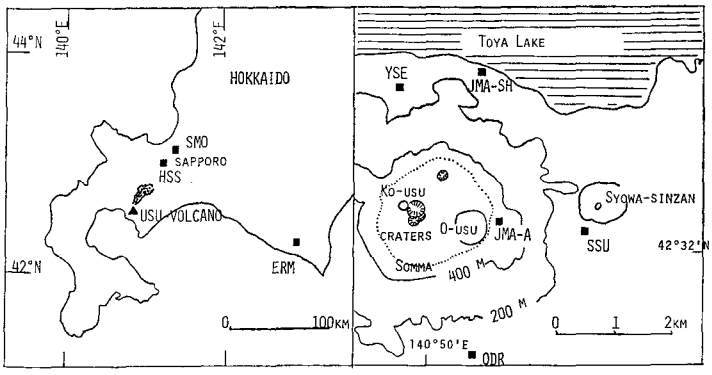

Fig. 1 Location maps of Usu Volcano and seismograph stations. Stations in the left and station JMA-A in the right are the routine stations, the other stations being set up on August 6, 1977.

east of Usu Volcano, respectively. Most seismic data used in this study are those recorded at HSS, ERM, and SSU by the multi-channel ink-writing recorders. In addition to these data, seismic data observed at JMA-A, JMA-SH, and SMO which were reported by the Sapporo Meteorological Observatory (SMO), JMA were also referred to.

Fig. 3 shows overall characteristics of the seismographs used. We can roughly estimate the detectivity of each seismograph for the earthquakes occurring in Usu Volcano from these characteristic curves. The stations, JMA-A and SSU, can observe all earthquakes with $M=0.6$ or larger and with $M=0.8$ or larger, respectively. The lower limit of magnitudes of the earthquakes to be observed at HSS varies from 1.5 to 2.5 and that to be observed at ERM varies from 2.5 to 2.8 depending upon whether predominant frequencies in seismic waves are relatively high or low.

3. Seismic activity immediately before the eruption

3.1 Temporal variation in frequency of earthquakes

JMA[4] reported that among the premonitory earthquakes observed at JMA-A the first one occurred at 01:09 a.m. and the earthquakes that were felt by residents near Toya Lake began to occur after 03:30 a.m. on August 6. From 12 to 18 o'clock on August 6, the distant stations, HSS and ERM, observed transitory seismic activity for the volcano (Fig. 4 and Fig. 7). After midnight of August 6 the occurrence of earthquakes having larger

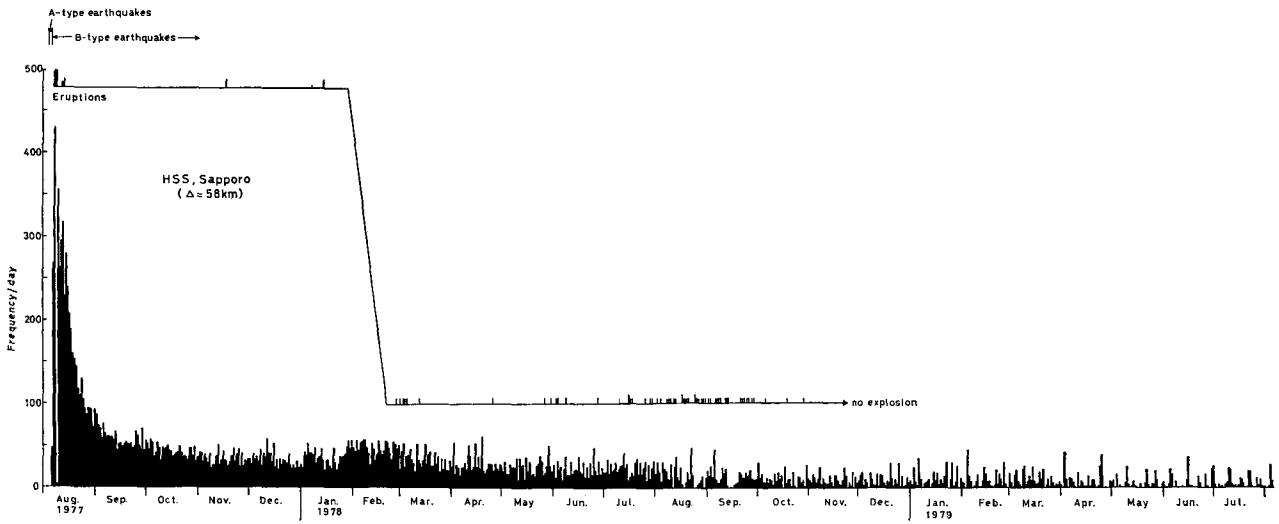

Fig. 2 Daily frequency of the earthquakes occurring in Usu Volcano observed at HSS (Sapporo Seismological Observatory). Magnitudes of the earthquakes are about 2.5 or larger.

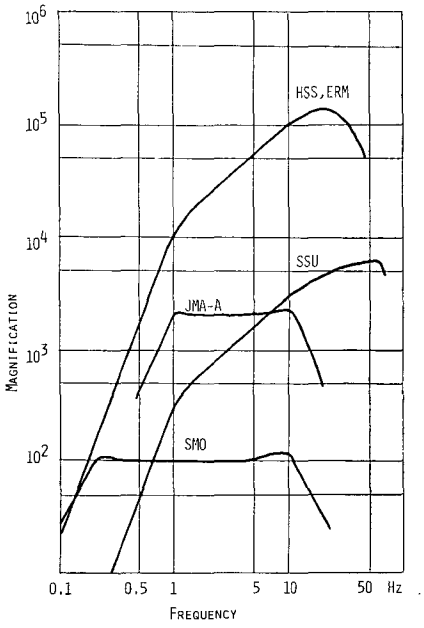

Fig. 3 Overall frequency responces of seismographs.

amplitude increased with time. Rapid increase in frequency of earthquakes occurred about 1 o'clock on August 7 and continued to the time of the outbreak of eruption (Fig. 4 and Fig. 6).

Sixty-five percent of the earthquakes observed at SSU had *S-P* times of 0.6 to 1.8 sec as shown in Fig. 5, which show that these earthquakes occurred near the summit of the volcano (Hokkaido University, in preparation). In addition to these earthquakes, many microearthquakes having *S-P* times of about 0.2 sec and seismic waves with very short period (about 20Hz) were observed only at SSU. Their hypocenters could be located almost under the Showa-Shinzan lava dome. These microearthquakes, which are tentatively named "AS-type earthquakes" by Suzuki and Okayama[5], have not occurred after the first eruption except for several ones. The number of earthquakes observed at SSU except the AS-type earthquakes increased exponentially with time just before the first eruption.

3.2 Premonitory change in seismic wave form

An evident change in seismic wave form was observed by near and distant stations from 4 to 7 hours before the outbreak of the first eruption[5)6)].

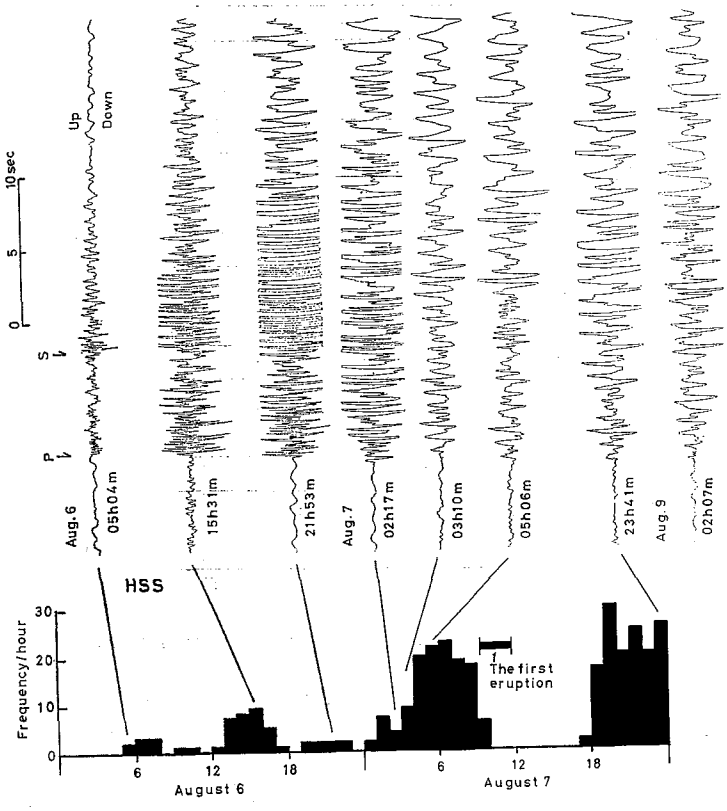

Fig. 4 Hourly frequency and seismograms of earthquakes observed at HSS. Several seismic traces are partly in saturation in amplitudes.

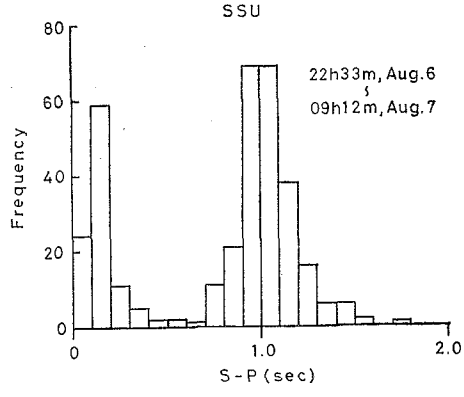

Fig. 5 *S-P* time distribution of the earthquakes observed at SSU immediately before the first eruption.

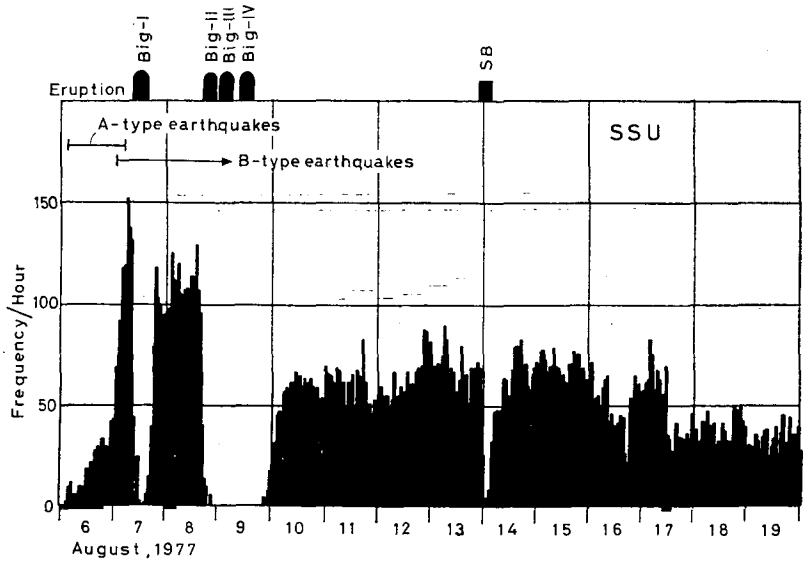

Fig. 6 Hourly frequency of earthquakes observed at SSU from August 6 to 19. Since no observations were made at SSU during the periods indicated by thick lines under the abscissa, the frequency of earthquakes during those periods is estimated from the observed data at JMA-A and JMA-SH.

Fig. 4 shows some examples of seismograms of vertical component with a histogram for the earthquakes observed at HSS. On the seismogram at 05:04 on August 6, *P* and *S* phases with clear onsets are recorded. In the part of *P* waves recorded, waves with a frequency of about 5Hz are predominant, while in the part of *S* waves those with a frequency of about 3Hz are predominant. Such characteristics in these waves as having clear onsets and followed by waves with a relatively high frequency component had been observed till about 2 o'clock on August 7.

After 3 o'clock, earthquakes in which *P* and *S* phases have weak onsets and are followed by low frequency waves of about 1.5Hz occurred, and increased in number up to the time of the first eruption. However, after that time earthquakes including high frequency waves decreased in number. The earthquakes with the latter characteristics still now occur. We conventionally call the former earthquakes "A-type earthquakes" and the latter ones "B-type earthquakes", referring to Minakami et al.[7] and Kizawa[8] who studied the seismic activity before and during the formation of the Showa-Sinzan lava dome in 1943–1945. The difference between the A- and B-type earthquakes

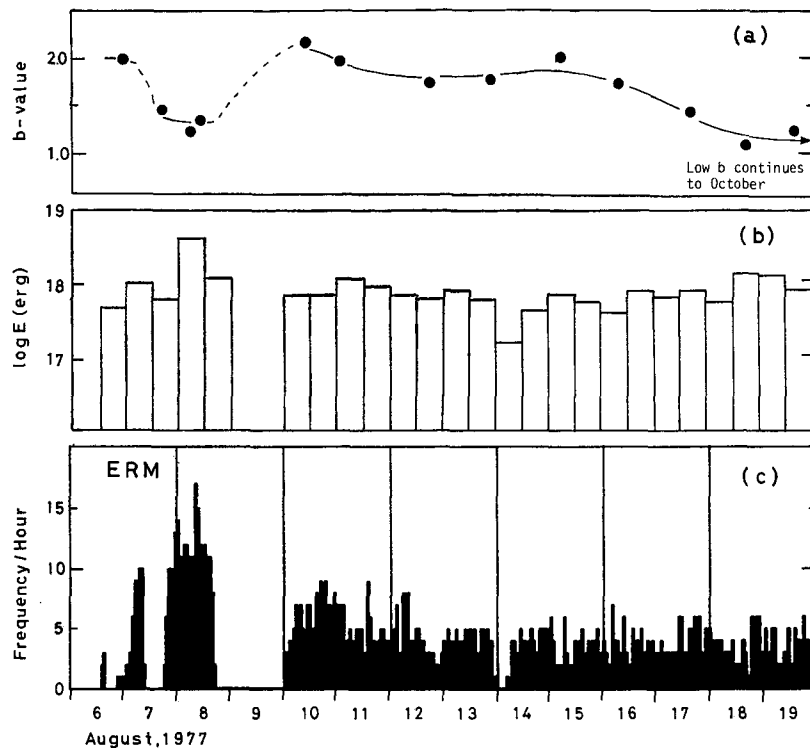

Fig. 7 Earthquake data observed at ERM from August 6 to 19. (a) Temporal variation in the value of b in the magnitude-frequency relation. (b) Released energy of seismic waves for every twelve hours. (c) Daily frequency of earthquakes.

in the 1977 eruption is considered to the result of the difference in focal conditions such as the depth of hypocenter and the stress drop at source region. Since we can not find the systematic difference in focal depths between A-type and B-type earthquakes, based on our judgement of the S-P time histogram at JMA-A and the data obtained by the tripartite array observation at SSU, it may be possible to conclude that the difference in the stress drop accounts for the difference in the earthquake type during the 1977 eruption.

4. Seismic activity in the early stage of the eruption

4.1 Frequency of earthquakes and the associated b-values

The frequency of earthquakes became maximum during the period of half a month after August 6, 1977, and since that time it decreased with time as

shown in Fig. 2. The eruptive activity was also the most active during that month. A summary for the activity compiled by Katsui et al.[1] is listed again in Table 1. A schematic illustration for some large eruptions is shown in the upper part of Fig. 6 and a detailed process for the eruption in Fig. 8.

Table 1. List of eruptions[1] and durations of their "calm stages"

Eruption	Date & time	Duration of eruption (A)	Maximum height of volcanic cloud (B)	Product of (A) & (B)	Occurrence time of the 1st earthquake after the eruption	Duration of calm stage
Big I	8/7 09h12m -11h40m	2.47 hrs	12,000 m	29.6hr·km	8/7 18h01m	381 min.
Big II	8/8 15h37m -18h00m	2.38	10,000	23.8	(Big III)	>340
Big III	8/8 23h40m -8/9 02h15m	2.58	10,000 ?	25.8 ?	(DT)	>195
DT	8/9 05h30m -07h30m	2.0	5,000 ?	10.0 ?	(Big IV)	>170
Big IV	8/9 11h20m -14h20m	3.0	9,000	27.0	8/10 00h10m	590
SB	8/13 22h37m -8/14 01h55m	3.3	4,000 ?	13.2 ?	8/14 04h49m	174

The hourly frequency of the earthquakes observed at SSU with magnitudes larger than about 1.0 is shown in Fig. 6. Fig. 7c shows hourly frequency of the earthquakes observed at ERM with magnitudes larger than about 2.8. Comparison of Fig. 6 with Fig. 7 shows that the maximum frequency of earthquakes in Fig. 6 occurred in the morning of August 7, while that in Fig. 7c at a time between the end of the first eruption (Big I) and the beginning of the second one (Big II) on August 8. Such difference in the times giving the maximum frequency must be responsible for b-values representing a magnitude-frequency relation which may change with time.

In Fig. 7a shown are b-values which are obtained for every 48 earthquakes observed at ERM with a magnitude equal to or larger than 3.1, the calculation of the b-values being made by Utsu's method[9]. The figure clearly shows that the b-values change with time. A value of b is 2.0 before the outbreak of Big I, which decreases to a value of 1.3 to 1.5 after that eruption. After Big IV it increases again and approximately in a constant, that is a high value about 1.9, during the period from August 10 to 15. After this period, the value of b decreases gradually with time and takes a value of about 1.0 on August 18,

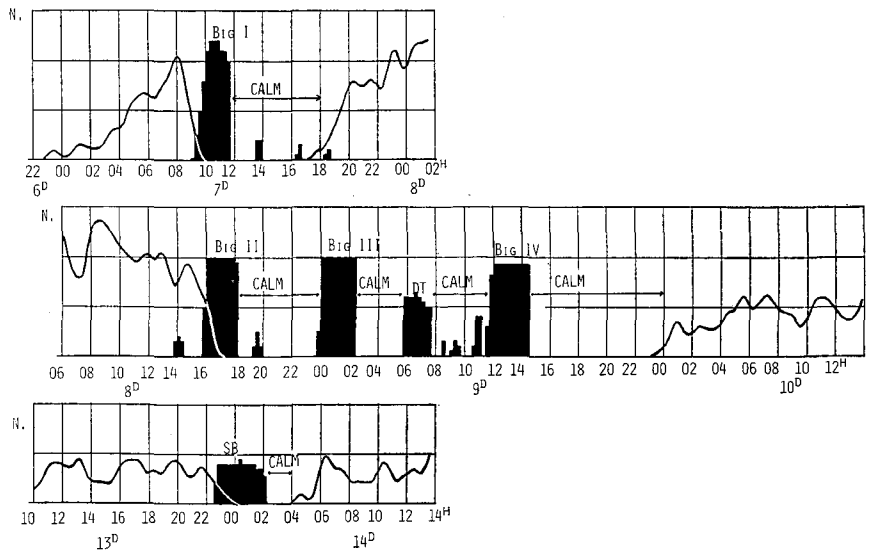

Fig. 8 Relationship between seismic and eruptive activities. Seismic activity is represented by a curve obtained by smoothing the frequency of earthquakes in Fig. 7c. Eruptive activity is represented by the cloud height[1].

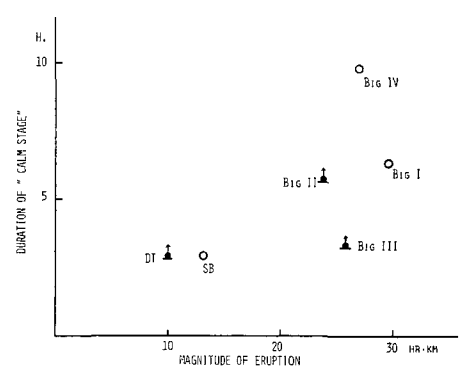

Fig. 9 Relationship between the duration of the calm stage in Fig. 8 and the magnitude of eruption defined by the product of the cloud height and the duration of eruption. These quantities are also listed in Table 1.

which is in a nearly constant of 1.1 till October. Shimozuru et al.[10] obtained a similar result from the analysis of acceleration seismograms, in which the m-coefficient ($=b+1$) foramplitud e-frequency relation changes from 3.1 during the time from August 13 to 15 to 1.5 during the time from 17 to 21. The

temporal variation in the frequency of earthquakes and the value of b must be affected by the rate of energy released by seismic waves as shown in Fig. 7. The maximum of released energy in a month through the time from 1977 to 1979 did not take place at the same time of the maximum frequency of earthquakes (in Fig. 2), but took place early in September, 1977 (JMA[11]).

4.2 Complimentary relation between the activities of eruptions and earthquakes

The frequency of earthquakes was drastically decreased just after eruptions took place, and gradually increased a little while following the eruptions (Fig. 6), (Suzuki and Okayama[5], JMA[11], Moriya[12], and Tohoku University[13]). Complimentary relation between the activities of the eruptions and the earthquakes were found except for the period of the following "calm stage". The details of the temporal relation between eruptive and seismic activities are shown in Fig. 8. The figure shows that the activity of earthquakes and tremors was not observed for a few hours after the end of eruptions. We call the state during the activity "calm stage". The durations of the calm stages estimated for the six eruptions are listed in Table 1. The duration of the calm stage is plotted against the eruptive magnitude as shown in Fig. 9. In this figure it may be possible to infer that the duration of the calm stage is roughly dependent on the eruptive magnitude.

4.3 Volcanic tremors

Volcanic tremors were observed during times in which the four large and two moderate eruptions occurred[5][11][12]. Fig. 10 shows examples of the tremors observed at SSU during the Big I the left figure shows tremors observed in the earlier stage of the eruption, the right one those observed in the most active stage during the eruption. Predominant frequency of the tremors in the earlier stage is 2-3Hz.

Fig. 11 shows the temporal variations of seismic activities and those of amplitudes of tremors for every five minutes for each eruption. For Big I, the number of earthquakes is rapidly decreased and the amplitude of tremors sharply grow up immediately after the beginning of the eruption. For Big II, the seismic activity did not rapidly decline, but lasted for about one hour after the beginning of the eruption. The tremors gradually increase in amplitudes. Seismic activity for SB, lasted longer than that for other eruptions and the tremors for the eruption started an action a few ten minutes before the end of the eruption.

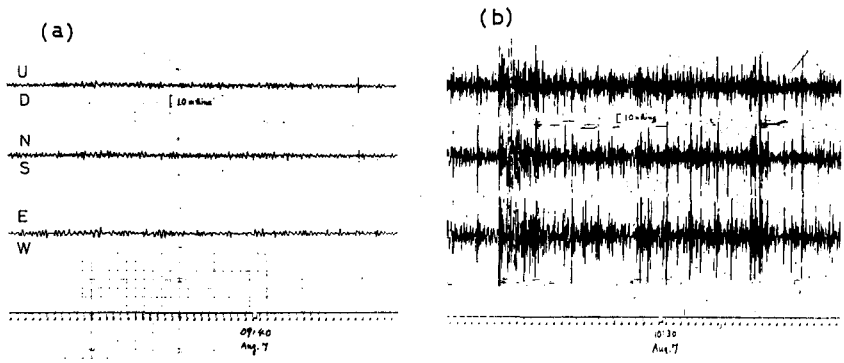

Fig. 10 Seismograms showing volcanic tremors observed at SSU during eruption Big I. The left is seismograms obtained in the early stage and the right those obtained in the most active stage. Many impulses recorded in the right seismograms are due to pumice falls near the geophones 2.5 km east of the vent. A pulse interval in the lowest trace presents one second.

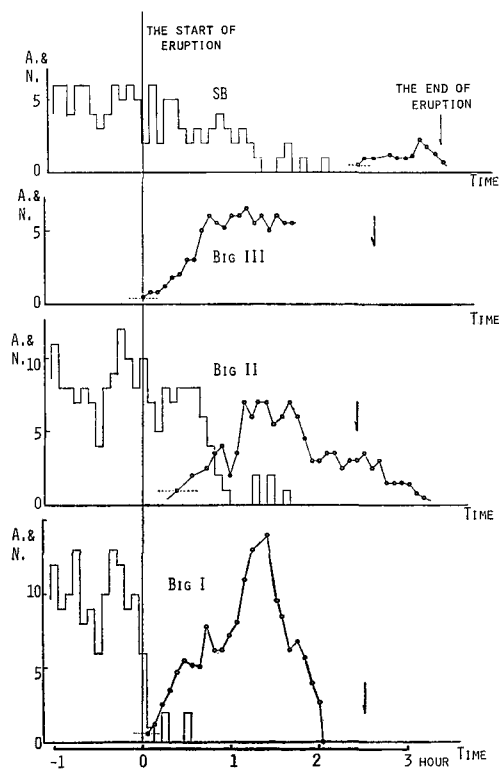

Fig. 11 Temporal variations in seismic activities and volcanic tremors during eruptions. The seismic events (bar graph) and the maximum amplitudes of tremors (circles) were measured every five minutes at SSU.

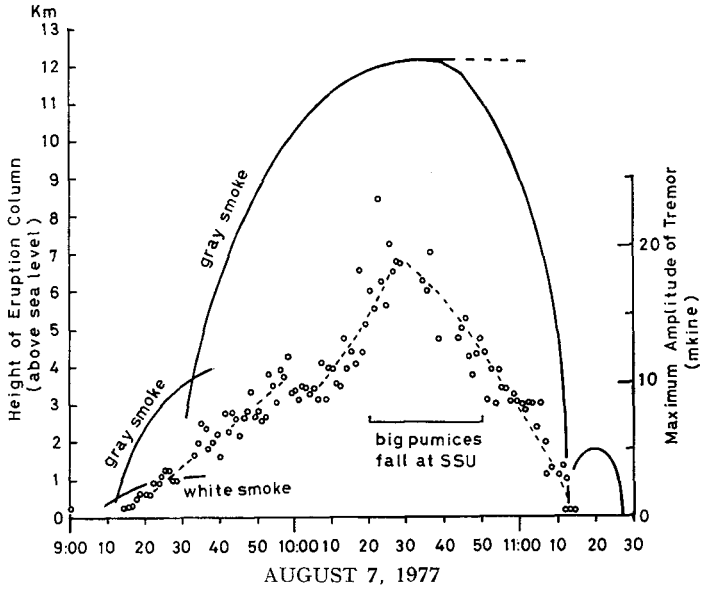

Fig. 12 Temporal variations in cloud height (solid lines) and amplitude of volcanic tremor for every minutes ovserved at SSU (circles) during the eruption Big I. The data of cloud height are referred to Katsui et al.[1] and personal communication from Niida.

Fig. 12 shows the temporal variation in the height of eruption column (Katsui et al.[1] and personal communication from Niida) together with the variation in the tremor amplitudes observed at SSU for Big I. The figure shows that the eruption cloud reached a maximum in height at about 10:30 at which the amplitude of tremors became maximum. The relation between the height of the ascending cloud and amplitude of the corresponding tremor obtained from Fig. 12 is shown in Fig. 13. The cloud height up to 10 km may approximately be expressed as a linear function of the amplitude of tremors. A least squares fit to these quantities is

$$H = 0.42 + 0.89A \tag{1}$$

where H is the cloud height in km, and A, the tremor amplitude in mkine.

The relation between the maximum cloud height and the maximum amplitudes of tremors for the eruptions, Big II, III, IV, and SB also may be approximated by eq. (1). Considerable deviation of the relation between both quantities with cloud heights over 10 km may be caused by atmos-

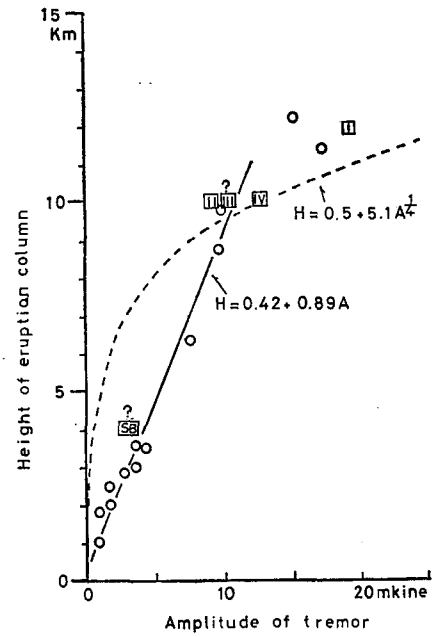

Fig. 13 Relationship between the amplitude of tremors and the height of clouds. Circles represent the heights of ascending cloud during Big I. Squares represent the maximum cloud heights for the five eruptions. The amplitude of tremor for Big IV is estimated from the data observed at JMA-SH. Cloud heights are referred to original data by Katsui et al[1].

pheric conditions different from those within 10 km.

According to Morton et al. formula (Wilson et al.[15]) the maximum height of volcanic cloud, H, can be correlated with the atmospheric and thermal condition, k, and the rate of mass release, $\dot{M}$, that is $H=k\dot{M}^{1/4}$. If k is constant and A is proportional to $\dot{M}$, then H is approximately proportional to $A^{1/4}$. Considerable deviation between a dashed curve of $H \propto A^{1/4}$ and square marks in Fig. 13 may be caused by impropriety to assume the relation of $A \propto \dot{M}$. If the assumption of $A \propto \dot{M}$ is proper, it may be possible to consider that there exists the relation $H \propto A^{1/4}$ only in the cloud heights over about 10 km.

5. Conclusions

Seismic activity immediately before the first eruption at 9:12 a.m. on August 7, 1977 was analyzed on the data observed at the permanent and

temporary stations.

(i) A premonitory earthquake swarm started 32 hours before the outbreak of the 1977 eruption.

(ii) The earthquakes which occurred near the summit of Usu Volcano increased exponentially in number for 9 hours before the first eruption. During this period many microearthquakes also occurred near Showa-Shinzan lava dome but after the eruption very few earthquakes occurred.

(iii) The earthquakes which occurred 4 to 7 hours before the outbreak of the first eruption changed in wave form from A-type to B-type.

The six eruptions among which four are large and two are moderate occurred during the period from August 7 to 14 through the following five stages: (i) cloud with ash and pumice ascending up high, (ii) seismic activity diminishing in intensity, (iii) successive tremors which last to the end of eruption increasing and decreasing in amplitudes, (iv) ejection of ash and pumice coming to rest, and (v) a calm state with no earthquakes and no tremors dominating for a while.

For the first eruption, a linear relationship was found between the height of volcanic cloud ascending up to 10 km and the amplitude of tremors.

The value of b, the coefficient of the magnitude-frequency relation of earthquakes varies with time from 2 to 1 during the period from August to September, 1977.

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