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VOLCANIC MICRO TREMOR OF THE THIRD KIND

By

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Abstract

Nature of the third-kind of volcanic micro tremor at the Volcano Aso and some related problems have been investigated.

At the Volcano Aso, there are four kinds of volcanic micro tremors when classified by their periods, and each has different characteristics. The volcanic micro tremor which has been called "third-kind" by K. Sassa has the Rayleigh type wave form and a period of about 0.5 sec. In the case of the surface wave, in general, its wave forms would greatly be influenced by the conditions of propagation. Therefore, the modes of generation and propagation of the "third kind" have been determined from its frequency spectrum.

The detailed analyses have been made in a series of simultaneous records of the third-kind volcanic micro tremor taken at two stations by the radio tele-recording system, and it is inferred that this wave is considered to be propagated in the form of the Rayleigh type wave having a phase velocity of about 1.2 km/sec.

The frequency analyses of this tremor have been made using an analog type frequency analyser which has a frequency range of 1 c/s to 43 c/s. From these analyses, it has been made clear that the mode of this tremor has a predominant frequency of about 2 c/s in its frequency spectrum. From the comparison between the spectral form of this tremor and theoretically obtained one of the Rayleigh wave in the layered media, it seems that the third-kind of volcanic micro tremor is the "Airy phase" of the normal mode Rayleigh wave which has been guided in a certain layered medium.

On the other hand, the same predominant frequency which could be considered as the leaking modes in the same layered medium, has also been found on the record of frequency-analysed seismic waves. This phenomenon shows that there is a certain layered medium in which the normal or leaking mode of wave can be guided under the observing station.

The Ishimoto-Iida's "m" value was obtained as 3.44 from the statistical study of the third-kind of volcanic micro tremor when it appeared in the form of isolated wave. This value corresponds to the case of very shallow volcanic earthquakes such as B-type.

The peculiar amplitude variations of this tremor before the small eruption of Nov. 17, 1963 were observed. Such a peculiar variation of volcanic micro tremor has always been observed before eruption of this volcano. Therefore, it may give a clue for the prediction of eruption of this volcano.

Introduction

The characteristics of the volcanic micro tremors at Volcano Aso are closely related to the activity of the volcano. According to K. Sassa, there are four kinds of volcanic micro tremors when classified by their periods. Each of these four kinds of tremors has different characteristics.

In the previous paper (Kubotera, [1963]), nature of the 2nd-kind of volcanic micro tremor and its source conditions have been discussed. The present paper is concerned with the nature of the 3rd-kind of volcanic micro tremor.

The volcanic micro tremors at Volcano Aso are observed in the form of several isolated groups of regular wave trains during active periods of the volcano, while during more active periods they become a continuous wave train, and each of the various types of micro tremors has its own peculiar period. From this phenomenon mentioned above, it seems that they have a different wave mode due to the different wave guide.

The wave forms of the tremors on the seismograms depend on, in general, the characteristics of the active origin of the volcano, the mode in which wave has propagated and observing instruments. However the main feature of the wave forms of bodily waves may not be greatly influenced by the condition of propagation, while in case of the surface waves, its wave forms may greatly be influenced by the condition of propagation.

In the previous paper (Kubotera, [1963]), the former case has been investigated. Namely, the spectrum of waves having a long period and compressional wave forms such as the 2nd-kind of volcanic micro tremor may be taken to indicate information concerning the nondistorted source conditions. For this reason, an attempt was made to determine the source conditions of the tremor from its character of frequency spectrum and it is concluded that the tremor of the 2nd-kind originates from the free oscillation of a liquid sphere (a model of the magmatic chamber) beneath the active crater of the volcano.

On the other hand, the volcanic micro tremor of the "3rd-kind" is the Rayleigh type wave having a period of about 0.5 sec. Therefore the later case may correspond to the 3rd-kind of volcanic micro tremor which has the features of surface waves. The present study was initiated to dertermine the mode of generations and propagations of the 3rd-kind of volcanic micro tremor from its frequency spectrum.

Simultaneous observations of the 3rd-kind of volcanic micro tremor at two stations

The 3rd-kind of volcanic micro tremors of Volcano Aso is recorded as several isolated wave groups, as shown in Fig. 1, during the active period of the volcano.

Simultaneous observations of this tremor have continuously been carried out at two stations since 1960 (Kubotera et al., [1963]). An example of the 3rd-kind of volcanic

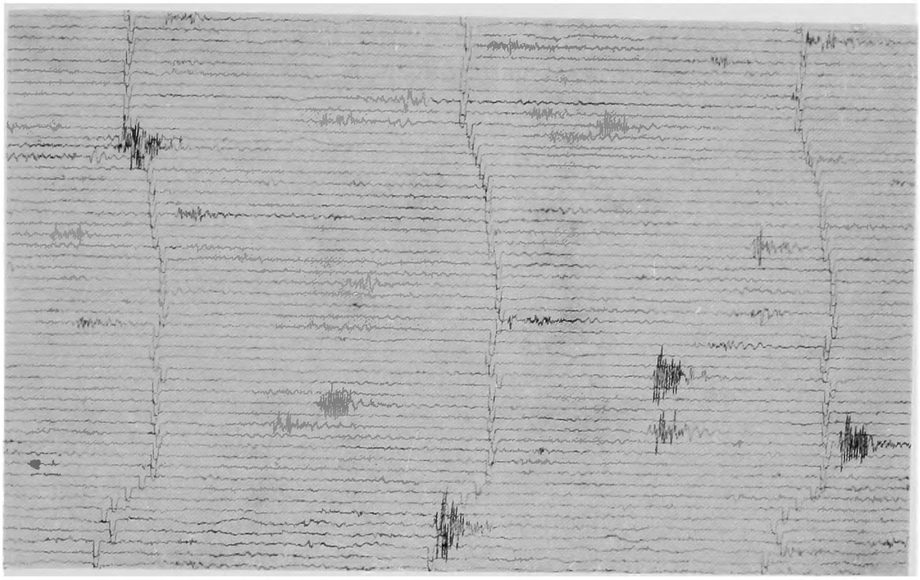


Fig. 1. Seismic record of the 3rd-kind volcanic micro tremor when it appears in the form of isolated waves.

Fig. 2. Simultaneous records of the 3rd-kind volcanic micro tremor.
Upper part : Hondō
Lower part Laboratory

micro tremor recorded simultaneously at both stations is shown in Fig. 2, when it appears in the form of isolated waves. The record on the upper part of Fig. 2 was obtained at the Volcanological Laboratory of KyotoUniversity by means of the radio-telemeter (Kawahara et al., [1960]) from Hondō observing station, about 1 km apart from the active crater of Naka-dake of the Volcano Aso, and that of the lower part was obtained at the Laboratory, about 7.2 km from the crater. At the both stations, same types of electromagnetic seismometer of the vertical one were used. Their natural period T_0 and the natural period of galvanometer T_g are $T_0=1.2$ sec. and $T_g=0.8$ sec., respectively, those damping constants being $h_0=h_g=1$.

These records shown in Fig. 2 may be compared, the gain of instrument at the "Hondō" station being about one-tenth of that at the Laboratory. From these records, it is found that this tremor was propagated near the crater. From the measurement of the time difference of the same phases on both records, the phase velocity of this tremor, when its origin was assumed to be near the crater, has been determined as about 1.2 km/s.

The observational results concerned with the longitudinal wave velocity (P-wave velocity) at the area of Volcano Aso have been obtained by various experimental methods. From the seismic prospecting tests which have been carried out near the active crater of the Volcano Aso, Naka-dake (Yoshikawa et al., [1959]), P-wave velocity was found 2.5 to 3.5 km/sec beneath the surface layer, having a P-wave velocity of 1.4 to 1.6 km/sec, while laboratory measurements of P-wave velocities made by the writer (Kubotera, [1964]) using ultrasonic wave, show

Taka-dake, Naka-dake, Neko-dake region	:	5.65∼4.58 km/sec
Kishima-dake, Oozyo-dake region	:	3.44∼3.05 km/sec
Eboshi-dake region	:	3.72∼2.62 km/sec

for Aso lava specimens.

On the basis of these observations, it seems that observed phase velocity of 1.2 km/sec is the probable velocity of the Rayleigh wave in this region.

From the similarity in both records of Fig. 2, this wave is considered to be propagated in form of a stational wave form near the crater, and from the analysis of this wave form, it seems to be the predominant surface wave regarded as the Rayleigh wave.

On the other hand, volcanic micro earthquakes have been observed near or in the active crater using the short period geophones by S. Kikuchi [1963]. This micro earthquakes and the volcanic micro tremors of 3rd-kind can simultaneously be observed and there is one-to-one correspondence between both waves. It is inferred that the volcanic micro tremor of the 3rd-kind originates from the disturbance due to the small earthquakes generated by gas explosions beneath the crater and it propagates along the surface layer.

Frequency spectrum of the 3rd-kind of volcanic micro tremor

Frequency analyses of the 3rd-kind of volcanic micro tremor have been made often, using an analog type frequency analyser which has a frequency range of

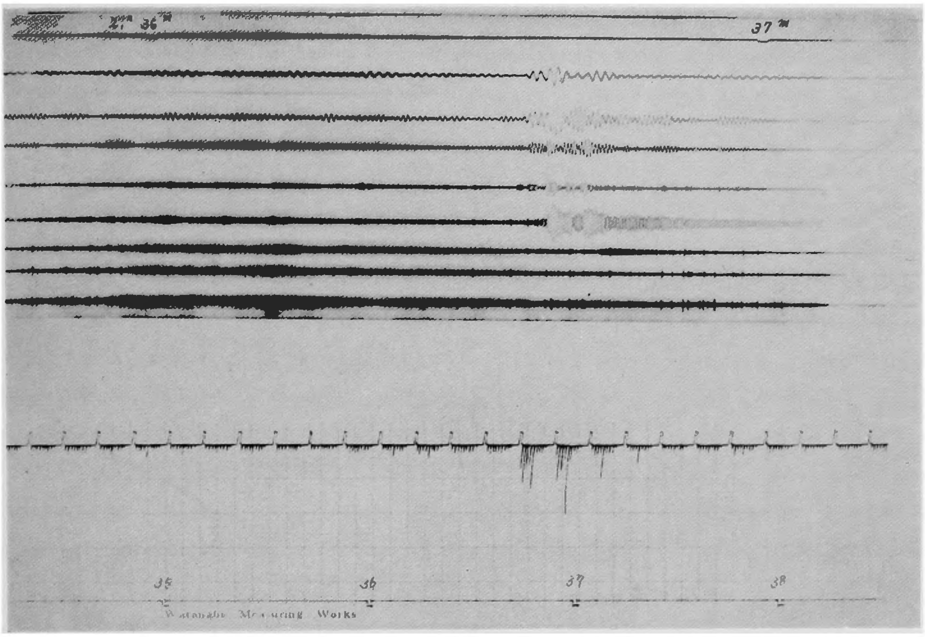


Fig. 3. Frequency analysed record of the 3rd-kind volcanic micro tremor.

1 c/s to 43 c/s of 8 bands. An example of an analysed record of the 3rd-kind volcanic micro tremor is shown in Fig. 3. The frequency bands of this analog type frequency analyser are as follows:

Trace number	Frequency band
1	1.0∼ 1.6 c/s
2	1.6∼ 2.6 c/s
3	2.6∼ 4.2 c/s
4	4.2∼ 6.7 c/s
5	6.7∼10.7 c/s
6	10.7∼17 c/s
7	17 ∼27 c/s
8	27 ∼43 c/s

As can be seen in this figure, the peak frequency band of this wave group is 1.6∼2.6 c/s. The trace amplitude of this record is the velocity amplitude, then the converted displacement amplitude is illustrated graphically in Fig. 4. In this figure, the frequency response of the 3rd-kind volcanic micro tremor is more marked.

As a result, it has been made clear that the mode of the 3rd-kind of the volcanic micro tremor is the Rayleigh wave type having a predominant frequency of about 2 c/s in its frequency spectrum.

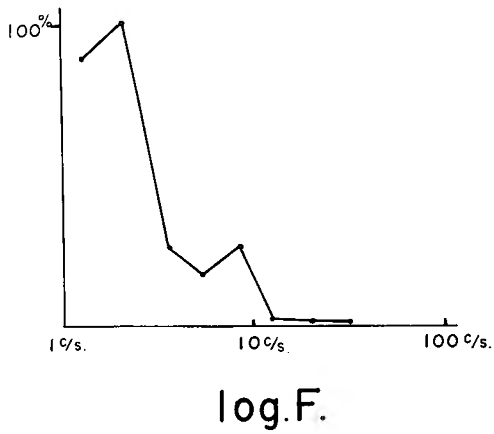


Fig. 4. Displacement-amplitude vs. frequency curve of Fig. 3.

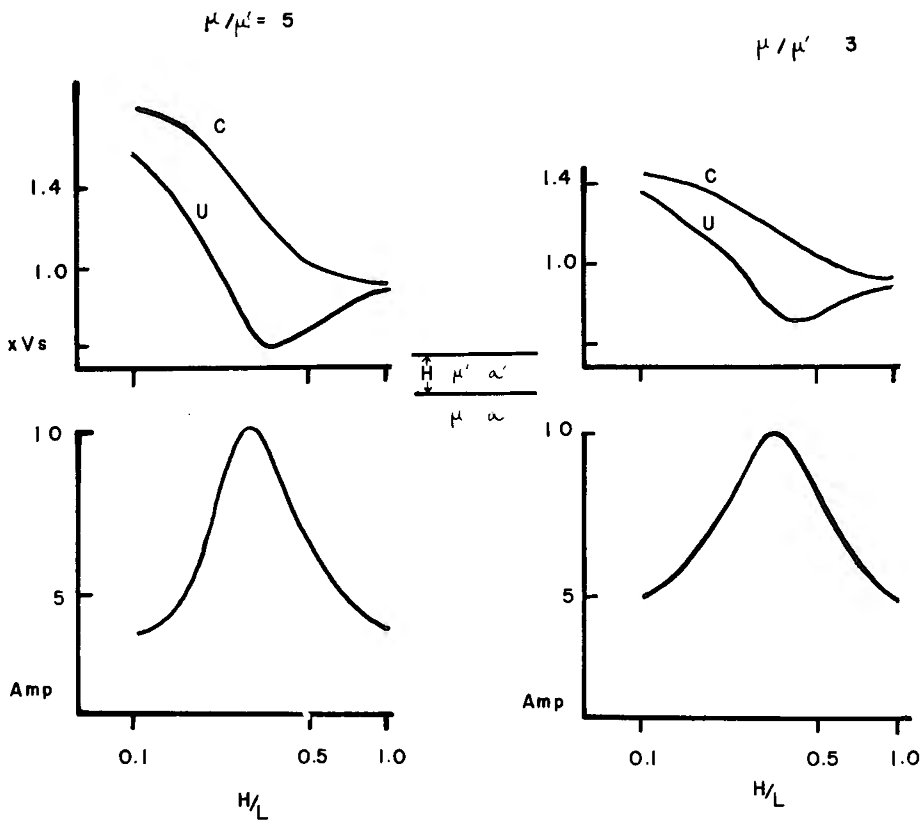


Fig. 5. Phase- and group-velocity and amplitude vs. H/L curves of the Rayleigh wave in a solid layer over solid half space. (after Y. Oota)

According to the theoretical investigation of the Rayleigh wave in the layered medium, the relation between its wave amplitude and the period has been obtained as shown in Fig. 5 (Oota, [1964]). In Fig. 5, the case of the Rayleigh wave in a solid layer over solid half space is shown.

From the comparison between the forms of the frequency spectrum of the 3rd-kind volcanic micro tremor (Fig. 4) and theoretically obtained one (Fig. 5) of the Rayleigh wave in the layered media, there is a remarkable agreement between those two frequency spectra. This agreement may show that the 3rd-kind of volcanic micro tremor is the "Airy phase" of the normal mode of Rayleigh waves which have been guided in a certain layered medium, which is peculiar to a volcanic district. The depth of this layered medium estimated 300~500 m from the Tazime's "quarter wave length law" (Tazime, [1956, 1957]).

On the other hand, the leaking mode of the PL-phase guided in the same layered structure was obtained at the same observing point from the frequency analysis of distant earthquake waves as shown in Fig. 6. In Fig. 7, displacement amplitude

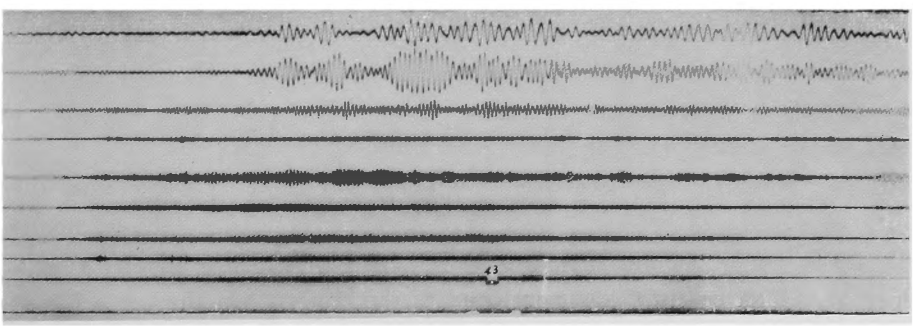


Fig. 6. The frequency analysed record of Northern Celebes Earthquake.

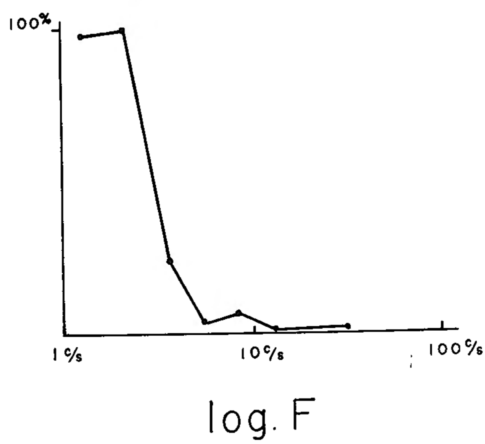


Fig. 7. Displacement-amplitude vs. frequency curve of Fig. 6.

vs. corresponding frequency is plotted. The epicenter, origin time and magnitude of the observed earthquake are 0.2°N, 123.6°E, Northern Celebes, 09h 55m 55.4s, Mar. 28, 1961 (G. M. T.) and $6\frac{3}{4}$ (Pas.), 7 (Pal.) (U. S. Department of Commerce, Coast and Geodetic Survey, [1961]). In this record, the wave train of PL-phase can be found from the P-phase to the beginning of the S-phase. The observed PL-phase may be considered to be the first PL-phase as termed by R. A. Phinnel [1961] or PL_{21} as termed by F. Gilbert and S. J. Laster [1962]. This wave group has the same frequency response as that of the 3rd-kind. From this fact, it is proved that certain layered structures exist guiding the normal or leaking mode which has a definite frequency response.

Ishimoto & Iida's "*m*" value of the 3rd-kind of volcanic micro tremor

The well known empirical relation between maximum trace amplitude "a" of the earthquakes and frequency "$N(a)$"

$$N(a)da = ka^{-m}da\,,$$

has been proved to be valid for aftershocks and other micro-earthquakes (Asada et al., [1951]; Suzuki, [1953, 1955, 1958, 1959]; Asada, [1957]). This empirical formula has been called "Ishimoto-Iida's relation (Ishimoto et al., [1939]). The value of m in this relation was estimated as 1.9 to 1.8 for all cases.

Similar empirical relation between amplitude and frequency was proved to hold for the earthquake of volcanic origin too (Minakami, [1960]). The value of m is really 1.9 to 1.8 for the volcanic earthquake of A-type which originates at a little deeper part than several kilometers beneath the crater. On the other hand, for

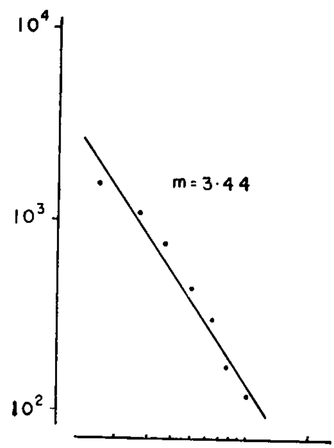


Fig. 8. Annual amplitude distributions of the 3rd-kind volcanic micro tremor.

the earthquakes which are accompained by outbursts or which are of extremely shallow origin (B-type) (Minakami, [1960]), the value m was found to vary from 2.5 to 4 or more.

According to the results of the previous sections, the 3rd-kind of the volcanic micro tremor originates from the disturbance due to small earthquakes beneath the crater and the normal mode Rayleigh waves which have been guided in a certain layered medium. Therefore this formula may be applied to this tremor of the isolated form, for instance as shown in Fig. 1. An attempt was made to the statistical study of this tremors which have been recorded at "Hondō" during the period Jan. 1962 to Dec. 1962. The obtained annual amplitude distributions of this tremor is shown in Fig. 8, the estimated value of m being 3.44. This value corresponds to the case of very shallow volcanic earthquakes such as B-type one.

Relation between volcanic eruptions and volcanic micro tremor of the 3rd-kind

At the Volcano Aso, there is a close relation between volcanic eruptions and volcanic micro tremors.

The crater of Naka-dake of the Volcano Aso was most active from the beginning of observations of our Laboratory until 1933. In this period, K. Sassa [1936] succeeded in finding a method which enables prediction of volcanic eruptions by making detailed studies of the peculiar amplitude variations of volcanic micro tremors. The peculiar amplitude variations are the process of a sudden increase in amplitude of tremors, the maintenance of the maximum amplitude during a certain period and a rapid decrease in the amplitude of tremor which is found before the volcanic eruption.

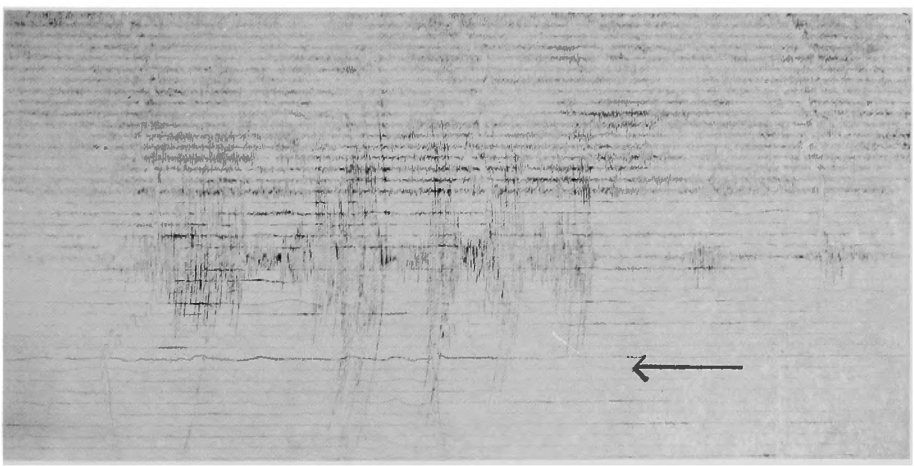
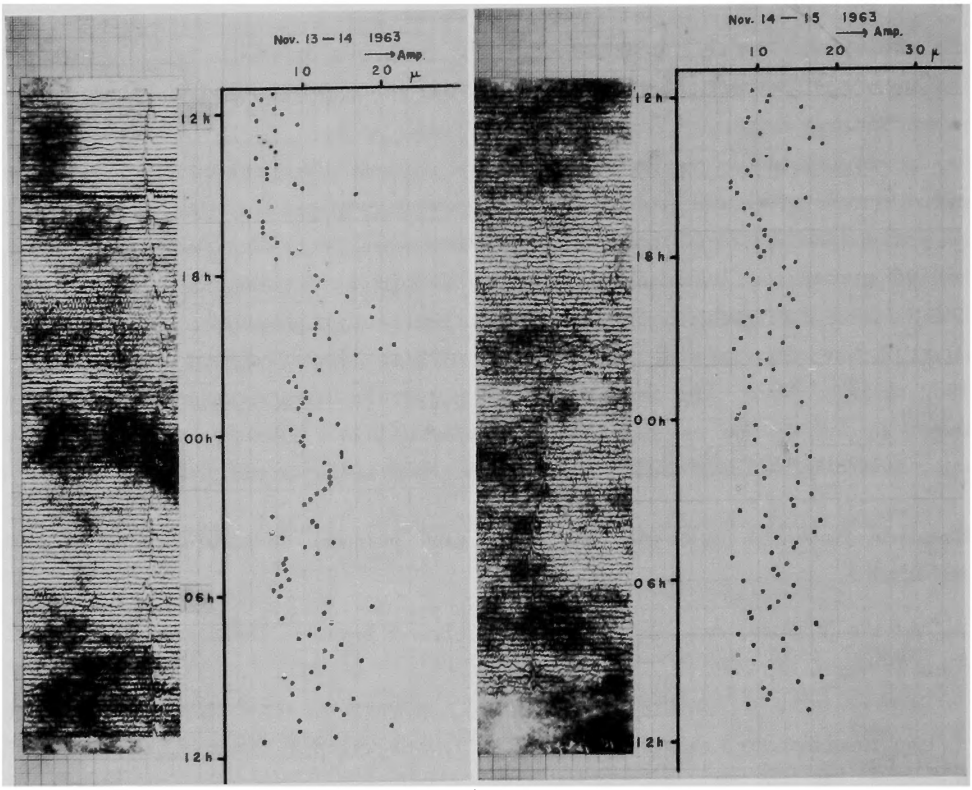
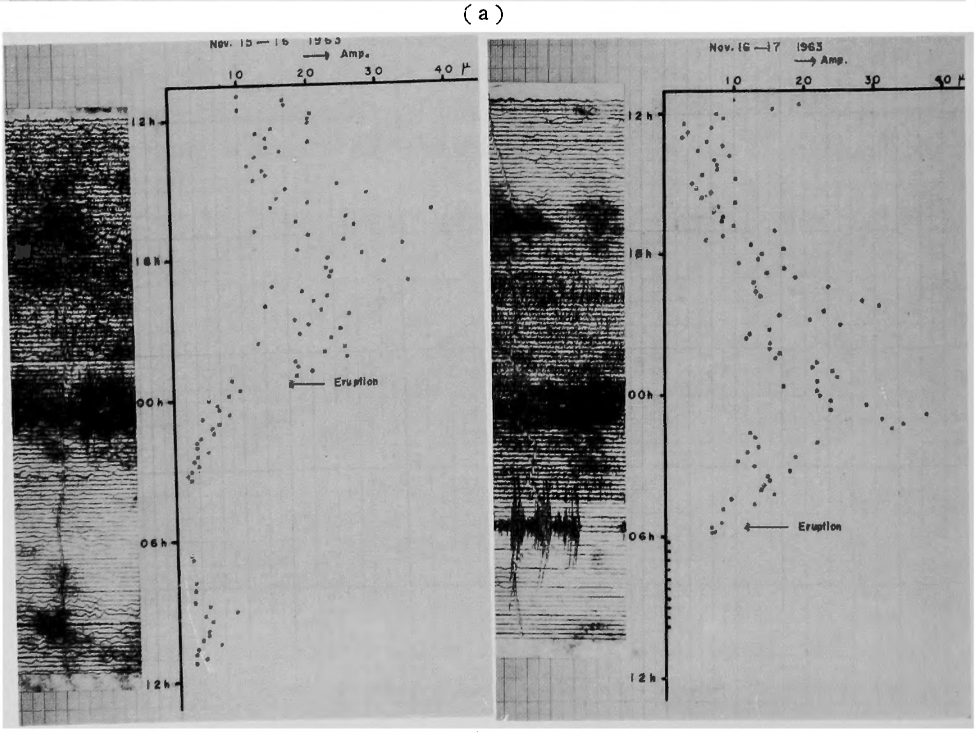


Fig. 9. Seismic record of the small eruption on Nov. 17, 1963.



(a)



(b)

Fig. 10. Peculiar variation of amplitude of the 3rd-kind volcanic micro tremor before the eruption on Nov. 17, 1963.

The peculiar amplitude variation of the 3rd-kind of volcanic micro tremors before the eruptions had also been observed in this duration and two typical examples were reported by K. Sassa.

In recent year, small eruption of the lst Crater of Naka-dake took place, i.e., at 05h49m, Nov. 17, 1963. Ashes or rocks were thrown out to the horizontal distance about 100 m of the western side of the crater.

Before this eruption, the peculiar amplitude variation of the 3rd-kind has also been observed at "Hondō". Therefore, prediction of this eruption has been made.

Before this eruption, the micro tremors of the 3rd-kind began to be recorded at 16h, Nov. 13 and increasing suddenly in amplitude at 15h, Nov. 15, soon reached maximum value. At 23h10m, Nov. 15, they rapidly decreased in amplitude and at 24h29m, small eruption took place. The amplitude of tremor again increased at 17h, Nov. 16. At 04h40m, Nov. 17, it rapidly decreased and kept very small during one hour. Then at 05h49m, Nov. 17, small eruption again took place.

Fig. 9 shows the seismic record of the small eruption at 05h 49m, Nov. 17 and Fig. 10 shows the peculiar variation of amplitude of the 3rd-kind before this eruption.

Summary

1) Detailed analyses have been made in a series of simultaneous records of the 3rd-kind of volcanic micro tremor taken at the two stations (Laboratory and summit station "Hondō"), and it is inferred that this wave is considered to be propagated in the form of the Rayleigh type wave having a phase velocity of about 1.2 km/sec from the crater.

2) Frequency analyses of this tremor have been made often, using an analog type frequency analyser which has a frequency range of 1 c/s to 43 c/s. From these analyses, it has been made clear that the mode of this tremor has a predominant frequency of about 2 c/s in its frequency spectrum. From the comparison between the spectral form of this tremor and theoretically obtained one of the Rayleigh wave in the layered media, it seems that the 3rd-kind of volcanic micro tremor is the "Airy phase" of the normal mode Rayleigh waves which have been guided in a certain layered medium.

3) On the other hand, the same predominant frequency which could be considered as the leaking modes in the same layered medium, has also been found on the record of frequency analysed seismic waves. This phenomenon shows that there is a certain layered medium in which the normal or leaking mode of waves can be guided under the observing station.

4) The Ishimoto-Iida's "*m*" value has been obtained as 3.44 from the statistical

study of the 3rd-kind of volcanic micro tremor when it appears in the form of isolated waves. This value corresponds to the case of very shallow volcanic earthquakes such as B-type.

5) The peculiar amplitude variation of the 3rd-kind of volcanic micro tremor before the small eruption of Nov. 17, 1963 was obtained. Such a peculiar variation of amplitude of volcanic micro tremor had always been observed before the eruption of this volcano and it may give a clue for the prediction of eruptions of this volcano.

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References

Asada, T., Z. Suzuki and Y. Tomoda, 1951; Note on the energy and frequency of earthquake, Bull. Earthq. Res. Inst. Tokyo Univ., Vol. 24.

Suzuki, Z., 1953, 1955, 1958, 1958; A statistical study on the occurrence of small earthquakes, I, II, III, and IV., Science Report, Tohoku Univ., Ser. 5., Geophysics Vol. 5, 7, 10, and 11.

Asada, T., 1957; Observation of near by micro-earthquakes, J. Phys. Earth, Vol. V.

Gilbert, F. and S. T. Laster, 1962; Experimental investigation of PL modes in a single layer, Bull. Seism. Soc. Am., Vol. 52.

Ishimoto, M. and K. Iida, 1939; Observations sur les seismes eneregistres par le microseismograph construit determinerement, Bull. Earthq. Res. Inst., Tokyo Univ., Vol. 17.

Kawahara, S., K. Fujimoto and K. Suzuki., 1960; V.H.F. multi-channel tele-recorder for seismograph (in Japanese), National Technical Report, Vol. 6.

Kikuchi, S., 1963; Observations of volcanic micro-earthquakes at Mt. Aso, Special Contributions of the Geophysical Institute, Kyoto Univ., No. 1.

Kubotera, A., 1963; Volcanic micro tremor of the second kind. Nature of its wave generation and source condition, Special Contributions of the Geophysical Institute, Kyoto Univ., Vol. 1.

Kubotera, A., 1964; Determination of elastic wave velocities in the volcanic rocks of Volcano Aso, (in Japanese), Read on the Volcanological Soc. Japan.

Kubotera, A. and K. Yoshikawa, 1963; Prediction of volcanic eruption Aso and Sakurazima and some related geophysical problems, Bull. Volcanologique, Tome XXVI.

Minakami, T., 1960; Fundamental research for predicting volcanic eruption (Part 1), Bull. Earthq. Res. Inst., Tokyo Univ., Vol. 38.

Oota, Y., 1964; Amplitude characteristics of dispersed Rayleigh waves (I) (in Japanese), Report of the Seismic Exploration Group of Japan, No. 34.

Phinney, R. and A. Phinney, 1961; Leaking modes in the crustal wave guide. Part 1, J. Geophys. Res., Vol. 66.

Sassa, K., 1935; Volcanic micro-tremor and eruption earthquakes, Mem. Coll. Science, Kyoto Univ., Vol. 18.

Sassa, K., 1936; Micro-seismometric study on eruptions of Volcano Aso, Mem. Coll. Science, Kyoto Univ., Vol. 19.

Tazime, K., 1956; Wave groups generated by a very small explosion, J. Phys. Earth., Vol. IV.
Tazime, K., 1957; Minimum group velocity, maximum amplitude and quarter wave-length law-Love wave in doubly stratified layer, J. Phys. Earth, Vol. V.
U. S. Department of Commerce, Coast and Geodetic Survey, 1961; Preliminary determination of epicenter, No. 27-61.
Yoshikawa, K., K. Kamo and C. Kitsunezaki, 1959; Seismic exploration in the vicinity of the crater of Nakadake, Aso Volcano (in Japanese), Bull. Volcanological Soc. Japan, Vol. 4.