Volcanic Micro-Tremors and Eruption-Earthquakes[1]

(Part I of the Geophysical Studies on the Volcano Aso)

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1. Introduction

During an explosively active time of volcanoes, micro-tremors of volcanic origin are generally observed, and have been described by various authorities for Usu-san,[2] Asama-yama,[3] Mihara-yama,[4] Taal,[5] Vesuvius,[6] Mauna Loa,[7] Kilauea,[8] etc., but neither the nature of the volcanic micro-tremors nor their modes of occurrence have not been investigated by these writers. As to the volcanic earthquakes directly accompanying eruptions, which will be called eruption-earthquakes in the present paper, Omori[9] simply mentions that the initial motion is sometimes directed towards, and at other times outwards from, the crater, giving no further information about the nature and the mechanism of occurrence of eruption-earthquakes. The present investigations and considerations based on the micro-seismometrical observations made at the Volcano Aso were undertaken to throw some light upon the above points, which will be discussed in the following pages.

2. Observing stations

Our Volcanological Laboratory, 7.3km to the west of the crater, was the central station. There are two mountain stations connected with the laboratory, one at Kusasenrigahama, about midway between the crater and the laboratory and the other at Hondô near the crater. Besides these, four temporary stations were established, one at the Miyadi Girls' High School, 7.3km NNE of the crater, and the three others at Suzuriisi, Sara-yama, and Taka-dake, around the crater. The

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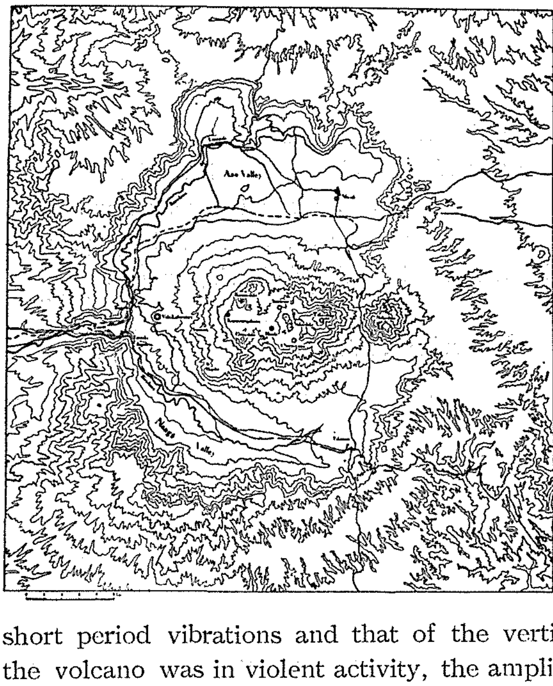
1. An abstract of this paper was read at the Annual Meeting of the Mathematico-Physical Society of Japan, Tokyo, 1934 April.
2. F. Omori: Bull. Imp. Eqke. Invest. Comm. 5 (1911). 3. F. Omori: Ditto. 7 (1914).
4. F. Omori: Shinsai Yobo Chosakwai Hokoku 81 (1915).
5. M. S. Maso: The eruption of Taal volcano January 30, 1911.
6. F. Signore: Publ. Bureau Cent. Seism. Intern. 7 (1932).
7. T. A. Jaggar: Bull. Seis. Soc. Amer. 10 (1920).
8. Ditto. 9. F. Omori: Loc. cit.

positions of the stations, 7 in all, will be seen in the following Table 1 and Fig. 1.

Table 1

Station	Azimuth from the crater	Distance from the crater	Height above sea-level
The Laboratory	W	7.3km	568m
Kusasenrigahama	W	3.1	1100
Hondô	WSW	1.0	1170
Miyadi	NNE	7.3	530
Suzuriisi	NNW	1.0	1190
Sara-yama	SSE	1.0	1250
Taka-dake	E	1.9	1520

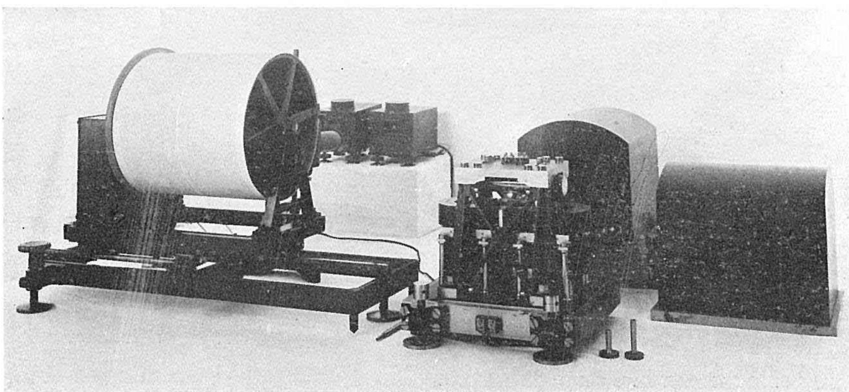
Fig. 1. Map of a part of the Volcano Aso showing the positions of the observing stations.



3. Instruments

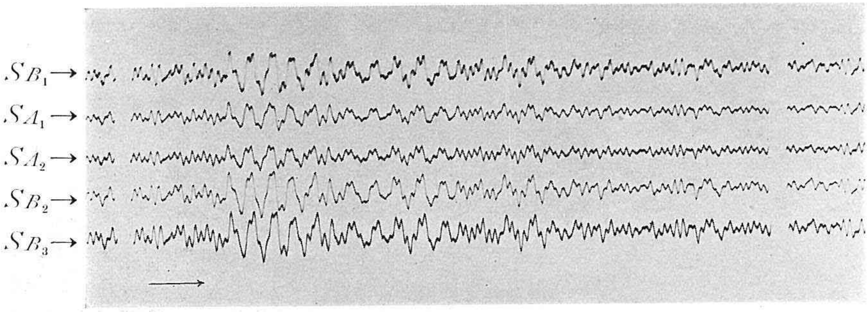
At the central station, the Volcanological Laboratory, Wiechert horizontal component seismograph of 1000 kgs weight and vetical one of 1300kgs weight have been installed on concrete bases 2 m. square and 2m. deep, insulated from the floor in the underground rooms and have been continuously at work since May 1929. The magnification for the horizontal component was kept at 200 for short period vibrations and that of the vertical one at 150. When the volcano was in violent activity, the amplitude of the micro-tremors recorded reached 3mm on smoked paper even at a distance of ca. 7.3km from the crater, and it was not necessary to raise the magnification of the instrument above this degree. But when the volcano is in repose, the amplitude of micro-tremors does not exceed a fraction of a micron, and therefore the following two types of electromagnetic system were prepared for the present investigation. The instruments of the first type, short period horizontal micro-seismographs of very high magnification (ca. 20,000 maximum), were essentially the same as that which was constructed in 1925, in our Geophysical Institute at Kyoto according to Prof. Shida's design, and successfully recorded more than ten thousands aftershocks of the Tadima Earthquake of 1925 during the period of the year following the main shock. But, since the stationary mass of the latter instrument was too great to be aperiodic, I reduced its weight to 1.8kgs, and interchanged the positions of the coils and the damper plate, putting the latter further than the former from the vibration axis. The period of the pendulum increased slightly (0.55 second) in consequence, which was rather to be preferred for our present works at Aso. Fig. 2 shows the horizontal

Fig. 2. Short Period Micro-seismographs, S_B, with Galvanometers and Recording Cylinder.



component micro-seismographs with galvanometers and recording drum. The general dimensions of the different parts of the instrument can be estimated from the dimensions of the recording drum which is about 30 cm. both in length and in diameter. The massive base is of bronze, supported on three strong levelling screws. Bolted to this is a rigid bronze frame-work which carries the pendulum. The pendulum is a simple vertical pendulum of a stationary mass of 1.8kg. to which are rigidly keyed the coils and copper plate. The axis of rotation is neatly arranged to avoid friction by using crossed Cardan springs screwed to the fixed framing and to the pendulum. The damping magnets and the magnets for the coils are mounted on the base and pairs of magnets are provided with screw adjustments so that the damping and magnification may be controlled to the desired extent. The galvanometer is of Moll's moving coil type. The coil of an area of 0.2×3 cm^2., moving in a strong magnetic field of ca. 2000 Gausses, is stretched between two fine strips. Two instruments of this type of short period micro-seismographs, S_A, were made in the spring of 1930 and set up in the underground room of the Laboratory. After the completion, in the summer of 1931, of three other sets of the same type of instrument, S_B, the comparison of these five sets of short period micro-seismographs was carried out by setting their pendulum parts on a single concrete base and facing in the same direction, and registering the movements of their galvanometer mirrors on a single recording drum. As shown in Fig. 3, the five recorded curves corresponding to the five sets of micro-seismographs are quite satisfactory,

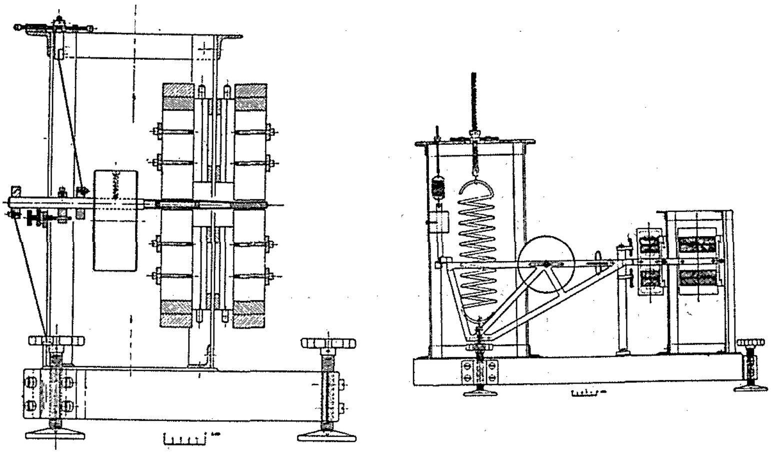
Fig. 3. A portion of the record of comparison of the five sets of the short period micro-seismographs. (Time between two consecutive marks=30 sec.)



(1/2×the original record)

being almost similar, even in detail. To see the effect on micro-tremors of a superficial layer of ashes on the ground and of the laboratory building, two components of S_B were set in December 1931 directly on volcanic rock in a pit of ca. 20 m. depth at a distance of ca. 60 m. NNE of the building. The lead-wires of ca. 90 m. length from the pendulums to the galvanometers, were inserted into iron-pipes burried in the ground at a depth of ca. 1 m., and, after careful observation, it was confirmed that no disturbances were introduced by the long lead-wires. As to the effect of surface layers and the building the readers will find some accounts in the subsequent articles. The second type of micro-seismograph is the Galitzin system of medium period. The pendulum parts of the set G_A of two horizontal components and one vertical component, were originally made by the Cambridge Instrument Co., but their galvanometers of Moll's moving coil type were constructed by the author to increase their magnification for shorter periods. The galvanometer coil was stretched between two fine phosphor bronze wires of 15 microns dia., taking the utmost care not to let its center of gravity fall outside the axis of rotation. Another set of the same type of instruments, G_B, consisting of two horizontal components and one vertical component, were made by the present writer in March 1933. Their construction is essentially similar to G_A, but their dimensions and weights were greatly reduced to make the instruments more portable, without changing their magnification. Fig. 4 (a) and (b) are sketches of the pendulum parts of the micro-seismographs G_B. In

Fig. 4. Pendulum parts of the microseismometer G_B.



(a) Horizontal component (b) Vertical component

order to give a longer period of free oscillation to the pendulum, in spite of the reduced dimensions of the instrument, the pendulum part of the vertical component seismograph, as shown in Fig. 4(b), has a second spring besides the main spiral spring suspending the pendulum. The instrumental constants of the seismographs are summarized in the following Table and their magnification curves are shown in Fig. 5.

Table 2

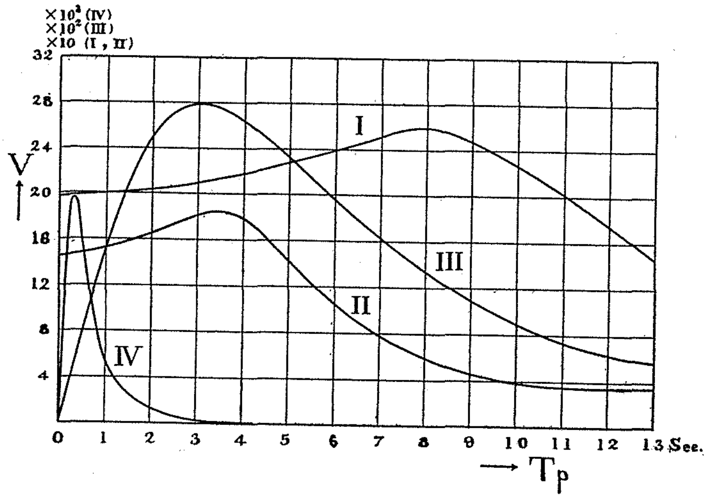
Instrument	T_0 sec.	μ^2_0	V	T_1 sec.	μ^2_1	k	l cm.	V_m	s cm.
Wiechert seismograph horizontal comp.	10.0	0.81	200						3
Wiechert seismograph vertical comp.	4.6	0.81	150						3
Micro-seismograph, S_A	0.55	0		0.55	0	16100	7.5	12300	30

Table 2 (Continued)

Instrument	T_0 sec.	μ^2_0	V	T_1 sec.	μ^2_1	k	l cm.	V_m	s cm.
Micro-seismograph, S_B	0.55	0		0.55	0	25600	7.5	19300	30
Micro-seismograph, G_A horizontal comp.	8.0	0		4.0	0	627	12	2800	3
Micro-seismograph, G_A vertical comp.	8.0	0		4.0	0	1975	38	2800	3
Micro-seismograph, G_B horizontal comp.	8.0	0		4.0	0	340	6.5	2800	3
Micro-seismograph, G_B vertical comp.	8.0	0		4.0	0	1410	27	2800	3

T_0: Period of free oscillation of the pendulum. μ^2_0: Damping constant of the pendulum, $\mu^2_0=1-(\epsilon_0/n_0)^2$. V: Magnification of the seismograph for short period vibrations. μ^2_1: Damping constant of the galvanometer, $\mu^2_1=1-(\epsilon_1/n_1)^2$. k: Uebertragungsfaktor of the seismograph. l: Length of the equivalent simple pendulum. V_m: Maximum magnification of the micro-seismograph. s: Speed of the recording paper per minute.

Fig. 5. Magnification curves of the seismographs. I: Wiechert horizontal comp. seismograph. II: Wiechert vertical comp. seismograph. III: Micro-seismographs, G_A and G_B. IV: Micro-seismographs, S_B.



4. Ordinary micro-tremors of non-volcanic origins.

Our sensitive micro-seismographs are never at rest, showing that there are always small movements of the earth's crust which are called micro-tremors. Micro-tremors of a period of about 0.3 seconds, caused by traffic, industry, wind, waterfalls, rain and probably some other causes, are incessantly recorded by our short period micro-seismographs,

$S_{A,B}$ at each of our observatories. The micro-tremors of this nature observed at our Geophysical Institute of Kyoto which is situated at the NE corner of the city, are about 1 micron in double amplitudes in the daytime and only ca. 0.3 micron at night, the period being 0.35 seconds. While at our Kamigamo Geophysical Observatory which is almost perfectly free from mechanical disturbances, being isolated on a hill at a distance of ca. 4.5 km. NNW of the University, the micro-tremors recorded were only ca. 0.1μ even in the daytime and ca. 0.03μ at night, the period being ca. 0.33 sec.. Micro-tremors of the same period of ca. 0.33 sec. and of constant amplitude of ca. 0.03μ both in the daytime and at night are observed at our Abuyama Seismological Laboratory, which is almost free from mechanical disturbances, being isolated at a distance of ca. 4 km. from the nearest railway and small town. The amplitude of the micro-tremors observed at our Aso Volcanological Laboratory was ca. 0.1μ in the underground room on calm days, while it was only ca. 0.02μ when observed directly on volcanic rock in the pit of ca. 20 m. depth. As to the micro-tremors observed on windy days, and to the effect of surface layers and the building the readers will find some account of these in a paper written by Mr. E. Nishimura.[1] Micro-tremors of ca. 0.5 sec. period caused mainly by water-falls were frequently recorded at our Volcanological Laboratory and will be described in Appendix of the present paper. The period of the micro-tremors observed at our mountain station of Kusasenrigahama was 0.35 sec., the amplitude being ca. 0.1μ, while that observed at our summit station of Hondô was only 0.22 sec.. The amplitude observed at the latter observing room standing on ground of lapilli of ca. 10 m. depth was almost always ca. 0.1μ, while that observed at Jabara, where the pendulum was set directly on volcanic rock, was only ca. 0.05μ. The micro-tremors above described, except those caused by strong wind and heavy rainfalls, are considered as proper oscillations of the ground of the observatories. Ordinary microseisms of periods ranging from 4 to 12 sec. recorded at our Volcanological Laboratory were less than 0.5μ in double amplitudes in a quiet season, and so they did not normally interfere with the volcanic micro-tremors of the second kind, the period of which is nearly the same.

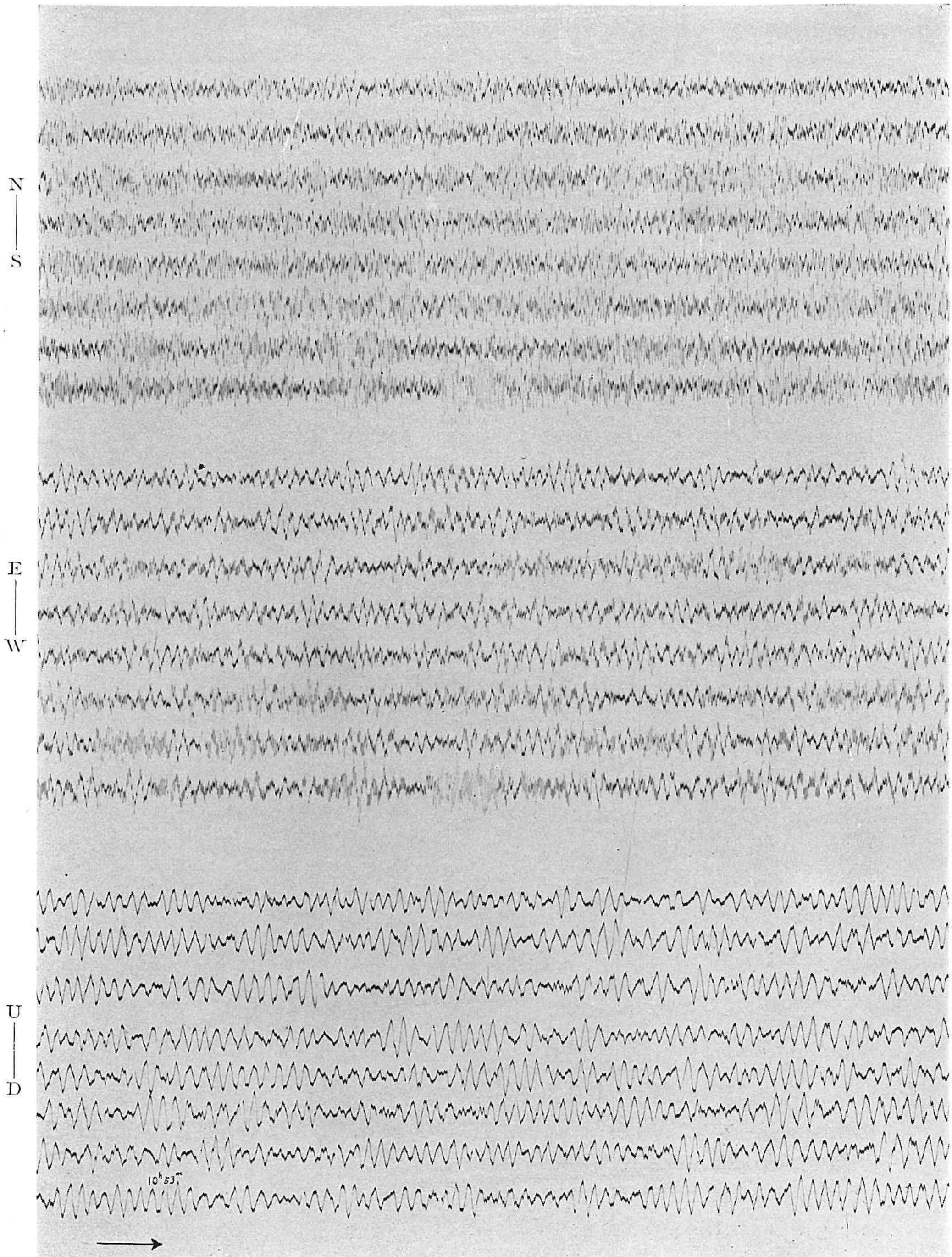
5. The volcanic micro-tremors of the first kind

There are four kinds of micro-tremors of volcanic nature observed at the Aso Volcanological Laboratory. When the new laboratory was

1. E. Nishimura's paper will appear in these Memoirs in near future.

finished and the Wiechert instruments were set up in May 1929, the Volcano Aso was still in activity, the first explosion having taken place on April 1, 1927, and the micro-tremors of the first kind with a period ranging from 0.8 to 1.5 sec. were almost continuously recorded till the end of the year. But when the high magnification instruments were introduced next year, it was found that the micro-tremors of this kind did not cease to exist even in quiescent periods of the volcanic activity. They occurred not in continuous trains, but intermittently, several groups per hour, each of which consisted of 5–10 somewhat regular waves of 1μ or less in double amplitudes. Fig. 6 in Plate I is a reproduction of the record of the micro-tremors of this kind registered by short period micro-seismographs, S_B on Nov. 28, 1931. As will be seen from the record the beginning of the group of waves is not clearly defined. When the volcano becomes active the wave-group of the micro-tremors of the first kind increases gradually in frequency and amplitude in parallel, and finally becomes a continuous train of irregular waves as shown in Fig. 7, which is a reproduction of a portion of a record registered by the micro-seismographs G_A, on Feb. 25, 1933. At that time the maximum magnification of the instruments was reduced to about 200, for the occasion was the day on which the great explosive eruptions of the First and the Second crater occurred frequently, and the amplitudes of the micro-tremors of the day were the greatest ever observed at our Aso Volcanological Laboratory. It will be noticed that the micro-tremors of the first kind are predominant in the N–S component, while those of longer period of the second kind are more predominant in the E–W and vertical components which will be described in the next article. The oscillatory displacements of the micro-tremors of the first kind are practically confined to the horizontal plane, and approximately to the N10°W–S10°E direction, which is roughly at right angles with respect to the direction of the crater. The amplitude of the tremors of this kind recorded by the seismographs set directly on volcanic rock in the pit of ca. 20 m. depth is reduced to 0.85 of the corresponding amplitude observed at the underground room of the laboratory. During an active period of the volcano, the amplitude at Hondô of the volcanic micro-tremors of the third kind, the period of which is ca. 0.5 sec. is far larger than that of the first kind, so that it is very difficult to study the nature of the latter tremors in detail. But in times of repose the former is vanishingly small in amplitude, while the latter still remains considerable in amplitude. The period of the micro-tremors of the

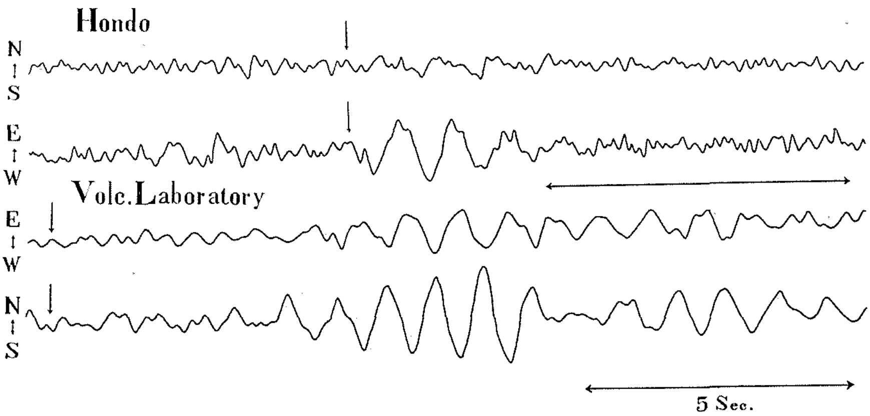
Fig. 7. A portion of the record obtained from the micro-seismographs, G_A, at the Volcanological Laboratory on Feb. 25, 1933. At that time the maximum magnification of the instruments was reduced to about 200 and the amplitudes of the micro-tremors of the day were the greatest ever observed at the laboratory. (Time between two consecutive marks = 1 min.)



(2/3×the original record)

first kind observed at Hondô ranges from 0.7 to 1.0 sec. and the displacement is wholly horizontal, or at least the vertical component is less than one twentieth of the former. The orbit of each element is elliptic, being clockwise in sence, and its major axis lies approximately in the direction N74°E–S74°W, the ratio of the major axis to the minor being ca. 3 : 1. The Hondô observing room which is of concrete and half underground, stands on a ground of lapilli of about 10 m. depth. To test the effect, if any, of the surface layer and the observing room, one of the pendulums was set in the room and the other one directly on volcanic rock at Jabara at a distance of 150 m. north of the former, but no differences of phase or amplitude were found between the two records. During a time of long repose, a group of micro-tremors of the first kind consists of 3 or 4 waves at the summit station of Hondô, while at the foot station of the Laboratory the number of waves of the corresponding group increases to 5 or 6 in general. By a series of simultaneous observations taken at the two stations from Sept. to Nov. 1931, it was found that the amplitude at the foot station was slightly reduced, being 0.92 that of the summit, while the period at the former was 1.2 times that at the latter. The time of occurrence at the Laboratory was delayed 6.4 sec. as compared with that at Hondô. The identification of the corresponding phases of the micro-

Fig. 8. Comparison of the records of simultaneous observation at the two stations on Oct. 25, 1931.



tremors observed at the two stations was easily made as shown in Fig. 8, in which the arrows indicate the same moment in the records at the two stations. Some results of these simultaneous observations are given in the following table :

Table 3

Date	Time of occurrence	At Hondô			At the Laboratory			Time diff.
		A_N	A_E	T	A_N	A_E	T	
1931	h m s	μ	μ	sec.	μ	μ	sec.	sec.
Oct. 6	21 43 06	0.22	1.14	0.83	0.77	0.53	0.98	6.50
16	21 39 45	0.22	0.78	0.77	0.53	0.18	1.05	6.00
16	21 40 26	0.19	0.64	0.89	0.50	0.18	1.05	6.60
20	21 39 17	0.69	0.97	0.76	1.17	0.55	1.12	6.30
25	21 41 03	0.56	1.70	0.93	1.33	0.67	0.93	6.46
29	21 37 02	0.33	0.97		0.58	0.33		6.24
29	21 40 49	0.42	1.10	1.10	1.00	0.55	1.13	6.25
Nov. 11	21 39 49	0.33	0.56		0.35	0.20	1.03	6.70
11	21 42 53	0.70	1.00	0.80	0.83	0.37	0.83	6.70
Mean		0.37	0.89	0.87	0.79	0.40	1.03	6.42
		μ 0.96			μ 0.89			
Ratio		0.96/0.89=1.08						

At the beginning of the great explosive activity of Oct. 1932, simultaneous observations were again taken at the summit and the foot stations. In this case the ratio of the amplitude at Hondô to that at the Laboratory was 2.4 instead of 1.1 in the preceding quiescent year of the volcano, while the time difference of occurrences was 5.2 sec. instead of 6.4 sec. This difference is very interesting and will

Table 4

Date	Time of occurrence	At Hondô			At the Laboratory			Time Diff.
		A_N	A_E	T	A_N	A_E	T	
1932	h m s	μ	μ	sec.	μ	μ	sec.	sec.
Oct. 21	18 44 48	0.28	0.70	0.90	0.35	0.17	1.00	5.20
	18 53 55	0.25	0.92	0.76	0.42	0.22	1.00	5.15
	18 58 12	0.25	0.97	0.90	0.35	0.18	1.00	5.60
	19 46 08	0.28	1.11	1.00	0.33	0.13	1.00	5.40
	21 24 34	0.47	1.39	0.98	0.50	0.25	0.87	5.03
	22 21 39	0.56	1.39	0.82	0.50	0.20	0.98	5.10
	22 33 08	0.58	1.39	0.83	0.50	0.23	0.90	5.15
22	10 36 51	0.97	2.50	0.81	0.88	0.37	0.80	5.10
Mean		0.45	1.30	0.88	0.48	0.22	0.95	5.22
		μ 1.38			μ 0.58			
Ratio		1.38/0.58=2.38						

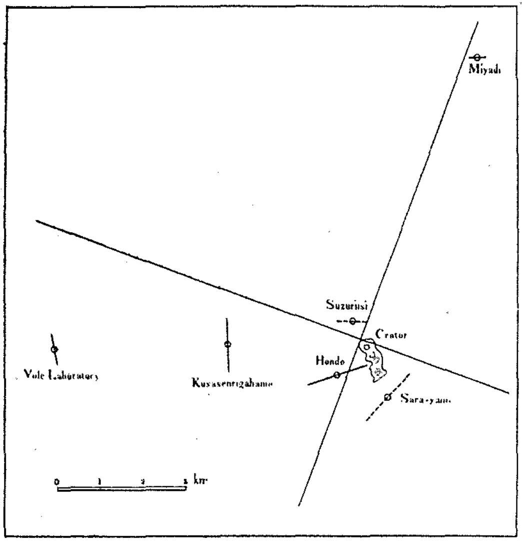
be considered in another place in this paper. Some results of the observations are given in Table 4.

For further study of the nature of the tremors the micro-seismographs, S_A were installed in the Girls' High School at Miyadi, which station is at nearly the same horizontal distance from the crater, as is the Volcanological Laboratory, while their directions are roughly at right angles with respect to the crater. The displacement of the micro-tremors of the first kind in Miyadi consists of elliptic oscillations, whose major axis is nearly in the E–W direction, the ratio of the major axis to the minor being about 3 : 1. The simultaneous observations at Miyadi and the Volcanological Laboratory show that the times of occurrence were nearly concurrent and the ratio of the amplitude at Miyadi to that of the laboratory was about 0.6 : 1. This latter result is rather contrary to expectation, seeing that the superficial layer of volcanic ashes at Miyadi is about 90 m. depth or more, and thicker than that at our laboratory. On Oct. 23–24, 1932 a set of two micro-seismographs, Type S_A was set directly on volcanic rock in a pit of ca. 10 m. depth at Kusasenrigahama, which lies in the line connecting the crater with the Laboratory as shown in Fig. 1. The period and the mode of oscillations of the micro-tremors of the first kind at the two stations were quite similar, but the amplitude at the former was twice that at the latter. On Aug. 24, 1933 the two components of the micro-seismographs, Type S_A were set in a tea-house which stands almost directly on the lava bed at Suzuriisi and is at a distance of ca. 500 m. NNW from the First Crater, the most northern of the four active craters. The amplitude of the micro-tremors observed at this station is exceedingly small as compared with that at Hondô and the displacement of the earth element describes an elliptic orbit, its major axis lying in the E–W direction and the ratio of the major axis to the minor being 3 : 1. On Aug. 29, 1933 micro-tremors of the same kind were registered by the same set of seismographs on a concrete base of 1.0×1.5 m^2. of 1.5 m. depth, which was constructed on a ground of volcanic fragments and ashes of about 10 m. depth at Sara-yama at a horizontal distance of 1.5 km. SES from the First Crater. The amplitude of the micro-tremors of the third kind was so great that the tremors of the first kind were almost perfectly masked, but from a close examination of the records, the major axis of the oscillating ellipse of the latter seems to be approximately in the direction N45°E–S45°W, the ratio of major to minor axis being 2 : 1. The results of the observations at the 6 stations described above, are tabulated in Table 5, in which Δ is the horizontal distance of each station from the First Crater and a the ratio of the amplitude at the Laboratory to that at the corresponding station, the former reduced to the surface value, for the observations were made in the pit and the amplitudes were reduced to 0.85 of the surface values.

Table 5

Station	Δ (km)	$\alpha_{obs.}$	$\alpha_{calc.}$	$\gamma_{obs.}$	$\gamma_{calc.}$	φ
The Laboratory	7.30	1	1	80°	90°	65°
Miyadi	7.25	0.5	0.1	64	45	1.5
Kusasenrigahama	3.10	1.7	1.4	90	90	65
Hondô	1.10	2.0	2.0	38	40	14
Suzuriisi	0.50			68	88	32
Sara-yama	1.30			60	79	44

Fig. 9. Directions of the major axes and amplitude ratios of the micro-tremors of the first kind.



From the results of observation above described it is concluded that the volcanic micro-tremors of the first kind are a kind of generalized Love waves, having a certain azimuthal distribution of displacement as demonstrated by H. Nakano[1] and K. Sezawa.[2] According to H. Nakano, the equation of the path of the element of the medium is given by $x = D_\omega R_2 \cos(pt - \theta_2)$, $y = D_\varphi R_1 \cos(pt - \theta_1)$, where the X-axis is along the radius vector passing the position at rest of the element, its positive sense coinciding with the increasing sense of ω, and the Y-axis, perpendicular to it, has the same positive sense as

1. H. Nakano; Geophy. Mag. **2** (1929).
2. K. Sezawa; Bull. Earthq. Res. Inst., **7** (1929).

the increasing sense of φ, and $D_\omega = 2Sn \cos\beta z \cos n\varphi \frac{1}{k\omega}$

$$D_\varphi = -S \cos\beta z \sin n\varphi$$

$$R_1 = \sqrt{\{J_{n-1}(k\omega) - J_{n+1}(k\omega)\}^2 + \{Y_{n-1}(k\omega) - Y_{n+1}(k\omega)\}^2}$$

$$R_2 = \sqrt{J_n^2(k\omega) + Y_n^2(k\omega)} \qquad \theta_1 = \cos^{-1}\frac{J_{n-1}(k\omega) - J_{n+1}(k\omega)}{R_1}$$

$$\theta_2 = \cos^{-1}\frac{J_n(k\omega)}{R_2}.$$

The angle γ between the major axis and X-axis is given by $\tan 2\gamma = \frac{2\varepsilon\cos(\theta_2 - \theta_1)}{\varepsilon^2 - 1}$, $\varepsilon = \frac{D_\omega R_2}{D_\varphi R_1}$, the sign of $\cos 2\gamma$ being the same as that of $\varepsilon^2 - 1$. Taking the position of the origin of the disturbance at the north wall of the First Crater as shown in Fig. 9, the amplitude and the angle γ corresponding to the distance of our observing stations were calculated by the above solution, taking $n = 2$. If two azimuths of purely radial motion are taken as drawn in Fig. 9, the calculated amplitude ratios $a_{calc.}$ and angles $\gamma_{calc.}$ are in fairly good coincidence with those of the observed values as given in Table 5. Since the oscillatory movements of the micro-tremors might be considered as being greatly disturbed by the irregular formations of the upper crust of the volcanic district and since, moreover, our observations at temporary stations cover only a few days, no conclusive discussions about the discrepancies between the calculated and the observed values can be admitted. As already described, the amplitude observed at Miyadi is to be considered as being increased by the deep surface layer of volcanic ashes at the station. As to the mode of oscillations at the internal source of disturbances as well as the mechanism of the volcanic eruptions to be inferred from the observed data, some considerations will be given in a subsequent article of the present paper. The case observed in the repose time of 1931 can not be explained by the above calculation, but in this case we have to take $n = 1$ instead $n = 2$ in the above calculation. If the azimuth of purely radial motion is considered as coinciding with the line, connecting Miyadi and Hondô as shown in Fig. 9, and the origin of the disturbance is directly under the First Crater, then the calculated amplitudes corresponding to the distances, and the azimuths of the Laboratory and of Hondô become as follows:

	Amplitude observed	Amplitude calc.	Azimuth
The Laboratory	1	1	65°
Hondô	1.1	1.1	15°

The calculated values are in good coincidence with those obtained by observation. The time difference of occurrence observed in Oct. 1931 between the summit and the foot stations was 6.4 sec., while in Oct. 1932 it was reduced to 5.2 sec.. If this change in time could be considered as occurring simply from the change in depth of the origin of disturbance, deeper in the active time of 1932 than in the repose time of the preceding year, then the velocity of propagation of the micro-tremors of the first kind is 0.99 km./sec., taking the origin of disturbance as just below the bottom of the First Crater.

6. The volcanic micro-tremors of the second kind

The volcanic micro-tremors which the writer calls the "second kind" are recorded in repose as well as in active times of the volcano, and the oscillatory movements are very smooth and regular and of periods ranging from 3.5 sec. to over 8 sec.. The period persists so long as the state of activity of the volcano does not change. The horizontal movement observed at the Volcanological Laboratory is practically confined to the direction of the crater and the vertical motion is as pronounced as the horizontal, the phase being upward corresponding to the westward motion. In a repose period in the summer of 1932, or, strictly speaking, in the time of preparation for next explosive eruptions, the micro-seismographs, Type G_A at the Volcanological Laboratory recorded several groups of micro-tremors of the second kind per hour, each group consisting of 3–6 regular waves of about 2μ in double amplitudes. Fig. 10, Plate I is a reproduction of the record obtained at the Laboratory on July 27, 1932. As shown in the record the micro-tremors of the second kind predominate in the E–W and vertical components, while in the N–S component those of the first kind predominate. When an explosive eruption approaches, the recorded group of waves of the micro-tremors gradually increases in frequency and finally becomes a continuous train of regular waves, the amplitudes of which also increase at the same time. Fig. 9 is a typical record obtained during the explosively active time of the volcano already described. At the Hondô observing room, observations were made twice with the micro-seismographs, G_A, once in Oct. 1932 and again in Aug. 1933. The horizontal motion of the micro-tremors of the second kind observed here was practically confined to the direction N74°E–S74°W which is the direction towards the centre of the four craters. In the right-angled direction the displacements were smaller than one-fifth of the former component while the periods were about half those of the former. The vertical component was recorded on all occasions with the same value as the horizontal, the phase being upward corresponding to a S74°W-ward motion in the horizontal plane. In Oct. 1932, when the last great explosive activity of the volcano began, the micro-tremors of the second kind were recorded about 10 groups per hour, each of which consisted of 5–7 waves of a few microns in double amplitudes. In the following figure 11 the amplitudes and the periods of the micro-tremors observed at Hondô during Oct. 21–26, 1932 are plotted but show no definite relation to one another. But Fig. 12 seems to show that the ratio of the recorded horizontal amplitude to the vertical increases as the period decreases.

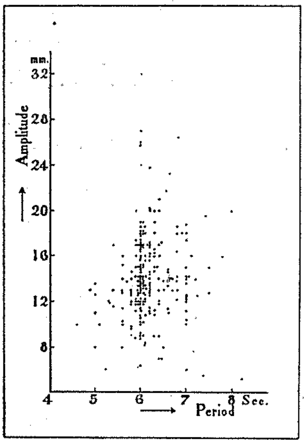


Fig. 11. Amplitudes and periods of the micro-tremors of the second kind at Hondô.

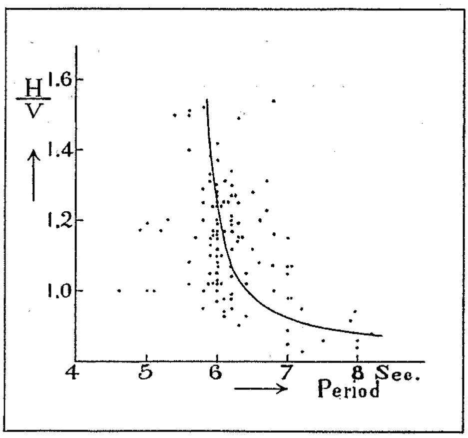
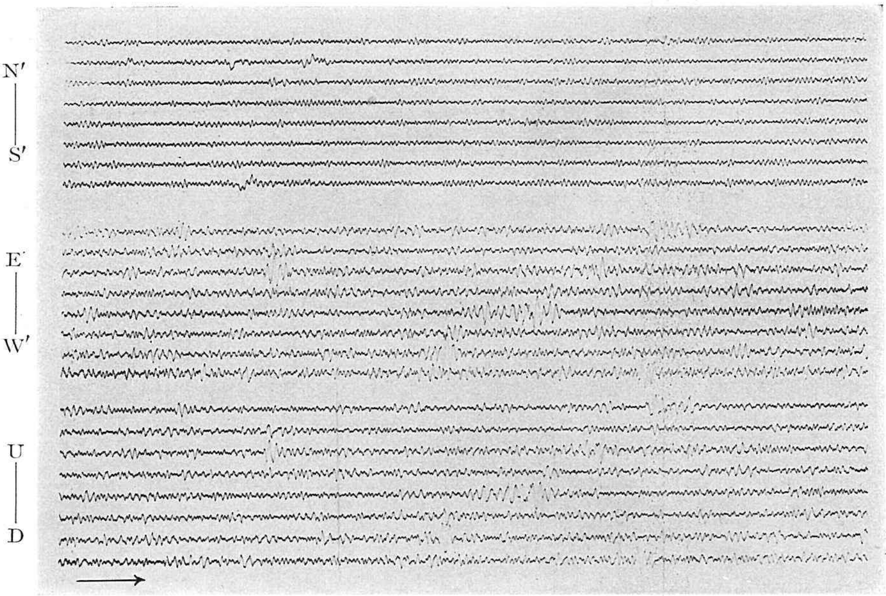


Fig. 12. Ratio, H/V, of the horizontal amplitude to the vertical and period of the micro-tremors.

Fig. 13 is a reproduction of a portion of the record registered by the micro-seismographs, Type G_A, on Oct. 23, 1932 at Hondô. The wave group of the micro-tremors of the second kind consists generally of two parts, the preliminary part of irregular waves of smaller amplitude and the regular waves of the principal part of larger amplitude. The duration of the preliminary part ranges from 10 sec. to over 30 sec., having no definite connection with the apparent emergent angles and the periods of the waves. The micro-tremors of the second kind were frequently observed to be accompanied by those of the first kind, which latter were recorded from 0 to 20 seconds before the recorded

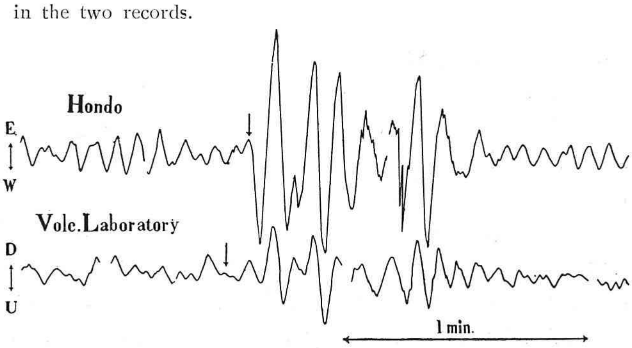
Fig. 13. A portion of the record obtained from our G_A type micro-seismographs on Oct. 23, 1932 at Hondô. Large wave groups in the E-W and the vertical component are the micro-tremors of the second kind. E′=E16°N, N′=N16°W (Time between two consecutive marks=1 min.)



(3/5×the original record)

initial phase of the principal part of the former, but sometimes they were observed independently of each other. This diversity of mode of occurrences is very interesting when we consider the origins of the disturbances. According to the simultaneous observations taken at Hondô on the summit and at the Laboratory at the foot, the modes of oscillatory motion of the micro-tremors of the second kind recorded were quite similar both in their periods and phases, but the amplitudes observed at the foot station were about 0.4 of those

Fig. 14. Comparison of records simultaneously registered at the two stations, the arrows indicating a simultaneous moment in the two records.



at the summit station as shown in Fig. 14. Table 6 contains some results obtained from simultaneous observations of the micro-tremors of the second kind at the summit and the foot stations.

Table 6

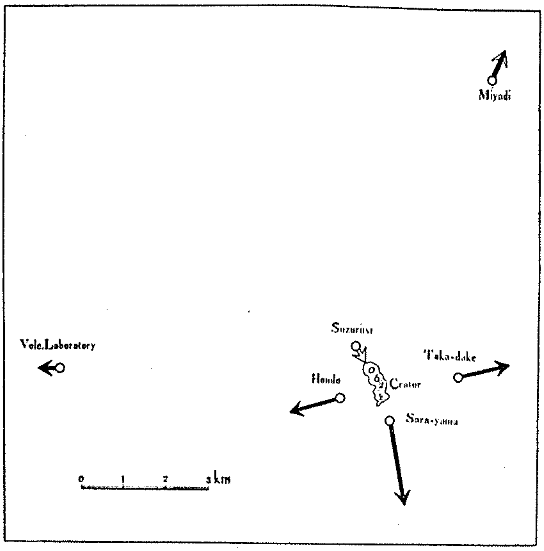
Date		Hondô		The Laboratory		Ampl. Ratio	Time Diff.
		A_E	T	A_V	T	A_E/A_V	
	h m	mm.	sec.	mm.	sec.		sec.
Oct. 26	21 47	12.6	6.2	7.0	6.2	1.80	7.6
	23 12	11.0	6.0	6.0	5.9	1.83	6.2
	39	9.1	6.0	3.7	6.2	2.46	6.4
	54	10.5	6.2	5.2	6.0	2.02	6.4
27	6 47	14.0	5.7	5.5	5.0	2.54	6.8
	7 07	11.0	6.4	6.4	6.0	1.72	7.4
	8 26	12.5	6.0	5.0	5.3	2.50	7.5
	11 04	27.0	6.0	10.0	6.1	2.70	5.8
	58	21.0	6.3	6.5	6.2	3.24	8.0
	12 43	22.0	6.0	7.4	5.2	2.97	8.0
	44	22.5	6.2	7.5	6.0	3.00	7.0
	13 39	30.0	6.0	11.5	6.2	2.61	6.8
	14 16	18.0	7.0	5.2	6.0	3.46	7.6
	40	18.0	6.0	6.7	6.0	2.69	7.0
	16 22	16.0	5.9	5.6	6.2	2.86	7.6
	26	19.5	6.2	6.4	6.1	3.04	6.8
	17 15	32.0	5.6	12.6	5.8	2.54	8.0
	18 14	19.0	6.6	7.1	6.4	2.67	7.6
	26	16.5	6.2	8.0	6.2	2.06	7.0
	30	12.5	6.0	7.4	6.0	1.69	6.7
	55	14.0	6.0	8.0	5.7	1.75	6.8
	20 10	17.5	6.0	5.2	5.9	3.36	7.0
	21 28	24.0	6.0	10.0	6.0	2.40	6.0
	Mean	17.82	6.11	7.12	5.94	2.50	7.05

The time of occurrence of the micro-tremors observed at the foot station was delayed about 7 seconds as compared with that at the summit station. The velocity of propagation of the micro-tremors of the second kind determined from the observed time difference of occurrences is 0.90 km./sec. which is to be taken as the velocity of Rayleigh waves in the district. As will be explained in the next paragraph, the micro-tremors of the second kind seem to be a kind of Rayleigh wave, but not the ordinary one, for the horizontal longitudinal vibrations virtually coincide in phase with the vertical, which is not in accord with the theory of ordinary Rayleigh waves. On Oct. 29, 1932 two horizontal component micro-seismographs, G_A were set up at the Girls' High School at Miyadi, where, the amplitude of the ordinary pulsatory oscillations being very large, the recorded micro-tremors of the second kind were greatly disturbed. The horizontal displacements of the micro-tremors here observed were practically confined to the direction of the crater. The simultaneous observations at Miyadi and the Laboratory give ca. 1 second as the time difference of occurrences of the micro-tremors at the two stations, being earlier at the former station than at the latter, while the amplitudes were nearly the same at both stations. For a further study of the nature of the micro-tremors of the second kind, the micro-seismographs, Type G_A were installed at the Hondô observing room on Aug. 17, 1933, and were at work till Sept. 7, and the micro-seismographs, Type G_B were temporarily set up at stations surrounding the crater. The horizontal motion of the micro-tremors of the second kind observed at Suzuriisi was virtually in the direction towards the First Crater, and the vertical motion was about 1.2 times the horizontal, the upward motion being in the phase of the NW-ward motion in the horizontal plane. The amplitude of the micro-tremors recorded at Hondô was 2.7 times that at Suzuriisi and the phase of waves was opposite at the two stations, the pull phase of every wave of the micro-tremors at Suzuriisi corresponding to the push phase at Hondô. But the wave-forms were quite similar at the two stations both as regards amplitude and period, and thus the identification of the corresponding phases of waves was made without much difficulty. The horizontal displacements of the micro-tremors of the second kind observed at Sara-yama were in the direction S10°E–N10°W and the vertical displacements were about twice as great as the horizontal, the upward motion being in phase with the corresponding S10°E-ward motion. The amplitude here recorded was about 1.6 times that recorded at Hondô, the westward phase at the latter station corresponding to the southward phase at Sara-yama. At Taka-dake, the horizontal displacements of the micro-tremors of the second kind were observed to be in the direction N77°E–S77°W. The amplitudes and periods here recorded were nearly the same as those recorded at Hondô, the eastward phase at Taka-dake corresponding to the westward at Hondô. Thus the directions of the horizontal displacements, their relative amplitudes and the corresponding phase of waves of the micro-tremors of the second kind at the six stations were as given in the following Table 7, and Fig. 15 shows graphically the results of observations.

Table 7

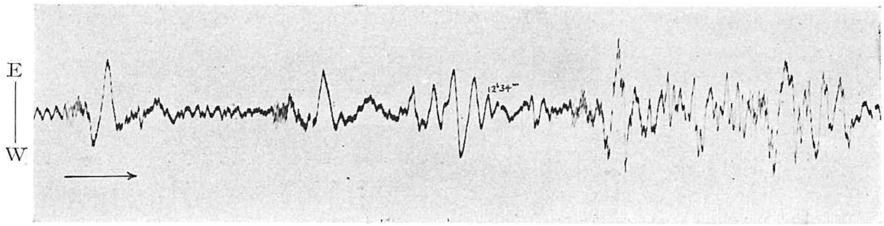
Station	Direction of horiz. disp.	Phase	Relative amplitude	V/H
The Laboratory	E–W	push	1	1.0
Miyadi	NNE–SSW	?	1	
Hondô	S74°W–N74°E	push	2.5	1.1
Suzuriisi	SE–NW	pull	0.9	1.2
Sara-yama	S10°E–N10°W	push	4.0	2.0
Taka-dake	N73°E–S73°W	push	2.5	

Fig. 15. Distribution of the direction of the horizontal displacement, the relative amplitude and the corresponding phase of the micro-tremors of the second kind.



Now, we come to the consideration of the origin of the disturbances of the micro-tremors of the second kind. It seems to lie immediately under the crater at a depth of 1 or 2 km. which is roughly determined from the observed facts above described. The horizontal displacement of the micro-tremors being practically confined to the direction of propagation at all observing stations, it should consist of a kind of longitudinal waves generated at the origin, the mode of oscillation being defined by the observed facts. Fig. 16 shows a portion of a record of eruption-earthquakes registered by the micro-seismographs, G_A at Hondô. The quick vibrations in the record of the eruption-earthquakes are followed by one complete large wave, the period of which is about 6 seconds and the direction of displacement is confined to the direction S74°W–N74°E, moving at first to S74°W upwards and then to N74°E downwards. This long wave may, so it seems to me, be considered as having been generated by the upward

Fig. 16. The eruption-earthquakes of the First Crater on Aug. 17, 1933 registered by the micro-seismograph, G_A, at the Hondô observation room. (Time between two consecutive marks = 1 min)



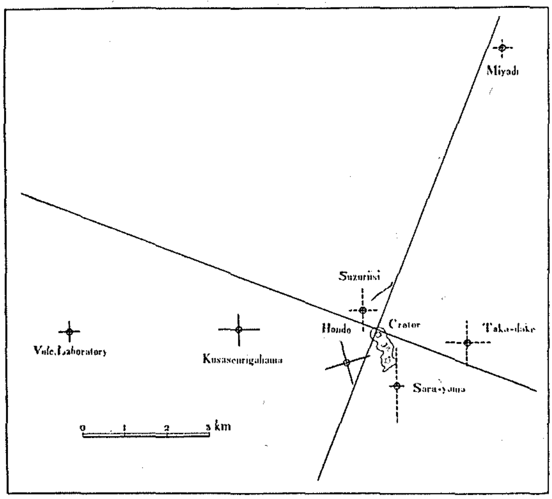
(4/5 × the original record)

mass movement to fill the space evacuated by the eruption. Since the eruption is estimated as occurring at about 1 km. depth, the initial displacement of the wave generated by the mass movement should be in push phase at near stations such as Hondô, which was not contrary to the observed fact. The mode of oscillation of the micro-tremors of the second kind is quite similar to that of the wave of an eruption-earthquake such as has just been described, and a similar mechanism of mode of occurrence is to be considered as probable. The distribution of the relative amplitude and the corresponding phase of the micro-tremors of the second kind given in Fig. 15 leads us to a consideration of a magmatic reservoir containing gas-riched magma in the active period of the volcano, which is set into vibration by some internal eruptive disturbance and generates spherical waves, whose principal phases propagating with the velocity of Rayleigh waves. But, to determine the mode of oscillation of the magmatic reservoir, the observing stations must be increased in number at different azimuths and different distances, and further investigation on this subject is now in progress, and the result will be reported on a subsequent occasion. If the mechanism of occurrence is as above supposed, the period of the micro-tremors of the second kind should be dependent on the dimensions of the magmatic reservoir and on the internal conditions of its contents. The observed period should thus have an intimate relation to the state of activity of the volcano. Actually, the periods of the micro-tremors of the second kind observed in the case of an isolated group of small eruptions of the Fourth Crater, the southern-most of the four craters, during Sept. 5–8, 1930, were less than 4 seconds, while in the case of the great explosive eruptions in 1932 and 1933 of the First and the Second, the northern two of the four craters, they were about 6 seconds and sometimes even more than 8 seconds as will be described in Part II of the present study.

7. The volcanic micro-tremors of the third kind

The micro-tremors which the writer calls the "third kind," and the period of which ranges from 0.4 to 0.6 sec., were observed only in active times of the volcano. The movements of the micro-tremors of this kind recorded at the Volcanological Laboratory are a continuous train of somewhat regular waves, constantly changing their directions of vibration. The mean amplitude of the tremors is nearly the same for the N–S and E–W components, and that of the vertical component is less than one-tenth of that of the former. Fig. 17 in Plate II is a reproduction of the record of the micro-tremors of the third kind obtained by the short period micro-seismographs, S_B on Sept. 10, 1932 at the Laboratory. As will be seen in the record, the micro-tremors of the third kind change their amplitudes at irregular intervals, which is an interesting phenomenon of these micro-tremors showing a certain intimate relation between the tremors and the activity of the volcano. When observed in the pit of ca. 20 m. depth, the amplitude of the micro-tremors reduces to about 0.6 of that observed at the surface of the ground, as is to be expected from the shortness of the periods. The mean amplitude recorded at Kusasenrigahama was twice as great as the corresponding mean amplitude simultaneously recorded at the Laboratory, the amplitude of the E–W component being 1.2 times that of the N–S component. At Hondô the mean amplitude of the micro-tremors of the third kind was the same for the N–S and E–W components, and that of the vertical component was about half that of the horizontal. The value for Hondô was 2.2 times that simultaneously observed at the Laboratory at the foot. At Suzuriisi the horizontal displacements of the tremors were very small as compared with those recorded at Hondô, and their N–S component was about 1.2 times of the E–W component, while at Sara-yama, they were exceedingly great as compared with those observed at Hondô and the vertical displacements recorded were as pronounced as the horizontal. The recorded mean amplitude of the N–S component at Sara-yama was about 5 times that of the E–W component. The horizontal displacements of the tremors under consideration observed at Takadake were the same both in the N–S and in the E–W component, while at Miyadi the N–S component was slightly greater than the E–W component. The distribution of the relative amplitude and the ratio of the mean amplitude of the N–S component to that of the E–W component observed at the above 7 stations are given in Fig.

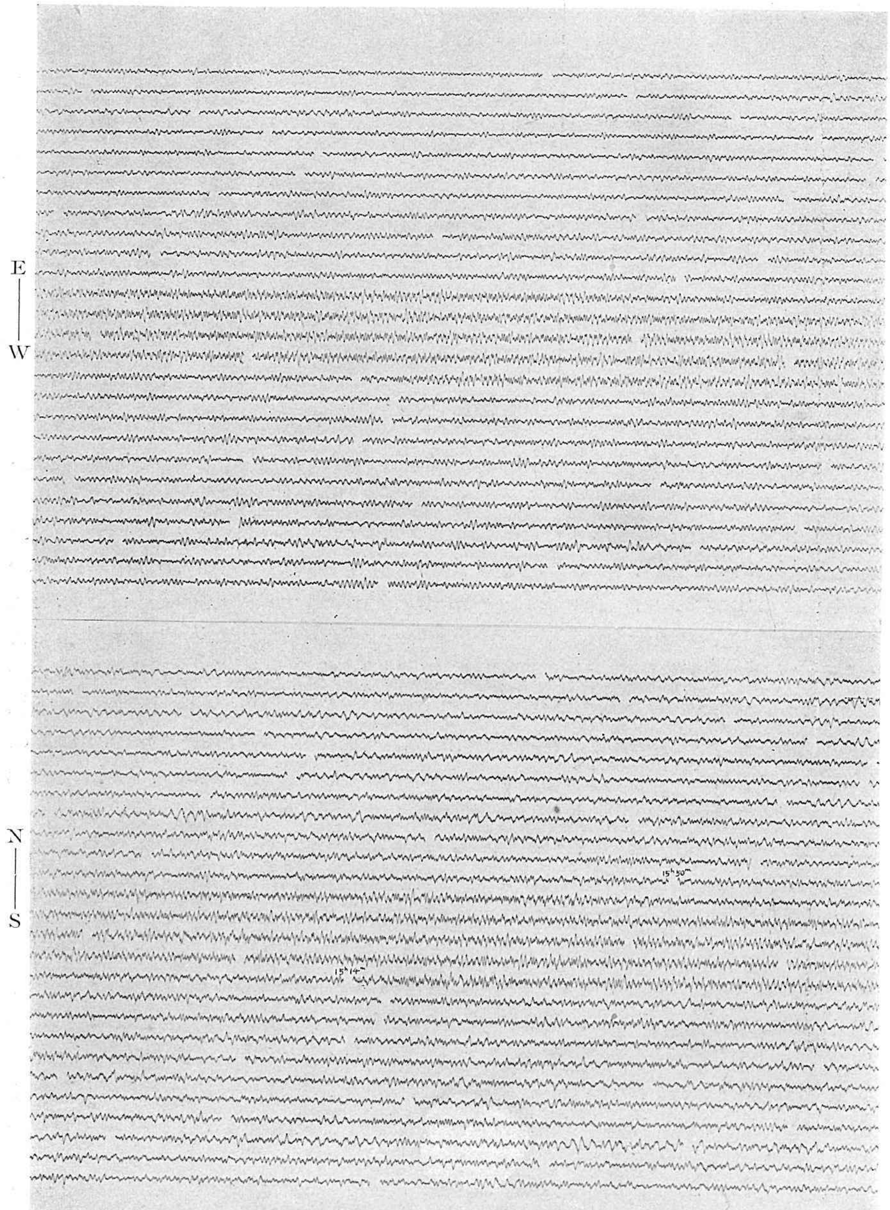
Fig. 18



18. The micro-tremors of the third kind being of short wave length of probably about 500 m., they are greatly disturbed by the geological irregularities of the district. Moreover the mode of oscillation recorded is very complex, which is probably due to the superposition of two different kinds of micro-tremors of nearly the same amplitude, one being micro-tremors of the third kind and the other of the first kind; consequently the directions of the vibrations of the micro-tremors observed could not be determined, but the distribution of the observed amplitudes given in Fig. 18 seems to throw some light upon the mechanism of their occurrence. As shown in the record reproduced in Fig. 20, the principal large vibrations of the eruption-earthquake resemble the micro-tremors of the third kind both in period and in mode of oscillation. According to the theory[1] that the Rayleigh wave has a certain azimuthal distribution of displacement, the transversal component of displacement, in the vicinity of the origin of disturbance, is large as compared with the longitudinal and vertical ones occurring close to certain specified lines of direction, whereas at increasing distances from these specified lines of direction, the latter become large as compared with the former. This property of the Rayleigh wave is in accord with the observed distribution of the horizontal and vertical displacements. Thus it seems that the micro-tremors of the third kind may be considered as a kind of Rayleigh waves generated by disturbances of Shida's crack type,[2] and it is very interesting to observe that the specified directions of the Rayleigh wave given in Fig. 18 are virtually coincident with those of the *P*-waves of the eruption-earthquakes given in Fig. 21.

1. H. Nakano; Geophy. Mag. **1** (1928), K. Sezawa; Bull. Eqke. Res. Inst. **6** (1929).
2. M. Hasegawa; Beit. z. Geophy. **27** (1930).

Fig. 19. The micro-tremors of the fourth kind, quick oscillations in the middle part of the record superimposed on those of the third kind, registered by the short period micro-seismographs, S_B, at the Volcanological Laboratory on Sept. 5, 1932. (Time between two consecutive marks = 1 min.)



(2/3×the original record)

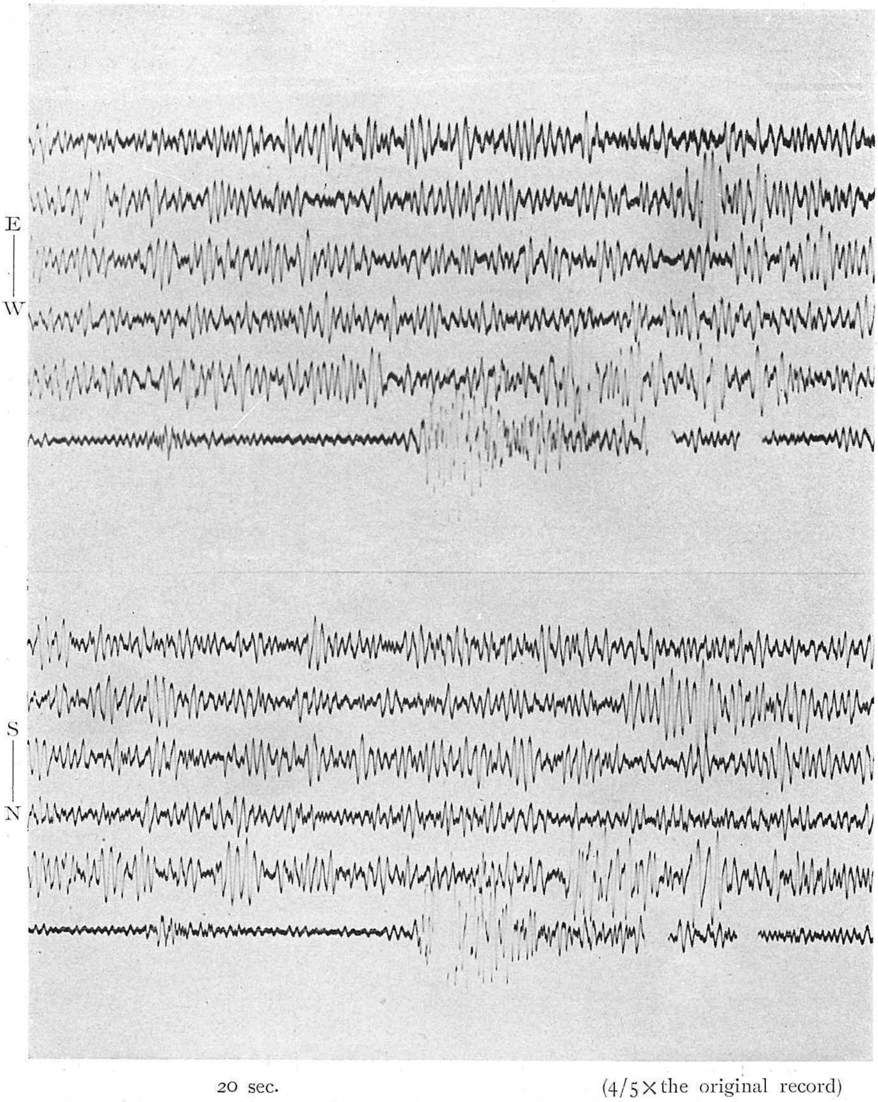
8. The volcanic micro-tremors of the fourth kind

Fig. 19 is a reproduction of a portion of the record obtained by the short period micro-seismographs, S_B, at the Aso Volcanological Laboratory on Sept. 5, 1932, where we see the quick oscillations of a period of ca. 0.2 sec. superimposed on the micro-tremors of the third kind. The amplitudes of the latter are much greater than those of the former, which are only about 0.05μ in double amplitudes. These quick oscillations, here called volcanic micro-tremors of the fourth kind lasted only for 30 minutes from 15^h14^m on Sept. 5, being the only occasion ever recorded clearly, and it is not yet certain whether the micro-tremors were due to volcanic disturbances or not, but it seems to the writer that they might have been due to volcanic disturbances at shallow depths under the crater. For, the time, when the micro-tremors were recorded, was the very time when the First Crater began, after a long repose, to emit black smoke more quickly, and with this exception, there was no disturbance that could be considered as the cause of the micro-tremors. Thus the micro-tremors may be supposed as due to the disturbance caused by the excavation of the volcanic pit, and fortunately on this unique occasion, the micro-tremors under consideration were recorded, without being masked by micro-tremors of the third kind of far large amplitude, which is not generally the case. At Hondô the recorded amplitudes of the micro-tremors of this kind seem to be of considerable magnitude, but the period of proper vibration of the ground being the same as that of the micro-tremors under consideration, it is very difficult to separate them. It will be very interesting to observe the micro-tremors of the fourth kind more closely, with a view to investigating the surface activity of the volcano, but suitable seismographs must be designed for the purpose.

9. The eruption-earthquake

Fig. 20 is a reproduction of the record of the eruption-earthquake of Aug. 16, 1933. It was registered by the short period micro-seismographs, S_A at the Hondô observation room. This eruption-earthquake was accompanied by an eruption of the First Crater, and volcanic fragments of medium size were ejected over the north wall of the crater. Eruptions of the First Crater of nearly the same strength continued for several days following. The recorded initial displacements of the eruption-earthquakes observed at Hondô and Suzuriisi on this occasion are given in Table 8. Of these, only the four cases

Fig. 20. The eruption-earthquake of Aug. 16th 23h 12m, 1933 registered by the short period micro-seismographs, S_A, at the Hondô observation room. Tremors continuously recorded in the record are the volcanic micro-tremors of the third kind.



20 sec. (4/5×the original record)

given in Table 8, (C) were simultaneously observed at the two stations. But, since, without a single exception, the initial displacements, recorded at Hondô, are directed away from the crater while those at Suzuriisi are directed towards the crater it may be inferred

Table 8.

(A) Hondô

Time of occurrence	A_N	A_E
	mm.	mm.
Aug. 16 23^h12^m	−3.8	−2.8
14	−1.4	−2.0
17 12 28	−1.4	−3.5
29	−3.0	−4.0
31	−1.2	−1.7
32	−1.0	−1.1
34	−2.0	−1.3
36	−3.0	−2.2
37	−5.0	−3.2

(B) Suzuriisi

Time of occurrence	A_N	A_E	$P \to B$
	mm.	mm.	sec.
Aug. 18 2^h31^m	−2.0	1.3	2.4
33	−1.3		2.0
34	−2.0		2.0
36	−3.0		2.4
37	−2.2		2.4
38	−1.4		2.4
39	−2.0	1.2	2.4
4 29	−2.5	1.4	2.2
31	−3.5	1.8	2.5
32	−3.0	1.5	2.8
33	−2.5	2.0	2.5
		Mean	2.36

(C)

Time of occurrence	Hondô	Suzuriisi	
	A_E	A_N	A_E
	mm.	mm.	mm.
Aug. 18 6^h31^m	−0.5	−1.5	1.1
33	−0.3	−2.0	
34	−0.7	−3.0	1.7
35	−0.4	−2.0	2.0

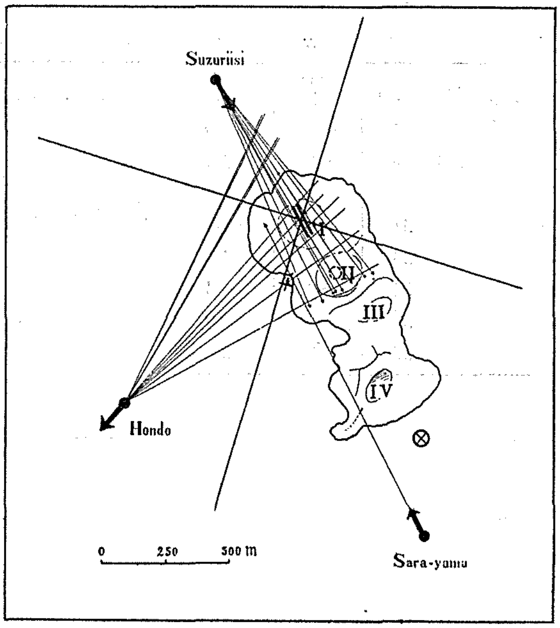
that the initial displacements of all the eruption-earthquakes given in the table are similar in character. From the observed directions of the initial displacements shown in Fig. 21 it is supposed that the hypocenters of the eruption-earthquakes lie approximately on a line connecting the four active craters. A single case of an eruption-earthquake was recorded at Sara-yama on Aug. 27, 1933. Its initial displacement was 5.2 mm. northward, 2.7 mm. westward, and 7.0 mm. downward on the record and its direction is shown in Fig. 21. The initial motions of the *S*-waves of eruption-earthquakes recorded at Hondô are directed to NNW. All these observed facts of the eruption-earthquakes are fairly well explained by taking them as instances of Prof. Shida's crack type, and the nodal lines as given in Fig. 21. It is also very interesting to consider the formation of the row of the present active craters in connection with the fact that the direction of cracks of the eruption-earthquakes is parallel to the row of craters, and moreover the cracks themselves lie side by side on the line joining the crater. The mean depth of the eruption-earthquakes was determined from the following data;

1. The mean real emergent angle observed at Hondô = ca. 40°. The mean epicentral distance from the Hondô obs. room = 1 km. The depth,

assuming the straight path of the seismic ray =0.84 km.

2. The mean duration of preliminary tremors observed at Hondô = 1.0 sec.. The mean duration of preliminary tremors observed at Suzuriisi = 0.8 sec.. The mean epicentral distance from the Hondô obs. room = 1 km. The mean epicentral distance from the Suzuriisi obs. station = 0.6 km. The depth, assuming the straight path of the seismic ray = 0.88 km. Taking the mean, the mean depth of the eruption-earthquakes was taken as about 860 m.

Fig. 21. Distribution of the initial motions of the eruption-earthquakes of the First Crater in Aug. 1933.



The velocities of propagation of the seismic waves in the district were determined by the following observed data of a volcanic earthquake on Oct. 22, 1932:

Station	Time of occurrence		P–S	$\bar{e}$	Δ
	P	S			
The Hondô obs. room	$12^h0^m11.8^s$	$0^m12.5^s$	sec. 0.7	29°	km. 0.8
The Volc. Laboratory	16.8	18.9	2.1		7.05

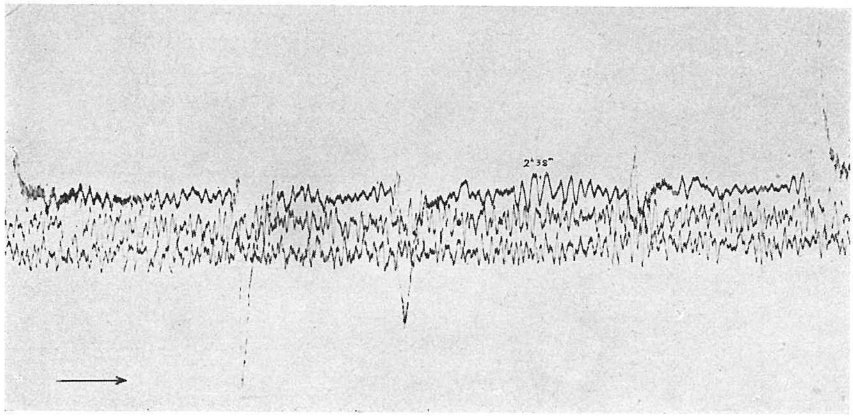
The position of the epicenter is given by the cross in Fig. 21, the depth of the origin, using the observed data of the eruption-earthquakes, being calculated as about 450 m.. The velocities of the seismic waves determined are as follows:

The velocity of the P-wave: 1.25 km./sec. The velocity of the S-wave: 0.98 km./sec. The velocity of the Rayleigh wave: 0.90 km./sec.

Fig. 22 shows a portion of the record obtained by the microseismographs, G_B, at Suzuriisi on Aug. 18, 1933. Five eruption-earthquakes are recorded on it. The large displacements following the quick vibrations of the eruption-earthquakes are due to the sound

Fig. 22. Five eruption-earthquakes registered by the micro-seismographs, G_B, at Suzuriisi on Aug. 18, 1933. The large displacements following the quick vibrations of the eruption-earthquakes are due to the sound shocks of the eruptions.

N—S

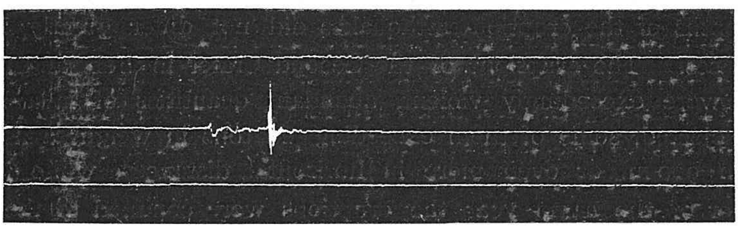


1 min. (4/5 × the original record)

shocks of the eruptions. The time differences between the sound shocks and the initial motions of the eruption-earthquakes are 2.36 seconds in the mean at Suzuriisi, and appear in the last column of Table 8 (B). The time taken by the *P*-wave to travel 1.05 km., taking the depth of the earthquake 860 m. and the epicentral distance 600 m., is 0.84 seconds and the time taken by the sound-shock to travel 700 m. is 2.05 seconds, taking the velocity of sound as 340 m./sec. for mean air temperature of 15°C. Accordingly the time taken by the sound-shock to travel from the origin of the earthquake to the mouth

Fig. 23. The eruption-earthquake and its sound shock of March 4^{th} 19^h 49^m, 1933 registered by the Wiechert vertical component seismograph at the Volcanological Laboratory.

D—U



(Full size the actual)

of the volcanic vent is to be taken as 1.15 seconds, from which the velocity of the sound-shock in gas-riched molten lava in the vent—the author observed red hot lava swelling up at its mouth—is calculated as about 790 m./sec.. Fig. 23 is a reproduction of the record of an eruption-earthquake and of its sound-shock, registered by the Wiechert vertical component seismograph at the Volcanological Laboratory, 7.3 km. from the crater on March 4, 1933. The time differences between the initial motions of the principal phases of the eruption-earthquakes and their sound-shocks recorded by the same instrument on March 4, 1933, are given in the following Table 9;

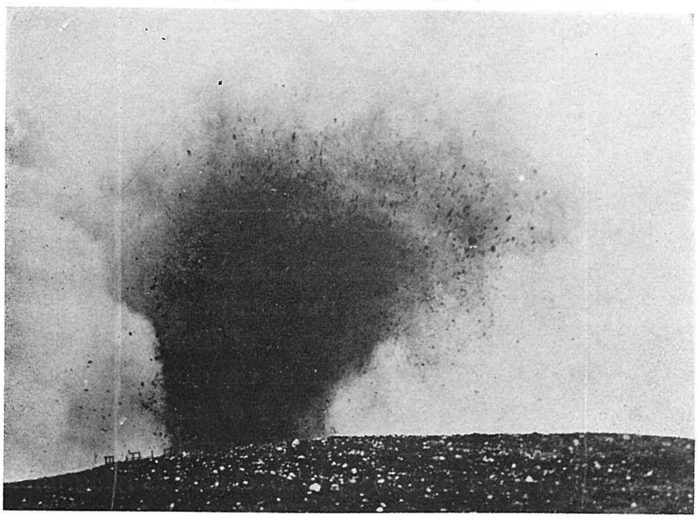
Table 9

Time of occurrence	L_Z	B_Z	$L \to B$
	mm.	mm.	sec.
March 4 11^h43^m	−0.5	−0.7	15.5
18 57	−0.3	−0.6	15.5
19 07	−0.4	−0.8	16.0
10	−0.1	−0.7	15.6
49	−0.8	−2.1	15.8
Mean			15.68

L_Z: Amplitude of the recorded initial motion of the principal phase of the eruption-earthquake.
B_Z: Amplitude of the recorded initial motion of the sound-shock.
$L \to B$: The time difference between the two phases.

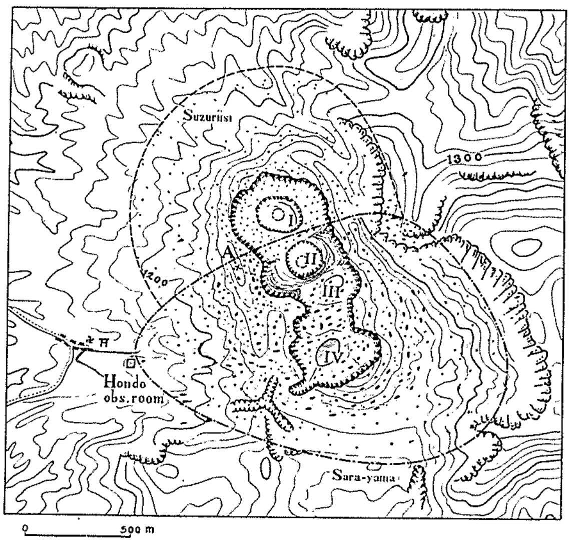
The durations of preliminary tremors of large eruption-earthquakes observed at the Laboratory being 2.0 seconds in the mean, the time difference of occurrence between the *P*-waves and the sound-shocks of the eruption-earthquakes is 17.7 sec. in the mean. The time taken by the *P*-wave to travel 7.3 km. is 5.85 seconds, and that taken by the sound-shock to travel 7.5 km., 22.43 seconds, taking the velocity of the sound wave as 334 m./sec. at a mean air temperature of 5°C. Accordingly the time taken by the sound-shock to travel from the origins of the earthquakes to the mouth of the vent of the crater, where the air wave is considered as starting, is 1.1 seconds, which value is nearly the same as that obtained at Suzuriisi as described above. Although there are no observational data to determine directly the depth of the violent eruption-earthquakes of the Second Crater in spring, the above fact seems to indicate that the depths of the eruption-earthquakes did not differ greatly in the two cases. The eruptions of the Second Crater in Feb. and March 1933, were exceedingly violent, abundant quantities of lava blocks being ejected, some of them exceeding 20 tons in weight and being thrown 900 m. or even more in horizontal distances, while in the summer of the same year the eruptions were confined to the First Crater, and were feeble, only a few blocks of lava of about 0.1 ton weight being thrown out to horizontal distances of 100 m. or less. The initial velocities of the lava blocks projected were estimated at about 94 m./sec. in the case of the eruptions in the early spring of 1933 and at about 30 m./sec. in the case of the eruptions in Aug. of the same year. If we take the pressure difference p between inside and outside the vent, which gives the initial velocity V to the lava block of density ρ, we have $p = 1/2 \times \rho V^2$, the pressure change due to the mass displacement being neglected. The equation gives a pressure difference of about 108 atmospheres for the case of the early spring of 1933, and about 9 atmospheres for the case of the summer of the same year, the former value (108 atms.) corresponding to a pressure at a depth of about 450 m. and the latter value (9 atms.) to a depth of about 37 m.. The density ρ is assumed as 2.5. We have seen that the depth of the eruption-earthquakes, being about 860 m., were not very different in the two cases. But the spring eruptions of the Second Crater were so exceedingly violent that the initial velocity of the ejected mass corresponded to the pressure at a depth of 450 m., while the summer eruptions of the First Crater were so feeble that the initial velocity of ejecta corresponded to the pressure at a depth of only 37 m.. Thus the depth at which the eruption starts seems to be roughly independent of the strength of the eruption and the cause of this apparent discrepancy seems to lie in that, in the case of small

Fig. 24. An eruption of the Second Crater at about 15^h on Feb. 24, 1933, taken at (A) in Fig. 25.



scale eruption, the quantity of volcanic gases explosively evolved from the magma to cause the eruption is not sufficient to maintain a constant pressure on the mass to be ejected. Thus the quantity and the initial velocity of lava blocks thrown out are to be taken as being mainly due to the quantity of volcanic gases explosively evolved from magma at the eruption and not to the depth at which the explosive expansion of volcanic gases occurs. Fig. 24 shows an eruption of the Second Crater at about 15^h on Feb. 24, 1933 photographed at *A* on a hill, west of, and about 250 m. distant from the crater, as shown in Fig. 25. The height of the volcanic ejecta seen in the photograph may be estimated from the fact that the height of the palisades is about 1 meter. The height of the crater rim above the mouth of the vent is roughly about 70 meters.

Fig. 25. Distribution of lava blocks thrown out from the First and the Second Craters in Feb. and March 1933.



As will be seen from the photograph, the greater part of the lava blocks thrown out from the Second Crater in the early spring eruptions of 1933 fell upon the southern sides of the vent forming new steep slopes of lava blocks and fragments on the inner side of the southern wall of the crater. The horizontal distribution of the ejecta thrown out from the Second Crater is exceedingly eccentric with respect to the vent of the crater. This eccentric distribution of the volcanic ejecta seems to the author to be mainly due to the southward inclination of the vent of the Second Crater, while the vent of the First Crater is practically vertical, the horizontal distribution of the ejecta thrown out from the latter being nearly circular, the center of the circle lying in the vent. From the above considerations the main magmatic reservoir, which was active in 1932 and 1933, is concluded as lying immediately under the First Crater, and as coinciding with the origin of disturbance determined from the observations of the volcanic micro-tremors described in the preceding pages.

10. Summary

From observational data on volcanic micro-tremors and eruption-earthquakes at Aso which were obtained by the present author with specially prepared seismographs, and considerations based on them, the following results were obtained:

1. There are four kinds of volcanic micro-tremors observed at the Volcano Aso.

2. The volcanic micro-tremors of the first kind, the period of which is about 1 second, form a kind of Love wave having a certain azimuthal distribution generated by internal eruptions of volcanic gases, and with a velocity of propagation of about 1.0 km./sec..

3. The distribution of amplitudes of the micro-tremors of the first kind observed during the active time of the volcano in Oct. 1932 is satisfactorily explained by Nakano's solution of the Love wave, taking $n=2$ in his equation, while in a repose time we have to take $n=1$ to explain the observational facts. The depths of the origin of disturbances are also different in the two cases, deeper for the former case than for the latter.

4. When the volcano is quiescent the micro-tremors of the first kind occur not in continuous trains, but intermittently, several wave groups of ca. 1 micron or less in double amplitudes per hour, but in an active time they become continuous trains of irregular waves.

5. The amplitudes of micro-tremors of the first kind recorded by seismographs set directly on volcanic rock in the pit of ca. 20 m. depth are reduced to 0.85 of the corresponding amplitudes observed on a ground of volcanic ashes.

6. The volcanic micro-tremors of the second kind, the period of which ranges from 3.5 to 7 seconds, are a kind of Rayleigh wave having a certain azimuthal distribution generated by the oscillation of the magmatic reservoir, and the velocity of propagation is 0.90 km./sec..

7. Between amplitudes and periods of the micro-tremors of the second kind no definite relation was found, but the ratio of the recorded horizontal amplitude to the vertical increases as the period decreases.

8. In a repose time of the volcano the micro-tremors of the second kind occur not in continuous trains, but intermittently, several groups of regular waves of a few microns in double amplitudes per hour, while in an active time they become continuous trains of somewhat irregular waves.

9. The micro-tremors of the second kind are frequently observed

accompanied by those of the first kind, which latter are recorded from 0 to 20 seconds before the recorded initial phase of the principal part of the former, but sometimes they are observed independently of each other.

10. The volcanic micro-tremors of the third kind, the period of which is about 0.5 seconds, is a kind of Rayleigh wave having a certain azimuthal distribution generated by internal eruptions of volcanic gases.

11. The micro-tremors of the third kind are observed only in an active time of the volcano and change their amplitudes at irregular intervals, which bear some resemblance to pulses of volcanic rumblings and of emission of volcanic smoke.

12. The volcanic micro-tremors of the fourth kind, the period of which is about 0.2 seconds seem to be generated by some disturbances due to surface eruptions of the volcano.

13. The mechanism of occurrence of the eruption-earthquakes is of Prof. Shida's crack type.

14. The direction of cracks of the eruption-earthquakes observed is parallel to the row of the present active craters, and moreover the cracks themselves stand side by side on the line joining the craters.

15. The velocities of propagation of seismic waves in the district observed are 1.25 km./sec. for the P-wave, 0.98 km./sec. for the S-wave, and 0.90 km./sec. for the Rayleigh wave.

16. The velocity of propagation of sound-shocks in gas-riched molten lava in the volcanic vent is calculated from observed time differences between the eruption-earthquakes and the sound-shocks at about 790 m./sec..

17. The depths of eruption-earthquakes observed, being about 860 m., were not very different in the two cases, one of which is the case of exceedingly violent eruptions of the Second Crater in the early spring of 1933, the initial velocity of lava blocks projected being about 94 m./sec. and the other, of feeble eruptions of the First Crater in the summer of the same year, the initial velocity of the ejecta being only about 30 m./sec..

18. The quantity and the initial velocity of lava blocks thrown out from the vents are mainly due to the quantity of volcanic gases explosively evolved from the magma and not to the depth at which the eruption-earthquake occurs.

19. The volcanic vent of the Second Crater is inclined towards

the south. The magmatic reservoir which was active in 1932 and 1933 seems to be just under the First Crater, coinciding with the origin of disturbances determined from the observations of the volcanic micro-tremors.

In conclusion, the writer wishes to express his thanks to Prof. Toshi Shida for his invaluable advice and to Mr. I. Yasuda who assisted in preparing some of the seismographs.

APPENDIX

Micro-tremors caused by Rainfalls

On rainy days our sensitive seismographs set up at the Aso Volcanological Laboratory frequently recorded small micro-tremors of a few microns in double amplitudes, their periods being about 0.5 seconds. A typical record of the micro-tremors registered by the short period micro-seismographs, S_A, on July 21, 1931 has been reproduced in Fig. 26, Plate II. The oscillatory motions of the micro-tremors of this nature are very smooth and regular, continuing in nearly the same amplitudes for many hours, as compared with those of the volcanic micro-tremors of the third kind which are of the same period and were described in the preceding paper. The oscillatory motions of a particle of the ground of the micro-tremors are very complex as will be seen in the record. The vertical motion of the micro-tremors recorded was about one-third of the horizontal motion. The period observed in the N-S component in the record is 0.46 seconds while that in the E-W component is 0.54 seconds. This difference in period should not be considered as simply due to the difference in amplitude, or to the difference in the periods of proper oscillation of the ground at the observing station, but may be due, as will be explained in the following pages, to the difference of the origins of disturbance generating the micro-tremors. The mean amplitudes of the micro-tremors and the amounts of precipitation observed at the Aso Volcanological

Laboratory during June 30–July 19, 1931 are given in the following Table 10 and shown in Fig. 27.

Table 10

Date	0h–4h			4h–8h			8h–12h			12h–16h			16h–20h			20h–0h		
	A	*F*	*P*	*A*	*F*	*P*	*A*	*F*	*P*	*A*	*F*	*P*	*A*	*F*	*P*	*A*	*F*	*P*
	μ		mm.	μ		mm.	μ		mm.	μ		mm.	μ		mm.	μ		mm.
June 30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0	0.3
July 1	0	0	20.4	0.6	6.8	27.5	1.6	18.6	0.2	2.1	19.4	0.1	1.9	13.7	1.7	2.2	9.2	6.3
2	2.0	6.3	58.2	1.5	22.5	6.4	1.0	31.4	0	0.5	24.0	2.6	0	17.0	0	0	10.0	0
3	0	1.6	0	0	0.6	2.3	0	1.4	0.9	0	1.1	5.4	0.2	2.5	2.4	0.2	3.6	0.7
4	0.2	2.8	0.6	0	2.2	7.2	0	3.5	0.5	0	3.9	3.4	0	3.6	4.3	0	4.5	1.5
5	0	4.9	0.3	0	3.7	0.9	0	2.2	0	0	1.0	0.5	0	0.7	1.0	0	0.9	0.9
6	0	1.0	41.0	1.6	14.0	41.0	2.9	32.0	35.2	4.0	43.8	50.5	5.5	52.8	14.4	4.5	52.3	58.2
7	4.4	63.9	29.7	4.2	55.6	8.8	4.0	43.6	35.5	3.5	39.6	15.2	3.9	36.2	0	3.6	23.7	0
8	2.5	14.1	0	1.0	7.2	0	0.2	1.8	0	0	0	0	0	0	0	0	0	0
9	0	0	1.1	0	0.5	5.5	0	2.6	6.2	0	5.3	0	0	5.1	0	0	3.7	11.5
10	0.5	5.8	33.9	2.0	17.0	40.1	2.9	33.0	4.3	2.0	33.0	0	2.4	24.5	0.8	1.1	14.0	5.4
11	1.0	7.6	8.2	0.6	6.0	9.6	1.1	8.7	16.5	1.6	8.8	6.0	0.6	15.2	1.4	0	12.0	0
12	0	7.7	0	0	4.1	1.5	0	1.7	6.7	1.2	3.2	49.9	2.5	19.7	53.7	3.9	41.7	3.5
13	4.7	44.0	12.3	3.4	35.6	1.7	1.6	25.0	0	0.6	12.0	0.1	0	3.5	0.3	0	1.8	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	2.2	0	0.8	3.8	0	2.1	1.5
17	0	3.0	0	0.4	2.3	0.3	1.6	1.6	11.6	2.3	4.7	0	2.1	5.7	14.2	1.7	9.0	0.4
18	1.2	9.0	0	0.8	7.4	2.2	0.6	4.5	0	0.5	2.7	0	0.3	0.7	0	0	0.3	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

A: The E-W component of the mean amplitudes of the micro-tremors. *F*: The calculated amounts of water flowing in the rivers in an arbitrary unit. *P*: The amounts of precipitation.

Fig. 27. Relation between the mean amplitudes of the micro-tremors and amounts of precipitation, and the estimated amounts of water flowing in the rivers.

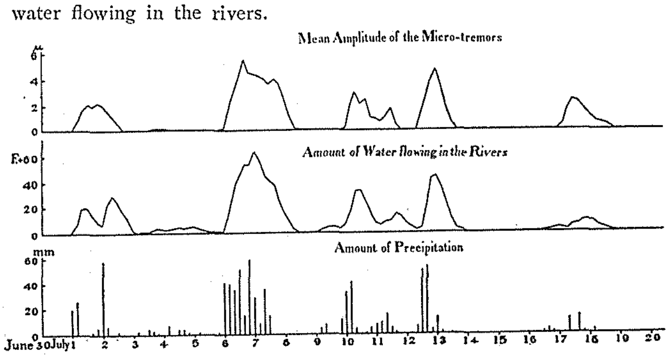


Fig. 27 shows how the observed amplitudes of the micro-tremors depend on the amounts of precipitation at Aso, and suggests that they are generated by some disturbances caused by the rainfalls. The waters of the two valleys, the Aso valley in the north and the Nangô in the south, flow down through the rivers, Kuro-kawa and Sira-kawa respectively, falling in finally to the two famous waterfalls of Sugaru in the former and Aigaeri in the latter. The waterfall of Sugaru, with a head of ca. 30 meters, is at a distance of 1.73 km. to W10°N and that of Aigaeri, whose head is ca. 20 meters, at a distance of 2.35 km. to S38°W from our Volcanological Laboratory as will be seen in Fig. 1 of the preceding paper. Though the amounts of water flowing in the rivers were not observed, their relative variation with respect to time may be roughly estimated from the amount of the precipitations. But, strictly speaking, the amount of water flowing in a river will depend not only on the amount of precipitation but also on its rate, and it is not an easy task to estimate the amount of flow of water from the amount of precipitation. In the present case a rough estimation was carried out on the assumption that the amount of water flowing in the rivers increases rapidly with rainfalls and attains a maximum about 6 hours after the rainfall, and then gradually decreases for 18 hours. The amounts of water flowing in the rivers thus estimated in an arbitrary unit are given in the F-column in Table 10 and shown in Fig. 27. The parallelism of the curves of the amplitude of the micro-tremors and the estimated amount of flow in the rivers in Fig. 27 seems to show that the micro-tremors are generated mainly by the two waterfalls and partly by the rushing streams in the rocky rivers. Thus the observed complexity of the mode of oscillations of the micro-tremors at the Laboratory is probably due to the superposition of different waves, one coming from the Sira-kawa in the south, and the other from the Kuro-kawa in the west, each component of them itself being not simple from the nature of the tremors. If the micro-tremors could be taken as kinds of Rayleigh wave propagated from the origins of disturbance, the horizontal displacements should be confined practically to the E-W component for the micro-tremors generated by the Sugaru waterfall, and should roughly have the same amplitude for both N-S and E-W components generated by the Aigaeri waterfall. Further the amplitude of the micro-tremors generated by the latter waterfall and observed at the Laboratory is to be estimated at about 0.6 of that of the micro-tremors caused by the former waterfall, taking into consideration two differences (a) that between the head of the waterfalls and (b) that between their distances from the laboratory. These reasons

Table 11

Hour	A_E	A_N	A_E/A_N	T_E	T_N	T_N/T_E
	μ	μ		sec.	sec.	
July 6 10h–12h	0.25	0.26	0.97	0.51	0.49	0.96
14 –16	0.55	0.43	1.28	0.58	0.56	0.96
16 –17	0.65	0.52	1.25	0.61	0.54	0.88
17 –18.5	0.65	0.52	1.23	0.59	0.54	0.92
21 –23	0.65	0.50	1.30	0.59	0.54	0.92
7 0 – 2	0.60	0.55	1.09	0.56	0.52	0.93
6 – 8	0.31	0.35	0.90	0.55	0.51	0.93
9 –11	0.35	0.35	1.00	0.55	0.50	0.91
15 –17	0.17	0.21	0.83	0.53	0.51	0.94
20 –22	0.60	0.48	1.23	0.57	0.54	0.95
8 7 – 9	0.70	0.58	1.20	0.61	0.56	0.92
12 –14	0.70	0.55	1.28	0.55	0.54	0.98
9 7 – 8	0.36	0.40	0.90	0.54	0.51	0.94

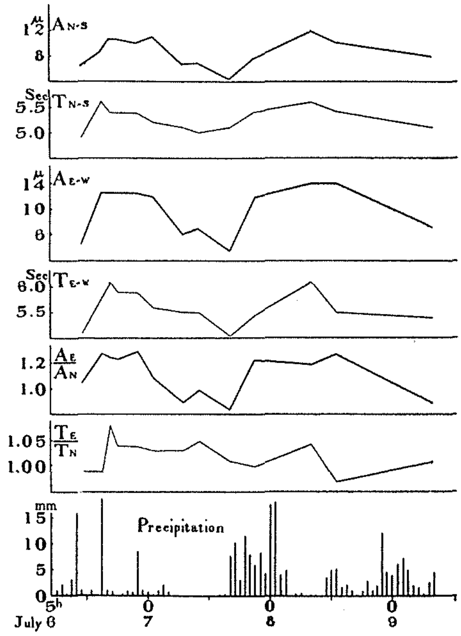
Amount of precipitation

Day / Hour	6	7	8	9
	mm.	mm.	mm.	mm.
0h	0.0	0.6	17.5	3.5
1	0.2	0.4	18.0	6.0
2	1.0	0.8	4.0	7.0
3	0.8	2.4	5.0	5.0
4	0.2	1.0	0.0	2.0
5	0.0	0.0	0.2	1.5
6	1.0	0.0	0.1	0.2
7	2.0	0.0	0.0	2.8
8	0.6	0.0	0.0	4.0
9	3.4	0.0	0.0	9.0
10	17.0	0.0	0.0	7.8
11	0.6	0.0	3.5	3.0

Day / Hour	6	7	8	9
	mm.	mm.	mm.	mm.
12h	0.0	0.0	5.0	2.0
13	0.8	0.0	5.0	1.2
14	0.0	0.2	1.4	3.5
15	18.6	0.3	1.8	4.0
16	1.0	7.7	1.0	3.2
17	0.4	10.2	0.0	2.5
18	0.0	3.0	1.0	3.4
19	0.4	11.5	3.0	3.2
20	0.8	8.0	1.0	6.0
21	0.5	6.0	2.0	0.0
22	9.0	8.0	15.0	0.0
23	1.0	4.0	4.0	0.0

explain why the amplitude of the E-W component of the tremors is generally greater than that of the N-S component. But the bed of the river Sira-kawa being steeper than that of the river Kuro-kawa, the water falling in the Aigaeri waterfall increases sooner than in the Sugaru fall after a rainfall, so that the micro-tremors observed at the laboratory at very early stage of a rainfall of some duration may be explained as being mainly due to the Aigaeri waterfall. The results of observations of the micro-tremors made with the short period micro-seismographs, S_B during July 6–10, 1932 were not contrary to this expectation as given in the foregoing Table 11 and shown in Fig. 28.

Fig. 28. Amplitudes and periods of the micro-tremors and amounts of precipitation.



The ratio of the amplitudes A_E/A_N in Fig. 28 shows that the horizontal displacements of the micro-tremors are predominant in the N-S component during the beginning stage of the rainfalls, but about five hours later, the two components become almost equal and the E-W component becomes predominant thereafter. The period varies in a similar way, but that of the N-S component is always slightly shorter than that of the E-W component. This is probably due to the difference in the head of the two waterfalls.

Summary

The micro-tremors observed at the Aso Volcanological Laboratory in and after rainy days are probably Rayleigh waves which are generated mainly by the two waterfalls, Sugaru and Aigaeri, in the river Kuro-kawa and Sira-kawa respectively. The period of the micro-tremors observed is about 0.5 seconds, being slightly shorter for the micro-tremors generated by the Aigaeri waterfall which is probably due to its smaller scale of disturbance.

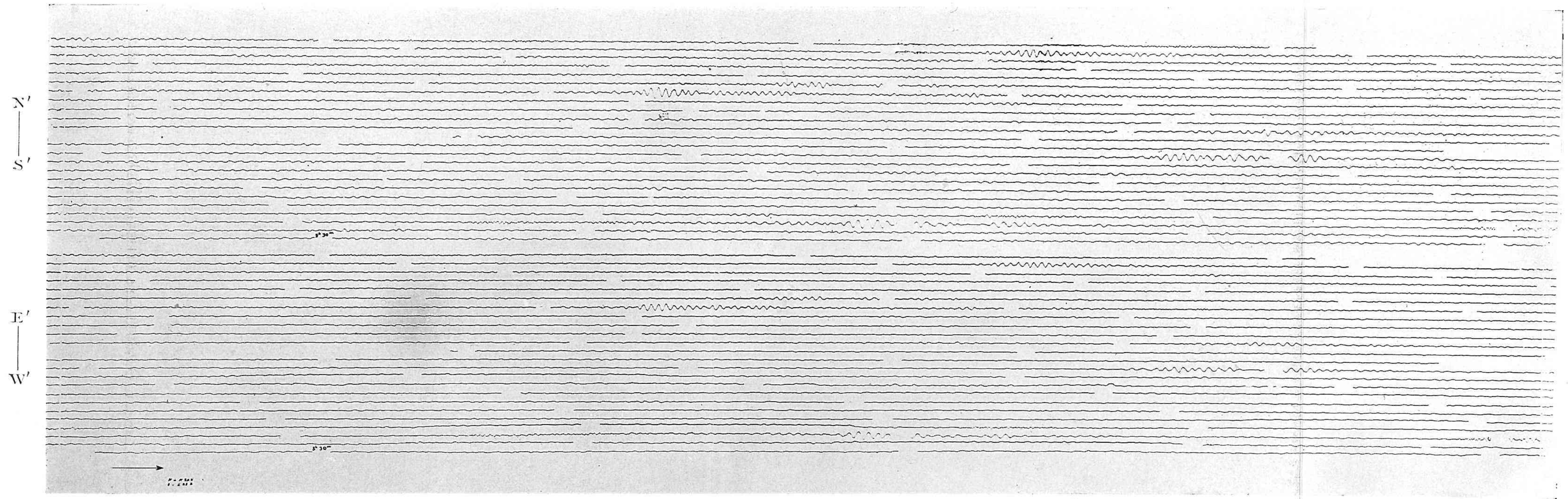


Fig. 6. A record obtained from the short period micro-seismographs, S_B, at the Aso Volcanological Laboratory on Nov. 28th 5^h30^m–6^h37^m, 1931 when the volcano was quiescent and the micro-tremors of the first kind were recorded intermittently. (N′=N20°E, E′=E23°S. Time between two consecutive marks= 1 min.).

(1/3×the original record)

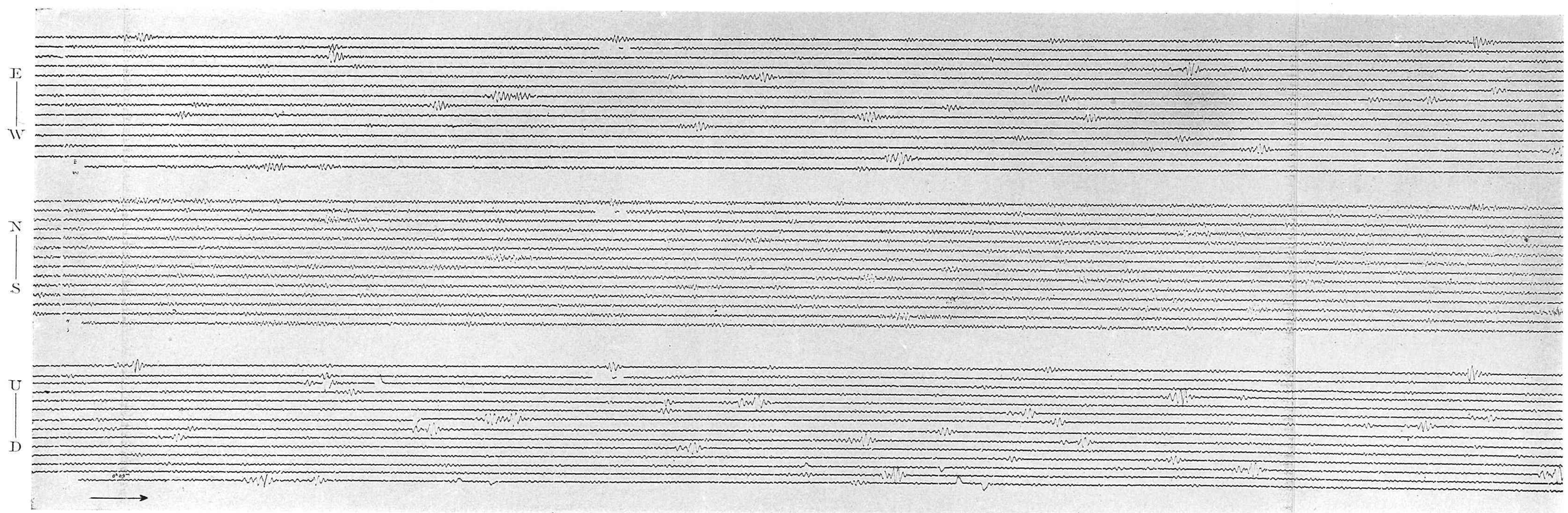


Fig. 10. A record obtained from the micro-seismographs, G_A, at the Volcanological Laboratory on July 27th 0^h09^m–6^h42^m, 1932 when the volcano was quiescent and the micro-tremors of the second kind were recorded intermittently. (Time between two consecutive marks=1 min.).

(1/3×the original record)

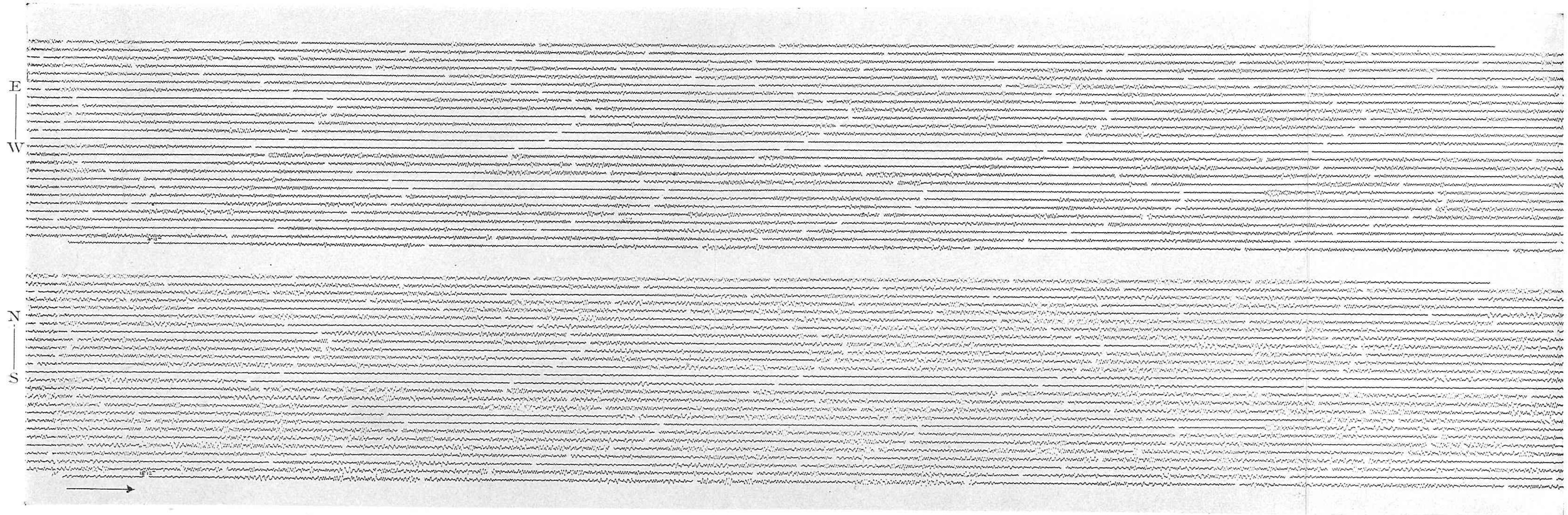


Fig. 17. The micro-tremors of the third kind registered by the short period micro-seismographs, S_B, at the Volcanological Laboratory on Sept. 10th 18^h12^m–20^h49^m, 1933 when the volcano was slightly active, constantly emitting black smoke from the First Crater.
(Time between two consecutive marks = 1 min.).

(1/3 × the original record)

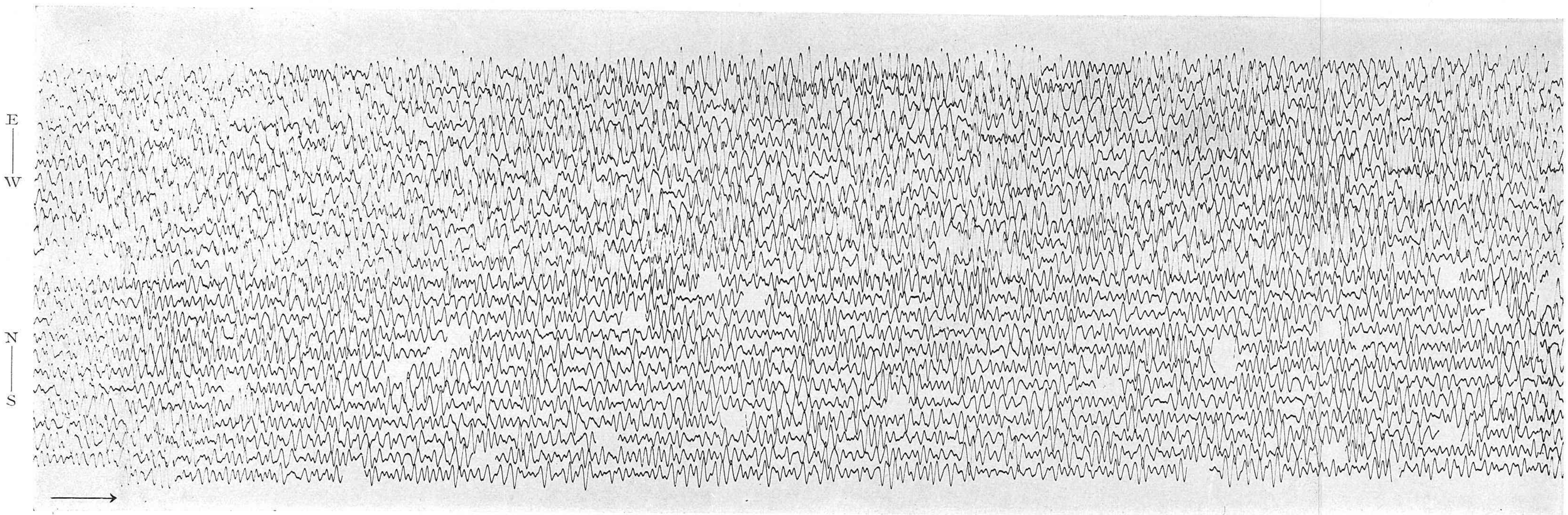


Fig. 26. The micro-tremors caused by rainfalls registered by the short period micro-seismographs, S_A, at the Volcanological Laboratory on July 21st 11^h03^m–11^h26^m, 1931.
(Time between two consecutive marks = 1 min.).

(1/3 × the original record)