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Volcanic Tremor of Me'akan-dake*

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At the volcano Me'akan-dake several steam-explosions occurred during the years 1955 and 1956. Weak tremor succeeded to the strongest explosion on June 15, 1956 and lasted continuously to the end of the summer. Distribution of its amplitude on the volcano, its direction of propagation and other characters of the tremor were studied mainly by means of a pair of seismographs. The place of the major origin was estimated from the amplitude distribution to have been at 300 m~400 m below the new craters. Possible mechanism of generation of the tremor is discussed on the basis of the various observations.

§ 1. Introduction

Continuous or spasmodic seismic wave-trains of nearly sinusoidal form which accompany volcanic activities are commonly called "volcanic tremors" (or pulsations). The volcanic tremors, especially those of continuous type, have been observed at the time of the eruptive activities of Vesuvius[1], Kilauea[2], Ōshima (Mihara)[3] and other volcanoes in the world. Some of the tremors could be explained as to have been nothing but the succession of many explosion-earthquakes which were caused by incessant ejections of lava-fragments. However, ebbs and flows of the amplitude of some continuous tremors are not always in accord with the intensity of eruptive activity. There is even a sort of tremor which occurs at the time of apparent quiescence of a volcano. Until the present day very little approach from the geophysical point of view has been made toward an explanation of that sort of continuous tremors, although many plausible causes have been proposed hypothetically from volcanological viewpoints.

The present writer observed the continuous weak tremor of Volcano Me'akan-dake. The tremor was indubitably not a succession of explosion-earthquakes. Efforts were made to estimate

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the position of its origin, to learn the direction and velocity of propagation of the waves, and so on.

§ 2. Brief descriptions of volcanic activity during the period of observation

Volcano Me'akan-dake (1503 m), situated in the northeastern part of Hokkaido, Japan, broke out on Nov. 19, 1955 for the first time in its recorded history. Several explosions took place during the succeeding eight months[4]. A number of non-perceptible earthquakes also originated within the volcano in this period. Besides the earthquakes, volcanic tremor of continuous type began immediately after the strongest explosion on June 15, 1956 and lasted for about three months.

The site of the present volcanic activity was limited to the southern rim of the old crater-bottom. Old lava-fragments and detritus which had accumulated there were hurled out by the explosions, but no juvenile lava-fragment was ejected during the activity. An immense volume of water-vapour was being emitted vigorously from the newly opened craterlets, sometimes accompanied with slight amount of ash. The surface activity was calm during the period from July 25 to the end of August, 1956, when the nature of the tremor was under study by the writer. That is, white smoke rose rather steadily from the craterlets without much hissing noise. The state of activity appeared to be more calm than that in the period prior to June 15, when tremor was much less significant.

§ 3. Instruments and method of observation

On June 13, a seismograph of moving coil type for horizontal component was installed at a distance of 600 m N (Station No. 1) from the most active craterlet. The instrument registered earthquakes and tremor to the end of August with very short intermissions. Another seismograph of the same type was moved from one station to another on and around the volcano in order to learn the distribution of amplitude and period of the tremor over the mountain (Fig. 1). The craterward component of the ground-motion was recorded by the seismographs. The seismographs were connected by long cables (0.6–3 km) to the galvanometers, installed

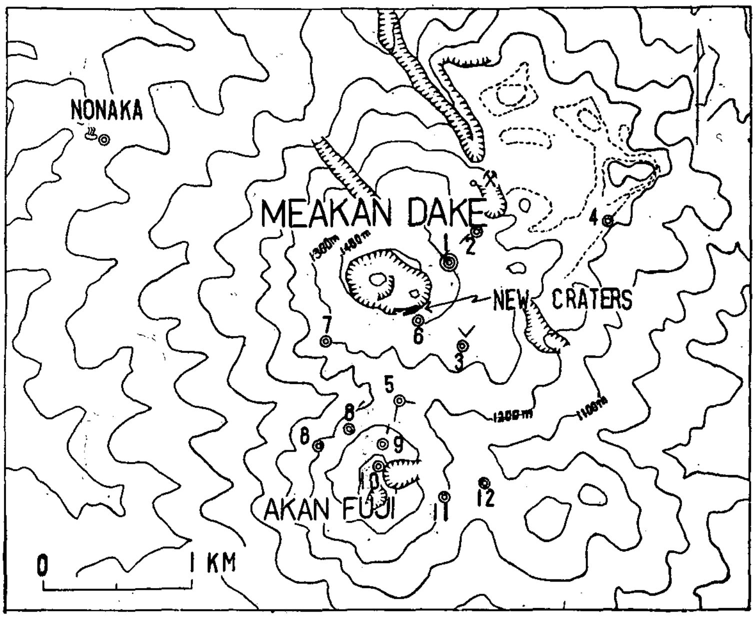

Fig. 1. Topography of Volcano Me'akan-dake and the position of the stations.

at 1.1 km N distance from the crater. For the study of phase velocity and direction of propagation, the two seismographs were sometimes both brought to the same station and placed in a line at a distance of 30–120 m.

Magnification varies in accordance with the series- and shunt-resistances between the seismograph and galvanometer. The constants of the instruments are: T (seismograph) $= 1.0$ sec, T (galv.) $= 0.2$ sec, magnification on bromide-paper $\doteqdot 4 \times 10^3$ for the seismic wave of 0.2 sec. Overall frequency characteristics are described in another paper[4].

§ 4. Variation of average amplitude at fixed station No. 1

Double-amplitudes of the largest 15 wave-crests are read among the recorded tremor during a certain 30 minutes, and the average of the 15 readings is adopted as the "average maximum amplitude" of the tremor for the time.

At Station No. 1, the tremor began just after the explosion of June 15. The amplitude of continuous ground motions was so small before the explosion that one may hesitate to infer that the vibration was really of volcanic origin. After the explosion, however, remarkable seismic wave-trains continued without intermission. Though the amplitude showed some ebbs and flows, the average max. amplitude suffered no essential alteration to the end of August. It tended to decrease from the middle of September. The tremor is a remarkable characteristic which distinguishes the period from that prior to the explosion (Fig. 2).

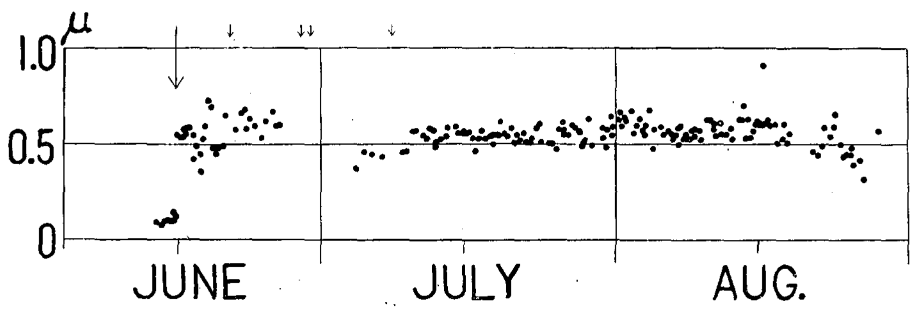

Fig. 2. Average max. amplitude of tremor during the period from June 13 to Aug. 31, 1956. Arrows indicate the occurrences of explosions.

Because the intensity of the surface activity, such as that of emission of vapour, was not stronger than that in the former period, the tremor could not be supposed to represent the vibration caused directly by the emitting vapour at the orifices or by any other origin at the surface. This sort of tremor in non-eruptive period is considered as a series of earth-shakings of extremely shallow —but not at the surface—origin.

§ 5. Distribution of amplitude

Investigations on the amplitude-distribution of volcanic tremors have been made several times at several volcanoes, and it was reported that the tremors have the nature of surface waves which propagate from some place near the crater. But the past observations were made at a small number of stations, most of which were remote from the origin. In the present study, 14 stations were distributed over the volcano; most of them were within 1 km from the new craterlets. Such concentration of stations near the source should render possible the reliable estimation of depth of origin.

When the tremor was observed simultaneously at two places, it is noticed immediately that the ratio of the average maximum amplitudes at the two places kept nearly a definite value throughout the period of observation (Fig. 3). The constant relationship may imply that no serious change took place concerning the position of origin of the tremor. Slight fluctuations in the ratio, however, were also noticed upon rare occasions. As illustrated in Fig. 4, the average max. amplitude at No. 1 increased as much as 70% above the normal level for about one hour, while the amplitude at No. 5 suffered very little change during that same period. Such a fluctuation suggests evanescent occurrence of seismic activity at a shallow depth near station No. 1. Except for such minor fluctuations, the activity of the tremor remained unchanged throughout the period of the present study (July 25–Aug. 29).

In Fig. 5 and Table 1 is

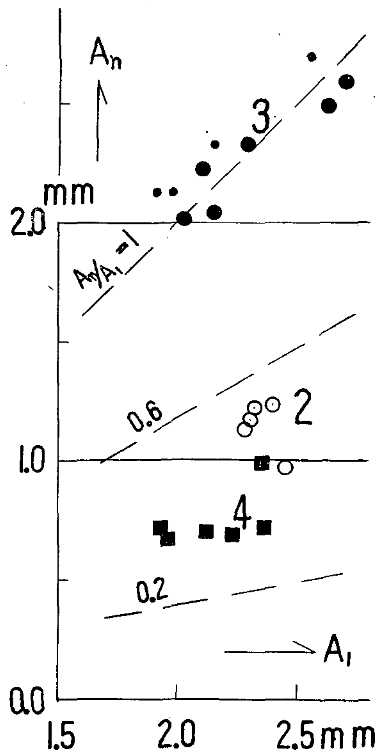

Fig. 3. Comparison of the average max. trace amplitudes, observed simultaneously at No. 1 and another station (Nos. 2, 3, 4).

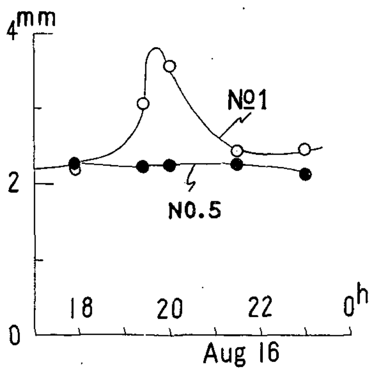

Fig. 4. Sporadic increase of amplitude of tremor at No. 1. (ordinate: trace amplitude on the record).

illustrated the ratio of the amplitudes at various stations to those observed at No. 1 simultaneously. There are two important features in the amplitude-distribution over the volcano. First, amplitude is surprisingly large on Volcano Akan-Fuji, especially along a belt-like zone at its flank. The cone has not shown any sign of eruptive activity within historic times nor through the period of the present activity of Me'akan-dake proper, though the formation of the mountain is geologically later than that of Me'akan-dake[5]. Second, amplitude is larger also near the site of the present activity.

A glance at the amplitude-distribution might lead one to the supposition that the major source of the tremor lies at shallow depth near the flank of Akan-Fuji (which is not in eruption), and that another minor source lies at some depth beneath the active craterlets of Me'akan-dake. But this tentative supposition on the place of origin requires examination by other means, as will be described below.

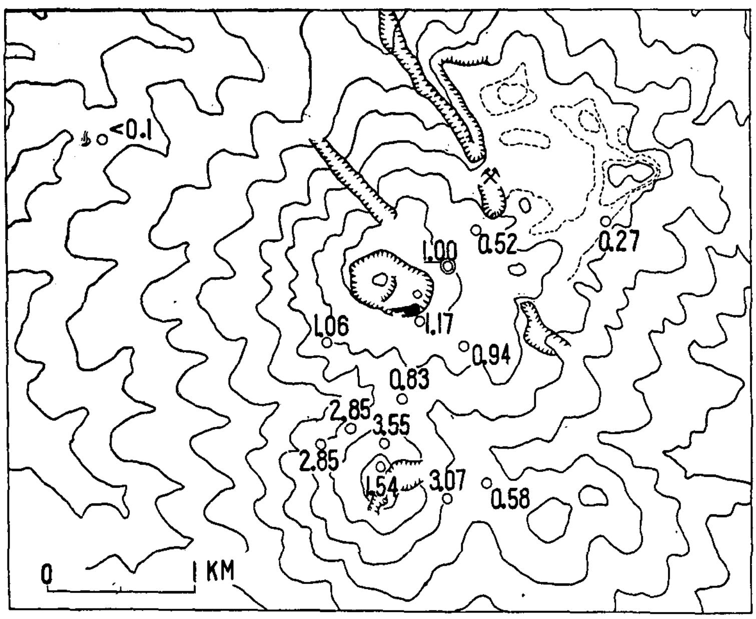

Fig. 5. Distribution of the ratio of average max. amplitude at the 13 stations to that at No. 1.

TABLE 1.
Average period and relative values of the average max. amplitude at various stations.

Stations No.	Ratio of amplitude to that at No. 1.	Average period (second)	Remarks
1	0.2	0.5	before June 15.
1	1.00	0.21	absolute value of amplitude is 0.56-0.46 μ.
2	0.52	0.28	waves of 0.4 sec and 0.2 sec are included.
3	0.94	0.23	
4	0.27	0.4	period is less accurate.
5	0.83	0.20	waves of 0.5-0.4 sec, 0.2 sec and 0.1 sec are included.
6	1.17	0.21	
7	1.06	0.17	
8	2.85	0.27	
8′	2.85	0.24	
9	3.55	0.21	
10	1.54	0.20	
11	3.07	0.23	
Nonaka	< 0.1	—	

§ 6. Cross-correlation between the amplitudes, observed simultaneously at different stations

The average max. amplitude, as adopted above, represents the average character of the observed tremor during about 30 minutes. However, comparison of amplitude of the tremor is also possible at every instant by the present simultaneous observation at two stations. Though identification of respective phase is almost impossible on the seismograms obtained at distant stations for the continuous tremor, there may still exist some correspondences between the amplitude of the observed wave-trains.

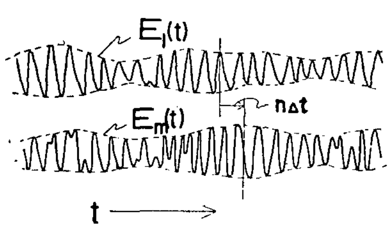

Fig. 6. Schematic representation of $E_1(t)$ and $E_m(t+n\Delta t)$.

Instead of comparison of the amplitude of every crest of waves, comparison of the envelope $E(t)$ of

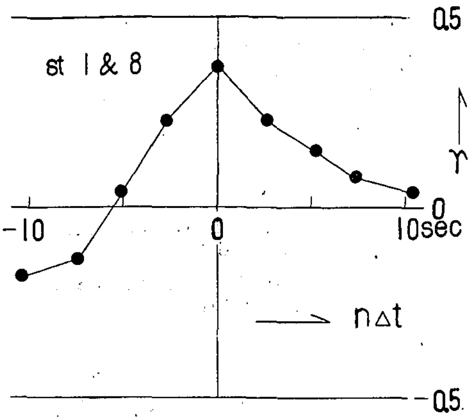

Fig. 7. Correlation between $E_1(t)$ and $E_8(t+n\Delta t)$. $t=260$ sec. interval $=2.6$ sec.

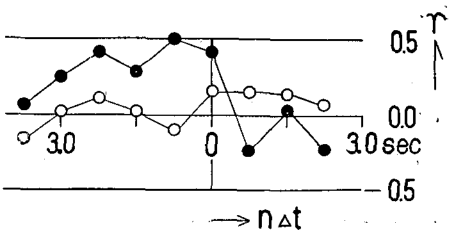

Fig. 8. Correlation between $E_1(t)$ and $E_9(t+n\Delta t)$. $n\Delta t>0$ means that E_1 is in advanced phase to E_9. The two curves correspond to different epochs. $t=45$ sec. interval $=0.75$ sec.

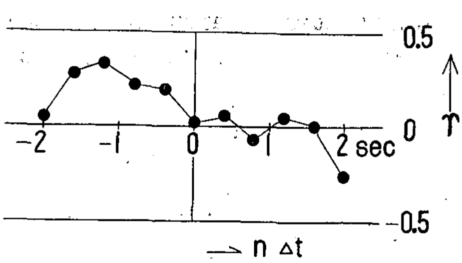

Fig. 9. Correlation between $E_1(t)$ and $E_{10}(t+n\Delta t)$. $n\Delta t>0$ means that E_1 is advancing in phase to E_{10}. $t=40$ sec. interval $=0.40$ sec.

the crests of waves was made between the seismograms obtained simultaneously at remote stations (Fig. 6). Cross-correlation coefficients were calculated between the amplitudes of the two envelopes $E_1(t)$ and $E_m(t+n\Delta t)$, for various $n\Delta t$. So far as the seismograms of slow recording speed (2 mm per sec) are concerned, the correlation coefficient (r) is the largest and positive at $n\Delta t=0$, though the absolute value of r is small. That is, the amplitude of tremor at a station varies in accordance to some extent with that at other stations at the same time (Fig. 7). When the seismograms obtained at a more rapid recording speed (6–7 mm per sec) are analysed, correlation becomes positive and comparatively large when $n\Delta t$ is chosen for the envelope obtained near Akan-Fuji as to be advancing in phase to that at Station No. 1 (Figs. 8. & 9). This result may appear to imply that the source is nearer to Akan-Fuji or that the activity of tremor migrates sometimes in the direction from Fuji to No. 1. However, final conclusion should be reached by other means, because r is not so great. Direct observation of propagation of the waves will be of use to ascertain the origin of the tremor.

§ 7. Direction of approach of tremor

Identification of phases on the seismograms of continuous tremor is not impossible if two seismographs are installed at a distance from each other of less than 30–90 m (for the present case). If three seismographs could have been used at one time, the tripartite method would have been adopted to learn the direction and the velocity of propagation of the tremor. Because of lack of seismographs of same characteristics in the present field work, the observations were repeated by changing the distance and azimuth of the line connecting the available two seismographs. The vibrations of the two galvanometers were recorded closely side by side on a bromide-paper which ran rapidly (ca. 2 cm per sec). That sort of survey was performed at four stations (Nos. 5, 3, 2 and near No. 9) (Fig. 1). Among them, the clearest results were obtained at No. 5, which is situated midway between the cone of Akan-Fuji and the new craterlets of Me'akan-dake.

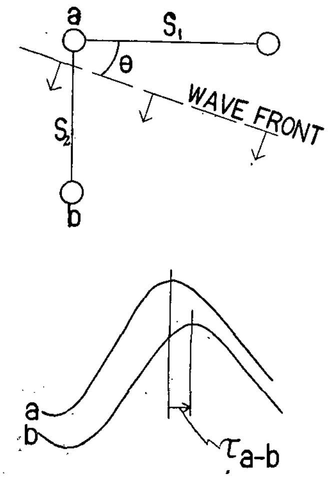

Fig. 10. Diagram showing the principle of determination of wave-front.

Direction of propagation of the tremor at No. 5 is principally from Me'akan to Akan-Fuji as described below.

If it be assumed that a wave-front advances to the direction θ (in Fig. 10) with velocity v, difference in arrival time is expressed as:

$$\tau_1 = (S_1 \sin \theta)/v \ , \quad \tau_2 = (S_2 \operatorname{con} \theta)/v \ ,$$

if the lines S_1 and S_2 are chosen perpendicularly. If the observations had been made simultaneously at three stations, v and θ could have been estimated directly from the observed phase differences. But the writer was able to use only two at a time, and the observed phase difference is treated statistically by observing many wave trains. The two seismographs were set at a and c ($S_2=60$ m) at first (Fig. 11). Next, the two were set at a and d ($S_1=60$ m). The wave crests which travel from a to b, c, that is, from Me'akan to Fuji, are far more numerous than those moving in a reverse direction (Fig. 11 & Plate II, c_1, c_2). In addition, the phase difference is larger at $a-c$ (60 m) than at $a-b$ (28 m). While,

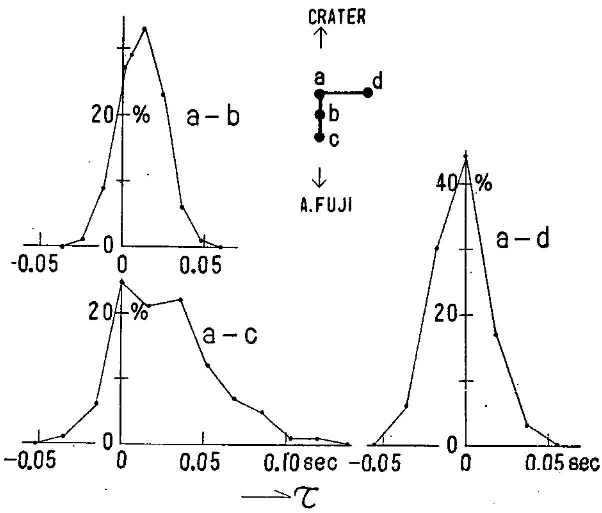

Fig. 11. Frequency distributions of observed phase differences, obtained at the network near No. 5. sample size: 356 for a-b (28 m), 282 for a-c (60 m), 223 for a-d (60 m).

the phase difference fluctuates around zero at the $a-d$ line which runs perpendicular to $a-c$ (Plate II d). The observed facts can be explained well by supposing that the direction of propagation of the tremor is from Me'akan-dake to Akan-Fuji in a majority of cases, that the direction fluctuates to some extent from time to time, and that some part (20-30 %) of the tremor appears to be not of progressive character as if it strikes the ground from beneath or is of the character of a standing wave.

At the flank of Akan-Fuji, the general character was found to be similar to that observed at No. 5, but identification of phase is not so easy as before because of higher distortion of the wave-form. At station No. 3, the direction of propagation was found to be much more random and the direction appeared often to be

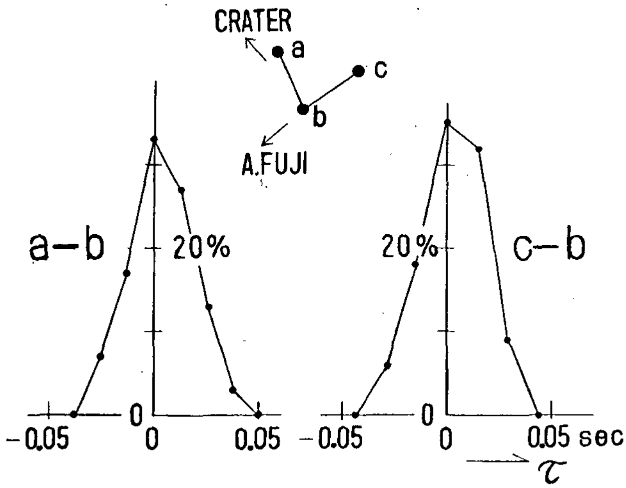

Fig. 12. Frequency-distributions of observed phase differences, obtained at the network near No. 3. sample size: 291 for each. $ab = bc = 30$ m.

reversed from one wave-group to another (Fig. 12). In addition, identification of phases was difficult even at a distance of 60 m. At station No. 2 also the direction was divergent and identification of waves was difficult.

§ 8. Period and other features of the tremor

The period of the insignificant ground vibrations in the epoch before the explosion of June 15 was about 0.5 sec. Average period of the conspicuous components of the tremor after the explosion was around 0.2 sec at every station (Table 1). Such recordings are partly due to the frequency characteristics of the instruments and may be partly because of the short epicentral distances of the stations.

By the high speed recording of the tremor, some other characters were brought to light. The tremor at No. 5 is not a beautifully sinusoidal one but contains higher harmonics. The predominant periods are about 0.5–0.4, 0.2 and 0.1 sec. The waves of the period of 0.23 sec only are predominant at No.3. At No. 2 also, predominant period is 0.2 sec, but waves of period of 0.4 sec also appear sometimes.

The amplitude of the waves of 0.4–0.5 sec is far larger in the direction of propagation in comparison with that in the transversal direction. The ratio of longitudinal to transversal amplitude is about 4–5. In contrast to that, there is no remarkable difference between the longitudinal and transversal components of the waves of 0.2 sec or of 0.1 sec (Plate II b). Quantitative difference in phase velocity and that in the direction of approach were scarcely distinguished among the waves of various periods, within the accuracy of the present method of observations.

Lack of vertical seismograph rendered impossible any studying of the exact locus of the wave-motion; hence no definite conclusion can be given concerning the nature of the waves. The writer is of the opinion, however, that the waves of shorter period would contain body-waves and those of the period of 0.4–0.5 sec would probably be surface waves principally, on the basis of known facts regarding the tremors of Ō-shima[6] and Aso[7].

§ 9. Place of origin of the tremor, estimated from the amplitude-distribution

The study of the direction of propagation of the tremor leads one to the conclusion that the major source of the tremor was not below Akan-Fuji but below Me'akan-dake proper, though the character of the tremor is neither simple nor uniform. Accordingly, the observed large amplitude at Akan-Fuji should be attributed to some other causes. Two ways of explanation would be possible. One is the possible effect of the topography of Akan-Fuji which rises steeply at the flank of Me'akan-dake. Theoretical as well as experimental data are scarcely available now (see next chapter). The other is the possible anomalous underground structure inside of Akan-Fuji. Seismic exploration would be the best criterion for testing this idea.

Here, the writer would avoid adhering to the anomaly but would like to treat the problem of the major source of the tremor. Let the data from the five stations (Nos. 8–11) which are on Akan-Fuji be excluded from the following discussion. The general distribution of the average max. amplitude of tremor is concentric, and the centre is at the active craterlets. However, the rate of increase of amplitude near the crater is not so great, and therefore one cannot conclude that the origin is at the earth's surface. The source of the tremor should not be a point actually but must have some extension. For mathematical simplicity, however, the source is regarded as a point. The point should consequently be an equivalent origin which could cause the distribution of the average max. amplitude.

Mode of decay of the present tremor is not known, but the tremor of the period of 0.2 sec seems to decline like body-waves at such a short epicentral distance[6]. The following relation between amplitude (A) and distance (r) is assumed:

$$A = A_0 r^{-1} \,. \qquad (1)$$

The place of origin at the first approximation is assumed to be at (x', y', z'), and the components $(\delta x, \delta y, \delta z)$ of its deviation from the true one and a constant A_0 are taken as unknown parameters in the following equation.

$$\begin{aligned}\sum_i \varepsilon_i^2 &= \sum_i (A_0 - A_i r_i)^2 \\ &= \sum_i \left\{A_0 - A_i r_i' + \delta x A_i (x_i - x') + \delta y A_i (y_i - y') + \delta z A_i (z_i - z')\right\}^2 \\ &= Min \,. \qquad (2)\end{aligned}$$

The four unknown parameters are obtained by the method of least squares, by using the amplitude (ratio) A_i at the eight stations (x_i, y_i, z_i). Ultimate position of the origin is obtained accurately by successive approximations. Actually, satisfactory convergence of the focus was obtained at the 3rd or 4th approximation.

The equivalent source of the tremor was thus estimated at 350 m below the southern rim of the old crater, that is, just below the midpoint of the new craterlets (Fig. 13 a & b). Calculated amplitude at $r = 100$ m becomes about 3μ. Even if other equations of decline of amplitude are adopted instead of (1), the most probable place of the origin does not move much. For example, for $A \propto r^{-\frac{1}{2}}$, the source is estimated at 300 m from the crater-bottom.

According to R. SATO's calculations[8], Rayleigh-waves of comparatively large amplitude can be generated at rough, two-dimensional surfaces, when P- or SV-wave strikes the surface with large (70°–80°) angle of incidence. The observed large amplitude at the belt-like zone on Akan-Fuji may possibly be explained by the large

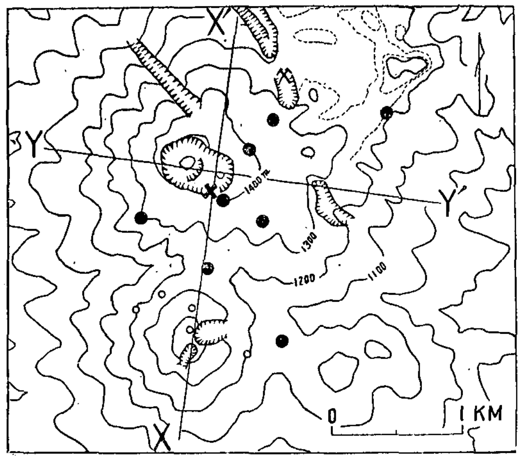

Fig. 13 a.

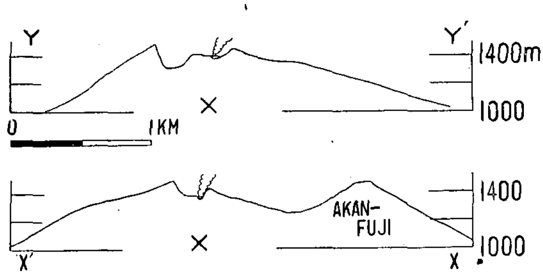

Fig. 13 b.

Fig. 13 a and b. Position of the equivalent source of the tremor (cross in the figure).

incident angle of tremor from the above supposed origin (Fig. 13 b). The calculations were based on the assumptions that the height of topography is far smaller than the wave-length of incident wave and that inclination of the surface is also small. Subsequently, quantitative discussion should not be offered on the basis of the theory.

§ 10. Concluding remarks

It may be noted that the nature of the tremor is by no means simple. The direction of travel of every crest of the waves was not always definite. Ebbs and flows in the amplitude at one station were not always in good agreement with those observed simultaneously at other stations. The tremor contains probably various reflected and refracted waves due to complicated volcanic formations. This may be the principal cause making the nature of tremor most complex.

In spite of the complexity, a certain idea could be built up concerning the tremor by virtue of the various sorts of measurements done, especially those close to the origin.

The tremor originated from a somewhat deep part of the old crater just below the new craterlets. The equivalent depth was estimated at 300–400 m and the possible amplitude at r=100 m was estimated at 3 μ. Actually, the source of the tremor should have some extension. The writer is of the opinion that the seismic active area would extend especially to the E–W or ENE–WSW direction, including the equivalent origin. The reason for that opinion is that the propagation of waves at No. 5 is least disturbed in comparison with that at other stations. The sporadic and local increase in amplitude and the observed fluctuation in the direction of propagation also would possibly be explained by the idea of extended seismic area, especially to the shallower part.

Because there is no direct evidence to indicate that the origin is nearer to Akan-Fuji majorly, the apparent advance in phase (of the envelope) of the tremor at Akan-Fuji to that at No. 1 should be explained by a certain other ideas. This question still remains unsolved.

The last and most important question is: how the tremor is caused, in such a continuous manner, at such a depth and in the period after the strongest explosion. The simple idea of release of the subterranen stress would fail, because accumulation of stress would have been greater in the period prior to the strong explosion. The idea of oscillation of fluidal lava-column or lava-reservoir would not be adequate for the reason that no incandescent material could be seen at the activity (the highest temperature of the ejecta did not exceed 300°C).

There is another idea which seems to the writer to be more reasonable. Vapour of high pressure which plays an important rôle in the explosive activity would be the possible cause of tremor too. At the strongest explosion of June 15, detritus and old lava were hurled out with the initial velocity of about 1×10^2 m/sec.

The pressure just before the explosion should accordingly have been around $1-2\times10^2$ bars. The strong explosion might have shattered the interior of the volcano, especially near the path of the issued vapour. The path may be imagined as to be along the southern rim of the old crater, not only at the surface but also at a depth. The sudden change of pressure and rapid issue of vapour at the time would have caused some new cracks along the path, or widened old fissures. If the imagined cracks happen to serve to lessen the subterranean pressure, the depth of generation of vapour phase will become deeper. The present tremor would probably be caused by the escape of vapour from a certain mother material at some depth and by the passage of the vapour along the cracks to the orifices. At ordinary state such as before the strongest explosion, liberation of water in the form of vapour can occur only near the surface, where the internal pressure cannot be so high as to cause any strong tremors. The estimated amplitude of vibration, $A=3\,\mu$ at $r=100$ m, may be caused by the present model, even if one thinks quantitatively. The above proposed idea may also explain the sudden commencement of the tremor, its long duration, its sporadic fluctuation and the apparent calmness of the orifices in the new craterlets. The insignificant vibration of the period of 0.5 sec, observed before the explosion might be a surface wave from the ground near the orifices which were vigorous at that time.

Does the estimated depth of the source of the tremor, that is around 300 m, imply the head of magma ? The writer has very few data upon which to base an answer to the question. The above supposed cause of tremor would not always be a common one to the tremors of various other volcanoes. But the tremors from the volcanoes which eject no juvenile lava as well as some of the post-explosion vibrations of active volcanoes may probably occur in a similar mechanism as that stated above.

In concluding, the writer would like to stress the point that the modern methods of seismology are most useful to the study of volcanoes.

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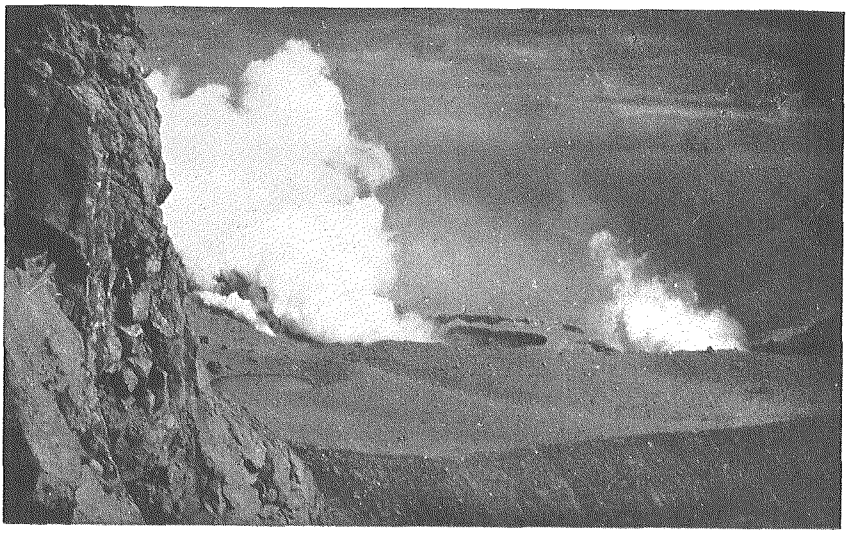
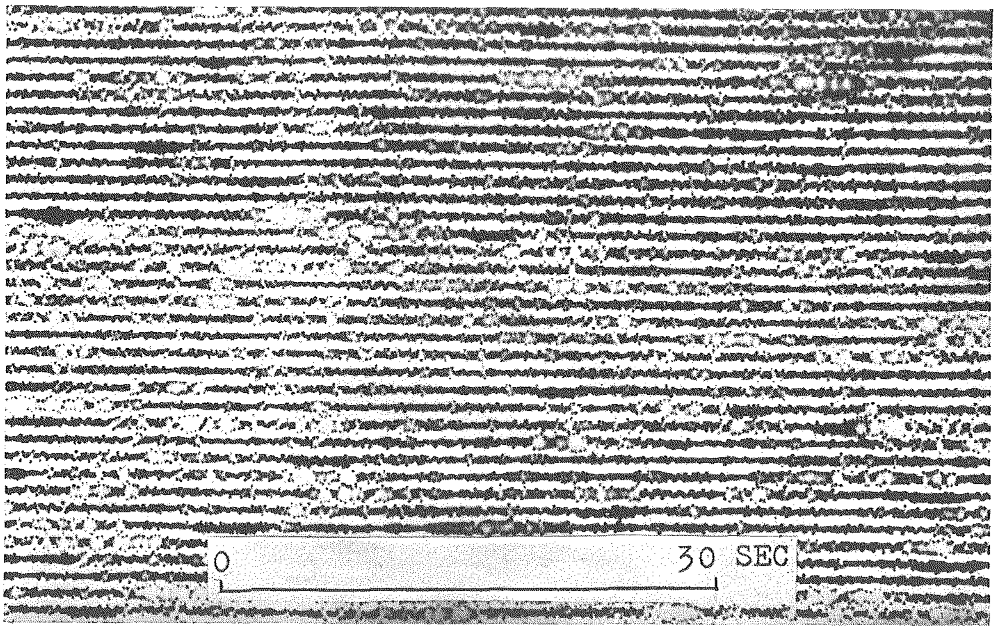




above: New craters, seen from western wall of old crater (June 16, 1956).
below: Tremor at Station No. 1 (August 3, 1956).

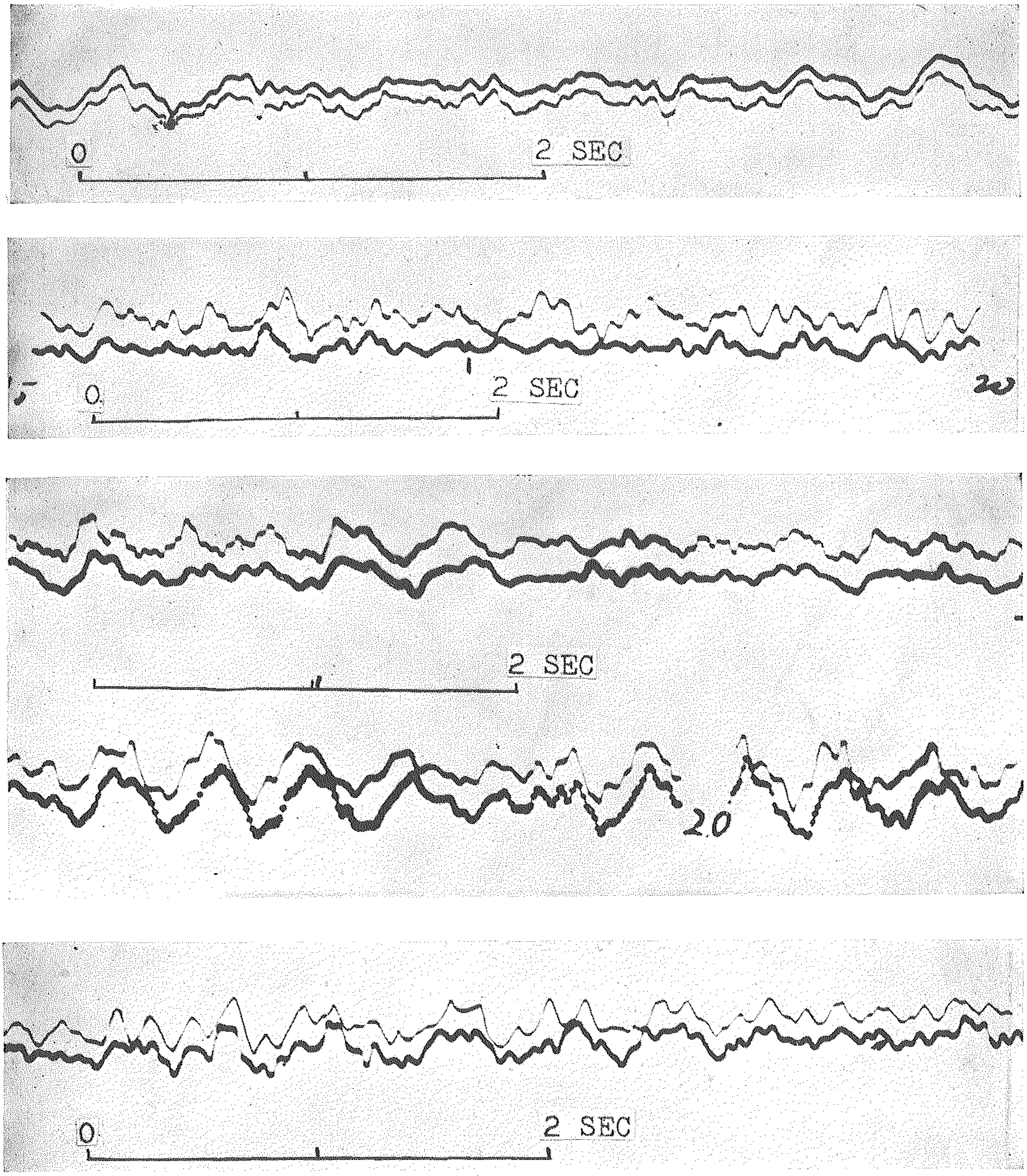
(a)

(b)

(c₁)

(c₂)

(d)



Observation at No. 5.

(a) : Two seismographs are set side by side, both in the craterward direction.

(b) : Two seismographs are set side by side, one (upper line) is craterward, and another (lower line) is in transversal direction to it.

(c_1), (c_2) : Two are set 60 m apart, one (upper line) is nearer to the crater of Me'akan-dake (cf. Fig. 11, *a–c*).

(d) : Two are set 60 m apart, but in nearly equal distance from the crater (cf. Fig. 11, *a–d*).