BULLETIN OF THE EARTHQUAKE
RESEARCH INSTITUTE
Vol. 44 (1966), pp. 1093-1133

54. *Volcanic Tremor of Kilauea Volcano, Hawaii, During July-December, 1963.*

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(Read Dec. 22, 1964 and Feb. 22, 1966.—Received June 30, 1966.)

Abstract

Two types of volcanic tremor were observed during July-December, 1963. One is accompanied by the eruptions in August and October and the other is associated with no eruptive activity. Spacial distribution of tremor amplitude in the case of the October eruption and amplitude spectra for various cases were studied from the records obtained by densely located seismometers in and around Kilauea caldera.

The results imply that a) before and during the eruption, movement or feeding of magma occurs beneath the region of Halemaumau, b) lava seems to flow through a more or less continuous conduit from beneath Halemaumau to the east rift zone, and c) long-period tremor (2 sec.) is of deep origin and short period tremor seems to be related with surface lava extrusion.

1. Introduction

Volcanic tremor is continuous ground movement caused by magmatic motion beneath or at the ground surface. The study of tremor is, therefore, one of the most useful tools for a better understanding of volcanic processes, especially of the behaviour and location of molten lava or magmatic reservoir underground.

Generally speaking, tremor is generated more intensively and more often at basaltic volcanoes than at andesitic volcanoes. Stationary and more or less continuous tremor is observed at Nyiragongo, Etna and sometimes even at ASO of which eruptive activities are the so called Hawaiian or Strombolian type.

In contrast, at andesitic volcanoes, such as Asama and Sakura-zima, we observe tremor on very few occasions. Nyiragongo is one of most typical of the Hawaiian type volcano because of its spectacular permanent lava lake. According to one of the authors (D.S.)¹⁾, most of the seismic energy is liberated not as earthquakes but as continuous tremor at Nyiragongo. On the other hand, at Sakura-zima, one of the most typical of the vulcanian type volcano, most of the seismic energy stored beneath the volcano is released as frequent small shocks. The different seismic phenomema of these two extremes is very likely related to the physicochemical nature of respective molten lavas, i.e., involved gases, silica content, viscosity, temperature and so on.

Previously, one of the authors (D.S.)2) suggested the close relation between the period of tremor and silica content and/or temperature of lava for several volcanoes. Basaltic volcanoes seem to generate tremor of longer period than andesitic volcanoes.

The observed period of tremor depends, of course, on the frequency characteristics of the seismograph. By use of various kinds of seismographs at Volcano Aso, K. SASSA3) classified the tremor into four kinds. They are: (1) period 1 sec., due to internal eruption of volcanic gases, (2) period 3.5 sec. to 7.0 sec., due to oscillation of magma reservoir, (3) period 0.5 sec. and (4) period 0.2 sec., the latter two caused by surface eruptions. One of the authors (K.K.)4) observed tremor having a period of 40–50 seconds at Volcano ASO by means of an ultra-long period seismograph. This long period tremor is sometimes generated prior to the eruption.

Thus, volcanoes generate tremor having apparent periods which cover a considerably wide range.

The present paper is concerned with the tremor that originated from Kilauea Volcano and recorded by 1 c/s and 3 c/s seismometers during July and December of 1963.

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1) D. SHIMOZURU and Ed. BERG, *Bull. des Seances, Academie Royale des Sciences D'-Outre-Mer*, **VII** (1961), 686–712.

2) D. SHIMOZURU, *Bull. Volcanol. Soc. Japan*, **5** (1961), 154–162.

3) K. SASSA, *Mem. Coll. Sci., Kyoto Univ. Ser. A*, **18** (1935), 255–293.

4) K. KAMO, *Bull. Volcanol. Soc. Japan*, **5** (1960), 35–48.

Kilauea Volcano is situated on the south east flank of Mauna Loa on the Island of Hawaii which in turn is located at the south eastern extreme of the Hawaiian Archipelago. Kilauea has been built largely by eruptions from two rift zones, extending eastward and southwestward from the summit caldera. Historic activity of Kilauea Volcano has been mostly in the caldera. Since the 1960 summit eruption, flank eruptions have taken place mainly on the upper part of the east rift zone. Previous to 1961, earthquake swarms originating at depths of about 60 km were frequently recorded and the source region for the magma was believed to be at that depth. However, since 1961 the 60 km deep earthquakes have not been recorded and they apparently have been replaced by 30 km deep earthquakes. We do not know whether there is a relation between the change of eruptive site as cited above and the depth of deep earthquakes or not.

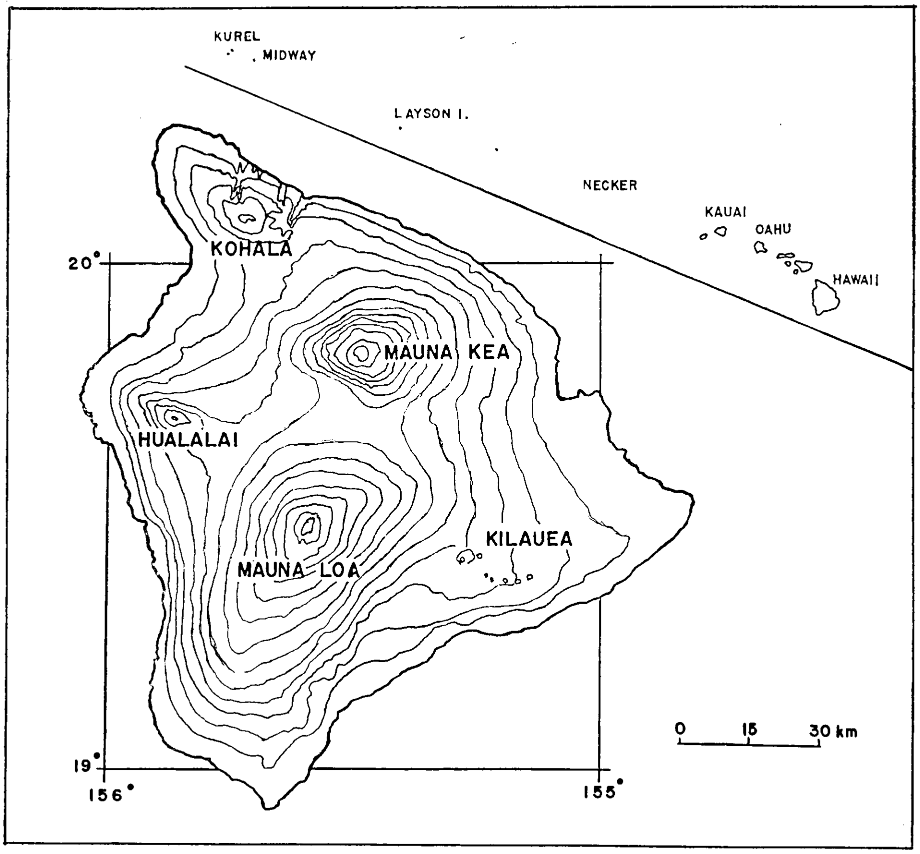

Fig. 1. Map of the Island of Hawaii.

As far as we know, Kilauea Volcano is one of the most valuable tools for a better and simplified understanding of volcanic processes and the structure of the earth's crust and the upper mantle beneath volcanoes. Since the establishment of the U.S. Geological Survey's Hawaiian Volcano Observatory, detailed geophysical studies, such as seismological and geodetic observations, have made it possible to sketch a model of the volcano and its eruptive mechanism. In Japan, many active volcanoes are andesitic and the application of geophysical tools in long terms has been concentrated to some of these volcanoes.

Taking the opportunity of the Japan-U.S. Science Cooperative Program, seismological events were cooperatively investigated for a period of six months. The purpose of this paper is to interprete the volcanic tremor as associated with volcanic processes and to research the existence and location of magma conduits and source regions.

2. Brief review of tremor studies of Kilauea Volcano

Shortly after Bosch-Omori seismographs were installed at the Kilauea summit in 1912, WOOD[5] noticed that they were recording "rapid vibrations of small amplitude." Later, in 1918, high speed drums were installed in the seismographs and JAGGER[6],[7] identified two types of tremor; (1) a long period (0.6 to 0.8 seconds) more or less continuous type called harmonic and (2) a discontinuous, shorter period (0.2 seconds) type called spasmodic.

According to JAGGER, neither type tremor showed any agreement with the rise or fall of lava in Halemaumau, the site of the continuously circulating lava lake, but their apparent direction of propagation suggested Halemaumau as a source. In 1924 when the continuous magmatic action in Halemaumau ceased the tremor also ceased. Tremor reappeared at the times of the short-lived activity in 1927, 1929, 1930, 1931 and 1934. During the September 1934 eruption at Kilauea, a direct correlation between violent fountaining in Halemaumau and especially large tremors were observed. JAGGER attributed this to a rather high viscosity of the lava and inception of the fountains at the bottom of a shaft.

FINCH[8], in 1944, summarized his observations about tremor as follows: "Harmonic tremor at Kilauea appears to be due to underground surging

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[5] H. O. WOOD, *Bull. Seis. Soc. Amer.*, **3** (1913), 14-19.

[6] T. A. JAGGER, *Weekly Bull. Hawaiian Vol. Obs.*, **6** (1918), 15-20.

[7] *ibid.*, *Bull. Seis. Soc. Amer.*, **10** (1920), 155-275.

[8] R. H. FINCH, *The Volcano Letter*, 483 (1944).

in feeding conduits below Halemaumau. If the surging is induced by the movement of very large gas bubbles in magma, then with a stationary lava lake the bubbles moving through lake magma cannot set up a harmonic tremor large enough to be recorded by the Observatory seismographs. When the surging take place in a conduit of more or less restricted dimensions the solid wall of the conduit may be induced to vibrate with sufficient amplitude to be recorded. In general the tremor is larger when the magma column is falling than when rising." He concludes that the origin of tremor at the Hawaiian volcanoes is produced by the rythmic hammering action of surging lava on strata forming the walls of feeding conduits or adjacent rifts.9)

OMER10) proposed that tremor originates in the vibration of laminae which are partly freed by the differential tilting of the surface of the earth around a volcanic vent during an eruption. He further proposes that, because of the presence of radial cracks and heterogeneity, the lamina can be treated as horizontal bars. His analysis consists of calculations of the effect of longitudinal, flexural and torsional vibrations in these bars. His conclusion is that the results of the longitudinal type vibration calculation best fit the observed seismic and deformation data. Longitudinal vibration would be caused by the fluctuating hydrostatic pressure of the magma column which has the effect of a hammering action against the ends of the bards.

Tremor has continued to be recorded in all the Kilauea and Mauna Loa eruptions of recent years. During August 1954, spasmodic tremor was recorded with a swarm of deep earthquakes (about 55 km) and EATON11) interpreted this as being caused by the movement of magma at depth. During the December 1959 Kilauea Iki eruption, EATON states some of the harmonic tremor was caused by drainback, the rate of which occasionally exceeded extrusion. In their description of the 1962 flank eruption of Kilauea, MOORE and KRIVOY12) mentioned the presence of both the short and long period (0.2 and 0.5 seconds) tremor. A large amplitude long period tremor beings or at least becomes visible about 35 hours after the beginning of the tremor.

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9) *ibid.*, *Bull. Seis. Soc. Amer.*, 39 (1949), 73-78.

10) Guy C. OMER, *Bull. Seis. Soc. Amer.*, 40 (1950), 175-194.

11) J. P. EATON, "Crust of the Pacific Basin," *Geophys. Monograph*, 6 (1962), 13-29.

12) J. G. MOORE and H. L. KRIVOY, *Jour. Geophys. Res.*, 69 (1964), 2033-2045.

3. Method of observations

In addition to the U.S.G.S. telemetering seismic network, we installed 18 seismometers at 16 places inside and outside the Kilauea caldera. These seismometers were telerecorded at the Hawaiian Volcano Observatory which is situated on the north-western rim of the caldera. Seven seismometers were located on the floor of the caldera and their locations are shown in Fig. 2 in which open circles indicate vertical 1 c/s seismometers and solid circles indicate holizontal 1 c/s seismometers.

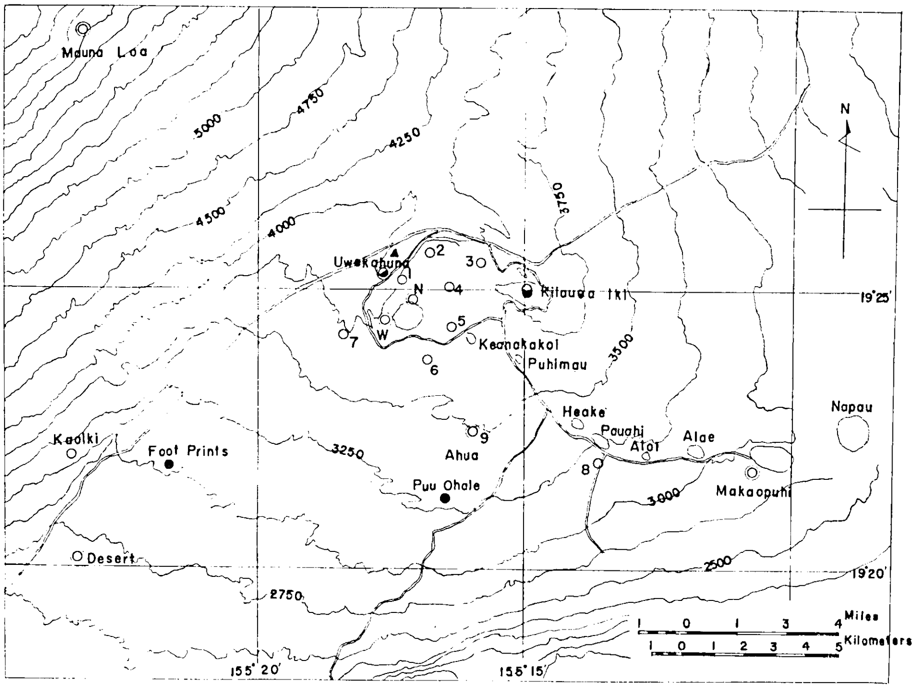

Fig. 2. Map of Kilauea Volcano showing seismograph stations. Double circles indicate U.S.G.S. seismometers, open circles and closed circles are vertical and horizontal 1 c/s seismometers. Triangle is a tripartite net of 3 c/s seismometer. Besides U.S.G.S. equipments, inside the vault of Uwekahuna, three components of 1 c/s seismometers, and at *N*orth Pit and *W*est vault, 1 c/s vertical seismometers were placed.

One vertical and two horizontal 1 c/s seismometers were placed inside Uwekahuna vault. Seismometers at Uwekahuna, Foot Prints, Kaoiki, Ohale and Kilauea *Iki* were continuously operated and telerecorded at the Observatory on smoked paper drums for monitoring seismicity during the period. The seismometer at Kilauea Iki was first placed at the center of the floor of the solidified crust and later it was moved to the northern margin of the crust. Two sets of Sony magnetic data recorders which have 3 channels in each and an oscillograph having 12 galvanometers were successfully used for recording tremor by an adequate combination of seismometers. For the purpose of calculating propagation directions and apparent phase velocities of termor, three vertical seismometers (3 c/s) were placed as a tripartite net just behind the Observatory building. Ordinarily seismographs with a magnification of 15,000 were used for monitoring the seismicity during the period. Maximum magnification of the data recorder is 3 million, however, high level of micro-seismic noise caused by atmospheric conditions prevented us from using such high magnifications. Instrumentation and magnification curves are illustrated in Figs. 3 and 4.

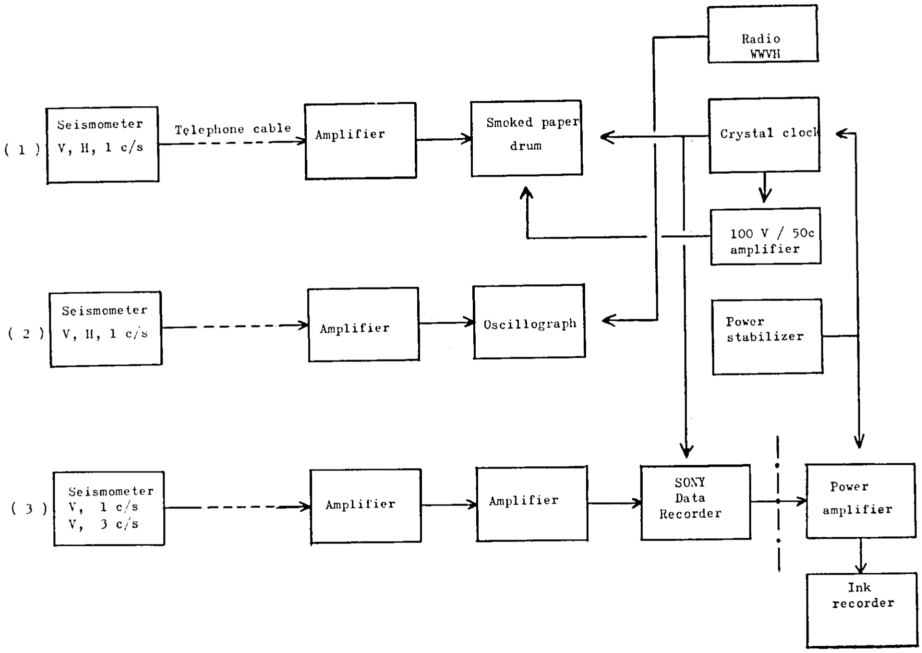

Fig. 3. Schematic diagram of seismographic equipments.

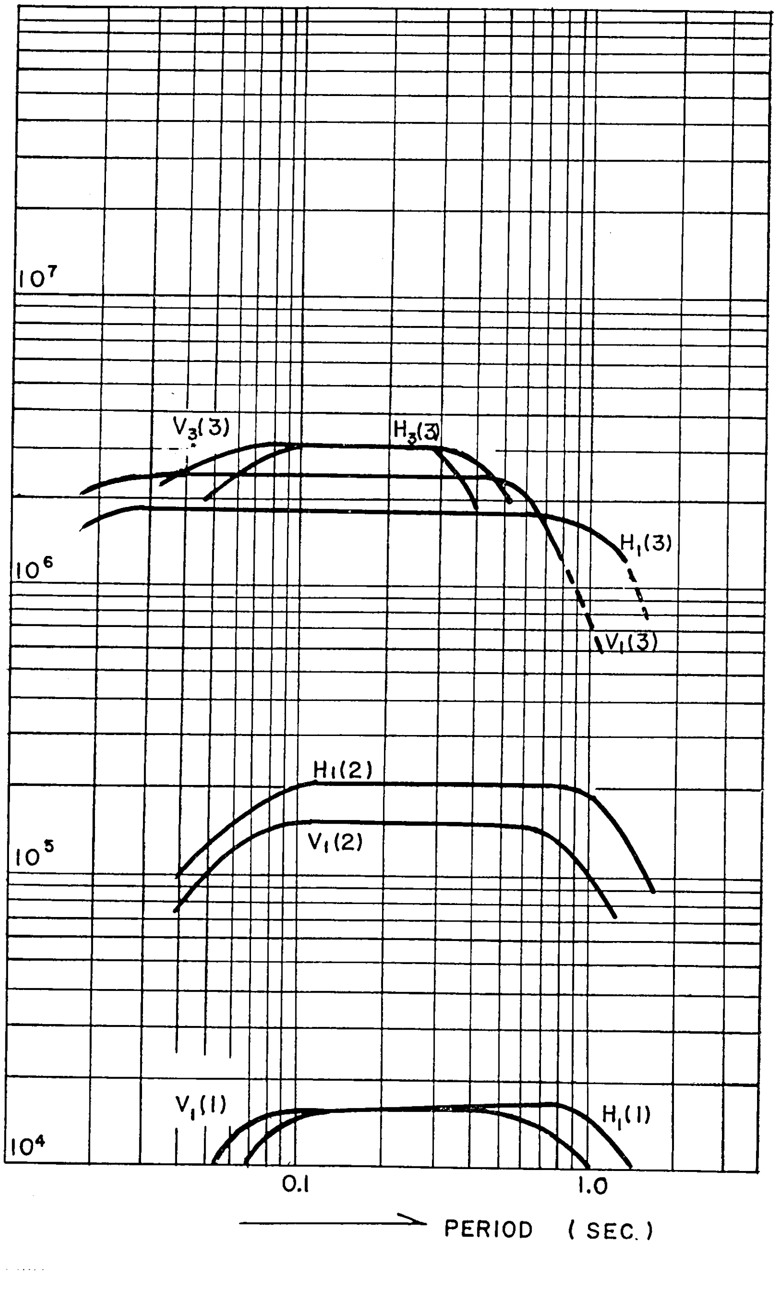

Fig. 4. Magnification curves for displacement. H_1 (3) means the magnification by use of horizontal 1 c/s seismometer and system (3) in Fig. 3.

4. Seismic and eruptive events during the period

During July and December of 1963, there were two major episodes of summit collapse, i.e., three swarms of earthquakes and two surface eruptions of lava. A sharp spasm of seismic activity began on July 1st and continued for 4 days near the upper east rift. Upward swelling in part of this rift and new surface cracks suggested lava migration from under the summit region into the east rift system. Although the observed amount of summit tilt was the same as during the December 1962 eruption in and east of Aloi Crater, no lava had appeared at the surface.

There was comparative inactivity, both seismically and tiltwise until August 21. On that day, lava appeared from fissures across the floor and up the northeast wall of Alae Crater. The eruption was preceded by two epochs of lava migration, July 1st and August 3rd, that were marked by seismic activity, detumescence of the summit area, and tumescence and surface cracking along the upper east rift zone. The eruption lasted about 38 hours and formed a lava lake in the crater bottom. Volcanic termor of relatively small amplitude accompanied this eruption.

On August 26 and September 21 two large earthquakes took place in the Kaoiki fault zone, their magnitudes being 4.9 and 4.8 respectively. These were followed by several hundred aftershocks, several of which were felt in the Kilauea summit area.

On October 5, 43 days after the eruption in Alae Crater, a flank eruption began in the central part of the east rift zone of Kilauea Volcano. The eruption was preceded by detumescence of the summit region of Kilauea Volcano as indicated by a deflection of the Press-Ewing seismographs at Uwekahuna. The eruption occurred at first from the floor of Napau Crater accompanied by strong volcanic tremor and local shallow shocks. Later, fountains broke out further down the rift zone near Kalalua Crater. The eruption lasted almost 30 hours and produced a shallow lava lake in Napau Crater and two major lava flows.

On October 23, a Kaoiki earthquake of magnitude 5.3 occurred and was followed by many aftershocks.

Fig. 5 shows summit activity during July and December of 1963 based on the U.S. Geological Survey seismograph network.[13)]
The earthquakes are classified into five groups by the Geological Survey according to their higher concentrations in active structural regions around

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[13)] Hawaiian Volcano Observatory Summary No. 31, 32 (1963)

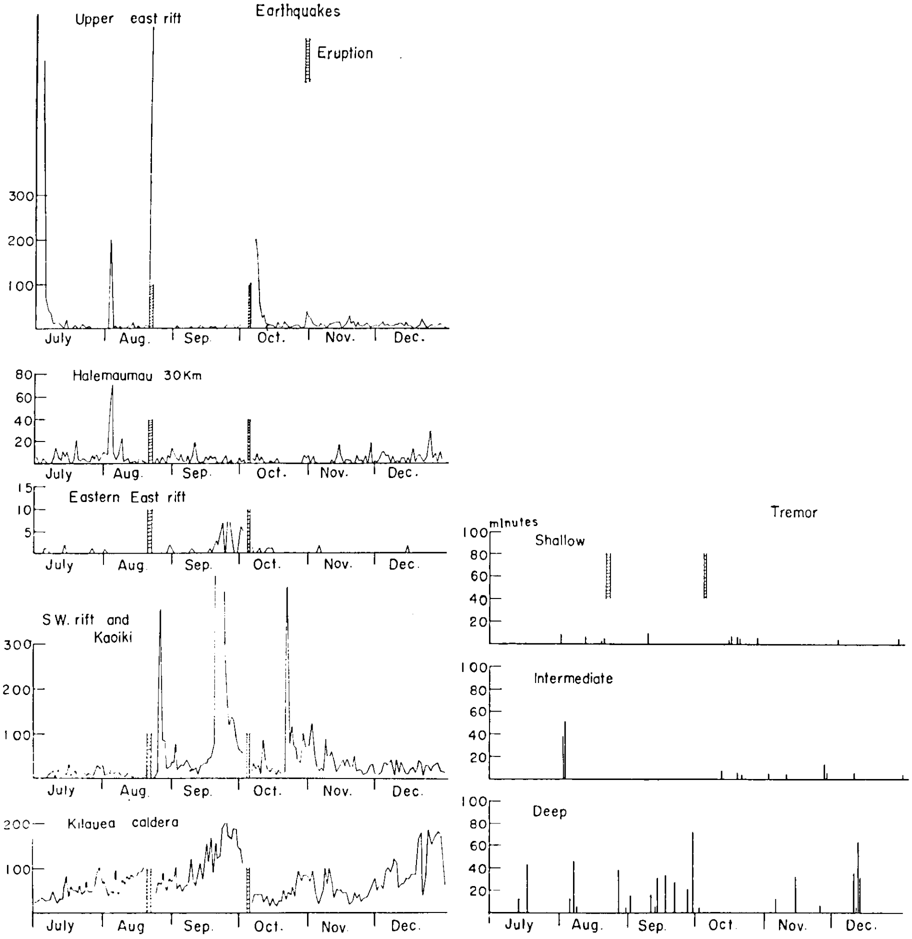

Fig. 5. Sequences of earthquakes and tremor during July-December, 1963.

Kilauea Volcano. These are: (1) shallow earthquakes in the Kilauea caldera region, (2) shallow earthquakes along the south west rift zone of Kilauea and the adjacent portion of the Kaoiki fault system, (3) earthquakes along the eastern half of Kilauea's east rift zone, (4) earthquakes from a source about 30 km beneath Halemaumau, and (5) earthquakes from the upper east rift zone and the adjacent fault system of Kilauea's south flank.

Occurrence of tremor is also plotted in the figure, as indicated by time duration of the appearance. Volcanic tremor is separated into three categories: deep, intermediate and shallow on the basis of relative amplitudes on seismographs in the summit region of Kilauea Volcano. Besides the above categories, one can distinguish the two types of tremor which seem to be connected with the activity of Kilauea Volcano and rift zones. One type is the tremor which appeared during the eruption and the other is that which occurred with no eruptive activity or lava extrusion to the surface.

5. Results of observations and general descriptions

During July and December of 1963, we recorded two types of tremor. One is the tremor accompanied by the eruptions in August and October and the other which occurred with no surface activity. The so called "spasmodic" tremor of deep origin was not recorded. From Fig. 5, it seems that a rough mode of occurrence of deep tremor is similar to the occurrence of Kilauea caldera earthquakes. Intermediate tremor seems to be related to 30 km earthquakes and further, shallow tremor seems to be related to earthquakes of the upper east rift.

Firstly, we present the general features of tremor accompanied by two eruptions in August and October. On August 21–23, 1963, a small but spectacular flank eruption occurred in and near Alae Crater in the upper east rift zone. The first indication of the eruption occurred at 13h 46m,[14] August 21, with continuous earthquakes and tremor recorded by Makaopuhi seismometer, the nearest seismometer to the eruptive site in the U.S.G.S. seismic net. Our seismometer recorded only continuous earthquakes at this early stage of the eruption. Even at Ohale, 8.7 km west of Alae Crater, the amplitude of tremor was almost the same with that of ordinary micro-seismic noise. From 18h 00m tremor began to increase, though small, and diminished by August 23. All activity at the lava fountain stopped at 18h 10m, August 23 and the eruption was over. Amplitude variations were read on smoked paper seismograms which are shown in Fig. 6.

Amplitude of tremor is small during the Alae eruption compared with that of October 5 eruption in and near Napau Crater contrary to their distance relationship with our seismic net. Amplitude relation of tremor in the above two cases seems to be proportional to the amount of extruded lava.

On October 5, Press-Ewing seismograph at Uwekahuna made de-

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[14] Hawaiian standard time is used throughout this paper.

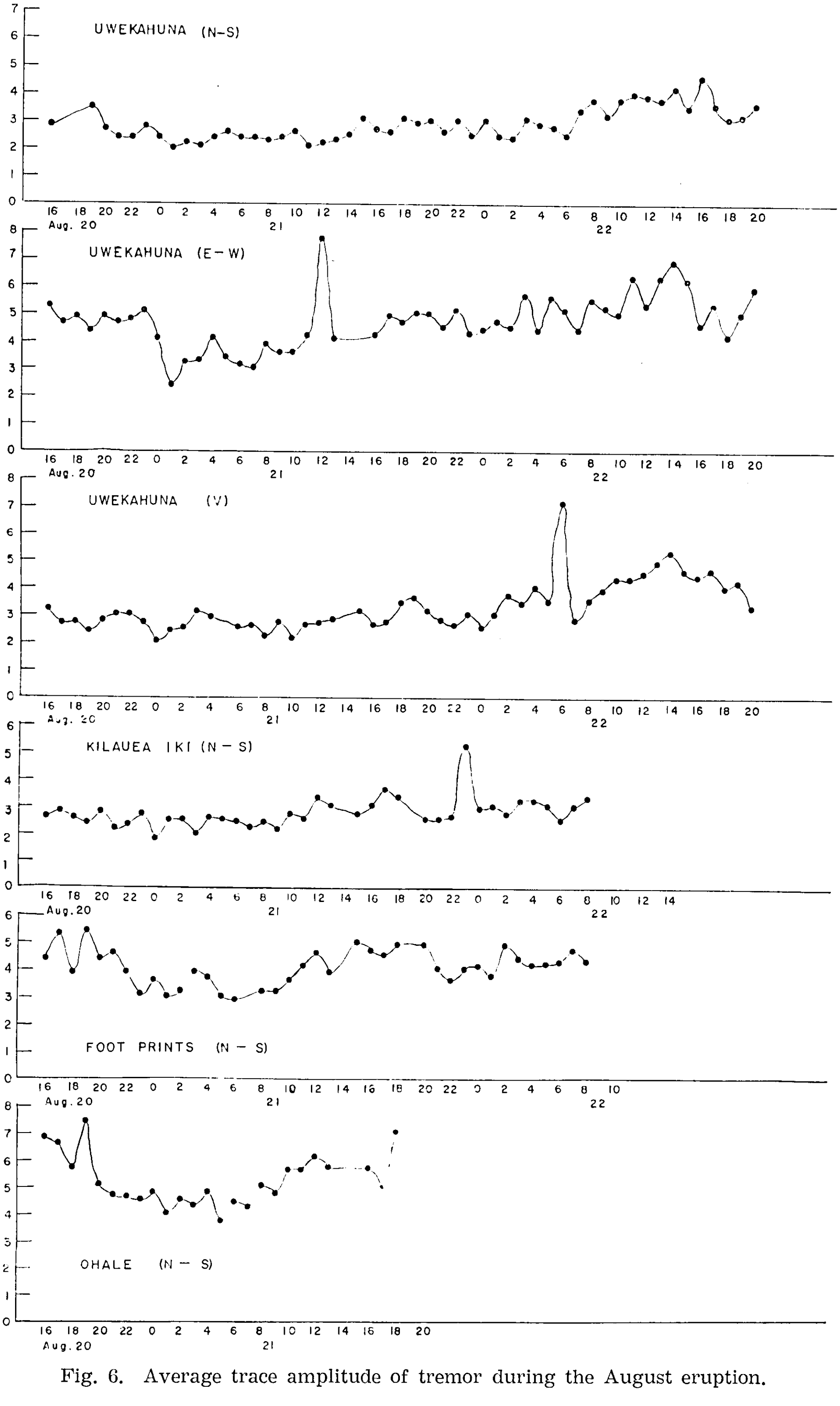

Fig. 6. Average trace amplitude of tremor during the August eruption.

Table 1. Average ground amplitude of volcanic tremor during the Napau eruption (unit expressed in micron)

Time	Uwekahuna (U-D)	Uwekahuna (N-S)	Kilauea Iki (N-S)	Ohale (N-S)	Foot Prints (N-S)	Kaoiki (U-D)
Oct. 5, 06^{h}	0.47	0.55	0.70	0.55	—	0.26
07	0.48	0.60	0.57	0.38	—	0.21
08	0.74	0.96	1.60	0.55	—	0.17
09	0.40	0.65	0.41	0.29	—	0.15
10	0.45	0.56	0.54	0.60	0.58	0.15
11	0.44	0.54	0.40	0.24	0.19	0.12
12	0.51	0.49	0.90	0.49	0.16	—
13	0.43	0.43	0.28	0.26	0.10	—
14	0.38	0.41	0.75	0.50	0.11	0.11
15	0.41	0.54	1.90	0.50	0.18	0.14
16	0.35	0.40	1.65	0.67	0.16	0.11
17	0.41	0.69	2·50	0.98	0.25	0.23
18	0.49	tr.	0.37	0·40	0.13	tr.
19	0.45	0.37	0.25	0.40	0.12	tr.
20	0.25	0.54	0.51	0.42	0.14	tr.
21	0.28	0.40	0.56	0.38	0.12	0.15
22	0.28	0.44	0.86	0.60	0.15	0.14
23	0.38	0.48	0.95	0.67	0.15	0.17
Oct. 6, 00	0.21	0.34	0.46	0.33	tr.	tr.
01	0.19	tr.	0.45	0.33	tr.	tr.
02	0·21	tr.	0.47	0.30	tr.	tr.
03	0.22	tr.	0.46	0.26	7r.	tr.
04	0.17	tr.	0.40	0.27	tr.	tr.
05	0.16	tr.	0.40	0.26	tr.	tr.
06	0.16	tr.	0.21	tr.	tr.	tr.
07	0.17	tr.	0.20	0.27	tr.	tr.
08	0.17	tr.	0.20	0.31	tr.	tr.
09	0.12	0.17	0.14	0.15	0.05	0.06
10	0.11	0.15	0.12	0.14	0.05	0.07
11	0.08	0.13	0.12	0.15	0.05	0.07
12	0·07	0.11	0.12	0.13	0.05	0.06
13	0.10	0.20	0.21	0.27	0.06	0.08
14	0.09	0.12	0.14	0.13	0.05	0.06
15	0.08	0.11	1.11	0.17	0.05	0.07

(to be continued)

(continued)

Time	Uwekahuna (U-D)	Uwekahuna (N-S)	Kilauea Iki (N-S)	Ohale (N-S)	Foot Prints (N-S)	Kaoiki (U-D)
h						
Oct. 6, 16	0.07	0.11	0.15	0.17	0.05	0.07
17	0.11	0.15	0.14	0.19	0.06	0.07
18	0.09	0.15	0.15	0.21	0.07	0.11
19	0.11	0.21	0.24	0.33	0.08	0.08
20	0.08	0.12	0.16	0.17	0.05	0.06
21	0.06	0.10	0.12	0.15	0.05	0.07
22	0.06	0.10	0.12	0.12	0.04	0.06
23	0.09	0.11	0.13	0.17	0.05	0.06
Oct. 7, 00	0.05	0.09	0.11	0·16	0.04	0.06
01	0.05	0.09	0.09	0.14	0.04	0.05
02	0.06	0.09	0.10	0.15	0.04	0.06
03	0.08	0.10	0.11	0.15	0.04	0.06
04	0.06	0.09	0.09	0.14	0.04	0.06
05	0.06	0.08	0.09	0.13	0.04	0.06
06	0·05	0.08	0.10	0.16	0.04	0.06
07	0.06	0.09	0.10	0.14	0.04	0.06
08	0.05	0.09	0.10	0.13	0.04	0.06
09	0.09	0.10	0.10	0.13	0.03	0.06
10	0.05	0.09	0.09	0.14	0.03	0.07
11	0.06	0.10	0.09	0.15	0.03	tr.

Microseismic noise level prior to the eruption

Uwekahuna (H)	0.087 micron
Uwekahuna (V)	0.036
Kilauea Iki	0.110
Ohale (H)	0.130
Foot Prints	0.070
Kaoiki (v)	0.48

flection at 03h 06m which is the first indication of impending eruption. At 03h 17m tremor began with small amplitude associated with local shallow earthquakes. At 05h 25m, tremor increased markedly at Makaopuhi. At the same time, we were awakend by strong air shock which is perhaps the indication of the beginning of the eruption in Napau Crater in the upper east rift zone. At about 14h of the same day, a long fire curtain broke out further down the rift zone near Kalalua Crater. At 04h 00m of October 6, the glow of fountains had ceased and flow had stopped.

During this eruption, tremor continued and diminished to noise level

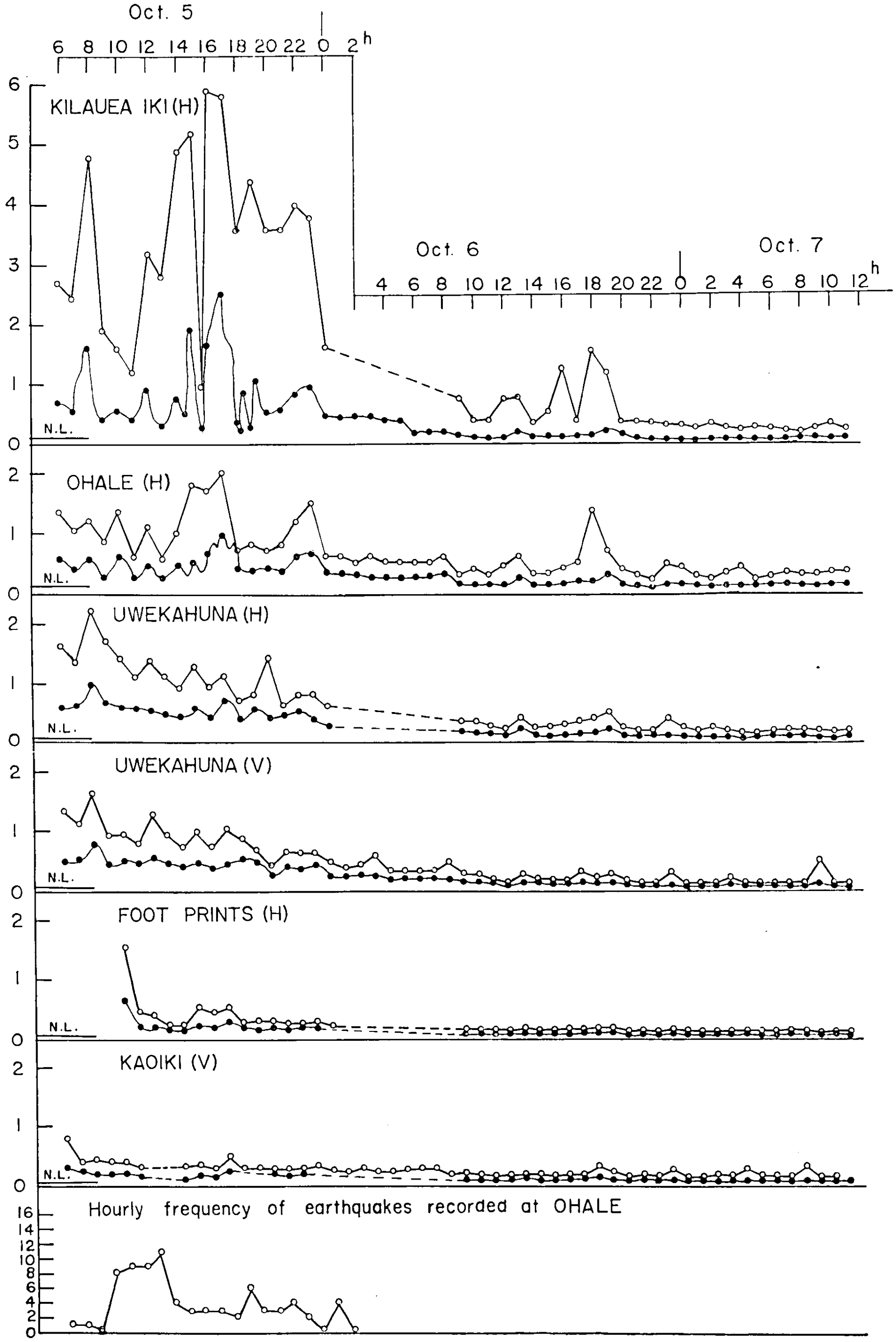

Fig. 7. Absolute ground amplitude of tremor during the October eruption.

by the end of Oct. 6. In spite of its shorter duration of eruption than the August eruption, total amount of extruded lava was estimated as 10 million cubic yards which is roughly ten times the amount erupted in Alae Crater in August. The fountain of the October eruption was from 2 to 5 times (20m–50m) higher than that of the August eruption. This implies intense feeding action of lava through the conduit from the reservoir in the October eruption, and this might be the reason for stronger tremor in the October eruption than the August eruption.

Absolute ground amplitude was read from the smoked paper seismograms as tabulated in Table 1. These are plotted in Fig. 7 as well as local shallow earthquakes recorded at Ohale.

Amplitude at Kilauea Iki is markedly large compared with other localities. The Kilauea Iki seismometer was placed on the solidified crust of the lava lake which was produced by the 1959 eruption. The cooling lava lake still has about 100m of molten lava below the crust and the thickness of the crust was probably about 18 m at that time. Some amplifying effect of tremor due to this structure is expected, however, no detailed discussion on this matter is made because of lack of shear wave velocities for each layer.

Amplitude of tremor at Foot Prints and Kaoiki is considerably smaller than at other stations because of the damping of short period tremor. At the above two stations, amplitude decreases monotonously with time, while at other stations it shows significant variation. Strong tremor occurred at around 08h, 17h and 22h of Oct. 5 and 18h of the next day. It is interesting that local shallow earthquakes recorded at Ohale occurred frequently from 09h to 12h of Oct. 5 as shown in the bottom of the figure. This is the time when tremor energy decreased.

In Fig. 8, rate of tilt at Uwekahuna calculated from the readings of short span (136.5″) water tube tiltmeter is plotted as well as chronological description of the eruption. Amplitude of tremor is also shown schematically.

Significant parts of variation of amplitude is described as p, q, r and s. Tremor p might reflect fountaining stage in Napau Crater. Time of occurrence of local shallow earthquakes at the upper part of rift zone corresponds to the time of detumescence of the summit region which implies the migration of magma from the summit region to the east rift zone. Tremor q seems to be the result of strong fountaining in and near Kalalua Crater. It does not mean, however, that these tremors originated only from the eruptive site. This is discussed later. The summit region showed

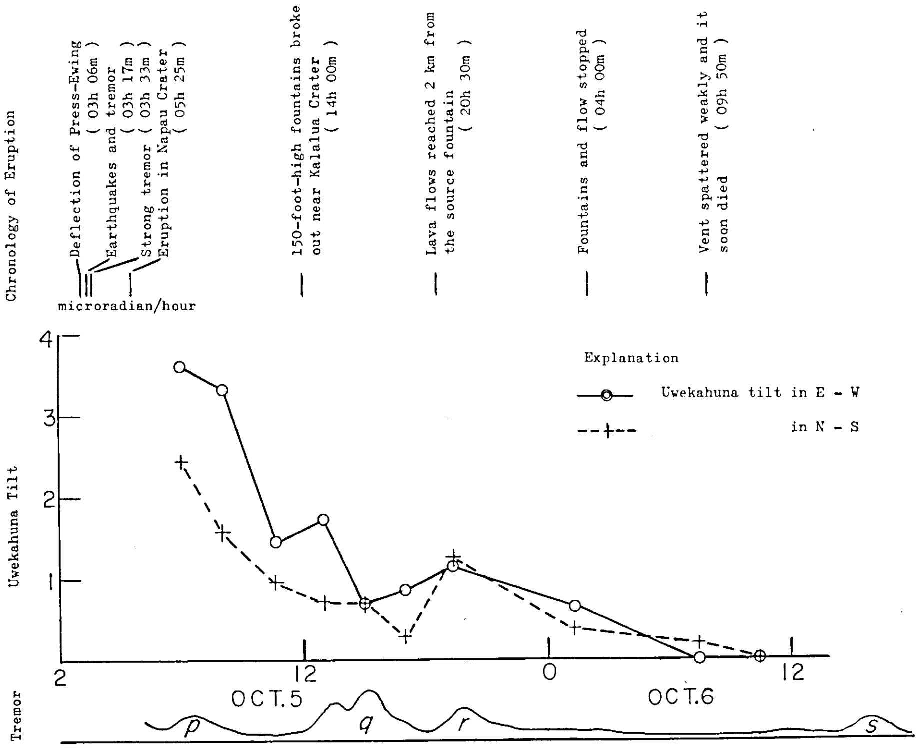

Fig. 8. Uwekahuna tilt and rough sketch of the amplitude of tremor.

a slight tumescence at about 20h–22h, when tremor increased. Tremor *r* may, therefore, be partly related with the feeding action of magma to the reservoir. Tremor *s* corresponds to no surface activity. Hence, it could be due to surging of magma in the reservoir or conduit. It remains questionable because there were no tilt readings during that period.

Secondly, general features of tremor associated with no eruptive activity is presented. Occurrence of these tremors is frequent, but their duration is, in most cases, short, i.e., from several minutes to one hour. The mean of the trace amplitude of every 30 successive waves is plotted for the following three cases as shown in Fig. 9 and 10.

(A) Aug. 1, 22h 40m 25s—22h 46m 05s....shallow
(B) Sept. 10, 06h 48m 25s—06h 50m 45s....deep
(C) Oct. 16, 08h 38m 04s—08h 41m 39s....shallow

For shallow tremor (A and C), mode of amplitude variation is not always the same with all localities. In contrast, for deep tremor (B), the

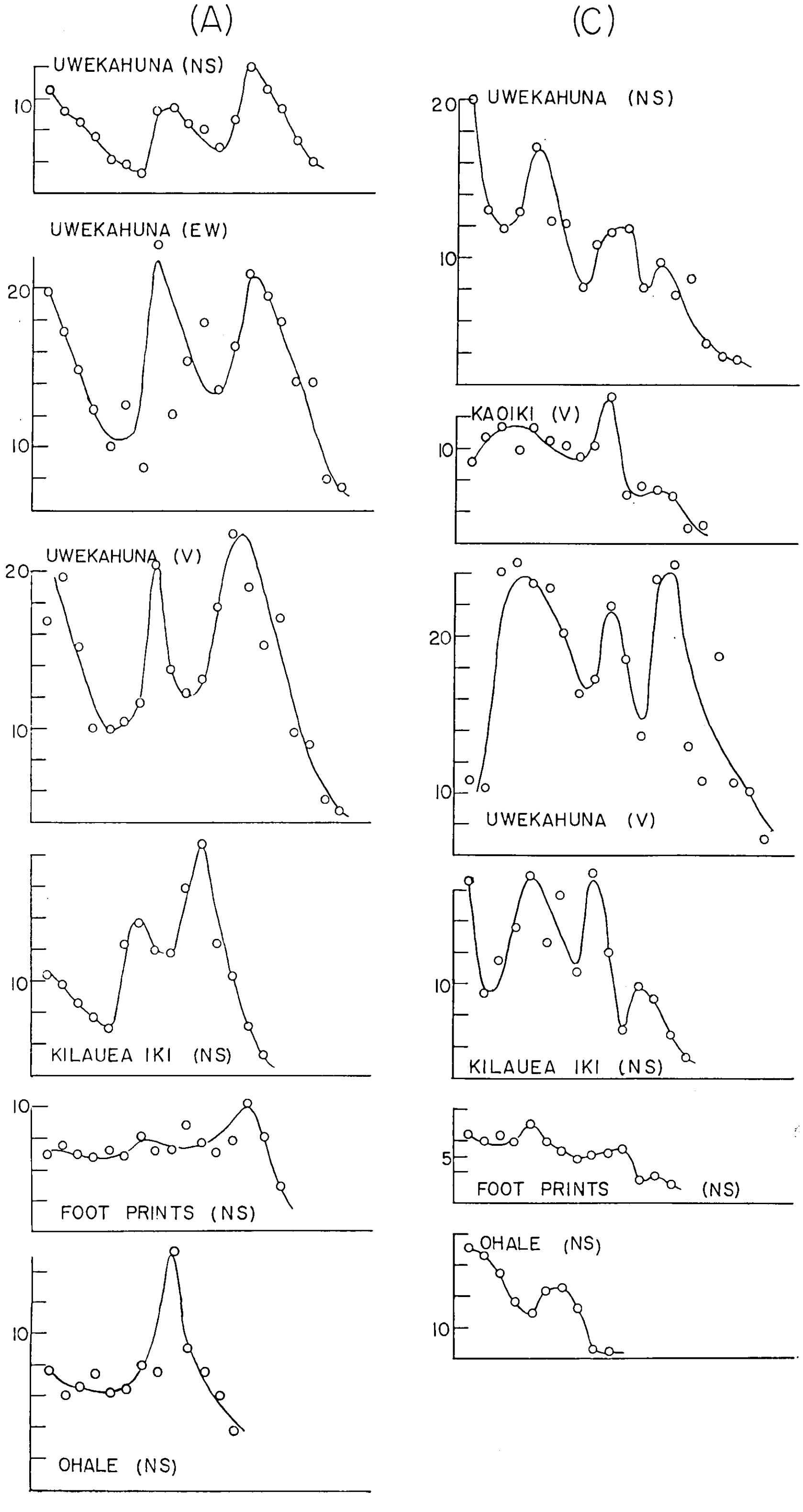

Fig. 9. Tremor amplitude with no surface activity. Ordinate is arbitrary scale.

(B)

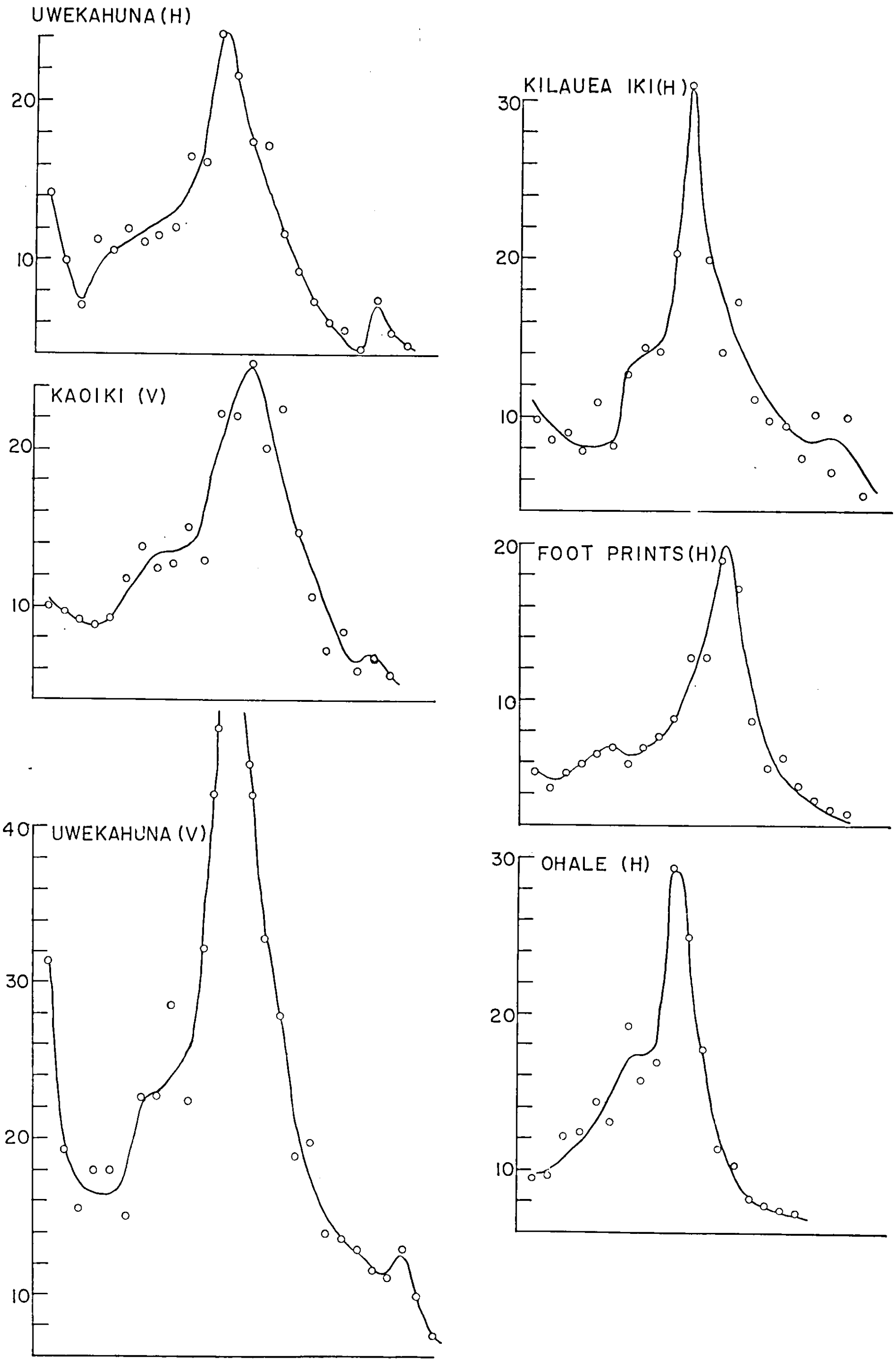

Fig. 10. Tremor amplitude with no surface activity.

tendency of amplitude variation is quite similar for all stations. In addition, vertical seismometers recorded extraordinarily large amplitudes. These facts are consistent with the tremor of deep origin.

6. Amplitude distribution of tremor accompanied by the October eruption

Just after the beginning of the eruption in and near Napau Crater on October 5, we recorded the tremor by means of oscillograph for the stations 7, 6, 9, 8, 3, 2, 1, 4, West Vault and 5 during 05h 54m—17h 00m with the recording speed of 1 cm per second. Mean ground amplitudes are listed in Table 2 for corresponding time.

Table 2. Average ground amplitude of volcanic tremor during the Napau eruption recorded by oscillograph
(unit expressed in micron)

Time	7	6	9	8	3	2	1	4	w	5
h m										
05 54	0.51	0.53	0.22	0.29	0.33	0.22	0.73	0.18	0.57	—
06 00	0.39	0.59	0.35	0.28	0.40	0.21	0.64	0.18	0.43	—
06 15	0.39	0.37	0.28	0.26	0.34	0.19	0.53	0.21	0.34	—
06 30	0.26	0.28	0.23	0.24	0.31	0.18	0.64	0.17	0.41	0.61
07 00	0.39	—	0.33	0.23	0.37	—	—	—	—	—
08 00	—	—	0.37	0.43	0.41	0.31	0.61	0.23	0.74	—
09 00	0.31	0.39	0.28	0.21	0.32	0.27	0.76	0.20	0.59	0.75
10 00	0·24	0.35	0.23	0.19	0.23	0.28	0.74	0.13	0.53	0.90
11 00	0.13	0.15	0.11	0.08	0.16	0.09	0.26	0.09	0.27	0.37
11 25	0.17	0.14	0.11	0.07	0.13	0.10	0.28	0.09	0.32	0.22
12 00	0.17	0.16	0.16	0.14	0.13	0.12	0.30	0.23	0.28	0.44
13 00	0.16	0.14	0.14	0.14	0.13	0.11	0.47	0.18	0.33	0.49
15 04	0.14	0.17	0.15	0.17	0.16	0.13	0.26	0.07	0.31	0.39
16 00	0.12	0.14	0.13	0.17	0.13	0.10	0.23	0.07	0.26	0.30
16 20	0.12	0.17	0.17	0.23	0.16	0.10	0.24	0.08	0.24	0.31
17 00	0.15	0.21	0.18	0.27	0.21	0.13	0.26	0.09	0.24	0.28

These values are plotted in Figures 11–22 for successive times. Amplitudes recorded by vertical (1 c/s) seismometers at Uwekahuna and Kaoiki are added.

In these figures, lines of equal ground amplitude of tremor are shown

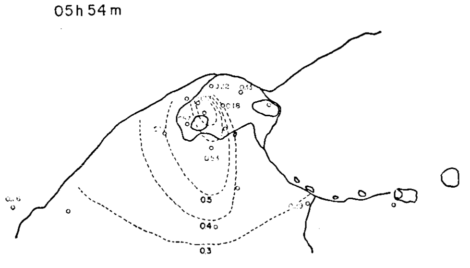

Fig. 11

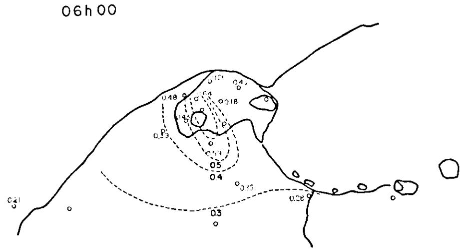

Fig. 12

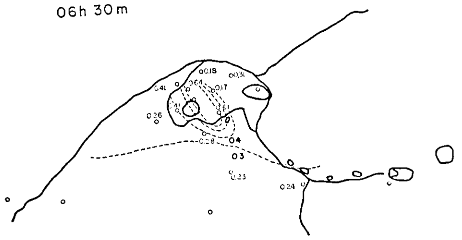

Fig. 13

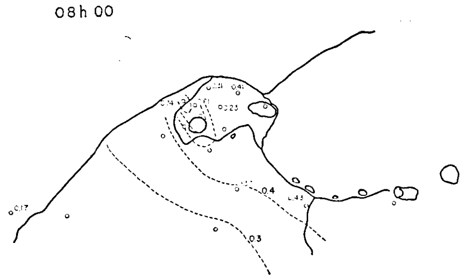

Fig. 14

Figs. 11.-14. Plots of absolute vertical ground amplitude of tremor during the October eruption expressed in microns.

Fig. 15

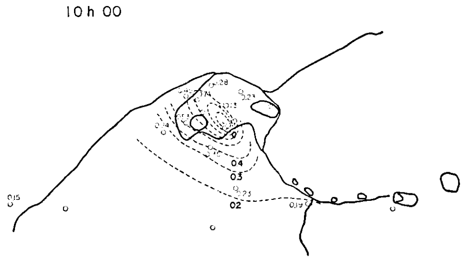

Fig. 16

Fig. 17

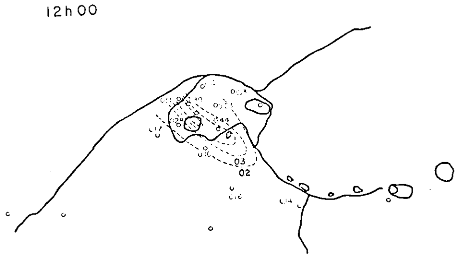

Fig. 18

Figs. 15.-18. Plots of absolute vertical ground amplitude of tremor during the October eruption expressed in microns.

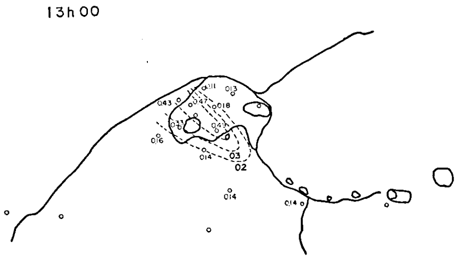

Fig. 19

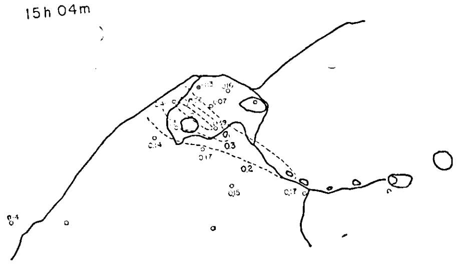

Fig. 20

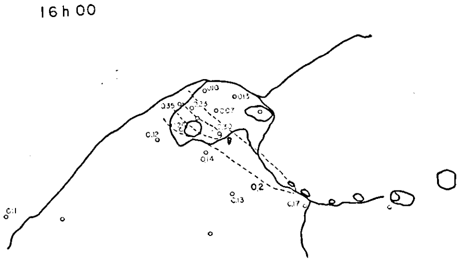

Fig. 21

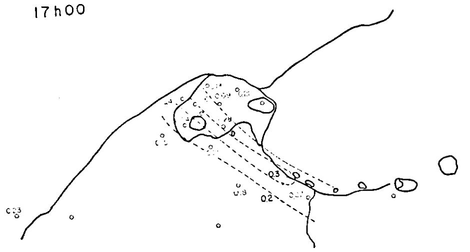

Fig. 22

Figs. 19.-22. Plots of absolute vertical ground amplitude of tremor during the October eruption expressed in microns.

by dotted lines. It is interesting to examine the figures in succession. During the early stage of the eruption, the center of the lines of equal amplitude in the region from Uwekahuna to the southern border of the caldera involving Halemaumau Crater Pit, in such a shape as to be elongated in a south east direction. The axis of this elongation tends to extend towards the east as time proceeds.

After 15h, the center of the lines of equal amplitude grows longer from the summit and extends along the upper part of the east rift zone. This was the period when a large amount of lava was erupted in and near Kalalua Crater with 150-foot-high fountains. Gross migration of magma through a more or less continuous conduit from beneath the summit to the east rift zone is suspected during this period because tremor increased and lines of equal amplitude are parallel to this presumed conduit.

So far as we are concerned with our seismic net, the pattern of tremor amplitude shows larger amplitudes towards the summit, and not towards the eruptive site. This is one of the important results for locating the magmatic foci of Kilauea Volcano.

From the eruptive site, intense short period tremor is generated as recorded by Makaopuhi seismometer. However, this tremor is absorbed considerably during its propagation and cannot be represented in our present results.

7. Spectral studies

It is likely that tremor does not originate from a single source but probably originates from several sources. It might happen, further, that these sources vary with time and space during eruptions. Location of

Table 3. Apparent period of volcanic tremor accompanied by the Napau eruption

Time	Uwekahuna (H)	Uwekahuna (V)	Kaoiki (V)	Kilauea Iki (H)	Foot Prints (H)	Ohale (H)
h m	s	s	s	s		s
Oct. 5, 06 00	0.50	0.42	0.79	0.90	—	0.84
08 00	0.71	0.65	0.84	1.10	—	0.91
10 14	0.60	0.55	0.86	0.71	0.74	0.79
17 57	0.71	0.57	0.93	1.05	0.99	0.73

these sources of tremor is a useful probe to investigate volcanic foci and to trace the movements of magma during volcanic processes.

Volcanic tremor, in general, involves both body and surface waves generated from a deep and shallow origin. One useful method that can be applied to distinguish tremors originating from different sources is to

Table 4. List of observations on magnetic tape for which amplitude spectra were computed

No.	Data	Station	Remarks
1	Aug. 3, 14h 13m	3, 8, 9, 2, 5, 7	Intermediate tremor
2	Aug. 15, 08 31	3, 8, 6, 2, 5, 7	T phase
3	Aug. 21, 16 45	3, 8, 6	Alae eruption
4	Aug. 22, 03 47	3, 8, 6, 2, 5, 7	〃
5	〃 10 19	3, 8, 6	〃
6	Oct. 5, 06 50	5, w, 6, 2, 4, 1	Napau eruption
7	〃 08 14	5, w, 6	〃
8	〃 15 31	3, 4, 2	〃
9	Oct. 6, 09 44	80m tripartite net	〃
10	〃 11 22	〃	〃
11	〃 14 26	〃	〃
12	〃 15 01	Circular neut	〃
13	〃 15 02	〃	〃
14	〃 15 10	〃	〃
15	〃 15 17	〃	〃
16	〃 15 22	〃	〃
17	〃 15 30	〃	〃
18	〃 15 39	〃	〃
19	〃 15 52	〃	〃
20	〃 16 00	〃	〃
21	〃 16 08	〃	〃
22	〃 16 14	〃	〃
23	〃 16 20	〃	〃
24	Dec. 3, 13 43	250m tripartite net	
25	〃 15 00	〃	
26	Dec. 4, 13 44	80m tripartite net	Micro-seismic noise
27	Dec. 12, 11 41	〃	Deep tremor
28	〃 12 27	〃	〃
29	〃 13 00	〃	〃
30	Dec. 13, 10 26	〃	〃

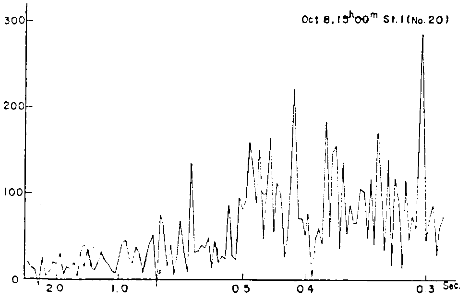

Fig. 23

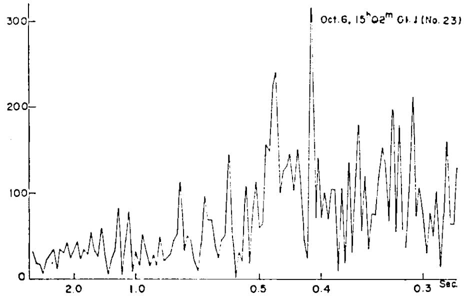

Fig. 24

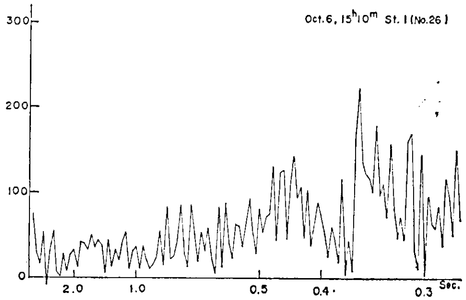

Fig. 25

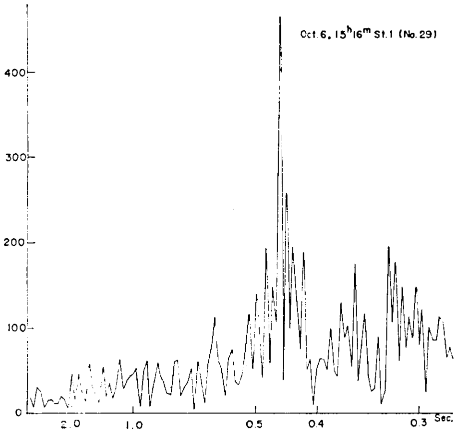

Fig. 26

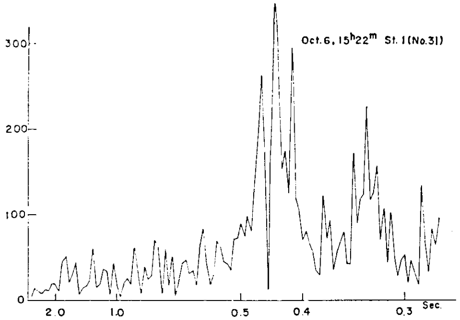

Fig. 27

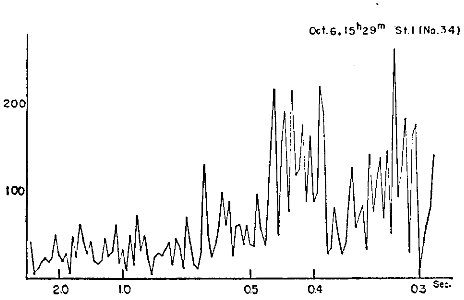

Fig. 28

Figs. 23-33. Amplitude spectra of tremor accompanied by the October eruption recorded at station 1 of the tripartite net by 3 c/s vertical seismometer.

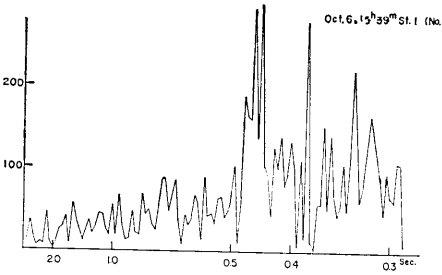

Fig. 29

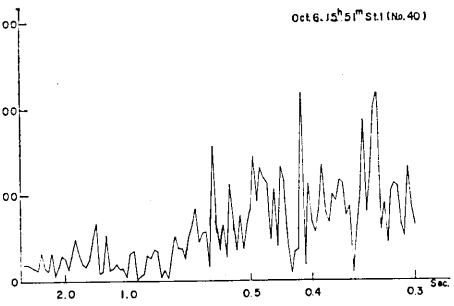

Fig. 30

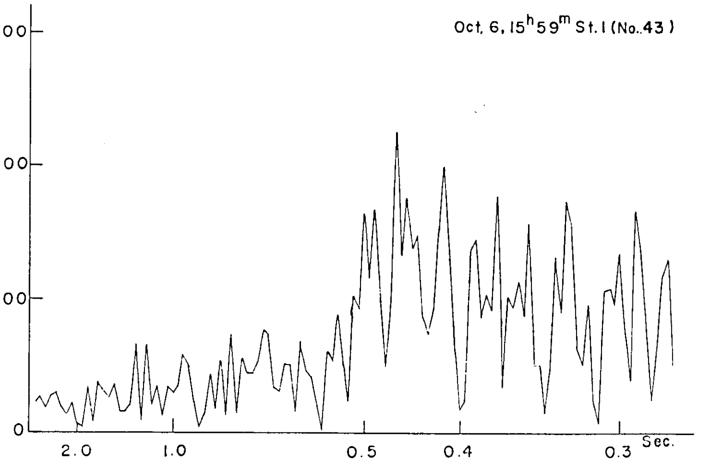

Fig. 31

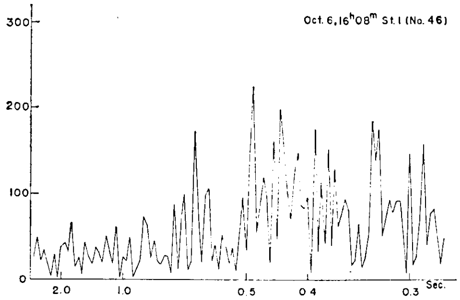

Fig. 32

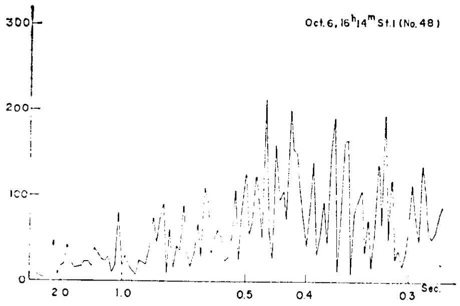

Fig. 33

Figs. 29-33. Amplitude spectra of tremor accompanied by the October eruption recorded at station 1 of the tripartite net by 3 c/s vertical seismometer.

compare their spectral components.

In this section, results of Fourier analysis of tremor are discussed. For convenience, the apparent period of tremor during the October eruption is listed in Table 3.

In the early stage of the eruption, apparent period is short compared with the later stage. Table 4 is the list of observations on magnetic tape for which Fourier analyses were carried out. Playbacked seismograms were read at every 1/10 second during one minute so each data has 600 readings.

First of all, we shall examine how spectrum change at one place with time. Figs. 23–33 are the spectra of tremor during the October eruption recorded by a 3 c/s vertical seismometer which was placed 50 meters behind the Observatory building. The spectra are not corrected by frequency characteristics of seismograph.

Significant peaks seem to exist in the range of 0.4–0.5 seconds. However, they show considerable variation in the short period range. For the time sequences of these spectra, eruptive activity has already died. Strong peaks in short period are, therefore, due to frequency response of seismometer.

Another feature of time variation of spectra can be found in Figs. 34–36. These spectra were computed from the tremor accompanied by the August eruption recorded at Station 8 with 1 c/s seismometer.

It shows that, as time proceeds, component of maximum amplitude shifts to longer period. It is interesting to compare the spectra with chronological description of the eruption written as follows:

Aug. 21, 19h 20m :	The fountains on the floor of Alae Crater formed an almost continuous curtain of fire 7 to 10 meters high and 90 meters long.
19h 45m :	The line of fountains in the forest on the north rim died.
20h 00m :	Rate of lava extrusion was 150×10^3 cubic yards/hr.
22, 03h 47m :	Decreased to 35×10^3 cubic yards/hr.
06h 00m :	Lava lake had reached its maximum thickness (about 20 meters)
23, 00h 03m :	The lake was dark except for scattered spots.
18h 10m :	The eruption was over.

Fig. 34 in which short period component is relatively strong corresponds to the stage of the eruption at its hight. Fig. 36 corresponds to the decreasing activity and short period components becoming relatively

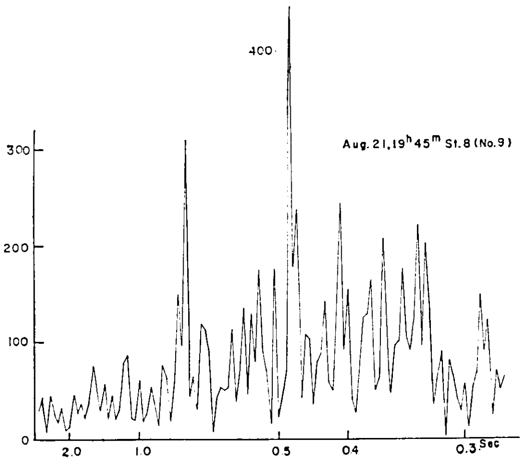

Fig. 34

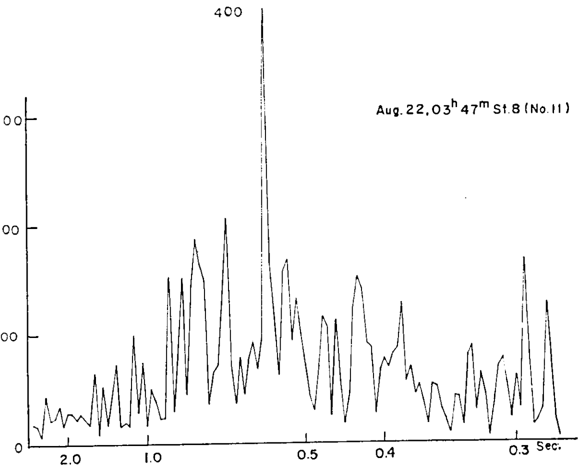

Fig. 35

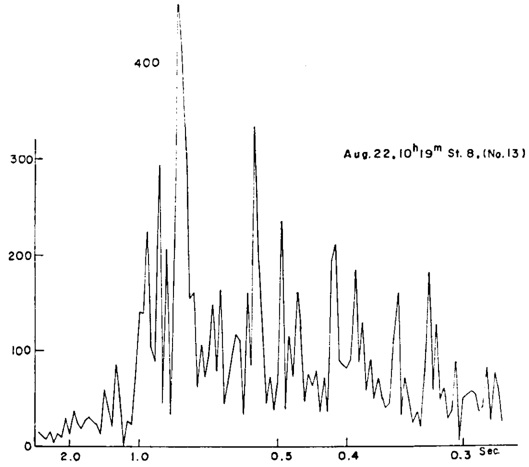

Fig. 36

Fig. 34–36. Amplitude spectra of tremor during the August eruption recorded at station 8 by 1 c/s vertical seismometer.

weak.

As can be seen from these spectra, we can deduce that volcanic processes such as temporary migration of magma, fountaining and formation of lava lake generate tremor of inconstant spectral features. It varies with eruptive stages. It means that tremor is generated from various sources, some of which are weakened and others newly generated becoming strong during the eruption. Therefore, the location of the sources of tremor is extremely complicated.

One of the authors (D.S.) observed the tremor at Nyiragongo Volcano in 1959 and made spectra at different epochs as shown in Fig. 37.

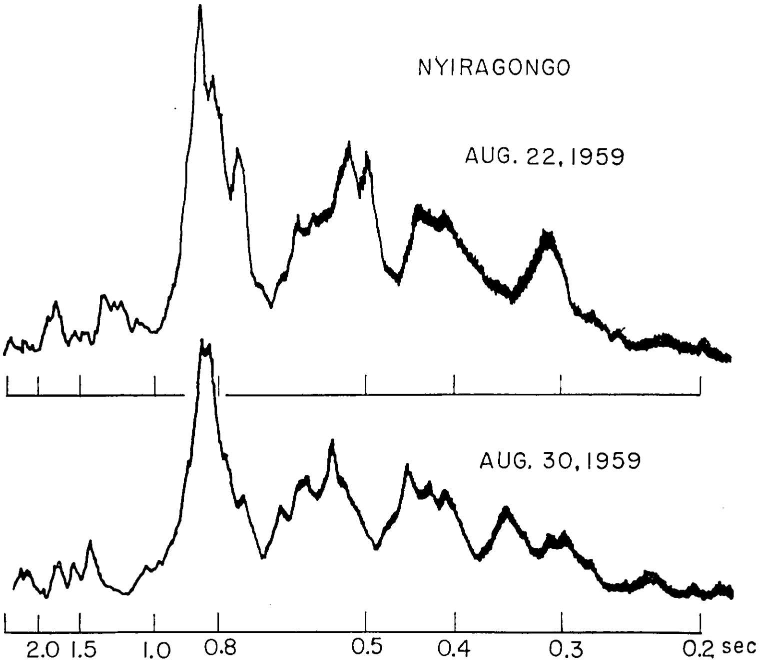

Fig. 37. Amplitude spectra of tremor recorded on the first platform inside the crater of Nyiragongo Volcano by use of 1 c/s vertical seismometer.

Nyiragongo Volcano has a permanent lava lake in the bottom of its crater with continuous fountaining and drainback of fluidal lava from/to its vent. In spite of the different times, the two spectra are completely the same. In this case, the source of tremor seems to be stationary with time and space.

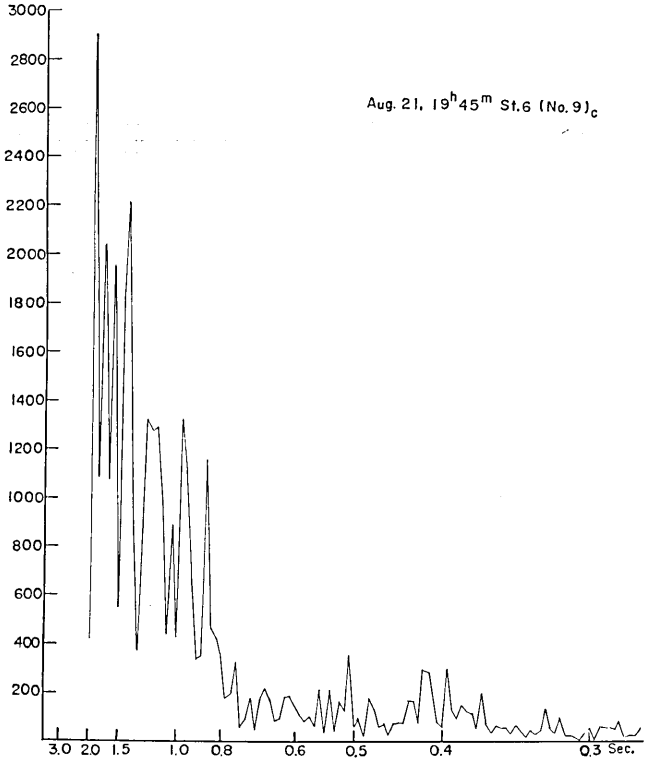

Fig. 38

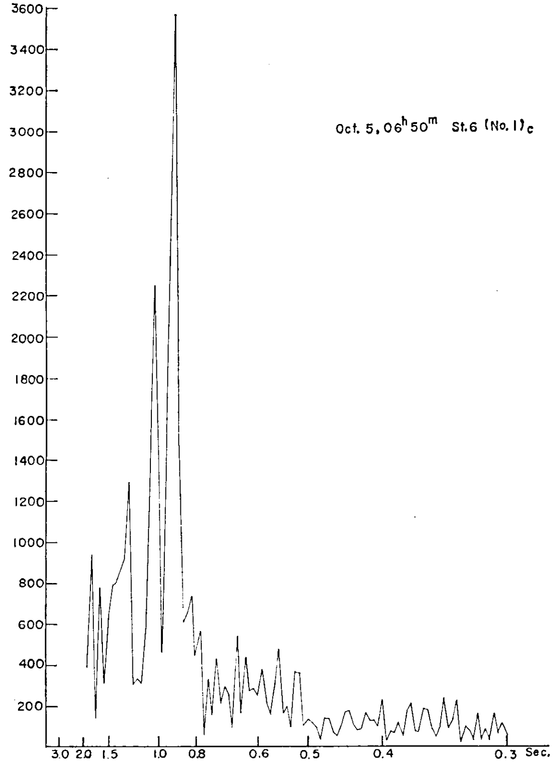

Fig. 39

Fig. 38-39. Amplitude spectra of tremor by 1 c/s seismometer. Frequency response is corrected.

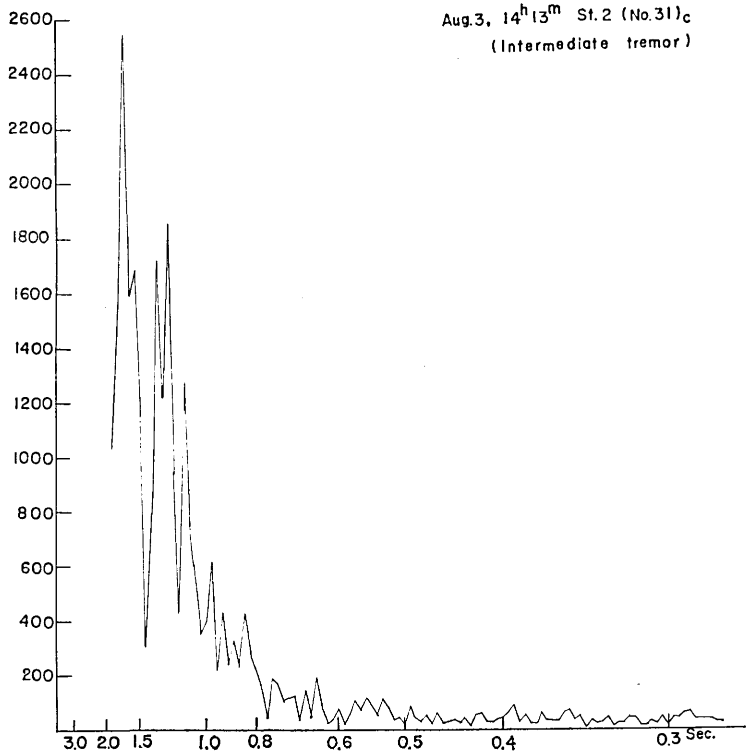

Fig. 40

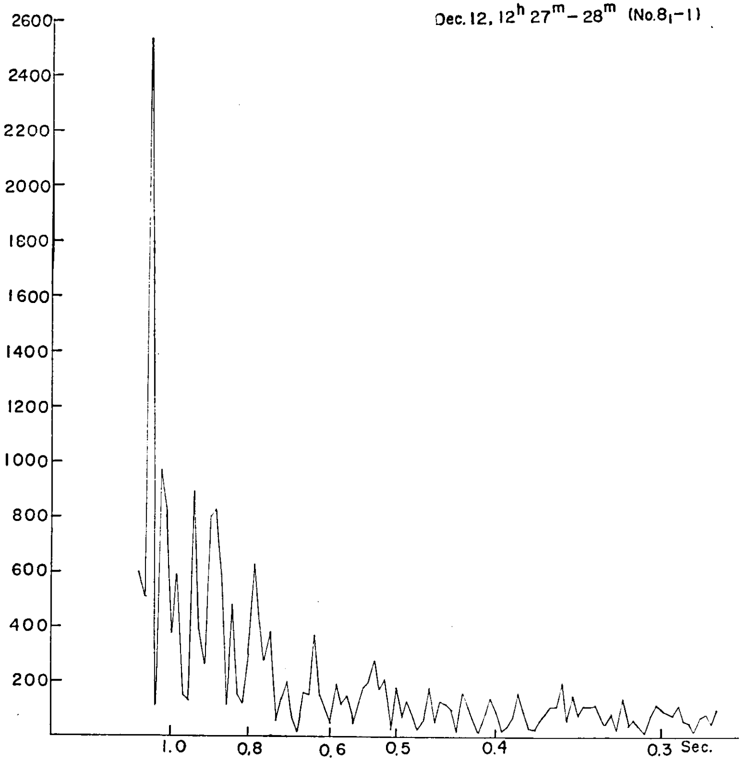

Fig. 41

Fig. 40–41. Amplitude spectra of tremor by 1 c/s seismometer. Frequency response is corrected.

Next we compare the spectra of tremor accompanied by two eruptions with that during no eruptive activity. Four examples are presented here for which the frequency response of the seismograph is corrected. Fig. 41 was computed from observations by 3 c/s seismometer, hence, frequency correction was not done for the period more than 1.4 seconds because of lack of accuracy.

Table 5. Description of the sources of spectra Fig. 38–41

Fig. No.	Time	Station	Seismometer	Remarks
38	Aug. 21, 19h 45m	No. 6	1 c/s	Alae eruption
39	Oct. 5, 06 50	No. 6	1 c/s	Napau eruption
40	Aug. 3, 14 13	No. 2	1 c/s	Intermediate
41	Dec. 12, 12 27	No. 1(Tripartite net)	3 c/s	Deep

All of these spectra show predominant component in long period 0.9–1.9 seconds. Deep and intermediate tremor have strong peaks near 1.7 seconds. Above two spectra which were accompanied by the eruptions seem to have a significant component in short period, while the lower figures have no component in short period.

It is interesting to find that the most predominating period in the case of the August eruption is 1.9 seconds while that in the case of the October eruption is 0.9 seconds. The spectrum of August 21 is very similar to the spectra of intermediate and deep tremor with the exception of short period component.

On the other hand, the spectrum on October 5 differs from these. It is very likely that during the August eruption, the supply of magma from the deep to the shallow reservoir was continued, and this movement of magma generated long period tremor. It cannot be well interpreted why the predominating period was longer than that of the October eruption.

Next we further discuss the propagation direction of tremor that accompanied the October eruption. Fourier analysis gives phase angle for respective components by which means we can calculate the propagation direction and apparent phase velocities of each component from the appropriate seismic net.

One example is the tremor recorded by the 1 c/s seismometers located at sites 1, 2 and 4 inside the caldera, and another example is the tremor

Fig. 42–47. Amplitude spectra of tremor from which apparent phase velocities and direction of approach were calculated for components as indicated by arrows.

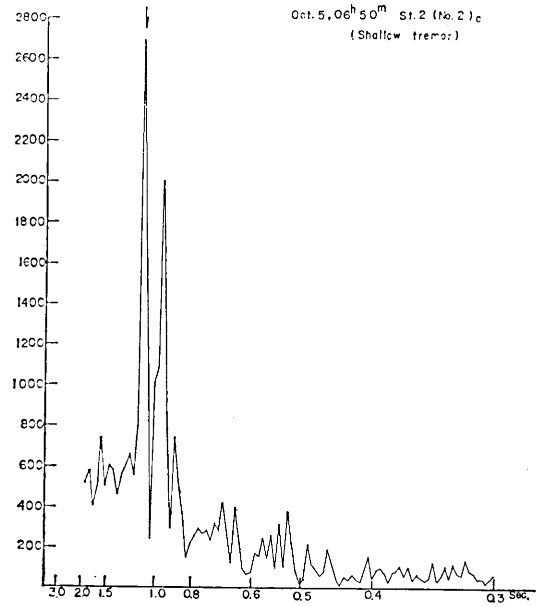

Fig. 42

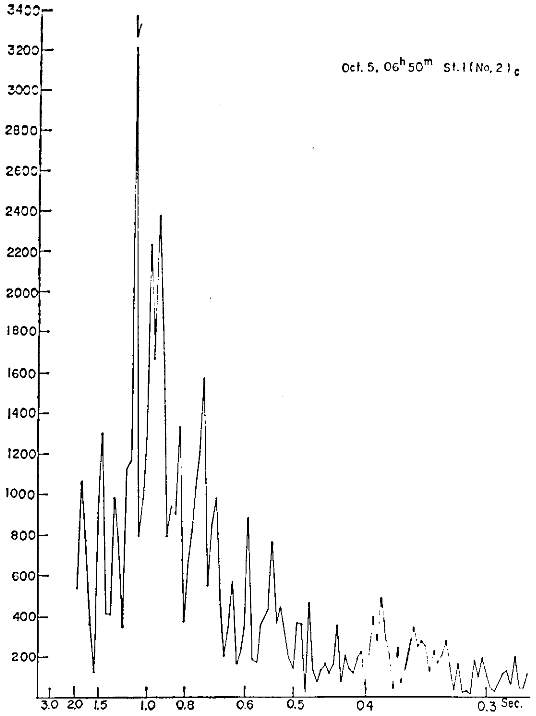

Fig. 43

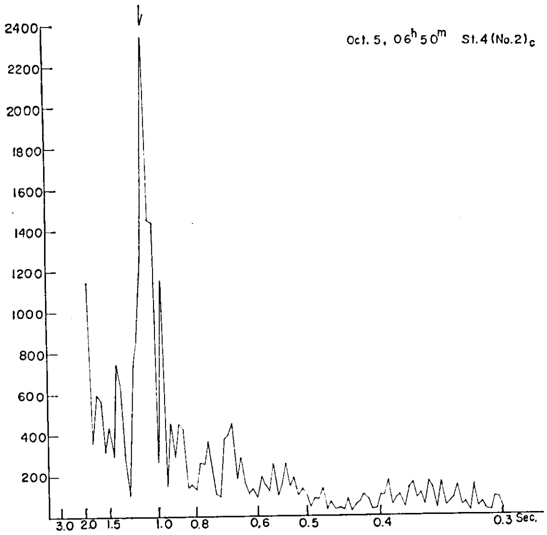

Fig. 44

recorded by 3 c/s tripartite seismometers which were placed at the corners of an equilateral triangle 80 m on a side.

The propagation directions and phase velocities were calculated from the significant components as shown by arrows in Fig. 42–47. The results are listed in Table 6 and shown as vectors in Fig. 48.

Table 6. List of apparent phase velocites V and propagation direction θ for respective period T
(azimuth taken from N in clockwise)

T in sec.	V in km/sec	θ in degree	Remarks
1.0909	3.18	164	Oct. 5, 06h 50m
0.6316	1.30	146	Oct. 6, 14h 26m
0.6000	0.86	163	(Tripartite net)
0.4737	0.42	144	〃
0.3243	0.52	136	〃
0.3711	0.30	41	〃

Tremor seems to originate beneath the region of Halemaumau and the southern border of the caldera. This result is consistent with the distribution of tremor amplitude as shown in Fig. 11–22. From the repeated precise levelling of Kilauea Volcano, and tilt observations, MOORE and

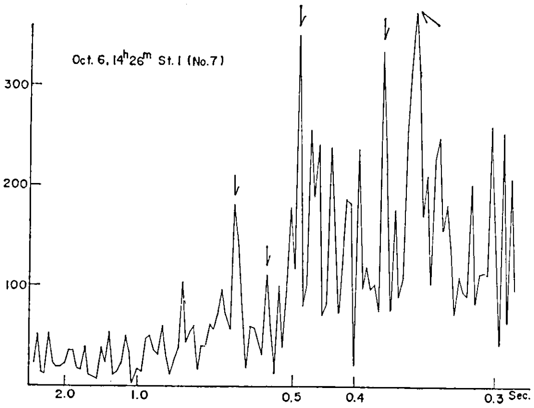

Fig. 45

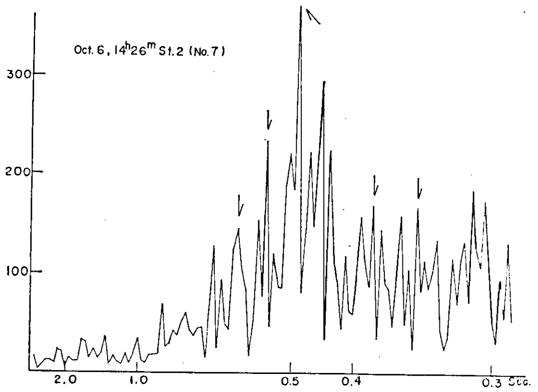

Fig. 46

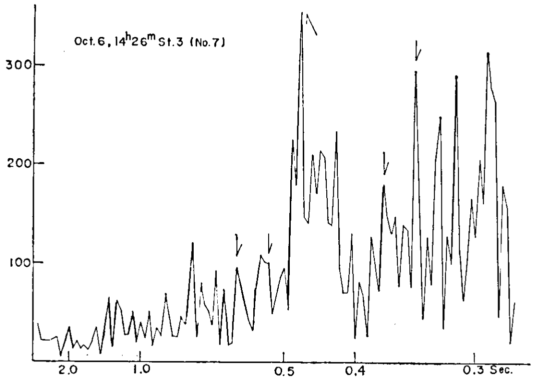

Fig. 47

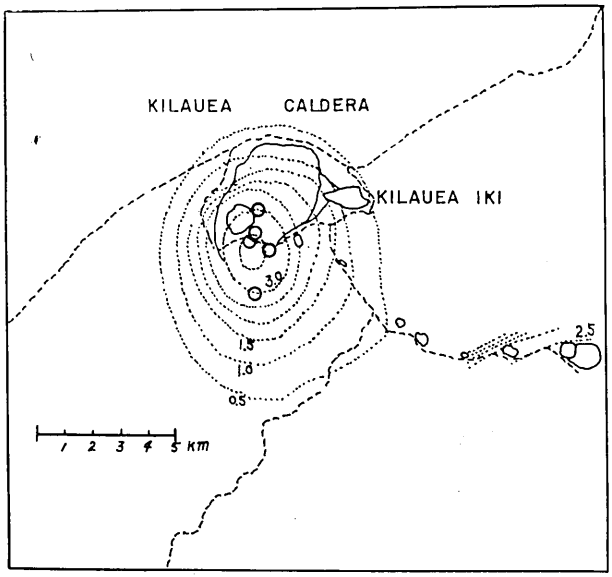

Fig. 48. Map showing change in elevation and tilting of ground at Kilauea summit before and slightly after the 1962 eruption. Change in elevation is expressed in feet and open circles indicate the center of tilt for respective period. (after J. G. Moore and H. L. Krivoy, 1964)

Krivoy[15] obtained the change in elevation and tilting of ground at the summit region before and slightly after the 1962 eruption. Their results are shown in Fig. 48.

The center of ground deformation and tilt is located around the southern border of the caldera. They believe that a shallow reservoir exists beneath this region. The location of the source of tremor as described above is in good agreement with their location of the shallow reservoir beneath the summit of Kilauea Volcano.

In order to distiguish volcanic tremor from ordinary micro-seismic noise caused by atmospheric conditions, an example of amplitude spectrum is shown in Fig. 50 which should be compared with Figs. 22–33.

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[15] J. G. Moore and H. L. Krivoy, *loc. cit.*, 12)

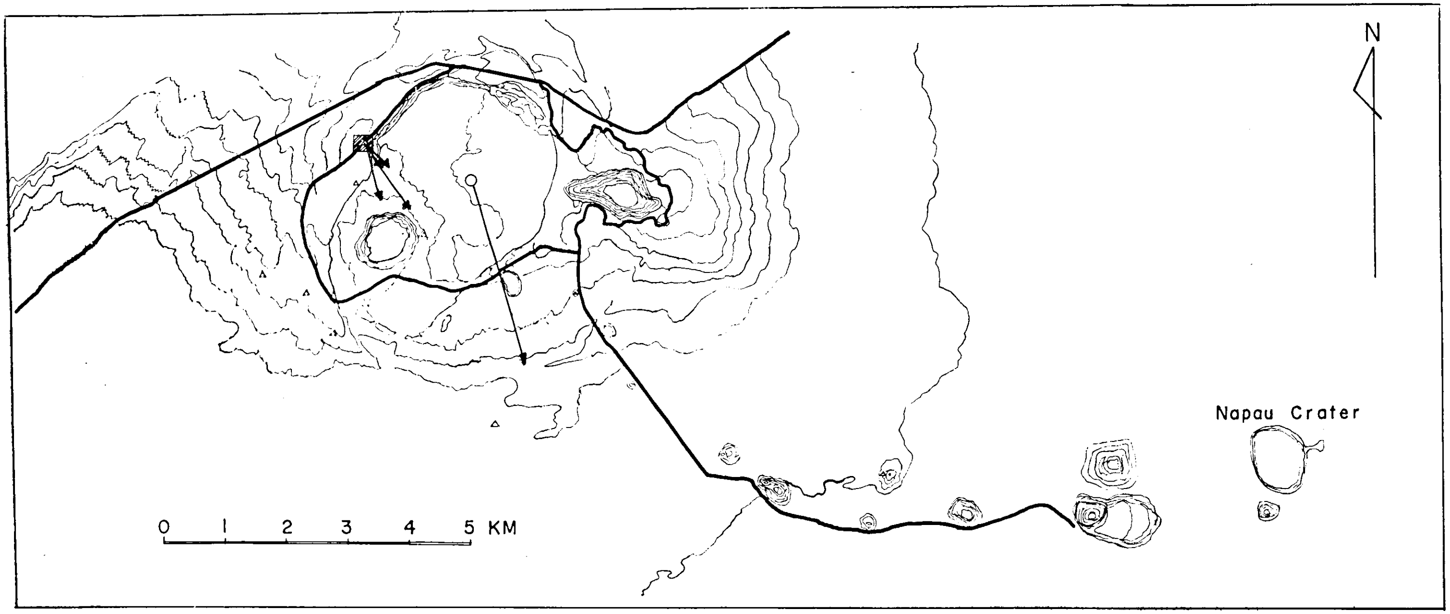

Fig. 49. Vectors showing direction of approach and apparent phase velocities of tremor for respective Fourier components.

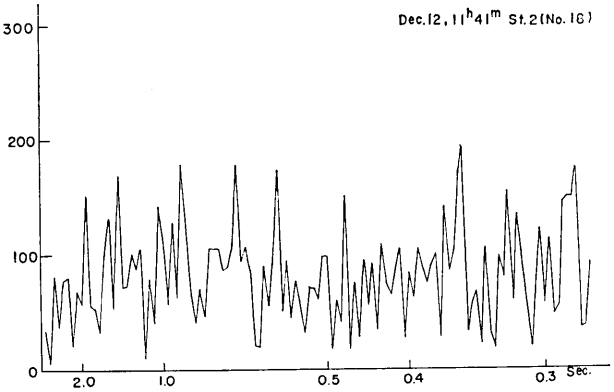

Fig. 50. Amplitude spectrum of micro-seismic noise recorded by 3 c/s seismometer.

8. Summary and conclution

Main results are as follows;

1) Amplitude of tremor was less during the August eruption than during the October eruption.
2) Amplitude spectra of tremor during eruptions show significant variation with eruptive stage.
3) During the October eruption, lines of equal ground amplitude (veritcal) were drawn at one hour intervals from the beginning of the eruption until the evening of the same day. These plots show that in the early stage of the eruption, the center of concentric lines of equal ground amplitude was located around Uwekahuna and Halemaumau. This pattern subsequently spreads out, and at the southern part of the caldera, the lines become parallel to a line from Halemaumau Crater Pit to the upper east rift zone.
4) Amplitude spectra have predominating peaks between 0.9 and 1.9 seconds for both the August and October eruptions.
5) Short period components in spectra are associated with eruptions.
6) Deep tremor accompanied by no eruptive activity is characterized by lack of short period components.
7) For the case of the October eruption, several predominating peaks in the amplitude spectra have their direction of propagation SSE of the Observatory.
8) Tremor of deep origin has a predominating period of about 2 seconds which seems to be essential evidence of movement of magma beneath Kilauea Volcano.

Present studies could not locate the sources of tremor exactly. However, it was clarified that tremor is mainly generated during feeding of magma from the deep source to the shallow reservoir beneath Halemaumau and also during migration and surging of magma through a more less continuous conduit from beneath Halemaumau to the east rift zone.

9. Acknowledgments

We wish to thank Professor T. MINAKAMI, the University of Tokyo, chief of visiting Japanese team, and Dr. J.G. MOORE of the U.S. Geological Survey, scientist in charge of the Hawaiian Volcano Observatory during the time of the observations, for their support and helpful discussions throughout this study. We are also indebted to Messrs. S. HIRAGA and T. MIYAZAKI and the staff of the Hawaiian Volcano Observatory for their assistance in the installation and operation of the equipment. Tremor records were read by Miss Y. SATO to whom our thanks are due. We wish to thank Professor Y. SATÔ who kindly made Fourier analysis by his IBM computor programme.

Acknowledgment is made of the partial financial support of this investigation through grants from the Japan Society for the Promotion of Science and the National Science Foundation as part of the Japan-U.S. Cooperative Science Program.

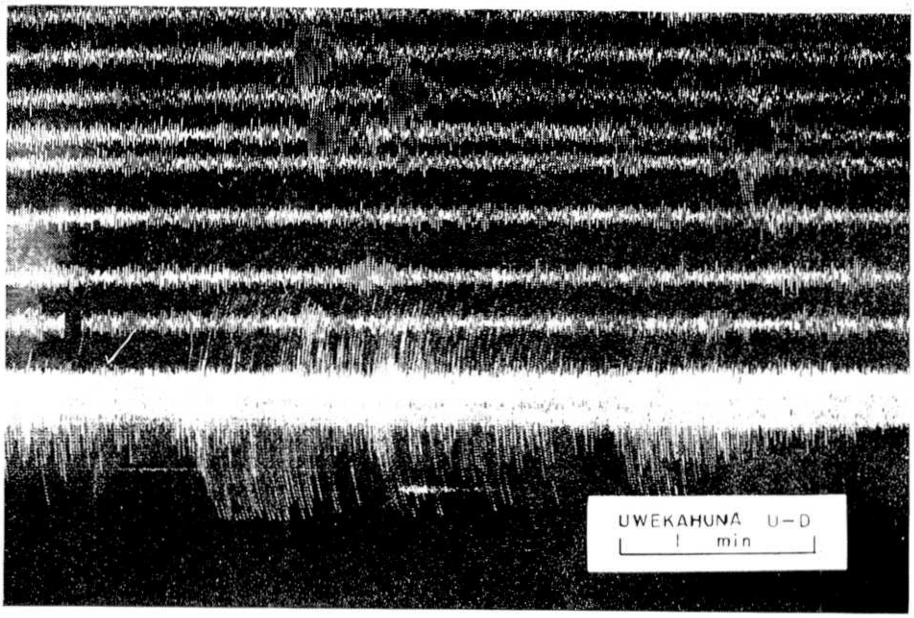

Fig. 51. A part of the tremor recorded by Uwekahuna vertical seismograph which was accompanied by the October eruption.

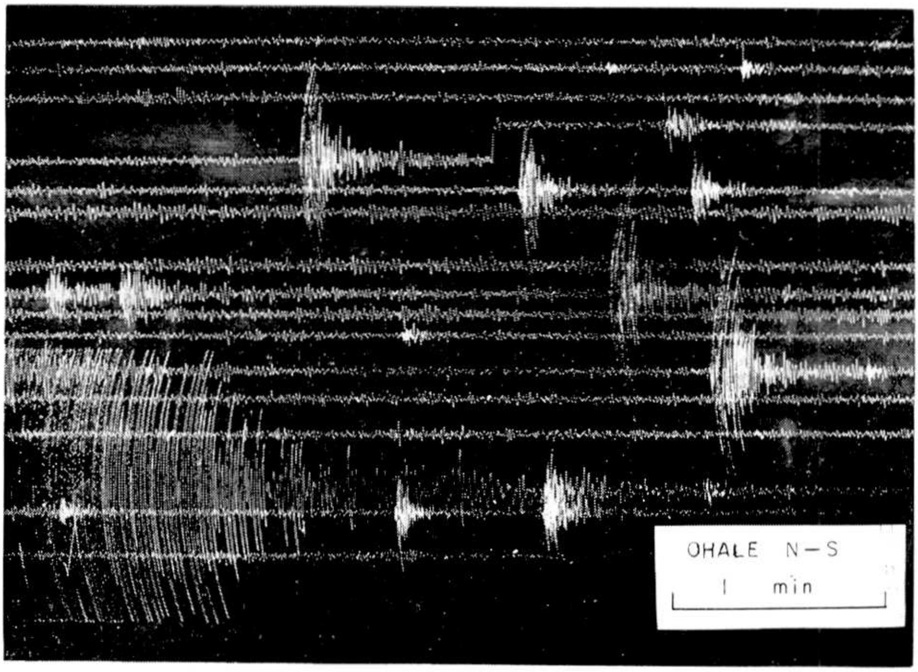

Fig. 52. Seismogram recorded at Ohale shows continuing tremor and shallow earthquakes during the October eruption.

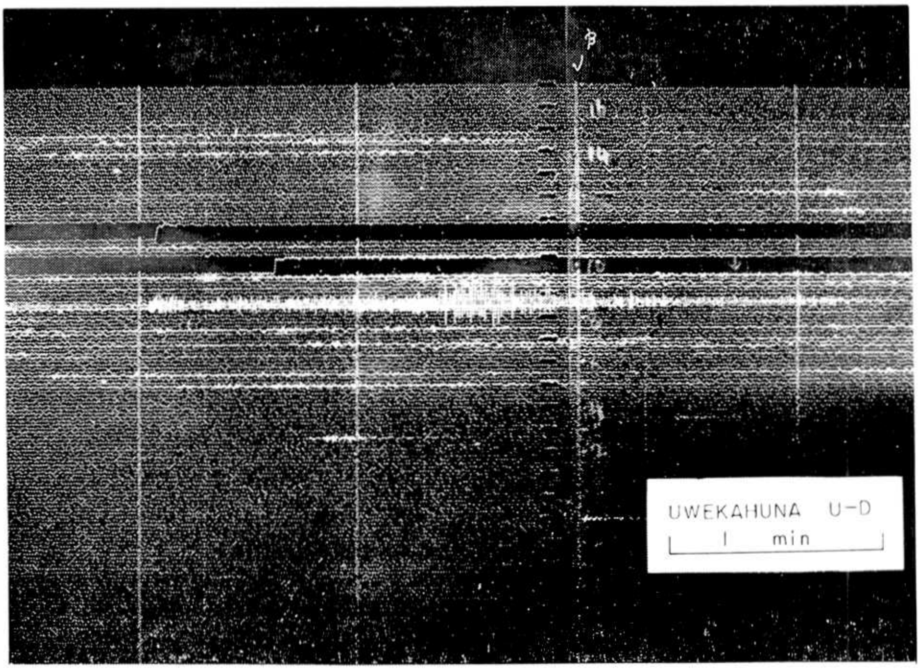

Fig. 53. An example of tremor which was associated with no surface activity.

Fig. 54. Volcanic tremor recorded by the tripartite network during the Octorber eruption by means of a 3-channel magnetic tape recorder.

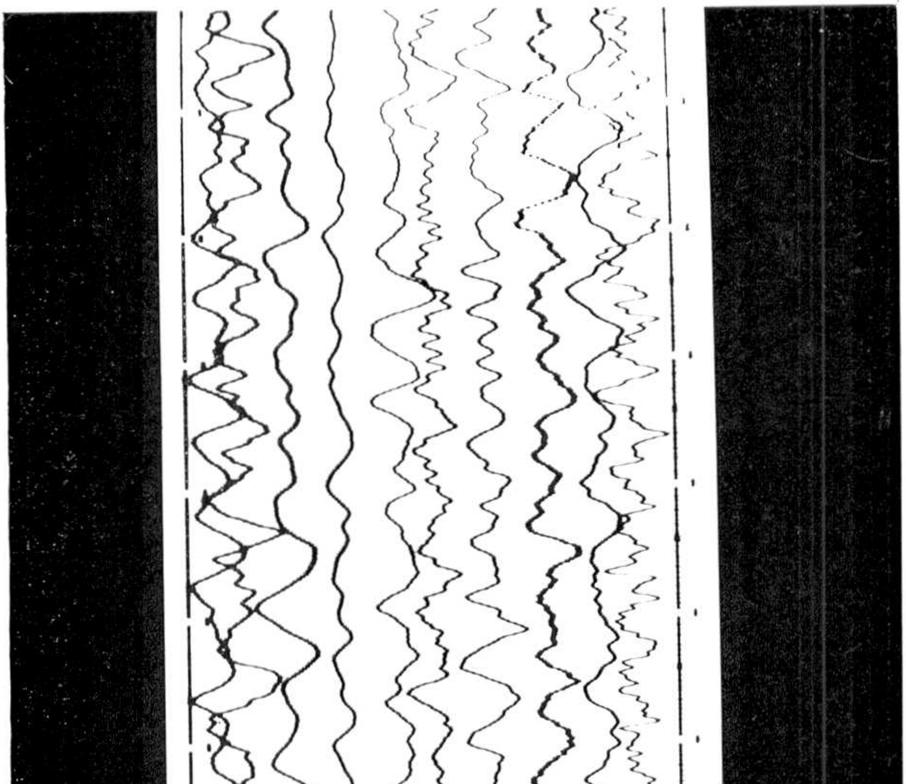

Fig. 55. An example of oscillogram of tremor during the October eruption.

54. 1963年7月——12月間のハワイキラウエア火山の脈動

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日米科学協力の一環として実施されたキラウエア火山の地球物理学的研究において得られた表記期間中の火山性脈動の観測結果をまとめて報告する．

同期間中に観測された火山性脈動は2つのタイプに分けられる．1つは8月21日と10月5日に起きた噴火に伴うものであり，他は，表面活動を伴わずに短時間出現する脈動である．U.S.G.S.の地震観測網に加えて，我々はカルデラ内に7ケ，カルデラ外に11ケの地震計を配置し，更に火山観測所近くに短かいスパンの三点観測網を作った．脈動出現の際に上記観測網に加えて，オッシログラフおよびデータレコーダーによる観測を行った．得られた解析の結果は次の通りである．

1) オッシログラフの記録から，10月噴火の時の上下動振巾分布をつくると，その最大振巾の目玉はハレマウマウ火口を中心としており，噴火が進むにつれて，等振巾線は東南に伸びてくる．このことは，ハレマウマウ火口下の浅いマグマ溜りから東のrift zoneにむかって，マグマを送り出すパイプがあることを示している．

2) フーリエ解析の結果，8月噴火および10月噴火の脈動中に周期2秒附近の成分が強く表われ，これはいわゆる“deep origin”の脈動の周期と等しい．溶岩噴出によって，脈動の短周期部分が表われてくる．

3) 脈動の振巾分布および，伝播方向より推定すると，脈動の源はハレマウマウ火口下にあり，ここから脈動のエネルギーの大部分が放出されていることが判明した．このことは，レベリングや，傾斜観測から推定されているマグマ溜りの場所とも一致していることが興味深い．

4) マグマ溜りよりrift zoneにのびるパイプ中を流動するマグマの振動も脈動の源の一部である．

5) 溶岩噴出場所でも強い短周期の脈動が観測されているが，これは吸収が大きいので，我々の観測網にはあまり記録されていない．

6) キラウエア火山の脈動は2秒前後の周期をもつ成分が重要であって，他の玄武岩火山および安山岩火山の脈動の周期に比して長いことが判った．このことはおそらくこれらの火山の溶岩の粘性に関係しているであろう．