A Study of Earthquakes in Relation to Volcanic Activity (III)

—Earthquakes during the period of activity of Volcano Usu (1943—1945),
two new phases of the earthquakes, and earthquakes of
crypto-volcanic activity at Itô—

By

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Abstract

The writer made a consecutive study of the earthquake swarms which occurred accompanied by the volcanic activity of Volcano Usu, Hokkaido, from December 1943 to October 1945. The famous Showa Shinzan was born in the course of this activity. As a sequel to the first and second papers, the writer prepared this third paper in which the following problems are discussed.

1). As a result of the study of the earthquakes (A-type earthquakes) that occurred prior to eruptions, the writer obtained the value of the distance coefficient, $k=8.2$ km/sec, near Showa Shinzan. At the same time the depth of the hypocenter was determined to be about 10 km. By using $k=8.2$ km/sec, the distribution of the epicenters of A-type earthquakes was studied.

2). From the decay formula of the maximum amplitude for surface waves

$$A=A_0 \Delta^{-1/2} e^{-\alpha \Delta},$$

the value α was obtained as follows:

$$\alpha=5.8 \times 10^{-3} \text{ km}^{-1} \quad (25 < \Delta < 700 \text{ km}),$$

$$\alpha=5.6 \times 10^{-3} \text{ km}^{-1} \quad (25 < \Delta < 800 \text{ km}).$$

By the following formulas the decay of frequency N and ground amplitude A with the lapse of time were studied.

$$N(t)=K(t+C)^{-p},$$

$$A(t)=K'(t+C')^{-p'},$$

where K , K' , C , C' , p and p' are constants. These constants were obtained from the data of the A-type earthquakes observed at Muroran, Mori and Sapporo.

3). In the waves of all earthquakes of A-type recorded by the seismograph at Mori Observatory (Mori Weather Station), S'-waves, reflected S-waves, were found several seconds after S-waves, and the depth of the Moho discontinuity was calculated as $H=25.0$ km (mean value).

4). Energy of earthquakes and energy of ground upheaval were cal-

culated, and their relation to the number of earthquakes and to other phenomena were considered.

5). In the seismograms at Mori Observatory two new phases were discovered. These were tentatively named the third phase and the fourth phase. Most of the path of the seismic waves are in shallow sea water. The waves were treated as Rayleigh waves, and various conditions were given to the crustal structure of "liquid-liquid-solid" layers or "liquid-solid-solid" layers. The dispersion curves of Rayleigh waves for every case were computed by IBM 704 electronic computer. The sedimentary layer, or the second layer, was assumed to be solid, and importance was attached to this layer. By assuming a condition such that the velocity of the compressional wave is smaller than that of the first layer, and by adjusting the ratio of the thickness, a result was obtained, by which the above-mentioned 3rd and 4th phases might be most satisfactorily explained.

Thus an important hint was obtained, in regard to the nature and effect of the sedimentary layer.

6). The values of m in the Ishimoto-Iida's formula, $n dA = K A^{-m} dA$, are calculated by the use of data of the Itô crypto-volcanic activity and the Kita-Izu earthquake swarms in 1930.

By means of cumulative frequency calculation, mean values for the above two groups were respectively given, as $m=1.85$ and $m=1.50$. These values were compared with those obtained from the forerunning earthquakes of Usu volcanic eruption.

1. Introduction

The activity of Volcano Usu is usually accompanied by marked earthquake swarms (ISHIKAWA, 1950; MINAKAMI and others, 1951; KIZAWA, 1957, 1959). The earthquakes, that occurred during the volcanic activity from 1943 to 1945 and formed Showa Shinzan, were especially striking. Some of them were recorded by the Wiechert seismograph installed at an 800 km distance from the epicenter.

With an aim to clarify the nature of these earthquakes, the writer has been studying the seismograms of Muroran ($\Delta=25$ km), Mori ($\Delta=54$ km) and Sapporo ($\Delta=69$ km) Observatories around the Volcano Usu, and other seismologic data obtained through the observation network of the Japan Meteorological Agency. Main results of the study have been reported (T. KIZAWA, 1957, 1959 and 1960).

The present paper summarizes the results of later research on some of these observation records. It comprises the following section; 2). Nature of pre-eruption earthquakes; 3). Relationships between maximum amplitude and epicentral distance; 4). Underground discontinuity between Volcano Usu and Mori; 5). Earthquakes and ground upheaval accompanying the birth of Showa Shinzan; 6). Two new phases discovered in the earthquakes of the Usu-Mori path; 7). Nature of submarine earthquakes of crypto-volcanic activity off Itô and the Kita-Izu earthquake swarms.

The writer intends to study the volcanic earthquakes of Sakurajima, Kyushu, as a part of his continuous research on the relationships between volcanic activity and associated earthquakes.

2. Nature of pre-eruption earthquakes

Hypocenter and distance coefficient

When x , y and 0 are the co-ordinates of a observatory, x_0 , y_0 and h those co-ordinates of the hypocenter of the earthquake which occurred at the depth of h , and t the duration from P to S , then the relation formula is as follows:

$$(x-x_0)^2+(y-y_0)^2+h^2=k^2 t^2.$$

As the equation contains four unknown quantities, inclusive of the distance coefficient k , the observation data of at least four stations are needed for determination of the hypocenter.

In general the hypocenter of forerunning earthquakes (A-type earthquakes) cannot be determined, because observations of such earthquakes are made only at three observatories, Muroran, Mori and Sapporo. Nevertheless, judging from the various phenomena observed on the ground surface (T. ISHIKAWA, 1950, T. MINAKAMI and others, 1951), the epicenter of A-type earthquakes is thought to lie at the foot of Volcano Usu. Presuming the epicenter of the A-type earthquakes so, the writer calculated the value of the distance coefficient k . For this calculation, observation data at two stations may be sufficient. When the S-wave in the seismograms at Sapporo was obscure, a combination of Muroran and Mori seismograms was used.

The values of the distance coefficient obtained by analysing the seven A-type earthquakes which were accurately recorded are shown in Table 1. On the basis of the distance coefficient k near Showa Shinzan, the mean value of them is 8.2. At the same time the depth of the hypocenter is determined to be about 10 km (mean value) as seen in Fig. 1.

KENZÔ SASSA (1936) used 4.5 km/sec as the distance coefficient at Volcano Aso. R. TAKAHASHI and T. NAGATA (1939) studied earthquakes at Osima, and obtained the distance coefficient as $k=2.2+0.41z$ for the earthquakes originating from near the earth's surface and 1 km below it. Around the Volcano Usu the distance coefficients were assumed to be 2.0 and 2.3~5.2 km/sec for the earthquakes near the earth's

Fig. 1. Distribution of epicenters of some A-type earthquakes occurred during one month from Jan. 4, 1944. Seismological observatories are Muroran, Mori and Sapporo. The table in Fig. 1 shows values of depth of hypocenter h and distance coefficient calculated by determining the hypocenter to be at the foot of Mt. Usu. The earthquake of Jan. 9 is different in nature from any other earthquakes, and it will be mentioned in Sections 2 and 3.

surface and 1~4 km deep by T. MINAKAMI, T. ISHIKAWA and Y. YAGI (1951). These values of k are small. On the other hand TOSHIMATU MATUMOTO (1959) gave $k=8$ km/sec for Tesikaga earthquakes in Hokkaido, which corresponds with the value obtained above.

Distribution of epicenters of A-type earthquakes

Using the mean value of the distance coefficient thus obtained, the writer attempted to determine the epicenter on the basis of the three-point observations.

Table 2. Duration of P-S and hypocentral distance Δ .

Date	P-S (sec.)			Δ (=8.2 t km)		
	Muroran	Mori	(Sapporo)	Muroran	Mori	(Sapporo)
1944						
Jan. 4	3.00	6.25	8.86	24.6	51.5	71.0
5	3.25	7.02	9.35	26.6	57.6	76.7
8	3.12	6.77	8.45	25.6	55.5	69.3
9	3.29	6.40	8.70	27.0	52.5	71.4
15	2.94	6.44	—	24.2	52.8	—
21	3.05	6.90	8.84	25.0	56.6	72.5
Feb. 2	3.13	6.84	8.77	25.7	56.1	71.9

The observation points were Muroran, Mori and Sapporo. As is mentioned above, the commencement of S-wave in the Sapporo seismograms was obscure, and so the writer attached importance to the seismograms of Muroran and Mori. The distribution of epicenters of A-type earthquakes is diagrammatized in Fig. 1. Refer also to Table 2.

Decay in frequency and amplitude of pre-eruption earthquakes by the lapse of time

Presuming that the frequency and ground double amplitude of earthquakes diminish with time according to the formulas (Cf.: F. OOMRI 1931, S. NAKAMURA 1954, and T. MATUMOTO 1959).

The frequency of A-type earthquakes and its lapse of time
Sapporo ($\Delta = 69$ km)

Fig. 2—a

$$N(t) = K(t+C)^{-p},$$

$$A(t) = K'(t+C')^{-p'},$$

the constants were determined as follows:

By taking logarithms on two sides

$$\log N + p \log t = \log K,$$

$$\log A + p' \log t = \log K',$$

where the values of $\log K$, $\log K'$, p and p' were constants obtained by the least square method. The

Fig. 2—b.

Fig. 2—c.

Fig. 3.

frequency data were prepared at three stations Muroran, Mori and Sapporo. And for the relationships between ground amplitude and the lapse of time, observation data of the horizontal component of ground double amplitudes of A-type earthquakes at Muroran and Mori were prepared. Here t is the lapse of days from Dec. 28, 1943 when the A-type Usu volcanic earthquake swarms began.

The same samples were studied on the basis of these observation data and calculations were made independently. The results are shown in Table 3 and Figs. 2 and 3. The values thus obtained revealed a fair coincidence.

Eruptions occurred after the A-type earthquakes had declined. Then the above-mentioned results are significant as they represent the mode of occurrence of the pre-eruption earthquakes.

Table 3. Constants on the formula.

(a) $N(t) = K(t+c)^{-p}$

Observatory	p	K
Sapporo	1.14	1.49×10^2
Mori	1.24	3.42 "
Muroran	1.33	5.40 "

(b) $A(t) = K'(t+c')^{-p'}$

Observatory	p'	K'
Mori	1.5	3.3×10^4
Muroran	1.4	4.6 "

3. Relationships between maximum amplitude and epicentral distance

On pre-eruption earthquakes

Some of the A-type earthquakes were remarkably great. Those that occurred on the 5th and 9th of January 1944 were especially great, and were recorded at many observatories, the latter being detected by the Wiechert seismograph at Tomisaki located 852 km in epicentral distance. On the basis of these data (Table 4), the writer obtained a diminution formula of the maximum amplitude A (composite value of horizontal components).

Table 4. Maximum ground amplitude of the A-type earthquakes.

(a) Jan. 5, 1944

Station	epicentral distance Δ (km)	A_E (μ)	A_N (μ)	$A_H (= \sqrt{A_E^2 + A_N^2})$	ground correction factor	ground amplitude (μ)
Muroran	25	680	S-out	—	—	—
Mori	54	365	453	582	0.7	407
Sapporo	69	129	150	198	1.1	218
Urakawa	164	32.0	32.0	44.3	2.7	120
Asahikawa	182	20.0	25.0	31.0	0.5	15.5
Hachinohe	300	5.5	11.1	12.4	2.3	28.5
Akita	345	12.9	8.9	15.7	0.8	12.5
Miyako	365	5.6	5.3	7.7	3.3	25.3
Sendai	473	3.2	6.3	7.1	1.3	9.2
Fukushima	538	2.8	3.1	4.1	1.6	6.6
Shirakawa	630	2.5	2.5	3.6	1.5	5.4

(b) Jan. 9, 1944

Station	epicentral distance Δ (km)	A_E (μ)	A_N (μ)	$A_H (= \sqrt{A_E^2 + A_N^2})$	ground correction factor	ground amplitude (μ)
Muroran	25	S-out	805	—	—	—
Mori	54	470	651	804	0.7	563
Sapporo	69	317	324	453	1.1	498
Urakawa	164	92.0	99.0	135	2.7	365
Asahikawa	182	30.0	35.0	45.1	0.5	22.6
Hachinohe	300	27.7	10.1	29.5	2.3	67.9
Morioka	330	12.5	4.0	13.1	1.8	23.6
Akita	345	23.5	11.8	26.3	0.8	21.0
Sendai	473	12.7	6.3	14.2	1.3	18.5
Fukushima	538	5.5	6.1	8.2	1.6	13.1
Shirakawa	630	6.3	6.3	8.9	1.5	13.4

(for calculation of the maximum amplitude decay formula, the data at Morioka were excepted)
 ("S—out" means scale out)

Using the diminution formula of the surface wave

$$A = A_0 \Delta^{-1/2} e^{-\alpha \Delta},$$

the results obtained for the two earthquakes of January 5 and 9, 1944 are shown in Fig. 4 and Table 5.

Fig. 4. Maximum ground amplitude and epicentral distance.

The values of the absorption coefficient at Oshima were reported as 2.7 to $3.3 \times 10^{-1} \text{ km}^{-1}$ (T. MINAKAMI and others, 1951). B. GUTENBERG obtained the value $\alpha = 0.36 \times 10^{-3} \text{ km}^{-1}$ ($T = 20 \text{ sec}$) from the surface waves that traveled through the Pacific Ocean, and the writer, by studying the observation data of the great earthquake of Chile in 1939, as recorded in various parts of Japan, obtained a mean value of $\alpha = 0.29 \times 10^{-3} \text{ km}^{-1}$ (T being 30-45 sec).

Concerning the present subject, there are some other works such as those by EWING and PRESS (1954), Y. SATÔ (1958), etc. However, these are the reports of distant observations, and only the values of earthquakes having great magnitude are mentioned. Thus, owing to different conditions, the values of the absorption coefficient in the above-mentioned reports are much smaller than those obtained by the writer during his recent research on volcanic earthquakes.

A noteworthy factor with regard to this problem is the values of α obtained by K. WADATI (1931) who succeeded in drawing a reliable $A-\Delta$ curve for the first time (see Table 6). The results of K. WADATI's study on some earthquakes that

Table 5. Constants on the formula $A = A_0 \Delta^{-1/2} e^{-\alpha \Delta}$.

		$A_0(\mu)$	$\alpha(\text{km}^{-1})$
Jan. 5, 1944	A-type	2.0×10^3	5.8×10^{-3}
Jan. 9, 1944	A-type	4.1×10^3	5.6×10^{-3}

fall within the magnitude range* of from 6.2 to 5.4, are shown in Table 6.

Table 6. Values of α (km^{-1}) (after K. WADATI).

size	earth- quakes	M	$\Delta=200$ km	400 km	600 km	800 km
large	5	6.7, 6.7, 6.2, 6.2, 5.9	7.1×10^{-3}	4.6×10^{-3}	3.9×10^{-3}	3.4×10^{-3}
medium	7	6.2, 6.0, 5.9, 5.8, 5.6, 5.5, 5.4	6.5 "	5.6 "	5.6 "	
small	3	5.6, 5.4, 5.4	8.5 "	7.2 "		

As was reported by the writer previously (Paper I), the magnitude (M) of the earthquakes associated with the recent volcanic activity of Volcano Usu was about 4.7 on January 5, and about 4.8 on January 9. The epicentral distance ranging from 25 km to 800 km, and the period of seismic waves are similar to those which Wadati dealt with. Hence, the two cases may be compared. The result has revealed that the values of α were almost identical for both cases, and therefore it is presumed that the nature of the A-type volcanic earthquakes of Usu is not different from that of the tectonic earthquakes (In this case, the observation values of the maximum amplitude were used as they are, because, if the ground coefficient at each observation point is taken into account, adjustment of the values becomes difficult).

4. Underground discontinuity around Volcano Usu and Mori

S'-waves, reflected S waves, observed

The seismogram at Mori Observatory which recorded the A-type earthquakes revealed various bodily waves consecutive to the S-waves, owing to the fact that the Mori-Usu path runs through the sea and that the arrival of the surface waves was considerably delayed.

Especially conspicuous bodily waves were tentatively named S'-waves. As shown

Fig. 5-a. Enlarged seismograms of Fig. 5-b.

Fig. 5-b. Seismograms at Mori Observatory in Hokkaido showing the P, S and S' related from the Moho.

Mori Observatory: $\varphi=42^{\circ}06'N$, $\lambda=140^{\circ}34'E$, $H=18.7$ m(a.s.l.)

Mori Wiechert seismograph

Magnification: $V_N=86$, $V_E=85$

Period: $T_{0N}=3.9$ sec., $T_{0E}=4.0$ sec.

in the upper diagram of Fig. 5, the amplitude of the E-W component surpasses the amplitude of the N-S component. The location of Mori Observatory is $S 27^{\circ} W$ from the hypocenter, as was already reported in the author's previous papers (I) and (II).

Judging from the predominance of the E-W components, these waves may have the character of SH-waves.

Depth of the discontinuous surface

However, the writer presumed that they are related to the discontinuity, on the basis of a model illustrated in Figs. 6-a, b and calculated the depth H of the surface of *discontinuity (A. MOHOROVIČIĆ, 1909). With regard to the velocity of S-waves, a large number of measurement data have been published, but the writer adopted in the present study the values by Prof. T. MATSUZAWA (1929).

For the calculation the depth of the hypocenter of A-type earthquakes was determined as 10 km, by referring to the previously obtained values (Section 1).

Fig. 6-a. Crustal model around Volcano Usu and the path of direct S-wave and refracted S'-wave.

The condition for θ is, $\sin \theta = \frac{v_s}{v_s^*} = \frac{3}{4}$.

Thus,

$$t^* - t = \left(\frac{2H - 10}{v_s \cos \theta} + \frac{54 - (2H - 10) \tan \theta}{v_s^*} \right) - \frac{\sqrt{54^2 + 10^2}}{v_s}$$

$$\therefore H = \frac{6}{\sqrt{7}} \left\{ (t^* - t) + \frac{29 + 5\sqrt{7}}{6} \right\},$$

was obtained. The result is tabulated in Table 7.

The mean value of the depth to the surface of discontinuity becomes

$$Hr_{(mean)} = 25.2 \text{ km}$$

Fig. 6-b. Crustal model around Volcano Usu and the path of direct S-wave and reflected S'-wave.

On the other hand, as the amplitude of S'-waves is comparable to S-waves, S'-waves are thought to be the transverse waves reflected by the base of the discontinuity (Fig. 6-b). Presuming such a case, the writer obtained the depth of the base H_t as shown in Table 7. And the mean value of H_t is obtained as $H_{t(mean)} =$

25.0 km, which is nearly equal to the result calculated by assuming S'-wave to be reflected transverse waves.

Table 7. Depth of the discontinuous layer around the Volcano Usu:

H_l : (S' as reflected wave)

H_r : (S' as refracted wave)

Date	t^*-t	H_l	H_r
1944	sec	km	km
Jan. 2	5.4	28.0	28.1
"	3.7	24.1	24.2
"	3.8	24.3	24.5
"	3.1	22.4	22.9
3	4.1	25.0	25.2
"	3.9	24.6	24.7
17	4.6	26.3	26.3
18	4.9	27.0	27.0
Feb. 1	4.1	25.1	25.2
24	3.5	23.5	23.8
mean value		25.0	25.2

TAKEO MATSUZAWA (1959), in the course of his observations of seismic explosion recognized a discontinuous layer at the depth of 20 to 25 km in northeastern Japan. And the depth of the discontinuity $H=22\sim 23$ km was obtained at Hokoda in northeastern Japan by the Explosion Group.* It is noticeable that the writer's value is approximately equal to this.

For Suggestion

In the previous case, the S' -wave was treated as a refraction waves of the S -wave, and $V_s=3.0$ km/sec and $V_s^*=4.0$ km/sec were adopted as the velocity of the transverse waves. The writer calculated for another case where $V_s=3.58$ km/sec, $V_s^*=4.44$ km/sec. These values were applied to the Hokoda Explosion by The Research Group for Explosion Seismology (1959). The result shows that the depth of the MOHOROVİČIĆ discontinuity H is 26.2 km.

The earthquake of January 9 seems to be related with the Mohorovičić discontinuity.

In the earthquakes of January 9, the depth of the hypocenter obtained from the travel-time was $H=20$ odd km, as was shown in Fig. 8 (See T. KIZAWA 1957, 1959). This fact suggests that these earthquakes were caused by the activity in the discontinuity (Moho layer) unlike other A-type earthquakes. The result of the writer's study, as was reported also in Parts I and II of this series of papers, implies that the earthquakes are related to the immigration and activity of a magma, and shows that, as time approached to the eruption, the depths of hypocenter became shallower gradually.** (See T. KIZAWA 1957, 1959). That is to say, the distribution of the initial motions of the P-waves were uniform through January and February as shown in Fig. 7, whereas the earthquakes of January 9 which probably occurred near the discontinuity showed a marked difference, for "compressional" waves and "dilational" waves are reversely distributed, as Fig. 7-b indicates. This is a noteworthy phenomenon.

From the fact that the values of initial motions at Mori are always small, it can be assumed that a nodal line runs through the vicinity of Mori. Although the data from only three observation points are insufficient for any definite conclusion, we will notice that the nodal lines drawn on Fig. 7 adequately coincide with the Ousu-Kousu tectonic line and another tectonic line intersecting the former nearly at right

* The Research Group for Explosion Seismology; Observations of Seismic Waves from the Second Hokoda explosion (1959), Bull. Earthq. Res. Inst. 37, 495-508.

** cf. section 1, Fig. 1

Depth of focus $H=12$ kmDepth of focus $H=11.1$ kmDepth of focus $H=10$ km

(a)

Depth of focus $H=25$ km

(b)

Fig. 7. Distribution maps of initial motion of P-waves in the Usu volcanic earthquakes, showing the so-called nodal lines (broken lines) and the direction of Ousu-Kousu tectonic line (Solid lines).

solid dots: Compressional wave

open dots: Dilatational wave

(For determination of the representation of nodal lines, more data would be required. The present representation is a tentative one.)

angles.

Prof. KENZÔ SASSA (1935-1936) pointed out in his valuable study of the volcanic activity of Volcano Aso (1932-1933) that the distribution of the initial motions near the volcano can be expressed by Prof. SHIDA's "crack type".

Discussion

The depth of the hypocenters of the earthquakes that occurred during the activity of Showa Shinzan is really interesting. In the early stage of the activity, from December 1943 to January 1944, the magma lay at the depth of 10 km underground, but in July 1944, the early stage of explosion and upheaval at Fukaba, the magma rose by 1 to 4 km (T. MINAKAMI and others, 1951). There is another point worth attention, that is, the depth of the hypocenter of the earthquakes of January 9 was 20 odd km which was obtained from the travel-time as shown in Fig. 8, whereas

the records of the reflection waves S' suggest the existence of a discontinuity (Moho plane?) at an average depth of 25 km.

Why none of the forerunning earthquakes has the hypocenter as deep as 25 km or more? The fact that the new lava of Showa Shinzan (like the cases of Ousu and Kousu) is extremely acidic containing about 70% SiO_2 , implies that the lava was not directly derived from the layer of such basic rocks as basalt or peridotite beneath the Moho layer, and that a basaltic magma may have formed a magma chamber at a depth of about 10 km and dissolved the sialic crust and thus became acidic.

When the magma of such depth commenced its activity, it would cause earthquakes having the hypocenter at about 10 km (although it is possible that the magma is connected with other magma beneath the Moho layer at 25 km, so that the deep-seated magma causes earthquakes). Thus, one need not assume an especially resistant layer at about 10 km through which the deep-seated magma rises causing earthquakes. If the above assumption were not correct, then the seismograph should have recorded the earthquakes occurring at much greater depth than the seat of the magma, but we have no such records. The existence of a magma chamber or reservoir may be open to discussion. However, much of andesitic lava is supposed to have resulted from the magma's assimilation of the crust, and it cannot be considered to have come up from a deeper place at the time of the activity. Therefore, in the case of Showa Shinzan, it is highly plausible that a reservoir of andesitic magma occurs at a depth of about 10 km, and the magma, with its fluidal movement and changing volume, brings about the initial earthquakes. It is also possible that the magma is connected with other magma in a deeper place, and both of them work together. Considering that the volcanic activity of the Chokai and the Norikura volcanic zones belong to this type, as T. ISHIKAWA (1959) maintains, the diversified lithologic characters of lavas may be explained.

The writer hopes to have an opportunity in future of discussing the mechanism of occurrence of earthquakes affording sufficient data.

5. Earthquakes and ground upheaval accompanying the birth of Showa-Shinzan

Introduction

Volcano Usu facing Lake Toya was strikingly active during the period from December 28, 1943 to October 1, 1945,

Fig. 8. Time-distance relation of the earthquake on Jan. 9, 1944. The travel time curve is by K. WADATI, S. SAGISAKA and K. MASUDA (1933).

Fig. 9. Activities of the period that formed the new dome "Showa-Shinzan" (Dec. 28, 1943-Oct. 1, 1945).

accompanied by such marked phenomena as earthquakes, eruptions and upheaval of the ground. The activity is illustrated in Fig. 9.

The seismographs at Sapporo, Mori and Muroran Observatories recorded this volcanic activity. Besides the above records, there is the Mimatsu diagram (1948) which diagrammatized the profile of the Showa-Shinzan according to the macroscopic monthly observations. On the basis of these data the writer analyzed and studied the following points:

- a. Time variations of the frequency of A-type earthquakes
- b. Time variations of the amplitude of A-type earthquakes
- c. Calculation of earthquake energy
- d. Calculation of energy of ground upheaval
- e. Relation between B-type earthquakes and ground upheaval
(analysis of the B-type earthquakes)

a. Time variations of the frequency of earthquakes

Fig. 10. Frequency-distribution of the Usu earthquakes from Dec. 1943 to Oct. 1945 as observed at Sapporo.

Fig. 10 shows the monthly totals of the time variations of earthquakes observed at Sapporo. All earthquakes, large and small, were counted (see also Table 8-a, b). A detailed consideration of the variations will be stated later.

b. Time variations of the amplitude of earthquakes

The earthquake waves were classified into several stages according to their amplitude. Time variation of the number of earthquakes in each stage is illustrated in Figs. 11, a and b.

When the A-type earthquakes were studied in detail (see Figs. 11-a and 12), it was known that the activity began with numerous minor earthquakes, which gradually became larger until January 9 when an earthquake of the largest scale occurred.

In the B-type earthquakes, as Fig. 11-b shows, an interesting phenomenon is noticed. That is, the number of earthquakes of each stage shows a pyramidal distribution, with the peak of the activity at the end of May 1945. While the occurrence of the A-type earthquakes is extended over about six months, the B-type earthquakes of a smaller scale are larger in number, being extended for a long period of more than a year. This is a noticeable difference between the A-type and the B-type earthquakes.

c. Calculation of earthquake energy

The earthquake energy was calculated by obtaining the value of magnitude M first, and then by using the formula of Gutenberg-Richter.

Tentatively, the magnitude M was obtained from Tsuboi's formula (1954)

Fig. 11. Frequency of the earthquakes severally graded by their amplitudes. (the axis of abscissa is the number of divided ten days from Sept. 13, 1944.)

Fig. 12. Amplitude-distribution of the A-type (N-comp.) earthquakes from Dec. 30, 1943 to Jan. 13, 1944 as observed at Sapporo.

Showing the beginning of A-type earthquakes and appearance of the largest earthquake on Jan. 9, 1944.

$$M = 1.73 \log \Delta + \log A - 0.83,$$

and earthquake energy E from Gutenberg-Richter's formula (1956)

$$\log E = 9.4 + 2.14 M - 0.054 M^2,$$

where A is the maximum amplitude of the earthquakes at the observation point located at Δ km in epicentral distance, and the unit is in micron.

i) Total energy of earthquakes

From the observation data at Sapporo total energy of earthquake was calculated

Fig. 13. Cumulation of energy of earthquakes.

as follows for the A-type earthquakes that occurred before the eruptive activity and for the B-type earthquakes that occurred after the eruption.

Total energy of A-type earthquakes: 11.5×10^{18} ergs.

Total energy of B-type earthquakes: 6.09×10^{18} ergs.

Logarithms of cumulative energy of A and B-type earthquakes with the stream of time are plotted in Fig. 13.

The total energy of the A-type earthquakes is about twice that of the B-type

earthquakes.

ii) Time variation of earthquake energy

In order to know the time variation of B-type earthquake energy, the data of about one month were used and a daily mean of the energy variation was diagrammatized.

d. Calculation of energy of ground upheaval

In order to obtain the energy of ground upheaval, the writer calculated the amount of increase in the potential energy against gravity, or the work to be done to raise the lava dome. For the calculation, various assumptions must be made. It should be kept in mind, therefore, that the resultant values represent only the relative changes and rough estimates.

In the first place it is assumed that the moving part of the strata to be considered in calculation is located above sea level, by seeing the movement of ground upheaval.

As the figure shows, the liquid magma underground rises to the sea level and pushes up the mountain body being formed on it. The work accomplished by the magma is calculated as the energy of upheaval (amount of increased potential energy against gravity).

Fig. 14. Distribution of energy of B-type earthquakes.

Fig. 15. Imagined motion of magma.

Fig. 16. A model for the calculation of increased potential energy by the upheaval of the roof mountain.

The mechanism of the upheaval is assumed as indicated in Fig. 16.

Suppose a base level on which lies the strata to be taken into consideration in calculation of the work done to raise the lava dome, and suppose that a surface element with its horizontal section of ds , which is initially at a height of H from the base level, is uplifted by h . The volume increased by the uplift is continuously pushed up from under the base level.

When the surface is raised by x ($0 \leq x \leq h$), the work done for raising the volume $(H+x) ds$ as much as dx is $\rho g (H+x) ds dx$. Then the work dw for raising the surface element from $x=0$ to $x=h$ becomes

$$dw = \int_0^h \rho g (H+x) ds dx = \rho g h \left(H + \frac{h}{2} \right) ds,$$

where g is the acceleration of gravity. Thus the whole work W for the upheaval of area S becomes

$$W = \int_S dw = \int_S \rho g h \left(H + \frac{h}{2} \right) ds,$$

where $h \cdot ds$ is the upraised volume.

In actual calculations, the Mimatsu diagram (1949) which is the record of topographic observations for about one month, was used, and the mountain body was assumed as a semi-rotational body (the entire mountain body is divided into two parts, and each part is thought to rotate as much as π). The upraised volume was obtained by letting the transverse area of the uplifted part during each period rotate as much as π around the center O . As Fig. 17 shows in detail, the part marked with oblique lines rotates around O_2 , and the other part around O_1 , both as much as π , and respectively to the right and to the left. The base level was settled at sea level, as already mentioned. Thus, by subdividing the transverse area of the uplifted part into several portions and by using the symbols ΔS_i for the transverse area i , r_i for the perpendicular line from the center of the area to the median axis, and H_i for the height from the sea level, the energy of upheaval can be calculated by the following formula:

$$W = \sum_i \pi \rho g r_i H_i \Delta S_i.$$

Fig. 17. Calculation of potential energy increased by the new-dome-formation.

Fig. 18-a is a cumulation graph of upheaval energy, and the daily variation of mean upheaval energy is illustrated in Fig. 18-b.

Fig. 18-(a). Cumulation of potential energy. (May. 25, 1944–Oct. 1, 1945)

Fig. 18-(b). Distribution of the daily averaged grown potential energy for the ground upheaval.

e. Relation between B-type earthquakes and ground upheaval (discussion for analysis of the B-type earthquakes)

i) Frequency and energy of the earthquakes

Fig. 19. Activities of the period that formed the new dome "Showa-Shinzan".

The B-type earthquakes culminated toward the end of May, 1945, when the maxima of amplitude and energy were recorded. However, the frequency of earthquakes was largest in February of that year, although the number was decreased at the supposed peak. From this fact, it is known that the number and the energy of earthquakes are not proportional.

ii) Relation between the frequency of earthquakes and the uplifted part

During the period when the number of earthquakes is supposed to become largest, the dome is active. In actuality, however, the number of earthquakes is diminished when the activity of the dome culminates. During the active period of the dome the scale of the earthquakes is smaller, as indicated in Fig. 20. These phenomena suggest the following: Numerous and minor earthquakes associated with the dome's activity have tendency to occur consecutively when the activity of the dome is suppressed, so that the earthquakes may not be caused by the dome's activity only.

iii) Energy of ground upheaval and that of earthquakes

Part ① in the above figure indicates that an extensive area centering at the

crater was upraised by a great energy. However, the seismic waves recorded by the seismograph were very few. Besides, the quantity of accumulated volcanic bombs due to eruptions is unknown. Hence, discussion on the upheaval is difficult.

Part ③ corresponds to the period of marked upheaval of the dome. As a matter of course, the energy of upheaval increased. But the energy of seismic waves was at a stand-still. In the culminant period of the B-type earthquakes, i.e., in May, the energy of seismic waves is thought to show natural and smooth changes. Therefore, the above-mentioned stagnancy energy may be interpreted as the result of the energy being consumed in the form of upheaval energy. The energy of underground activity that brings about various volcanic phenomena, such as earthquakes, ground upheavals and eruptions, seems to come from a same source. In other words, there is no separate source of energy for earthquakes only, or for ground upheavals, and the like, but the energy exists as one and the same source, from which each of all these phenomena is produced according as the surrounding conditions vary.

Part ③ indicates that the energy of seismic waves gradually declined after its culmination. It is suggested that the volcanic activity was going to terminate, whereas the upheaval energy increased owing to the new uprising movement at the foot of the mountain. This uprising movement, as in the case of ①, is not accompanied by seismic waves. This phenomenon may be explained by assuming a volume expansion due to the falling temperature. Otherwise, it can be explained as follows.

After the volatile components of the magma were volatilized out during the previous eruption, the markedly viscous magma, characteristic of Volcano Usu, was moved by the last underground energy and advanced to the surrounding field where it could conduct a relatively free movement which was not large enough to cause seismic waves. This does not go beyond an imagination. At any rate, in this case the underground energy for the formation of Showa Shinzan after the eruptive

Fig. 20. Partial upheaval around the new dome "Showa-Shinzan".

Fig. 21. Relation between the energy of B-type earthquakes and the potential energy for the upheaval of lava dome.

Table 8. The daily frequency of the earthquake swarms of more than 3 microns of maximum amplitude observed by seismographs at the Mori ($\Delta=54$ km) and Sapporo Observatory ($\Delta=69$ km). during December, 1943—September, 1945.

A type earthquakes: Dec., 1943—Apr., 1944 B type earthquakes: Sept., 1944—Sept., 1945

Date	Mori	Sapporo	Date	Mori	Sapporo	Date	Mori	Sapporo	Date	Mori	Sapporo	Date	Mori	Sapporo
1943			1944			17-30								
Dec. 28	1	0	Mar. 1	1	0	1944			23	1	2	11		2
29	18	5	2	1	0	Oct. 1	0		24		3	12		2
30	42	18	3		0	2	0		25	0		13		2
31	22	12				3	0		26	2		14		1
1944			4	1	0	4	0		27	1		15		2
Jan. 1	23	7	5	2	0	5	1							
			6	0	0				28	1		16		3
2	18	8	7	1	0	6	3		29	0		17		3
3	28	11	8	1	0	7	1		30	5		18		1
4	15	5				8	0		1944			19		1
5	11	8	9		0	9	0		Dec. 1	2		20		0
6	6	2	10		1	10	0	0	2	0				
			11		0	11	0	0				21		1
7	5	4	12	1	1	12	1		3	1		22		2
8	5	3	13-31		0	13	1		4	1		23		2
9	6	4	1944			14	0	0	5	0		24		4
10	5	2	Apr. 1	0	0	15	0	1	6	1		25		3
11	7	2							7	0				
			2	0	0	16		2	8	0		26		1
12	4	0	3		0	17	1		9	1		27		4
13	3	1	4	0	0	18	0	0	10	1		28		3
14	4	1	5	0	1	19	1		11	1		29		1
15	5	2	6-14	0	0	20		2	12	3		30		4
16	0	0								0				
			15	1	0	21		0	13	3		31		1
17	2	1	16-30		0	22	1		14	2		1945		
18	2	2	1944			23	0		15	2		Feb. 1		3
19	0	0	May 1	0	0	24	1	2	16	1		2		3
20	0	0	2		0	25	0	0	17	2		3		2
21	2	2	3	0	0							4		1
						26-31		0	18	0		5		1
22	2	1	4	0	0	1944		1	19	1		6		1
23	0	0	5		0	Nov. 1	0		20	2		7		3
24	0	0	6		0	2	1		21	1				
25	3	1	7	0	0									
26	0	0	8	1	0	3	3		22	3		8		5
						4	1		23	2		9		2
27	0	0	9	0	0	5	0		24	2		10		2
28	0	0	10		0	6	0		25	3		11		1
29	0	0	11-31		0	7	1		26	2		12		3
30	1	0	1944											
31	0	0	June 1	0	0	8	0		27	0		13		2
			2	1	0	9	1		28	1		14		1
1944						10	0		29	2		15		3
Feb. 1	1	1	3		0	11	0		30	2		16		2
2	1	1	4		0	12	0		31	2		17		3
3	1	1	5-30		0				1945					
4	0	0	July 1-16		0	13	0		Jan. 1	1	2	18	1	1
5	0	0	17	1	0	14	1		2	1	2	19		2
						15	0		3	2	2	20		4
6	0	0	18-31		0	16	0		4	3		21		3
7	2	1	Aug. 1-31		0	17	0		5	1		22		1
8-22	0	0	Sept. 1-12		0									
23	1	1				18	0		6	2		23		3
24	2	2	13		1	19	1		7	2		24		0
			14		1	20	0		8	2		25		1
25-29	0	0	15		1	21	2	1	9	3		26		3
			16		1	22		0	10	3		27		1

—Continued—

Date	Mo-ri	Sap-poro	Date	Mo-ri	Sap-poro	Date	Mo-ri	Sap-poro	Date	Mo-ri	Sap-poro	Date	Mo-ri	Sap-poro
1945 Mar. 28		3												
1		4	18		2	5	1	4	23	1	3	10	1	1
2		3	19		3	6		1	24	1	2	11		0
3		2	20		3	7		3	25	1	2	12		0
4		1	21		1	8		3	26	0	0	13	1	1
			22		4	9		3	27	2	2	14	0	0
5		5	23		0	10		2	28	1	1	15		0
6		3	24		5	11		2	29	0	2	16	0	0
7		3	25	2	3	12		1	30	2	2	17	1	1
8		1	26		3	13		2	31	0	0	18		0
9		1	27		3	14		1	1945 Aug. 1	1	1	19	0	0
10		4	28		3	15		4	2	1	0	20	1	1
11		0	29		2	16		2	3	1	1	21		0
12		2	30		3	17		1	4	1	1	22		0
13		2	1945 May 1		1	18	1	2	5	1	1	23	0	0
14		4	2		3	19	1	2	6		1	24	0	0
15		2	3		2	20	1	2	7	1	2	25		0
16		5	4		3	21		2	8	1	1	26		1
17		1	5		2	22	1	2	9	1	1	27		0
18		5	6		2	23	1	1	10	2	0	28		0
19		2	7		3	24		0	11	2	1	29		0
20		3	8		6	25	0	1	12		2	30		0
21		3	9		3	26	1	2	13		1			
22		5	10		2	27		2	14		1			
23		0	11		0	28	1	1	15	0	0			
24		1	12		1	29	2	2	16	1	1			
25		2	13		2	30	1	1	17	1	2			
26		2	14		3	1945 July 1		1	18	0	0			
27		0	15	3	3	2		1	19		3			
28		4	16	1	2	3	2	2	20	0	0			
29		3	17		2	4		1	21	1	1			
30		2	18	1	1	5		5	22	1	1			
31		3	19		1	6		0	23		0			
1945 Apr. 1		1	20		3	7	1	2	24	1	1			
2		2	21	1	1	8	1	3	25		0			
3		2	22		1	9	1	2	26		0			
4		2	23		1	10	1	2	27	0	0			
5		1	24		3	11		0	28	1	1			
6		1	25		3	12		2	29		0			
7		2	26		2	13	1	1	30		1			
8		0	27	1	1	14	2	1	31		0			
9		4	28		3	15	1	0	1945 Sept. 1	1	1			
10		2	29	1	1	16	2	2	2		1			
11		5	30		2	17	1	0	3	0	0			
12		2	31	1	3				4	1	1			
13		1	1945 June 1			18	1	1	5	0	0			
14		2	2		3	19	0	0	6	1	1			
15		2	3		2	20	1	1	7	0	0			
16		0	4		2	21	1	4	8	0	0			
17		3		1	1	22	0	1	9	0	0			

activity cannot be considered to show a gradual decrease toward the end. As a matter of fact, no final conclusion could be reached before a synthetic study is made on the nature of magma, the mechanism of volcanic activity, etc.

6. Two New Phases observed at Mori Observatory*

Introduction

The volcanic activity of Volcano Usu from 1943 to 1945, which gave birth to Showa Shinzan, was accompanied by numerous earthquakes. Among the seismic waves recorded then, there were observed two new phases having remarkably slow group velocities. These special phases were detected only when the propagation path ran through the sea. The writer tentatively named them the third and fourth phases, respectively. They were recorded by the Wiechert seismograph at Mori Observatory which is situated at a place to which the direct path from the hypocenter is mostly through shallow sea water.

Fig. 22. Cross section of the path between hypocenter (Showa-Shinzan) and Mori Observatory and patterns of the A-type and the B-type earthquake recorded at Mori Observatory.

Mode of occurrence of 3rd and 4th phases

Mori Observatory is located at $\lambda : 140^{\circ}34'E$ and $\phi : 42^{\circ}06'N$, $\Delta = 54$ km, $S 27^{\circ}W$ of Volcano

Usu, the hypocenter. As Fig. 22 shows, most part of the propagation path lies in shallow water. The two new phases did not occur when the seismic waves were propagated over a land path, as shown in Fig. 23. The waves form of the third and the fourth phases somewhat differed between the A-type earthquakes that occurred prior to the eruptions (December 1943-April 1944) and the B-type earthquakes associated with the lava dome upheaval after the eruptions (September 1944-October 1945), but the lapse of time from the P-waves was nearly uniform in all earthquakes recorded throughout the active period (see section 2 of this report). The seismograms at Mori Observatory which recorded about 1,400 earthquakes revealed that the wave forms of the two phases were identical even to the details; the likeness was especially striking in the B-type earthquakes. The 3rd phase was distinctively observed in the A type earthquakes, but the occurrence of the 4th phase was less frequent and on a minor scale. In the B-type earthquakes, on the other hand, both phases were observed quite distinctively.

Such differences as mentioned above may be due to the different depths of the hypocenters of A-type and B-type earthquakes, because the hypocenter of the A-type earthquake is considered to lie at about 10 km below the ground surface

* TAKASHI KIZAWA, 1960.

Fig. 23. Seismograms at Mori, Sapporo and Muroran, showing the 3rd phase that appeared only on the water path(Usu-Mori). In these figure the mark A shows the point where the 3rd phase seems to appear. Interval of time check marks is one minute.

The group velocity of the 3rd phase where the maximum amplitude appears is about 0.6 km/sec.

(Section 1) and that of the B-type earthquakes is supposed to occur at a very shallow depth, i.e. less than 1 km (See the author's previous papers).

The examples of seismograms of A-type and B-type earthquakes are illustrated in Fig. 24 to show the differences of the two types and the mode of occurrence of the 3rd and 4th phases.

Fig. 24. Seismograms of earthquakes recorded at Mori Observatory, Hokkaido.
Mori Wiechert seismograph. Interval of time check marks is one minute
Magnification: $V_N=83$, $V_E=82$
Period: $T_{0N}=4.1$ sec. $T_{0E}=4.2$ sec

Dispersion curves of Rayleigh waves

For explanation of the two new phases introduced above, the writer treated them as Rayleigh waves* and pursued the Rayleigh-wave dispersion. This work** was done using the I.B.M. 704 electronic computer in co-operation with Mr. R. Yamaguti.

We first assumed two liquid layers, a water layer and a sedimentary layer, both of which overlie a semi-infinite solid medium.

Then, assuming that the velocity of compressional wave in the sedimentary layer is lower than that in the water layer, the dispersion curves of Rayleigh waves were calculated for various cases.

As is already reported by the writer (1958), the analytical study of the wave trains of the two new phases disclosed that the phases have characters in common with the Rayleigh wave.

The results obtained from the IBM 704 electronic computer for the above model are shown in Fig. 37. (See also Tables 10, 11, 12)

*Cf.: Pekeris, C. L. (1948, 1958, 1959); Press, F. and others (1950, 1951).

**Cf.: T. Kizawa and R. Yamaguti (1960).

However, these results failed to coincide with the results of actual observation which showed that the velocity and the period of 3rd phase are $V=0.6$ km/sec and $T=ca. 2$ sec, as shown in Table 13. Thereupon, the writer considered another case "liquid-solid-solid" for explanation of the 3rd and 4th phases.

The case of (liquid—solid—solid) structure

In this case, the second, or sedimentary, layer is treated as a solid, and the symbols used in the consideration are shown below.

— Free surface — Water layer Sedimentary layer Semi-infinite solid medium	0 ↓ Z	Velocity		Density	Thickness	Rigidity → X
		Compressional	Shear			
		C_1		ρ_1	H_1	
		C_2	C_{2s}	ρ_2	H_2	μ_2
		C_3	C_{3s}	ρ_3		μ_3

The calculations were made by a method similar to that employed by Y. SATO and R. YAMAGUTI (1959) to obtain the "velocity equation of the Love waves propagated in multi-layered media".

When the displacement potential of each layer is considered as follows,

$$\phi_1 = \{A_1 \cos \tilde{\alpha}_1 z + B_1 \sin \tilde{\alpha}_1 z\} \exp \{ipt - ifx\}$$

$$\phi_2 = \{A_2 \cos \tilde{\alpha}_2 z + B_2 \sin \tilde{\alpha}_2 z\} \exp \{ipt - ifx\}$$

$$\psi_2 = \{C_2 \cos \tilde{\beta}_2 z + D_2 \sin \tilde{\beta}_2 z\} \exp \{ipt - ifx\}$$

$$\phi_3 = F_3 \exp \{-\alpha_3 z\} \exp \{ipt - ifx\}$$

$$\psi_3 = F_3 \exp \{-\beta_3 z\} \exp \{ipt - ifx\}$$

where

$$\alpha_k = f \sqrt{1 - (C/C_k)^2} = i \tilde{\alpha}_k, \quad (k=1,2,3)$$

$$\beta_k = f \sqrt{1 - (C/C_{ks})^2} = i \tilde{\beta}_k, \quad (k=2,3)$$

and C is the phase velocity. The wave length and period are expressed as $L = \frac{2\pi}{f}$ and $T = \frac{2\pi}{p}$, respectively. Since the displacement and the stress are in the following relation:

$$\begin{cases} u = \frac{\partial \phi}{\partial x} + \frac{\partial \psi}{\partial z}, \\ w = \frac{\partial \phi}{\partial z} - \frac{\partial \psi}{\partial x}, \\ \begin{cases} xz = 2\mu \frac{\partial^2 \phi}{\partial x \partial z} - \rho p^2 \psi - 2\mu \frac{\partial^2 \psi}{\partial x^2}, \\ zz = -\rho p^2 \phi - 2\mu \frac{\partial^2 \phi}{\partial x^2} - 2\mu \frac{\partial^2 \psi}{\partial x \partial z}, \end{cases} \end{cases}$$

Fig. 25. Theoretical phase and group velocity of Rayleigh waves for the case of [liquid-solid-solid] structure when $H_2/H_1 = 3.40, 3.70$ and 4.20 . (See Table 14)
Group velocity was obtained by numerically differentiating the phase velocity.

the relation between the velocity and the period can be deduced through calculations which would satisfy the conditions at the respective boundaries. Calculations were done by the IBM 704 electronic computer.

Agreement of experimental data with theoretical curves

Trying the computation for several cases of the structure, the writer has obtained a result shown in Fig. 25 and Table 14, which explains the observation data of the

Table 9. A model of the structure adequately explained the observation data.

— Surface —			
(1) Water	$C_1=1.50$ km/sec		$\rho_1=1.00$ gm/cm ³
(2) Sediment	$C_2=1.04$	$C_{2s}=0.60$ km/sec	$\rho_2=1.80$
(3) Solid	$C_3=5.40$	$C_{3s}=3.00$	$\rho_3=2.70$

C_i ($i=1, 2, 3$): velocity of compressional wave

C_{is} ($i=2, 3$) : velocity of distortional wave

ρ_i ($i=1, 2, 3$): density of each layer

3rd and 4th phases. In this case, as shown in Table 9, the velocity of compressional waves in the sedimentary layer is assumed to be smaller than that in the water layer, and the value of poisson's ratio is assumed to be 0.25.

Referring to the Fig. 25, we can recognize that the branches of the fundamental mode and the higher mode in phase velocity approach to each other at their branch points as if two straight lines are crossing, and the curves of their group velocity intersect and present remarkable appearance of stationary states.

Then we have two striking velocities which show the existence of the 3rd phase and the 4th phase, i.e. the relation between the group velocity (U) and the period (T) obtained from the above theoretical curves in Fig. 25 is shown in Fig. 26 and Table 15 with good agreement with the observed data.

Examination

In the following the writer intends to examine the variation of the above situation under the different conditions of the sedimentary layer. The same cases except in the compressional wave velocity as the above are shown in Fig. 27, in which the velocity of compressional waves in the sedimentary layer is larger than that in the water layer. As will be easily seen, Fig. 28 is much different from the above results in Figs. 25 and 27. There is no appearance of the two remarkable group velocities. For reference, when the velocity C_{2s} of distortional waves in the sedimentary layer is larger or smaller than that of the above cases, the aspects are shown in Figs. 29, 30 and 31.

After all paying attention to the nature of the sedimentary layer, assuming the velocity of compressional waves of the sedimentary layer to be smaller than that of the water layer, and letting the water layer and the 2nd layer to be adequately thick, we have a suitable result which explains the observation data. Whether or not the results of the writer's experiment represent the actual crustal structure cannot be judged at the present stage of our knowledge, but it can be said at least that the model is most favorable for the abovementioned hypothesis.

Although reports on the character of the sedimentary layer have been scanty it

Fig. 26-(a), (b). Agreement of experimental data with theoretical curves. Observed group velocity of 3rd phase in A-type earthquakes compared with the theoretical Rayleigh waves dispersion. (cf. Fig. 24-(a) and Table 13-(a))

Fig. 26. Agreement of experimental data with theoretical curves. Experimental data of the 3rd and 4th phases of B-type earthquakes compared with the theoretical curves.
(cf. Fig. 24-(b) and Table 13-(b))

Fig. 27. Theoretical phase and group velocity of Rayleigh waves for the case of (liquid—solid—solid) structure (see Table 14 a, b). Group velocity of the Fig. 27 (a) and (b) was obtained by numerically differentiating the phase velocity.

Fig. 28. This is the case appearing no such a striking phenomenon as seen in Figs. 25 and 27, when the velocity of compressional wave in the sedimentary layer is larger than that of the water layer.

Fig. 29. Theoretical phase and group velocity of Rayleigh waves for the case of [liquid-solid-solid] structure. Group velocity was obtained by numerically differentiating the phase velocity.

(a)

(b)

Fig. 30. Theoretical phase and group velocity of Rayleigh waves for the case of [liquid-solid-solid] structure. (see Table 17)

Group velocity was obtained by numerically differentiating the phase velocity.

Fig. 31. Theoretical phase and group velocity of Rayleigh waves for the case of [liquid-solid-solid] structure.

Group velocity was obtained by numerically differentiating the phase velocity.

is fully understood that the role of the layer is very important in solving the present problem. And in the future the existence of the sedimentary layer will be significant to research as on seismic waves.

The writer intends to discuss the amplitude and other factors at a future opportunity.

Consideration

The writer drew the dispersion curves of Rayleigh waves of higher mode for the same model of Figs. 25 and 27. The computation was made up to the 3rd shear mode. The results are shown in Fig. 32 and Table 16. They revealed, as was ex-

Fig. 32. Theoretical phase velocity of Rayleigh waves in the first four modes.

pected, that the 2nd and 3rd shear modes did not show such a unique phenomenon as is seen in the 1st shear mode (see Figs. 25 and 27). Thus, it can be concluded that the case illustrated in Figs. 25 and 27 is the most appropriate for the explanation of the above-mentioned phenomenon.

Problems for Future Study

—A few phases detected in the earthquakes during the Sakurajima volcanic activity—

Sakurajima in Kagoshima Prefecture, Kyushu is an active volcano. Kagoshima Local Meteorological Observatory (L.M.O.) is situated at $\Delta=10$ km from Sakurajima across Kagoshima Bay. Hence, from the viewpoint of location, the relation between the volcano and this observatory is similar to that between Volcano Usu and Mori Observatory. The writer, in the course of the study of the seismograms of the Sakurajima volcanic activity as recorded at Kagoshima L.M.O., discovered a few phases which seem to have originated from the same cause as in the case of Volcano Usu.

Fig. 33 shows the seismogram of 1939, and Fig. 34 that of 1946. Three phases represented by a, b and c in both figures were distinctly observed in the *E-W* component which is much stronger than that of the *N-S* component. Throughout the whole period of the volcanic activity, in both 1939 and 1946, these phases appeared

Fig. 33. Seismograms of the earthquakes in relation to Sakurajima volcanic activity in 1939, recorded at Kagoshima L.M.O., showing new phases a, b and c.

Fig. 34. Seismograms of the earthquakes in relation to Sakurajima volcanic activity in 1946, recorded at Kagoshima L.M.O., showing new phases a, b and c.

with an identical lapse of time after the time of arrival of P. Time deviation is noticed between the phases in *N-S* component and those in *E-W* component. It is also noticeable that the amplitude of each phase greatly differs between the two groups. These phases are interesting because they involve some factors that may be related to the mechanism of volcanic activity. The writer is now calculating the dispersion curves of the Rayleigh waves and the Love waves by using the IBM 704 electronic computer.

Supplement

With the help of the IBM 704 electronic computer, the dispersion curves of the Rayleigh waves can be drawn for oceanic models in general in the same way as for the "liquid-solid-solid" case.

As a preliminary step of the study of oceanic paths, the writer has been observing the Rayleigh waves propagating through the Pacific Ocean (T. KIZAWA, 1941). Comparison of the observation data with the results of the calculation gives the curves bearing a close resemblance as shown in Figs. 35-a,b (see also Tables 18-a and 18-b).

Fig. 35-a. Theoretical phase and group velocity of Rayleigh waves for oceanic path. Group velocity was obtained by numerically differentiating the phase velocity.

This problem has been studied by many researchers such as B. Gutenberg, C.F. Richter, W.S. Jardetzky and F. Press. According to their reports, the form of long-period dispersion curves does not vary greatly with the number of crustal layers, so that most of the observed values can be explained by the curves. In the great earthquake of Chile (T. KIZAWA, 1941), the period range was between 25 sec and 48 sec. Hence, if the thickness of the water layer of the Pacific Ocean is 4.5 km, the

Fig. 35-b. Agreement of experimental data with theoretical curves. Observed group velocity of Rayleigh waves for oceanic path from Chile to Japan compared with theoretical curves for the case. when $H_1=4.5$ km.

Fig. 36. Theoretical phase and group velocity of Rayleigh waves for oceanic path.

resultant curve will easily explain this, as Fig. 35-b shows.

A case of smaller period is another interesting problem (Fig. 36). Assuming the second layer to be a solid layer and the velocity of its compressional wave to be $C_2=5.0$ km/sec, and using the ratio of thickness $H_2/H_1 (=0.5 \sim 5.0)$ as a parameter, the writer found that the curves of the group velocity show intricate variations as the value of H_2/H_1

Table 10

Theoretical phase velocity of Rayleigh waves for the case of [liquid-liquid-solid] structure

(a) Fundamental mode

When: $\rho_2/\rho_1=1.50$ $\rho_3/\rho_1=2.70$ $C_2/C_1=0.53$ $C_3/C_1=3.60$ $C_{3s}/C_1=2.00$

C/C_1	L/H_1	C/C_1	L/H_1	C/C_1	L/H_1	C/C_1	L/H_1
$H_2/H_1=0.20$		1.75	44.855	1.60	54.050	1.45	63.694
1.80	21.973	1.70	38.500	1.55	50.866	1.40	60.476
1.75	14.509	1.65	35.041	1.50	48.127	1.35	57.439
1.70	12.176	1.60	32.620	1.45	45.659	1.30	54.496
1.65	10.918	1.55	30.694	1.40	43.352	1.25	51.642
1.60	10.049	1.50	29.029	1.35	41.167	1.20	48.830
1.55	9.362	1.45	27.529	1.30	39.061	1.15	46.059
1.50	8.773	1.40	26.131	1.25	37.006	1.10	43.308
1.45	8.243	1.35	24.806	1.20	34.993	1.05	40.564
1.40	7.749	1.30	23.527	1.15	33.005	1.00	37.810
1.35	7.280	1.25	22.281	1.10	31.031	0.95	35.036
1.30	6.826	1.20	21.059	1.05	29.058	0.90	32.224
1.25	6.381	1.15	19.852	1.00	27.083	0.85	29.353
1.20	5.941	1.10	18.652	0.95	25.089	0.80	26.394
1.15	5.502	1.05	17.455	0.90	23.070	0.75	23.306
1.10	5.060	1.00	16.253	0.85	21.006	0.70	20.024
1.05	4.612	0.95	15.041	0.80	18.879	0.65	16.414
1.00	4.154	0.90	13.810	0.75	16.659	0.60	12.180
0.95	3.683	0.85	12.552	0.70	14.296	0.55	6.070
0.90	3.196	0.80	11.253	0.65	11.696	$H_2/H_1=5.80$	
0.85	2.692	0.75	9.894	0.60	8.640	1.80	171.401
0.80	2.183	0.70	8.444	0.55	4.222	1.75	118.027
0.75	1.700	0.65	6.842	$H_2/H_1=4.20$		1.70	101.422
0.70	1.276	0.60	4.952	1.80	128.969	1.65	92.359
0.65	0.915	0.55	2.281	1.75	88.790	1.60	86.030
0.60	0.594	$H_2/H_1=2.60$		1.70	76.288	1.55	80.994
0.55	0.254	1.80	86.492	1.65	69.472	1.50	76.629
$H_2/H_1=1.00$		1.75	59.539	1.60	64.720	1.45	72.690
1.80	43.891	1.70	51.129	1.55	60.920	1.40	69.043
1.75	30.049	1.65	46.551	1.50	57.632	1.35	65.560
1.70	25.732	1.60	43.359	1.45	54.681	1.30	62.201
1.65	23.382	1.55	40.802	1.40	51.923	1.25	58.939
1.60	21.742	1.50	38.604	1.35	49.307	1.20	55.747
1.55	20.437	1.45	36.616	1.30	46.779	1.15	52.581
1.50	19.313	1.40	34.766	1.25	44.330	1.10	49.439
1.45	18.297	1.35	33.009	1.20	41.918	1.05	46.308
1.40	17.353	1.30	31.314	1.15	39.535	1.00	43.170
1.35	16.456	1.25	29.668	1.10	37.177	0.95	40.002
1.30	15.592	1.20	28.048	1.05	34.818	0.90	36.794
1.25	14.750	1.15	26.451	1.00	32.451	0.85	33.516
1.20	13.923	1.10	24.864	0.95	30.070	0.80	30.141
1.15	13.106	1.05	23.280	0.90	27.653	0.75	26.618
1.10	12.292	1.00	21.691	0.85	25.185	0.70	22.873
1.05	11.480	0.95	20.089	0.80	22.641	0.65	18.758
1.00	10.663	0.90	18.465	0.75	19.989	0.60	13.932
0.95	9.838	0.85	16.804	0.70	17.167	0.55	6.976
0.90	8.999	0.80	15.093	0.65	14.062	$H_2/H_1=5.00$	
0.85	8.137	0.75	13.306	0.60	10.418	1.80	150.195
0.80	7.246	0.70	11.400	0.55	5.154	1.75	103.419
0.75	6.309	0.65	9.302	$H_2/H_1=3.40$		1.70	88.851
0.70	5.305	0.60	6.830	1.80	107.749	1.65	80.917
0.65	4.196	0.55	3.266	1.75	74.177	1.60	75.372
0.60	2.911	$H_2/H_1=1.80$		1.70	63.726	1.55	70.946
0.55	1.271	1.80	107.749	1.65	58.022	1.50	67.134
$H_2/H_1=1.80$		1.75	74.177				
1.80	65.245	1.70	63.726				
		1.65	58.022				

(b) Higher mode

When: $\rho_2/\rho_1=1.50$ $\rho_3/\rho_1=2.70$ $C_2/C_1=0.53$ $C_3/C_1=3.60$ $C_{3S}/C_1=2.00$

C/C_1	L/H_1	C/C_1	L/H_1	C/C_1	L/H_1	C/C_1	L/H_1
$H_2/H_1=0.20$		1.75	10.987	1.60	15.919	1.45	19.643
1.80	3.337	1.70	10.276	1.55	15.238	1.40	18.790
1.75	3.022	1.65	9.750	1.50	14.590	1.35	17.947
1.70	2.830	1.60	9.302	1.45	13.966	1.30	17.112
1.65	2.675	1.55	8.892	1.40	13.354	1.25	16.280
1.60	2.534	1.50	8.504	1.35	12.751	1.20	15.447
1.55	2.398	1.45	8.129	1.30	12.152	1.15	14.611
1.50	2.265	1.40	7.762	1.25	11.555	1.10	13.771
1.45	2.132	1.35	7.399	1.20	10.958	1.05	12.924
1.40	1.997	1.30	7.039	1.15	10.359	1.00	12.064
1.35	1.859	1.25	6.680	1.10	9.756	0.95	11.191
1.30	1.715	1.20	6.321	1.05	9.148	0.90	10.300
1.25	1.564	1.15	5.960	1.00	8.531	0.85	9.382
1.20	1.403	1.10	5.596	0.95	7.903	0.80	8.430
1.15	1.225	1.05	5.229	0.90	7.262	0.75	7.430
1.10	1.024	1.00	4.856	0.85	6.602	0.70	6.360
1.05	0.796	0.95	4.477	0.80	5.917	0.65	5.176
1.00	0.631	0.90	4.089	0.75	5.197	0.60	3.783
0.95	0.548	0.85	3.692	0.70	4.427	0.55	1.804
0.90	0.485	0.80	3.281	0.65	3.579	$H_2/H_1=5.80$	
0.85	0.428	0.75	2.853	0.60	2.592	1.80	33.444
0.80	0.374	0.70	2.403	0.55	1.227	1.75	30.015
0.75	0.321	0.65	1.920	$H_2/H_1=4.20$		1.70	28.147
0.70	0.268	0.60	1.377	1.80	25.083	1.65	26.760
0.65	0.213	0.55	0.649	1.75	22.497	1.60	25.571
0.60	0.153	$H_2/H_1=2.60$		1.70	21.092	1.55	24.486
0.55	0.072	1.80	16.628	1.65	20.047	1.50	23.455
$H_2/H_1=1.00$		1.75	14.888	1.60	19.155	1.45	22.460
1.80	7.802	1.70	13.944	1.55	18.337	1.40	21.485
1.75	6.929	1.65	13.244	1.50	17.564	1.35	20.524
1.70	6.459	1.60	12.647	1.45	16.815	1.30	19.570
1.65	6.113	1.55	12.100	1.40	16.082	1.25	18.620
1.60	5.818	1.50	11.582	1.35	15.359	1.20	17.670
1.55	5.548	1.45	11.081	1.30	14.642	1.15	16.717
1.50	5.291	1.40	10.592	1.25	13.926	1.10	15.758
1.45	5.044	1.35	10.108	1.20	13.212	1.05	14.791
1.40	4.801	1.30	9.628	1.15	12.495	1.00	13.811
1.35	4.560	1.25	9.150	1.10	11.773	0.95	12.815
1.30	4.321	1.20	8.671	1.05	11.045	0.90	11.798
1.25	4.083	1.15	8.191	1.00	10.307	0.85	10.752
1.20	3.844	1.10	7.707	0.95	9.557	0.80	9.667
1.15	3.603	1.05	7.218	0.90	8.790	0.75	8.527
1.10	3.361	1.00	6.723	0.85	8.001	0.70	7.308
1.05	3.117	0.95	6.219	0.80	7.182	0.65	5.959
1.00	2.871	0.90	5.703	0.75	6.322	0.60	4.368
0.95	2.622	0.85	5.173	0.70	5.401	0.55	2.092
0.90	2.371	0.80	4.623	0.65	4.384	$H_2/H_1=5.00$	
0.85	2.118	0.75	4.046	0.60	3.191	1.80	29.267
0.80	1.862	0.70	3.430	0.55	1.515	1.75	26.263
0.75	1.605	0.65	2.758	$H_2/H_1=5.00$		1.70	24.627
0.70	1.342	0.60	1.987	1.80	29.267	1.65	23.410
0.65	1.068	0.55	0.938	1.75	26.263	1.60	22.370
0.60	0.765	$H_2/H_1=3.40$		1.70	24.627	1.55	21.417
0.55	0.360	1.80	20.875	1.65	23.410	1.50	20.516
$H_2/H_1=1.80$		1.75	18.712				
1.80	12.303	1.70	17.538				
		1.65	16.665				

Table 11

Theoretical phase velocity of Rayleigh waves for the case of [liquid-liquid-solid] structure

when: $\rho_2/\rho_1=1.80$ $\rho_3/\rho_1=2.70$ $C_2/C_1=0.60$ $C_3/C_1=3.60$ $C_{3S}/C_1=2.00$

C/C_1	L/H_1	C/C_1	L/H_1	C/C_1	L/H_1	C/C_1	L/H_1
$H_2/H_1=0.20$		0.90	7.125	1.20	23.999	1.55	54.909
1.80	21.866	0.85	6.310	1.15	22.506	1.50	51.518
1.75	13.761	0.80	5.452	1.10	21.025	1.45	48.540
1.70	11.269	0.75	4.525	1.05	19.547	1.40	45.821
1.65	9.963	0.70	3.491	1.00	18.062	1.35	43.268
1.60	9.082	0.65	2.274	0.95	16.558	1.30	40.847
1.55	8.398	$H_2/H_1=1.80$		0.90	15.023	1.25	38.503
1.50	7.820	1.80	68.473	0.85	13.438	1.20	36.219
1.45	7.304	1.75	43.384	0.80	11.774	1.15	33.970
1.40	6.827	1.70	35.761	0.75	9.988	1.10	31.743
1.35	6.374	1.65	31.808	0.70	7.987	1.05	29.523
1.30	5.936	1.60	29.177	0.65	5.537	1.00	27.292
1.25	5.506	1.55	27.161	$H_2/H_1=3.40$		0.95	25.034
1.20	5.079	1.50	25.479	1.80	114.969	0.90	22.731
1.15	4.651	1.45	24.000	1.75	72.885	0.85	20.354
1.10	4.217	1.40	22.647	1.70	60.081	0.80	17.861
1.05	3.772	1.35	21.380	1.65	53.449	0.75	15.188
1.00	3.312	1.30	20.173	1.60	49.044	0.70	12.202
0.95	2.833	1.25	19.007	1.55	45.663	0.65	8.553
0.90	2.336	1.20	17.869	1.50	42.846	$H_2/H_1=5.00$	
0.85	1.843	1.15	16.748	1.45	40.363	1.80	161.505
0.80	1.401	1.10	15.638	1.40	38.101	1.75	102.370
0.75	1.038	1.05	14.529	1.35	35.984	1.70	84.393
0.70	0.736	1.00	13.414	1.30	33.963	1.65	75.075
0.65	0.458	0.95	12.284	1.25	32.013	1.60	68.895
$H_2/H_1=1.00$		0.90	11.129	1.20	30.112	1.55	64.147
1.80	45.194	0.85	9.935	1.15	28.243	1.50	60.193
1.75	28.624	0.80	8.681	1.10	26.389	1.45	56.712
1.70	23.577	0.75	7.330	1.05	24.540	1.40	53.532
1.65	20.959	0.70	5.815	1.00	22.683	1.35	50.561
1.60	19.213	0.65	3.961	0.95	20.803	1.30	47.725
1.55	17.875	$H_2/H_1=2.60$		0.90	18.883	1.25	44.985
1.50	16.757	1.80	91.733	0.85	16.903	1.20	42.318
1.45	15.771	1.75	58.134	0.80	14.826	1.15	39.697
1.40	14.869	1.70	47.920	0.75	12.598	1.10	37.096
1.35	14.025	1.65	42.630	0.70	10.106	1.05	34.503
1.30	13.217	1.60	39.115	0.65	7.058	1.00	31.896
1.25	12.437	1.55	36.417	$H_2/H_1=4.20$		0.95	29.261
1.20	11.674	1.50	34.171	1.80	138.253	0.90	26.571
1.15	10.922	1.45	32.190	1.75	87.626	0.85	23.796
1.10	10.175	1.40	30.379	1.70	72.241	0.80	20.888
1.05	9.428	1.35	28.687	1.65	64.259	0.75	17.769
1.00	8.675	1.30	27.077	1.60	58.966	0.70	14.286
0.95	7.909	1.25	25.519			0.65	10.034

Table 12

Theoretical phase velocity of Rayleigh waves for the case of [liquid-liquid-solid] structure

when: $\rho_2/\rho_1=1.80$ $\rho_3/\rho_1=2.70$ $C_2/C_1=0.27$ $C_3/C_1=3.60$ $C_{3S}/C_1=2.00$

C/C ₁	L/H ₁	C/C ₁	L/H ₁	C/C ₁	L/H ₁	C/C ₁	L/H
H ₂ /H ₁ =0.20		0.80	17.292	1.20	57.231	1.60	123.114
1.80	27.52	0.75	16.018	1.15	54.571	1.55	117.537
1.75	20.46	0.70	14.732	1.10	51.912	1.50	112.521
1.70	18.10	0.65	13.434	1.05	49.287	1.45	107.771
1.65	16.74	0.60	12.115	1.00	46.670	1.40	103.274
1.60	15.74	0.55	10.769	0.95	44.062	1.35	98.953
1.55	14.91	0.50	9.382	0.90	41.461	1.30	94.700
1.50	14.18	0.45	7.933	0.85	38.857	1.25	90.542
1.45	13.51	0.40	6.383	0.80	36.247	1.20	86.501
1.40	12.88	0.35	4.655	0.75	33.632	1.15	82.465
1.35	12.28	H ₂ /H ₁ =1.80		0.70	31.001	1.10	78.444
1.30	11.69	1.80	95.829	0.65	28.345	1.05	74.484
1.25	11.12	1.75	75.251	0.60	25.657	1.00	70.532
1.20	10.56	1.70	68.171	0.55	22.920	0.95	66.590
1.15	10.00	1.65	63.867	0.50	20.111	0.90	62.672
1.10	9.45	1.60	60.617	0.45	17.192	0.85	58.736
1.05	8.91	1.55	57.828	0.40	14.089	0.80	54.813
1.00	8.36	1.50	55.341	0.35	10.643	0.75	50.861
0.95	7.81	1.45	53.006	H ₂ /H ₁ =3.40		0.70	46.899
0.90	7.26	1.40	50.797	1.80	161.414	0.65	42.889
0.85	6.70	1.35	48.646	1.75	127.003	0.60	38.837
0.80	6.14	1.30	46.562	1.70	115.098	0.55	34.714
0.75	5.57	1.25	44.525	1.65	107.844	0.50	30.483
0.70	4.99	1.20	42.513	1.60	102.354	0.45	26.089
0.65	4.41	1.15	40.521	1.55	97.691	0.40	21.426
0.60	3.80	1.00	38.549	1.50	93.490	0.35	16.257
0.55	3.19	1.05	36.594	1.45	89.584	H ₂ /H ₁ =5.00	
0.50	2.58	1.00	34.647	1.40	85.855	1.80	226.708
0.45	2.00	0.95	32.702	1.35	82.212	1.75	178.424
0.40	1.47	0.90	30.763	1.30	78.712	1.70	161.739
0.35	0.98	0.85	28.828	1.25	75.286	1.65	151.673
0.30	0.52	0.80	26.886	1.20	71.888	1.60	143.936
0.25	0.32	0.75	24.935	1.15	68.519	1.55	137.419
H ₂ /H ₁ =1.00		0.70	22.975	1.10	65.213	1.50	131.466
1.80	62.721	0.65	20.996	1.05	61.900	1.45	125.909
1.75	49.032	0.60	18.991	1.00	58.629	1.40	120.712
1.70	44.329	0.55	16.947	0.95	55.341	1.35	115.594
1.65	41.482	0.50	14.849	0.90	52.080	1.30	110.663
1.60	39.332	0.45	12.665	0.85	48.808	1.25	105.856
1.55	37.515	0.40	10.340	0.80	45.547	1.20	101.067
1.50	35.875	0.35	7.749	0.75	42.267	1.15	96.345
1.45	34.351	H ₂ /H ₁ =2.60		0.70	38.961	1.10	91.678
1.40	32.903	1.80	128.628	0.65	35.632	1.05	87.063
1.35	31.505	1.75	101.131	0.60	32.260	1.00	82.423
1.30	30.141	1.70	91.678	0.55	28.830	0.95	77.836
1.25	28.808	1.65	85.900	0.50	25.309	0.90	73.263
1.20	27.493	1.60	81.546	0.45	21.653	0.85	68.665
1.15	26.194	1.55	77.836	0.40	17.771	0.80	64.070
1.10	24.912	1.50	74.484	0.35	13.463	0.75	59.452
1.05	23.635	1.45	71.345	H ₂ /H ₁ =4.20		0.70	54.821
1.00	22.363	1.40	68.373	1.80	194.145	0.65	50.143
0.95	21.096	1.35	65.479	1.75	152.681	0.60	45.401
0.90	19.829	1.30	62.697	1.70	138.484	0.55	40.583
0.85	18.564	1.25	59.940	1.65	129.769	0.50	35.642
						0.45	30.512
						0.40	25.067
						0.35	19.038

Table 13—(a) Group velocity (U) and the period (T) of the main A-type earthquakes
observation data at Mori Observatory

07 ^h 40 ^m , Dec. 29, 1943 (G. M. T.)		0.744	1.80	1.114	2.68	0.763	1.13	0.774	1.84
		0.726	0.80	1.118	3.00	0.751	1.35	0.799	2.15
		0.719	2.23	1.273	3.05	0.738	0.96	0.831	2.57
3rd Phase		0.698	2.81	1.374	3.11	0.728	1.08	0.855	1.83
		0.674	2.67	1.492	3.11	0.718	0.75		
		0.652	2.12	1.632	3.10	0.710	2.47	0.958	2.36
U km/sec.	T sec.	0.636	1.91	1.804	3.16	0.688	1.99	0.995	2.10
		0.622	2.07			0.671	2.31	1.046	2.62
0.810	1.89			18 ^h 37 ^m , 16.1 ^s Jan. 2, 1944 (G. M. T.)		0.652	1.88	1.094	2.26
0.788	0.77	0.719	2.33			0.638	2.37	1.151	2.46
0.779	0.88	0.744	2.60			0.620	1.83	1.219	2.62
0.769	0.83	0.766	2.01			0.608	1.61	1.296	2.63
0.760	1.00	0.791	2.28	3rd Phase				1.392	2.88
0.750	1.00	0.819	2.33			0.735	2.42	1.515	3.15
		0.853	2.60	U km/sec.	T sec.	0.761	2.52	1.662	3.14
0.720	0.77	0.889	2.54			0.786	2.26	1.834	3.05
0.712	1.00	0.928	2.60			0.817	2.58		
0.703	0.83	0.973	2.65	0.828	1.23	0.845	2.21	20 ^h 29 ^m , 38.2 ^s Jan. 17, 1944 (G. M. T.)	
0.696	1.12	1.022	2.70	0.813	1.11	0.877	2.31		
0.686	0.94	1.078	2.70	0.799	1.76			3rd Phase	
0.678	0.71	1.139	2.71	0.779	1.64	0.939	2.36		
0.672	0.53	1.211	2.81	0.761	0.81			U km/sec.	T sec.
0.667	0.77	1.294	2.86	0.752	1.76	1.097	2.47		
0.661	2.42	1.393	2.97	0.734	2.23	1.158	2.58	0.799	1.42
0.642	2.00	1.511	3.02	0.713	2.22	1.233	2.85	0.783	1.47
0.627	1.83	1.653	3.07	0.693	1.70	1.322	2.96	0.766	0.68
0.614	2.30	1.828	3.13	0.678	1.46	1.415	2.69	0.759	0.63
				0.665	2.40	1.534	2.96	0.752	1.21
0.677	2.07	15 ^h 49 ^m , 16.0 ^s Jan. 2, 1944 (G. M. T.)		0.646	1.93	1.661	2.68	0.740	0.73
0.696	2.18			0.632	2.17	1.837	3.12	0.733	1.84
0.717	2.30			0.616	1.93			0.715	1.21
0.737	2.00	3rd Phase		0.755	1.87	04 ^h 46 ^m , 00.8 ^s Jan. 11, 1944 (G. M. T.)		0.703	1.68
0.759	2.06			0.779	2.22			0.688	2.10
0.786	2.54			0.802	1.99	3rd Phase		0.670	2.41
0.816	2.47			0.829	2.23			0.651	1.79
		U km/sec.	T sec.	0.918	2.34	U km/sec.	T sec.	0.637	2.15
0.900	2.65			0.955	2.28			0.621	1.99
0.940	2.54	0.810	1.68	1.004	2.76				
		0.790	0.90			0.831	0.84	0.832	1.99
1.049	2.48	0.780	1.68					0.860	2.10
1.100	2.36	0.723	1.00	1.081	2.34	0.798	0.78	0.889	2.05
1.169	2.88	0.714	2.47	1.144	2.75	0.789	1.16	0.927	2.52
1.241	2.71	0.700	1.32	1.221	2.99	0.776	0.94	0.974	2.78
1.322	2.66	0.688	2.05	1.310	2.98	0.766	1.05	1.022	2.62
1.414	2.65	0.671	2.32	1.414	3.04	0.755	1.36	1.072	2.47
1.507	2.36	0.652	2.10	1.552	3.40	0.740	0.74	1.131	2.62
1.633	2.77	0.636	1.74	1.711	3.22	0.733	1.05		
		0.623	2.21			0.723	1.25	1.287	2.62
04 ^h 43 ^m , 43.1 ^s Jan. 2, 1944 (G. M. T.)		0.701	1.42	10 ^h 05 ^m , 45.8 ^s Jan. 8, 1944 (G. M. T.)		0.711	1.47	1.371	2.57
		0.723	2.37			0.697	1.89	1.456	2.31
		0.741	1.79			0.681	1.78	1.570	2.68
3rd Phase		0.787	2.31	3rd Phase		0.666	2.36	1.688	2.41
		0.812	2.11			0.647	2.05		
		0.845	2.63	U km/sec.	T sec.	0.631	2.31		
		0.880	2.53			0.615	1.57		
		0.914	2.26						
		0.963	3.00	0.823	0.86	0.721	2.47		
		1.007	2.47	0.813	1.02	0.737	1.57		
		1.056	2.48	0.801	1.35	0.755	1.73		

Table 13—(b) (Continued)

		0.231	1.9	1.174	1.9	0.305	2.2	0.683	1.7	0.259	2.2
		0.225	1.6	1.129	1.5	0.302	2.2	0.669	2.2	0.257	1.7
		0.224	1.9	1.094	1.5	0.298	1.8	0.651	2.2	0.255	1.9
		0.222	1.6	1.062	2.1			0.634	2.2	0.252	2.1
		0.221	1.9	1.020	1.6	0.293	1.5	0.618	2.1	0.250	2.3
		0.219	1.8	0.990	1.9	0.291	2.3			0.247	2.1
				0.957	1.9	0.287	1.9			0.245	2.1
				0.927	2.1	0.284	2.3				
04 ^h 40 ^m , July 8, 1945, (G. M. T.)						0.281	2.2			0.237	1.8
				0.875	1.7	0.278	2.0			0.235	2.1
				0.851	2.3	0.275	1.5			0.233	2.0
				0.822	2.2	0.273	2.2			0.231	2.0
				0.795	1.5	0.270	2.2			0.229	1.6
				0.777	2.1	0.267	2.1			0.228	2.0
				0.755	1.5	0.264	2.0			0.226	1.9
				0.739	2.2	0.262	2.0			0.224	1.7
				0.718	2.3	0.259	2.2			0.223	2.0
				0.697	2.3	0.257	2.2			0.221	1.6
				0.677	2.2	0.254	1.4				
				0.659	2.0	0.252	1.9				
				0.644	1.5			17 ^h 32 ^m , July 19, 1945 (G. M. T.)			
				0.632	2.0	0.239	2.2				
				0.618	2.0						
						0.234	1.6				
						0.232	2.1				
						0.230	1.7				
						0.228	2.2				
						0.223	1.7				
						0.221	2.1				
						0.219	1.7				
						0.218	1.6				
						0.216	2.0				
						0.215	1.5				

Table 14—(1)

Theoretical phase velocity of Rayleigh waves for the case of [liquid-solid-solid] structure

(a) Fundamental mode

when: $\rho_2/\rho_1=1.80$ $\rho_3/\rho_1=2.70$ $C_2/C_1=0.69$ $C_{2S}/C_1=0.40$ $C_3/C_1=3.60$ $C_{3S}/C_1=2.00$

C/C ₁	L/H ₁	C/C ₁	L/H ₁	C/C ₁	L/H ₁	C/C ₁	L/H ₁
H ₂ /H ₁ =0.20		0.45	3.171	0.50	8.562	0.55	14.680
		H ₂ /H ₁ =1.80		0.45	7.373	0.50	12.979
1.80	22.816	1.80	84.192	H ₂ /H ₁ =3.40		0.45	11.149
1.75	13.716	1.75	50.023	1.80	147.365	H ₂ /H ₁ =5.00	
1.70	11.017	1.70	39.829	1.75	89.039	1.80	210.673
1.65	9.662	1.65	34.842	1.70	71.984	1.75	128.320
1.60	8.782	1.60	31.716	1.65	63.765	1.70	104.549
1.55	8.115	1.55	29.424	1.60	58.586	1.65	93.003
1.50	7.563	1.50	27.573	1.55	54.701	1.60	85.672
1.45	7.076	1.45	25.962	1.50	51.496	1.55	80.164
1.40	6.631	1.40	24.502	1.45	48.631	1.50	75.533
1.35	6.212	1.35	23.132	1.40	46.003	1.45	71.409
1.30	5.811	1.30	21.817	1.35	43.502	1.40	67.569
1.25	5.421	1.25	20.541	1.30	41.080	1.35	63.917
1.20	5.038	1.20	19.285	1.25	38.707	1.30	60.367
1.15	4.658	1.15	18.037	1.20	36.362	1.25	56.907
1.10	4.279	1.10	16.789	1.15	34.031	1.20	53.465
1.05	3.899	1.05	15.532	1.10	31.685	1.15	50.038
1.00	3.515	1.00		1.05	29.322	1.10	46.589
0.95	3.130	0.95	13.389	1.00	26.913	1.05	43.117
0.90	2.746	0.90	12.597	0.95	24.443	1.00	39.574
0.85	2.373	0.85	11.812	0.90	21.888	0.95	35.948
0.80	2.028	0.80	11.031	0.85	20.049	0.90	32.186
0.75	1.725	0.75	10.252	0.80	18.752	0.85	28.353
0.70	1.471	0.70	9.472	0.75	17.461	0.80	26.405
0.65	1.259	0.65	8.688	0.70	16.167	0.75	24.585
0.60	1.079	0.60	7.897	0.65	14.863	0.70	22.764
0.55	0.922	0.55	7.090	0.60	13.544	0.65	20.929
0.50	0.780	0.50	6.257	0.55	12.193	0.60	19.065
0.45	0.643	0.45	5.373	0.50	10.789	0.55	17.152
H ₂ /H ₁ =1.00		H ₂ /H ₁ =2.60		0.45	9.283	0.50	15.151
1.80	52.905	1.80	115.677	H ₂ /H ₁ =4.20		0.45	12.989
1.75	31.038	1.75	69.436	1.80	179.020		
1.70	24.434	1.70	55.821	1.75	108.645		
1.65	21.156	1.65	49.227	1.70	88.257		
1.60	19.082	1.60	45.074	1.65	78.367		
1.55	17.568	1.55	42.013	1.60	72.113		
1.50	16.359	1.50	39.486	1.55	67.428		
1.45		1.45	37.272	1.50	63.514		
1.40		1.40	35.231	1.45	60.029		
1.35	13.616	1.35	33.298	1.40	56.787		
1.30	12.867	1.30	31.437	1.35	53.714		
1.25		1.25	29.614	1.30	50.733		
1.20		1.20	27.816	1.25	47.807		
1.15	10.907	1.15	26.029	1.20	44.911		
1.10		1.10	24.233	1.15	42.035		
1.05	9.745	1.05	22.422	1.10	39.140		
1.00	9.185	1.00	20.580	1.05	36.215		
0.95	8.635	0.95	18.693	1.00	33.243		
0.90	8.090	0.90	16.989	0.95	30.197		
0.85	7.549	0.85	15.948	0.90	27.040		
0.80	7.010	0.80	14.912	0.85	24.147		
0.75	6.473	0.75	13.878	0.80	22.580		
0.70	5.935	0.70	12.844	0.75	21.027		
0.65	5.396	0.65	11.804	0.70	19.469		
0.60	4.854	0.60	10.751	0.65	17.901		
0.55	4.307	0.55	9.677	0.60	16.310		
0.50	3.749						

(b) Higher mode

when: $\rho_2/\rho_1=1.80$ $\rho_3/\rho_1=2.70$ $C_2/C_1=0.69$ $C_{2S}/C_1=0.40$ $C_3/C_1=3.60$ $C_{3S}/C_1=2.00$

C/C ₁	L/H ₁	C/C ₁	L/H ₁	C/C ₁	L/H ₁	C/C ₁	L/H ₁
H ₂ /H ₁ =0.20		0.65	2.066	0.90	16.738	1.15	33.736
1.80	4.642	0.60	1.581	0.85	14.685	1.10	32.081
1.75	4.116	0.55	1.276	0.80	12.492	1.05	30.453
1.70	3.772	0.50	1.017	0.75	10.095	1.00	28.853
1.65	3.521	0.45	0.738	0.70	7.481	0.95	27.263
1.60	3.318	H ₂ /H ₁ =1.80		0.65	5.239	0.90	25.687
1.55	3.142	1.80	29.749	0.60	4.403	0.85	23.699
1.50	2.981	1.75	28.550	0.55	3.292	0.80	20.159
1.45	2.830	1.70	27.365	0.50	2.639	0.75	16.262
1.40	2.685	1.65	26.210	0.45	1.919	0.70	11.965
1.35	2.545	1.60	25.094	H ₂ /H ₁ =3.40		0.65	8.256
1.30	2.407	1.55	24.015	1.80	53.230	0.60	6.379
1.25	2.271	1.50	22.982	1.75	50.379	0.55	5.231
1.20	2.135	1.45	21.989	1.70	47.648	0.50	4.224
1.15	1.999	1.40	21.029	1.65	45.147	0.45	3.091
1.10	1.862	1.35	20.104	1.60	42.884	H ₂ /H ₁ =5.00	
1.05	1.724	1.30	19.204	1.55	40.827	1.80	76.494
1.00	1.583	1.25	18.326	1.50	38.929	1.75	71.879
0.95	1.437	1.20	17.468	1.45	37.158	1.70	67.590
0.90	1.287	1.15	16.629	1.40	35.493	1.65	63.784
0.85	1.129	1.10	15.800	1.35	33.900	1.60	60.429
0.80	0.962	1.05	14.985	1.30	32.372	1.55	57.451
0.75	0.780	1.00	14.185	1.25	30.892	1.50	54.733
0.70	0.584	0.95	12.940	1.20	29.455	1.45	52.227
0.65	0.413	0.90	11.587	1.15	28.048	1.40	49.879
0.60	0.348	0.85	10.168	1.10	26.671	1.35	47.634
0.55		0.80	8.652	1.05	25.315	1.30	45.492
0.50	0.106	0.75	7.001	1.00	23.979	1.25	43.416
0.45		0.70	5.214	0.95	22.655	1.20	41.394
H ₂ /H ₁ =1.00		0.65	3.679	0.90	21.344	1.15	39.426
1.80	17.698	0.60	2.830	0.85	19.199	1.10	37.496
1.75	17.118	0.55	2.292	0.80	16.326	1.05	35.595
1.70	16.541	0.50	1.831	0.75	13.181	1.00	33.722
1.65	15.966	0.45	1.329	0.70	9.729	0.95	31.865
1.60	15.393	H ₂ /H ₁ =2.60		0.65	6.760	0.90	30.027
1.55	14.820	1.80	41.544	0.60	5.223	0.85	28.085
1.50	14.246	1.75	39.542	0.55	4.270	0.80	23.983
1.45		1.70	37.601	0.50	3.437	0.75	19.338
1.40		1.65	35.762	0.45	2.508	0.70	14.193
1.35	12.498	1.60	34.058	H ₂ /H ₁ =4.20		0.65	9.735
1.30	11.895	1.55	32.476	1.80	64.864	0.60	7.520
1.25		1.50	30.999	1.75	61.141	0.55	6.179
1.20		1.45	29.607	1.70	57.636	0.50	5.001
1.15	9.980	1.40	28.284	1.65	54.474	0.45	3.671
1.10		1.35	27.020	1.60	51.974		
1.05	8.619	1.30	25.807	1.55	49.147		
1.00	7.914	1.25	24.625	1.50	46.829		
0.95	7.189	1.20	23.475	1.45	44.695		
0.90	6.437	1.15	22.353	1.40	42.679		
0.85	5.649	1.10	21.248	1.35	40.765		
0.80	4.809	1.05	20.164	1.30	38.929		
0.75	3.897	1.00	19.094	1.25	37.158		
0.70	2.916	0.95	18.306	1.20	35.423		

Table 14—(2)

Theoretical phase velocity of Rayleigh waves for the case of [liquid-solid-solid] structure

(a) Fundamental mode

when: $\rho_2/\rho_1=1.80$ $\rho_3/\rho_1=2.70$ $C_2/C_1=0.69$ $C_{2S}/C_1=0.40$ $C_3/C_1=3.60$ $C_{3S}/C_1=2.00$

C/C ₁	L/H ₁	C/C ₁	L/H ₁	C/C ₁	L/H ₁	C/C ₁	L/H ₁
H ₂ /H ₁ =3.50		1.10	33.548	1.75	98.832	0.95	28.039
1.80	151.387	1.05	31.043	1.70	80.124	0.90	25.107
1.75	91.469	1.00	28.496	1.65	71.062	0.85	22.608
1.70	74.038	0.95	25.882	1.60	65.346	0.80	21.146
		0.90	23.175	1.55	61.055	0.75	19.691
1.65	65.585	0.85	21.071	1.50	57.497	0.70	18.232
1.60	60.277			1.45	54.331	0.65	16.764
1.55	56.290	0.80		1.40	51.397	0.60	15.275
		0.75	18.353	1.35	48.602	0.55	13.750
1.50	52.989	0.70	16.993			0.50	12.161
1.45	50.054	0.65	15.625	1.30	45.898	0.45	10.453
1.40	47.343	0.60	14.238	1.25	43.256		
		0.55	12.817	1.20	40.633	H ₂ /H ₁ =4.00	
1.35	44.773	0.50	11.339	1.15	38.030	1.80	171.207
1.30	42.289	0.45	9.753	1.10	35.409	1.75	103.740
1.25	39.848	H ₂ /H ₁ =3.70		1.05	32.769	1.70	84.192
		1.80	159.178	1.00	30.079	1.65	74.726
1.20	37.437	1.75	96.408	0.95	27.320	1.60	68.724
1.15	35.032	1.70	78.063	0.90	24.465	1.55	64.249
1.10	32.616			0.85	22.096	1.50	60.503
		1.65	69.227	0.80		1.45	57.170
1.05	30.180	1.60	63.639	0.75	19.245	1.40	54.094
1.00	27.706	1.55	59.474			1.35	51.152
0.95	25.162	1.50	55.996	0.70	17.819	1.30	48.310
		1.45	52.902	0.65	16.384	1.25	45.534
0.90	22.532	1.40	50.038	0.60	14.930		
0.85	20.559			0.55	13.440	1.20	42.773
0.80		1.35	47.329	0.50	11.888	1.15	40.027
		1.30	44.699	0.45	10.220	1.10	37.272
0.75	17.907	1.25	42.123	H ₂ /H ₁ =3.90		1.05	34.491
0.70	16.580	1.20	39.574	1.80	167.116	1.00	31.660
0.65	15.245	1.15	37.032	1.75	101.322	0.95	28.756
		1.10	34.483	1.70	82.128	0.90	25.750
0.60	13.891	1.05	31.905			0.85	
0.55	12.506	1.00	29.285	1.65	72.898	0.80	21.624
0.50	11.064	0.95	26.602	1.60	67.034		
				1.55	62.648	0.75	20.136
0.45	9.518	0.90	23.820	1.50	58.994	0.70	18.645
H ₂ /H ₁ =3.60		0.85	21.583	1.45	55.744	0.65	17.144
1.80	155.335	0.80		1.40	52.746		
1.75	93.926	0.75	18.799	1.35	49.883	0.60	15.620
1.70	76.033	0.70	17.407	1.30	47.107	0.55	14.060
		0.65	16.005	1.25	44.390	0.50	12.434
1.65	67.428	0.60	14.584			0.45	10.685
1.60	61.948	0.55	13.128	1.20	41.708		
1.55	57.890	0.50	11.613	1.15	39.026		
		0.45	9.986	1.10	36.346		
1.50	54.497	H ₂ /H ₁ =3.80		1.05	33.632		
1.45	51.480	1.80	163.216	1.00	30.870		
1.40	48.690						
1.35	46.055						
1.30	43.490						
1.25	40.985						
1.20	38.503						
1.15	36.028						

(b) Higher mode

when: $\rho_2/\rho_1=1.80$ $\rho_3/\rho_1=2.70$ $C_2/C_1=0.69$ $C_{2S}/C_1=0.40$ $C_3/C_1=3.60$ $C_{3S}/C_1=2.00$

C/C ₁	L/H ₁	C/C ₁	L/H ₁	C/C ₁	L/H ₁	C/C ₁	L/H ₁
H ₂ /H ₁ =3.50		1.10	28.023	1.75	55.758	0.95	25.536
1.80	54.696	1.05	26.600	1.70	52.655	0.90	24.062
1.75	51.723	1.00	25.196	1.65	49.817	0.85	22.016
1.70	48.908	0.95	23.809	1.60	47.284	0.80	18.722
1.65	46.317	0.90	22.431	1.55	44.983	0.75	15.107
1.60	43.986	0.85	20.325	1.50	42.884	0.70	11.127
1.55	41.868	0.80		1.45	40.931	0.65	7.697
1.50	39.915	0.75	13.952	1.40	39.090	0.60	5.948
1.45	38.100	0.70	10.289	1.35	37.339	0.55	4.873
1.40	36.393	0.65	7.136	1.30	35.651	0.50	3.930
1.35	34.757	0.60	5.514	1.25	34.022	0.45	2.873
1.30	33.193	0.55	4.512	1.20	32.443	H ₂ /H ₁ =4.00	
1.25	31.677	0.50	3.635	1.15	30.892	1.80	61.966
1.20	30.202	0.45	2.654	1.10	29.380	1.75	58.453
1.15	28.760	H ₂ /H ₁ =3.70		1.05	27.887	1.70	55.146
1.10	27.347	1.80	57.595	1.00	26.417	1.65	52.143
1.05	25.957	1.75	54.418	0.95	24.962	1.60	49.480
1.00	24.588	1.70	51.409	0.90	23.516	1.55	47.062
0.95	23.231	1.65	48.657	0.85	21.452	1.50	44.857
0.90	21.887	1.60	46.184	0.80		1.45	42.815
0.85	19.763	1.55	43.950	0.75	14.722	1.40	40.889
0.80		1.50	41.890	0.70	10.848	1.35	39.052
0.75	13.567	1.45	39.984	0.65	7.510	1.30	37.296
0.70	10.009	1.40	38.190	0.60	5.804	1.25	35.588
0.65	6.948	1.35	36.475	0.55	4.753	1.20	33.936
0.60	5.869	1.30	34.832	0.50	3.832	1.15	32.313
0.55	4.391	1.25	33.241	0.45	2.800	1.10	30.733
0.50	3.536	1.20	31.695	H ₂ /H ₁ =3.90		1.05	29.172
0.45	2.581	1.15	30.185	1.80	60.520	1.00	27.633
H ₂ /H ₁ =3.60		1.10	28.703	1.75	57.104	0.95	26.112
1.80	56.147	1.05	27.245	1.70	53.890	0.90	24.603
1.75	53.072	1.00	25.807	1.65	50.986	0.85	
1.70	50.159	0.95	24.386	1.60	48.379	0.80	19.201
1.65	47.493	0.90	22.975	1.55	46.025	0.75	15.493
1.60	45.084	0.85	20.890	1.50	43.866	0.70	11.407
1.55	42.907	0.80		1.45	41.868	0.65	7.884
1.50	40.910	0.75	14.337	1.40	39.984	0.60	6.092
1.45	39.043	0.70	10.569	1.35	38.190	0.55	4.992
1.40	37.287	0.65	7.323	1.30	36.475	0.50	4.028
1.35	35.619	0.60	5.659	1.25	34.810	0.45	2.946
1.30	34.015	0.55	4.632	1.20	33.186		
1.25	32.457	0.50	3.733	1.15	31.602		
1.20	30.945	0.45	2.727	1.10	30.055		
1.15	29.471	H ₂ /H ₁ =3.80		1.05	28.530		
		1.80	59.054	1.00	27.025		

Table 15

Theoretical relationship between the group velocity (U)
and the period (T) for the case of [liquid-solid-solid] structure.
when: $\rho_2/\rho_1=1.80$ $\rho_3/\rho_1=2.70$ $C_2/C_1=0.69$ $C_{2S}/C_1=0.40$ $C_3/C_1=3.60$ $C_{3S}/C_1=2.00$

Fundamental mode

U	km/sec.	T	sec.	U	km/sec.	T	sec.
$H_2/H_1=3.70$				$H_2/H_1=4.00$			
	0.147		1.64		0.540		1.89
	0.150		1.66		0.705		2.06
	0.666		1.81		0.663		2.21
	0.683		1.98		0.638		2.33
	0.650		2.11		0.630		2.43
	0.630		2.21		0.651		2.51
	0.645		2.30		0.750		2.59
	0.731		2.39		0.930		2.68
	0.903		2.48		1.185		2.79
	1.173		2.57		1.485		2.90
	1.506		2.69		1.755		3.03
	1.791		2.82		1.965		3.17

Higher mode

U	km/sec.	T	sec.	U	km/sec.	T	sec.
$H_2/H_1=3.70$				$H_2/H_1=4.00$			
	0.608		0.59		0.510		0.61
	0.810		0.96		0.765		0.98
	0.825		1.32		0.840		1.35
	0.693		1.60		0.765		1.65
	0.176		1.72		0.375		1.75
	0.180		1.76		0.165		1.87
	0.345		1.79		0.270		1.90
	0.563		1.83		0.435		1.94
	0.855		1.90		0.668		1.99
	1.155		1.99		1.005		2.07
					1.230		2.16

Table 16
Theoretical phase velocity of Rayleigh waves for the first four modes
when: $\rho_2/\rho_1=1.80$ $\rho_3/\rho_1=2.70$ $C_2/C_1=0.69$ $C_3/C_1=3.60$ $C_{3S}/C_1=2.00$

Fundamental mode				1st shear mode			
C/C ₁	L/H ₁			C/C ₁	L/H ₁		
	H ₂ /H ₁ =2.60	H ₂ /H ₁ =3.40	H ₂ /H ₁ =4.20		H ₂ /H ₁ =2.60	H ₂ /H ₁ =3.40	H ₂ /H ₁ =4.20
1.80	115.677	147.365	197.020	1.60	34.059		
1.75	69.436	89.039	108.645	1.55	32.473		
1.70	55.821	71.984	88.257	1.50	30.995	38.928	
1.65	49.227	63.765	78.367	1.45	29.605	37.157	
1.60	45.074	58.586	72.113				
1.55	42.013	54.701	67.428	1.40	28.284	35.492	
1.50	39.486	51.496	63.514	1.35	27.022	33.902	38.928
1.45	37.272	48.631	60.029	1.30	25.806	32.371	37.152
1.40	35.231	46.003	56.787	1.25			
1.35	33.298	43.502	53.714				
1.30	31.437	41.080	50.733	1.20	23.475	29.453	35.424
1.25	29.614	38.707	47.807	1.15	22.352	28.050	33.738
				1.10	21.250	26.669	
1.20	27.816	36.362	44.911	1.05	20.164		
1.15	26.029	34.031	42.035				
1.10	24.233	31.685	39.140	1.00	19.095	23.978	28.852
1.05	22.422	29.322	36.215	0.95		22.657	27.263
1.00	20.580	26.913	33.243	0.90			
0.95	18.693	24.443	30.197				
				0.85	14.685		
0.90	16.989	21.888	27.040	0.80	12.492	16.328	20.158
0.85	15.948	20.049		0.75	10.095	13.181	16.263
0.80	14.912	18.752	22.580				
0.75	13.878	17.461	21.027	0.70	7.481	9.729	11.965
0.70	12.844	16.167	19.469	0.65	5.239	6.760	8.256
0.65	11.804	14.863	17.901	0.60	4.043	5.223	6.379
0.60	10.751	13.544	16.310				
0.55	9.677	12.193	14.680	0.55	3.292	4.270	5.231
0.50	8.562	10.789	12.979	0.50	2.639	3.437	4.224
0.45	7.373	9.283	11.149	0.45	1.919	2.507	3.092

(Continued)

2nd shear mode				3rd shear mode		
C/C ₁	L/H ₁			C/C ₁	L/H ₁	
	H ₂ /H ₁ = 2.60	H ₂ /H ₁ = 3.40	H ₂ /H ₁ = 4.20		H ₂ /H ₁ = 2.60	H ₂ /H ₁ = 3.40
1.80	16.587	21.674	26.763	1.80		15.610
1.75	15.352	20.073	24.795	1.75		14.598
1.70	14.534	18.986	23.438	1.70		13.870
1.65	13.872	18.099	22.330	1.65	10.512	13.276
1.60	13.279	17.307	21.337	1.60		12.749
1.55	12.721	16.564	20.408	1.55		12.258
1.50	12.183	15.847	19.515	1.50		11.876
1.45		15.148	18.642	1.45		11.526
1.40		14.458	17.783	1.40		11.289
1.35		13.775	16.931	1.35		11.060
1.30		13.093	16.082	1.30		10.835
1.25	9.592	12.412	15.234	1.25	7.431	
1.20			14.385	1.20		
1.15			13.533	1.15		
1.10		9.664	12.677	1.10		7.779
1.05			11.813	1.05		
1.00				1.00	5.247	
0.95				0.95		
0.90		7.528	9.164	0.90	4.860	6.346
0.85			8.245	0.85		5.828

Table 17

Theoretical phase velocity of Rayleigh waves for the case of [liquid-solid-solid] structure

(a) Fundamental mode

when: $\rho_2/\rho_1=1.80$ $\rho_3/\rho_1=2.70$ $C_2/C_1=1.20$ $C_{2S}/C_1=0.33$ $C_3/C_1=3.60$ $C_{3S}/C_1=2.00$

C/C ₁	L/H ₁	C/C ₁	L/H ₁	C/C ₁	L/H ₁	C/C ₁	L/H ₁
H ₂ /H ₁ =0.20		0.75	7.097	1.15	31.517	1.55	76.722
1.80	21.408	0.70	6.435	1.10	29.603	1.50	73.096
1.75	12.044	0.65	5.786	1.05	27.687	1.45	69.677
1.70	9.342	0.60	5.154	1.00	25.775	1.40	66.370
1.65	8.056	0.55	4.542	0.95	23.866	1.35	63.115
1.60	7.254	0.50	3.952	0.90	21.963	1.30	59.940
1.55	6.662	0.45	3.381	0.85	20.082	1.25	56.767
1.50	6.177	0.40	2.816	0.80	18.240	1.20	53.625
1.45	5.753	H ₂ /H ₁ =1.80		0.75	16.460	1.15	50.478
1.40	5.364	1.80	79.094	0.70	14.774	1.10	47.343
1.35	5.000	1.75	46.831	0.65	13.203	1.05	44.183
1.30	4.651	1.70	39.675	0.60	11.759	1.00	41.027
1.25	4.314	1.65	36.657	0.55	10.432	0.95	37.860
1.20	3.986	1.60	34.638	0.50	9.193	0.90	
1.15	3.667	1.55	32.966	0.45	7.999	0.85	
1.10	3.359	1.50	31.458	0.40	6.788	0.80	
1.05	3.064	1.45	30.026	H ₂ /H ₁ =3.40		0.75	25.543
1.00	2.785	1.40	28.648	1.80	140.296	0.70	22.782
0.95	2.525	1.35	27.301	1.75	86.922	0.65	20.262
0.90	2.284	1.30	25.970	1.70	74.831	0.60	18.001
0.85	2.060	1.25	24.653	1.65	69.257	0.55	15.962
0.80	1.850	1.20	23.729	1.60	65.372	0.50	14.079
0.75	1.652	1.15	22.041	1.55	62.140	0.45	12.266
0.70	1.465	1.10	20.740	1.50	59.212	0.40	10.409
0.65	1.286	1.05	19.443	1.45	56.448	H ₂ /H ₁ =5.00	
0.60	1.118	1.00	18.147	1.40	53.786	1.80	201.945
0.55	0.962	0.95	16.857	1.35	51.185	1.75	127.204
0.50	0.817	0.90	15.574	1.30	48.617	1.70	109.982
0.45	0.670	0.85	14.306	1.25	46.068	1.65	101.835
0.40	0.657	0.80	13.061	1.20	43.525	1.60	96.115
H ₂ /H ₁ =1.00		0.75	11.851	1.15	40.996	1.55	91.313
1.80	49.048	0.70	10.689	1.10	38.466	1.50	86.969
1.75	27.207	0.65	9.587	1.05	35.940	1.45	82.890
1.70	22.145	0.60	8.551	1.00	33.402	1.40	78.944
1.65	20.368	0.55	7.581	0.95	30.864	1.35	75.075
1.60	19.283	0.50	6.664	0.90	28.336	1.30	71.251
1.55	18.405	0.45	5.777	0.85	25.828	1.25	67.484
1.50	17.607	0.40	4.880	0.80	23.377	1.20	63.715
1.45	16.850	H ₂ /H ₁ =2.60		0.75	21.016	1.15	59.962
1.40	16.118	1.80	109.607	0.70	18.794	1.10	56.211
1.35	15.397	1.75	66.839	0.65	16.750	1.05	52.436
1.30	14.687	1.70	57.252	0.60	14.896	1.00	48.646
1.25	13.983	1.65	52.954	0.55	13.213	0.95	44.848
1.20	13.447	1.60	50.007	0.50	11.652	0.90	41.059
1.15	12.586	1.55	47.553	0.45	10.150	0.85	37.289
1.10	11.892	1.50	45.328	0.40	8.618	0.80	33.597
1.05	11.199	1.45	43.233	H ₂ /H ₁ =4.20		0.75	30.056
1.00	10.507	1.40	41.217	1.80	171.025	0.70	26.751
0.95	9.818	1.35	39.236	1.75	107.054	0.65	23.758
0.90	9.131	1.30	37.289	1.70	92.415	0.60	21.087
0.85	8.448	1.25	35.355	1.65	85.535	0.55	18.694
0.80	7.769	1.20	33.430	1.60	80.727	0.50	16.490
						0.45	14.365
						0.40	12.180

(b) Higher mode

when: $\rho_2/\rho_1=1.80$ $\rho_3/\rho_1=2.70$ $C_2/C_1=1.20$ $C_{2S}/C_1=0.33$ $C_3/C_1=3.60$ $C_{3S}/C_1=2.00$

C/C_1	L/H_1	C/C_1	L/H_1	C/C_1	L/H_1	C/C_1	L/H_1
$H_2/H_1=0.20$		0.75	3.040	1.15	14.312	1.55	34.079
1.80	5.197	0.70	2.719	1.10	13.538	1.50	32.113
1.75	4.733	0.65	2.393	1.05	12.764	1.45	30.476
1.70	4.366	0.60	2.067	1.00	11.982	1.40	29.035
1.65	4.072	0.55	1.750	0.95	11.188	1.35	27.709
1.60	3.823	0.50	1.451	0.90	10.376	1.30	26.452
1.55	3.601	0.45	1.169	0.85	9.546	1.25	25.244
1.50	3.393	0.40	0.883	0.80	8.694	1.20	24.054
1.45	3.193	$H_2/H_1=1.80$		0.75	7.826	1.15	22.877
1.40	2.995	1.80	33.147	0.70	6.954	1.10	21.698
1.35	2.795	1.75	28.178	0.65	6.092	1.05	20.511
1.30	2.588	1.70	23.245	0.60	5.259	1.00	19.298
1.25	2.369	1.65	19.942	0.55	4.472	0.95	18.053
1.20	2.128	1.60	17.774	0.50	3.734	0.90	
1.15	1.854	1.55	16.238	0.45	3.028	0.85	
1.10	1.526	1.50	15.063	0.40	2.293	0.80	
1.05	1.147	1.45	14.104	$H_2/H_1=3.40$		0.75	12.557
1.00	0.951	1.40	13.280	1.80	58.538	0.70	11.087
0.95	0.866	1.35	12.544	1.75	47.521	0.65	9.651
0.90	0.798	1.30	11.867	1.70	38.779	0.60	8.300
0.85	0.734	1.25	11.231	1.65	33.546	0.55	7.060
0.80	0.669	1.20		1.60	30.298	0.50	5.922
0.75	0.595	1.15	10.033	1.55	28.067	0.45	4.834
0.70		1.10	9.456	1.50	26.374	0.40	3.685
0.65		1.05	8.887	1.45	24.973	$H_2/H_1=5.00$	
0.60		1.00	8.320	1.40	23.749	1.80	83.655
0.55		0.95	7.754	1.35	22.630	1.75	66.804
0.50		0.90	7.184	1.30	21.573	1.70	54.455
0.45		0.85	6.610	1.25	20.561	1.65	47.353
0.40		0.80	6.030	1.20	19.571	1.60	43.045
$H_2/H_1=1.00$		0.75	5.444	1.15	18.595	1.55	40.104
1.80	20.024	0.70	4.855	1.10	17.620	1.50	37.866
1.75	18.255	0.65	4.267	1.05	16.637	1.45	35.994
1.70	15.683	0.60	3.688	1.00	15.641	1.40	34.334
1.65	13.455	0.55	3.131	0.95	14.620	1.35	32.794
1.60	11.866	0.50	2.604	0.90	13.569	1.30	31.337
1.55	10.690	0.45	2.104	0.85	12.480	1.25	29.926
1.50	9.760	0.40	1.589	0.80	11.354	1.20	28.540
1.45	8.984	$H_2/H_1=2.60$		0.75	10.196	1.15	27.162
1.40	8.311	1.80	45.907	0.70	9.029	1.10	25.782
1.35	7.711	1.75	37.866	0.65	7.883	1.05	24.383
1.30	7.165	1.70	30.981	0.60	6.793	1.00	22.956
1.25	6.664	1.65	26.698	0.55	5.779	0.95	21.484
1.20		1.60	23.983	0.50	4.839	0.90	19.954
1.15	5.774	1.55	22.101	0.45	3.938	0.85	18.349
1.10	5.376	1.50	20.672	0.40	2.991	0.80	16.665
1.05	5.003	1.45	19.502	$H_2/H_1=4.20$		0.75	14.913
1.00	4.652	1.40	18.484	1.80	71.116	0.70	13.135
0.95	4.316	1.35	17.564	1.75	57.165	0.65	11.404
0.90	3.992	1.30	16.705	1.70	46.612	0.60	9.789
0.85	3.673	1.25	15.886	1.65	40.437	0.55	8.325
0.80	3.357	1.20	15.092	1.60	36.658	0.50	6.991
						0.45	5.718
						0.40	4.369

Table 18—(a)

Theoretical phase velocity of Rayleigh waves for the oceanic path

(a) when: $\rho_2/\rho_1=1.80$ $\rho_3/\rho_1=3.00$ $C_2/C_1=1.14$ $C_{2S}/C_1=0.66$ $C_3/C_1=5.20$ $C_{3S}/C_1=3.00$

C/C_1	L/H_1	C/C_1	L/H_1	C/C_1	L/H_1
$H_2/H_1=0.10$		$H_2/H_1=0.20$		$H_2/H_1=0.30$	
2.70	23.149	2.70	26.506	2.70	30.123
2.65	16.008	2.65	17.615	2.65	19.426
2.60	13.642	2.60	14.720	2.60	15.936
2.55	12.420	2.55	13.274	2.55	14.227
2.50	11.623	2.50	12.360	2.50	13.173
2.45	11.028	2.45	11.692	2.45	12.419
2.40	10.541	2.40	11.157	2.40	11.826
2.35	10.120	2.35	10.700	2.35	11.328
2.30	9.741	2.30	10.294	2.30	10.889
2.25	9.391	2.25	9.921	2.25	10.490
2.20	9.061	2.20	9.572	2.20	10.119
2.15	8.746	2.15	9.240	2.15	9.768
2.10	8.442	2.10	8.922	2.10	9.432
2.05	8.146	2.05	8.612	2.05	9.108
2.00	7.857	2.00	8.310	2.00	8.792
1.95	7.571	1.95	8.013	1.95	8.482
1.90	7.289	1.90	7.721	1.90	8.178
1.85	7.009	1.85	7.431	1.85	7.877
1.80	6.730	1.80	7.143	1.80	7.579
1.75	6.452	1.75	6.856	1.75	7.283
1.70	6.173	1.70	6.570	1.70	6.988
1.65	5.894	1.65	6.284	1.65	6.694
1.60	5.612	1.60	5.996	1.60	6.399
1.55	5.328	1.55	5.706	1.55	6.103
1.50	5.041	1.50	5.414	1.50	5.806
1.45	4.749	1.45	5.119	1.45	5.506
1.40	4.451	1.40	4.819	1.40	5.204
1.35	4.145	1.35	4.514	1.35	4.897
1.30	3.830	1.30	4.201	1.30	4.585
1.25	3.502	1.25	3.880	1.25	4.268
1.20	3.158	1.20	3.547	1.20	3.942
1.15	2.792	1.15	3.200	1.15	3.609
1.10	2.393	1.10	2.835	1.10	3.265
1.05	1.947	1.05	2.450	1.05	2.910

Table 18—(b)

Theoretical phase velocity of Rayleigh waves for the oceanic path

(b) when: $\rho_2/\rho_1=2.80$ $\rho_3/\rho_1=3.00$ $C_2/C_1=3.34$ $C_{2S}/C_1=1.93$ $C_2/C_1=5.30$ $C_{3S}/C_1=3.04$

C/C ₁	L/H ₁	C/C ₁	L/H ₁	C/C ₁	L/H ₁	C/C ₁	L/H ₁
H ₂ /H ₁ =0.50		1.45	4.623	1.70	6.495	1.95	9.248
2.70	22.397	1.40	4.321	1.65	6.177	1.90	8.780
2.65	16.403	1.35	4.011	1.60	5.859	1.85	8.330
2.60	13.801	1.30	3.689	1.55	5.540	1.80	7.895
2.55	12.388	1.25	3.352	1.50	5.218	1.75	7.470
2.50	11.481	H ₂ /H ₁ =1.50		1.45	4.891	1.70	7.055
2.45	10.822	2.70	41.633	1.40	4.557	1.65	6.648
2.40	10.298	2.65	27.117	1.35	4.214	1.60	6.246
2.35	9.855	2.60	20.242	1.30	3.859	1.55	5.851
2.30	9.464	2.55	16.466	1.25	3.487	1.50	5.459
2.25	9.107	2.50	14.221	H ₂ /H ₁ =2.50		1.45	5.071
2.20	8.773	2.45	12.786	2.70	62.066	1.40	4.686
2.15	8.457	2.40	11.793	2.65	39.481	1.35	4.301
2.10	8.153	2.35	11.050	2.60	28.527	1.30	3.912
2.05	7.858	2.30	10.457	2.55	22.350	1.25	3.517
2.00	7.571	2.25	9.958	2.50	18.609	H ₂ /H ₁ =3.50	
1.95	7.288	2.20	9.520	2.45	16.209	2.70	82.659
1.90	7.009	2.15	9.124	2.40	14.565	2.65	52.133
1.85	6.732	2.10	8.758	2.35	13.364	2.60	37.257
1.80	6.457	2.05	8.412	2.30	12.433	2.55	28.837
1.75	6.182	2.00	8.082	2.25	11.673	2.50	23.740
1.70	5.907	1.95	7.764	2.20	11.028	2.45	20.468
1.65	5.630	1.90	7.454	2.15	10.462	2.40	18.222
1.60	5.352	1.85	7.150	2.10	9.953	2.35	16.570
1.55	5.070	1.80	6.850	2.05	9.485	2.30	15.281
1.50	4.784	1.75	6.554	2.00	9.049	2.25	14.224
1.45	4.493	1.70	6.238	1.95	8.625	2.20	13.273
1.40	4.196	1.65	5.963	1.90	8.240	2.15	12.531
1.35	3.889	1.60	5.668	1.85	7.858	2.10	11.816
1.30	3.571	1.55	5.370	1.80	7.486	2.05	11.159
1.25	3.238	1.50	5.068	1.75	7.122	2.00	10.545
H ₂ /H ₁ =1.00		1.45	4.762	1.70	6.764	1.95	9.963
2.70	31.673	1.40	4.448	1.65	6.409	1.90	9.408
2.65	21.331	1.35	4.126	1.60	6.056	1.85	8.873
2.60	16.616	1.30	3.791	1.55	5.704	1.80	8.354
2.55	14.106	1.25	3.439	1.50	5.351	1.75	7.850
2.50	12.614	H ₂ /H ₁ =2.00		1.45	4.995	1.70	7.359
2.45	11.628	2.70	51.808	1.40	4.636	1.65	6.883
2.40	10.910	2.65	33.231	1.35	4.270	1.60	6.420
2.35	10.344	2.60	24.287	1.30	3.896	1.55	5.972
2.30	9.870	2.55	19.280	1.25	3.509	1.50	5.540
2.25	9.456	2.50	16.266	H ₂ /H ₁ =3.00		1.45	5.121
2.20	9.080	2.45	14.339	2.70	72.342	1.40	4.714
2.15	8.732	2.40	13.021	2.65	45.789	1.35	4.315
2.10	8.403	2.35	12.057	2.60	32.866	1.30	3.919
2.05	8.088	2.30	11.305	2.55	25.555	1.25	3.520
2.00	7.784	2.25	10.688	2.50	21.125	H ₂ /H ₁ =4.00	
1.95	7.488	2.20	10.159	2.45	18.280	2.70	92.993
1.90	7.197	2.15	9.691	2.40	16.328	2.65	58.497
1.85	6.910	2.10	9.265	2.35	14.896	2.60	41.674
1.80	6.626	2.05	8.869	2.30	13.783	2.55	32.163
1.75	6.344	2.00	8.496	2.25	12.874	2.50	26.410
1.70	6.062	1.95	8.141	2.20	12.101	2.45	22.725
1.65	5.779	1.90	7.797	2.15	11.424	2.40	20.195
1.60	5.495	1.85	7.463	2.10	10.816	2.35	18.329
1.55	5.208	1.80	7.136	2.05	10.258	2.30	16.869
1.50	4.918	1.75	6.814	2.00	9.738	2.25	15.669

(Continued)

C/C_1	L/H_1	C/C_1	L/H_1	C/C_1	L/H_1	C/C_1	L/H_1
2.20	14.641	2.65	64.883	1.45	5.167	1.90	11.636
2.15	13.733	2.60	46.117	1.40	4.736	1.85	10.783
2.10	12.911	2.55	35.514	1.35	4.325	1.80	9.936
2.05	12.151	2.50	29.117	1.30	3.923	1.75	9.095
2.00	11.437	2.45	25.046	1.25	3.521	1.70	8.274
1.95	10.758	2.40	22.215	$H_2/H_1=5.00$		1.65	7.498
1.90	10.104	2.35	20.140			1.60	6.798
1.85	9.470	2.30	18.513	2.70	113.649	1.55	6.186
1.80	8.853	2.25	17.171	2.65	71.261	1.50	5.652
1.75	8.252	2.20	16.019	2.60	50.566	1.45	5.176
1.70	7.668	2.15	14.997	2.55	38.884	1.40	4.739
1.65	7.106	2.10	14.068	2.50	31.849	1.35	4.326
1.60	6.571	2.05	13.205	2.45	27.353	1.30	3.923
1.55	6.067	2.00	12.390	2.40	24.266	1.25	3.751
1.50	5.595	1.95	11.609	2.35	21.984		
1.45	5.151	1.90	10.852	2.30	20.192		
1.40	4.729	1.85	10.111	2.25	18.710		
1.35	4.322	1.80	9.383	2.20	17.434		
1.30	3.922	1.75	8.669	2.15	16.300		
1.25	3.520	1.70	7.975	2.10	15.265		
$H_2/H_1=4.50$		1.65	7.312	2.05	14.300		
		1.60	6.697	2.00	13.384		
2.70	103.294	1.55	6.137	1.95	12.500		
		1.50	5.631				

increases within the range of smaller values of L/H_1 .

From now on the writer will continue his research on this problem by paying special attention to these points.

Explanation of Figures and Tables of Section 6

The dimensionless values of velocity C/C_1 and wave length L/H_1 for the various thickness ratio H_2/H_1 . Computed values are based on the constants (H, C, ρ) of the first layer.

- H_k ($k=1,2$) thickness of the layer in kilometers.
 C_k ($k=1,2,3$) compressional wave velocity of the layer in km/sec.
 C_{ks} ($k=2,3$) shear-wave velocity of the layer in km/sec.
 ρ_k ($k=1,2,3$) density of the layer in gm/cm³.
 T wave period in seconds.
 C phase velocity in km/sec.
 U group velocity in km/sec.
 L/H_1 L is wave length and H_1 is thickness of the 1st water layer.

For example: $H21$ represents H_2/H_1 the ratio of thickness of secondary layer (sedimentary layer) to the first water layer. $V21$ represents C_2/C_1 , the ratio of compressional wave velocity. $V3S1$ represents C_{3S}/C_1 , the ratio of shear wave velocity of the third solid medium to the compressional wave velocity of the first water layer. $RO21$ represents ρ_2/ρ_1 the ratio of density.

Fig. 37. Theoretical phase and group velocity of Rayleigh waves for the case of [liquid-liquid-solid] structure (see Tables 10, 11, 12.) Group velocity was obtained by numerically differentiating the phase velocity.

Fig. 38. Group velocity (U) against period (T) for the case of the model 37 (a) and (d). When $H_1=100\text{m}$.

7. Nature of submarine earthquakes of crypto-volcanic activity off Itô and the Kita-Izu earthquake swarms

From February to June, 1930, remarkable earthquake swarms occurred on the sea bottom off Itô. From November to December of the same year, the northern Izu district was shaken by a number of earthquakes. The writer studied the seismograms taken at Tomisaki ($\Delta=67\text{ km}$), Tokyo ($\Delta=97\text{ km}$) and Yokohama ($\Delta=68.5\text{ km}$) with the aim of comparing the nature of these earthquakes with that of various

other volcanic earthquakes.

(a) Seismogram at Yokohama (L.M.O.)
March 12, 1930 (12^h46^m32.2^s)
Wiechert seismograph
Magnification: $V_N=79$, $V_E=79$
Period: $T_{0N}=5.7$ sec, $T_{0E}=5.7$ sec.

(b). Seismogram at Tokyo (J.M.A.)
March 13, 1930 (12^h46^m39.3^s)
Wiechert seismograph
Magnification: $V_N=80$, $V_E=80$
Period: $T_{0N}=4.5$ sec, $T_{0E}=4.5$ sec.

Fig. 39. Seismograms of the Itô crypto-volcanic activity observed at Yokohama (L.M.O.) and Tokyo (J.M.A.).

Fig. 40. Frequency-distribution of the Itô and Kita-Izu earthquakes in 1930 by "Kishō-yōran."

19 to April 23 belong to *A* group, those that occurred off Itô from April 24 to June 30 belong to *B* group, and the earthquakes of northern Izu from November 8 to December 10 are *C* group.

The relation between the amplitude A and the frequency n of the earthquakes can be expressed by the ISHIMOTO-IDA formula,

$$n(A) dA = kA^{-m} dA, \quad (1)$$

and when the formula is integrated by using

The time variations of the frequency of earthquakes are diagrammatized in Fig.40. As is known from the figure, the earthquakes can be classified into three groups by their number varying with the lapse of time. These groups were tentatively named *A*, *B* and *C*. The earthquakes that occurred off Itô from February

19 to April 23 belong to *A* group, those that occurred off Itô from April 24 to June 30 belong to *B* group, and the earthquakes of northern Izu from November 8 to December 10 are *C* group.

$$N(A) = \int_A^{\infty} n(A) dA,$$

Then the following formula is obtained:

$$N(A) = \frac{k}{m-1} A^{-m+1}. \quad (2)$$

On the basis of the formulas (1) and (2), the value of m for each group of A , B and C becomes as shown in Tables 19 and 20.

Table 19. Values of m on amplitude-cumulative frequency relation

Observatory	A-group Feb. 19-Apr. 23	B-group Apr. 24-June 30	C-group Nov. 8-Dec. 10
Tokyo	1.79	1.76	1.50
Tomisaki	1.88	1.80	—
Yokohama	1.94	1.92	—
Average	1.87	1.83	1.50

Table 20. Values of m on amplitude-frequency relation

Observatory	A-group Feb. 19-Apr. 23.	B-group Apr. 24-June 30	C-group Nov. 8-Dec. 10
Tokyo	1.33	1.06	0.88
Tomisaki	1.56	1.66	—
Yokohama	—	—	—
Average	1.45	1.36	0.88

The values are expressed by the graph of Figs. 41 and 42.

The result revealed that the values obtained through the integral formula are larger by about 0.5. Little difference is recognized between A group and B group, and their values are nearly equivalent to the values obtained by many researchers from the A -type earthquakes of volcanic origin, whereas the values of m of C group are much smaller. This suggests, therefore, that the earthquakes of C group may have a mechanism different from that of the other groups.

The values of the exponent m so far known were $m=1.91$ of the earthquakes at Tesikaga, Hokkaido, obtained by Tosimatsu Matumoto through the cumulative frequency calculation (1959), and $m=1.7$, 1.8 and 1.9 of the earthquakes at Tango, Nankai and Fukui, calculated by Ziro Suzuki.

(a)

(b)

(c)

(d)

(e)

(f)

(g)

Fig. 41. Relation of amplitude-cumulative frequency of the Itô crypto-volcanic activity and Kita-Izu earthquake swarms (1930).

(a)

(c)

(d)

(b)

(e)

Figs. 42. Relation of amplitude-frequency of the Itô crypto-volcanic activity and Kita-Izu earthquake swarm (1930).

Remarks

The present paper deals with the principal results of the writer's study on the earthquakes in association with the volcanic activity of Volcano Usu (1943-1945). The writer's next plan is a study of the earthquakes related to the volcanic activity of Sakurajima, Hakone (1959-1960) and Itô (1930), from the same viewpoint as in the case of Usu. He intends to compare the result to be obtained with the known data of Usu (1943-1945), (1910), Rabaul (1942-1945), Aso (1946) and Ōshima (1950-1951), to analyse the general characters and differences of each volcanic activity, to extract common features of volcanic activity, and to contribute something to the solution of the problem of prediction of eruption.

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References

- EWING, M. and F. PRESS, 1954: An investigation of mantle Rayleigh waves, *Bull. Seism. Soc. Amer.*, **44**, 127~147.
- GUTENBERG, B. and C. F. RICHTER, 1936: *Gerl. Beitr.*, **47**, 92.
- GUTENBERG, B. and C. F. RICHTER, 1956: Earthquake magnitude, intensity, energy, and acceleration (Second paper). *Bull. Seism. Soc. Amer.*, **46**, 105~145.
- ISHIKAWA, T., 1950: New eruption of Usu volcano. Hokkaido, Japan during 1943~1945, *Jour. Fac. Sci., Hokkaido Univ.*, Ser. 4, **7**, 237~260.
- JARDETZKY, W. S. and FRANK PRESS, 1953: Crustal structure and surface-wave dispersion, Part III, *Bull. Seism. Soc. Amer.*, **43**, 137.
- KATSUMATA, M., 1955: Ground coefficient for amplitude of earthquakes; *Quart. Jour. Seism.*, **19**, Nos. 3-4, 77~80.
- KIZAWA, TAKASHI, 1941: Investigation of the great earthquake in Chile of January 25, 1939, *Quart. Jour. Seism.*, **11**, 435~468.
- KIZAWA, TAKASHI, 1951: Volcanic tremor and tilting of ground, *Quart. Jour. Seism.*, **15**, 18~34.
- KIZAWA, TAKASHI, 1951: Geophysical phenomena in relation to volcanic activity (I), *Jour. Met. Res.*, **3**, 249~260.
- KIZAWA, TAKASHI, 1951: Geophysical phenomena in relation to volcanic activity (II), *Jour. Met. Res.*, **3**, 277~291.
- KIZAWA, TAKASHI, 1952: Geophysical phenomena accompanied by volcanic activities, *Geophys. Mag.*, **23**, 389~397.
- KIZAWA, TAKASHI, 1957: A study of earthquakes in relation to volcanic activity (I), *Pap. Met. Geophys.*, **8**, 150~169.

- KIZAWA, TAKASHI, 1959: A study of earthquakes in relation to volcanic activity (II), *Pap. Met. Geophys.*, **9**, 204~239.
- KIZAWA, TAKASHI, 1960: Some new phases observed in a study of earthquake swarms relating to volcanic activity (I), *Geophys. Mag.*, **29**, 477~498.
- KIZAWA, TAKASHI and RINZO YAMAGUTI, 1960: Some new phases observed in a study of earthquake swarms relating to Volcanic Activity (II), *Geophys. Mag.*, **30**, 93~129.
- MATUMOTO, T., 1959: Tesikaga earthquake of Jan. 31, 1959, *Bull. Earthquake Res. Inst.*, **37**, 531~544.
- MATUZAWA, T., 1928: "Observation of some of recent earthquakes and their time-distance curves", *Bull. Earthquake Res. Inst.*, **5**, 1~28.
- MATUZAWA, T., 1959: On the crustal structure in North-East Japan by explosion seismic observations, *Bull. Earthquake Res. Inst.*, **37**, 123~154.
- MIMATSU, M., 1949: Read at E.R.I. (June 1949).
- MINAKAMI, T., T. ISHIKAWA and K. YAGI, 1951: The 1944 eruption of volcano Usu in Hokkaido, *Japan Bull. Volcanologique*, Ser. 2, Tome 11, 45~157.
- MINAKAMI, T., T. MIYAZAKI and T. TAKAHASHI, 1951: The 1950-1951 eruption of Oo-sima and its seismometrical investigations (I), *Bull. Earthquake Res. Inst.*, **29**, 359~381.
- MOHOROVIĆ, A., 1909: "Das Beben, Vom 8, X 1909" *Zagreb.*, **9**, 1~63.
- NAKAMURA, S., 1954: *Seismology*, 277.
- PEKERIS, C.L., 1948: Theory of propagation of explosive sound in shallow water, *Geol. Soc. Amer. Mem.*, **27**, 1~116.
- PEKERIS, C.L. and I.M. LONGMAN, 1958: Ray theory solution of the problem of propagation of explosive sound in a layered liquid, *Journ. Acoust. Soc. Amer.*, **30**, 323~328.
- PEKERIS, C.L., I.M. LONGMAN and H. LIPSON, 1959: Application of ray theory to the problem of long-range propagation of explosive sound in a layered liquid, *B.S.S.A.*, **49**, 247~250.
- PRESS, F., M. EWING and I. TOLSTOY, 1950: The Airy phase of shallow-focus submarine earthquakes, *B.S.S.A.*, **40**, 111~148.
- PRESS, F., A.P. CRARY, J. OLIVER and S. KATZ, 1951: Air-coupled flexural waves in floating ice, *Trans. Amer. Geophys. Un.*, **32**, 166~172.
- PRESS F. and M. EWING, 1951 a: Theory of air-coupled flexural waves, *Journ. Appl. Phys.*, **22**, 892~899.
- PRESS, F. and M. EWING, 1951 b: Ground roll coupling to atmospheric compressional waves, *Geophysics*, **16**, 416~430.
- SASSA K., 1935: Volcanic micro-tremors and eruption-earthquakes, *Memoirs Colle. Sci. Kyoto Univ.*, **18**, 255~293.
- SASSA K., 1936: Micro-seismometric study on eruptions of the Volcano Aso. *Memoirs Colle. Science, Kyoto Univ.*, **19**, 11~56.
- SASSA K., 1936: Anomalous deflection of seismic rays in Volcanic Districts, *Memoirs Colle. Sci. Kyoto Univ.*, **19**, 65~78.
- SATÔ, Y. and RINZO YAMAGUCHI, 1959: Velocity equation of the love waves propagated in multi-layered media, *Zisin (Jour. Seism. Soc. Japan.)*, **12**, 61~67.
- SUZUKI, Z., 1955: A statistical study on the occurrence of small earthquakes, II, *Sci. Rep. Tohoku Univ.*, Ser. 5, *Geophy.*, **6**, 2, 105-118.
- TAKAHASHI R. and T. NAGATA, 1939: On the earthquake swarm which occurred in Oshima on June 18, 1938, *Jour. Seism. Soc. Japan.*, **11**, 161~167.
- TSUBOI, C., 1954: Determination of the Gutenberg-Richter's magnitude of earthquakes occurring in and near Japan, *Jour. Seism. Soc., Japan*, Ser. 2, **7**, 185~193.
- TSUBOI, C., 1957: On the magnitudes of earthquakes, *Jour. Seism. Soc. Japan*, **10**, 6~23.
- WADATI K., 1931: Shallow and deep earthquakes (3rd paper), *Geophys. Mag.*, **4**, 231~283.
- WADATI, K., K. SAGISAKA and K. MASUDA, 1933: On the travel time of earthquake waves (Part I), *Geophys. Mag.*, **7**, 87~99.

火山活動に關係する地震の研究 (III)

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有珠火山の活動に伴って出現した一連の地震群 (Dec. 1943~Oct. 1945) について 引続き研究して得られた結果の主な概要を ここに第3報として報告する

1. 噴火活動に先駆する地震群 (A-type 地震) を調べた結果 昭和新山付近の distance coefficient の値として $k=8.2$ km/sec を得た 同時に震源の深さは 10 km と求められた そしてその深さは噴火に近づくに従い次第に浅くなる事を示した

2. 表面波についての最大振巾の減衰式

$$A=A_0 \Delta^{-\frac{1}{2}} e^{-\alpha \Delta}$$

において 主な A-type 地震の観測値から $\alpha=5.8 \times 10^{-3}$ km⁻¹ 及び $\alpha=5.6 \times 10^{-3}$ km⁻¹ を得た 構造地震の諸値 (α) と比較した

3. 先駆地震群の地震数 $N(t)$ と振巾 $A(t)$ が時間と共にどう変化して噴火に近づくかを求めた 3 観測所の値はいずれも一応

$$N(t)=K(t+c)^{-p}, \quad A(t)=K'(t+c')^{-p'}$$

で現わされることを知った 各常数をそれぞれ求めた

4. 森測候所 ($\Delta=54$ km) に記録された多くの A-type 地震波から S波の数秒後に明瞭なその反射波 S' を見出し モホ層の深さ $H=25$ km (平均値) を得た

5. 地震のエネルギー及び 土地の隆起エネルギーを算出し 地震数 その他の現象との関連を考察した

6. 森測候所の地震記録から 特別な新しい2つの相を見出した 伝播径路は海である 伝播径路の地殻構造を [liquid-liquid-solid] 及び [liquid-solid-solid] の3層構造とし 各層に常数をいろいろと与えて I. B. M. 704 電子計算機により 各 case の Rayleigh wave の分散曲線を求めた 第2層の Sedimentary layer が solid の場合 その Compressional wave の速度を第1層のそれよりも小さくとり thickness を適当にとる事によつて始めて問題の2つの相を説明する最も有望な結果が得られた

Sedimentary layer の存在と性質更にはその大きな作用について強力な暗示を得た 桜島 - 鹿児島 (1939, 1946年) でも 同じ性質と思われる 2, 3 の相を見出した

7. 1930年の Itō crypto-volcanic activity 及び同年の北伊豆地震群について石本-飯田の表現

$$ndA=kA^{-m} dA$$

における m の値を求めた 有珠の地震群から得られた m と比較した