Special Contributions, Geophysical Institute, Kyoto University, No. 4, 1964, 91-104

A SIMPLIFIED MODEL OF UPPER CRUST FROM SEISMIC WAVE VELOCITIES AT VOLCANO ASO

By

Tatsuhiko WADA and Kosuke KAMO

(Received September 30, 1964)

Abstract

The observation of the volcanic earthquakes occurred near the Volcano Aso and the tectonic earthquakes of near-distance was carried out by the method of a tripartite net using a magnetic tape recorder, and the wireless telemetering system by which seismic signals were transmitted from Hondô, being near the crater, to the Laboratory. The seismic wave velocities for the upper layer are $V_p = 2.8$ km/sec and $V_s = 1.6$ km/sec, and $V_p' = 5.0$ km/sec for the under layer. The thickness of the upper layer is at least 3.7 km. The locations of source for the volcanic earthquakes originated in the Volcano Aso were determined based on the model with a single layer over a half space.

Introduction

To determine the foci of volcanic earthquake is difficult since the structure of the crust in the volcanic area is generally complex and moreover the epicentral distance of observed earthquake is small due to small energy of the shot. The authors try to get a model of the crustal structure of the Volcano Aso, as the first approach, and determined the velocities of seismic waves for the shallow part of the crust from the observation of the small earthquake swarm originated near the crater, and for the deeper part from that of near-distant earthquakes.

Near the Aso Volcanological Laboratory of Kyoto University, a tripartite observation of seismic waves was carried out during the period from October 1962 to March 1963 to detect the volcanic earthquakes originated in and near the Aso caldera. The locations of the volcanic earthquakes were determined based on the crustal structure of a layer over half space deduced from the velocities of seismic waves.

Observing system

Since 1960, the wireless telemetering equipment of FM-FM modulation for seismographs has been working as a routine of the Laboratory. The transmitter connected with seismometers ($T_0 = 1$ sec., $h_0 = 1$), through pre-amplifiers, is set at the

Hondô station, 1 km westward to the crater, and the receiver is at the Laboratory, 6.4 km westward to Hondô as shown in Fig. 1. The same kinds of seismographs were set at Hondô and the Laboratory. The time signals from one clock are marked on both records, the smoked paper type driven with 2 mm/sec drum-speed. The

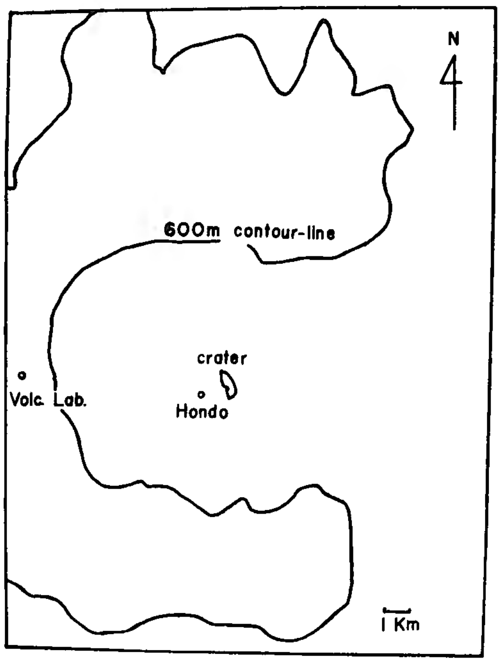

Fig. 1. Topographic map of the stations.

schematic diagram is shown in Fig. 2. On good condition of weather and radio-wave transmission, both traces of seismographs at the Laboratory and Hondô were recorded simultaneously on an oscillograph. An oscillogram is shown in Fig. 3, where (1) is the trace of the seismometer of 1 sec. period, (2) is of 1/15 sec., (3) is of 4 sec. at the Laboratory and (4) is of 1 sec. at Hondô by the telemetering system. The period of galvanometer of oscillograph is 30 cycles. The arrival times can be read within precision of 0.05 seconds in time.

On the other hand, the tripartite observing net was set near the Laboratory and the length of each side was 580 m. Three horizontal seismometers (T_0=0.7 sec. and h_0=1) at the vertexes of the triangle net were connected through pre-amplifiers to the data recorder equipped with PWM modulator and demodulator, of which tape speed is 1.9 cm/sec for recording and 19 cm/sec for reproducing. Then the reproducing seismogram can be recorded on the oscillograph by driving oscillo-

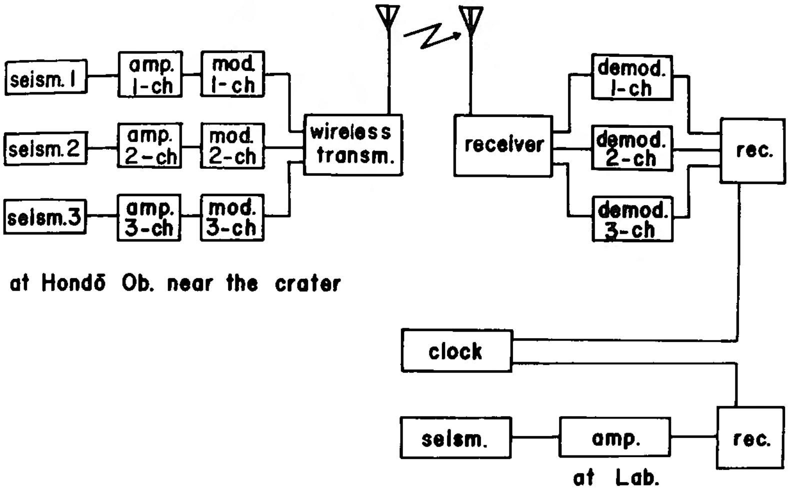

Fig. 2. Block diagram of telemetering system.

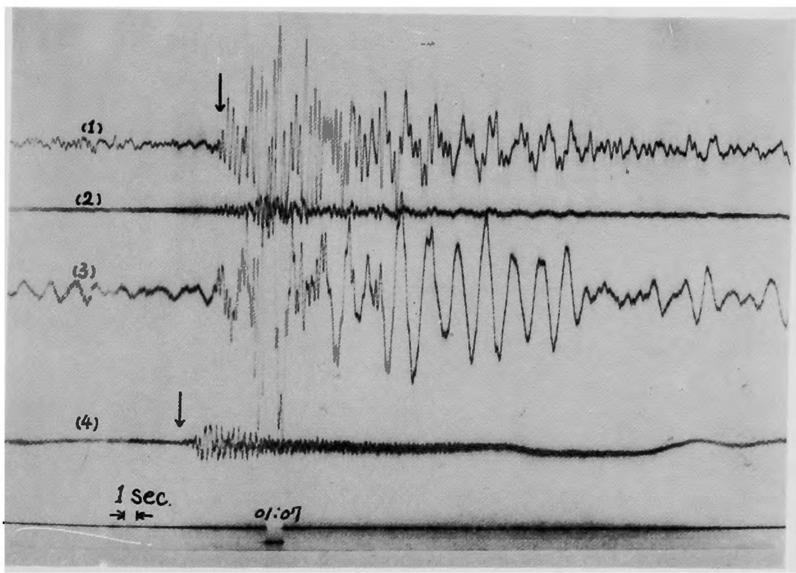

Fig. 3. An example of oscillogram.

graph high speed. The apparent velocity and coming direction of seismic wave can be determined by identifying each phase within the precision of several degrees in direction and of 10 percents in velocity.

Data and analysis

1. Velocities of seismic waves near the ground surface

The swarm of the micro volcanic earthquakes originated near the crater was observed during the period from Jan. to June in 1962. The number of the earthquakes amounted to 200 per day in peak as shown in Fig. 4. A seismogram recorded by the telemetering system is shown in Fig. 5. It is examined by the seismometric observation with the temporary five stations that the epicenters of the swarm were at

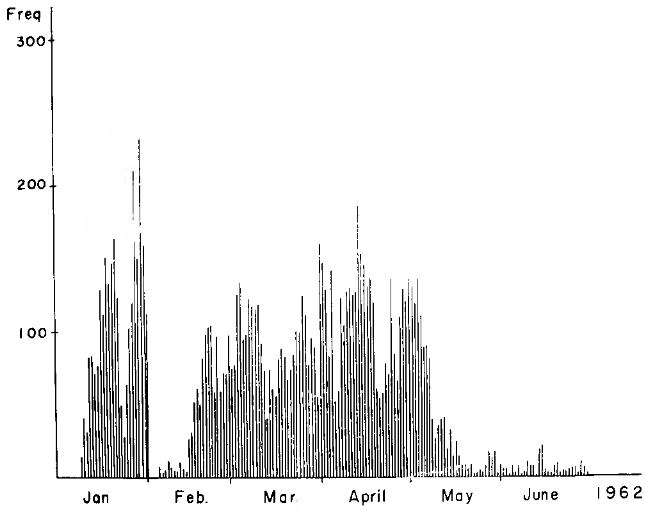

Fig. 4. Frequency of the volcanic micro earthquakes generated near the crater of Volcano Aso from Jan. to June 1962.

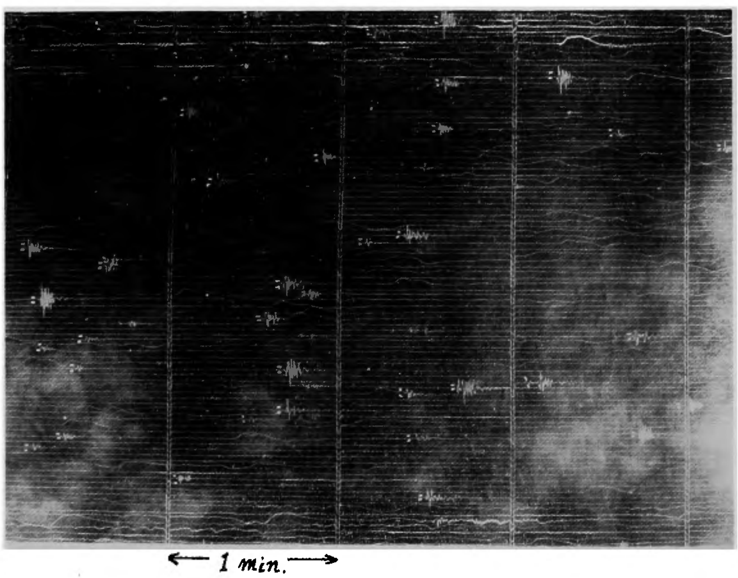

Fig. 5. A seismogram of the volcanic micro-earthquakes generated near the crater, recorded by the telemetering system.

the west side of the crater and its depth was about 500 m.

On the April 20th, 1962, about 30 earthquakes were recorded for several hours. Among them, 15 earthquakes were clear enough to distinguish the arrival times. The observed data are listed in Fig. 3. The similarity of the seismic wave form suggests that the swarm may occur in the same area. The values of S-P time, V_p and V_s in Table 1 are scattered widely beyond the reading error and it may show that the foci

Table 1. Velocities of seismic waves near the ground surface

Shock No.	Time	S-P in sec.		V_p km/sec.	V_s km/sec.
		Lab.	Hondô		
3	00 : 00	2.54	0.75	2.96	1.86
4	00 : 01	2.17	0.81	2.66	1.52
7	00 : 30	2.53	0.73	3.00	1.60
8	00 : 34	2.45	0.91	2.79	1.74
10	00 : 53	2.32	0.90	2.71	1.61
12	00 : 59	2.36	0.87	2.90	1.76
13	01 : 04	2.49	0.81	2.74	1.56
14	01 : 06	2.53	0.98	2.52	1.61
16	01 : 32	2.84	1.05	2.69	1.54
18	01 : 43	2.10	0.68	2.74	1.58
19	01 : 48	2.87	0.90	2.76	1.51
21	02 : 08	2.50	0.75	2.70	1.57
22	02 : 15	2.33	0.85	2.71	1.62
25	02 : 24	2.44	0.81	2.70	1.55
26	02 . 33	2.54	0.78	2.84	1.64

Mean: $V_p=2.8\pm0.3$ km/sec
$V_s=1.6\pm0.2$ km/sec
$k=3.7\pm0.3$

of those earthquakes are in a definite space and each path of wave is different due to micro-structure. The values of V_p, V_s and k for the layer near the ground surface are evaluated as mean value in disregard of the minute structure of local crust, as following;

$$V_p = 2.8\pm0.3 \quad \text{km/sec}$$
$$V_s = 1.6\pm0.2 \quad \text{km/sec}$$
$$k = 3.7\pm0.3$$

where k is $V_pV_s/(V_p-V_s)$. The velocity V_p of P-wave obtained is in coincidence with the mean velocity of 2.9 km/sec measured by means of the seismic refraction for the volcanic rocks including tuff at the central part of Kyushu by Hattori [1962].

2. Analysis of near-distant earthquakes

Now we assume, for simplicity, a layered structure for the Aso Volcano region, then the true velocity V_p in the under layer may be approximated with the minimum value of apparent velocity obtained from the data observed at two stations. To obtain the apparent velocities, if the direction connecting the Laboratory with Hondô is slightly differed from the epicentral direction, the distance between the Laboratory and Hondô may be approximated by that between the Laboratory and H', where H' is the projected point of Hondô on the line connecting the Laboratory with the epicenter, as shown in Fig. 6. The region where the approximation error is within 1% or 10% as a function of epicentral direction is shown in Fig. 7.

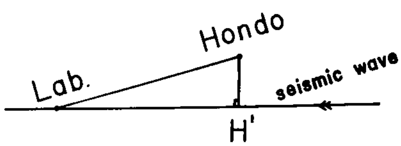

Fig. 6. Schematic illustration of the seismic path and stations.

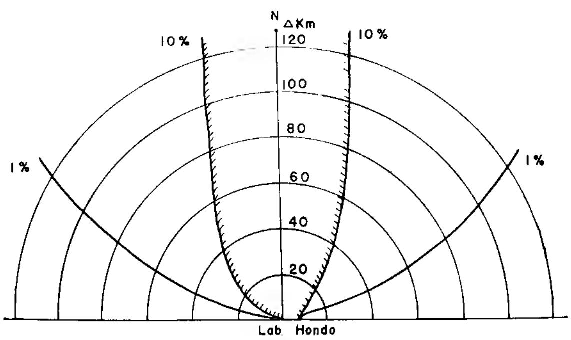

Fig. 7. The region where the approximation error of epicentral distance is within 1% or 10%.

During the period from April 1960 to December 1962, the onsets of 159 earthquakes were recorded clearly. The apparent velocities were evaluated from 38 earthquakes of them, of which epicenters had been determined by Japan Meteorological Agency and U.S.C.G.S., and were in the zone of 10 percents illustrated by the outer part of shadow in Fig. 7.

Table 2. Data of near-distant earthquakes

(1) Off Miyazaki

Earthquake No.	Date	Time	Azimuth of epicenter	Δ km	$\Delta T_{(L-H)}$ sec.	$V_{app.}$ km/sec	Published data
6007- 3	July 3	18 : 39	141°25′	135.3	−0.74	6.07	31°54′N, 131°54′E, h=40 km
6009- 3	Sep. 4	10 : 14	137°15′	135.3	−0.83	5.80	32°00′N, 132°00′E, h=20 km
6009- 9	Sep. 26	20 : 37	106°55′	102.2	−0.58	10.83	32°30′N, 132°00′E, h=20 km
6101- 2	Jan. 6	21 : 52	156°30′	135.3	−0.35	9.00	31°46′N, 131°35′E, h=20 km
6102- 5	Feb. 27	03 : 12	151°45′	162.8	−0.32	11.28	31°36′N, 131°51′E, h=40 km
6102- 6	Feb. 27	15 : 30	150°10′	160.6	−0.09	41.67	31°38′N, 131°52′E, h=00 km
6108- 4	Aug. 11	13 : 28	142°05′	170.6	−0.80	5.55	31°40′N, 132°07′E, h=00 km
6108- 5	Aug. 11	15 : 09	140°55′	173.2	−0.82	5.52	31°41′N, 132°11′E, h=40 km
6108- 7	Aug. 14	00 : 41	140°55′	180.0	−0.47	9.64	31°37′N, 132°12′E, h=40 km
6108-10	Aug. 15	07 : 05	153°20′	177.8	−0.16	21.56	31°27′N, 131°51′E, h=00 km
6111- 1	Jan. 4	06 : 14	163°05′	190.3	−0.40	6.22	31°31′N, 131°37′E, h=60 km
6111- 4	Jan. 27	14 : 57	165°15′	182.8	−0.17	13.35	31°18′N, 131°33′E, h=40 km
6201- 1	Jan. 23	21 : 28	148°45′	123.7	−0.10	38.70	31°56′N, 131°42′E, h= ?
6202- 2	Feb. 10	03 : 23	162°10′	101.0	−0.13	19.92	32°01′N, 131°27′E, h=00 km
6209- 3	Sep. 24	19 : 21	90°00′	95.1	−0.34	39.75	32°42′N, 132°00′E, h=40 km
6212-23	Dec. 28	13 : 00	146°35′	155.8	−0.40	9.90	31°42′N, 131°54′E, h=10 km
(2) Kumamoto & Ariake							
6102- 4	Feb. 20	23 : 44	283°55′	60.8	+1.05	6.04	32°57′N, 130°22′E, h=20 km
6105- 3	May 3	11 : 33	282°20′	55.7	+0.99	6.42	33°05′N, 130°28′E, h=20 km
6107-10	July 23	02 : 32	282°20′	58.3	+0.71	8.96	33°05′N, 130°26′E, h=00 km
6108- 8	Aug. 14	11 : 14	270°00′	68.6	+1.13	5.63	32°58′N, 130°17′E, h=40 km
6108-15	Aug. 23	09 : 07	288°00′	64.0	+1.18	5.31	32°59′N, 130°20′E, h=00 km
6109- 4	Sep. 10	12 : 46	302°45′	26.5	+0.89	6.43	32°57′N, 130°44′E, h=00 km
6110- 1	Oct. 2	00 : 22	90°00′	19.5	−0.80	7.95	32°53′N, 131°13′E, h=20 km
6110- 2	Oct. 11	07 : 41	278°40′	52.0	+1.25	5.11	33°00′N, 130°28′E, h=00 km
6111- 2	Nov. 9	20 : 20	90°00′	22.4	−0.71	8.96	32°55′N, 131°14′E, h=40 km
6112- 1	Dec. 11	13 : 58	270°00′	31.6	+0.73	8.71	32°46′N, 130°42′E, h=00 km
6202- 3	Feb. 10	03 : 23	288°00′	61.6	+0.27	23.19	33°03′N, 130°23′E, h=20 km
6204- 1	Apr. 13	15 : 41	270°45′	95.2	+0.89	7.16	33°00′N, 130°00′E, h= ?
(3) Off Oita							
6108- 2	Aug. 1	19 : 30	90°00′	44.7	−0.14	45.43	32°57′N, 131°29′E, h=100 km
(4) Honshu & Shikoku							
6012- 3	Dec. 26	10 : 46	60°55′	330.5	−0.35	18.23	34°12′N, 134°12′E, h=60 km
6104- 6	Apr. 28	06 : 32	62°50′	135.7	−0.49	12.96	33°25′N, 132°19′E, h=20 km
6109- 9	Sep. 14	10 : 08	90°00′	122.1	−0.89	7.15	32°44′N, 132°18′E, h=20 km
6110- 3	Nov. 13	18 : 53	64°05′	119.6	−0.18	30.17	33°24′N, 132°08′E, h=80 km
6209- 2	Sep. 8	13 : 39	68°40′	388.1	−0.54	10.54	32°42′N, 132°00′E, h=40 km
6209- 4	Sep. 25	11 : 37	54°05′	125.6	−0.53	8.98	33°48′N, 131°48′E, h=10 km

$\Delta T_{(L-H)}$ is corrected for elevation. Valcanological Laboratory: 32°53′N, 131°00.5′E

The earthquakes used for analysis are grouped according to their location into four sections which are Off Miyazaki, Off Oita, Honshu and Shikoku, and Kumamoto and Ariake. The data are listed in Table 2.

In Fig. 8, the apparent velocities and coming directions of P-waves are shown

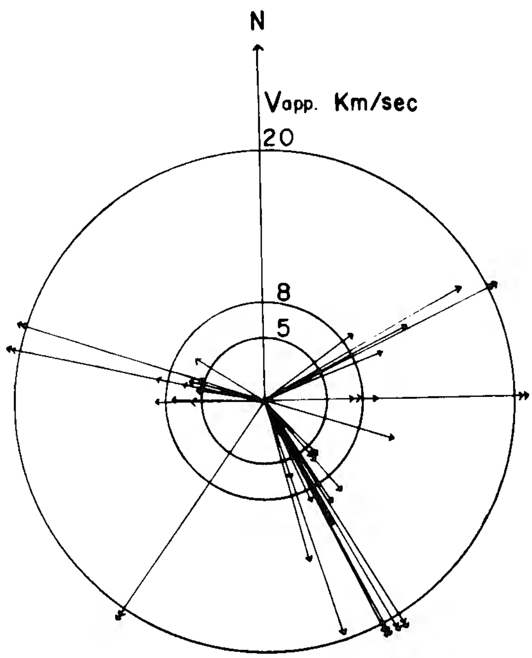

Fig. 8. Distribution of the apparent velocities and coming directions of the near-distant earthquake waves in vectors.

in vector, and the double arrows illustrate the apparent velocities over 20 km/sec. The relation between the epicentral distance and the apparent velocity is shown in Fig. 9. From this figure it is seen that the apparent velocity 5 km/sec for the earthquakes originated at Kumamoto and Ariake, 6 km/sec for Off Miyazaki and more than 6 km/sec for Honshu and Shikoku are obtained as the minimum value. It may be suggested that 5 km/sec represents the velocity of P-wave in the lower layer under the upper layer where the velocity of P-wave is 2.8 km/sec and for the third layer the P-wave velocity may be more than 6 km/sec.

3. Directional distribution of volcanic earthquakes

The tripartite observation was carried out from October 1962 to March 1963.

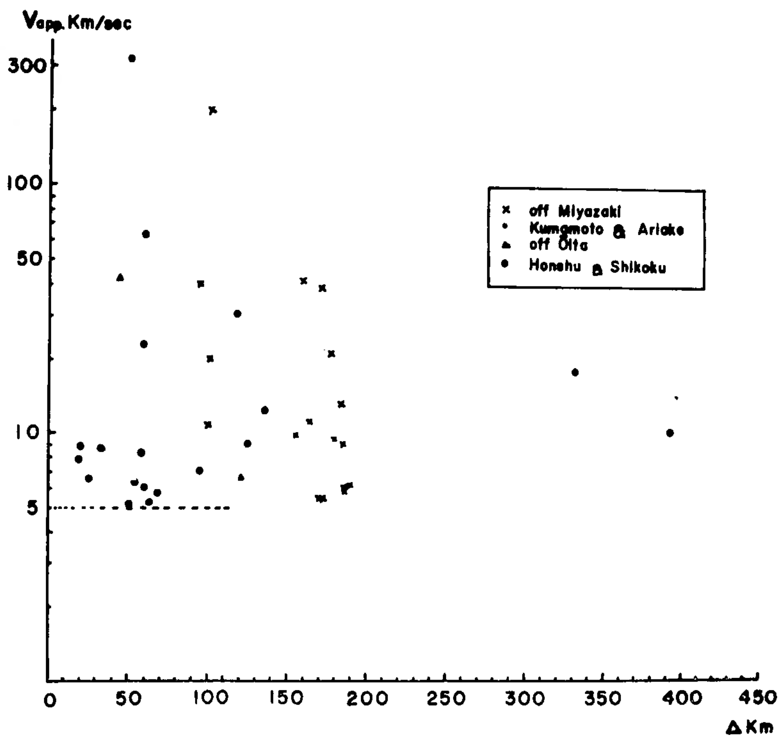

Fig. 9. Relation of epicentral distance and apparent velocity for the near-distant earthquakes.

On the seismograms of three stations, the identification of each phases is well established, as shown in Fig. 10.

Among the earthquake's records, the earthquakes of which the P-S times were smaller than 14 sec. were picked up, that is, their epicenters were located in and near the Aso caldera. It is noted that the "volcanic earthquake" used here is defined only by the mean that the foci are located in the volcanic area, and all of them may be regarded as dependent on volcanism.

The apparent velocity and coming direction of seismic wave are determined by the phase method. We calculated the values from the initial phase. The apparent velocities and coming direction of seismic waves distribute as shown in Fig. 11 and the relation between the apparent velocities and P-S times is plotted in Fig. 12. From the latter figure, it is seen that the minimum value of the apparent velocity is compatible with 2.8 km/sec of P-wave velocity in the upper layer obtained previously. It is considered that the focal depth may be deep, because the apparent velocities are larger than the estimated velocity of the upper layer and the foci distribute in the direction from the west to the north of the crater.

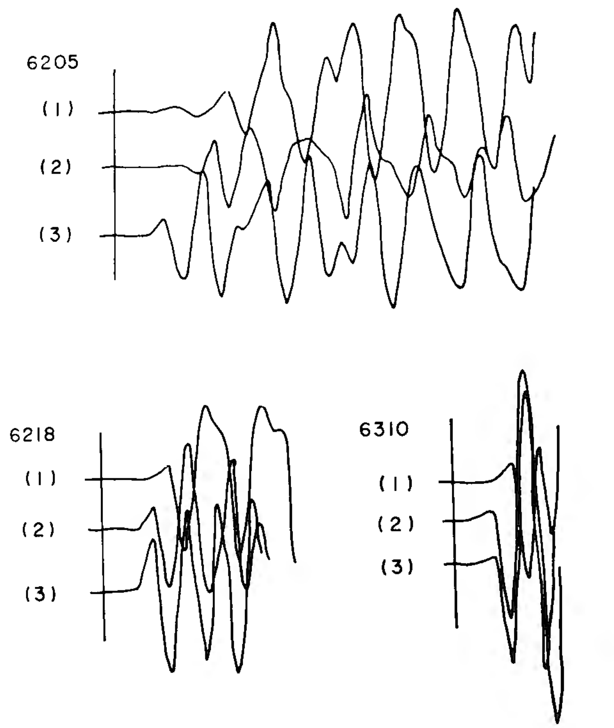

Fig. 10. Examples of the oscillogram of tripartite observation.

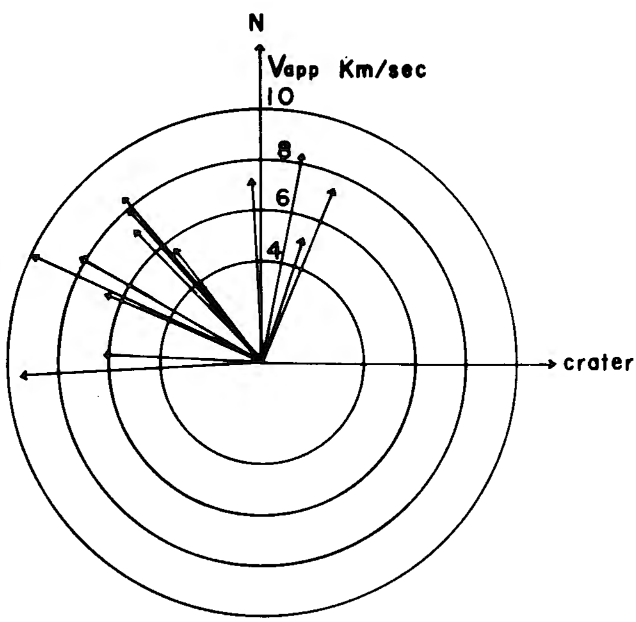

Fig. 11. Distribution of the apparent velocities and coming directions of volcanic earthquake waves in vectors.

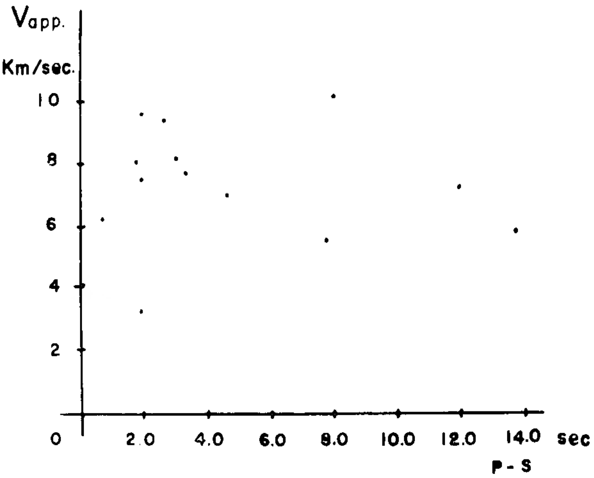

Fig. 12. Relation of the apparent velocity and P-S times for volcanic earthquakes.

4. A model of crustal structure and the distribution of volcanic earthquakes

The minimum apparent velocities are obtained from the tectonic and volcanic earthquakes by the observation of two stations and the tripartite observation in previous sections. A simplified crustal structure may be deduced from the relation of the minimum apparent velocities and their epicentral distances. $V_1=2.8$ km/sec and $V_2=5$ km/sec are taken as the P-wave velocity in the upper layer and under layer, respectively. The $V_2=5$ km/sec in the under layer is not found in the observation of the volcanic earthquake swarm originated near the Hondô station, with two stations, the Laboratory and Hondô, which are apart by 6.4 km in distance. Thus the value of $V_2=5$ km/sec cannot be obtained in calculation even if the thickness of the upper layer is taken as 4.7 km, that is, the thickness of the upper layer must be taken as larger than 3.7 km. Then limiting to consider for the model of a layer over half space, we assume that the thickness of the upper layer where the P-wave velocity is 2.8 km/sec, is 4 km, of which value should be improved by more detailed data in future. It is considered that this model is comparable with the Eaton's model [1960] of Hawaii Is., where the layer of P-wave velocity 3.4 km/sec has the thickness of 5 km.

None of the information about the Mohorovičić discontinuity, one of the subject of this study, is obtained from seismic data.

The pattern of P-wave path in the crustal structure model is shown in Fig. 13 where $k_1=3.7$ for the upper layer and $k_2=7.2$ for the under layer which is used to be taken generally for the crust in Japan. According to the pattern of P-wave path in

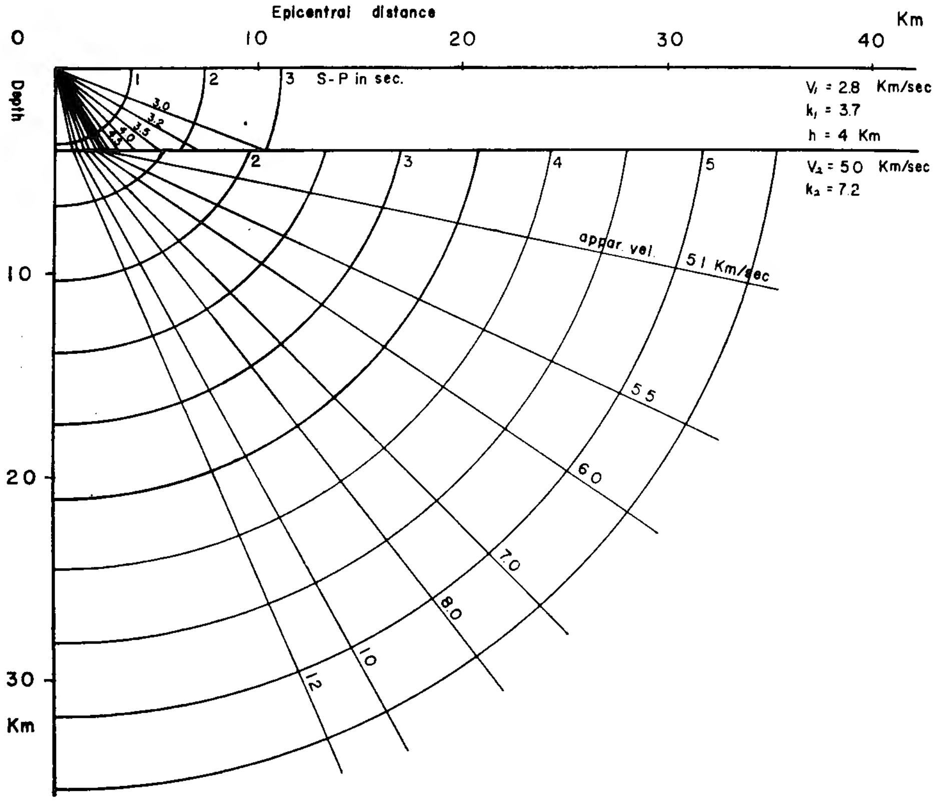

Fig. 13. A model of crustal structure and the pattern of P-wave path.

Fig. 13, the epicenters of the volcanic earthquakes originated in and near the Aso caldera are plotted in Fig. 14 where the numbers represent their depth in km. The deeper the depth of epicenter becomes, the longer P-S time is, or the larger the apparent velocity is, because of the lack of data about the third layer in the model.

It may be suggested that the foci of volcanic earthquakes at the Volcano Aso concentrate in the area near the north-westward rim of the caldera and their depth becomes suddenly deep at the outside of the caldera rim compared with that at inside of it. All the initial motion are push phase except one.

The model was examined for the earthquakes detected simultaneously by the tripartite observing system and the two stations, by the following way: the location is determined with the data of tripartite observation and the crustral structure, the travel times of P-wave from the focus obtained above to each of two stations are calculated on the crustal structure and then we compare the difference of arrival time observed with that calculated above. As the results, both values obtained coincide

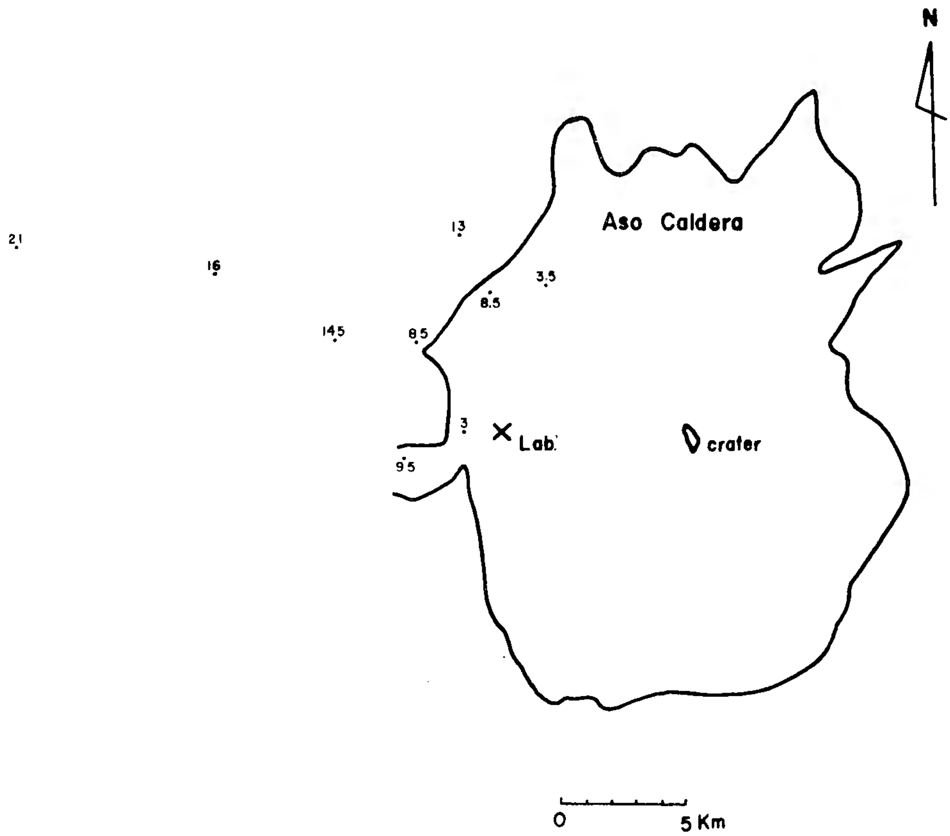

Fig. 14. The distribution of the foci of the volcanic earthquakes in and near the Aso caldera.

satisfactorily with each other within the accuracy that the focus lies within the sphere of 1 km in radius.

5. Summary and discussion

A simplified model of upper crust of the Volcano Aso is deduced from the velocities of seismic waves under the assumption of a homogeneous and parallel layer over half space. Conclusive results are as following:

1. The velocity of P-wave is 2.8 km/sec for the upper layer and 5 km/sec for the under layer from the observation of the tectonic and volcanic earthquakes, respectively.
2. The thickness of the upper layer must be taken more than 3.7 km to find the velocity of 5 km/sec of the under layer for the assumed structure.
3. The foci concentrate in the limited area near the northwestward rim of the caldera.

4. The depth of focus is deeper at the outside than at the inside of the caldera rim.
5. The initial motions of the volcanic earthquakes except one are push type.

We compare our results with those by Sassa [1936], who determined the epicenters from the emergent angles of P-wave at the Laboratory. The epicentral distribution determined here is compatible with that obtained in the most active stage of volcanism in 1933, but the depth distribution of the focus is not. According to his results, the epicenters distribute in the district westward to the present active crater, and the foci are located at the deepest part near the caldera rim. By his opinion, this fact may be related with the formation of caldera.

In our results, it is interesting that the epicenters at the outside of caldera lie on the line connecting the present active craters of Naka-dake and Kuraga-dake which is an older volcano than the Volcano Aso, and that this line coincides with the main rupture line in the caldera where the four volcanoes, Kisima-dake, Ozyô-dake, Kome-zuka and Zyano-o, lie.

By Sassa's opinion, it is probable that the initial motion of push type is found more frequently than of pull type in the decayed stage of volcanism. It seems that the volcanism is now in quiescent stage.

Acknowledgements

Acknowledgement is due to the Emeritus Professor K. Sassa of Kyoto University who advise and encourage us. The authors wish also to thanks Mr. T. Hoka and Miss K. Imamura of the Aso Volcanological Laboratory of Kyoto University for the observation and reading of seismograms.

References

Eaton, J. P. and K. J. Murata, 1960; How volcanoes grow, Science, 132, No. 3432, 925-938.

Hattori, Y., 1962; A study on the interpretation of the time-distance curves of refraction wave, Nippon Butsuri-Tanko K., Enginerring Geology, Ser. 2.

Sassa, K., 1936; Micro-seismometric study on eruption of the Volcano Aso, Mem.Fac. Scienec, Kyoto Univ., Ser. A, 19, 11-56.