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APPARENT AZIMUTHS OF P WAVES AND A STRUCTURE UNDER THE VOLCANO ASO

By

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Abstract

Azimuthal deviations of P waves, differences between the true azimuths and directions of arrivals of the initial phases, are examined by analyzing the seismetric data at the Aso Volcanological Laboratory.

The recent data are added to the previous data given by Sassa [1936] and the total data exhibit a systematic azimuthal deviation with azimuth. The deviation can be interpreted by the following structural model under the Aso Caldera: a tectonic line or zone runs across the center of the caldera from east to west, the northern block inclining nearly eastwards with the dip of about 15° and the southern block toward NNE with the dip of about 25°

It is also shown that the chain of the central volcanoes is situated on the tectonic line or zone and that the sky-line of the caldera rim has a similar inclination to that of each block.

1. Introduction

A geophysical study of the Aso Caldera was made for the first time by Sassa [1936]. From the data of earthquakes which occurred outside the caldera he pointed out that the apparent directions of approach of P waves to the observatory inside of the caldera are different from the true azimuths and that the azimuthal deviations also vary systematically with each azimuth. Considering the topographical particularity of the caldera form, he thought it reasonable to assume a cylindrical model to interpret the deviation. Beside of the problem of volcano structure, some seismologists, at that time, also considered azimuthal deviations and tried to utilize them to determine the crustal structure (Nakamura (S.) [1929], Kishinoue [1932] and Matsuzawa [1935]). As shown by the history of seismology, however, since then major efforts of seismologists have been made to elucidate the grobal structure of the earth and then the azimuthal deviations of P waves seem to be considered as less important. So only a few, for example Utsu [1956] and Ritsema [1959], have attended to the phenomena.

Recently, the fine structure of typical parts of crust have studied from the geotectonic aspect, which is enforced by the study of earth's evolution. The Aso Caldera is not only an active volcano, but is also situated in Central Kyushu, which is a very interesting part of the Japan Island Arc. From this point of view the authors studied the azimuthal deviation of P wave by the data from the seismographs of the Volcanological Laboratory of Kyoto University which is situated inside the caldera.

2. Data

The seismograms used in this study were recorded by the Wiechert-type seismographs with a pendulum weighing 1 ton. Among the instruments operated at the laboratory, they are the most adequate for the purpose of this study. Galitzin seismograms were also used as auxiliary data to improve the accuracy.

After instrumental corrections the apparent azimuths were determined as accurately as possible and compared with the true azimuths which were determined from the Seismological Bulletin of the Japan Meteorological Agency (JMA). In such a way 36 earthquakes during the period from 1958 to 1969 were picked up and the azimuthal deviations were indicated as a function of azimuth. They are listed

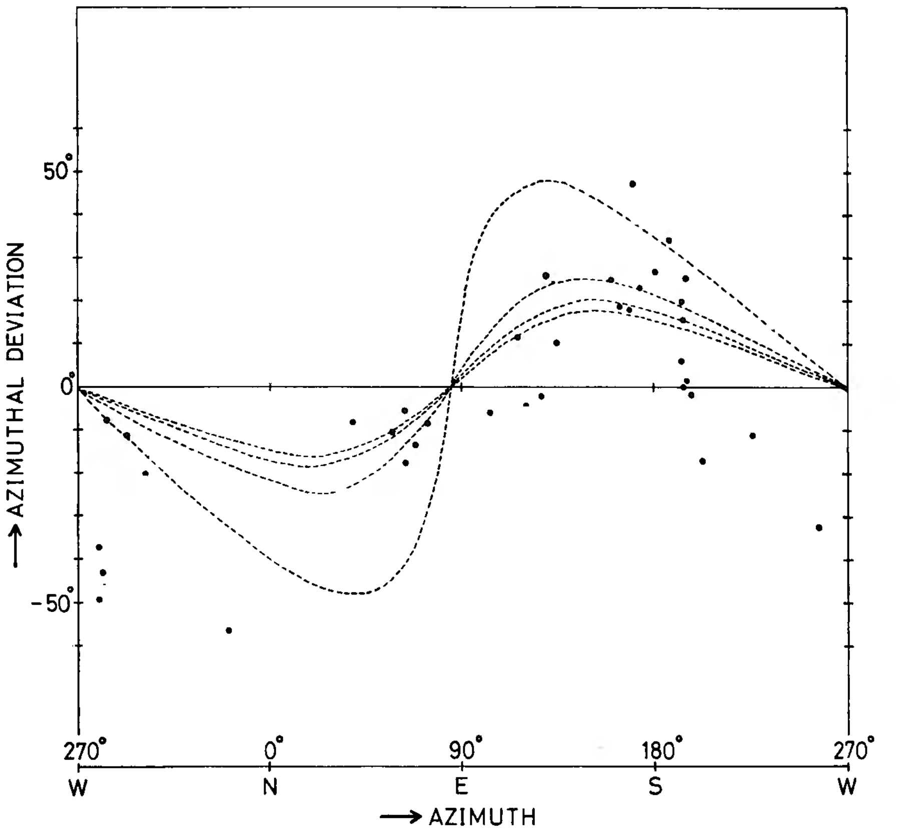

Fig. 1. Additional data of azimuthal deviation of P wave and curves calculated from the model (B) in Fig. 3.

Table 1 List of the additional data shown in Fig. 1. (The previous data given by Sassa are listed in his paper.)

No.	Date						Epicenter		H	M	A	γ
	Y	M	D	h	m	s	λ	φ	km			
1	1958	9	8	23	57	17.0	131°54′	33°48′	80		38.9°	−8.1°
2	1961	5	17	6	45	26.7	132°02′	30°27′	60	5.8	159.9°	24.9°
3		7	18	23	03	37.9	131°46′	29°37′	60	6.6	168.5°	17.9°
*4	1962	4	23	4	16	32.0	130°54′	32°10′	160		187.4°	34.1°
5		12	28	13	00	33.7	131°10′	31°41′	0	4.7	173.6°	22.9°
6	1963	10	4	8	24	31.0	132°09′	31°53′	20	6.3	154.2°	10.2°
7	1964	12	24	4	47	59.2	130°14′	30°14′	40	5.1	194.3°	0.4°
8	1965	2	7	0	06	59.9	130°26′	33°11′	0	4.0	302.0°	−20.3°
9		3	24	12	51	45.2	130°02′	33°14′	40	4.2	293.4°	−11.4°
10		12	8	14	25	12.2	130°36′	32°33′	20	4.8	226.3°	−11.4°
11	1966	2	22	11	38	40.2	130°10′	31°14′	0	4.9	203.7°	−17.5°
12		8	1	8	02	13.7	130°17′	33°02′	0	3.8	284.1°	−7.8°
*13	1967	3	2	12	25	26.7	131°22′	31°03′	10	4.9	170.5°	47.1°
*14		5	19	8	39	14.8	130°59′	30°44′	70		180.6°	26.7°
*15		7	3	5	34	41.6	130°33′	31°14′	120		193.5°	19.8°
16		11	7	9	06	10.3	130°49′	33°21′	10	4.0	341.0°	−56.7°
17	1968	1	12	11	58	35.1	132°30′	33°30′	50	4.8	63.3°	−5.7°
18		2	21	8	51	37.4	130°43′	32°01′	0	5.7	196.1°	1.5°
19		2	22	19	19	04.5	130°46′	32°00′	0	5.6	193.2°	5.9°
*20		2	25	17	49	39.6	130°44′	32°02′	10	4.7	195.5°	25.0°
21		4	1	16	13	14.2	132°23′	32°18′	0	6.3	116.2°	11.5°
*22		5	1	21	54	36.8	130°46′	32°04′	20	4.7	194.2°	15.7°
23		5	14	23	05	03.3	129°48′	29°35′	160		197.8°	−1.9°
24		8	6	11	34	39.0	132°24′	33°20′	40	4.9	68.5°	−13.5°
25		8	8	2	44	02.7	132°22′	33°12′	50	4.4	74.1°	−8.6°
26		8	8	4	20	13.2	132°22′	33°26′	40	4.2	63.9°	−17.8°
27		8	13	21	39	18.9	130°04′	32°42′	0	4.6	257.4°	−32.5°
28		8	23	22	05	52.2	132°23′	33°18′	40	4.8	69.8°	−12.4°
29		9	28	19	48	39.5	132°11′	32°17′	0	4.6	120.7°	−4.5°
30	1969	1	30	7	15	31.4	132°12′	32°38′	0	4.5	103.6°	−5.9°
31		2	5	15	09	15.8	130°14′	33°00′	10	4.2	280.4°	−49.3°
32		4	21	16	19	24.5	132°07′	32°09′	10	6.5	127.7°	−2.4°
33		4	21	19	59	26.1	132°05′	32°07′	10	4.7	129.8°	25.9°
34		5	2	2	01	06.4	130°47′	32°55′	10	3.5	280.4°	−36.9°
35		6	4	4	37	12.9	130°20′	33°00′	20	3.4	281.9°	−42.9°
36		9	18	3	40	44.8	131°41′	30°56′	0	5.9	163.4°	18.6°

* The events which deviate above from the theoretical curves in Fig. 4. Comments to those:

No. 4, No. 15: Both events have the deep foci. Generally speaking, the deep focus events should not be applied for the present purpose.

No. 20, No. 22: These events belong to the Ebino earthquake swarm. It is recognized that some of the Ebino events show a particular deviation of arrival direction. This fact may be influenced by the caldera structure of the Kakuto district.

No. 13: The arrival time is abnormal, and then the initial phase may be read wrong.

No. 14: The arrival time is normal, and then the deviation from the model can not be yet interpreted.

on Table 1 and shown in Fig. 1. (Curves in the figure are calculated from a dipping model which will be explained later.) They show essentially the same systematic deviation as those given by Sassa previously, which can be seen in his paper [1936].

3. Dipping model and twin-blocked model

In this section the azimuthal deviation will be interpreted by a dipping model. Of course, the effects of anisotropy of the upper crust may be probable, but the authors consider that the former is preferable for the first approximation and the latter is auxiliary. An advantage of this model is that one can assume plane waves and theoretical deviations can be easily calculated from ray theory.

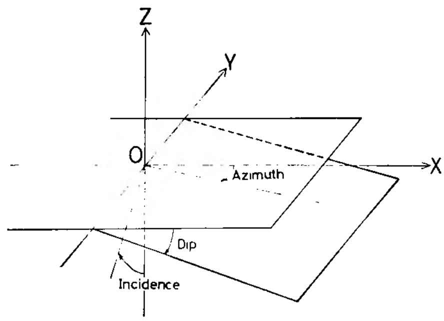

Fig. 2. Illustration of the dipping model for calculation.

In Fig. 2 a dipping model is illustrated. Some explanations would be needed about the model. By Wada and Kamo [1964] and Kamo and Kikuchi [1968], a simplified two-layered model of upper crust under the Volcano Aso was proposed from seismic wave velocities of earthquakes and explosions. They showed that the dilatational velocity of the upper layer is about 3 km/sec and that of the half-space is about 5 km/sec. They also showed that the upper layer should be fairly thick. Considering this, the upper layer of the dipping model is thought as andesitic and the depth of the dipping interface is several kilometers. The material of the lower layer can not be determined here, therefore it is only referred to as the basement. Therefore, assuming that the value of V_1/V_2 is varied from 1.0/0.3 to 1.0/2.0, where V_1 and V_2 are the dilatational velocities of the upper layer and the lower half-space, respectively, the plausible structure could be considered.

As for the incident angle it is not always easy to determine the individual value for each earthquake, and therefore the travel time model used by Sagisaka [1931], who estimated the incident angles of near earthquakes, are adopted and the incident angles from 15° to 75° are considered corresponding to the epicentral distance of the present data.

Table 2. List of three parameters, dip angle, incident angle and velocity ratio which classify the dipping models.

V_1/V_2	1.0/1.3, 1.0/1.4, 1.0/1.5, 1.0/1.6, 1.0/1.7, 1.0/1.8, 1.0/1.9, 1.0/2.0
Dip	5°, 10°, 15°, 20°, 25°, 30°
Incidence	15°, 30°, 45°, 60°, 75°

Thus, the calculation of deviation curves was made for the cases as shown in Table 2. The method of calculation is same as that of Matsuzawa as shown in Appendix. In Fig. 3 are shown the typical examples of computation for the numerical

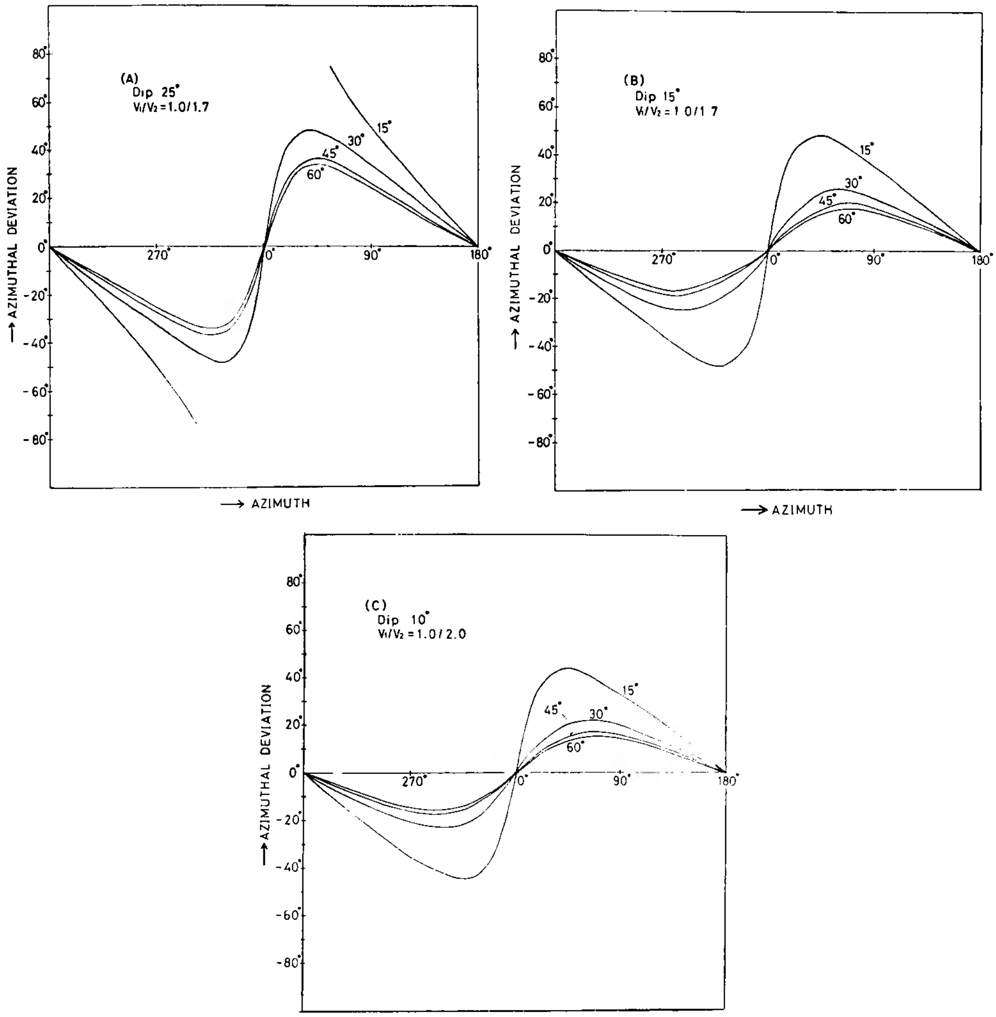

Fig. 3. Azimuthal deviations calculated from the dipping model. Each curve is marked by the value of incident angle.

values: $V_1/V_2=1.0/0.7$, $\omega=25°$; $V_1/V_2=1.0/1.7$, $\omega=15°$ and $V_1/V_2=1.0/2.0$, $\omega=10°$, where ω is dip. Among them the best fitting curve may be picked up. The curves of Case B in Fig. 3 seem to fit the data best. They are shown in Fig. 1 by dotted lines. However, the agreement is not satisfactory and then it seems impossible to interpret the deviation by applying such a simple model.

Before considering the composite model, the previous data given by Sassa may be added to the present data. The total data are shown in Fig. 4. Examining the figure, it is found that the data are divided into two contradicting groups; if we want to fit a curve to one data group, then it deviates from the other group and vice versa. Arrows in Fig. 4 show the boundary of the two groups. Hereafter one (left) is called the northern block and the other (right) called the southern block.

Finally it is found that in the northern block the data are in good accordance with the curves of Case B in Fig. 3 and in the southern block with the curves of Case A. Note that the value of V_1/V_2, 1.0/1.7, is reasonable according to the model of Wada and Kamo and that it is common to both Case A and Case B, that is, the base-

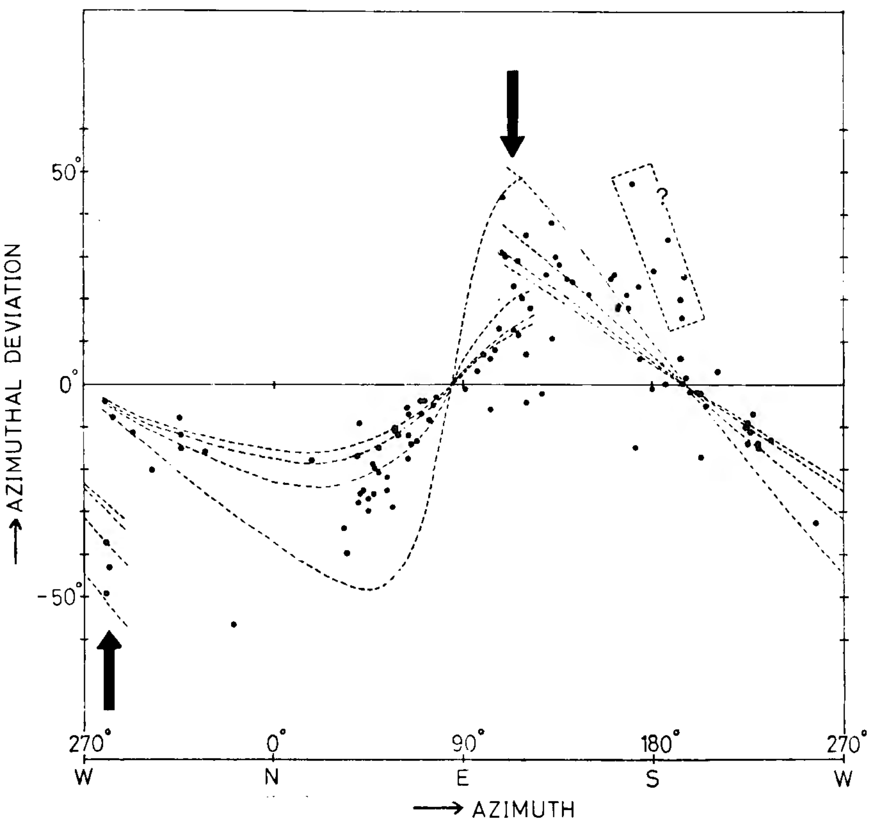

Fig. 4. Total data including the Sassa's as well as the present data and curves from the twin-blocked model. Arrows indicate the boundary of the two blocks.

ment is common to the two blocks. The best fitting curves are shown in Fig. 4 by dotted lines. As can be seen in the figure, some observed points deviate upward from the theoretical curves. These were reexamined and some explanations are given in Table 1.

From Fig. 4 the following structural model may be put forward: a tectonic line or zone runs across the center of the caldera from east to west and the northern block inclines nearly eastwards with the dip of about 15°, and the southern block inclines toward NNE with the dip of about 25°. The tectonic line or zone can be considered as a part of the so-called Ōita-Kumamoto Tectonic Line. The above mentioned model, that is to say a twin-blocked model, is shown schematically in Fig. 5.

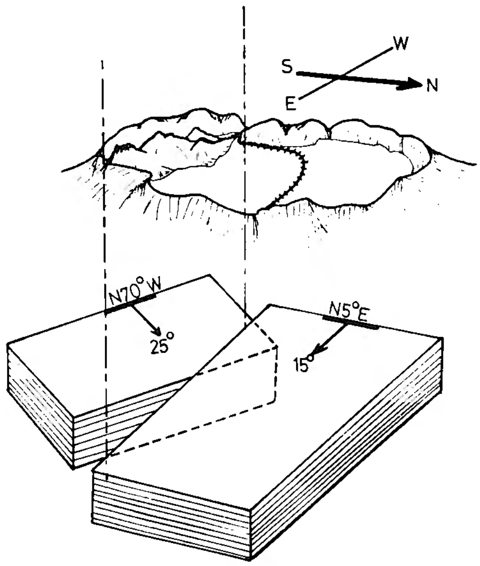

Fig. 5. Schematic representation of the structure under the Aso caldera.

With reference to the twin-blocked model some topographical facts should be pointed out. First, the chain of the central volcanoes, one of which, the Nakadake, is now active, is situated just on the tectonic line or zone. In the topographical map of the Volcano Aso, Fig. 6, is shown the chain of the central volcanoes, and the dips of the southern and the northern blocks are indicated by AA′ and BB′, respectively. Secondly, the sky-line of the caldera rim exhibits a similar inclination to that of the blocks, though the former inclination is quantitatively smaller than the latter. Fig. 7 shows the sky-line, the upper indicating the southern part of the rim projected on the vertical plane including AA′ in Fig. 6 and the lower indicating the northern part projected on the vertical plane including BB′. From the facts described above we can presume that if the caldera was formed after the formation of the fault zone, the inclination of the sky-line indicates the remaining movement of the fault.

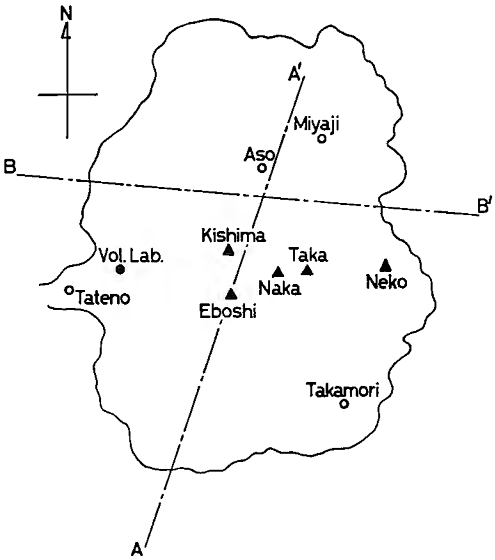

Fig. 6. Topographic map of the Volcano Aso. AA′ and BB′ show the dip directions of the southern and the northern block, respectively.

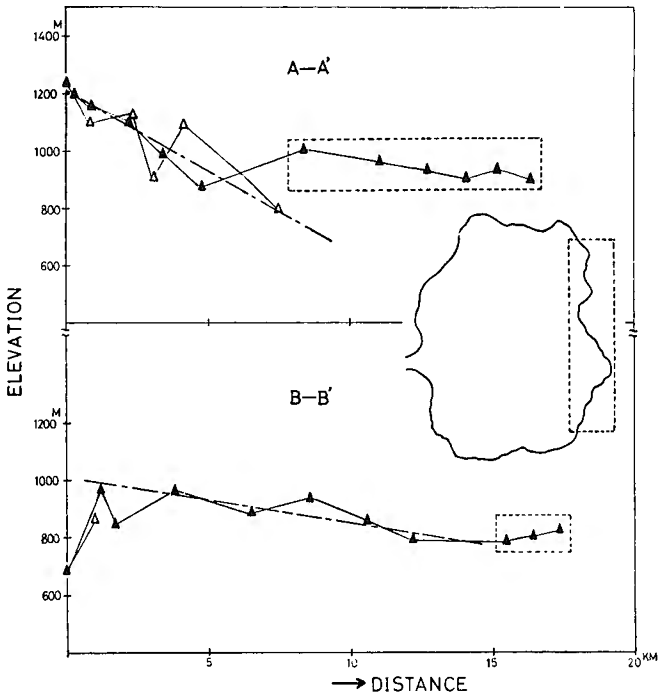

Fig. 7. Profile of the sky-line of the caldera rim projected on the section parallel to AA′ or BB′. The northern block has a dip of about 1° and the southern block of about 3°.

4. Conclusion

In this study azimuthal deviation of P wave was investigated from the Wiechert seismograms recorded at the Volcanological Laboratory of Kyoto University. By applying dipping models the following conclusions were drawn from the present data and the previous data given by Sassa:

1. A tectonic line or zone runs across the center of the Aso Caldera from east to west. This line or zone can be thought as part of the Ōita-Kumamoto Tectonic Line.

2. The chain of the central volcanoes, Kishimadake, Eboshidake, Nakadake, Takadake, Nekodake and so on, is situated just on the tectonic line or zone.

3. The northern part of the basement of the caldera inclines nearly eastwards and the southern part inclines toward NNE. Considering the similar inclination of the sky-line of the caldera rim, it may be suggested that the movement of the fault has continued after the formation of the caldera.

On the other hand it is necessary to investigate some related problems; what is the basement composed of? Relating to this we can only point out that xenolithes in the Nekodake lava are composed of crystalline schists and that granites have been found in boring cores near the northern cliff inside the caldera. The problems of formation of the fault——the age and dimension——and of the dimensions of basement blocks are yet unknown. We must leave such problems for future investigations.

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Appendix

The method of calculation of azimuthal deviation was shown by Matsuzawa [1935]. Here we follow his method.

In Fig. 2 let the imaginary intersection of the dipping interface with the horizontal surface, i.e., direction of strike, be taken as y-axis, x-axis and z-axis being in the dip-direction and vertically upward, respectively. Let the dip angle be ω, and let x'-axis be the intersection of the vertical plane containing x-axis and z-axis with the dipping interface, z'-axis be the upward normal to the interface and y'-axis be the same as y-axis.

If we donote the direction cosines of the incident ray by ($\sin\theta\cos\varphi$, $\sin\theta\sin\varphi$, $\cos\theta$) with respect to the xyz-coordinate system and by ($\sin\Theta\cos\Phi$, $\sin\Theta\sin\Phi$, $\cos\Theta$) with respect to the x'y'z'-coordinate system, the following relations should be satisfied that

$$\begin{cases} \sin\Theta\cos\Phi = \sin\Theta\cos\varphi\cos\omega - \cos\theta\sin\omega\,, \\ \sin\Theta\sin\Phi = \sin\theta\sin\varphi\,, \\ \cos\Theta = \sin\theta\cos\varphi\sin\omega + \cos\theta\cos\omega\,, \end{cases} \tag{1}$$

where the angle φ is the true azimuth.

To satisfy the condition that seismic waves arrive at the dipping interface from below, it follows that

$$\cos\Theta = \sin\theta\cos\varphi\sin\omega + \cos\theta\cos\omega > 0.$$

The refraction of the ray takes place according to Snell's law, i.e.,

$$\sin\Theta' = \frac{V_1}{V_2}\sin\Theta\,, \qquad \ldots\ldots (2)$$

where the direction cosines of the refracted ray are denoted by ($\sin\Theta'\cos\Phi$, $\sin\Theta'\sin\Phi$, $\cos\Theta'$) with respect to the x'y'z'-coordinate system. If the direction cosines of the refracted ray are ($\sin\theta'\cos\varphi'$, $\sin\theta'\sin\varphi'$, $\cos\theta'$) with respect to the xyz-coodinate system, then we obtain the following relations similar to (1):

$$\begin{cases} \sin\theta'\cos\varphi' = \sin\Theta'\cos\Phi\cos\omega + \cos\Theta'\sin\omega\,, \\ \sin\theta'\sin\varphi' = \sin\Theta'\sin\Phi\,, \\ \cos\theta' = -\sin\Theta'\cos\Phi\sin\omega + \cos\Theta'\cos\omega\,, \end{cases} \tag{3}$$

with the angle φ' being the apparent azimuth.

From (1), (2) and (3) we obtain

$$\cot\varphi' = \cot\varphi - \cot\varphi\sin^2\omega - \cot\theta\frac{\sin\omega\cos\omega}{\sin\varphi} + \frac{\sqrt{1-n^2+n^2(\sin\theta\cos\varphi\sin\omega+\cos\theta\cos\omega)^2}}{n\sin\theta\sin\varphi}\sin\omega \qquad \ldots\ldots (4)$$

where $n=V_1/V_2$.

Thus, the azimuthal deviation is obtained as $\varphi'-\varphi$ from (4).

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